The WWRP Polar Prediction Project (PPP)

Book or Report Section

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MONTRÉAL, CANADA

We are entering a new era in technological innovation and in use and integration of different sources of information for improving well-being and the ability to cope with multi-hazards. New predictive tools able to detail weather conditions to neighbourhood level, to provide early warnings a month ahead, and to forecast weather-related impacts such as flooding and energy consumption will be the main outcomes of the next ten years research activities in weather science. A better understanding of small-scale processes and their inherent predictability should go together with a better comprehension of how weather- related information influences decisional processes and with better strategies for communicating this information. Within this perspective, this book is intended to be a valuable resource for anyone dealing with environmental prediction matters, providing new perspectives for planning and guiding future research programmes.

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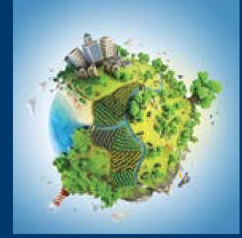

SEAMLESS PREDICTION OF THE EARTH SYSTEM: FROM MINUTES TO MONTHS

JN 15828

World Meteorological Organization
Weather • Climate • Water

WMO-No. 1156

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$$\frac{\partial q}{\partial t} + J(\psi,q) + \beta\frac{\partial \psi}{\partial x} = 0$$

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FOREWORD

The World Meteorological Organization (WMO) has always attached great importance to the global coordination of research efforts required to develop and improve weather, climate, water and related environmental services. In this regard, the World Weather Research Programme (WWRP) has made significant contributions relating to high-impact weather systems such as tropical cyclones, in particular to the application by Members of research results aimed at further improving not only early warning systems for extreme events but also reducing the damaging effects of natural weather hazards. WMO has taken the lead and co-organized the World Weather Open Science Conference (Montréal, Canada, 16-21 August 2014), the first-of-a kind event bringing together a diverse community in order to foster the science needed to make society less vulnerable to weather-related impacts.

This conference has brought together the entire weather science and user communities for the first time to review the state-of-the-art and map out the scientific frontiers for the next decade and more. The outcomes of the debates and discussions have been synthesized in this book through a peer-reviewed process.

We are entering a new era in technological innovation and in use and integration of different sources of information for the wellbeing of society and their ability to cope with multi-hazards. New predictive tools that will detail weather conditions down to neighbourhood and street level, and provide early warnings a month ahead, and forecasts from rainfall to energy consumption will be some of the main outcome of the research activities in weather science over the next decade. A better understanding of small-scale processes and their inherent predictability should go together with a better comprehension of how weather related information influence decisional processes and with a better communication strategy.

I wish to take this opportunity to sincerely thank the members of the International and Local Organizing Committees, the chairs, rapporteurs, participants and all those who assisted in the preparation of this book, for their valuable collaboration.

Finally, I would like to thank the host country, Canada, and to express my appreciation to the other sponsors for providing supplementary support. I hope that this book will serve as a useful source of information and inspiration as well as a road map for weather research worldwide in the years to come.

(M. Jarraud)
Secretary-General

PREFACE

New sources of atmospheric observations, faster supercomputers and advances in weather science together have revolutionized weather forecasting in the latter part of the 20th century. On the global scale, we can today predict out to six days ahead as accurately as we could do for four days 20 years ago. This means society has much more advance warning of weather hazards than before, allowing people to prepare and, thereby, limit the loss of lives and property.

As weather science advances, critical questions are arising such as about the possible sources of predictability on weekly, monthly and longer time-scales; seamless prediction; the development and application of new observing systems; the effective utilization of massively-parallel supercomputers; the communication, interpretation, and application of weather-related information; and the quantification of the societal impacts. The science is primed for a step forward informed by the realization that there can be predictive power on all space and time-scales arising from currently poorly-understood sources of potential predictability.

Consequently the time was right in 2014 for a major Open Science Conference to examine the rapidly changing scientific and socio-economic drivers of weather science. This conference was designed to draw the whole research community together to review the frontiers of knowledge and to act as an international stimulus for the science and its future. The first World Weather Open Science Conference (WWOSC-2014 "The weather: what's the outlook?") was held in Montréal, Canada from 16 to 21 August 2014.

WWOSC-2014 was designed to consider both the state-of-the-art and imagine the future evolution of weather science and also the related environmental services and how these need to be supported by research. The timing of the conference was also chosen to coincide with the end of the ten-year THORPEX programme of the World Weather Research Programme, enabling the knowledge arising from that initiative to be synthesised. It was particularly exciting to bring together the international community - those starting out in science and those with longer experience - to review progress and set the long-term agenda. There has never been a more important time for weather science, which is poised for further breakthroughs. Society is extremely vulnerable to weather-related impacts and desperately needs that science

The research presented at WWOSC-2014 reviewed the state of knowledge in weather and weather-prediction science. In addition it explored the many applications of weather prediction to the natural environment. The Earth System Prediction approach for weather and environmental phenomena is seen as an effective way to better address the rapidly changing and increasing socio-economic requirements for weather services. A new generation of research scientists attended the conference and will contribute to new and advanced Earth system prediction models. WWOSC-2014 raised the visibility and importance of a strong and vibrant world weather science research activity, in harmony with the needs of operational weather services and their stakeholders, in the public and the private sectors.

This book collects together White Papers that have been written to describe the state of the science and to discuss the major challenges for making further advances. The authors of each chapter have attempted to draw together key aspects of the science that was presented at WWOSC-2014. The overarching theme of this book and of WWOSC-2014 is "Seamless Prediction of the Earth System: from minutes to months". The book is structured with chapters that address topics regarding: Observations and Data Assimilation; Predictability and Processes; Numerical Prediction of the Earth System; Weather-related Hazards and Impacts. This book marks a point in time and the knowledge that has been accumulating on weather science. It aims to point the way to future developments. We hope it will be of great interest to researchers and practitioners alike. We also hope that it stimulates and excites the next generation of weather scientists. Finally, we would like to thank the authors who have contributed so much in creating this volume.

Michel Béland
(past-President of the Commission
for Atmospheric Sciences)

Alan Thorpe
(Director-General of ECMWF)

ACKNOWLEDGEMENTS

We would like to express our gratitude to all those who wrote, provided support, talked things over, read, offered comments, assisted in the editing, proofreading and design. More than 100 people, scientists, scientific officers and staff officers, have been involved in preparing this book. All of them are listed in the Afterword including the list of authors. We would like to thank Gilbert Brunet, Sarah Jones and Paolo M. Ruti for their work as the main editors.

CHAPTER 1. INTRODUCTION

Gilbert Brunet, Sarah Jones and Brian Mills

Weather prediction has achieved immense progress during the last few decades, driven by research, by the development of an increasingly sophisticated infrastructure such as telecommunications, computational and observational systems, and by the expectations of users of weather information. Predictive skill now extends in some cases beyond 10 days, with an increasing capability to give many days early warning of severe weather events. At shorter lead times more detailed forecasts of the structure and timing of weather-related hazards can be provided. The concomitant development of ensemble methods now routinely provides essential information on the probability of specific events, a key input in numerous decision-making systems. Partly because of these advances, the needs of the users have simultaneously diversified, and now routinely encompass “environmental” prediction products, such as air quality or hydrological predictions.

This progress has been possible because of the research and technical developments carried out in operational centres, academic institutes, by surface and spaced-base observational data providers and in the computing industry. Over the last decades a number of major international research programmes have been critical in fostering the necessary collaboration. In particular, the World Weather Research Programme (WWRP) and THe Observing System Research and Predictability Experiment (THORPEX) have been major initiatives to accelerate this progress. As the science is advancing critical questions are arising such as about the possible sources of predictability on weekly, monthly and longer time-scales; seamless prediction from minutes to months; optimal use of local and global observing capabilities and the effective utilization of massively-parallel supercomputers. The science is primed for a step forward informed by the realization that there can be predictive power on all space and time-scales arising from currently poorly-understood sources of potential predictability.

Consequently, the time was right for the first major World Weather Open Science Conference (WWOSC-2014) to examine the rapidly changing scientific and socio-economic drivers of weather science. The Open Science Conference was designed to draw the whole research community together to review the frontiers of knowledge and to act as an international stimulus for the science and its future. Hence, this conference considered the state-of-the-art and the future evolution of weather science and also the related environmental services and how these need to be supported by research. These discussions were informed by research presentations and input by both providers and users of weather and environmental prediction services. The merits of key components of modern operational systems were discussed in depth, as well as the major scientific challenges still facing the community. The event also provided an important platform for early career scientists to obtain an overview of the state-of-the-art of weather science, to enter into discussions with established scientists, and to build their own network of early career scientists. The conference was co-sponsored by major scientific and operational bodies such as Environment Canada, National Council Research Canada, World Meteorological Organization (WMO) and the International Council for Science (ICSU). Finally, the World Weather Open Science Conference, attended by more than 1,000 meteorologists, forecasters, social scientists and application developers from 57 countries, has laid the foundations to face future challenges. The highly successful Conference, held in Montreal from 16 to 21 August, 2014, achieved its grand goal to chart the future course of scientific research and its potential for generating new and improved weather services.

The overarching theme of the conference was “Seamless Prediction of the Earth System: from minutes to months”. The conference highlighted recent advances in weather science and in the science and practice of weather prediction. The conference considered also areas where a predictive capability is emerging, including for a range of aspects of the natural environment, to provide predictions of importance in a range of different socio-economic sectors.

In this context the Earth system, and environmental prediction, encompasses the atmosphere and its chemical composition, the oceans, sea-ice and other cryosphere components, the land-surface, including surface hydrology, wetlands, and lakes. It also includes the short time-scale phenomena that result from the interaction between one or more components, such as severe storms, floods, heat waves, smog episodes, ocean waves and storm surge. On longer (e.g. beyond seasonal climatic) timescales, the terrestrial and ocean ecosystems, including the carbon and nitrogen cycles, and slowly varying cryosphere components such as the large continental ice sheets and permafrost are also part of the Earth system, but these timescales were not the subject of this conference.

Conference speakers, panels and the audience investigated the opportunities for achieving major breakthroughs in weather science at the same pace as in the last 20 to 30 years if not more rapidly.

The scientific programme was organized around five science themes:

- The Data Assimilation and Observations research theme covers understanding and improving our current and future observational capability and ensuring it is used optimally for forecasting high-impact weather through advances in data assimilation. This research contributes to the international efforts to optimize the use of the current WMO Integrated Global Observing System (WIGOS), to design regional observing networks, and to develop well-founded strategies for the evolution of observations to support Environmental and Weather Prediction primarily for timescales of minutes to one season.
- The Predictability and Dynamical/Physical/Chemical Processes theme covers the knowledge of the dynamical, physical, and chemical processes needed to advance our understanding of the sources of predictability for seamless prediction of the Earth system. It includes evaluation and improvement of parameterizations and explicit representations of dynamical, physical and chemical processes in numerical weather prediction (NWP) systems. It provides the link between field programmes, especially those associated with WWRP and THORPEX, and dynamics and predictability of high-impact weather events. It considers fundamental research into the design and utilization of ensemble prediction systems. This theme connects research in the academic dynamical/physical/chemical meteorology communities and the operational numerical weather prediction centres.
- The Interactions between Subsystems theme covers research into the fundamental processes that determine these interactions, the technical developments needed to couple models of the interacting sub systems, and the evaluation of the resulting coupled system. It focuses on the coupling (one or two-way) of two subsystems for prediction from a few hours to one season and for regional and global modelling forecasting applications. Interactions consider the following subsystems: atmosphere, land-surface, ocean, sea-ice, chemistry and eco-systems.
- The Numerical Prediction of the Earth system: putting it all together research theme covers the development, the verification and the application of coupled NWP systems. The advances discuss in this theme build on the science of the previous three themes and result in state-of-the-art environmental forecasting systems for the atmosphere, ocean, cryosphere, land-surface, hydrology, and air-quality. The predictive skill of these NWP systems is such that they need now to be coupled to other physical subsystems; i) to be able to continue improving their predictive skill; and, ii) to respond to an increase demand of new environmental applications.
- The Weather-related Hazards and Impacts theme, jointly convened with the User, Application and Social Science programme, covers research that combines advances made in observing systems, coupled NWP systems and new technology to provide decision-level information related to both hazards and impacts. With respect to hazards it includes techniques to merge information from observations and NWP towards seamless prediction at short time and space scales, applications such as meteorological workstations, and advances in the forecasting process including semi-automation of warnings to support operational meteorologists In addition, research into vulnerability and exposure for both single hazards and multi-hazards is included. With respect to impacts it focuses on the interactions between weather-related hazards, events or conditions, and important biophysical systems that are known to produce substantive societal consequences. Here emphasis is placed on research that quantifies impacts along with our ability to predict them using both deterministic and probabilistic methods, and lends itself to inclusion in decision support systems. Weather events on

timescales, from minutes through to a season, and many types of hazard (acute and chronic) including muliti-hazard scenarios are considered. Example applications include models developed to estimate hydrologic or water quality conditions and attendant impacts (inundation, drought, and pollution), storm surge and structural wind damage, agricultural production, forest fire occurrence, energy demand, aviation hazards, and health-related outcomes from air pollution or excessive heat.

In addition to these five themes, the three THORPEX legacy projects were discussed and presented in specific sessions:

- The WWRP Polar Prediction Project (PPP) that aims to promote cooperative international research that will enable the development of improved weather and environmental prediction for polar regions on the time-scale of hours to days.
- The Sub-seasonal to Seasonal Prediction Initiative, which is a joint WWRP- World Climate Research Programme (WCRP) project to improve forecast skill and enhance knowledge of processes on the sub-seasonal to seasonal timescale with a focus on the risk of extreme weather, including tropical cyclones, droughts, floods, heat waves and the waxing and waning of monsoon precipitation.
- The High-Impact Weather (HIWeather) project to promote cooperative international research to achieve a dramatic increase in resilience to high-impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications for a set of weather-related hazards: urban flood, wildfire, localized extreme wind, disruptive winter weather, urban heat waves and air pollution.

The aim of the user, applications and social sciences programme was to provide an open forum where the experiences and perspectives of a variety of information providers and users could be combined with the latest applications and methodological advances in social science to:

- Demonstrate and document recent progress, highlighting and sharing lessons from both successful and 'less successful' projects and applications.
- Identify and deliberate areas of practice, social science research methods, and training and education requiring new or continued attention.
- Expand and connect the interdisciplinary weather and society community.
- Develop conference positions and recommendations regarding the state and advancement of knowledge and practice.

Three focal areas were targeted for examination during the conference:

- Individual, collective, and institutional behaviour in response to the communication, interpretation, and application of weather-related information in decision-making.
- Understanding, measuring, and predicting the societal impacts of weather and the costs, benefits, and other impacts of weather-related information.
- Better practices and guidance for designing, implementing, evaluating and sustaining decision support systems and tools.

1.1 CHALLENGES AND PRIORITIES FOR WEATHER SCIENCE

1.1.1 Observations and data assimilation

A well-designed observing system is prerequisite for seamless prediction of the Earth system. Observations are essential for nowcasting, for initializing NWP models, as well as for evaluating both the individual components (e.g. parameterizations) and the end products of a seamless prediction system. The last fifty years have seen great progress in the availability of innovative observations of many geophysical variables on various different spatiotemporal scales; especially the environmental satellite network. Weather radar, lightning detector, ceilometers and other evolving instruments, including opportunistic observations like Global Navigation Satellite System, are expected to play an increasingly important role in future. The continuous exploitation of these observations with new observing platforms is now the priority. A major future challenge is to provide high-resolution observations networks for convective-scale NWP, whilst maintaining global observational coverage, including burden sharing at international level. Opportunities for the future observing system include synergetic use of different ground-based remote sensing systems, exploitation of new satellite platforms and sensors, full utilisation of in situ observations and integrating new sources of data such as from crowd sourcing. Forthcoming environmental prediction systems will necessitate also a greater span of parameters (e.g. river flow, atmospheric pollutant concentration and aerosol).

Data assimilation is the foundation stone of numerical weather prediction bridging models and observations. Data assimilation methods combine increasing number and variety of observations with prior probabilistic information on flow-dependent model error. Pushing the limit of spatial resolution toward convective scale and forecast lead time to sub-seasonal scale will unfold a new landscape of predictability, model uncertainties and ensemble prediction issues.

Data assimilation systems must account for the NWP model and observation error characteristics in the evolving global observation network. Only about 20% of most satellite data are actually assimilated because of difficulties in using the data over land, cloud and sea-ice, and the need to thin the data to diminish horizontal error correlations between measurements. A key challenge is to increase the amount of satellite used in these areas. As an example in cloud area the highly nonlinear and multi-variable characteristic of precipitation forbid active microwave rain radars to be assimilated in operational systems. To prioritize the research agenda on the utilization of observations, different and complimentary methodologies to address forecast sensitivity to observations have been developed like variational based and the more costly observing system experiments, real and simulated. Observation impact information is being used also for cost-benefit studies to guide the design of the future global observing system.

Variational data assimilation algorithms like 4D-Var can accommodate large numbers of observations. Nevertheless such algorithms require significant NWP model dependent infrastructure and representation of model errors requiring linear modelling of complex physical and dynamical processes. They also do not fully account for the model and flow-dependent prediction error characteristics. In contrast with 4D-Var, an ensemble data assimilation scheme typically requires fewer infrastructures and is less dependent on model. The ensemble permits fully flow-dependent error representation. Especially for increasing ensemble sizes, they scaled very well on massively parallel high performance computer (HPC). The advantages of both approaches have been implemented successfully in hybrid data assimilation schemes in numerous NWP centres. As horizontal resolution is increasing, data assimilation methods will need to tackle more assimilation of observations with non-Gaussian error distributions, like cloud and precipitation. This will be important challenges for both the variational and ensemble schemes. In the latter more physically based stochastic perturbation approaches perturbing the physics tendencies will be needed.

Major international field campaigns provide opportunities to both test scientific hypotheses and to test and develop new observing systems and observing strategies. Data assimilation methods can be used in the experimental design for field campaigns; the additional observations obtained can contribute to testing and developing data assimilation systems. Field campaigns designed to advance the science of weather forecasting require are increasingly dependent on strong international cooperation and the participation of academic and operational research scientists.

1.1.2 Processes and predictability

Advances in our knowledge of the fundamental processes that determine weather-related hazards allows us to identify the factors that limit their predictability, evaluate weaknesses in forecast systems, and identify potential for significant improvements. Significant progress has been made in understanding the fundamental role of diabatic processes in the development and structure of weather systems and in tropical - extratropical interactions but open questions remain. In particular, the impact on predictability of organized convection on synoptic-to-planetary scale motions through the triggering and modification of Rossby wave trains should be identified. Further challenges are linked to identifying and predicting the fine-scale structure in weather systems, such as the distribution severe surface winds.

A key research goal in NWP is to quantify and reduce uncertainties in the representation of processes in numerical models relevant to the improvement of predictive skill. It includes evaluation and improvement of parameterizations and explicit representations of dynamical, physical and atmospheric composition processes in NWP systems through numerical experiments and field programmes studies. The representation of sub-grid physical processes with increasing spatial resolution will need to be revisited, especially for convection parameterization schemes where their underlying physical-statistical premises break down in the so-called “grey-zone” (horizontal resolution of 4 to 10 kilometres).

The modelling of diabatic and dynamical processes for convective clouds for the prediction of midlatitude and tropical weather systems is an outstanding challenge, including cloud micro-physics processes crucial for accurate quantitative precipitation prediction and types. The representation of tropical convection remains particularly difficult with most global models struggling with convective organization and the diurnal cycle. The accuracy of NWP forecasts is hugely sensitive to errors in the representation of convection that can have significant influence on the nonlinear dynamics associated with intensification of tropical cyclones. Making significant progress may require challenging some of the traditional paradigms for parameterization with future convection schemes across multiple columns that have memory and an inherent representation of uncertainty. They will also have to be scale-aware and able to cope with the problem of convection becoming partially resolved like in the grey-zone.

Eventually the advent of global convection-permitting numerical weather prediction models that have resolutions of the order of 1 km and increasingly represent explicitly nonlinear and turbulent processes will avoid the convection grey-zone issue. This will be a significant step forward to improve prediction of mesoscale weather systems and their interaction with synoptic scale circulation. These NWP systems of the future will be significantly larger as a computational task than today and would require significantly more power than is available with existing HPC technology. Hence a change of paradigm is needed regarding hardware, design of codes, and numerical methods. Various numerical innovative methods will need to be developed addressing numerical stability, accuracy, computational speed and flexibility to deal with more prognostic variables, and the interaction between resolved and unresolved dynamical and physical processes. The new numerical methods challenges will need to revisit choice of spatial discretization, the time stepping method and the treatment of boundaries.

The future modelling and observational challenges for atmospheric chemistry will include better: i) transport and dispersion of chemical species; ii) cloud microphysics, especially interaction with aerosols; iii) radiative transfer; and iv) turbulent fluxes in the boundary layer. The first is one of the most crucial requirements for the next generation of numerical schemes for global meteorology atmospheric composition models. The numerical schemes will need to have better conservation, shape-preservation and prevention of numerical mixing or unmixing. The latter is important since inaccurate mixing is similar to introducing erroneous chemical reactions. Eulerian flux-based schemes are suitable for mass conservation, but several semi-Lagrangian mass conservative schemes are now available.

In addition to cloud and convective processes we need to understand how radiation works to shape the water cycle and energy balance. Water and energy connect globally and then systematically in terms of finer and finer scales to the cloud microphysics level including cloud-aerosol interactions important for precipitation. There will be limited progress in environmental prediction unless a more accurate modelling of the water and energy budget is achieved.

An essential component of NWP is an ensemble prediction system to quantify the uncertainty in weather forecasts. Major advances have been made in designing ensemble prediction systems on the global and more recently for convective-scale forecasts. Particular challenges are associated with specifying the uncertainty in the initial conditions and in the representation of physical processes in the NWP model. The development of post-processing techniques and tailored forecast products are further priority research areas. Ensemble prediction systems can also be used to extend our knowledge and understanding of the processes that determine the evolution of weather systems and

limit their predictability. The THORPEX Interactive Grand Global Ensemble (TIGGE) database has been particularly effective in this respect.

1.1.3 Interactions between subsystems

The demonstration that many components of the Earth system (e.g. atmosphere, oceans, cryosphere, land-surface, hydrology, composition,) are influential for medium-range weather predictions is more and more evident (numerous references are available). Also analyses and predictions of these subsystems, on a wide range of time-scales, have significant socio-economic benefits. Hence NWP is now evolving into numerical weather and environmental prediction. The trend to include various environmental interactions in atmospheric models, initiated in the 1970s, will continue. It is very likely that the models will be used increasingly to address problems of environmental emergencies and management of ecosystems. The potential for new applications linking the environmental models and the economy is vast. This will get even larger with the increasing realism of the sub-models representing chemical processes, hydrology, the biosphere, and ocean circulation.

To attain these objectives we will need to better understand fundamental processes that determine the two-way interactions between the atmosphere, land-surface, ocean, sea-ice, air composition and eco-systems.

The land surface and the atmosphere interact through the global water cycle (exchanges of precipitation and evaporation) and control high-impact environmental events from regional to continental scales like floods and droughts. The latter can potentially be predicted because the land surface states vary more slowly than do the atmosphere. A better representation of the water cycle will open the way to more accurate prediction of floods and will most likely lead to better water management of large catchments such as the Great Lakes and St-Laurence river water levels. One of the major sources of error in hydrological predictions is due to uncertainties in the predicted rainfall.

The water cycle is closely connected to the energy cycle (e.g. latent heat flux and evapotranspiration) and the carbon cycle (through the vegetation transpiration and carbon uptake through photosynthesis). One challenging aspect is the chain of linkages between the surface processes, boundary layer and cloud formation that models must represents over hundreds square kilometres. If one sub-model is highly accurate but others are significantly in error, the overall simulation of land-atmosphere feedback will be poor. The utilization and interpretation of observations for calibration and validation to address such issue is challenging, especially to assess the long-standing diurnal cycle problem. They are typically in situ measurements and area averages, like satellite pixels, which are smaller than the model spatial resolution or larger like catchment runoff. More accurate representation and validation of these processes in Earth system models are crucial to close properly the water and energy budget and achieve eventually increase predictive skill.

Meteorology atmospheric composition modelling has developed significantly in the last decade for air quality applications like smog and pollen warnings, forecasting of hazardous plumes from volcanic eruptions, forest fires, oil and gas fires and dust storms. Mainly developed to account the effects of meteorology on air quality, they are also used more and more to understand better the possible feedbacks of the atmospheric composition on NWP predictive skill, especially by changing the radiation budget or ultimately by affecting cloud formation and precipitation. There is still a long way to go for near-real-time weather and chemical data assimilation to improve both weather and chemical weather forecasts, but the retrieval of satellite data and direct assimilation of radiances is likely to achieve this. Some encouraging results are emerging like the positive impact of assimilation of ozone on the wind fields.

Ocean-sea-ice-atmosphere interaction is one of the key challenges of weather and climate prediction from days to seasons. For example, there is evidence that the evolution of hurricanes on time-scales of 3-7 days can be significantly influenced by the presence of a coupled ocean in numerical prediction models. This and other societal needs has led NWP centres to add interactive components such as a coupling to an ocean-sea-ice circulation model even from day zero in weather predictions. An example is the demand for atmosphere-ocean-ice forecasts is being amplified by the increased economic activities in the Arctic. This is not without challenges like the low observational data density in the ocean, including sea-ice, makes data assimilation difficult and better air-sea exchange parameterizations at high wind speeds is needed. Also some consideration will be required for ensembles in coupled systems, and particularly to the potential for improving ensemble spread through perturbed ocean initialisations and/or perturbed ocean parameters.

Research in the last three decades on tropical modes of ocean-atmosphere interaction, like the El Niño/Southern Oscillation (ENSO) oceanic phenomenon and its complex interaction between the large-scale tropical atmosphere and organized moist convection, has permitted significant advances in seasonal prediction. Similarly research in the intra-seasonal variability has point out another ocean-atmosphere interaction mode, the Madden-Julian Oscillation (MJO), as an important source of predictability. MJO modulates significantly the mid-latitude intra-seasonal variability through tropical and mid-latitude teleconnections, like the Canadian winter temperature and precipitation. Another example is the two-way link between the MJO and the North Atlantic Oscillation (NAO) modulates significantly weather regimes over western Europe. This has important consequence in terms of the predictability of the global atmosphere.

1.1.4 Numerical prediction of the Earth system

The skill of global numerical weather predictions has significantly improved. These days' weather forecasts involve precise and reliable probabilistic numerical predictions estimating the range of likely future weather conditions. The advances in global Numerical Weather Prediction (NWP) made in the past decades are mainly due to:

- Reducing numerical errors through more accurate and efficient numerical techniques and increased spatiotemporal resolution, enabled by increasing supercomputer capacity.
- Improving the quality of the initial conditions by developing data assimilation methods that optimally combine the increasing number and variety of observations with prior information from forecasts.
- Improving the representation of physical processes, using fundamental meteorological research on: clouds, convection, sub-grid scale orographic "drag", surface interactions, aerosols, etc.
- Enabling the design of reliable ensemble predictions through the inclusion of initial condition and model uncertainties such that probabilities can be estimated by using an ensemble of realizations.

World leading global forecasting systems in 2015 operate with around 20-50 ensemble members and a horizontal resolution in the range 13 to 50 km with of order 100 vertical levels. We can currently predict large-scale weather patterns and regime transitions out to a month or more ahead and high-impact events, such as tropical cyclones, out to two weeks ahead. Under certain conditions, even sub-seasonal to seasonal forecast has some predictive skill. In a decade from now global NWP will approach convective-scale resolutions with more accurate quantity precipitation forecast.

An adequate representation of high-impact weather phenomena such as severe summertime convection, intense localised wind, or winter weather requires higher resolution and a more accurate representation of key physical processes than can be achieved in current global forecasting systems described above. Regional NWP systems operated at km scale allow for a better description of physical processes leading to an improved description of the atmosphere such as a better representation of the interaction with the land surface and of the diurnal cycle. Furthermore, km scale resolution allows deep convection to be simulated explicitly rather than parameterized. Recognition of the high uncertainty associated with high-impact weather has led a number of centres to run a convection-permitting ensemble rather than just a deterministic regional forecast. Challenges in regional NWP are associated with developing scale-aware parameterizations with a consistent coupling of different schemes, with dealing with partially-resolved processes such as shallow convection and turbulence, and with the design of initial-condition and model ensemble perturbations for convection permitting models.

As the NWP system skill increases more and more components of the Earth system (e.g. atmosphere, oceans, composition, land surface, cryosphere) need to be taking in account to maintain progress. We are approaching a new era of environmental prediction where these geophysical subsystems coupled to the atmosphere need to be better simulated not only for advancing weather prediction, but also to provide new forecasted variables (e.g. river flow and sea ice) with undeniable socio-economic benefits.

Overall demand has grown for many environmental prediction systems. As an example air quality can degrade with increases in population and industrial capacity, particularly in urban areas and megacities, which increases the need for air quality forecasts. Water management has also become a more important issue as the scarcity of potable water spreads and urban and river flooding effects more people as population densities have grown rapidly in areas at risk, such as coastal plains and river valleys.

Hence it will become increasingly important at convective-scale (and sub-kilometre scale) resolution to include a realistic representation of the effects of large cities for reliable prediction of the water cycle, energy budget and the atmospheric flows and dispersion in complex urbanized environments. New land cover databases are needed to describe the spatial distribution and variability of urban areas and a general classification method based on satellite imagery is needed. In this context, high-resolution numerical modellers will need to develop techniques for how to treat surfaces where the roughness elements are (much) taller than the lowest model level (typically 10 m for a convective-scale resolution model). It will also be necessary to develop a methodology to characterize the spatial and temporal distributions of anthropogenic heat emissions from large metropolitan areas. This will have to be tested over major world cities using detailed observations from urban field campaigns.

The development of more sophisticated forecasting systems from global to urban scale requires research into new approaches to verifying the forecast quality. Challenges are associated with verification of probabilistic forecasts, developing user-relevant forecast evaluation, accounting for uncertainty in observations, and developing appropriate methods for longer range forecasts.

1.1.5 Weather-related hazards and impacts

The seamless weather prediction system of the future must provide accurate and timely information on a range of time and space scales regarding the location, timing, and structure of weather-related hazards. This information can make an effective contribution to mitigating the impacts of weather-related hazards only if it is translated into products suitable for end users and communicated in a manner that allows it to be integrated directly into the decision-making process. Different regions of the world are faced with different weather-related challenges, have different technological capabilities with regards to observations, nowcasting and NWP, and different socio-economic and cultural factors to consider. Furthermore, aspects such as growing population, increasing urbanization and increasing reliance on complex infrastructures and networks influence the demands on weather forecasting. These challenges must be taken into account as progress is made towards developing seamless high-impact weather forecast systems.

In this context, the concept of seamless prediction includes the provision of consistent products and services irrespective of the method used to produce them and the lead times involved. The future high-impact weather forecast system will combine observations, nowcasting techniques and probabilistic NWP using scientific and technological tools to deliver tailored output to the end-user. The role of the forecaster depends on both the weather situation and on local and regional needs and resources. Input from the human forecaster will focus on interpretation and decision-making as well as on the creation and communication of final products. Automation will become increasingly important and require innovative scientific and technological developments.

Improvements in the provision of weather information must be translated into improved use of this information in critical decision-making. Challenges include understanding and quantifying weather impacts, accounting for and communicating forecast uncertainty, dealing with a wide range of stakeholder requirements, providing actionable information, and incorporating weather data and information into the decision-making process effectively. Research and development aimed at improving the decision-making process requires effective collaborations between a broad range of professionals in an interdisciplinary framework that brings physical and social scientists together. Particular focus should be given to societal impacts, working closely with forecast end users to better understand and quantify weather-related impacts, as well as developing strategies for communicating information that will enable end users to more effectively manage risk.

1.2 CHALLENGES AND PRIORITIES FOR USER, APPLICATION AND SOCIAL SCIENCES

Despite all of the progress and advances in scientific understanding, monitoring, prediction, computing, telecommunications, and specialized services alluded to previously, major loss event statistics such as those offered in Figure 1 from Munich Re constantly remind us of the gaps between scientific knowledge and its beneficial application to both routine and complex weather-related problems facing society[a]. Describing, measuring, analysing, explaining and addressing these gaps is the subject matter for social and interdisciplinary scientists working in close collaboration with those affected by weather and related hazards, those charged with the responsibility of managing risks and consequences, and of course elements of the weather enterprise.

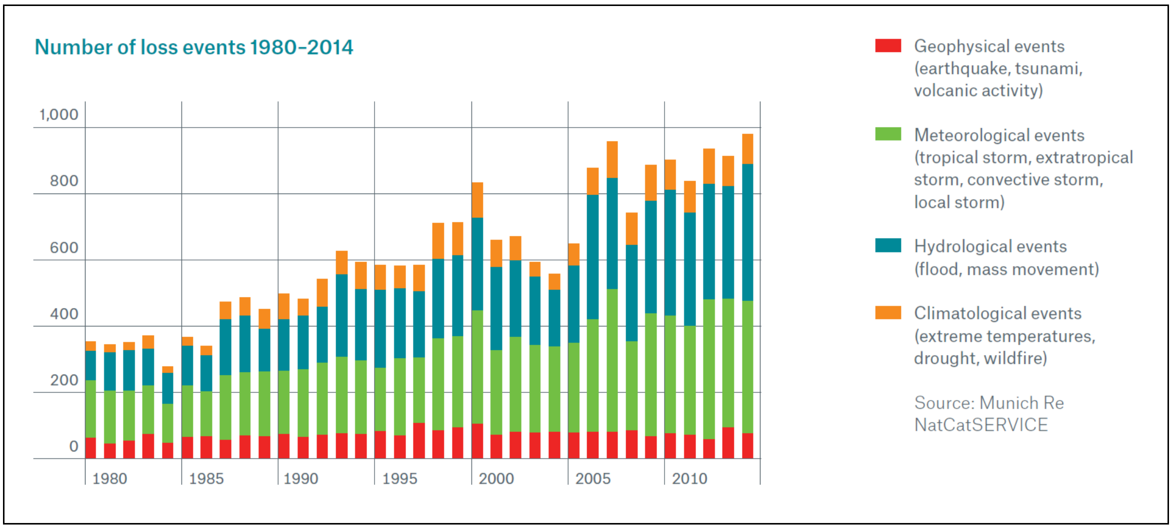

Figure 1. Number of loss events 1980-2014 (Munich Re, 2015)

The weather enterprise is the cumulative effort of individuals, businesses, and organizations to produce, communicate, interpret and apply knowledge concerning weather and its interactions with, and implications for, society for individual or collective benefit. It includes National Meteorological and Hydrometeorological Service (NMHS) organizations, the traditional source of weather observations, forecasts, and warnings, but is increasingly comprised of private enterprises and non-government organizations that provide, communicate, and tailor weather and related risk or impact information, advice and services to others in support of their decision-making.

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[a] *Interestingly this observation remains as valid in the 21st century as it was when initially identified in the 1940s (see White 1945, White et al. 2001)*

Modern social science inquiry into aspects of the weather enterprise may be traced back to the human ecology and hazard traditions in geography (e.g. White, 1945; Burton et al. 1978), disaster orientations in sociology (e.g. Carr 1928, Fritz and Williams 1957, Quarantelli 1978) and anthropology (e.g. Wallace 1956, Tory 1978), and value-of-information research in economics and decision science (e.g. Thompson and Brier 1955, Lave 1963, Nelson and Winter 1964). The weather enterprise has also been taken up as the subject of psychology, social-psychology, and communication studies.

The contemporary state of social science research was on display through the presentations and remarks delivered by over 100 speakers in over 25 sessions of the User, Application and Social science (UAS) programme of the WWOSC-2014. The UAS touched upon a broad spectrum of research questions, methodological issues, and weather-sensitive issues, topics, and sectors. These included relatively mature application areas having well-developed relationships with service providers (e.g. energy, transportation, agriculture), emerging areas with tremendous benefit potential (e.g. health, disaster risk reduction and management), and sessions focused on under-studied topics critical to the future exploitation of weather-related knowledge (e.g. bridging disciplinary and practitioner boundaries, communication of weather and related risk information, future of the weather enterprise).

While not fully comprehensive, the material and opinions shared during and immediately following the WWOSC-2014 provided an impressive snapshot of reflections on social science achievements over the past decade and remaining challenges that serve as directions for future research and organizational change. A few of the more salient and widely supported ones are noted below. Given the breadth of UAS topics, more detailed and focused session summaries are being submitted to specific journals (see Jancloes et al. 2015, for a health session example) with a synthesis or collation to be developed for a future WMO publication.

1.2.1 Dissolving disciplinary, professional, and expert-public boundaries

The advancement receiving the strongest support from WWOSC-2014 participants related to improvements in understanding and working across disciplinary, professional, and expert-public boundaries. The epistemological wall that was perceived to have diminished the relevance or questioned the legitimacy of social science and substantive user engagement within the domains of meteorological research and NMHS operational communities prior to 2000 has been significantly eroded. In part, this change has been facilitated in a top-down manner by the recognition of the value of social sciences within the WMO and other international bodies (e.g. WMO 2015, International Social Science Council (ISSC) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) 2013); national academies and professional associations, especially through their various meetings (e.g. American Meteorological Society, European Meteorological Society); large industries promoting and investing in weather-risk research and development (e.g. re-insurance); NHMS organizations, several of which regularly contract out or hire staff with social science expertise (e.g. Australian Bureau of Meteorology, UK Met Office, Finnish Meteorological Institute); and funding agencies which often require some level of involvement from social and applied sciences or justification of research in terms of anticipated societal benefit.

Even more crucial to this advancement has been the bottom-up involvement of weather-sensitive enterprises and organizations in jointly defining research problems and co-producing research (e.g. City of Toronto Health, or the collaboration between Deutscher Wetterdienst and University of Berlin - Weissmann et al. 2014); private sector expansion to develop and serve emerging weather information needs; formation of multi-disciplinary teams and programmes at academic and other research institutes (e.g. National Center for Atmospheric Research (NCAR)-Societal Impacts Programme, Asia-Pacific Economic Cooperation (APEC) Research Center for Typhoon and Society, International Research Institute for Climate and Society); and training, exchange, and visiting scholar programmes that have explicitly encouraged communicating, learning and sharing across disciplines. Through programmes such as Weather and Society*Integrated Studies (WAS*IS) (Demuth et al. 2007) and smaller-scale exchanges, scientists and practitioners trained in social or physical sciences are becoming familiar with the methods, concepts, limitations, and strengths native to multiple disciplines. This exposure, especially early on in a given career path and often maintained through social media connections, has opened new opportunities for the next generation of truly inter- or trans-disciplinary research and has provided essential capacity for NMHSs to begin extending their role, in collaboration with partners, into impact-based forecasting and risk communication. Significant organizational, funding, and other challenges remain to sustain and improve upon the progress made over the past decade, however, it is generally no longer acceptable to conduct large natural science projects without social, interdisciplinary, or applied elements.

1.2.2 An expanding volume of research

The number of researchers and volume of social and interdisciplinary science focused on weather and climate has expanded considerably over the past decade, a point reinforced by the large contingent of projects and applications represented at the WWOSC-2014 and by even a cursory review of the peer-reviewed literature. Perhaps as or more important, is the growing breadth of outlets in which this research is being published (e.g. Accident Analysis and Prevention, Applied Cognitive Psychology, Energy Economics, Journal of Ecological Anthropology, Journal of Risk Research, Journal of Urban Planning and Development, Tourism Management). While articles are still often targeted to the major meteorological journals such as the Bulletin of the American Meteorological Society, Meteorological Applications, Climate Change, or Climate Research - where social scientists were communicating with and to natural scientists - research is now finding a place in a greater range of disciplinary journals within social science which potentially entrains new social scientists into examining weather-related topics. New publications dedicated to the emerging space between the social sciences, meteorology and climatology (e.g. Weather, Climate and Society) are fostering multi- and interdisciplinary research. There remains a significant regional bias towards Europe and North America that must be addressed, both in terms of the study subject matter and the home institutions and agencies of the funded investigators. Clearly there is also a need to incorporate findings from non-English literature, conference proceedings, and other meetings.

1.2.3 Quality and framing of research

Many UAS participants noted that researchers were beginning to tackle more complex research questions with commensurate sophistication in study designs, methods, and novel data sources, often borrowing from other well-developed application fields (e.g. health promotion, transportation demand, behavioural economics). Certainly the significant progress that has been made in developing impact models with societal dimensions, for example for storm surge inundation, agricultural crop yields, electricity demand, wildfire propagation, and heat-related mortality, is laudable and a bold step towards the Earth system prediction initiative for the twenty-first century envisioned by Shapiro et al. (2010). A major challenge is to adequately deal with the dynamic nature of people and society and to test the underlying assumptions contained in such impact models. At an individual level, this means accounting for changing attitudes, beliefs, actions and behaviours of people upon which such models make hefty assumptions. At a macro level, even when well-understood, social and technological change coupled with shifts in the economic, political, and environmental landscape continuously alter the operating context thereby creating new risks and opportunities and demands for weather-related knowledge (e.g. renewable energy).

More importantly, however, such impact research is framed squarely within the structure, approaches, and questions of the physical sciences with an underlying assumed utility in more precise and accurate information. An equally significant advancement, but one needing further development, has been the reframing of the ‘weather’ problem using social science perspectives and concepts, including vulnerability, resilience, risk perception and communication, and various behavioural and decision theories. The notion that tools and techniques from economics, social psychology, evaluation and knowledge utilization research can be used assess, reflect upon, and improve the weather enterprise - and not just defend its budget allocation - has come. While the overall quality of weather-focused social science research has improved, there is also a general need over the next decade to expand the modest amount of critical and theoretical research which one would expect in a mature field of study.

1.3 AIMS OF THIS BOOK

In the long term, improvements in weather forecasting will continue along the lines denoted by the conference themes. This book reviews the different emerging research challenges related to the themes of the science programme that will need particular attention in the future. The material presented in this book is based on white papers developed by the convenors of the individual sessions of the science programme. Each chapter reviews the state-of-the art for a particular theme and discusses future challenges that need to be addressed in the next decade so as to improve the seamless prediction of the Earth system from minutes to months.

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CHAPTER 2. OBSERVATIONS FOR GLOBAL TO CONVECTIVE SCALE MODELS

R. Saunders, S. Crewell, R. Gelaro, P.J. Minnett, V-H. Peuch, J. Schmetz, D. Turner and C. Velden

Abstract

Substantial progress has been made in global numerical weather prediction (NWP) through advances in data assimilation and the availability of better and novel observations of many variables on various different space and time scales. Sensor networks such as weather radar, Global Navigation Satellite System receivers, lightning detectors, ceilometers and other emerging instruments are expected to play an increasingly important role in future observing systems. Environmental satellites have become the backbone for the assimilation systems, and are crucial to provide the needed spatial and temporal coverage. It is essential to continuously improve the exploitation of these observations, and to strive for future innovations with new observing platforms to mitigate remaining gaps in the current observing system. The challenge now is to provide observational networks for kilometre-scale models that represent phenomena with much shorter temporal and spatial scales. Novel observations from different platforms are required for these fine scale models, as conventional in situ observing networks do not have a sufficient spatial sampling. Environmental prediction models are now being developed for representing a wider range of variables (e.g. atmospheric pollutant concentration) that will expand the range of observations required. More efficient methods are needed to be able to ingest the observational data with frequent update cycles in a computationally affordable way. This paper summarizes the status and some of the challenges for the future of observations for NWP.

2.1 INTRODUCTION

The use of observations from satellites for assimilation into NWP models, for monitoring the climate and for evaluating weather and climate models has increased significantly over the last two decades. Satellite observations are now the most important contribution to initialise current operational NWP models. However it is important to remember that in situ data (e.g. from radiosondes and aircraft) remain as a significant reference for NWP, mainly because of better vertical resolution and also because much of the space-based remotely sensed data are still prone to biases which in situ data can help to correct. Recently activities such as the Global Space-based Intercalibration System (GSICS) (Goldberg et al. 2011) have made progress toward reducing the biases of satellite radiance observations. In addition, ground-based remote sensing networks are developing that can provide valuable information in the boundary layer that is more difficult to infer from satellites. Methods developed for assimilating observations in global-scale NWP over the last two decades are now being extended with increasing success down to finer scale models, with the latter providing demonstrated improvement over simply “down-scaling” lower-resolution analyses. New tools developed from data assimilation also allow the impact of observations in NWP model forecasts to be quantified (see Chapter 3) allowing more informed decisions to be made on what types of observations to be deployed in the future.

The global observing system (GOS) is co-ordinated by the World Meteorological Organization (WMO) and includes many diverse types of observation as shown in Figure 1. The OSCAR[a] database maintained by WMO is a good summary of the observational requirements[b] for NWP and current/planned capabilities of the space based observations. The observations are transmitted to NWP centres in near-real-time (typically less than 3 hrs for global NWP) on the global telecommunication system in several different formats, although BUFR (Binary Universal Form for the Representation of meteorological data) is being increasingly adopted for all observation types. BUFR allows a more complete description of the observations encoded in a compact format. The suite of observations made of the atmosphere, land and oceans can be divided into four classes: surface in situ (land, ocean and cryosphere), ground based remote sensing, upper air in situ, and

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[a] *http://www.wmo-sat.info/oscar/*
[b] *http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html*

satellite remote sensing of the atmosphere and surface. All of these are described briefly below. As an example, the observations received at the UK Met Office for assimilation into its global NWP model are given in Table 1 together with a summary of their characteristics and the percentage of the data actually assimilated after quality control and thinning.

An ongoing challenge is to maintain the coverage of the observing system as satellite instruments fail and are not replaced, and surface networks over land and ocean decline. A positive trend is that in recent years more nations are sharing the burden of contributing to the global observation network, both in situ and satellite, which can provide some redundancy.

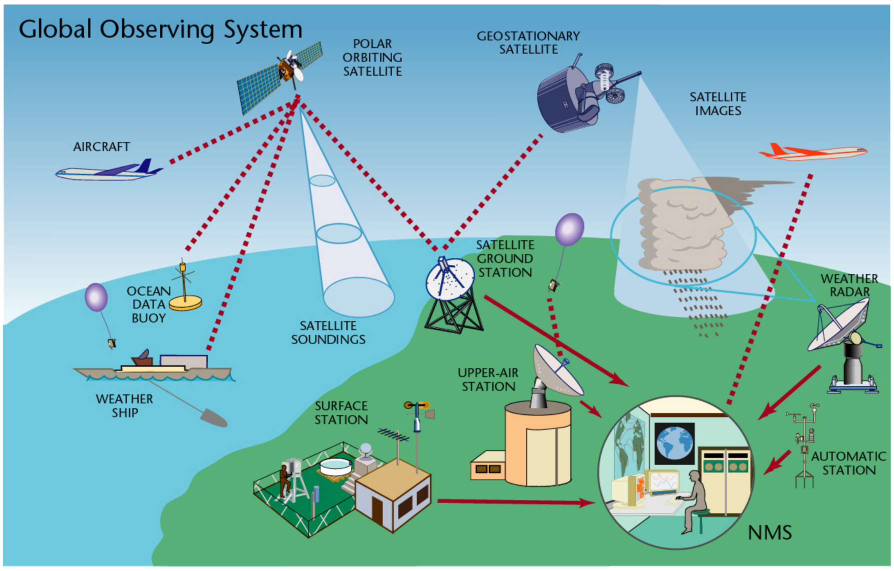

Figure 1. The main components of the current global observing system

Use of fine-scale observations in convective scale models is still at an early stage, and more work is needed on developing regional observational networks but this is an emerging activity. Also the range of observations being used in models is expanding as environmental prediction models start to be used operationally.

Operational satellite systems have typical renewal cycles longer than a decade. Although this might be thought to hinder progress, it has advantages too, notably that the operational observations are continuous over longer periods (provided that the sensor does not fail prematurely) and that the user community has time to develop the optimum utilisation of the data over time. In addition the exploitation of the data is a crucial element to help define the next generation satellite systems. Ground-based techniques can respond to new technologies on a much shorter time scale. This is particularly true for advances in automation, miniaturization and communication that allow new types of sensor networks to emerge.

In this paper we will concentrate on present and future observing systems with a focus on the developing challenges for NWP moving towards finer spatial resolution to improve the representation of the atmospheric boundary layer and convective precipitation. However, it should be noted that for the operational systems, the improvements are often only incremental because they need to continue well-established services both for NWP and climate monitoring.

2.2 IN SITU OBSERVATIONS

2.2.1 Surface in situ observations

Surface in situ observations of meteorological parameters over land are provided from the global network of Surface Synoptic Observations (SYNOP) stations which provide measurements at least every six hours of temperature, pressure, wind and relative humidity nominally at a height of 1.5-2 m (Ingleby, 2014). Over 80,000 observations are received in a day within 3 hrs of the measurement time to be assimilated in NWP models. In addition to the SYNOP network, METeorological Airport Reports (METars) of pressure and temperature for aviation purposes, typically at airfields, are now also being used by NWP centres.

Sensor miniaturization and integration may lead to new sources of data, especially for convective scale models, such as from crowd sourcing sites and utilising mobile phone technology. Meteorological variables such as temperature and pressure can now be measured by many millions of devices (e.g. smartphones, tablets, watches). Industry sources (IHS Technology[c]) expect that by 2016 between 500 million and one billion smartphones and tablets will have the capacity to measure pressure as well as parameters such as position, humidity, and temperature (Mass and Madaus, 2014). However, how the data from these non-standard sensors can be exploited for NWP is an ongoing research topic. In particular the surface pressure data collected seem to be suitable for data assimilation as observational problems are relatively minor, e.g. calibration offsets can be avoided by considering temporal change. Other lines of research explore whether flexible and biodegradable electronic components can be deployed in a wireless network to capture the 3D structure of the atmosphere (Manobianco and Zack, 2014). The integration of new and standard technologies offer new possibilities not only for NWP but also for climate monitoring. However, new challenges arise in terms of data homogenization and error characterization. It should be emphasised that these new data sources are not a replacement for the conventional observations which will continue to provide the reference, but are a way forward to improve the coverage and space/time resolution.

The correct representation of surface exchange processes is becoming more important in NWP as is evidenced by recent advances in land surface data assimilation schemes. However, the use of specialised in situ networks that are increasingly being set up by various communities for meteorological applications is still in its early stages. In situ soil moisture measurements are increasingly performed in small-scale wireless networks. To ensure commonality between the different measurement techniques and networks quality control is vital and is promoted by the International Soil Moisture Network (Dorigo et al. 2013).

Over the ocean the in situ observations (the Global Ocean Observing System, http://www.ioc-goos.org) are mainly from the drifting buoy network introduced in the late 1990s supplemented by moored buoys, rigs and ships. Pressure, wind and sea surface temperature are all measured. Funding constraints have led to cutbacks in the data return from the moored buoys in the Pacific which has experienced a decline in recent years, but efforts are underway to restore the capabilities of the network, involving additional international contribution, and to improve its resilience. In addition, Argo floats have started to provide profiles of temperature and salinity down to/from 2000m to the near surface (5-10 m). Marine mammals are being instrumented to provide a new source of three dimensional ocean data primarily in the southern high latitude oceans where conditions, including seasonal ice cover, render measurements from other platforms difficult. Underwater gliders are also being deployed to sample the upper ocean in undulating depth patterns along local or long-range trajectories at several depths over periods from weeks to months. Gliders are very versatile platforms and have been equipped with a wide variety of oceanographic sensors. In addition, new robotic platforms with a surface float are being developed and deployed to measure near-surface variables along programmed tracks.

Observations in the polar regions are still limited in coverage but becoming more important for the Arctic as the sea-ice retreats and transport and other industries expand their operations at these latitudes. There are some initiatives to extend observing networks for the Arctic such as the International Arctic Systems for Observing the Atmosphere[d] with a limited number of 10 observation sites distributed over the Arctic, the Arctic Monitoring and Assessment Programme (http://www.amap.no) and the Sustaining Arctic Observing Networks

[c] *https://technology.ihs.com*
[d] *http://www.esrl.noaa.gov/psd/iasoa/*

(http://www.arcticobserving.org). Each site measures a range of surface variables such as aerosols, atmospheric state and greenhouse gas concentrations which have been measured since 2001. The coverage of observations available in near-real- time is limited as shown in Figure 2. For the Arctic, ice buoys provide some coverage and over the Antarctic there is a sparse array of SYNOP stations. The Polar Prediction Programme co-ordinated by the World Weather Research Programme will focus on providing additional observations during intensive observing periods of the ten year project.

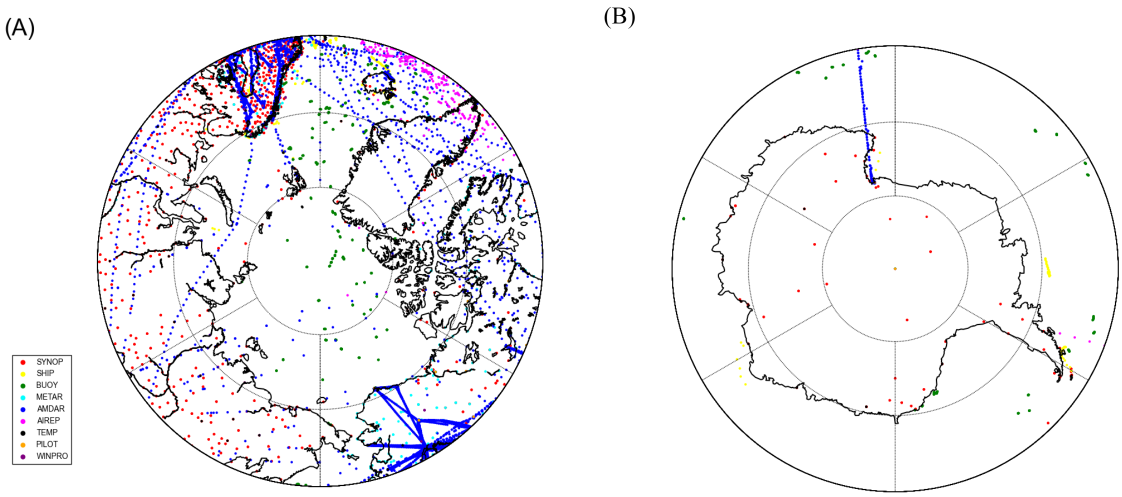

Figure 2. Observations received over the Arctic (A) and Antarctic (B) at the Met Office (UK) in a 24 hr period from 21Z 09/02/15 to 21Z 10/02/15

With increasing evidence of the deleterious effects of bad air quality on health and well-being (see for instance WHO, 2014), a range of atmospheric constituents are now monitored in populated areas in several regions, supporting the implementation of new regulations. Even though the first air quality measurements date back to the 19th Century (Volz and Kley, 1988), only in recent decades has significant progress in the accuracy and reliability of observational methods and instrumentation been made. In the case of aerosols, significant progress has been more recent especially concerning the characterisation of the ultrafine fraction and of the chemical composition. Laj et. al. (2009) provides a comprehensive overview of measurement techniques, which have been developed to observe atmospheric composition. A significant difficulty in using the vast amount of air quality observations available globally for data assimilation, or for evaluation of hindcasts/forecasts, is that the measurement sites are in general established close to sources in or around cities, because the primary aim is to quantify exposure of populations. Stringent data filtering methods need to be applied in order to assess the representativeness of the observations and keep only those observations that are consistent with the spatial discretisation of models (Joly and Peuch, 2012). For the purpose of characterising global atmospheric composition changes, only a few sites are available globally and are maintained under the framework of the Global Atmosphere Watch (GAW) programme of WMO. Data available in the GAW World Data Centres (see http://gaw.empa.ch/gawsis/) are vital to the understanding of the changes in reactive gases, aerosol and greenhouse gases and to the validation of chemistry-climate models (Lamarque et al. 2013) but GAW has to work towards near-real-time data delivering to make atmospheric composition data more relevant to NWP.

2.2.2 Ground-based remotely sensed observations

The high cost of measurements which need manual intervention and the need for better observations of convective processes with high temporal and spatial resolution have pushed forward new sensor technologies that have now reached various degrees of maturity. While some of the techniques presented below are already used in NWP, other challenges lie in the setup and operation of unattended all-weather observations and consistent quality assurance to make them suitable for NWP and eventually for climate monitoring. The geographical coverage of some exemplary networks is shown in Figure 3.

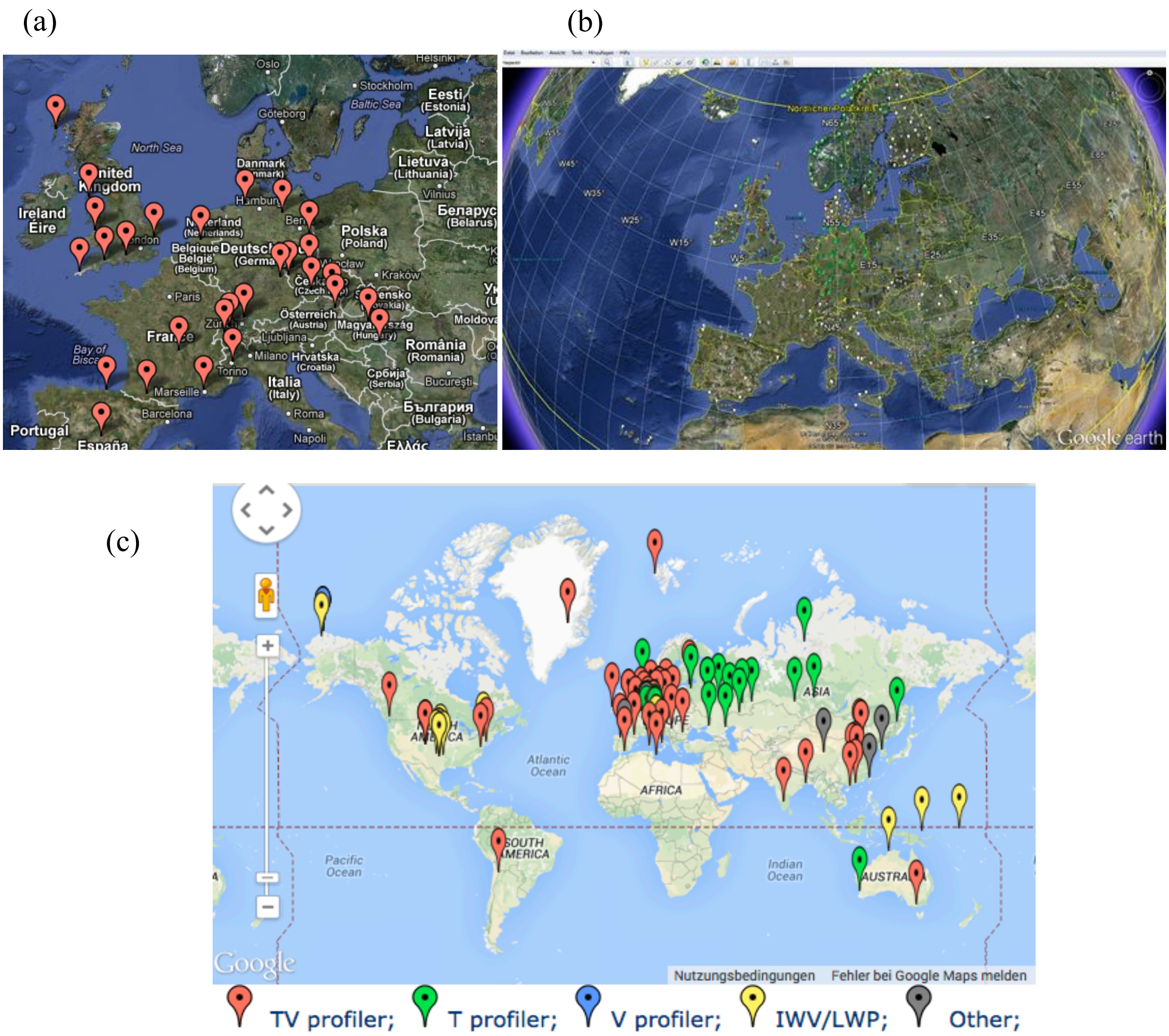

Figure 3. Maps of exemplary ground-based networks a) CWINDE network; b) European lidar and ceilometer network; and c) MWRnet from COST EG-CLIMET final report

Ground-based measurements of signals from the Global Navigation Satellite System (GNSS) that give the zenith total delay (ZTD) are starting to be widely distributed. ZTD (Yan et. al., 2009) is related to the total column water vapour in the atmosphere and can be measured under all weather conditions. The measurements are made in many countries but the dissemination of the data to NWP centres in real-time is still work in progress. Europe and the US have good networks which provide data in near-real-time time but there is scope for much more data to be made available from other countries.

For continuous profiling of the atmospheric state, i.e. winds, humidity, temperature, ozone, clouds and aerosol properties, various remote sensing instruments offer inexpensive, unmanned ground based observational possibilities. The following are examples of some networks:

- Ceilometer networks that are deployed by meteorological services for visibility and cloud base height also give aerosol backscatter profiles that can be used for operational boundary layer monitoring (Haeffelin et al. 2012).
- Doppler wind lidar networks exist, but the number of these instruments is currently much smaller than the number of ceilometers that are deployed. However, the Doppler lidar offers a more direct measurement of the turbulence together with the horizontal wind vector but

are limited to the lower (aerosol rich) part of the atmosphere. In recent years their usefulness for wind energy applications has led to a rapid increase in the number of operating systems making them a candidate for future networks.

- Radar wind profilers can cover the full troposphere and have a much higher degree of maturity than Doppler lidars. Networks on both sides of the Atlantic, e.g. US and southern Canada, CWINDE (Co-ordinated wind profiler networking Europe) have already been established and data from several stations are already assimilated into NWP models and have shown substantial value (Benjamin et. al., 2004, Illingworth et. al. 2015). However the coverage of this network has declined in recent years particularly over the US.
- Microwave radiometers can operationally provide temperature profiles of the lower atmosphere though the vertical resolution rapidly decreases with altitude during nearly all weather conditions (Löhnert and Maier, 2012). In addition, cloud liquid water path and some information on the water vapour profile is available. More than 100 radiometers are organized in the voluntary MWRnet (an International Network of Ground-based Microwave Radiometers) that develops joint quality assurance procedures and has supported first attempts to assimilate them into NWP. They are also used for climate studies and NWP validation. Experimental studies are also exploring the use of volume scanning microwave radiometry for severe convection forecasting.
- Infrared spectrometers are superior to microwave radiometers in terms of vertical resolution in the retrieved temperature and humidity profiles. These retrievals are limited to cloud free scenes; however, new research has demonstrated that accurate thermodynamic profiles can also be retrieved below cloud (Turner and Löhnert 2014). Ideas for a ground-based observing network, where ground-based infrared spectrometers serve as the core instruments at each station are currently under consideration.
- Water vapour lidar, i.e. Raman and differential absorption lidar (DIAL) allow the determination of high vertical resolution water vapour and aerosol profiles under clear sky conditions or below cloud base. Though they are currently rather complex in terms of operation and cost, research efforts to develop low-cost versions are ongoing. Some Raman lidars are also configured to measure temperature profiles.
- Weather radars are now widely used in NWP models both for defining the wind field and mostly in research mode for defining areas of precipitation through assimilation of the radar reflectivity. Phased array radar techniques that make use of electronic scanning instead of mechanical scanning offer an exciting possibility for much faster and flexible scanning of precipitation and also of clear-air convection.
- Lightning networks that can observe cloud-ground lightning and Cloud-Cloud lightning (Rodger et. al., 2006) are increasingly used to investigate the evolution of convective cells, lightning activity and electrical vertical structure of heavy rainfall cells.
- GALION (**GAW** Aerosol **Lidar** Observation Network) is a network of networks as it is not feasible to implement a global aerosol lidar network by installing a homogeneous set of systems at a number of stations selected for optimal coverage. Instead GALION makes use of existing systems at established stations, of the experienced operators of these systems, and of existing network structures. The structure and development of GALION is described in the GAW Report No. 178.
- The international Network for the Detection of Atmospheric Composition Change (NDACC) is composed of more than 70 high-quality, remote-sensing research stations for observing and understanding the physical and chemical state of the stratosphere and upper troposphere with an emphasis on the long-term evolution of the ozone layer (http://www.ndsc.ncep.noaa.gov/).

Each of the instrument networks above provides limited information on the atmospheric state. Hardesty et al. (2012) summarize the suitability of the different instruments for operational thermodynamic profiling. Data assimilation into NWP models involving observation operators to convert model variables into the measured quantities provides an efficient means to exploit these non-standard measurements. Alternatively, the synergy of different instruments is exploited by combining their measurements within one retrieval algorithm providing products that can be assimilated without the use of complex forward operators. Both methods are used in current NWP models depending on the type of measurement being assimilated.

Despite the developments within the last decade, some gaps in the current observation system exist, e.g. a true reference turbulence observation 'away from the surface'. In this respect several efforts are made to characterize turbulence by deriving higher order moment distributions of temperature, water vapour, and vertical wind in the convective boundary layer with specialized lidar systems (e.g. Turner et al. 2014, Lenschow et al. 2012) though much work needs to be done.
In order to demonstrate the utility of the different instruments for NWP, prototype networks have been setup for different applications and limited areas, e.g. the Front Range Observational Network Testbed (FRONT). For Europe the COST action TOPROF aims to specify an optimum European network of inexpensive, unmanned ground based profiling stations, which can provide continuous profiles of winds, humidity, temperature, clouds and aerosol properties. A ground-based remote-sensing network consisting of 5 climatologically different stations for the observation of wind, aerosol particles, cloud and precipitation has recently been set up in Finland (Hirsikko et al. 2014). In addition tools for data assimilation, e.g. a version of the fast radiative transfer model, RTTOV, (Saunders et al. 1999) for up-looking geometry, are also being developed.

2.2.3 Upper air in situ observations

Upper air observations by radiosonde ascents are a key ingredient for data assimilation at NWP centres. The recent move of all observations to be reported in the high resolution BUFR format will enable users to be able to access more detailed vertical profile information and the location of the balloon during the ascent. Almost all radiosondes today exploit GPS for determining horizontal wind. They have become smaller and flexible but the provision of high quality datasets, even for the meteorological services, is only now being realised, e.g. by providing high vertical resolution and better correction of upper troposphere humidity. The provision of data during the descent as well as the ascent is one initiative that would provide additional datasets for NWP models. Dropsondes released from aircraft can provide unique views in otherwise poorly observed areas, e.g. hurricane flights into tropical storms and polar regions. Constellations of driftsonde systems - gondolas floating in the stratosphere are able to release dropsondes upon command - are currently employed only during field campaigns (Cohn et al. 2013). These profiles are often used in real-time in operational NWP models and the ConcordIASI project is a good example of this (Rabier et. al., 2013). Recently a small subset of high quality radiosonde stations has set up the GCOS Reference Upper Air Network (GRUAN) with a suite of complimentary measurements of the atmospheric profile are made (Immler et al. 2010) to reduce the uncertainty in the profiles.

Aircraft wind and temperature data are now widely provided to NWP centres and assimilated but are restricted to the main flight paths of commercial airlines with profiles close to airports. Aircraft profiles of water vapour concentration are now starting to become available as instrumentation is developed, but currently these are limited to over the US (WVSS-II) and over Europe (Tropospheric Airborne Meteorological Data Reporting (TAMDAR), Gao et. al. 2012). Recent studies have shown that Reporting and Aircraft Meteorological Data Relay (AMDAR) measurements are at least as good as radiosondes for water vapour profiles and the coverage over the US is good as shown in Figure 4. More development is needed on the TAMDAR system which is being deployed over Europe. Other variables of interest which can be measured from aircraft are Global Position System (GPS) height, turbulence and icing.

Polarimetric Doppler weather radar has also been deployed on aircraft to measure the 3D structure of tropical cyclones and the next generation employing phased array antenna is expected to show improved spatial resolution and flexibility (Vivekanandan et al. 2014). The increasing use of unmanned aerial vehicles (UAV) for various in situ and remote sensing applications offers new possibilities to enhance the observing system particularly above and below the boundary layer and will surely be more widely used in the next decade.

For other gases (O3, CO, CO2, NOy, NOx, H2O, aerosols and cloud particles), the In service Aircraft for a Global Observing System (IAGOS) (http://www.iagos.org) European research infrastructure, which builds upon the MOZAIC (Marenco et al. 1998) and CARIBIC (Brenninkmeijer et al. 2007) programmes, provides a large number of measurements of concentrations of gases such as ozone, water vapour, carbon monoxide, and total nitrogen oxides (NOy) from commercial aircraft. In addition, methane and carbon dioxide concentrations will be measured on some flights. Similar airborne programmes are also in operating in Asia, such as CONTRAIL in Japan (Machida et al. 2008). These data are valuable for validation of atmospheric chemistry models.

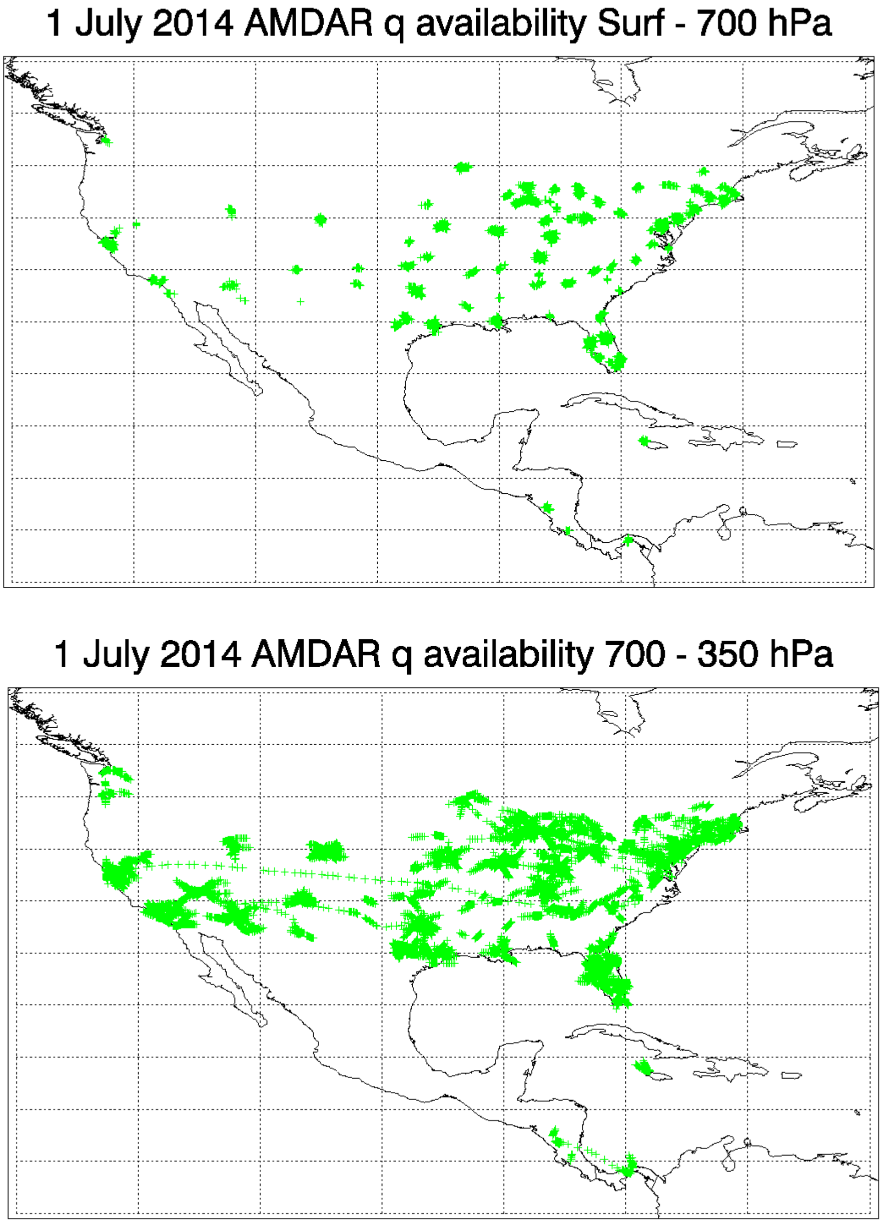

Figure 4. Coverage of AMDAR water vapour profile data over the US for 1 July 2014 at high (lower panel) and low levels (top panel)

Source: ECMWF

2.3 SATELLITE OBSERVATIONS

2.3.1 Current status of satellite observing system

Figure 5 provides a summary of the current Global Space-based Observing System (WMO Space Programme Office, 2014, Lafeuille, personal communication) as coordinated by the World Meteorological Organization (WMO) and the Coordination Group for Meteorological Satellites

(CGMS) with support from the Committee on Earth Observation Satellites (CEOS). For global NWP and climate observations, Low-Earth Orbit satellites (LEO), either operational or research missions, provide essential data, whereby the lion's share of data come from the sustained observations from operational satellites. The baseline for a core LEO constellation is to be deployed over three sun-synchronous orbits with orbital planes around 9:30, 13:30, and 17:30 equatorial crossing time (ECT). This ensures a nearly even temporal sampling of the atmosphere from low-earth orbit.

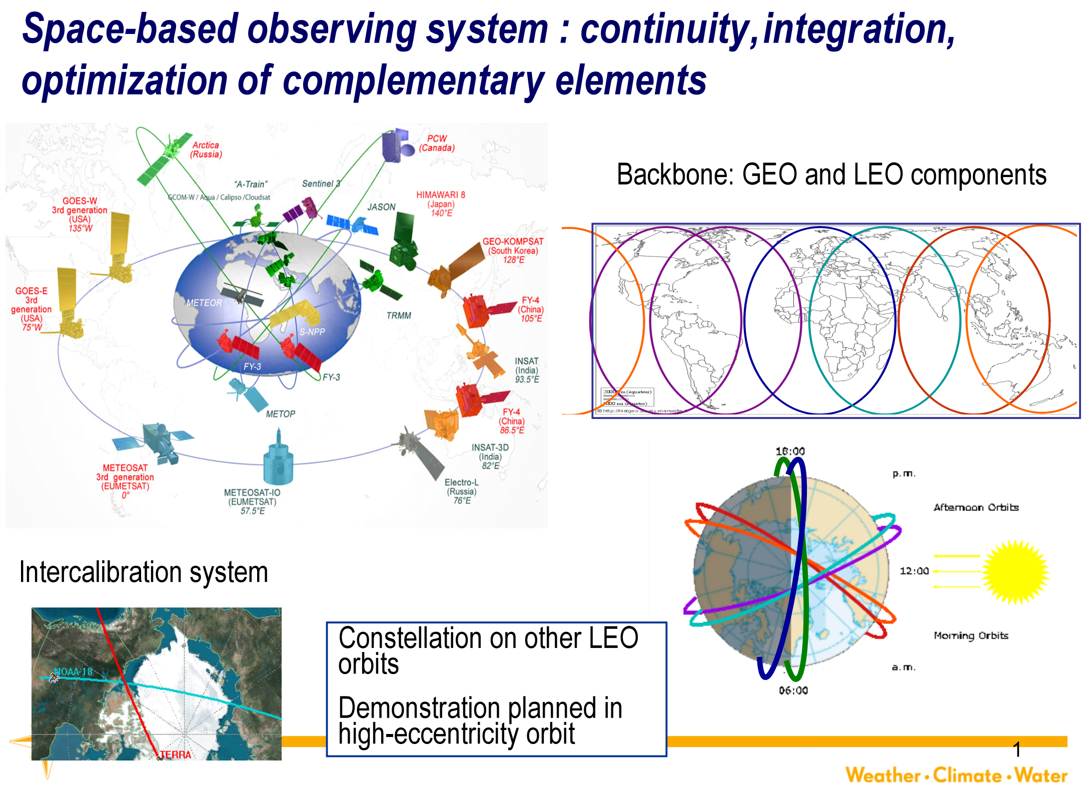

Figure 5. Sketch of the space-based global observing system for both geostationary and polar orbiting operational satellites. The Global Space-Based Inter-Calibration System, (Goldberg et al. 2011) concept is also shown where satellite orbits intersect allowing simultaneous nadir overpasses.

Geostationary satellites provide more frequent repeat cycles, typically 10-15 minutes for the full disk, and 5 minutes or better for so-called 'rapid scans' covering only limited areas. The frequent observations from geostationary orbit enables the observation of rapidly changing weather phenomena (e.g. convective storms); the viewing geometry confines geostationary observations to low and mid-latitudes. The constellation of operational meteorological geostationary satellites placed around the equator remains the backbone of monitoring rapidly changing weather with observations repeated every 10-15 minutes. The chief application is in providing rapid-update information for nowcasting and short-range weather forecasting, although these observations are also used for assimilation in global and regional NWP models. More frequent observations at high latitudes using multiple overlapping polar orbiting satellite passes helps to meet the needs for rapid updates at higher latitudes.

Satellites provide a wealth of observations of the atmosphere and surface which in principle provide good global coverage. Typically more than 10^5 measurements for a specific satellite observation type (see Table 1) are received every day at operational centres. However, due to difficulties in using the data over land, cloud and sea-ice, and the need to thin the data to reduce horizontal error correlations between measurements, only about 20% of most satellite data types are actually assimilated into NWP models. A future goal in order to better optimize the use of satellite data is to increase the amount used, especially over the more challenging areas (e.g. land surface, sea-ice). Reducing the amount of data thinning is especially relevant for convective scale models.

Table 1. Observations assimilated in the Met Office global NWP model during one day in 2013

Observation group	*Observation sub-group*	*Items used*	*Daily extracted observations[1]*	*% assimilated*
Ground-based vertical profiles	TEMP PILOT PROFILER	T, V, RH processed to model layer average As TEMP, but V only As TEMP, but V only	1,300 830 18,000	96, 95, 76 21 17
Satellite-based vertical profiles	METOP-A/B NOAA-15/16/18/19, Aqua AIRS, IASI, HIRS, AMSU-A/B, MHS, ATMS, CrIS. GOES-13/15, Met-10, MTSAT-2. Radio-occultation COSMIC, GRAS AOD MODIS AQUA, MSG	Radiances directly assimilated with channel selection dependent on surface instrument and cloudiness Profiles of refractive index Aerosol Optical Depth	ATOVS: 4,000,000 IASI: 500,000 AIRS: 300,000 ATMS: 320,000 CrIS: 300,000 GOESclr: 600,000 SEVERI: 400,000 MTSATclr: 160,000 GPSRO: 3000 SATAOD: 700,000 MSGAOD: 2,300,000	5 10 13 22 12 2 7 9 80 15 0
Aircraft	Manual AIREPS (incl. ADS) Automated AMDARS TAMDAR	T, V as reported, with duplicate checking and reject lists	13,500 380,000 62,000	77, 62 24, 24 0, 0
Satellite atmospheric motion vectors	GOES 13,15 BUFR Meteosat 7 BUFR Meteosat 10 BUFR MTSAT BUFR Terra/Aqua MODIS NOAA polar AMVs MetOp polar AMVs	IR, WV IR, VIS, WV IR, WV IR, VIS, WV IR, WV, clear sky WV IR IR	190,000 80,000 400,000 240,000 130,000 85,000 110,000	13 20 5 8 8 6 3
Satellite-based surface winds	METOP-A/B ASCAT CORIOLIS WINDSAT OceanSat-2 OSCAT	KNMI retrievals NRL winds KNMI retrievals	1,800,000 1,200,000 400,000	4 1 6
Ground-based surface	Land SYNOP Ship Fixed Buoy + Rigs Drifting Buoy METAR Mobile SYNOP	P (processed to model surface), V, T, RH P, V, T, RH P, V, T P, T P, V, T, RH P, T, RH	80,000 6,000 11,500 11,000 140,000 2,700	88, 86, 90, 91 80, 67, 77, 47 72, 90, 80 87, 8 35, 30, 32, 32 20, 15, 15
Ground-based satellite	GPSIWV	ZTD	450,000	0.3

[1]*Observations here refer to profiles of variables or radiance vectors or single level observations*

The primary measurement of the atmosphere and surface properties from space is from the top of atmosphere radiation emitted, reflected and scattered by the surface, atmosphere and clouds. The atmosphere is sensed across the electromagnetic spectrum from the microwave to ultra violet wavelengths. The variable spectral absorption of atmospheric gases allows profiles of atmospheric temperature and water vapour to be inferred from the measured radiances. Table 1 lists the radiances received from many sensors in polar and geostationary orbit which are currently assimilated in NWP models. Radiances from both advanced infrared (IR) sounders with high spectral resolution and microwave radiometers with broader spectral responses are routinely assimilated into NWP. Assimilation of IR radiances over cloud and land/ice surfaces is still an area of research but increasingly more data are being exploited here. It is noted that, microwave radiances give a much better global coverage, but lower vertical resolution, compared to infrared radiances as they are not affected by non-precipitating clouds. Visible and near infrared radiances are not assimilated at present but studies are underway to facilitate this (e.g. Kostka et al. 2014).

Table 2. Satellite data in the ECMWF/MACC global NRT assimilation and forecasting system. The assimilated observations (a) are the observations that are currently used to constrain the model; the monitored observations (b) are the observations that are part of the full system (NRT data acquisition, calculations of observation-model difference.), but are not used yet to constrain the model; planned observations (c) are observations that are being considered for implementation.

(a) Assimilated satellite observations				
Instrument	*Satellite*	*Space agency*	*Data provider*	*Species*
MODIS	EOS-Aqua, EOS-Terra	NASA	NASA	Aerosol optical depth (AOD), Fire radiative power (FRP)
MLS	EOS-Aura	NASA		O3 profile
OMI	EOS-Aura	NASA	KNMI	O3, NO2, SO2
SBUV-2	NOAA-16, -17, -18, and -19	NOAA	NOAA	O3 profile
IASI	METOP-A, METOP-B	EUMETSAT/CNES	ULB/LATMOS	CO
MOPITT	EOS-Terra	NASA	NCAR	CO
GOME-2	METOP-A, METOP-B	EUMETSAT/ESA	DLR	O3
(b) Monitored satellite observations				
Instrument	*Satellite*	*Space agency*	*Data provider*	*Species*
GOME-2	METOP-A, METOP-B	EUMETSAT/ESA	DLR	NO2, SO2, HCHO
SEVIRI	METEOSAT	EUMETSAT	LandSAF	O3, FRP
Imager	GOES-11, -12	NOAA	UCAR	FRP radiances
(c) Planned satellite observations				
Instrument	*Satellite*	*Space agency*	*Data provider*	*Species*
CALIOP	CALIPSO	NASA	NASA	Aerosol lidar backscatter
OMPS	Suomi NPP	NASA/NOAA	NOAA	O3
IASI	METOP-A, -B	EUMETSAT/CNES	EUMETSAT	O3 radiances
Imager	MTSAT-2	JMA	JMA	FRP radiances
VIIRS	Suomi NPP	NASA/NOAA	EUMETSAT	AOD, FRP
SEVIRI	MSG	EUMETSAT	ICAR	AOD

The total column amounts of trace gases (e.g. ozone, nitrous oxide, methane and carbon dioxide) and aerosol optical depths can be inferred from UV, VIS and Near-IR radiance observations. Also to some extent these variables can also be inferred from IR radiances, but they do not perform as well in the lower troposphere. High vertical resolution profile information can also be obtained with limb view measurements. Atmospheric composition models make use of these trace gas measurements. As an illustration, Table 2 describes the satellite observations that are taken into account in the

Monitoring Atmospheric Composition and Climate (MACC) assimilation and forecasting system. This global near-real-time (NRT) production system uses satellite data in its 4-dimensional variational (4D-Var) data assimilation system to constrain the initial atmospheric state that is used for the 5-day forecast. These satellite observations of atmospheric composition are assimilated in the system on top of all the meteorological observations that form part of the ECMWF operational numerical weather prediction system (resulting in more than 70 individual instruments).

An important step toward increasing the accuracy and consistency of satellite radiance measurements are improvements to the calibration. The established Global Space-based InterCalibration System (GSICS) (Goldberg et al. 2011) provides a unique framework to put various satellite data into a system where the observations are made mutually consistent. The idea is: if those measurements could be traced to an absolute standard, the need for bias-correction by NWP systems could be reviewed as any biases would be due to those from the NWP model and not the satellite data. The realisation of this objective within GSICS will enable improved evaluation of numerical models (NWP and climate) and their physical parameterizations.

Bending angles from GPS radio occultation measurements have been available in near-real-time time to the meteorological community since the early 2000's. The constellation of these satellites has increased to give reasonable global coverage, although in recent years it is declining as the original satellites start to come to the end of their life. A new constellation of satellites is being planned. The advantage of these bending angle measurements is that they do not rely on any calibration, which is in contrast to the radiometers, and so can be considered as an absolute reference measurement of upper tropospheric and stratospheric temperature (Eyre, 1994). This makes these measurements attractive for climate monitoring and investigating biases in radiosonde temperature profiles and NWP models.

Scattering of microwaves from the sea surface provides important information about the surface wind strength with usually several possible wind directions (ambiguity problem) which the assimilation system can then select from (Figa-Saldaña et. al., 2002; Cotton, 2013). Studies have shown that having at least 2 of these active microwave instruments in polar orbit provides significant impacts in NWP forecasts, particularly for tropical cyclone forecasts. Currently, operational scatterometers are only available in the morning orbit to forecasting centres (there are none in the afternoon orbit), which is sub-optimal for providing a good daily coverage (note Table 1 includes data from OSCAT before it failed in February 2014). These active microwave measurements have also proven useful over land surfaces to infer soil moisture in the upper surface levels, and these data are now assimilated in land surface models to improve the surface fluxes which can influence precipitation forecasts. Passive microwave radiometers (Aquarius and SMOS) also measure land surface soil moisture.

Atmospheric Motion Vectors (AMVs) are derived from tracking clouds or water vapour features in geostationary image sequences or from successive overlapping polar orbiter passes (Velden et. al. 2005). They yield a reasonable estimation of the local wind, and provide good coverage in the upper and lower troposphere where coherent clouds and moisture gradients normally occur. Their positive impact in NWP models has been well documented. Various techniques have been developed to improve their assimilation, for instance by reducing AMV observational weights in regions of strong vertical wind shear where accurate height assignments are crucial and by characterising the height assignment errors though comparisons with NWP model fields.

Novel ways to process AMVs to provide better coverage are emerging (Velden et al. 2005). For example, AMVs are now being generated from a combination of polar and geostationary satellite imagery with the aim of filling the gap between the latitudes of 55°-65°N and 55°-65°S where geostationary and polar AMVs alone cannot be inferred. Another example is the use of geostationary satellite rapid-scanning operations to allow the production of mesoscale AMV datasets at very high densities for use and assimilation in high-resolution NWP and tropical cyclone models (Wu et al. 2014). Studies on the AMV height attribution (e.g. Velden and Bedka, 2009; Hernandez-Carrascal and Bormann, 2014) show that AMVs better correlate to a motion over a tropospheric layer rather than to a single discrete level. Consistent with that approach it has been demonstrated that AMV wind errors are reduced when the AMVs are assigned to a 120-hPa-deep layer below cloud tops derived from lidar observations from the CALIPSO satellite (Folger and Weissmann, 2014).

Experiments with scatterometer winds (Valkonen, 2014) show that a reduced thinning distance could be beneficial for forecasting storms, notably polar lows. It is expected that in general a reduced thinning will better depict mesoscale features. For AMVs a pertinent example is that high resolution AMV products better depict wind field divergence and convergence which could improve the positioning of tropical convective systems in models (Schmetz et. al., 2005). More recently Stoffelen et al. (2014) demonstrated the utility of high-resolution scatterometer winds to resolve mesoscale dynamics (downbursts) in tropical convective systems.

Active microwave rain radars are now in space (e.g. TRMM, GPM) but assimilation of the precipitation information (Benedetti et. al. 2005; Iguchi et. al. 2009) has not yet been developed to a stage where it is used in operational systems due to the highly non-linear nature of the sensed precipitation and how it is related to the model variables. More research is expected to lead to a greater exploitation of these data and the addition of a dual-frequency precipitation radar on GPM should lead to improved accuracy.

For convective scale models, with a rapid-update cycle, it is envisaged that more and better use of geostationary satellite data (e.g. 3D fields of water vapour and cloud observations) will be made to better depict the wind fields associated with atmospheric features such as fronts and larger (tropical) convective systems. The rapid evolution of convection can be better represented in the convective scale models using these measurements. An example of the potential is shown in Figure 6 where a simulated Meteosat-10 visible image from the UK model is compared with an observed Meteosat-10 visible image. This was a case where most of the UK was covered with low cloud under a region of high pressure. In general the cloud cover of the model agrees well with the satellite image but the model clouds are more broken than reality and there are some differences. The simulated imagery helps the model developers to improve the representation of cloud and fog in the models and also helps forecasters to assess the accuracy of the model predictions.

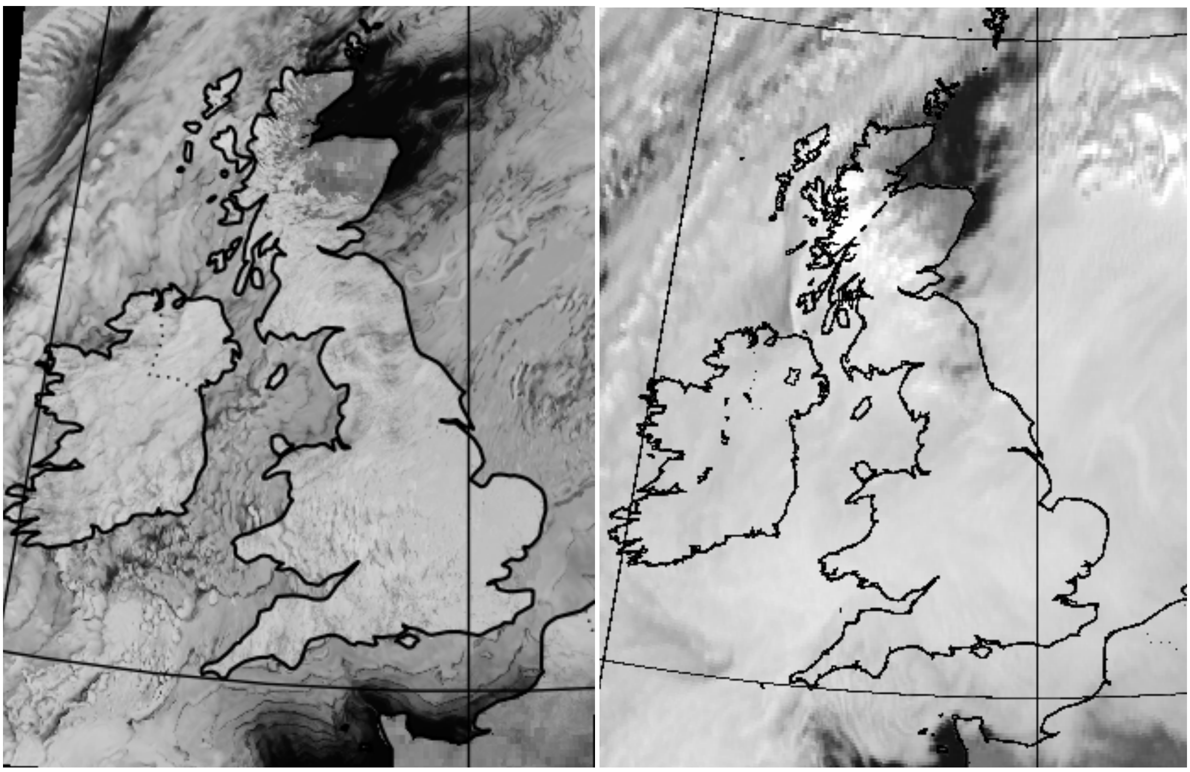

Figure 6. Simulated Meteosat-10 visible channel image for 11 February 2015 (left) compared with actual image on the right. The simulations are for the 12Z analysis of the UK 1.5 km model and the satellite image is for the same time.

The derivation of sea-surface temperature from satellites is a mature activity with a history of nearly four decades. Measurements are taken by well-calibrated IR radiometers on satellites in polar and geostationary orbits and microwave radiometers on polar orbiters; each has different and complementary characteristics. Infrared data from polar orbiters have the highest spatial resolution, at 0.75km for VIIRS and 1km for AVHRR's and MODIS's, but have many gaps due to clouds, while microwave SST retrievals are robust to the presence of non-precipitating clouds but have a spatial resolution of ~50km and cannot provide data within ~100km of coastlines. Infrared data from geostationary satellites have a resolution of a few km, and have a rapid revisit time that is very useful for resolving diurnal variability, but are limited to low- and mid-latitudes. The utility of satellite-derived SSTs in assimilation schemes is determined by the accuracy of the retrievals, and, within the auspices of GHRSST (Group for High Resolution SST; Donlon, et al. 2007), efforts continue to be directed at improved methods of determining the accuracy of individual SST estimates. The accuracies of the satellite-SSTs are determined by comparisons with independent measurements that are provided by drifting and moored buoys, Argo profilers, and ship-board infrared radiometers, and are currently estimated to be a few tenths of a degree. The actual values are governed by the effects of compensating for the intervening atmosphere, which is a function of several variables.

2.3.2 Future plans

For the future satellite observing systems, new generations of geostationary satellites will gradually be launched by different space agencies over the next five years. Advanced imagery with better spatial (2km or better in the infrared) and temporal resolution (10 minutes or better) will become available with the advent of Himawari-8/9 from JMA, the GOES-R series from NOAA, the FY-4 series from CMA and the Meteosat Third Generation (MTG) from EUMETSAT. There will also be new versions of geostationary satellites from India (IMD and ISRO) and Russia (Roshydromet). Improved co-ordination of orbits for polar satellites is being implemented with the agreement of the Chinese FY-3 orbiters filling a gap. More common instrumentation types in polar and geostationary orbits will improve coverage e.g. GNSS soundings, hyperspectral sounders, microwave sounders and imagers and pave the way for coordinated development and a quicker transition into operations. These scheduled launches go a long way toward realising the vision of WMO for the space-based component of the Global Observing System.

A summary of technical aspects of the realisation of the WMO vision 2025 includes two main aspects: i) an upgrade of both the geostationary and low Earth orbiting satellite systems in terms of coverage and ii) more commonality in the instrumentation of each new satellite system which will create opportunities for enhanced international cooperation toward applications on the basis of a joint scientific development. The development of new instruments in geostationary orbit, i.e. lightning imagers (Goodman et al. 2013) and hyper-spectral sounders (Hilton et al. 2012) and new 16 channel imagers provides greatly enhanced capabilities to observe temporal changes in the atmosphere, i.e. changes in water vapour, clouds, storms, aerosol, volcanic ash, etc. (Stuhlmann et al. 2005, Schmit et al. 2005). The use of the geostationary orbit is also important for improving the skill of air quality forecasts (Lahoz et al. 2012). The use of multispectral (UV-VIS-IR) retrievals is a promising approach for obtaining sensitivity in the mid- to low troposphere for the key pollutant ozone (Natraj et al. 2011).

One proposed novel element is observations from a highly elliptical orbit providing improved temporal coverage of high latitudes. Several proposals are advancing this concept e.g. the Canadian PCW mission with a possible flight opportunity around 2020. This would allow frequent observations over the N. Polar regions similar to geostationary platforms over the Tropics. AMVs and radiances could be generated for NWP assimilation.

In the next few years a satellite Doppler wind lidar (ADM/Aeolus, Stoffelen et al. 2004; Tan et. al., 2008) is due for launch which will provide line of sight winds at multiple vertical levels in clear skies and be a step forward in obtaining 3 dimensional wind measurements of the atmosphere. These data are potentially of great value for NWP especially in the tropics (see Baker et al. 2014).

There are also opportunities being provided and challenges raised by proposals and initiatives for space-based remote sensing systems by private, industrial consortia often pursued with public support. These opportunities might include a potential for reducing cost for some systems, however some important challenges need to be considered, such as the compatibility with the current world-wide accepted data exchange coordinated by WMO, and whether those observing systems adequately fulfill current and future sustained user requirements.

2.4. ADAPTIVE OBSERVATIONS

Adaptive or targeted observations refer to those, in addition to the regular observing network, which can be specifically directed to certain locations with the aim of improving NWP forecasts in particular weather situations. These locations are chosen in order to improve forecasts of high-impact weather events. Examples include dropsondes launched from aircraft or balloons, additional radiosonde ascents, directed remotely sensed observations, the inclusion of more densely sampled satellite observations (such as radiances or winds) that are normally excluded from the assimilation due to routine thinning or quality control procedures. A new development is the potential use of unmanned aerial systems to provide the required observations. As a consequence of many field campaigns worldwide during the past two decades, advances have been made in the development of objective strategies for targeting observations, and in quantitative evaluations of the impact of assimilating these extra observations on NWP.

To date, observations have primarily been targeted to improve short-range (1-3 day) forecasts of extratropical and tropical weather. For extratropical systems, the value of targeted data has been found to be mixed and small on average although it is dependent on the flow regime, the NWP model, and the treatment of both routine and targeted observations in the data assimilation scheme (Majumdar et. al., 2011; Hamill et. al., 2013). For forecasts of the track of tropical cyclones (TC), targeted observations have been shown to provide statistically significant benefit to NWP systems (Majumdar, et. al., 2013). A simple sampling strategy of observing uniformly around the TC has been shown to be effective, with some models exhibiting an improvement in their track forecasts. Recent studies have also demonstrated that observations targeted for TCs can improve the skill of forecasts in regions well away from the TC. The mechanisms behind how TC forecasts are improved, and can be improved further, by targeted observations is a subject for continuing research.

2.5 SUMMARY AND FUTURE PROSPECTS

Observations continue to be a critical input to NWP models both for assimilation, to define the initial state of the atmosphere/surface, and for verification of the model predictions in close to real-time. Both NWP and climate models are increasingly being compared to observations both to validate the physical processes represented in the models and also to study long term trend analyses in the model climatology. The verification of NWP models is increasingly based on a range of different observation types to validate a wider range of weather parameters (e.g. rainfall, aerosol optical depth) more relevant to the general public. For climate models metrics are being developed to assess them using observational datasets (Hurk et. al., 2012).

In situ observations are facing a new challenge to provide good coverage and resolution for the new generation of kilometre scale models. This will inevitably involve making use of some form of “crowd sourced” data of lower quality together with higher quality reference networks as described in this paper. Data assimilation systems will need to respond to this challenge. Modern technology such as smart phones and increasingly instrumented vehicles are providing the platforms for these new mesonets. In parallel accurate ground based observational techniques are being developed such as lidars and zenith viewing radiometers to provide reference observations. The maintenance of the existing network of SYNOPs and radiosondes is proving challenging for some countries due to increasing financial constraints. A co-ordinated effort is required to maintain some of the more remote stations where few other observations are available. A global coverage of high quality island radiosonde stations is required to help provide a reference which can determine biases seen in the satellite radiance measurements. The reference GRUAN stations are being set up to contribute to the network for ‘calibrating’ satellite radiance data. The GRUAN sondes and stable (calibrated) radiance measurements from space are complementary so instruments, such as hyperspectral sounders, can serve as a ‘single travelling reference instrument’ for GRUAN sondes. In situ observations in the oceans are expanding with new innovative measurements such as instrumented marine mammals and gliders starting to feed into the operational observations networks.

Polar orbiting satellites with their global coverage now provide the main impact in NWP models with the high resolution infrared sounders (e.g. IASI and CrIS) and microwave temperature sounder (AMSU, ATMS) top of atmosphere radiances providing the most impact in the troposphere controlling the synoptic scale features. Agreement has now been reached whereby 3 polar orbiters in well-spaced orbital planes will be provided by the USA, Europe and China ensuring a uniform temporal coverage. The GNSS-RO bending angle measurements are also providing a good reference observation of the atmospheric temperature in the upper troposphere and stratosphere between 300-50 hPa (Collard and Healy, 2003). There is potential to retrieve low level humidity and surface pressure information from these data but this remains to be proven in an operational context. The framework for the future operational GNSS-RO constellation of satellites is still being debated by space agencies and commercial companies willing to offer a service to the Meteorological Services. GNSS reflectometry is a new area of research where measuring the reflection of GNSS signals from the sea surface can potentially provide information about the sea state for use in ocean and atmosphere models. This would help to fill the gaps in the temporal coverage of active scatterometer ocean surface wind measurements which are currently only available from the European polar orbiter. These all-weather ocean wind observations could help to define the location of tropical cyclones and the centres of mid-latitude depressions. Finally, the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission is being proposed to provide a better estimate of the uncertainties in satellite climate data records for monitoring of the Earth system (Anderson et. al., 2004).

Geostationary satellites provide frequently updated imagery used for nowcasting applications, except at high latitudes. The radiances from the imagers are used in NWP models, at both global and regional scales, and also provide a suite of products that are used for a variety of different applications (e.g. AMVs, fog, cloud properties, instability indices, volcanic ash and snow cover). More advanced imagers with more spectral channels are now being launched (Himawari-8, GOES-R, FY-4) to extend the range of products from geostationary imagery and improve their accuracy. AMVs are an important observation for global and regional NWP models and work on improving their height assignment is increasing their impact. Within the next decade high resolution infrared sounders are planned from geostationary orbit to provide more detailed vertical information of the humidity and winds with frequent sampling. To improve the coverage of satellite observations over the high latitudes of the Arctic a proposal to fly satellites in highly elliptical orbits has been proposed.

Over the past 40 years observations of the Earth’s atmosphere and surface have become more accurate and, thanks to increasing amounts of satellite data, provide much improved coverage of our planet. The next 40 years will see a consolidation of the global observing system with the conventional reference observations better co-ordinated worldwide and in parallel new innovative measurements reaching maturity by being assimilated into NWP models. The constellation of current satellites will be maintained both for NWP and climate monitoring. Improvements in technology will allow some measurements to be made with much smaller instruments allowing their deployment on small satellites reducing costs. Conversely new instruments will be developed to improve and expand the measurements made from space which will be exploited to better monitor the Earth-Atmosphere system in the future.

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CHAPTER 3. DATA ASSIMILATION METHODS AND APPLICATIONS

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Abstract

This chapter provides an overview of the wide variety of data assimilation approaches and related diagnostic tools developed to improve the analysis, reanalysis and prediction for the atmosphere and other geophysical components of the Earth system. Data assimilation systems are often based on either variational or ensemble-based approaches and increasingly combine aspects of both, as in ensemble-variational approaches. Diagnostic tools mostly focus on quantifying the complex links within complete analysis-prediction systems or only within the data assimilation component, for example the impact on forecast error of each type of assimilated observation. An overview of several areas of application for these data assimilation methods is also provided, including weather, ocean, sea ice, and systems that couple two or more of these geophysical components. Due to the large volume of assimilated observations and the high dimensionality of forecast models used in most applications, methods and tools need to be highly computational efficient on the current and future generations of massively parallel supercomputers. To conclude, some thoughts are provided on how data assimilation methods and related diagnostic tools will likely evolve in the future.

3.1 INTRODUCTION

Modern numerical weather prediction (NWP) systems and prediction systems for related geophysical components of the Earth system require accurate and timely estimates of the system state for initializing numerical forecast models. Alternatively, when performing a re-analysis the goal is to seek an accurate and consistent series of state estimates over a past period. These estimates for either prediction or re-analysis are typically produced by combining information from the forecast model with a large number of observations through the process of data assimilation. For example, the current generation of data assimilation methods for global NWP typically assimilate many millions of observations per day to produce initial conditions for forecast models with $O(10^8)$ to $O(10^9)$ state variables, often in less than an hour of wall-clock time. All methods must incorporate significant approximations to make such calculations possible on currently available supercomputers. These include: assuming error distributions are Gaussian; assuming corrections to the model background state are sufficiently small that simplified linearized models can accurately evolve them through time; and assuming forecast error covariances for models with $O(10^8)$ or more state variables can be approximated with an ensemble of $O(10^2)$ error realizations. Some of the biggest differences between data assimilation approaches are due to different choices with respect to such approximations. New approaches are also being developed that may soon reduce the requirement of using many of these approximations.

Current data assimilation and prediction systems are sufficiently complex that it is often difficult to interpret the impact of, for example, adding a new type of assimilated observation, or modifying some aspect of the error covariances used for assimilation. Consequently, a significant amount of research has focused on developing diagnostic tools with the aim of better informing the choices made when working to improve data assimilation systems.

Data assimilation approaches and related diagnostic tools are applied to various components or combinations of components of the Earth system over a variety of spatial and temporal scales. Consequently, the way in which they are used for each type of application can differ significantly.

3.2 DATA ASSIMILATION METHODOLOGY AND DIAGNOSTIC TOOLS

The current status of data assimilation methodologies and related diagnostic tools are provided with respect to the different types of approaches. The first two addressed are the main categories of currently mainstream data assimilation: variational and ensemble-based, followed by ensemble-variational (EnVar) methods that combine aspects of both. Next, approaches for estimating and modelling the error statistics that are an essential part of any data assimilation approach are then described. The next section deals with newer data assimilation methods that do not require the usual assumption of Gaussian-distributed errors that is necessary for most approaches currently used in realistic applications. The final section provides an overview of several types of diagnostic tools for assessing the impact of observations.

3.2.1 Variational data assimilation

In variational data assimilation, the analysis is produced by minimizing a cost function with terms involving the fit to the observations, the fit to the background state, plus additional terms representing constraints that limit, for example, the amount of imbalance or noise within the model states being estimated. As in most common data assimilation approaches, the main components within the variational data assimilation framework are the background and observation error covariance matrices, and the observation operator that relates the model state to the observations. In three-dimensional variational assimilation (3DVar), the state being estimated and the observation operator are both three-dimensional (i.e. valid at a single time), while in four-dimensional variational assimilation (4DVar, Le Dimet and Talagrand 1986), the observation operator is four-dimensional and it is usually assumed that the sequence of states through time exactly satisfies the forecast model that is embedded in the observation operator. Alternatively, in so-called weak constraint 4DVar, the simplifying assumption that the embedded forecast model is “perfect” is removed, and an additional term involving the model error covariance is included in the cost function (see below). In this case, the entire 4D state is estimated (Sasaki 1970).

In general, the cost function may include nonlinear terms and therefore be non-quadratic and difficult to minimize. Consequently, in practice the minimization procedure is applied to a slightly simpler, approximate quadratic cost function whose repeated minimizations define the so-called outer loops of an incremental variational data assimilation scheme (Courtier et al. 1994). This and a typically simple description of the observation-error covariances are at the heart of 3DVar and 4DVar methods that find the best state estimate using all available observations. The specified background-error covariances can incorporate inter-variable relationships and balance, and, by using a linearized forecast model and its adjoint, 4DVar methods also represent relationships between tendencies and gradients in different variables (e.g. Rabier et al. 2000). They are thus ideal for making the best use of observations from satellites or radars, which give good four-dimensional coverage of some variables but no direct information about others. They are also very flexible, able to cope with a wide range of observation types and densities. The inclusion of bias correction terms, critical for assimilating satellite radiances and other observations, is also relatively straightforward in variational assimilation schemes.

The main scientific weakness of variational assimilation schemes is the difficulty of making the background-error covariances reflect flow-dependent “errors of the day”. The main technical weakness of 4DVar in particular is that it requires significant infrastructure development, including tangent linear (TL) and adjoint (AD) versions of the forecast model that will likely become increasingly difficult to run efficiently on next-generation massively parallel computers. While there is some scope for improving the parallelization of the TL and AD models in 4DVar (Fisher et al. 2011), much research addressing the computational weakness of 4DVar is directed towards replacing the use of the linearized forecast model by relatively small ensembles of pre-calculated short-term forecasts known as the EnVar approach, described below. The technical difficulties described here notwithstanding, 4DVar schemes have been implemented successfully in many operational forecast centres including the European Centre for Medium Range Weather Forecasts (ECMWF), Met Office, Météo France, Environment Canada, Japan Meteorological Agency (JMA), and Fleet Numerical Meteorology and Oceanography Center, with most reporting significant positive impact on forecast performance (Rabier et al. 2000; Rabier 2005; Honda et al. 2005; Rawlins et al. 2007; Gauthier et al. 2007). In particular, the use of 4DVar has led to significant advances in the use of satellite radiance observations (see below), which are now predominant in the global observing system.

While weak constraint extensions to 4DVar are, in principle, straightforward, their implementation in operational data assimilation presents significant challenges. At current operational resolutions, the full 4D control state and model error covariance matrix required for the unapproximated form of weak constraint 4DVar are too large even for today's super computers. Approximations are thus required, but, so far, estimation of the model error covariance (that is, characterization of the statistical properties of model error) has proven to be very difficult. Reasonable first attempts such as assuming the model error covariance is simply proportional to the background error covariance, or applying the same statistical model for computing background errors to tendencies instead of analysis increments, have met with limited success. Other approaches include using tendency differences between members of an ensemble as a proxy for samples of model error (Trémolet 2012, personal communication). Despite such challenges, Trémolet (2006) presents several approximate formulations of weak constraint 4DVar, including the use of model bias or model error forcing as a control variable, that appear feasible for operational implementation.

3.2.2 Ensemble data assimilation

Ensemble data assimilation approaches use Monte Carlo simulation to represent the analysis and forecast uncertainty throughout the data assimilation cycle. Specifically, an ensemble of short-term forecasts is used to represent the prior probability density function (pdf) and then observations are assimilated to obtain an ensemble of analysis states that represents the posterior pdf. Development of an ensemble data assimilation scheme requires comparatively less initial infrastructure development than 4DVar, since the TL and AD models are not required. Most importantly, background-error covariances used for assimilation are computed from the current ensemble of short-term forecasts and are therefore fully flow-dependent and capture the effect of balance relations and complex physical processes from the full nonlinear forecast model.

The fundamental idea of the ensemble Kalman filter (EnKF) was first proposed by Evensen (1994), and was applied to global NWP by Houtekamer and Mitchell (1998). Burgers et al. (1998) provided the theoretical basis for the need to add independent random perturbations to the observations assimilated by each ensemble member. Whitaker and Hamill (2002) proposed an alternative approach, the square root filter (SRF), that properly accounts for observation error without the need of observation perturbations. Tippett et al. (2003) summarized the various SRF methods, including the ensemble adjustment Kalman filter (EAKF, Anderson 2001), the ensemble transform Kalman filter (ETKF, Bishop et al. 2001), and the serial ensemble SRF (Whitaker and Hamill 2002). Another related approach was proposed by Ott et al. (2004), the so-called local ensemble Kalman filter (LEKF), which assimilates a set of observations simultaneously in each local area. The LEKF was updated to the local ensemble transform Kalman filter (LETKF, Hunt et al. 2007) by taking advantage of the ensemble perturbation update of the ETKF.

While still computationally intensive, especially for large ensemble sizes, these algorithms are well suited for implementation on large parallel computers. For a given computational resource, the trade-off between ensemble size and model complexity (resolution and physics) is a primary factor in determining the system configuration. Usually the model complexity is chosen such that it is affordable to produce forecasts for O(100) ensemble members, the typical size for operational ensemble systems for NWP. However, the practical necessity of having to rely on small ensemble sizes (relative to the dimension of the model state) presents ongoing challenges. These systems typically require the incorporation of *ad hoc* technical controls to which the system's performance is highly sensitive. For example, the error covariance estimated from 100 random samples has large sampling errors and requires limiting the spatial influence of observations to within a finite radius. This is accomplished through covariance localization and the localization radius is an important tuning parameter of the EnKF. In particular, localization for spatially averaged observations such as satellite radiances is a challenge. Also, the limited ensemble size can result in the underestimation of error variance, which is usually compensated for by inflating the ensemble spread artificially.

Ensemble data assimilation systems have been applied with considerable success at several operational forecast centres. Houtekamer and Mitchell (2005) pioneered the first operational implementation of an EnKF at Environment Canada for initializing an ensemble prediction system.

Bowler et al. (2008) described the UK Met Office implementation of the ETKF in operations, known as the MOGREPS (Met Office Global and Regional Ensemble Prediction System). Bonavita et al. (2008; 2010) implemented the LETKF with the Italian operational regional NWP system. Other centres, including the German Weather Service, Japan Meteorological Agency, Brazilian Centro de Previsao de Tempo e Estudos Climaticos (CPTEC) and the Argentinean Servicio Metorological Nacional (SMN) have also been developing EnKF methods.

3.2.3 Ensemble-variational data assimilation

Efforts to combine the recognized strengths of both the variational and ensemble approaches have catalyzed the development of EnVar data assimilation schemes. Since the most practical methods for describing “errors of the day” use ensembles, while variational schemes allow flexibility to accommodate a wide range of observation types, much research currently focuses on the use of ensemble information within the variational framework (Liu et al. 2008, 2009, Buehner et al. 2010a,b, Lorenc et al. 2015, Wang and Lei 2014). Two techniques that have emerged are: 1) deriving parameters such as variance and correlation length scales in a background-error model from a current ensemble (Berre and Desroziers 2010); and 2) directly using localized ensemble perturbations in a hybrid error covariance model (Figure 1, also Lorenc 2003, Buehner 2005, Clayton et al. 2013, Kleist 2012). The forecast ensemble can simply be imported from a separate and independent ensemble data assimilation method, such as the EnKF. Alternatively, the variational method and EnKF can be coupled more closely (Zhang and Zhang 2012); ensembles of variational data assimilation systems may be used (Bonavita et al. 2012); or the Hessian of the variational minimization can be used (Zupanski 2005).

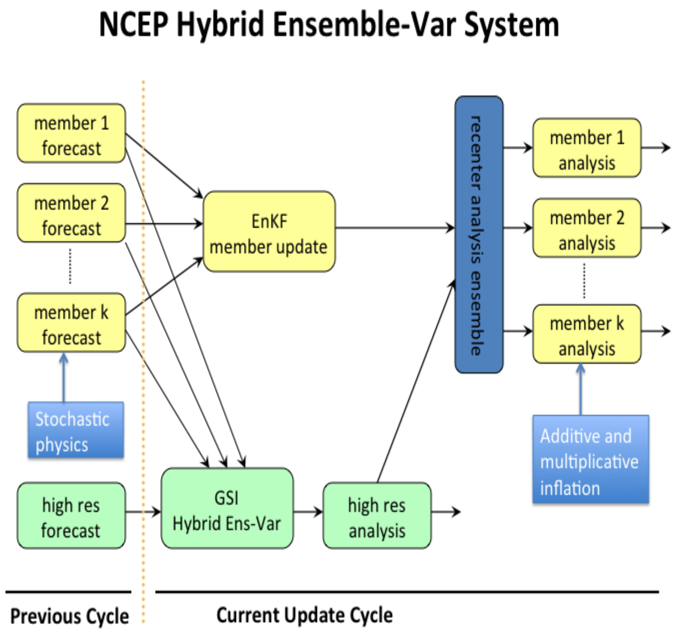

Figure 1. Schematic of the NCEP hybrid data assimilation system. The EnKF provides background-error covariance information to the Gridpoint Statistical Interpolation (GSI) analysis scheme which, in turn, provides the updated central analysis to re-centre the ensemble for the next assimilation cycle.

Source: Jeff Whitaker, NOAA/ESRL

In Canada, the availability of 4DVar for operational deterministic forecasting and the EnKF for operational ensemble prediction, led to research on the 4DEnVar approach that uses 4D flow-dependent covariances estimated from the ensemble to produce a 4D analysis without the need of the TL and AD of the forecast model (Buehner et al. 2010a,b). This approach has the advantage of implicitly incorporating the effects of the full suite of model physics within the variational minimization while eliminating the need to run and maintain additional TL and AD codes.

It also ameliorates some of the computational limitations of traditional 4DVar stemming from the inefficient use of large numbers of processors to run relatively low-resolution versions of the TL and AD models sequentially within the minimization loop (as compared with the typically higher resolution background forecast model).

A key question in 4DEnVar is whether small ensembles can adequately represent the dynamic effects of the TL and AD models during the minimization process. Future research needs to focus on improving the ensemble quality and their use in 4DEnVar so that its performance matches the more expensive hybrid-4DVar approach that combines 3D ensemble covariances with the TL and AD of the forecast model (Lorenc et al. 2015). This will need advances in covariance localization or similar approaches discussed in the next section. Nonetheless, the development of 4DEnVar systems is a current focus at several centres as it has promise to best accommodate the competing operational requirements for quality performance, computational efficiency, and code maintenance.

3.2.4 Estimation and modelling of error statistics

The ability of all data assimilation approaches to optimally combine the information from observations and short-term forecasts depends strongly on having accurate estimates of the observation and background-error statistics. For most approaches already discussed, the observation and background errors are assumed to be Gaussian and unbiased and therefore only their covariances are required. Even with this simplifying assumption, the estimation of the error covariances remains a significant challenge, due to both computational and scientific aspects. The computational challenges relate to the very large number of assimilated observations (for observation error) and the very high number of state variables of typical forecast models (for background error). The scientific challenges mostly result from the fundamental issue that we only have direct access to the covariance of the difference between observations and short-term forecasts (i.e. the innovations), which is an unknown combination of the observation and background-error covariances that we require. In addition, the covariance of the innovations is in observation space and therefore provides no direct information about background error in regions or for variables that are not observed. With respect to systematic errors, techniques are well advanced for estimating and correcting observation error bias in data assimilation, especially in the context of re-analyses. Systematic background errors are more difficult to correct within a data assimilation system; instead, effort is normally directed towards reducing identified biases by improving the models.

As already discussed in the previous sections, Monte Carlo simulation allows an ensemble of background states to be obtained that is representative of a random sample of the background error. To obtain useful covariance estimates from relatively small ensembles requires additional information to be imposed. Among the numerous possibilities so far examined, the most efficient approach has been to assume that the spatial covariance decreases as a function of separation distance and eventually becomes zero at some specified distance, typically O(1000km) for global NWP applications. Consequently, the raw ensemble covariance is modified in a way that increasingly reduces its amplitude with separation distance. Some of the early studies demonstrating the very large benefit of spatial covariance localization include Houtekamer and Mitchell (2001) and Hamill et al. (2001). While these studies showed that even simple approaches to spatial localization are highly beneficial, other studies showed that additional improvement can be achieved through more sophisticated adaptive approaches that vary the localization function in a way that depends on the raw ensemble covariance (Bishop and Hodyss, 2007 and 2009). In other approaches the optimal covariance localization is empirically computed from the output of an observing system simulation experiment (Anderson and Lei, 2013; Lei and Anderson 2014). An alternative to localizing covariances only in the spatial domain was evaluated by Buehner (2012) in which a simple localization with respect to spectral wavebands was combined with scale-dependent spatial localization. Since spectral localization is equivalent to local smoothing in the spatial domain, this is closely related to studies that show the benefits of applying a spatial smoothing to variances or spatial correlations (Berre and Desroziers, 2010). It may also be beneficial in some applications to apply temporal localization to 4D covariances or to reduce the covariances between different analysis variables.

Because the true state of the atmosphere is not known, we are forced to make certain assumptions that enable the background and observation error statistics to be estimated from statistics of the innovations (Talagrand 1999). A common example of this it to assume the observation error is spatially uncorrelated, whereas the background error is correlated. Following this basic assumption, one can fit a simple parameterized function to the innovation covariances that consists of the sum of uncorrelated and correlated components that are associated with the observation and background-error covariances, respectively (Hollingsworth and Lonnberg 1986). Other approaches involve assumptions that allow the background and/or observation error statistics to be computed from the output of an existing data assimilation system (Desroziers et al. 2005). Such approaches have been applied to estimate both spatial and inter-channel observation-error correlations (Garand et al. 2007; Bormann and Bauer 2010; Gorin and Tsyrulnikov 2011). However, with all of these approaches, it is usually difficult to independently validate the results, except in idealized experiments where the truth is known.

Another approach to estimating error covariances, discussed in more detail below, is closely related to the adjoint sensitivity approaches. The adjoints of both the forecast model and the complete assimilation procedure are used to compute the sensitivity of a scalar measure of forecast error with respect to changes to a set of error covariance parameters to propose changes to these covariance parameters (Daescu and Langland 2013).

There are numerous inseparable links between the approaches described in this section for modelling and estimating error statistics and the research described in the sections on variational and ensemble data assimilation approaches. This is because the choice of data assimilation algorithm often dictates what approaches for modelling error statistics can and cannot be used in realistic applications. For example, most ensemble data assimilation approaches cannot use covariance localization applied directly to background-error covariances, but must apply it to the covariances after they are partially or completely transformed into observation space, which may not be optimal for non-local observations, such as satellite radiances.

With increasing computational power, future data assimilation systems will need to be capable of efficiently estimating and utilizing background-error statistics from forecast ensembles with a much higher number of members and higher spatial resolution. This will likely require some type of scale-dependent localization, on which preliminary research has already been conducted (e.g. Zhang et al. 2009; Buehner 2012; Miyoshi and Kondo 2013). Finally, research is required to evaluate which assumptions or methods or observing networks are needed to be able to reliably separate innovation covariances into its observation error and background error components. Such procedures are needed for both maintaining accurate ensemble spread in ensemble data assimilation systems and obtaining accurate observation error covariance estimates.

3.2.5 Non-Gaussian data assimilation

With ever increasing spatial and temporal resolution of numerical weather, ocean, and climate prediction models and progressively more complicated relations between observations and model variables, the data-assimilation problem is becoming increasingly nonlinear. All data assimilation methods in use today, including 4DEnVar, are either linear or based on linearizations and mostly assume that errors are Gaussian. While these methods can be expected to work well for weakly nonlinear systems, new models, for example convection-permitting models, are highly nonlinear and standard methods are likely to fail or give strongly suboptimal results.

The underpinning research in data assimilation methods for highly nonlinear and non-Gaussian systems mainly resides in academia since NWP centres generally allocate resources in other areas. This is understandable given the focus on making short-term improvements to operational prediction systems, but may hamper more rapid development in this field. Several nonlinear data assimilation techniques do exist for small-dimensional problems and recently significant progress has been made for application to higher dimensional systems. This progress has invariably been made with particle filters and with Gaussian mixture models. Both are based on using ensembles (note that a particle is the same as an ensemble member), but are quite different from the EnKF approaches already discussed. Another related approach is the multivariate rank histogram filter (Metref et al. 2014).

To make particle filters efficient for high-dimensional systems they must be steered towards future observations. Ades and van Leeuwen (2014) used a simple relaxation technique and showed that their Equivalent-Weights Particle Filter can be used with very high-dimensional systems. Morzfeld and Chorin (2012) used variational techniques related to 4DVar in their Implicit Particle Filter for geophysical systems. While it can be shown that the Implicit Particle Filter is degenerate for high-dimensional systems the approach can be combined with the Equivalent-Weights idea to form a new nonlinear data assimilation method. This new method would be similar to the ensemble of 4DVar analyses used at ECMWF, however, it would now be fully nonlinear. A major difference with traditional 4DVar is that the initial condition is fixed (the position of the particle at initial time) and model errors must be included. A potential advantage of this approach is that the background-error covariance, either climatological or derived from an ensemble, is not needed. This means that all efforts can be instead placed on improving estimates of the covariances for model error, which is where the true interaction with the physics lies.

In Gaussian Mixture models the pdf is described by a sum of a set of Gaussians (see e.g. Hoteit et al. 2008). Typically, the mean of each Gaussian is propagated forward with the model equations, similar to the EnKF, but the covariance of each Gaussian cannot be dynamically propagated since this would be too computationally expensive. The covariances are instead determined in an *ad hoc* way at analysis time, making this method a mix between fully nonlinear and EnKF methods. Another issue is that the filter is degenerate when the number of observations is large, which can however be alleviated by employing localization. Note specifically that, unlike in particle filters, the state covariances are needed and must be accurate. Also hybrids between the Gaussian mixtures and particle filters have been developed (see e.g. Stordal et al. 2011).

There is a need for systematic training in the area of data assimilation applied to nonlinear and non-Gaussian systems. A stronger engagement of the operational NWP community in this area is highly desirable to be able to properly test new methods for operational applications. Academia neither has the resources nor the technical capacity to do this. A strong community effort is needed to improve our understanding and ability to accurately estimate model error covariances. This is not only essential for particle filters, but also for existing data assimilation methods like weak-constraint 4DVar and the EnKF as we know that these errors are substantial and need to be included in the data assimilation problem.

3.2.6 Assessing observation impact

Currently there are millions of observations assimilated in operational NWP analysis-prediction systems, so that when a new observing system is introduced, the task of assimilating the observations and assessing their impact is complex. Specifically, this requires the development of a quality control (QC) procedure, an observation operator, an estimate of the observation error statistics, and intense experimentation to demonstrate that assimilating these observations actually improves the forecasts. Although very sophisticated QC methods have been implemented into operations, poor quality observations are still accepted and have been shown to be an important contributor to forecast failures (e.g. Alpert et al. 2009, Kumar et al. 2009, Rodwell et al. 2013). Thus, there is increasing need for the development of efficient, robust methods for assessing observation impact on system performance. It also recognized that such assessments provide important feedback to data providers, and inform the process for developing the global observing system.

3.2.6.1 Forecast sensitivity-based methods

Over the past few years, tools have been developed to quantify the impact of all observations in NWP systems both for short-range forecasts and longer-range predictions. For the former, as a by-product of the development of 4DVar systems, Baker and Daley (2000) introduced the concept of forecast sensitivity to observations (FSO) based on the adjoint of the analysis scheme. Langland and Baker (2004) extended this concept to introduce the forecast sensitivity observation impact

(FSOI) as a way of quantifying for the first time how much each observation improves or degrades a measure of the forecast accuracy, based on the adjoint of the complete analysis-prediction system. With this flexible approach, results can be aggregated by, for example, observing system type (Figure 2), geographic location, satellite instrument channel, or other observation attribute. The technique works best for impacts on short-range forecasts, typically 24 hours for global applications, owing to limitations inherent in the use of adjoint models (i.e. assumption of linearity, simplification of the model physics). The FSOI approach has become widely adopted for monitoring the impact of different observing systems on short-range forecasts (e.g. Cardinali 2009; Lorenc and Marriott 2014), and results between different centres have been compared and shown to be broadly consistent giving confidence in the technique (Gelaro et al. 2010). The FSOI approach has also been adapted to ensemble-based data assimilation systems. Liu et al. (2009) implemented it with the LETKF. Liu and Kalnay (2008) and Li et al. (2010) introduced the ensemble forecast sensitivity to observations (EFSOI) for the LETKF. Kalnay et al. (2012) provided an improved, simpler EFSOI formulation that is more accurate and can be applied to any type of EnKF.

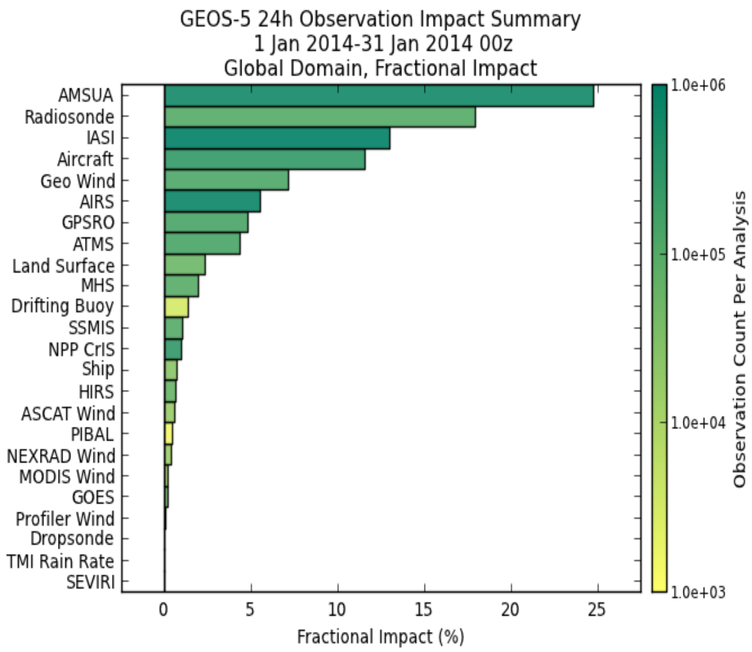

Figure 2. Adjoint-based 24-h observation impact in the NASA/GMAO data assimilation system for forecasts initialized at 00Z during January 2014. The values for each observation type are plotted as a fraction of the total forecast error reduction based on a moist global energy norm from the surface to 1 hPa. The colour shading indicates the average observation counts.

Daescu (2008) and Daescu and Langland (2013) introduced the forecast sensitivity to the observation error covariance matrix **R** (FSR) as an extension of the FSO concept and a potential method of tuning **R** to optimize observation impact. The ability of diagnostic tools such as (E)FSOI and (E)FSR to improve the use of observations opens the door to several additional improvements of the NWP systems. One important application might be to provide the developers of observation algorithms with detailed information about when and where each type of observation succeeds or fails in improving the forecasts, with all the necessary metadata for each observation needed to allow the improvement of the observation algorithm or quality control procedures. Another application is to provide an efficient means of optimizing the assimilation of data from new observing systems.

3.2.6.2 Observing system experiments

For longer forecast periods, the more traditional observing system experiments (OSE) are the most common means of assessing observation impact. In an OSE, the data assimilation is run with and without a particular observation type and the results are compared (e.g. Bouttier and Kelly 2001). This shows the impact of that observation type for the complete forecast period. OSEs are much more expensive to run than the FSOI, but give a more complete picture of the impacts of a selected observation type, including accumulative effect through multiple data assimilation cycles. Both the FSOI and OSE estimates of observation impacts are being used for routine operational assessments, and for cost-benefit studies to inform the design of the future global observing system. A detailed comparison of the OSE and FSOI approaches is presented in Gelaro and Zhu (2009).

OSEs have been further developed to assess the impact of new types of observations not yet available (e.g. line-of-sight Doppler winds) and these have been termed observation system simulation experiments (OSSE), as described in Becker et al. (1996) and Masutani et al. (2002), and more recently by Errico et al. (2013) and Privé et al. (2013). These OSSEs rely on a "nature run", typically an extended integration of an NWP model, from which the observations can be simulated using the observation operators and specified observation error covariances. These simulated observations are then assimilated into a different forecast model as an OSE type experiment to assess their impact. A drawback of OSSEs is the continued need for providing updated nature runs from an independent model to generate simulated observation data sets, which requires significant resources.

3.3 DATA ASSIMILATION APPLICATION AREAS

3.3.1 Global to convective scale atmospheric prediction

The steady increase in computing power and availability of diverse, high-quality atmospheric observational datasets have combined to make data assimilation an essential component of operational NWP systems from global to convective scales. Like the forecast models themselves, the data assimilation systems for global and convective-scale applications have been developed separately, but generally employ similar methodologies including, for example, 3DVar, 4DVar and the EnKF. Variational algorithms, being well suited to accommodate large numbers and types of satellite radiance observations, remain the cornerstone of most operational data assimilation systems, especially for the global scale. On the meso- and convective scales, ensemble methods have been applied with considerable success.

While the methodologies used for global and convective-scale data assimilation are similar in origin, their application, and hence the details of the resulting algorithms, can differ significantly. For example, in convective-scale data assimilation, rapid updates are essential and involve novel observation types such as radar reflectivity, radial wind information and lidar backscatter. The background error covariances can vary significantly depending on whether convection is present or not, and highly nonlinear dynamics often result in non-Gaussian error distributions while the analysis is designed to produce the best state estimate under Gaussian assumptions. The latter may be especially challenging for the assimilation of cloud and precipitation data where displacement errors and highly non-linear physical processes can dominate. In addition, the increasing focus on observation types with non-Gaussian error distributions or highly non-linear relationships with the model variables pose significant challenges in both the variational and ensemble approaches.

Requirements for data assimilation methods are driven by specific applications in global and convective-scale NWP, and by the available observations. These requirements and the capabilities of future supercomputers will determine which data assimilation method is most cost effective for each application. Background-error models used in variational methods have many parameters which affect the performance of the method; it is practically impossible to tune them all empirically through the brute force method of trial and error. Consequently, efficient diagnostic methods for determining them are essential, as already touched on previously. Effective methods are also needed for convective-scale EnVar for a regional ensemble nested in a larger-scale ensemble, using the latter both for boundary conditions and for modelling large-scale errors. Future application of EnVar methods to large ensembles of high-resolution models will require both an increase in computing power combined with more efficient data assimilation algorithms.

As already mentioned, accounting for model error in the assimilation process is becoming increasingly important, especially at convective scales, but remains a significant challenge. In the variational context, approximate formulations of weak constraint 4DVar are feasible, as described in Section 3.2.1, but estimation of even a simplified form of the model error covariance has been difficult. In the ensemble context, the focus is on replacing simple additive or multiplicative covariance inflation with more physically based approaches such as the stochastic kinetic energy backscatter scheme (Berner et al. 2009), the use of stochastic physical parametrizations (e.g. Song et al. 2007), the use of multiple physics packages within the ensemble (e.g. Houtekamer et al. 2009), or the application of stochastic perturbations to the physics tendencies (Buizza et al. 1999).

3.3.2 Use of satellite radiances

Modern data assimilation systems for NWP make abundant use of satellite observations. The assimilation of satellite radiances, in particular, has been an area of great progress over the last two decades and a major factor in the improvement of forecast skill, especially in the southern hemisphere. These data currently account for a large majority of the available observations used in operational systems. While some of the improvement in forecast skill comes from improved instruments and the increased number of available observations, most of it comes from improvements to how the information in these observations is used (Derber and Collard, 2012, hereafter DC12). Figure 3 shows the increase in forecast skill with time from the evolving ECMWF operational forecast system (top panel), as well as from fixed versions of the system used in recent reanalyses (bottom panel). Two points are readily discerned from the Figure: 1) forecast skill increases at a considerably faster rate in the operational forecast system, reflecting system improvements in addition to changes in the observing system, and 2) forecast skill in the southern hemisphere improves dramatically beginning in the mid to late 1990's. This period coincides with the implementation of direct assimilation of satellite radiances using 3DVar and 4DVar.

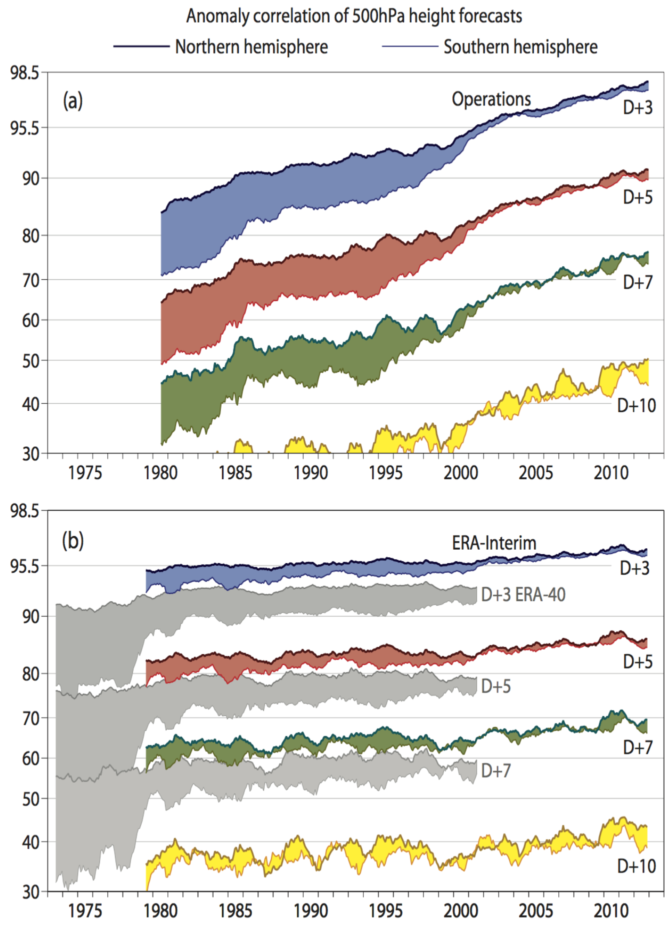

Figure 3. Twelve-month running mean of anomaly correlation of 500 hPa height for various lead times in the ECMWF operational forecast system (top) and in the ERA-40 and ERA-Interim reanalysis systems (bottom). The shading shows the differences in skill between the northern and southern hemispheres.

Source: Dee et al. (2014).

Satellite observations have characteristics that make them unique and especially challenging to use compared with most other observation types. Most of these data are widely distributed through time, exhibit significant biases due to instrument characteristics and other factors, and provide only indirect measurements (radiances) of the model and analysis variables (e.g. temperature and humidity). Accordingly, much of the progress in the use of satellite data has stemmed from careful consideration of these characteristics in the design of the assimilation system, including quality control procedures, bias correction, observation operator development, and observation error specification.

Key to the assimilation of satellite radiances is the observation operator (also referred to as the forward model). In the case of satellite radiances, the forward model involves integration of a fast radiative transfer model whose inputs include model profiles of temperature, humidity and ozone, as well as surface characteristics including skin temperature, emissivity and surface type. For low-peaking channels with strong surface sensitivity, the latter can be a significant source of uncertainty in the radiative transfer calculation. Thus, most of these data go unused in current data assimilation systems. For channels that have a significant moisture signal, the forward model calculation may be weakly nonlinear, while the inclusion of clouds and precipitation can lead to strong nonlinearity, adding significant complication and expense to minimizing the variational cost function that defines the analysis problem (DC12). For this and other reasons, the vast majority of the data currently assimilated is limited to cloud-free scenes or channels that peak above clouds. However, efforts are underway in many research and operational centres to expand the use of cloud- and rain-affected radiances, sometimes referred to as “all-sky” radiance assimilation. In 4DVar, the forward model also includes an integration of the TL version of the forecast model from the analysis time to the observation time. Use of 4DVar has proven to be especially effective for extracting information from satellite observations that are distributed throughout the assimilation time window as well as other non-conventional data types.

Advances in the detection and removal of observational bias have also been an important part of the progress in assimilating satellite radiances. The bias in a given satellite channel can vary significantly in space and time depending on the atmospheric conditions, errors in the radiative transfer model, and quality and age of the instrument (Rienecker et al. 2011). Currently, most operational centers employ a variational bias correction scheme in which bias parameters for each satellite channel are added to the control vector and updated during the analysis cycle along with all the other analysis variables (Derber and Wu 1998; Dee and Uppala, 2009). The bias estimates thus adapt in response to natural phenomena, such as volcanic eruptions, or changes in the instrument quality and orbital position of the satellite that can severely affect the radiance measurements (see, for example, Figures 4 and 5 in Dee and Uppala 2009). It should be noted that a drawback of this procedure is the difficulty in distinguishing between model and observation bias when no other data are available, potentially making erroneous corrections to the observations due to biases in the forecast model. In particular, it is important that the observing system maintain a significant amount of unbiased observations to “anchor” the bias estimation for satellite radiances. The growth in the number of GPS radio occultation data over the last decade has played an important role in this context, but a possible decline in the number of these data if aging instruments are not replaced, while unfortunate in its own right, could also adversely affect the use of satellite radiances.

Observations from satellites now enable the estimation of new variables such as 3D winds, clouds, precipitation, trace gases, aerosols, and characteristics of the land surface and ocean. DC12 point out that inclusion of additional analysis variables poses several challenges emphasizing the integration of all components of the assimilation system. These include accounting for nonlinearities in the assimilation of clouds and precipitation, and specifying background-error covariances so as to use information in the data at the correct scales and make proper adjustments to other variables. Other suggested focus areas for improving satellite data usage include properly accounting for biases in the forecast model, and improving our ability to simulate surface properties such as skin temperature and emissivity.

3.3.3 Ocean and cryosphere analysis

3.3.3.1 Introduction

Data assimilation is increasingly being applied to the ocean and cryosphere. These systems are designed for either stand-alone analysis and prediction systems that are forced by existing atmospheric and other geophysical data sets, or they represent one component in a coupled prediction system for which the data assimilation procedure is often applied independently for each component. The focus of this section is on the use of data assimilation for ocean and sea ice analysis and prediction, whereas the following section focuses on specific aspects of coupled applications.

3.3.3.2 Ocean analysis

A wide range of methods have been used for assimilating observations to correct the solutions of oceanographic models, including most of the methods described at the beginning of this chapter. Some methods render the resulting ocean analyses more amendable to certain applications. For example, the use of ocean data assimilation to study the mixed-layer heat budget and water mass pathways mostly involve methods that do not produce internal sources and sinks of heat and salt, such as variational methods that use the model as a strong constraint within a long assimilation window, thus facilitating the closure of budgets. For initialization of climate and/or seasonal-to-interannual prediction, applications are mostly based on sequential filter or short-window smoother methods because the use of very long windows with smoother-type methods is not practical for applications of initializing climate models on an operational basis.

There is a requirement for data assimilation techniques appropriate for ocean models with high spatial resolution, including methods to reduce the computational cost. These need to be applicable not only to the estimation of an ocean state containing mesoscale eddies, but also to research on the coastal environment, which is directly connected with human activities such as fisheries, marine transportation, coastal security, and marine leisure. Data assimilation for oceanic biogeochemical and ecological modelling is of interest because of their possible application to sustainable management of marine resources. However, there are many issues to be addressed in biogeochemical and ecological data assimilation for such a complex system. In particular, there remains a high degree of uncertainty in oceanic biogeochemical and ecosystem models, including optimal parameter values. Furthermore, a dynamically and kinematically consistent ocean state, deduced from a smoother approach or equivalent methods (e.g. Daley 1991), may be required to ensure realistic solutions from such models, since three-dimensional advection is a key process in determining the distribution of nutrients and plankton (e.g. Anderson and Robinson 2001). At present, ocean colour measurement from satellites is one of the most effective methods to constrain biogeochemical and ecosystem models. "During the next decade coupled physical–biogeochemical assimilation can be expected to mature, providing new insights not only to ocean biological variations and the marine carbon cycle but also into the feedbacks within the physical climate system" (Rienecker et al. 2010).

Because of recent progress in data assimilation methodology and advances in computing power, a number of national centers have developed ocean analysis and forecasting systems that operate on regional and global scales (e.g. Brasseur et al. 2005). The Global Ocean Data Assimilation Experiment (GODAE) and now GODAE OceanView (http://www.godae-oceanview.org) have fostered the development and improvement of operational ocean analysis and forecast systems worldwide. Short-term ocean analysis and forecasting as championed by GODAE and GODAE OceanView involve timescales of days, whereas climate-oriented state estimation and assimilation fall in CLIVAR's realm and involve intraseasonal (see Chapter 20) to decadal timescales. The interplay between these two efforts is increasing as ocean analysis and forecasting extend the scope to reanalysis and as the spatial resolution of climate-oriented ocean models and assimilation systems increases.

Further examples of data assimilation applications in oceanography are contained in Schiller et al. (2013); and Schiller et al. (2015) contains a detailed discussion of future directions in ocean data assimilation.

3.3.3.3 Sea ice analysis

Sea ice analyses are currently produced in several countries to assist the planning of marine transportation and other marine activities through the highly time consuming process of manually analyzing a wide variety of satellite, aircraft and in situ observations (e.g. Carrieres et al. 1996). Though the necessarily restricted spatial and temporal coverage of such analyses limit their application, these manual analyses have been used for initializing sea ice forecasts (e.g. Pellerin et al. 2004). However, for many applications automated high quality gridded analyses of sea ice conditions are required in near-real-time for which data assimilation techniques are increasingly being used. These techniques are applied either in isolation to correct only the sea ice component of a coupled ice-ocean model, or are incorporated within a single analysis procedure for simultaneously estimating the coupled ice-ocean state. Consideration of the ocean state when assimilating sea ice observations is important for obtaining accurate forecasts, since the addition of sea ice to a warm ocean (or removal of sea ice from a cold ocean) often results in the rapid melting (or formation) during the subsequent forecast. Observations of ice motion and concentration are the most commonly assimilated, whereas thickness observations have been assimilated to a lesser extent due to the lack of reliable observations from satellite sensors with sufficient spatial coverage and latency.

Several early sea ice data assimilation studies focused on the use of ice motion estimated from processing sequential satellite images. In the studies of Meier et al. (2000) and Meier and Maslanik (2003) optimal interpolation was used to assimilate ice motion estimated from Special Sensor Microwave Imager (SSM/I) data to initialize a stand-alone ice model for the Arctic. The assimilation improved the agreement of the modelled ice motion with buoy observations and also substantially altered the average ice thickness in some regions. Similarly, using a coupled ice-ocean model of the Arctic Ocean, Zhang et al. (2003) assimilated ice motion from buoy motion and SSM/I imagery using optimal interpolation. Rollenhagen et al. (2009) used an ensemble-based data assimilation method to assimilate ice drift observations. This resulted in realistic corrections made to the ice concentration and thickness fields due to the multivariate ensemble covariances. Stark et al. (2008) assimilated ice concentration and motion from satellite data in addition to a full set of ocean data using an optimal interpolation scheme and a global coupled ice-ocean model. While they adjusted ocean salinity in response to changes made to the ice mass, the ocean temperature was not directly modified by the assimilation of ice data. Possibly because of this, they only obtained significant improvements for either ice concentration or ice motion from assimilating observations of only concentration or motion, respectively.

The Canadian Regional Ice Prediction System includes an ice concentration analysis produced by assimilating scatterometer data, retrievals from passive microwave data and manual ice analysis products using a 3DVar approach (Buehner et al. 2013; Buehner et al. 2014). Scott et al. (2012) used a simple radiative transfer model within a similar 3DVar assimilation system to directly assimilate passive microwave brightness temperature observations to estimate sea ice concentration and several other geophysical variables related to the observed brightness temperature. They found that the direct assimilation of brightness temperatures produced ice concentration estimates in better agreement with independent observations than when assimilating an ice concentration retrieval. Posey et al. (2011) described the Naval Research Laboratory (NRL) Arctic Cap Nowcast/Forecast System that also uses 3DVar to assimilate numerous sources of oceanographic observations in addition to ice concentration derived from passive microwave satellite data to initialize a coupled ice-ocean model. Lisæter et al. (2003) used an EnKF applied to a coupled ice-ocean model of the Arctic Ocean to assimilate ice concentration derived from SSM/I. In a subsequent study, Lisæter et al. (2007) assimilated synthetic ice thickness data using the EnKF and a coupled ice-ocean model resulting in a significant impact on both sea ice and ocean variables with the ice thickness being improved. Similarly, Yang et al. (2014) demonstrated a positive impact on both ice concentration and thickness forecasts with a coupled ice-ocean model when retrievals of ice thickness from the Soil Moisture and Ocean Salinity (SMOS) satellite data were assimilated in combination with ice concentration retrievals.

3.3.4 Coupled analyses and re-analyses

3.3.4.1 Introduction

Coupled models are becoming increasingly used for environmental forecasting. These provide a more complete and realistic representation of the physical world. Increasingly, coupled atmosphere-ocean-ice models are being used in seasonal to decadal prediction. There is also a move towards coupling for forecasts at the short and medium-range, the coupling of physical and biogeochemical models of the ocean and the inclusion of atmospheric constituents. Typically, these coupled systems have very different physical characteristics and different spatial and temporal scales. Similarly the observations of the components may have different properties in terms of spatial and temporal frequency and the kind of quantities that can be observed.

Coupled data assimilation is a new initiative driven by the need to analyze coupled components of the earth system in a consistent way. Coupled climate forecasts require the initialization of the coupled system (ocean, atmosphere, land, and cryosphere) in a consistent manner. In the past these components have been initialized with analyses produced from separate assimilation systems. By assimilating observations directly into a coupled model, the resulting analyses and model initial conditions are likely to be better balanced and less likely to lead to initialization shock. Coupled assimilation of the earth system is also likely to lead to re-analyses that are more consistent between the different components. This will produce fields that are likely to have more consistent variability and trends.

3.3.4.2 Global coupled re-analyses

Coupled assimilation is still in its infancy, with several groups having attempted weakly coupled assimilation, with no cross-covariance in errors between different components. The Climate Forecast System Reanalysis (CFSR) at NCEP is the first partially coupled reanalysis of its kind in the world, using a background first guess from a fully coupled model representing the interaction between the Earth's atmosphere, oceans, land and sea-ice. More recently, the Modern Era Reanalysis for Research and Applications, Version-2 (MERRA-2) at NASA's Goddard Space Flight Center includes interactive aerosols with assimilation of aerosol optical depth from a variety of remotely sensed and in situ sensors.

In recent years, there has been a concerted effort by several NWP centers to implement coupled atmospheric constituent-meteorological models, including aerosols, greenhouse and reactive gases. An extensive review of data assimilation capabilities implemented in such systems can be found in Bocquet et al. (2014). These systems are routinely used for air-quality forecasting, atmospheric constituent reanalyses and, by means of inverse calculations, to constrain natural and anthropogenic emissions. Sessions et al. (2015) describes International Cooperative for Aerosol Prediction Multi-Model Ensemble (ICAP-MME), involving near-real-time aerosol forecasts from ECMWF, NASA, NOAA/NCEP, JMA, NRL, among other centers. While aerosol direct and indirect effects have the potential to impact meteorological forecast skill, evidence for these benefits remains scant (e.g. Reale et al. 2014, Remy et al. 2014). Assimilation of ozone has the immediate benefit of improving the representation ozone radiative forcing in the stratosphere. Given the link between ozone and potential vorticity, assimilation of upper tropospheric ozone can potentially impact weather forecasts, but these benefits are yet to be realized (e.g. Dee et al. 2014).

Chemical data assimilation faces multiple challenges that include scarcity of observations (compared to meteorology), non-Gaussian error distributions (due the constraint that concentrations and emissions are positive or range-limited), large model errors as a consequence of deficiencies in parameterizations, and significant model sensitivities to external forcings such as emission sources that are highly uncertain.

ECMWF is currently developing a coupled data assimilation system for reanalysis purposes. This system has been called CERA (Coupled ECMWF ReAnalysis) and uses the ECMWF coupled model where the atmospheric component is the ECMWF Integrated Forecast System (IFS) and the oceanic component is the Nucleus for European Modelling of the Ocean (NEMO) model. The ultimate purpose is to generate a self-consistent atmosphere-ocean state by assimilating both atmospheric and oceanic observations within the coupled model.

The IFS model at ECMWF has fully interactive components for the atmosphere, the land surface (since 1991), and the sea state (since 1998). The ERA datasets therefore include estimates of land surface parameters (e.g. soil temperature, soil moisture, snow) and, beginning with ERA-40, parameters that describe the sea state (e.g. wave spectra, significant wave height). These estimates are consistent with the meteorological parameters, in the sense that they are constrained by the coupled model. However, the analysis schemes for the different components are separate and use different methodologies.

A coupled ensemble-based ocean assimilation system called the POAMA Ensemble Coupled Data Assimilation System (PECDAS) has been developed at the Australian Bureau of Meteorology. PECDAS is an approximate form of ensemble Kalman filter system, its approximations being necessary to reduce computational cost. It is based on the multivariate ensemble optimum interpolation, but uses covariances from a time evolving model ensemble. The first version of the system is weakly coupled, only ocean observations are assimilated into the coupled model and the atmospheric component is nudged towards pre-existing atmospheric analyses. A re-analysis from 1980 to present has been completed with this system. Both in situ temperature and salinity observations are assimilated, and ocean current corrections are generated based on the ensemble covariances.

3.3.4.3 Regional re-analyses

As part of the European Reanalysis and Observations For Monitoring project (EURO4M), a regional reanalysis system for the atmosphere has been developed. It uses 4DVar to assimilate conventional and satellite data, and also cloud and visibility from surface stations. It relies on the ECMWF ERA-Interim global reanalysis for boundary conditions and for observation data.

The model developed by the Consortium for Small-scale Modeling (COSMO) has been used to produce a regional reanalysis for Europe, matching the 0.11° resolution European domain of the Coordinated Regional Climate Downscaling Experiment (CORDEX) regional climate domain specifications, albeit at a higher spatial resolution of 6 km. The production of a 30-year period of reanalysis data in several streams is currently in progress.

The High Resolution Land Data Assimilation System (HRLDAS) has been used to prepare a land surface dataset over the Indian region at 20 km special resolution. This was done using an uncoupled HRLDAS simulation carried out for the period of 1 January 2001 to 31 October 2013.

3.3.4.4 Coupled assimilation strategies

The Community Earth System Model (CESM) has been interfaced to a community facility for ensemble data assimilation (Data Assimilation Research Testbed – DART). In the CESM-DART framework, data is assimilated into each of the respective atmosphere/ocean/land model components during the assimilation step, and information is exchanged between the model components during the forecast step.

As a first step towards the development of an ocean-atmosphere coupled data assimilation system, the NASA-Global Modeling and Assimilation Office (GMAO) atmospheric system has been extended to model and analyze skin sea surface temperature (SST) using a simple air-sea interface layer. This layer modifies the bulk SST to include near-surface effects, such as diurnal warming due to solar insolation and cool-skin that were previously not felt by the atmosphere. The impact of surface waves is parametrized in this initial version of interface layer. By directly assimilating infrared and microwave satellite radiance observations that include SST sensitive channels and in situ data from ships and buoys, using the Gridpoint Statistical Interpolation (co-developed with NCEP) realistic diurnally varying skin SST can be estimated.

At the University of Washington, strategies in fully coupled data assimilation have been considered in an idealized low-dimensional analogue of the coupled atmosphere-ocean North Atlantic climate system, featuring the Atlantic meridional overturning circulation (AMOC). The ability to initialize the multi-frequency AMOC with an EnKF has been assessed over a range of experiments with varying levels of observations available for assimilation (atmosphere, upper and deep ocean).

Scarcity of observations of the ocean interior is a key barrier to further improvements in ocean state estimation and forecasting. Coupled data assimilation has the potential to ameliorate this problem by extracting information from atmospheric observations to correct the ocean state using coupled atmosphere-ocean covariances. This is being investigated at NRL by evaluating the impact of scatterometer wind measurements on ocean analyses in the Mediterranean Sea (Frolov 2014, personal communication).

3.4 SUMMARY AND FUTURE PROSPECTS

The application of data assimilation in the context of forecast models and observing systems that are both becoming increasingly complex represents a significant challenge. To address this, research to improve data assimilation methodologies, diagnostic tools and their application to a wide range of geophysical systems will continue.

Increases in computing power allow for the use of forecast models with improved temporal and spatial resolution that are also increasingly coupled with other components of the Earth system. Computing power has become sufficient to also facilitate the use of ensembles of increasing size with the goal of enabling the use of more advanced data assimilation procedures. Existing data assimilation methods and diagnostic tools must be improved and new methods developed to take full advantage of these increases in the complexity of prediction systems. Methods must be highly computationally efficient and readily parallelize over a very large number of processors. In addition, the explicit inclusion of additional physical processes, increases in spatial resolution and the coupling of multiple components of the Earth system require data assimilation methods that can better account for nonlinearity and non-Gaussian uncertainties.

In summary, the development of data assimilation systems will progress in the future towards systems that have higher resolution, larger ensemble size, higher degree of coupling, and a greater volume and variety of the types of assimilated observations.

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CHAPTER 4. THORPEX FIELD PROGRAMMES

Patrick A. Harr and Chun-Chieh Wu

Abstract

An objective of THe Observing Research and Prediction EXperiment (THORPEX) was to develop science and implement plans to meet regional forecast needs in Asia, North America, Europe and the Southern Hemisphere. As such, THORPEX regional committees were formed to propose, organize, and implement field projects and forecast demonstration projects related to improving forecasts of high-impact weather specific to each region. Over the THORPEX time period, programmes were conducted that spanned from each pole to the tropics. While the geographic settings varied greatly, the objectives of each campaign were consistent with the THORPEX goals of improving prediction from 1 day through 2 weeks for the benefit of society and the economy of each region.

4.1 INTRODUCTION

In THORPEX, it was recognized that improvement to forecasts of high-impact weather would be dependent on increased understanding of key dynamical processes associated with forcing factors such as Rossby-wave activity and diabatic influences. Much of these activities were focused in the Predictability and Dynamical Processes (PDP) working group of THORPEX. It was also recognized that increased predictability required improved representation of key processes in numerical forecast models, which required careful use of observations to define initial conditions for numerical integration. Many of the THORPEX field campaigns were then constructed to be combined efforts between the PDP and Data Assimilation and Observing Systems (DAOS) THORPEX communities.

Field campaigns conducted within THORPEX typically required unique techniques for obtaining observations of key processes that may be related to a variety of spatial and temporal scales. Additionally, experiments were designed to not only identify key observations but to place those observations such that their spatial and temporal distributions were consistent for improved initial conditions. These observations often required new data assimilation techniques to be explored for increasing the utility of observations in the numerical integrations.

Early in the THORPEX cycle, it was clear that much high-impact weather had global origins that projected onto regional conditions. Therefore, there was a link between longer time intervals and near global connections to short time period and regional impacts. Specific factors such as the leading edges of Rossby wave trains and diabatic forcing of divergent flow were identified as representative of these global-regional linkages that often lead to high-impact weather. In this summary of the THORPEX Field Campaign Session, several programmes are summarized to provide examples to the global aspect of THORPEX-related technology, retrieval of complex data sets, and their usage in the prediction of high-impact weather.

4.2 GLOBAL PROGRAMMES

The THORPEX field campaigns were deeply rooted in subgroups of the PDP and DAOS. In particular, the Predictability and Dynamics of Weather systems of the Atlantic-European sector (PANDOWAE) highlighted the generation, propagation, and evolution of upper-level Rossby wave trains. Additionally, research investigated the roles of moist processes as modifying factors to wave train evolution and impact on the larger-scale circulations. While PANDOWAE provided a focus on dynamical and physical processes over midlatitudes, the Year of Tropical Convection (YOTC, Waliser et al. 2012) and the International Polar Year (IPY) typified the global extent of investigations of regional high-impact weather events. Though not all explicitly containing field campaigns, these three programmes provided support and a framework under which collaborations could be formed for the benefit of regional campaigns.

While it was not possible to include reports on all THORPEX-related field campaigns, key arctic, tropical, and midlatitude programmes are summarized. Additionally, summaries of technological advances detail the capability by which operations could be planned and observations taken and interpreted.

4.2.1 International Polar Year (IPY)

Under the umbrella of the IPY, the CONCORDia Infrared Atmospheric Sounding Interferometer (CONCORDIASI) field programme (Rabier et al. 2013) provided observations (Figure 1) over the Antarctic continent to improve satellite data assimilation, improve model representation of physical processes over the Antarctic, and provide observations of troposphere-stratosphere processes and exchanges. The joint effort between the United States and France employed zero-pressure balloons that provided dropsonde coverage from high altitude while circumnavigating the south pole (Cohn et al. 2013). Six of 13 total driftsonde balloons were designed to obtain new observations of temperature, ozone, and particle size along near-Lagrangian paths. From all the driftsonde balloons, approximately 640 dropsondes were launched (Figure 1). The dropsondes were targeted in regions of gravity wave activity and in areas that exhibit sensitivity of numerical weather prediction to initial conditions.

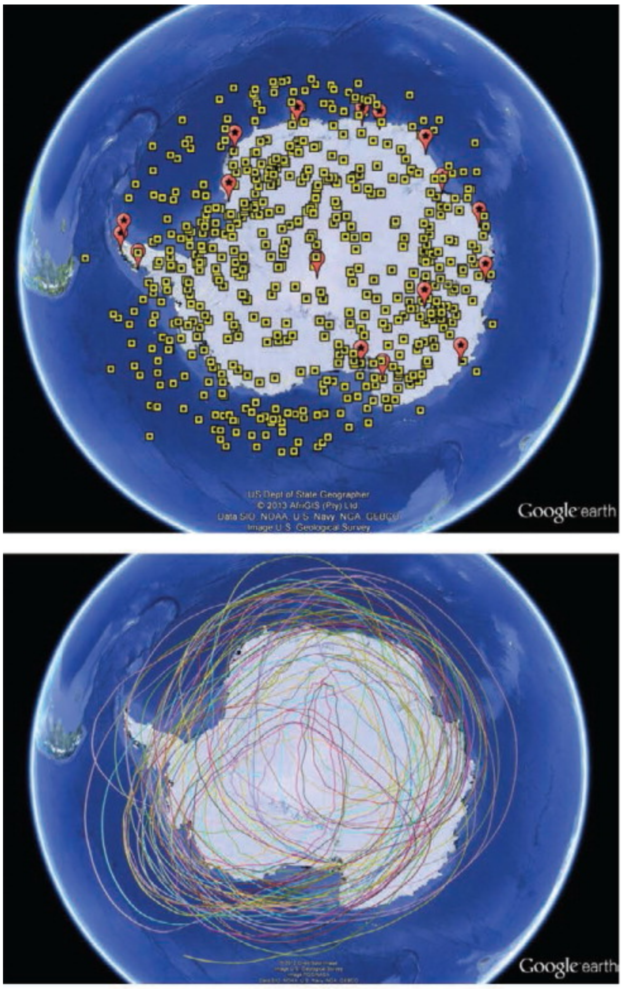

Figure 1. (top) locations of 644 dropsondes (yellow squares) released over Antarctica during Concordiasi. The red circles are radiosonde locations. (middle) Flight tracks of the 13 driftsondes during Concordiasi.

Source: adapted from Cohn et al. 2013

While Concordiasi was conducted over the Antarctic, several programmes were conducted over the Arctic. The Greenland Flow Distortion Experiment (GFDex) examined the Greenland tip jet, barrier winds, and polar lows (Petersen et al. 2009). While in situ observations of these phenomena were taken, objectives also included targeted observations and forecast sensitivity experiments (Irvine et al. 2011). Experiments conducted with the United Kingdom Meteorological Office (UKMO) Unified Model using four-dimensional variational data assimilation indicated that the largest impact to forecasts was achieved from observation away from the steep orography of Greenland. A general conclusion was that observations placed within a correlation length scale of steep orography may degrade forecasts through anomalous upslope spreading of analysis increments along terrain-following model levels.

The Storm Studies in the Arctic (STAR, Hanesiak et al. 2010) examined gap flow, air-sea interactions, and topographic impacts over the eastern Canadian arctic. The research programme encompassed several themes, which included:

- Strong winds, precipitation processes, and storm structure
- Remote sensing of clouds and precipitation
- Blowing snow, visibility, and prediction
- Regional sea ice formation and decay
- Community interactions
- Atmospheric modelling

The STAR programme was focused on the southern portion of Baffin Island of Atlantic Canada. The National Research Council of Canada provided for the Convair-580 research aircraft to collect internal storm measurements of cloud microphysics, thermodynamics, and the 4-D dynamic and precipitation structures of storms. Since no surfaced-based operational radars exist in northern Canada, a mobile ground-based, X-band radar was deployed to map precipitation structures.

The THORPEX Arctic Weather Prediction Initiative (TAWEPI) was a programme dedicated to forecasting over the Canadian arctic. A focus of TAWEPI was to develop and validate a high-resolution regional numerical model over the Canadian Arctic and combine weather data and weather forecasting through collaboration with national and international partners. As such, processes related to sea ice, ozone, arctic clouds, and coupling with sea, ice, and ocean currents are incorporated into Arctic prediction systems based on the Polar-Global Environmental Multiscale model (Norden et al. 2007).

The Norwegian IPY-THORPEX: Polar Lows and Arctic Fronts Programme (Kristjànsson et al. 2011) examined the utility of targeted observations with respect to polar lows in addition to various physical processes related to high latitude maritime weather conditions. This included cloud - radiation feedback processes, latent heat release, and use of a high-resolution numerical ensemble prediction system.

Over polar regions, observations are sparse and important weather phenomena such as orographic influences, fronts, and polar lows are not resolved well in numerical forecast models. These factors lead to significant challenges in weather forecasting and predictability over the polar regions. Through the combination of several high-latitude THORPEX-related observing programme, new results are leading to the development of improved weather prediction systems over polar regions. These improvements are in conjunction with increased understanding of physical processes, predictability, and data assimilation over the Arctic and Antarctic regions.

4.2.2 Year of Tropical Convection (YOTC)

The objectives of YOTC (Waliser et al. 2012) are to increase understanding of processes controlling the organization of tropical convection and its interaction over a variety of spatial and temporal scales. An overarching goal is to improve the representation of multi-scale convective interactions in numerical models via improved data assimilation, process definition, and vertical and lateral exchanges of heat and momentum.

Although no field campaign was conducted under the umbrella of YOTC, it is considered here as it was an important virtual campaign based on the specification of a comprehensive database of global numerical analyses and forecasts. Special emphasis was placed on archival and specification of subgrid-scale tendencies by which physical processes as represented in high-resolution global weather prediction models could be examined. The YOTC experiment period spans several years in which the El Niño/Southern Oscillation (ENSO) cycle, Madden-Julian Oscillation, monsoon systems, and synoptic-scale tropical waves underwent significant variation and seasonal changes. These variations provide for a wide range of conditions by which YOTC-provided analysis and forecasts can be used for diagnosis and initial conditions related to a variety of physical and dynamical processes.

In addition to the database of global numerical analyses and forecasts, satellite data have also been organized via the Geospatial Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) system developed at the Goddard Earth Sciences and Data and Information Services Center. The GIOVANNI system contains several interfaces designed to allow access and processing for a variety of Earth science research.

The YOTC connection to THORPEX via a virtual field campaign is unique and instrumental in providing for increased understanding of physical and dynamical processes related to tropical convection and its organization and interaction across a range of spatial and temporal scales. Additionally, several THORPEX-based regional field campaigns have benefited directly from the YOTC database to provide for studies of sensitivities to observations and initial conditions for high-resolution simulations.

4.2.3 Regional field campaigns

4.2.3.1 Hydrological cycle in Mediterranean EXperiment (HyMeX)

Heavy precipitation events (HPE) frequently impact the Mediterranean. Flash-floods, landslides and mudslides during these HPE cost several millions of euros in damage and many casualties. Predictability associated with these high-impact events is often low due to the importance of diabatic processes and small scale features over complex terrain that are not represented well in numerical prediction models. These high-impact weather events were initially examined within the the MEDiterranean EXperiment on cyclones that produce high-impact weather in the Mediterranean (MEDEX) campaign, which was a WMO-endorsed programme to examine cyclones over the Mediterranean Sea and their role in weather over the southern Alpine region (Jansa et al. 2014). The success of MEDEX contributed to the design and eventual implementation of the 10 year international HyMeX programme (Ducrocq et al. 2014), which was dedicated to the hydrological cycle and related processes in the Mediterranean.

As part of HyMeX, a major field campaign was conducted during September to November 2012 to examine heavy precipitation and flash-floods events. The 2 month field campaign took place over the northwestern Mediterranean Sea and its surrounding coastal regions in France, Italy and Spain. The observation strategy was aimed at documenting four key components (Figure 2) leading to heavy precipitation and flash-flooding in that region: (i) the marine atmospheric flows (Nuissier et al. 2011) that transport moist and conditionally unstable air towards the coasts (Duffourq and Ducrocq 2013); (ii) the Mediterranean Sea as a moisture and energy source; (iii) the dynamics and microphysics of the convective systems (Ducrocq et al. 2008; Bresson et al. 2012; Buzzi et al. 2011); (iv) the hydrological processes during flash-floods. In addition to these important air-sea and hydrologic processes, the large-scale flow patterns related to Rossby-wave breaking at the eastern end of the North Atlantic synoptic-scale storm track.

To examine the myriad of scientific issues associated with coupled atmospheric and hydrologic processes, specific Intense Observations Periods (IOPs) were conducted during HyMeX using aircraft and ground-based observations. Associated modelling studies have been conducted to increase understanding of atmospheric process, HPE, flash floods and to improve and validate numerical models.

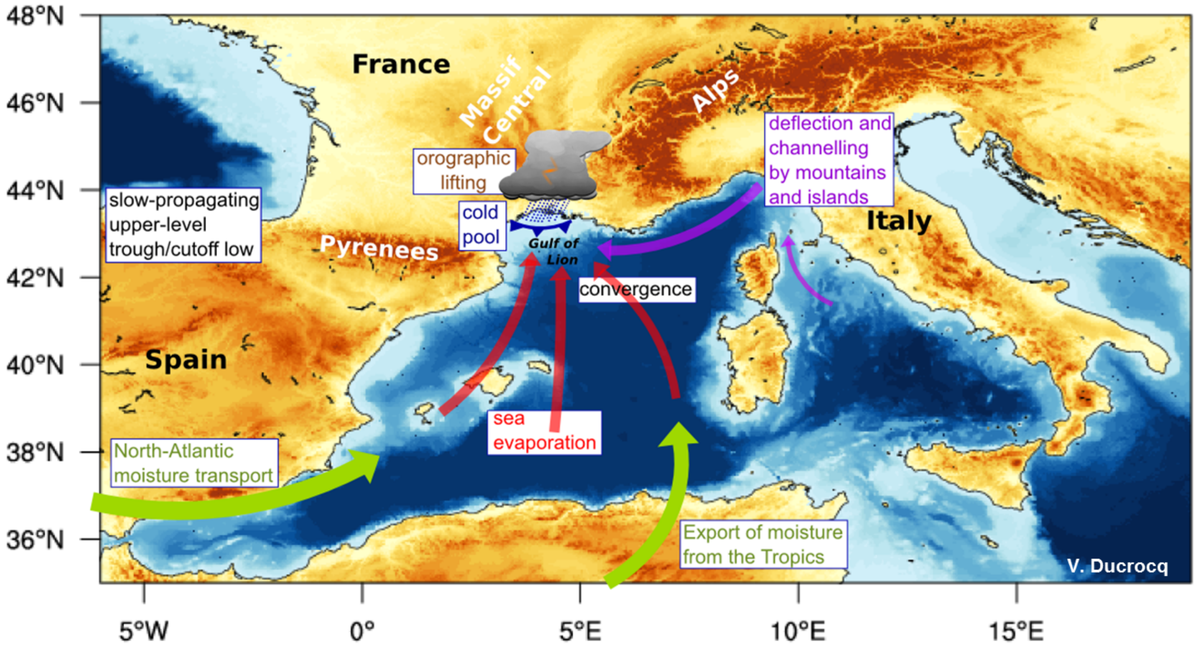

Figure 2. Schematic of the four HyMeX foci associated with heavy precipitation events during HyMeX SOP-1

Source: Figure from V. Ducrocq

A second Special Observation Period (SOP) dedicated to regional wind regimes, air-sea fluxes, and oceanic convection was conducted in February-March 2013. During the HyMEX IOPs, more than 200 research instruments provided an unprecedented data set for regional impacts of extreme weather events over the Mediterranean region.

As THORPEX was intended to examine all aspects of the forecast process, HyMeX contained a significant component to monitor social vulnerability to extreme events. This involved the use of interviews, surveys, and impact reports to collect behavioural, perceptual, and physical impact data. The results from the social impacts portion of HyMeX will allow continual learning of social capacity and resilience over a variety of space and time scales at which the Mediterranean and Alpine high-impact weather events occur.

4.2.3.2 The DIAbatic influences on Mesoscale structures in ExTratropical storms (DIAMET)

The primary objective of DIAMET was to measure dynamical characteristics, cloud properties, and air-sea fluxes to calculate the diabatic heating rate in intense cyclones (Vaughan et al. 2015). Detailed observations of the mesoscale structure of these features are important for identifying regions of high-impact weather that may rapidly evolve over small spatial and fast time scales. A second objective of DIAMET was to improve the depiction of important physical processes such as convection, air-sea fluxes, and cloud microphysics in numerical models.

During DIAMET (Vaughan et al. 2015), in situ and dropsonde observations were obtained during research flights through a notably intense cyclone over the North Atlantic (Cyclone Friedhelm, Figure 3a) in December 2011. In conjunction with the observations, diabatic production and removal of potential vorticity (PV) anomalies were evaluated with respect to their representation in a numerical weather prediction model. Linkages were made between the PV anomalies and the strong wind regions within the three types of "air streams". Two types are identified with the conveyor belts (Figure 3b) that hooks around the cyclone centre. A third air stream is identified as a sting jet (Figure 3b) that descends from the west of the cyclone. Observations of chemical tracers indicate that the cold conveyor belt (or cold jet as indicated in Figure 3b) and sting jet air streams are distinct air masses even when the associated low-level wind maxima are not spatially distinct. In the model, the cold conveyor belt experiences slow latent heating through weak resolved ascent and convection, while the sting jet experiences weak cooling associated with microphysics during its subsaturated descent. Diagnosis of mesoscale instabilities in the model shows that the cold conveyor belt passes through largely stable regions, while the sting jet spends relatively long periods in locations characterized by conditional symmetric instability, which is a plausible forcing of the banding structures visible in Figure 3a.

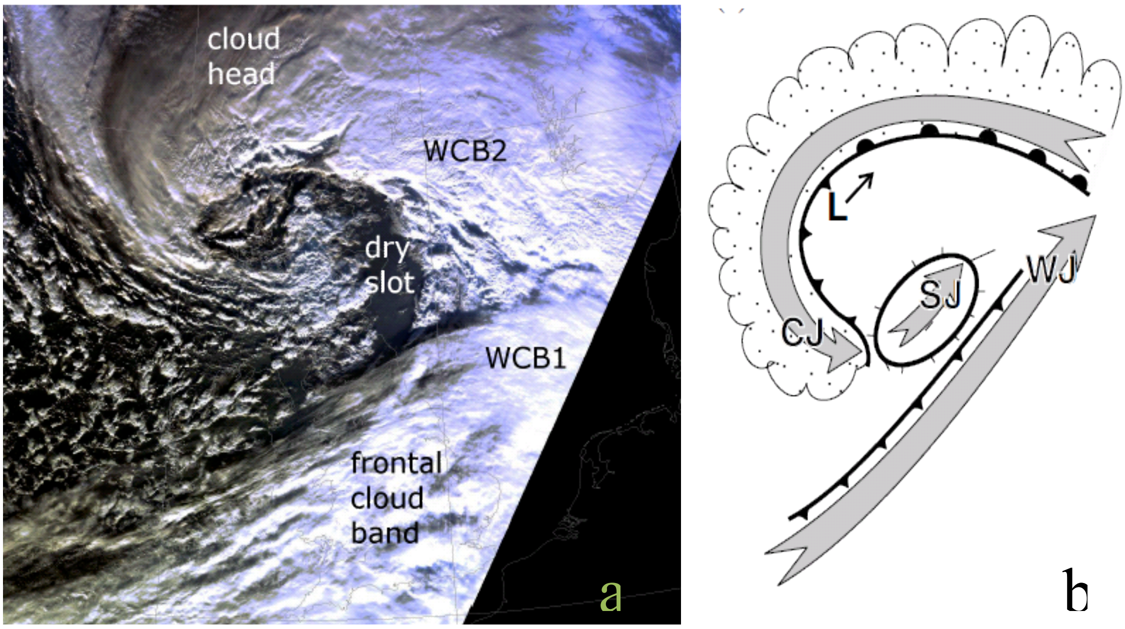

Figure 3 (a) Visible METEOSAT imagery of Cyclone Friedhelm at 0000 UTC 8 December 2011. The warm conveyor belt (WCB) air streams are labeled as WCB1 and WCB 2. (b) Schematic of the principal cyclone airstreams defined as the warm jet (WJ), the cold jet (CJ), and the sting jet (SJ).

Source: Figure 3b adapted from Clark et al. 2005

In relation to the occurrence of high-impact weather, the wind speeds are greatest in the clear regions between rainbands. The high winds occur in rather long lanes that are parallel to the mean flow. The ability for numerical simulations to accurately depict mesoscale banding features in the environment of a rapidly-developing cyclone is important for increased predictability of extreme weather conditions.

4.2.3.3 THORPEX North Atlantic Waveguide and Downstream Impact Experiment (T-NAWDEX)

Over the past years, airborne observations constituted an important component of THORPEX. The German Aerospace Center (DLR) research aircraft Falcon participated in several airborne campaigns that directly originated from THORPEX or that provide a strong link to relevant topics. These past campaigns concentrated on observations used to investigate the importance of diabatic processes for the predictability in the extratropics.

In October 2012, the THORPEX-North Atlantic Waveguide and Downstream Impact Experiment (T-NAWDEX)-Falcon campaign conducted 9 research flights (Figure 4) over Europe to measure in-cloud properties in warm conveyor belts (WCBs). During each IOP, quasi-Lagrangian flight scenarios were designed to measure the same air mass along different stages of the WCB. This strategy allowed computation of the moisture transport and latent heat release along each WCB.

These factors were then related to forecast errors associated with each case. Additionally, dropsondes released across and along each WCB provided for a complete three-dimensional view of the WCB structure.

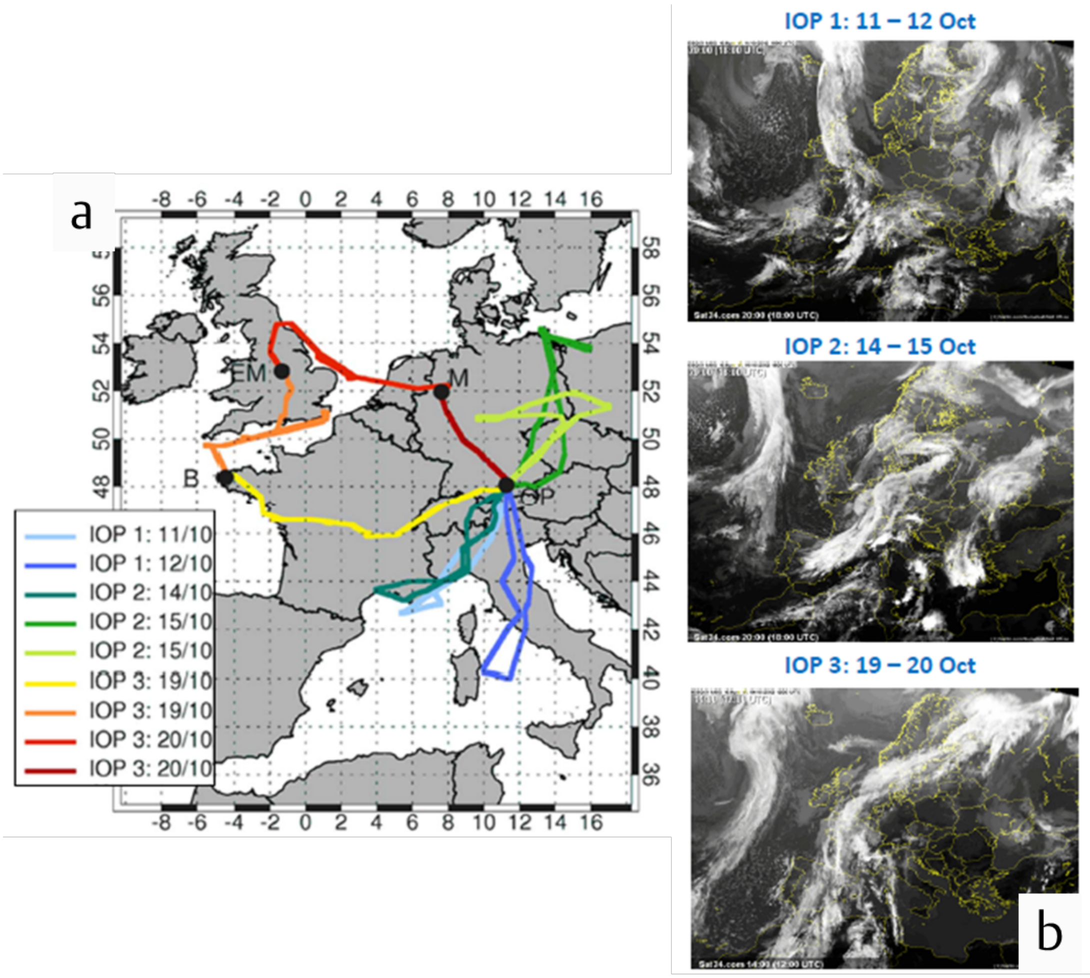

Figure 4. (a) Flight tracks of the DLR Falcon during the 3 intensive observing periods (IOPs) and 9 flights during T-NAWDEX-Falcon. (b) Infrared METEOSAT imagery of the warm conveyor belts investigated in each of the three IOPs.

In addition to flights over upper regions of WCBs, T-NAWDEX included one flight over the western Mediterranean as part of a HyMeX intensive observing period. During this time, the T-NAWDEX mission observed the WCB origination region as over the Mediterranean while later observing the upper portion of the WCB over northern Europe.

To extend the observations of such diabatic factors, a T-NAWDEX is planned for September and October 2016. The science objectives are strongly motivated by the results from the previous campaigns. Flights with High Altitude and LOng Range Research Aircraft (HALO) will be conducted over the North Atlantic to investigate the triggering of disturbances along the North Atlantic waveguide, their subsequent evolution and the associated downstream impacts over Europe.

4.2.3.4 Atlantic THORPEX Regional Campaign (A-TReC)

The A-TReC was a collaborative effort between European Meteorological Network (EUMETNET) Composite Observing System (EUCOS) programme and THORPEX, which was designed to test the forecast impact from a wide range of observational platforms. The A-TReC was designed to gather observations in a quasi-operational framework over the North Atlantic storm track. The A-TReC involved collaboration among a number of operational numerical forecast centres, academic institutions, national funding agencies, and observing platform providers.

A significant aspect of the A-TReC was the use of multiple methods to identify geographic regions and time periods over which targeted observations may help reduce forecast errors. Verification regions for forecasts were located over eastern North America and Northern Europe. The targeted observations were often placed in regions of strong jet stream characteristics, rapidly developing extratropical cyclones, or decaying tropical cyclones that were undergoing extratropical transition.

A variety of observing platforms were deployed during the A-TReC. These included research aircraft, commercial aircraft, satellite data, surface ship data, and routine radiosonde observations.

Results from the A-TReC were mixed in that no consistent signal of forecast improvement could be identified. Rather, the majority of cases resulted in neutral or slightly positive impacts. However, a noteworthy result of the A-TReC was that the impact of targeted observations varied significantly with the numerical model system.

4.2.3.5 THORPEX Pacific Asian Regional Campaign (T-PARC)

The THORPEX Pacific Asian Regional Campaign (T-PARC) was a multi-national field campaign that addressed the shorter-range dynamics and forecast skill of high-impact weather events in one region (Eastern Asian and the western North Pacific) and the downstream impact on the medium-range dynamics and forecast skill of another region (in particular, the eastern North Pacific and North America). Although many significant weather events occur over eastern Asia and the western North Pacific, the focus of T-PARC was on various aspects of typhoon activity, which included formation, intensification, structure change, motion, and extratropical transition. Because of the significant impact of typhoon activity on the region of eastern Asia and the western North Pacific, T-PARC was comprised of several affiliated programmes. The experimental design (Figure 5) for T-PARC addressed three primary components: (1) A tropical measurement strategy to examine circulations of the tropical western North Pacific monsoon environment as they related to tropical cyclone formation, tropical cyclone intensification, and tropical cyclone structure change. (2) Extratropical transition (ET) and downstream impacts was based on the poleward movement of a decaying tropical cyclone and the resulting intense cyclogenesis that results from its interaction with the midlatitude circulation. (3) Identification of regions in which extra observations may reduce numerical forecast error growth associated with forecasts of tropical cyclone track over the western North Pacific. Results addressed multi-scale factors in tropical cyclone formation, impacts of tropical cyclones on midlatitude flow characteristics, and the role of in situ observations in improving tropical cyclone track forecasts.

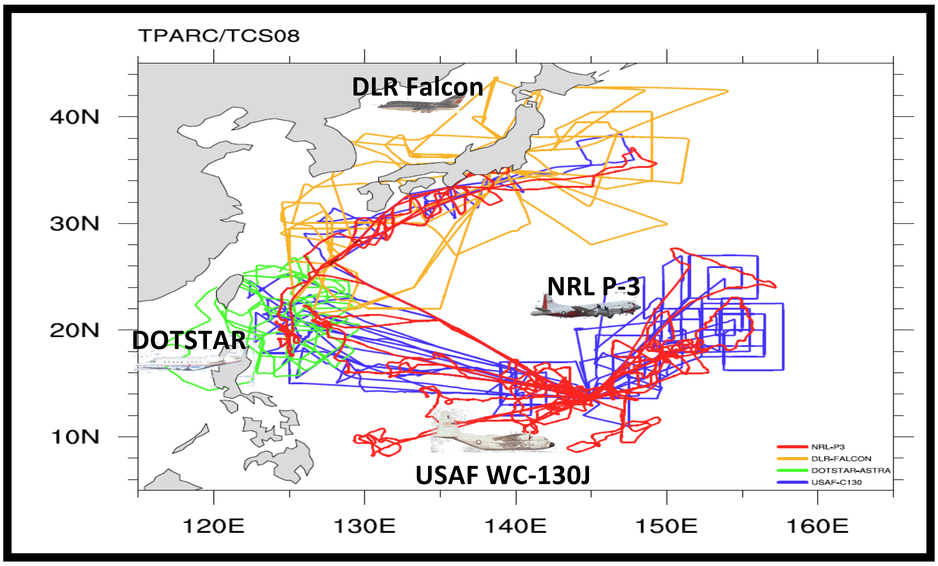

Figure 5. Aircraft missions conducted in four typhoons during the TPARC field programme

Key issues related to prediction of tropical cyclone structure were defined by the first ever multiple plane observing missions into one typhoon over the western North Pacific. While Typhoon Sinlaku was at peak intensity of 130 kt, aircraft missions concentrated on examination of the outer rainband structures in terms of wind distribution and formation of secondary eyewall formation (Wu et al. 2012). A following two aircraft mission was conducted to observe a region of explosive re-development of deep convection (Figure 6). Sanabia (2010) related the deep towers of vertical vorticity to stretching due to updrafts that had peak intensity of near 30 m s^{-1} between 10 -12 km, with convergence into the column below 10 km and divergence aloft. Therefore, multi-aircraft missions addressed significant unknown factors related to tropical cyclone formation, structure, and wind distribution.

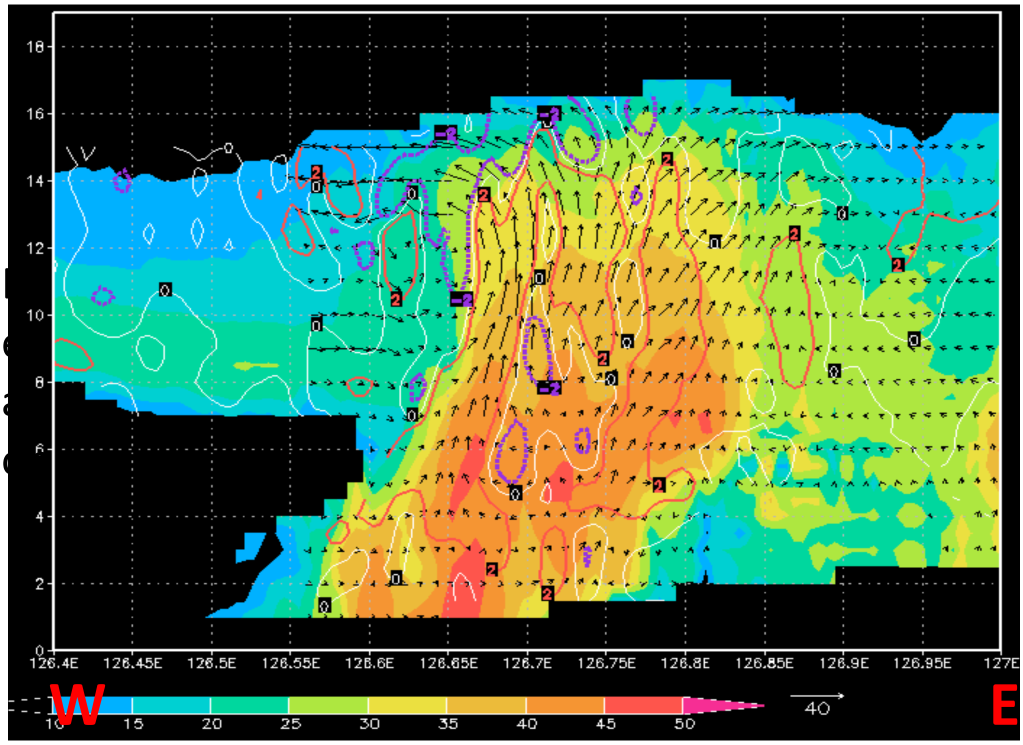

Figure 6. Vertical cross section of radar reflectivity (shaded according to color bar, dBz), wind horizontal and vertical winds in the plane of the cross section (vectors, reference vector in the lower left, m s^{-1}) and vertical vorticity (contours 10^{-3} s^{-1}).

Source: After Sanabia 2010

A similar measurement strategy was followed to make observations of a typhoon during the transformation stage of extratropical transition. A three-plane mission was again conducted to measure the changes in tropical cyclone structure as the storm interacted with the midlatitude westerlies. Foerster et al. (2014) examined the airborne Doppler radar data (Figure 7) collected as the NRL P-3 flew through the centre of TY Sinlaku during the extratropical transition. The end of the extratropical transition process was observed during a two-plane mission with dual Doppler radar data (Quinting et al. 2014) that documented a strong convective outbreak and the interaction of the remnants of Sinlaku with the midlatitude jet.

Decreased predictability, which is defined as an increase in standard deviation in 500 hPa height among individual and a collection of ensemble prediction systems, is often observed during the interaction between a decaying tropical cyclone and a midlatitude jet. Keller et al (2011) used the THORPEX Interactive Grand Global Ensemble (TIGGE) database to show that increased variability was consistently observed over the central North Pacific between 160°E and 160°W with subsequent relative maxima occurring downstream at intervals of approximately 40 deg. of longitude (Figure 8).

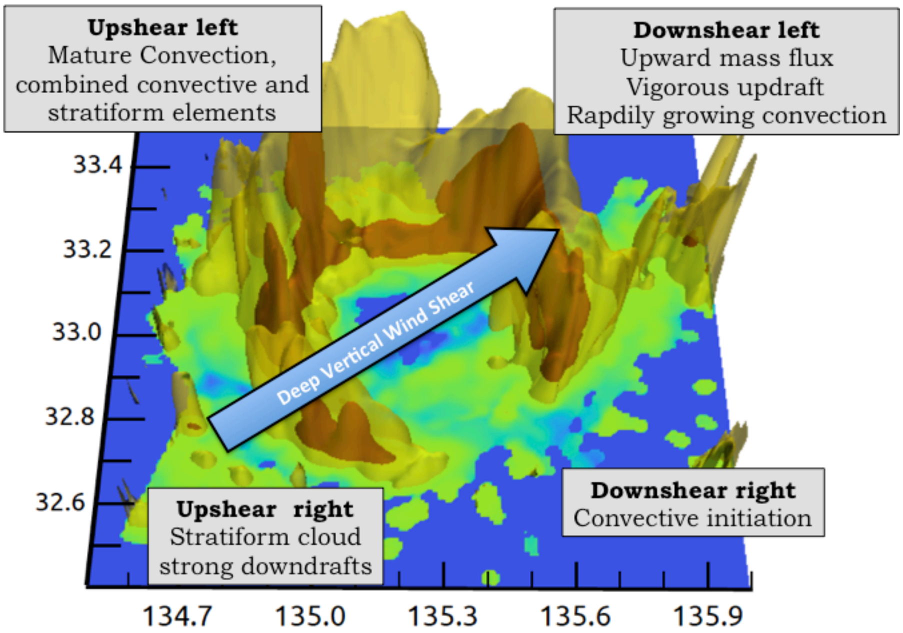

Figure 7. Reflectivity (shaded, dBz) of the core of TY Sinlaku derived from airborne Doppler radar on board the NRL P-3 near 0000 UTC 21 September 2008.

Source: After Foerster et al. 2014

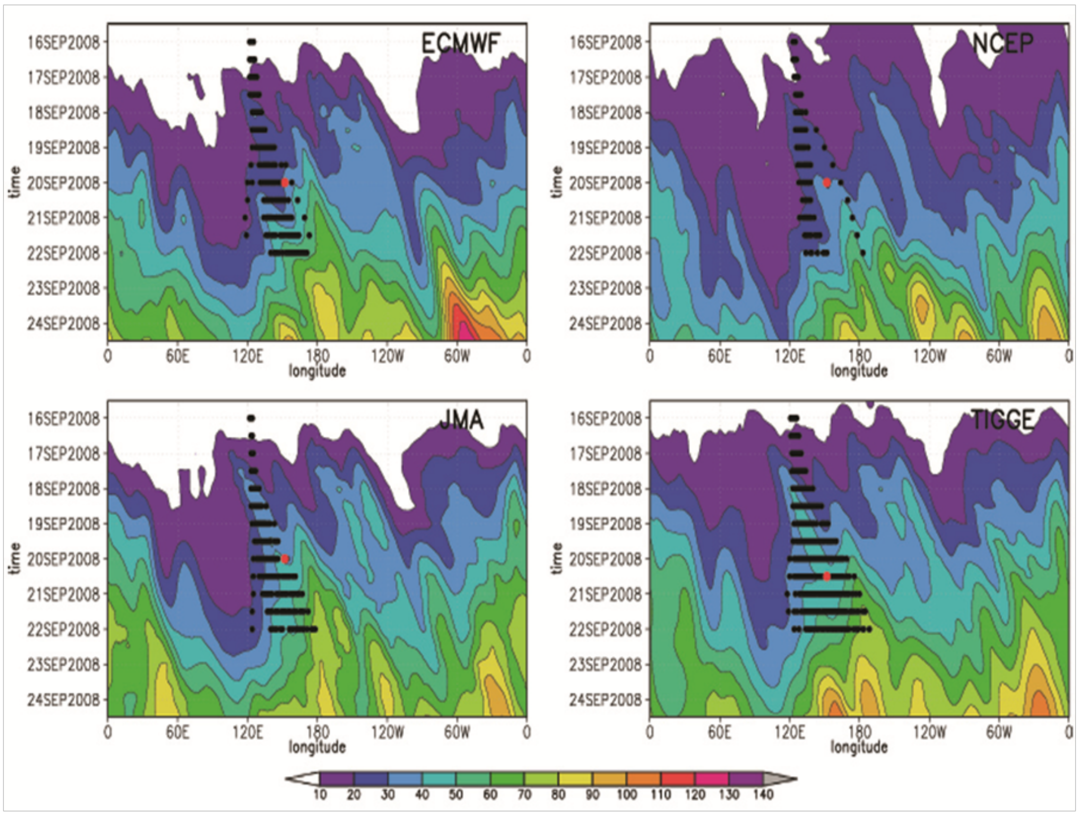

Figure 8. The 500 hPa height standard deviation (m) among ensemble forecasts initiated at 1200 UTC 15 September 2008 from the (a) ECMWF; (b) NCEP; (c) JMA operational ensemble prediction systems; and (d) all systems contained in the TIGGE database. The standard deviation is averaged between 40°N-60°N. The black dots define the forecast positions of TY Sinlaku in all ensemble members. The red dot defines the location of TY Sinlaku at the time of ET.

Source: After Keller et al. 2011

The T-PARC observations (Figure 5) were assimilated in a number of global and regional models to draw conclusions on the benefit of targeted dropsonde observations for typhoon and mid-latitude forecasts (Weissmann et al. 2011, Harnisch and Weissmann 2010, Chou et al. 2011, Wu et al. 2012, Wu et al. 2013), to evaluate different targeting strategies and the potential of lidar instruments for the initialization of weather prediction models. Major findings from these studies include (Weissmann et al. 2011): (a) Targeted dropsondes overall improve typhoon track predictions, but their impact significantly depends on the assimilation system; (b) targeted dropsondes only have a small impact on mid-latitude forecasts and the impact is mainly due to improved typhoon tracks that indirectly lead to mid-latitude improvements; (c) dropsondes in the vicinity of typhoons have the largest impact, whereas the impact of dropsondes in distant sensitive regions and the core and eyewall region is small; (d) wind lidar observations have a comparably high impact, which underlines high expectations for planned space-based lidar and suggests considering the deployment of wind lidars on commercial airplanes in the future; (e) the average impact of water vapour lidar observations is small, but forecasts can be affected considerably under certain conditions; (f) lidar cloud top observations can be used to adjust the height assignment of satellite-derived atmospheric motion vectors and by this significantly reduce their wind errors.

4.2.3.6 Winter THORPEX - Pacific Asian Regional Campaign (T-PARC)

While the T-PARC campaign investigated tropical cyclone track forecast sensitivity to observations in the environment of a tropical cyclone, the Winter T-PARC programme examined downstream forecast sensitivity to observations across the North Pacific and in the environment of the strong winter jet stream and midlatitude cyclones. Winter T-PARC utilized the National Oceanic and Atmospheric Administration (NOAA) G-IV aircraft flying from Japan (Figure 9) to gather observations in conjunction with the use of the United States Air Force (USAF) WC-130 J aircraft flying over the eastern North Pacific as part of the NOAA Winter Storms Reconnaissance programme. Specific hypotheses were formulated to examine:

- The connection between tropical convective activity and extratropical storms over the western North Pacific and their impact downstream over North America
- The role of Rossby-wave propagation in the development of weather events over North America and the Arctic over time scales of 3-6 days
- The impacts on forecast accuracy of improved observations of the vertical structure of developing cyclones over the North Pacific
- The impacts on forecast accuracy on improved observations of diabatic processes in winter cyclones over the North Pacific

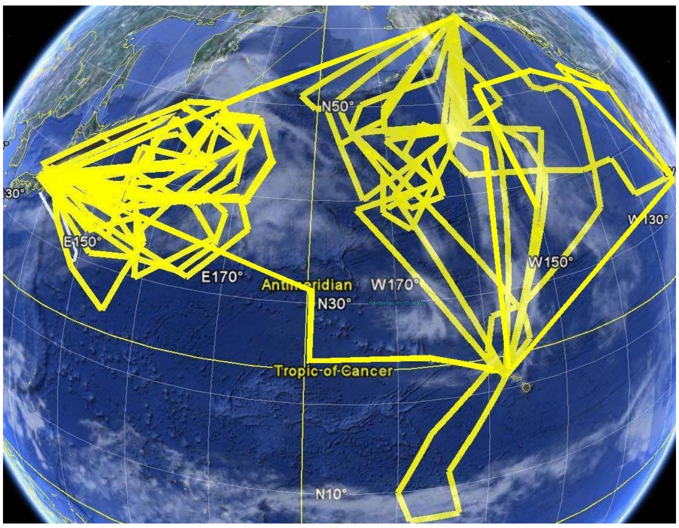

Figure 9. Tracks of aircraft missions flown during January - February 2009 during the Winter T-PARC campaign. Aircraft track that originate from Japan were flown by the NOAA G-IV aircraft and tracks originating from Hawaii and Alaska were flown by the USAF WC-130J during the NOAA Winter Storms Reconnaissance Project in collaboration with Winter T-PARC.

During the Winter T-PARC period several cases of tropical convection impacts on the midlatitude jet over the western North Pacific were observed in conjunction with cyclone development and propagation across the North Pacific. Overall, observation impacts to forecast errors downstream were positive (Figure 10) in that errors were general reduced. However, variability in impact magnitudes was quite large in relation to forecast interval and observation location.

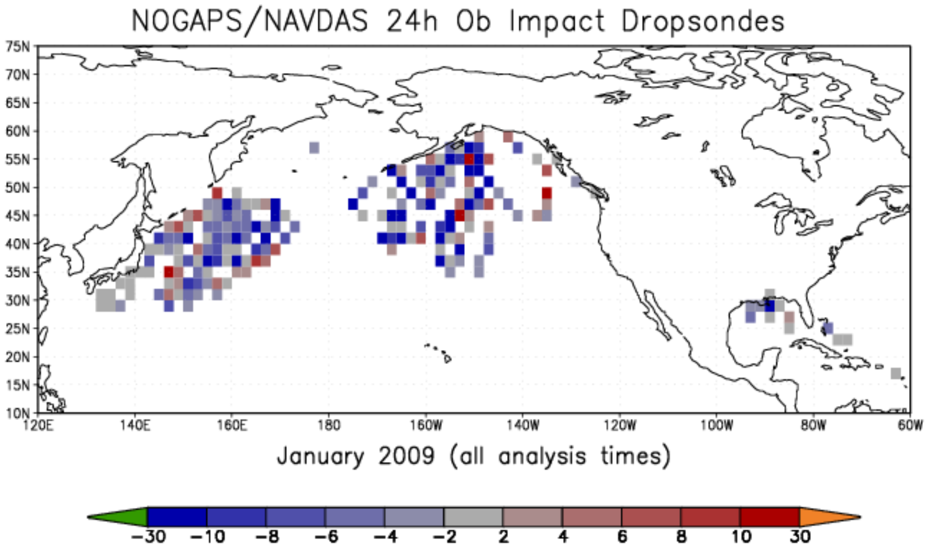

Figure 10. Impacts on 24-h forecast error from dropsondes over the North Pacific in January 2009 during the Winter T-PARC campaign. Negative values define a reduction in forecast error.

Source: Figure provided by R. Langland

4.3 UNIQUE THORPEX FIELD CAMPAIGN ADVANCEMENTS

As defined above, many THORPEX-related field campaigns addressed the utilization of observations for improved prediction of high-impact weather. To facilitate the planning of adaptive observations during field programmes, the European Center for Medium range Weather Forecasting (ECMWF) developed the Data Targeting System (DTS, Figure 11) as an interactive web-based system to allow users in different centres to participate in real-time adaptive control of the observing system with a minimum of manual effort. The DTS provided a facility to efficiently manage the data targeting process from weather event selection to issuing requests for additional observations, and has been used in several THORPEX field campaigns. The DTS enables users to a) identify potential high-impact weather events, in particular cases with large uncertainty; b) request computation of sensitive areas (regions where additional observations are likely to have most impact in reducing the forecast uncertainty); c) identify and issue requests for additional real-time observations; and d) monitor the observation requests and confirm their subsequent deployment.

Field campaigns using the DTS have been able to issue requests for additional radiosonde ascents from 20 different participating countries, and for Aircraft Meteorological DAta Relay (AMDAR) aircraft observations and radiosondes from Automated Shipboard Aerological Programme (ASAP) ships participating in the EUCOS observing programme. In addition, the DTS has allowed users to identify sensitive areas for research aircraft observations. The DTS was used in a long-term quasi-operational trial (EURORISK PREVIEW) as well as in field campaigns, including summer and winter T-PARC, and most recently MEDEX and HyMeX campaigns to study the predictability of high-impact weather over the Mediterranean.

An interactive three-dimensional (3D) visualization of ensemble weather predictions is a highly desired product for weather forecasting during aircraft-based atmospheric field campaigns. Research flights with high-flying aircraft require the flight route to be planned several days in advance, hence, being able to assess the uncertainty of the forecast on which a flight is based is very valuable. Since the targeted upper-level features are of an inherently three-dimensional nature, it seems natural to aid their identification with three-dimensional visualization methods. The "Met.3D" system is a novel forecasting tool that makes recent advances in 3D and uncertainty visualization available to the forecaster (Figure 12). Interactive 2D and 3D visualization elements, displaying forecast meteorological fields and uncertainty measures derived from the ECMWF ensemble prediction system, enable the meteorologist to quickly identify atmospheric features relevant to a flight and to assess their uncertainty. The Met.3D was applied during the 2012 T-NAWDEX Falcon field campaign, a project that aimed at taking in-situ measurements in warm conveyor belts.

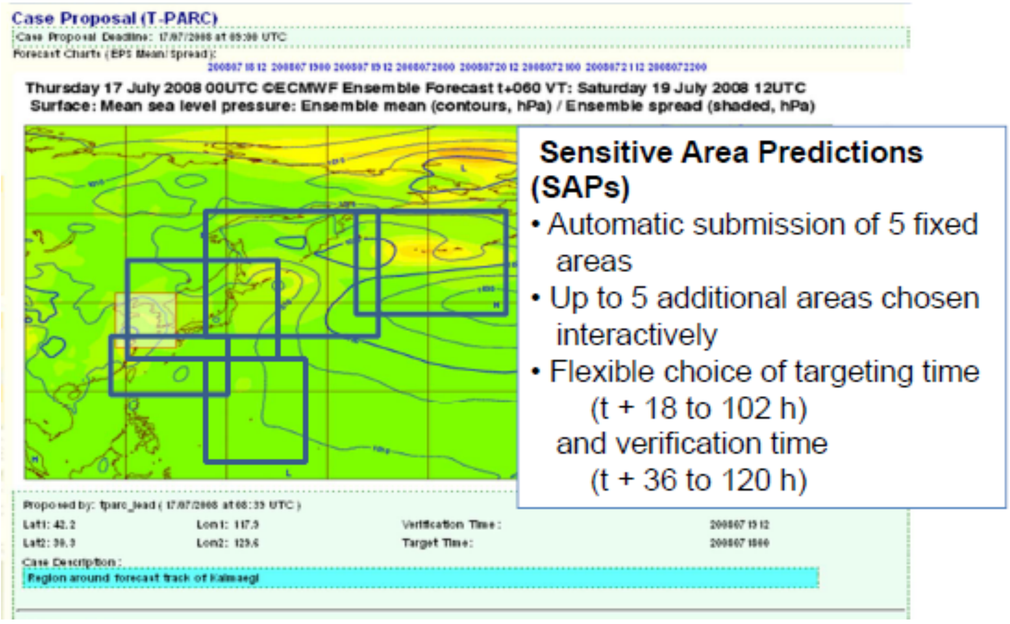

Figure 11. Schematic of the Data Targeting System definition of standard observation sensitivity areas placed along typical tropical cyclone paths over the western North Pacific.

Source: Figure supplied by D. Richardson

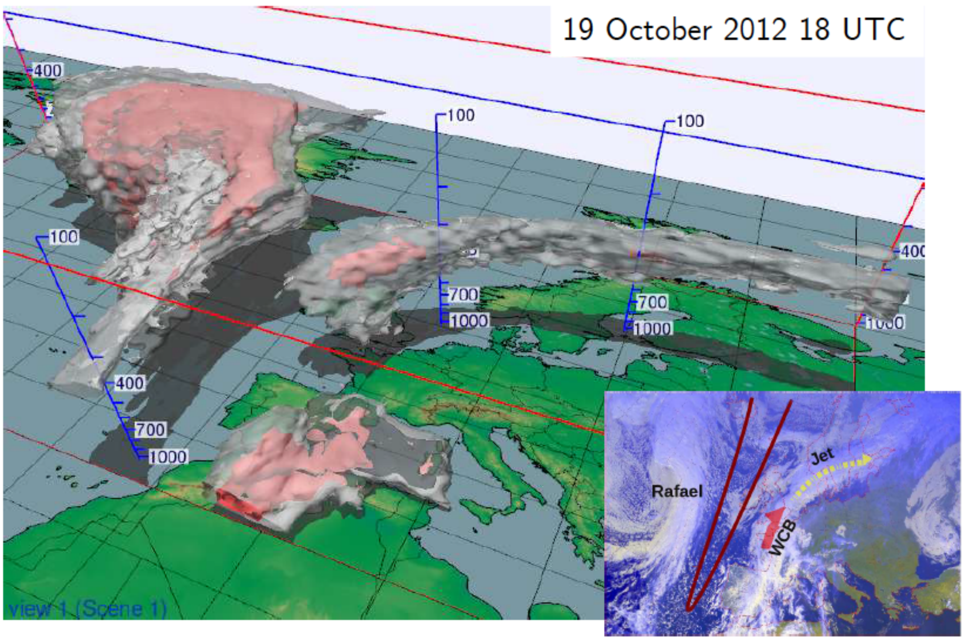

Figure 12. Met-3D display of the probability of a warm conveyor belt occurrence in advance of a developing cyclone over the North Sea. Grey shade indicates a 10% probability and the pink shade represents a 30% probability.

Source: Figure by M. Rautenhaus

4.4 SUMMARY

The THORPEX-related field campaigns have led to study of factors and processes related to the forcing and predictability of high-impact weather over high-, mid-, and tropical latitudes. Throughout the 10 year period of THORPEX, field campaigns have been conducted over polar, midlatitude, and tropical regions. Additionally, several themed programmes served to provide frameworks for field programme planning, execution, and data analysis. Additionally, careful planning has been undertaken to maintain active and accessible data resources for many of the THORPEX-era field programmes. While all field programmes have not been included in this summary, those chosen represent the diverse topic, geographic, time, and spatial scales associated with all THORPEX-related campaigns.

A significant aspect of the scientific success of THORPEX was to provide a framework by which communities in academia, laboratory, and operational forecasting could collaborate on research priorities with direct pathways to benefiting the entire process of weather forecasting. The field campaigns represent a unique aspect of that collaboration in which all of the communities became focused on specific hypotheses related to a particular physical process, modelling characteristics, and forecast problem.

Through THORPEX field campaigns, significant results were obtained in relation to processes related to high-impact weather over numerous regions of the tropics, midlatitudes, and poles. Many field programmes incorporated observing strategies, capabilities, and types that were never attempted in the past. Improved understanding of processes and better representation of them in numerical models increased predictability of high-impact weather systems. Additionally, field programmes that provided means of obtaining special observations lead to analysis of the observation impact to forecasts. Important results identified sensitivities to numerical weather prediction systems and to the weather phenomenon itself. It is clear that a THORPEX legacy will be the scientific results attributed to field programmes and to the ability of field programmes to address THORPEX objectives related to the entire forecast process from 1-14 days.

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CHAPTER 5. DYNAMICS AND PREDICTABILITY OF MIDDLE LATITUDE WEATHER SYSTEMS AND THEIR HIGHER AND LOWER LATITUDE INTERACTIONS

Suzanne L. Gray and Heini Wernli

Abstract

This theme addresses all aspects of the dynamics and predictability of midlatitude weather systems including Rossby wave trains, high-pressure systems and blocking, extratropical cyclones and fronts, and also embedded mesoscale phenomena. A particular focus is on studies investigating interactions of these midlatitude systems with the (sub)tropics and polar regions, and on high-impact weather events. Also included are novel results from recent field experiments, theoretical and idealised studies, numerical modelling case studies, and ensemble and long-term evaluations of the forecasting performance for specific midlatitude weather systems. The article provides a selective overview of key research accomplishments during the last decade and highlights important open science questions for the coming years - some of them requiring continued international collaboration and increased cooperation between operational weather centres and academic research institutions.

5.1 INTRODUCTION

Research on the dynamics and predictability of midlatitude weather systems has been a central element of the 10-year World Meteorological Organization (WMO)/World Weather Research Programme (WWRP) THe Observing System Research and Predictability EXperiment (THORPEX), which was conducted from 2004 to 2014. Throughout this period, improved numerical models and the availability of global and high-resolution limited-area ensemble prediction systems and high-quality multi-decadal reanalysis datasets led to substantial progress in the analysis, understanding, and prediction of the different categories of midlatitude weather systems. This progress was aided by an increased cooperation of (and knowledge transfer between) operational centres and academia, contributing to increased utility. This article summarizes some of the key achievements in this vibrant research area during the last decade and suggests a selection of unresolved research questions to be addressed by the global research community, supported by WWRP, in the near future. The article is structured into seven sub-themes that overlap substantially to emphasize the challenging interactions associated with midlatitude weather systems in terms of regions (e.g. interactions with polar and tropical weather systems), scales (e.g. upscale error growth and spawning of mesoscale subsystems), and processes (e.g. interactions between dry dynamics and cloud processes). This research summary and outlook will elucidate the following aspects of this research field as particularly novel, fruitful and important:

- The potential vorticity (PV) framework as a particularly insightful theoretical backbone for the analysis of synoptic-scale weather systems (cyclones and anticyclones) and planetary-scale Rossby waves and waveguides.
- The quantification of the role of diabatic processes (e.g. latent and radiative heating and cooling associated with stratiform and convective clouds), and their model representation, in the evolution and prediction of midlatitude weather systems as an outstanding challenge.
- The advent of convection-permitting numerical weather prediction models (deterministic and ensemble systems) as a potential quantum jump for investigating mesoscale details in weather systems and improving their prediction.
- The combination of novel diagnostics, high-resolution modelling and modern observational techniques, in particular during field experiments, as a promising strategy for further enhancing our understanding and predictive capability of potentially high-impact midlatitude weather systems.

Following each subtheme, a list of currently outstanding research questions is provided.

5.2 SUB-THEMES

5.2.1 Tropical interactions

The movement of tropical cyclones from the tropics into the midlatitudes and their development into extratropical cyclones is generally referred to as extratropical transition (ET). The state of knowledge and future challenges in this field were reviewed by Jones et al. (2003); substantial research and advancement of understanding in this area has occurred since this review. The interaction between the transitioning tropical cyclone and midlatitude flow can arise from interactions between the low-level tropical cyclone circulation and midlatitude frontal zone and between the upper-level outflow and tropopause structure. The ET process often reduces atmospheric predictability, both of the transitioning tropical cyclone and downstream through its influence on the Rossby waveguide (Anwender et al. 2008). Case studies have been performed using PV techniques to characterize the transition and its interaction with the midlatitudes (e.g. Röbcke et al. 2004; Agusti-Panareda et al. 2004, 2005; Pantillon et al. 2013a; Grams et al. 2013) and complemented by climatological studies (e.g. Archambault et al. 2013, 2015; Quinting and Jones, 2015). Idealised modelling studies have been also performed (Riemer et al. 2008; Riemer and Jones, 2010). The aim of these studies has typically been to characterize scenarios leading to the different outcomes of ET, i.e. strong or weak re-intensification of the transitioning cyclone as an extratropical cyclone or decay of the transitioning tropical cyclone.

Tropical sources of errors in extended-range forecasts of midlatitude weather are related to tropical cyclones, convection and the organisation of convection by the Madden-Julian Oscillation, and convectively coupled equatorial waves (e.g. Takaya and Matsueda, WWOSC-2014[a] SCI-POW1187). Tropical convection (not associated with TCs) can impact the midlatitude flow, as reported by Ricard et al. (2012) for the particularly intense North Atlantic jet stream in December 1999 associated with two devastating European storms. Cold surges, low-level air streams of midlatitude origin that penetrate into regions below 20^0 in either hemisphere, constitute another important mechanism for tropical-extratropical interaction (Lau and Chang 1987; Garreaud 2001). They occur along the east of large-scale orographic features such as the Andes, the Rockies and the Mexican Sierras, and the Himalayas, constituting an important sink of energy for the tropics and, therefore, an important source of energy for the extratropics. This energy is released by the tropical regions and transferred into the extratropics via the enhancement of convective activity as the cold air destabilises the warm air near the surface of tropical oceans. The convective activity can potentially effect the predictability of extratropical weather systems, providing strong forcing throughout the troposphere and perturbing the development of extratropical cyclones over cold surge regions (e.g. Chen et al. 2002; Jiang and Deng 2011).

Recognition of the reduction in forecast skill often associated with ETs of tropical cyclones led to a component of The THORPEX Pacific Asian Regional Campaign (T-PARC) being focused on identifying important physical characteristics associated with these ETs. During T-PARC an international field programme was conducted in 2008 to investigate the development, intensification, and extratropical transition of tropical cyclones in the western North Pacific Ocean (Elsberry and Harr, 2008). The predictability of the downstream impacts of ETs has been assessed in a number of studies using ensemble forecasts (Anwender et al. 2008; Harr et al. 2008; Torn and Hakim, 2009; Torn, 2010; Lang et al. 2012a, 2012b; Pantillon et al. 2013b). A study of nearly 300 recurving tropical cyclones in the west Pacific showed decreased forecast skill for forecasts initialised prior to tropical cyclone recurvature but verifying afterwards (Harr and Archambault, WWOSC-2014 SCI-PS119.04). Singular vectors have also been used to demonstrate the sensitivity of forecasts of recurving tropical cyclones to the initial state (Reynolds et al. 2009; Lang et al. 2012a). Sensitivity develops to the northwest of transitioning tropical cyclones, normally associated with a trough moving in from the west and perturbations optimised to change the two-day forecasts

[a] *References to WWOSC-2014 refer to presentations at the World Weather Open Science Conference in Montreal (17-21 Aug 2014), accessible online at www.wmo.int/pages/prog/arep/wwrp/new/wwosc/presentations.html*

of transitioning tropical cyclones grow and propagate quickly downstream. A range of diagnostics is employed to assess the mechanisms by which transitioning tropical cyclones affect the midlatitudes. These include eddy kinetic energy budgets (Keller et al. 2014; Quinting and Jones, WWOSC-2014 SCI-PS218.02), partitioning of the divergent and non-divergent wind (through piecewise PV inversion) and upper-level wave waviness (Riemer and Jones, 2014) and wave activity flux as defined by Takaya and Nakamura (1997) (Quandt et al. WWOSC-2014 SCI-PS130.04).

The use of trajectories and moisture tagging to identify the sources of moisture for heavy precipitation events has led to the terminology “atmospheric rivers” (ARs) and “tropical moisture exports” (TMEs) entering or being more widely used in the dynamical meteorology literature. ARs are typically identified as long narrow plumes of high integrated water vapour (e.g. Special Sensor Microwave Imager (SSM/I) integrated water vapour (IWV) values of at least 2 cm that are at least 2000 km long and not more than 1000 km wide); this terminology originated the work of Newell in the 1990s (e.g. Newell et al. 1992; Zhu and Newell, 1998) but an increasing number of recent papers are using it. The related TMEs are strong water vapour fluxes from the subtropics into the extratropics as defined by Knippertz et al. (2013). ARs are not necessarily but typically of tropical origin (and so also TMEs). Recent research has proposed that ARs are the trails left behind as cyclones channel atmospheric moisture into narrow filaments between their cold and warm fronts as they travel polewards from the subtropics (Dacre et al. 2014). The development of severe extratropical cyclones can be critically dependent on an associated AR. Using a high-resolution moist adjoint modelling system Doyle et al. (2014) showed that only a relatively small filament of moisture present at the initial time within an AR was critical for the development of extratropical cyclone *Xynthia* (2010). Similar sensitivity has also been found for extratropical cyclone *Klaus* (2009) and the *St Jude’s* day storm (2013) (Doyle et al. WWOSC-2014 SCI-PS109.03). Related to ARs and TMEs are “tropical plumes”. These are defined as elongated cloud bands connecting the tropics and subtropics at synoptic time and spatial scales in the climatology by Fröhlich et al. (2013). The poleward moisture transport occasionally leads to extreme precipitation events in the outer tropics or subtropics (e.g. Fink and Knippertz, 2003; Knippertz and Martin, 2005; Hart et al. 2010).

Open questions:

- How can the impact of factors that reduce the predictability of the midlatitude flow during periods of extratropical transition be minimised?
- What aspects of the phasing between recurving tropical cyclones and the midlatitude flow determine the “outcome of ET” in terms of downstream impact?
- What is the role of tropical modes of convection for modifying the large-scale midlatitude flow?
- How relevant are atmospheric rivers/tropical moisture exports/tropical plumes for increasing the intensity and reducing the predictability of midlatitude weather systems?

5.2.2 Heavy precipitation events

Heavy precipitation events can have devastating impacts due to the associated flash flooding, landslides and debris flows. These events have been the subject of national and international projects, recognizing the need to coordinate the work of meteorologists, hydrologists and emergency responders in this field. Of particular note within Europe are the HyMEX (Mediterranean) and MAP (Alps) projects:

HyMeX (HYdrological cycle in the Mediterranean EXperiment) aims at a better understanding and quantification of the hydrological cycle and related processes in the Mediterranean, with emphasis on high-impact weather events, inter-annual to decadal variability of the Mediterranean coupled system, and associated trends in the context of global change (Drobinski et al. 2014). This project initially began as a French initiative in 2007 but has now extended to the international community. A first intense observation period with a focus on heavy precipitation and flooding in the western Mediterranean took place in autumn 2012 (Ducrocq et al. 2014).

MAP (The Mesoscale Alpine Programme, Bougeault et al. 2001) was a major international research initiative in the Alpine region. It aimed towards better understanding and improved numerical prediction of atmospheric flow, precipitation, and hydrological processes in the Alpine region. Particular consideration was given to natural hazards such as heavy precipitation, flash flooding and windstorm events. The project culminated in a large international field campaign in the Alpine region in 1999 and pioneering studies on convection-permitting forecasting (Richard et al. 2007), and a subsequent demonstration period of hydrological forecasting in 2007 (MAP D-PHASE) (Rotach et al. 2009).

The reduction of risk associated with heavy precipitation events is a multifaceted problem. Focusing on the dynamics and predictability component of the associated weather systems research has (i) examined the moisture sources of the weather systems through the development of new techniques such as 'water-tagging' using water vapour tracers (e.g. Sodeman et al. 2009; Winschall et al. 2012) and water budgets from high-resolution model output (Duffourg and Ducrocq, 2013), (ii) characterized the importance of the forcing from upper-level stratospheric streamers or intrusions with high values of PV (e.g. Martius et al. 2006; Vich et al. 2012; Martius et al. 2013), (iii) explored the role of orographic forcing and enhancement (e.g. Rotunno and Houze, 2007; Miglietta and Rotunno, 2014; Bresson et al. 2012; Buzzi et al. 2014), (iv) more generally explored the environmental and mesoscale 'ingredients' necessary for heavy precipitation (e.g. Kunz and Kottmeier, 2006; Ducrocq et al. 2008), (v) quantified the role of extratropical cyclones in precipitation extremes (Pfahl and Wernli, 2012), and (vi) examined the role of i.e. clustering of extreme precipitation events in large-scale flooding (Barton et al. WWOSC-2014 SCI-PS229.03). Predictability studies using ensemble forecasts are still in their early phase with Walser et al. (2004) and Hohenegger and Schär (2007) (on Alpine precipitation), Nuissier et al. (2012) (on Mediterranean heavy prediction events) and Barrett et al. (2015) (on mesoscale precipitation bands) being notable examples.

Open questions:

- Given complex physical processes related to heavy precipitation and their multiscale interaction, what factors limit predictability?
- What is the relative importance of the horizontal moisture transport, thermodynamic instability (CAPE) and cloud microphysics for the intensity of heavy precipitation events on different time scales (from an hour to days)?
- Can we better quantify and understand how predictability of heavy precipitation is limited by catchments of different sizes and in different climatic zones?

5.2.3 Mesoscale structures

Various phenomena come into this category. Here we consider sting jets, mesoscale convective systems and gravity waves. The effect of these phenomena on synoptic-scale predictability is also considered. During the THORPEX period notable field campaigns are DIAMET, COPS and CSIP:

The UK-based DIAMET (DIAbatic influence on Mesoscale structures in ExTratropical storms) project (2010-2015) provided unique airborne and ground-based observations of mesoscale structures in extratropical storms affecting the UK. Mesoscale structures observed include a sting jet (Martínez-Alvarado et al. 2014; Baker et al. 2013) and a prefrontal gravity wave (Knippertz et al. 2010); an overview of the DIAMET cases is presented in Vaughan et al. (2014).

The German-based COPS (The Convective and Orographically Induced Precipitation Study) project had its field campaign in summer 2007 and had an overarching goal to advance the quality of forecasts of orographically induced convective precipitation by four-dimensional observations and modelling of its life cycle (overview paper Wulfmeyer et al. 2008; special issue of Quarterly Journal of the Royal Meteorological Society, editors Wulfmeyer et al. 2011).

The UK-based CSIP (Convective Storm Initiation Project) project had the aim to understand precisely where, when, and how convective clouds form and develop into showers in the mainly maritime environment of southern England (overview paper Browning et al. 2007).

Over the last ten years, series of papers have been published on a phenomenon called a 'sting jet'. This jet descends from the tip of the hooked cloud head in rapidly intensifying extratropical cyclones and is distinct from other low-level wind jets, in particular the cold conveyor belt, associated with these cyclones (Martínez-Alvarado et al. 2014). This jet reaches the top of the boundary layer in the dry slot of the cyclone and has been associated with strong or intensified surface winds and wind gusts in European windstorms. The terminology 'sting jet' came from a reanalysis of the *Great October storm* of 1987 by Browning (2004) in which he identified the feature from observations and called it 'the sting at the end of the tail', terminology similar to that used by Grønås (1995). Modelling studies of this and other cases followed (e.g. Clark et al. 2005; Parton et al. 2009; Martínez-Alvarado et al. 2010; Smart and Browning, 2014) with the sting jet typically diagnosed as a coherent ensemble of trajectories with particular characteristics. Current work is using automated clustering methods to objectively identify these coherent ensembles (Hart et al. WWOSC-2014 SCI-PS171.02 and in press). Studies have also associated cloud banding observed in satellite imagery with sting jets (Browning, 2004; Browning and Field, 2004). Proposed mechanisms are the release of conditional symmetric instability and evaporative cooling (see previous papers and Gray et al. 2011) and frontolysis (Schultz and Sienkiewicz, 2013). To date, identified cases in the published literature have only originated over the North Atlantic - a climatology of cases in this region has been published in Martínez-Alvarado et al. (2012) - though this does not exclude their existence over other ocean basins. Sting jets have also been simulated in idealized baroclinic lifecycle simulations of extratropical cyclones (Baker et al. 2014). The evolution of synoptic conditions favourable for the existence of sting jets in cyclones has been diagnosed using eddy kinetic energy (Rivière et al. 2015). Eddy kinetic energy redistribution after the cyclone crosses the large-scale low-frequency jet axis (from the warm to the cold side) is shown to lead to the formation of a low-level westerly jet to the south of the cyclone centre behind the cold front.

Recent research into mesoscale convective systems (and associated vortices and tornadic systems) in the midlatitudes has considered case studies (e.g. Browning et al. 2010; Smart et al. 2012; Clark, 2012; Lombardo and Colle, 2013), regional environmental climatologies (e.g. UK - Lewis and Gray, 2010 and Clark, 2013; Iberia and Balearic Islands - Garcia-Herrera et al. 2005; US - Schumacher and Johnson, 2005 and Lombardo and Colle, 2011; Finland - Punkka and Bister, 2005; South Africa - Blamey and Reason, 2012; South America - Durkee and Mote, 2010) and predictability (Jirak and Cotton, 2007; Wandishin et al. 2010). Clearly, there is also a strong link of this research field to the more general investigation of heavy precipitation events (Section 5.2.2).

Jets and fronts are a significant source of internal gravity waves and these waves have impacts on the atmosphere ranging from the local scale (tropospheric convection and local mixing and turbulent) to the global scale (vertical propagation into the middle atmosphere and global circulation). Our current state of knowledge was recently reviewed by Plougonven and Zhang (2014). Recent work has extended knowledge of the generation of mesoscale gravity waves in the dry baroclinic jet-front system (Zhang, 2004) to the moist system (Wei and Zhang, 2014) and shown coupling between convectively-generated gravity waves and dry gravity wave modes for high moisture contents.

The upscale growth of errors from the convective scale to the synoptic scale has been analysed in recent studies. Zhang et al. (2007) derived a three-stage conceptualised error growth model in which errors grow initially from small-scale convective instability, then change to error growth associated with large-scale balanced motions (with the energy associated with some of the original error radiated away as gravity waves), and finally grow with the background baroclinic instability. Selz and Craig (2014) confirmed in a case study the three stage conceptual model of error growth that Zhang et al. (2007) derived by considering an idealised moist baroclinic wave, whereas other studies (e.g. Hohenegger et al. 2006) focused on the so-called predictability mystery that, depending on the large-scale flow setting, moist convection may or may not reduce predictability. Currently work is assessing the difference in perturbation growth behaviour in simulations with and without convective parameterization. A reduction in perturbation growth with convective parameterization has been found, indicating an intrinsic overconfidence that can be mitigated by the use of a stochastic parameterization scheme (Selz and Craig, WWOSC-2014 SCI-PS119.01).

Open questions:

- What is the global distribution of sting jet cyclones?
- What is the relative importance and predictability of different flow settings leading to extreme surface winds (e.g. sting jets, stratospheric intrusions, orographic flow channelling)?
- What is the upscale influence (i.e. effect on synoptic-scale predictability) of midlatitude mesoscale convective systems and how and when does this upscale influence occur?

5.2.4 Polar interactions

Midlatitude weather systems can potentially be influenced by the polar latitudes through disturbances to the Rossby waveguide from tropopause polar vortices or from polar mesocyclones or polar lows. Tropopause polar vortices are coherent radiatively-maintained cyclonic circulation features over the Arctic with lifetimes up to months and radii up to 800 km (Cavallo and Hakim, 2013). Polar mesocyclones are small but intense cyclones typically forming in cold air outbreaks via mixed baroclinic and convective processes, with polar lows being a more intense subset of these (Bracegirdle and Gray, 2009).

Polar lows in the North Atlantic have been found to occur preferentially in specific wintertime weather regimes (Claud et al. 2007; Mallet et al. 2013). Several studies have explored the climatology and environmental conditions favourable for polar low development (most recently Kolstad, 2011 and Noer et al. 2011). There are commonalities with extratropical and tropical cyclones in the methods used to analyse these polar weather features, in particular the use of PV diagnostics including PV inversion and surgery techniques (e.g. Bracegirdle and Gray, 2009; Cavallo and Hakim, 2009; Nordeng and Rosting, 2011).

Recent field campaigns focusing on the influence of the polar regions on weather include the Greenland Flow Distortion experiment (GFDex) (see overview paper by Renfrew et al. 2008). GFDex was an international fieldwork and modelling-based project to investigate the role that Greenland plays in distorting atmospheric flow over and around it and its effect on local and remote weather systems and, via air-sea interaction processes, the coupled climate system.

Recent modelling experiments have examined the impact that improved Arctic forecasts would have on the skill of midlatitude forecasts and found no discernible impact over the North Pacific and North Atlantic storm track regions (Jung et al. 2014). The effect of the reducing sea ice extent and thickness over the Arctic ocean on synoptic weather systems in the midlatitudes (Jung et al. WWOSC-2014 SCI-PS242.01; Chen and Zhang, WWOSC-2014 SCI-PS242.03) and on tropospheric polar vortices, which can act as precursors to midlatitude cyclogenesis, (Lusk and Cavallo, WWOSC-2014 SCI-PS242.04) is a current area of research.

Data coverage in polar latitude regions is lacking. In recognition of the importance of the polar regions for weather and climate prediction, the World Weather Research Programme (WWRP) of WMO have established the Polar Prediction Project (PPP) (see Chapter 19 of this book) whose mission is to "Promote cooperative international research enabling development of improved weather and environmental prediction services for the polar regions, on time scales from hours to seasonal."

Open questions:

- Given the relatively small size of tropopause polar vortices and polar mesocyclones, can they perturb the Rossby wave guide enough to have an important effect on downstream predictability?
- How can cold air outbreaks from polar regions influence midlatitude weather and how well can these events be predicted?
- Is there an impact of diabatic processes associated with midlatitude weather systems on the formation of persistent anticyclones in polar regions?

5.2.5 Diabatic processes in extratropical cyclones

Diabatic processes in extratropical cyclones can modify the structure and amplitude of tropopause-level ridges and troughs. Errors in the representation of diabatic processes in extratropical cyclones, perhaps resulting from the necessity to parameterize convection and other diabatic processes in global (and most regional) weather forecast models, could thus lead to errors in forecasts. Brennan et al. (2008) advocated a PV-based interpretation in operational forecasting to identify diabatically-driven parts of the model solutions that might thus be associated with increased uncertainty. A failure to forecast Rossby wave breaking can result in so called `forecast busts'. Rodwell et al. (2013) hypothesized that mis-representation of diabatic processes within mesoscale convective systems across North America leads to the most extreme forecast busts over Europe. Gray et al. (2014) diagnosed systematic error in Rossby-wave structure (ridges develop insufficient amplitude with too weak isentropic PV gradient) in medium-range model forecasts from the Met Office, ECMWF and NCEP.

One research focus during the past ten years has been in the use of piecewise PV inversion to attribute the development of weather systems to different PV anomalies (upper-level PV anomalies, surface potential temperature anomalies and diabatically-generated PV anomalies in the lower-mid troposphere (around 700 hPa)). This technique has been applied, for example, to extratropical cyclones (Ahmadi-Givi et al. 2004), Mediterranean cyclones (Romero, 2008), tropopause polar cyclones (Cavallo and Hakim, 2009), mesoscale snowbands (Novak et al. 2009), and the downstream effects of precipitation near surface warm fronts (Baxter et al. 2011). Alternative approaches to attributing the diabatic contribution to the development of extratropical cyclones are through the use of the pressure tendency equation (Fink et al. 2012) and the geostrophic relative vorticity tendency equation known as the extended Zwack-Okossi development equation (Kuwano-Yoshida and Enomoto, 2013). A more recent strand of work has developed diagnostics to attribute the role of individual diabatic processes (e.g. different cloud microphysical processes and radiation) leading to the modification of PV, particularly in the warm conveyor belt (Joos and Wernli, 2012; Chagnon et al. 2013, 2015). Despite similar overall PV modification and heating this attribution can vary significantly between models (Martínez-Alvarado et al. 2014, Joos et al. WWOSC-2014 SCI-PS148.03).

Evidence of the importance of diabatic Rossby waves as a low-level cyclonic precursor to rapid deepening extratropical cyclones has grown from idealised modelling experiments (Moore and Montgomery, 2004) through case study analysis (Moore et al. 2008; Boettcher and Wernli, 2011) to climatological analysis (Boettcher and Wernli, 2013). Recent case study analysis has demonstrated uncertainty in Rossby wave breaking (and associated extreme weather events) related to variability in the interaction between a diabatic Rossby wave and upper-level PV disturbance (Moore et al. WWOSC-2014 SCI-PS109.02).

Analysis of the structure of diabatically produced PV anomalies in convection-permitting simulations has demonstrated the existence of horizontally-oriented dipoles, in agreement with theory and contrary to the vertically-oriented dipoles found in coarser-resolution convection-parameterizing simulations (Chagnon and Gray, 2009).

Climatological analysis of the PV structure in extratropical cyclones has revealed regional variations in the contribution of the lower-tropospheric diabatically-produced anomalies (Campa and Wernli, 2012) with stronger values in western parts of the ocean basins and in the more intense cyclones. Climatologically, the mean PV evolution in ascending warm conveyor belts has been shown to increase to almost 1 PVU at 700 hPa and then decrease to less than 0.5 PVU at 300 hPa, a significant negative PV anomaly that can influence downstream flow (Madonna et al. 2014). Methven (2014) argues the main effect of diabatic processes in the WCB is to raise the isentropic level of the outflow air in the upper-troposphere rather than to modify the PV of the outflow. During the last ten years the accuracy of prediction of the intensity and location of warm conveyor belts has improved for the ECMWF high-resolution model; ten years ago warm conveyor belts were systematically over-predicted at all lead times whereas now they are neither under- nor over-predicted as diagnosed using feature-based forecast verification (Madonna et al. 2014). The recent T-NAWDEX (THORPEX-North Atlantic Waveguide and downstream Impact Experiment)-Falcon aircraft observational campaign aimed to quantify the transport of moisture and net latent heating along warm conveyor belts (Schäfler et al. WWOSC-2014 SCI-POS1084).

Open questions:

- What are the systematic effects of diabatic processes on the development of extratropical cyclones and downstream evolution?
- Are limitations in our ability to represent diabatic processes in weather and climate forecast models (given these processes are typically parameterized) limiting our forecasting abilities?
- How can we make better use of aircraft and remote sensing observations to constrain diabatic processes in models and the impact on the large-scale dynamics?

5.2.6 Rossby wave triggering, amplification, breaking and blocking

A Rossby wave train can be described as a coherent envelope or packet of baroclinic waves that develops in the zonal mean flow (Lee and Held, 1993). Rossby waves can be triggered by a range of atmospheric phenomena (e.g. warm conveyor belts associated with extratropical cyclones, recurving tropical cyclones undergoing extratropical transition, and tropospheric polar vortices).

During the past ten years much research has focused on the categorisation and generation of climatologies of Rossby wave breaking and the link between Rossby wave breaking, blocking (and other weather regimes) and teleconnection patterns such as the North Atlantic Oscillation (Berrisford et al. 2007; Woollings et al. 2008; Strong and Magnusdottir, 2008; Altenhoff et al. 2008; Gabriel and Peters, 2008; Song et al. 2011; Ndarana and Waugh, 2011; Michel and Rivière, 2011). Some authors have distinguished between poleward and equatorward Rossby wave breaking events as defined in Peters and Waugh (1996).

More recent work has examined the link between Rossby waves, Rossby wave breaking and high-impact weather events. Associations have been found between long-lived Rossby wave trains and/or Rossby wave breaking and intense European cyclones (Wirth and Eichhorn, 2014; Gomara et al. 2014), torrential rainfall and heatwaves in Japan (Enomoto et al. 2009), Southern Hemisphere cut-off lows (Ndarana and Waugh, 2010), high-impact weather in the Mediterranean and subtropical Africa (Lambert and Cammas, 2010), heavy precipitation events on the Alpine south side (Martius et al. 2008), the extratropical transition of tropical cyclones (Quinting and Jones WWOSC-2014 SCI-PS218.02; Archambault et al. 2015), European flooding (Grams et al. 2014), heat waves and wildfires in southeastern Australia (Parker et al. 2014; Reeder et al. 2015), and extratropical cyclone clustering (Pinto et al. 2014).

Other recent work has examined the predictability of Rossby wave breaking using ensemble forecasts and found systematic errors and underdispersive behaviour in the subtropics during PV streamer events (Wiegand and Knippertz, 2014), implying forecast busts could result in poor forecasts of heavy precipitation events in the Mediterranean region and Saharan dust outbreaks. Langland et al. (2002) found Rossby wave trains originating over the Western Pacific played an important role in the medium-range predictability of a US snow storm.

Novel diagnostics are being developed for the identification and categorization of Rossby wave trains (Glatt et al. 2011; Glatt and Wirth, 2014). The amplification of the wave pattern can be partitioned into advective, baroclinic feedback and diabatic processes (Gierth et al. WWOSC-2014 SCI-PS139.01) and the propagation diagnosed using wave activity flux, which is shown to have advantages over the conventional meridional wind diagnostic (Wolf and Wirth, WWOSC-2014 SCI-PS139.02). Object-based verification tools of Rossby wave trains are being developed, enabling error statistics to be derived over climatological periods (Giannakaki and Martius, WWOSC-2014 SCI-PS139.04).

Medium-range ensemble forecasts (from the TIGGE - the THORPEX Interactive Grand Global Ensemble - archive) have been shown to be capable of predicting blocking (Matsueda, 2009) and several papers have explored the ingredients required for successful numerical modelling of long-lived blocking. High resolution (Matsueda et al. 2009; Scaife et al. 2011), correct simulation of upstream troughs (Matsueda, 2011) and correct simulation of the mean state, in particular sea surface temperatures (Scaife et al. 2011), have all been shown to be important under certain conditions and in certain models. Croci-Maspoli et al. (2009) explicitly suggested that the correct representation of diabatic features might play a crucial role in the forecast of blocking. This is consistent with the association found between improved blocking frequencies in the ECMWF model over the North Pacific and Euro-Atlantic region and the introduction of a new convection scheme (Jung et al. 2010). Zappa et al. (2014) found some evidence that CMIP5 models with stronger cyclones upstream tend to have higher European blocking frequencies, again consistent with a role for diabatic processes since stronger cyclones tend to have stronger warm conveyor belts.

Open questions:

- How does model error affect forecasts of the amplification and propagation of Rossby wave trains?
- How important is model error due to poor representation of diabatic processes compared to other sources of forecast error: initial condition error, boundary condition error, insufficient resolution, and other sources of model error such as associated with the dynamical core?
- What physical processes are crucial for the blocking onset, persistence and decay, and how well are they represented in model forecasts?
- How relevant is the accuracy of the waveguide representation (e.g. meridional PV gradient, jet amplitude) compared to capturing the amplitude of waveguide disturbances (e.g. polar vortices, diabatic outflows) for medium-range weather prediction?

5.2.7 Synoptic climatologies

The availability of several novel and temporally-extended reanalysis data sets (e.g. ERA-Interim (Dee et al. 2009), Modern Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011), 20th-Century Reanalysis (Compo et al. 2011)) has been very useful for compiling a large number of synoptic climatologies for a diversity of atmospheric flow features on the global and regional scale. Classical approaches (e.g. composites) and new technical approaches have been developed and applied. Only a few of them are mentioned here as important examples.

Several global climatologies of extratropical cyclones were produced during the last decade (e.g. Hoskins and Hodges, 2002; Jung et al. 2006; Trigo, 2006; Wernli and Schwierz, 2006; Inatsu, 2009; Hewson and Titley, 2010; Hodges et al. 2011), using different cyclone identification and tracking algorithms. Raible et al. (2008) compared three of these techniques and found that for trend analyses, results are sensitive to both the choice of the detection and tracking scheme and the reanalysis dataset. This was an important motivation for starting a major cyclone tracking intercomparison project, which identified the robust and more sensitive aspects of cyclone climatologies produced with different algorithms (Neu et al. 2012). Some of these techniques have also been applied to investigate the occurrence of cyclones in simulations of the present and future climate (e.g. Lionello et al. 2002; Löptien et al. 2008; Bengtsson et al. 2009; Raible et al. 2010; Ulbrich et al. 2012).

Other climatological cyclone studies looked in more detail at specific characteristics or categories of extratropical cylcones, e.g. dynamical forcing mechanisms (Gray and Dacre, 2006), extreme North Atlantic cyclones (Pinto et al. 2009), explosive cyclones (Allen et al. 2010), the vertical PV structure of cyclones (Campa and Wernli, 2012), and the specific category of diabatic Rossby waves (Boettcher and Wernli, 2013). In addition, climatologies have been compiled of extratropical transition events in the North Pacific (Archambault et al. 2013; Wood and Ritchie, 2014).

Other novel synoptic climatologies focused on surface fronts (Berry et al. 2011; Simmonds et al. 2012), atmospheric blockings (Pelly and Hoskins, 2003; Croci-Maspoli et al. 2007), upper-tropospheric jet streams (Koch et al. 2006; Schiemann et al. 2009; Limbach et al. 2012; Manney et al. 2014), near-surface barrier jets (Harden et al. 2011), Rossby wave packets (Souders et al. 2014) and Rossby wave breakings (Peters and Waugh, 2003; Waugh and Funatsu, 2003; Wernli and Sprenger, 2007; Martius et al. 2007), spectral properties of midlatitudes waves (dell'Aquila et al. 2005, 2007) and processes leading to heavy precipitation events (e.g. Reale and Lionello, 2013; Lavers and Villarini, 2013; Viale and Garreaud, 2014; Collins et al. 2014; Winschall et al. 2014). It is important to note that a broad range of methodological concepts have been used in these studies, including the shape of contours, PV anomalies, and region growing algorithms for 4-dimensional feature detection - illustrating that progress in this area is also related to methodological innovation.

Open questions:

- How well do reanalysis datasets represent extreme events?
- Do systematic climatologies provide a basis for novel and more meaningful classifications of weather systems?
- How can synoptic climatologies be used for a better process understanding and forecast performance analysis of midlatitude weather systems?

5.3 CONCLUSION

Although far from being comprehensive, this overview provides evidence of the impressive progress in research on midlatitude weather systems and their prediction during the THORPEX decade. Advances, due to more sophisticated reanalysis datasets and the emergence of ensemble systems and convection-permitting models, led to unprecedented increases in understanding and predictive skill of the complex interplay of atmospheric processes relevant for midlatitude weather systems. Special consideration has been given to interactions between dynamics and physics and their representation in numerical models for the understanding and prediction of high-impact weather systems. Researchers have continued to amalgamate theoretical concepts of atmospheric dynamics (e.g. the PV framework and Rossby wave dynamics) and aspects related to the atmospheric water cycle (e.g. latent heating and cooling in clouds), leading to improved insight into the mechanisms determining the evolution of weather systems and a set of novel unresolved research questions. Research in this area had a first boom at the time of the ERICA (Experiment on Rapidly Intensifying Cyclones over the Atlantic) field experiment in 1989 and remains crucial for further improving numerical weather prediction in the next decades. It will likely profit from (i) increased cooperation between weather services and academia (as established during THORPEX), (ii) a continuation of international field experiments, (iii) novel modelling capabilities with a more realistic representation of moist convection, and (iv) an emphasis on dynamically motivated feature-based analyses of forecast errors. Finally, in addition to these specific challenges, an essential task is to further bridge the gap between weather and climate research. This will be achieved by establishing the seamless modelling approach for time scales from hours to centuries and, even more challenging, by using the weather system perspective and dynamical expertise for an in-depth evaluation of the enormous amount of data from simulations of the current and future climate.

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CHAPTER 6. NUMERICAL METHODS OF THE ATMOSPERE AND OCEAN

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Abstract

We review the various aspects of global model development in the light of concurrent progress in science and in computer technology and in the development of seamless numerical prediction for weather and climate. There is an expected increase in computing power that will allow an improved model representation of the Earth's system. This requires the adaptation of the numerical and programming techniques for General Circulation Models so that the computational resources are efficiently exploited to their full extent.

6.1 INTRODUCTION

Atmosphere and ocean models, and in particular their fluid flow components (the "dynamical cores", see Williamson (2007)), are at an important crossroads. One motivation for numerical design changes is the emergence of a new generation of computer architectures that promises to be "as disruptive as the transition from vector to parallel computing in the 1990s" (Dongarra et al. 2014). The new supercomputer architectures with millions of (most often) quite diverse processing elements demand that computations stay local in memory and minimize the number of global communication steps. In addition, the unleashed power of new computer generations enables modellers to run multi-scale simulations at unprecedented, fine grid resolutions that approach the km-scale. This in turn impacts the choice of the underlying equation sets and the numerical discretization methods that allow a more faithful and detailed numerical representation of atmospheric and oceanic phenomena at all scales. The anchors of new model developments are the operational meteorological offices, national climate centres and laboratories as well as the university research community. We group the current and projected future research activities in various categories and focus the discussion on the design of atmospheric General Circulation Models (GCMs). Most categories will similarly apply to ocean models. The performance of the GCM dynamical cores will also continue to play a significant role in future data assimilation applications, ensemble forecasting (see Chapters 3 and 11 of this book) and for uncertainty estimation strategies, all facing similar parallel scalability challenges. At the same time, the demand for much increased complexity of Earth system modelling in the Numerical Weather Prediction (NWP) and climate communities mandates efficient strategies for strong coupling to land-surface, ocean, wave, sea-ice and chemistry modules.

6.2 EQUATIONS SETS AND BUILD-IN PHYSICAL CONSTRAINTS

6.2.1 Equation set

Traditionally, most operational weather and climate GCMs were built upon the "primitive equations" which imply the use of the shallow-atmosphere, hydrostatic, spherical geopotential (considering the Earth as a perfect sphere) and constant gravity approximations (White et al. 2005). More recently, the global modelling community has moved towards more realistic fluid flow equations. In particular, both shallow- and deep-atmosphere non-hydrostatic equation sets (White and Bromley, 1995; Staniforth and Wood, 2003; White et al. 2005) are now becoming the new standard for global weather and climate models. They allow for grid spacings below approximately 5-10 km where non-hydrostatic effects start to become important. Note that these nominal grid spacings do not reflect the scales of the resolved processes. The resolved scales are better described by the "effective resolution" of a model (Skamarock, 2004; Ullrich, 2014; Kent et al. 2014a, 2014b) or the "believable scales" (Lander and Hoskins, 1997). They are typically a multiple of the grid spacing Δx and often lie between 4-10 Δx depending on the characteristics of the numerical algorithm. This is due to the use of numerical filters, explicitly-added diffusion or other damping mechanisms, like implicit numerical diffusion, in the dynamical cores that strongly distort and damp the representation of the waves near the grid scale (Jablonowski and Williamson, 2011).

Deep-atmosphere formulations of the non-hydrostatic equations demand that gravity becomes dependent on height and needs to vary with $(a/r)^2$ where a and r denote the Earth's radius and the distance to the centre of the Earth, respectively. Furthermore, deep atmosphere formulations require the inclusion of the cosine-Coriolis terms and certain metric terms that are neglected in shallow-atmosphere formulations. The latitudinal variations of gravity can also be accounted for in ellipsoidal coordinates that have recently been considered for GCMs. These ellipsoidal or oblate spheroidal representations relax the commonly used spherical geopotential approximation and pay tribute to the slight oval shape of the Earth (White et al. 2008; White and Wood, 2012; Staniforth, 2014a, 2014b, 2015; Staniforth and White, 2015a, 2015b; Tort and Dubos, 2014b; Bénard, 2014, 2015). However, no 3D GCM has been built upon the non-spherical equation sets yet. All approximations and equation sets need careful attention and require that certain terms in the equations of motion, like the cosine-Coriolis terms or selected metric terms, be either included or neglected so that the set is coherent with definite conservation properties: mass, momentum, axial angular momentum, energy and potential vorticity (White et al. 2005; Staniforth, 2001; Thuburn et al. 2002a, 2002b; Tort and Dubos, 2014a). A long-term goal is to move towards a truly 3D representation of the Earth and its gravitational anomalies. An inconvenient aspect of using the non-hydrostatic equation sets is the stringent limit on the time step in explicitly time-discretized models. This is due to the presence of fast sound waves that travel with speeds of over 300 m/s in all directions. Although insignificant for atmospheric motions, the vertically propagating acoustic modes demand sub-second time steps to guarantee numerical stability in explicit time-stepping schemes. This stringent limit is caused by the very small vertical grid spacings near the ground, which are typically on the order of 10s of meters. One workaround is the application of vertically-implicit time discretizations. Alternatively, filtered approximations of the non-hydrostatic equations are considered to eliminate the acoustic modes in the vertical direction (Durran, 2008; Arawawa and Konor, 2009; Konor, 2014; Smolarkiewicz et al. 2014). However, it should be noted that the latter mimics the effect of naturally occurring viscosity acting directly at the finest scales.

6.2.2 Conservation

The numerical discretization of the chosen equations should preferably possess the same conservation properties as the continuous equations (Thuburn, 2008a). Conserving mass, total energy and potential vorticity is important for climate models, but less so for forecast models that are integrated for shorter time periods. Nevertheless, following the "unified" or "seamless" principle the current trend is to develop models that conserve mass, total energy and the monotonicity ("shape") of transported fields, or at a minimum the positive-definiteness of advected tracers. Mass-conserving and positive-definite numerical discretizations are therefore paramount. It is also desirable to choose numerical discretizations that guarantee conservation without a-posteriori mass or total energy fixers. At the high resolutions used in global NWP models today (10-20 km grid spacings), global conservation is often considered less of an issue. This view is also partially motivated by the fact that NWP models are only run for 7-10 days. However, appropriate local conservation properties are important for cloud-resolving simulations and for the emerging applications in assimilating and simulating chemical processes. Mixing ratios of water substances and other tracers need to stay positive during a simulation to obey their physical principles. In addition, the physical relationships between correlated tracers need to stay intact (Lauritzen and Thuburn, 2012; Lauritzen et al. 2014b; Kent et al. 2014c) to reliably predict chemical reactions like ozone formation. However, these physical correlations are often violated due to the influence of implicit numerical and explicitly-added mixing processes. As an aside, conservation of potential vorticity is not standard in 3D GCMs as e.g. assessed in Whitehead et al. (2015), but has been shown to be feasible for quasi-geostrophic models on Charney-Phillips or Lorenz vertical grids (Arakawa and Moorthi, 1988; Bell, 2003). In addition, 2D shallow water models have demonstrated that potential vorticity can be selected as a conservative prognostic variable (Thuburn, 1997).

6.2.3 Balance

The parameters of the Earth (mass, radius, speed of rotation and the energy received from the sun) are responsible for the maintenance of approximate hydrostatic and geostrophic balances that should be maintained at the same level by the discretized equations. For the geostrophic balance this implies that it is important to have the proper sign of the numerical group velocities of the relevant waves (Williams, 1981). This guarantees that the physical properties propagate in the correct direction. This property also helps prevent the appearance of numerical noise in the numerical simulations (Melvin et al. 2012; Thuburn and Staniforth, 2004).

6.2.4 Stability and accuracy

Numerical stability and accuracy are required of any model. Stability and consistency of the discretization ensures that the model converges toward the exact solution, at least under some controllable conditions. The order of accuracy determines at which rate the solution will converge in terms of time step and grid spacing. It is necessary to operate at the correct level of accuracy for each component in the simulation. Otherwise the time step and/or grid spacing required will be too small, resulting in computational inefficiency. However, as soon as the required accuracy is reached for a component there is no need to further improve it because the improvement is invisible in the final result. It can only be justified if it leads to efficiency gains as measured by a reduced time-to-solution (wallclock time) for weather forecasts or climate simulations. A typical quantity used for performance assessments is “forecast days per day” in the NWP or “forecast years per day” in the climate community, respectively.

6.3 TIME AND SPACE DISCRETIZATIONS

The equation sets are a prescription for advancing the meteorological fields in time for one time step. They furthermore determine the choice of the prognostic variables. For example, the thermodynamic energy can be represented by a temperature or potential temperature equation. Alternatively, some models predict the evolution of moist thermodynamic quantities, like the virtual potential temperature, which is e.g. implemented in the Finite-Volume dynamical core (Lin, 2004) at the National Center for Atmospheric Research (NCAR) or the Geophysical Fluid Dynamics Laboratory (GFDL). Another alternative is a conservation equation for the total energy as documented in Satoh et al. (2008). However, the latter can create ambiguity with respect to the inclusion or non-inclusion of moisture-related contributions to the total energy. Once the equation set has been chosen, it needs to be determined on what kind of horizontal and vertical grids the fields are represented, and how each term in the set will be discretized. The advective terms can be treated from an Eulerian or a Lagrangian point of view either in advective or in flux form. In the Lagrangian point of view the set is supplemented by a trajectory algorithm. The semi-Lagrangian method is reviewed in Staniforth and Côté (1991). The remaining terms are responsible for the atmospheric oscillations and can be treated either implicitly or explicitly to preserve stability of the model with the chosen time step. Note that the discretization errors in time and in space are connected via the fluid equations.

6.3.1 Horizontal discretization

Traditionally, the global spectral-transform method on latitude-longitude (or Gaussian/reduced-Gaussian) computational grids has been the dominant choice for weather and climate GCMs for solving the horizontal components of the equations on the sphere. Newly-developed global models today are built upon quasi-uniform grids that have recently been reviewed by Staniforth and Thuburn (2012). The quasi-uniform grids avoid the convergence of the meridians, the so-called pole problem, that has plagued latitude-longitude grids for so long. This convergence leads to very small grid spacings in the longitudinal direction, which either necessitate very short time steps or the application of polar filters, mostly in the form of Fourier filters. The latter become increasingly difficult to apply on parallel computing architectures since they require enhanced communication of the data along latitudes and thereby limit the parallel scalability.

Today, there is a general move towards local spatial discretization methods that avoid global communication on parallel hardware architectures. Examples are finite-difference (Qaddouri and Lee, 2011; Wood et al. 2014), finite-element (Kritsikis and Dubos, 2014; Melvin et al. 2014; Cotter and Thuburn, 2014; Staniforth et al. 2013; Cotter and Shipton, 2012), finite volume (Thuburn et al. 2014; Lee, 2013; Ullrich and Jablonowski, 2012b, Szmelter and Smolarkiewicz, 2010), spectral element (Giraldo and Rosmond, 2004; Taylor and Fournier, 2010; Dennis et al. 2012) and discontinuous Galerkin (Nair et al. 2009; Bao et al. 2015) methods that utilize almost uniform polyhedral grids on the sphere. The expected future computer architectures with fast computations and relatively slow memory movement favour the development of high-order numerical approximations by making extra local computations almost free. One also has to take into account that the anticipated amount of memory per processing element will be smaller than today. In a finite-element discretization one has the choice of reducing the element size (h-convergence) or increasing the discretization order in each element (p-convergence). At least for smooth problems the global error can then be minimized with a gain in efficiency but without forgetting that numerical spatial errors have to balance the errors that come from all other sources. A good introduction to these modern numerical methods can be found in Lauritzen et al. (2011).

Current dynamical core developments are on cubed-sphere meshes (Adcroft et al. 2004; Ullrich and Jablonowski, 2012b; Dennis et al. 2012), triangular grids (Walko and Avissar, 2008; Lee, 2013; Zängl et al. 2015; Satoh et al. 2014), hexagonal meshes (Lee and McDonald, 2009; Skamarock et al. 2012; Gassmann, 2013) and the Yin-Yang composite grid system (Qaddouri and Lee, 2011; Qaddouri et al. 2012; Sakamoto et al. 2013). In the longer term one might use mesh-free representations but these approaches are not competitive today (Flyer et al. 2015). Icosahedral and hexagonal grids are often used as optimized grids to enhance the regularity of the grid spacing even further. This can be accomplished via a spring dynamics algorithm (Iga and Tomita, 2014) or other iterative techniques (Miura and Kimoto, 2005; Heikes et al. 2013). The more uniform grid point distributions lessen potential grid imprinting issues. These arise when the computational grid becomes visible as a flow feature, which is undesirable from a physical viewpoint. A variety of such grid imprinting signatures has been analyzed by Lauritzen et al. (2010) and Weller et al. (2012). Experience furthermore shows that high-order numerical methods help reduce grid imprinting (Ullrich and Jablonowski, 2012b).

Concerning the horizontal grid staggering technique, the most dominant choice today is the Arakawa C-grid. It offers beneficial gravity wave propagation and dispersion characteristics, but also contains some computational modes on quasi-uniform grids as for example discussed by Thuburn and Staniforth (2004), Thuburn (2008b), Thuburn et al. (2009), Gassmann (2011b) and Weller (2012). As outlined in Staniforth and Thuburn (2012) the computational modes are wave modes that are supported by the numerical discretization, but have no analog among the waves that are represented by the continuous equations. The computational modes usually appear at or near the grid scale and can be the cause for numerical noise. Weller et al. (2012) found that such computational modes are most easily controlled on a hexagonal grid via a diffusive advection algorithm.

Although spectral transform methods are being predicted to be phased out, the current spectral model at the European Centre for Medium-Range Weather Forecasts (ECMWF), the Integrated Forecasting System (IFS), in its operational form (albeit hydrostatic) is the benchmark to beat, and it is not clear that any of the new developments are ready to replace it. In addition, there is no pole problem in the reduced Gaussian grid, at least for some time to come, and the IFS has also already been extended to a non-hydrostatic framework (Wedi et al. 2009). Recently, there have been some powerful developments in the use of spectral transform methods, and this is likely to extend the lifetime and use of spectral transform methods for perhaps another decade (Wedi et al. 2013; Wedi, 2014). In addition, hybrid approaches are under investigation that can combine multiple (e.g. soundproof and compressible) equation sets and discretization methods (Smolarkiewicz et al. 2014).

6.3.2 Vertical discretization

In the vertical there are generally four choices, which are a height-based (e.g. Gal-Chen and Sommerville, 1975; Schär et al. 2002; Klemp, 2011), pressure-based (e.g. Phillips, 1957; Simmons and Burridge, 1981), hydrostatic mass-based (e.g. Laprise, 1992; Bubnová et al. 1995, Côté et al. 1998; Wood and Staniforth, 2003) or isentropic-based (e.g. Hsu and Arakawa, 1990; Toy and Randall, 2009; Bleck et al. 2010) generalized coordinate with various arrangements of the variables in the vertical direction. All four choices are mostly employed as terrain-following coordinates. However, a pure height coordinate is suitable for models with shaved-cell or cut-cell approaches as outlined in Section 6.3.5. The pressure-based vertical coordinates are typically selected for hydrostatic models. The other three choices are mostly used in combination with non-hydrostatic equation sets. The exception is the isentropic-based approach, which has been implemented in both hydrostatic and non-hydrostatic dynamical cores. Most new dynamical core developments today are either built upon the height-based or mass-based vertical coordinate, and emphasis is put on a smooth transition between the terrain-following levels and the levels of constant height (Klemp, 2011).

Concerning the vertical staggering of the prognostic variables, Lorenz staggering (co-located variables at full model levels except the vertical velocity is represented at model interfaces, see Lorenz (1960)) has been favoured in the past because conservation is easier to implement with this arrangement. Charney-Phillips staggering (both the vertical velocity and the thermodynamic variable are located at the model interface) is preferred for computational reasons as e.g. extensively discussed by Thuburn and Woollings (2005), Girard et al. (2014) and Arakawa and Konor (1996). The choice of the vertical staggering seems to be less important if higher-order numerical discretizations in the vertical are used. However, care must still be taken to control computational modes (Staniforth and Wood, 2005).

If centred finite-difference discretizations are used in the vertical direction, they formally degrade to first-order accuracy for the typical non-equidistant (stretched) vertical grids with smaller level spacings near the ground. Traditionally, continuous mappings are used to minimize vertical discretisation errors. Second-order finite-volume techniques (Ullrich and Jablonowski, 2012a, 2012b) or even higher-order finite-element techniques (Untch and Hortal, 2004) have been explored for the vertical discretization. Such higher-order methods lead to a considerable increase in accuracy and reduce numerical noise. Alternatively, Lin (2004) implemented a floating Lagrangian vertical coordinate that traps the flow field within the 2D horizontal layers for about 5-10 dynamics time steps. The flow fields are then periodically remapped to a reference grid, which captures the vertical advection. The floating Lagrangian method has gained increased popularity in recent years (Chen et al. 2013; Dubos and Tort, 2014; Penner et al. 2007), and has also been introduced into the Spectral-Element dynamical core at NCAR (Dennis, 2012). Vertically adaptive meshes and vertical nesting (McTaggart-Cowan et al. 2011) are other active areas of research.

6.3.3 Advection

The Lagrangian form for the advection terms allows for point-wise or flux-form semi-Lagrangian (SL) methods. The mass-conservative flux-form SL discretization has recently regained popularity for the advection component of GCMs due to its projected computational efficiency gains especially in the presence of many tracers (Erath et al. 2012; Wong et al. 2013; Ullrich et al. 2014; Wood et al. 2014). SL discretizations allow long, efficient time steps with Courant-Friedrichs-Lewy (CFL) numbers greater than one. However, it is likely that future computer architectures will favour Eulerian or SL methods with CFLs not much larger than 1. This will keep the computations local and reduce the parallel communication costs, thereby off-setting the costs of a shorter time step.

6.3.4 Temporal discretization

The minimization of global communication will favor a splitting between slow and fast waves, which can then be treated differently from the viewpoint of the time discretization scheme. A popular split is HEVI that stands for horizontal explicit and vertical implicit. Active research is also underway to explore other IMplicit/EXplicit (IMEX) combinations and non-traditional time integrators such as semi-implicit predictor corrector schemes or exponential time integration methods for stiff problems (Bao et al. 2015; Durran and Blossey, 2012, 2013; Garcia et al. 2014; Giraldo et al. 2013; Ullrich and Jablonowski, 2012a; Weller et al. 2013a; Clancy and Pudykiewicz, 2013a, 2013b). Research also continues into 3D implicit solvers suitable for massively parallel implementation. These typically feature hierarchical, multi-scale designs using multi-grid techniques (Heikes et al. 2013; Müller and Scheichl, 2014). Looking further ahead “Parallel-in-time” time integrators would exploit untapped parallelism in GCMs, utilize the newest computing architectures more efficiently and thereby reduce the wall-clock execution time of GCMs (Haut and Wingate, 2014; Haut et al. 2014). New efficient multi-scale time integration algorithms are an active area of research considering the large impact of the chosen time-step on the overall timeliness of product delivery in NWP (Weinan et al. 2007).

6.3.5 Orography

Orography is most often considered via terrain-following vertical coordinates but this can lead to large discretization errors, instabilities or noise in the presence of steep terrain (Li et al. 2014; Weller and Shahrokhi, 2014). The trend towards high horizontal resolutions will further steepen the mountain slopes and worsen this problem. More research is needed to assess the pros and cons of alternative approaches and to include them efficiently in global models such as the cut-cell (Good et al. 2014; Steppeler et al. 2011), shaved-cell (Yamazaki and Satomura, 2008) or the combined-grid approach (Yamazaki and Satomura, 2012, 2010). Moreover, the increasing, yet still only partially resolved, orographic gravity wave activity has profound implications on the global circulation. In particular, their non-local effect is increasingly more difficult to describe by columnar physical parameterizations of gravity wave drag as these are designed to switch off with increasing resolution. It can be shown that this problem is a function of increasing resolved topographic slopes. A recent review of orographic gravity-wave drag can be found in Teixeira (2014).

6.4 TREND TOWARDS HIGH-RESOLUTION, VARIABLE-RESOLUTION AND ADAPTATIVE MESH REFINEMENT (AMR) GCMs

6.4.1 High-resolution

There is an increasing scientific demand for high-resolution, even cloud-resolving, GCM simulations that can accurately represent processes at regional and local scales. This places strong demands on the numerical designs of GCMs and their computational efficiency since the doubling of the horizontal resolution and the consequent halving of the model time step due to CFL stability constraints increases the computational workload by a factor of around 8. The latter estimate assumes perfect parallel scalability and that the memory footprint of the higher-resolution model configuration can be accommodated by the computer hardware.

Uniform high-resolution GCM grid spacings, that are currently feasible for multi-year simulations, range from 3.5-14 km as e.g. documented by Miura et al. (2007), Putman and Suarez (2011), Satoh et al. (2012), Jung et al. (2012), Manganello et al. (2012) or Miyamoto et al. (2014). The finest “ultra-high” resolution to date was employed by Miyamoto et al. (2013) who utilized a sub-km global grid with 870 m grid spacing. Such a small grid spacing only allows very short model calculations on the order of hours or days on current High Performance Computing (HPC) hardware platforms. However, it is likely that such resolutions will become the new norm in future decades as called for by the 2008 “World Modelling Summit for Climate Prediction” (Shukla et al. 2009). The summit demanded that the grid spacings of climate models must decrease towards the 1 km scale to accurately represent key regional processes in the atmosphere without parameterizing deep convection. This “grand challenge” can only be met by a significant boost of the available computing resources (Shukla et al. 2010) which reflects the tight coupling between scientific discoveries and HPC in climate and weather modelling (Washington et al. 2009). This is further discussed in Section 6.6.

High-resolution grid spacings under 10 km necessitate non-hydrostatic dynamical core designs since the scales of horizontal and vertical motions become comparable in these cloud-permitting or cloud-resolving model configurations. This invalidates the hydrostatic approximation that has been built into most GCM equation sets until very recently. Today, new dynamical core model developments recognize that non-hydrostatic designs are paramount for the future GCM generation as e.g. reflected by Walko and Avissar (2008), Wedi et al. (2009), Ullrich and Jablonowski (2012b), Skamarock et al. (2012) or Wood et al. (2014). At hydrostatic scales the non-hydrostatic models reproduce the hydrostatic solution, although typically at higher computational cost, and provide a seamless transition into the meso-scale flow regimes. This multi-scale GCM design allows the development of unified modelling systems (Palmer et al. 2008; Hurrell et al. 2009; Hoskins, 2013) that can be used for both local weather predictions and global climate projections without any algorithmic dynamical core changes. However, this raises questions concerning the scale-awareness (or scale sensitivities) of the subgrid-scale physical parameterizations that are not necessarily well suited for a wide range of resolutions, as briefly discussed further in Section 6.5.

As mentioned before high-resolution GCM modelling puts strong demands on HPC resources, and only very few modelling centres are currently equipped to handle the computational workload and data volumes. The big data volumes might even break existing data analysis and visualization software. Therefore, variable-resolution technologies have been emerging over the last decade, which build a bridge between the scientific and computational requirements. Variable-resolution GCMs place fine grid spacings in selected (non-moving) areas of interest while keeping the rest of the global domain at coarser resolutions. This technique even has the potential to replace traditional Limited-Area Models (LAMs) that can be nested within a coarse-resolution host GCM and rely on periodic updates of the boundary conditions. These boundary data updates can cause inconsistencies, like the violation of mass conservation constraints, and numerical noise, which is often damped via diffusion in "sponge zones" (Harris and Durran, 2010). In addition, some LAMs employ a nudging (relaxation) of the high-resolution solution towards the large-scale flow conditions of the host GCM to prevent the splitting between the LAM and GCM flow fields. This might become important for regional long-term climate modelling applications with LAMs. On the downside, the nudging compromises the versatility of regional climate assessments since the flow is not allowed to freely evolve in the high-resolution domain. Most often, the LAMs are also only coupled to the host model in a one-way interactive way and do not feed back the fine-grid information to the coarse GCMs. These issues are not present in global variable-resolution models that automatically provide consistent two-way interactions (and thereby dynamic up- and downscaling of flow features) between the coarse- and fine-resolution domains.

6.4.2 Variable-resolution

Variable-resolution GCMs come in many different flavours. Until about 2010, most variable-resolution GCMs used a grid stretching technique, like the Schmidt (1977) transformation, to zoom into a single region of interest with high resolution. The papers by Fox-Rabinovitz et al. (2006), Tomita (2008) and McGregor (2013) provide a comprehensive review of various stretched-grid GCMs. More recently, variable resolution grids are provided as an option in selected GCMs that are built upon unstructured icosahedral, hexagonal or cubed-sphere grid topologies. Examples are the variable-resolution model ICON by the German Weather Service and the Max-Planck Institute for Meteorology (Gassmann, 2011a; Zängl et al. 2015), the model OLAM which is under development at the University of Miami (Walko and Avissar, 2008, 2011), the cubed-sphere Finite-Volume GCM at the Geophysical Fluid Dynamics Laboratory (Harris and Lin, 2013, 2014), the Model for Predictions Across Scales (MPAS) for atmosphere and ocean simulations developed at the National Center for Atmospheric Research (NCAR) and the US Department of Energy's (DoE) Los Alamos National Laboratory (Skamarock et al. 2012; Ringler et al. 2013; Rauscher et al. 2013; Rauscher and Ringler, 2014; Park et al. 2013, 2014), and the Spectral Element (SE) version of the NCAR/DoE Community Atmosphere Model (CAM) (Guba et al. 2014; Zarzycki et al. 2014a, 2014b, 2015; Zarzycki and Jablonowski, 2014). The importance of variable-resolution and multi-scale modelling has also been recognized in the special issue on "Mesh Generation and Mesh Adaptation for Large-Scale Earth System Modelling" by the journal *Philosophical Transactions of the Royal Society A* in 2009 (Nikiforakis, 2009 and other special issue articles), and the 2013-2014 special issue on the "Isaac Newton Institute Programme on Multiscale Numerics for the Atmosphere and Ocean" by the journal *Geoscientific Model Development* (http://www.geosci-model-dev.net/special_issue27.html). The latter was a four-month program that took place in Cambridge, U.K., in 2012. It brought together the international research community in the pursuit to advance numerical, computational and Adaptive Mesh Refinement (AMR) techniques for atmosphere and ocean GCMs (Ham et al. 2012; Weller et al. 2010, 2013b).

An example of a variable-resolution CAM-SE grid is depicted in Figure 1. The figure shows a high-resolution region with grid spacings of about 14 km in the inner domain. The grid then transitions to a grid spacing of 28 km (midlevel) and 55 km in the outermost domain. The figure also provides close-up views of the sharp transition regions.

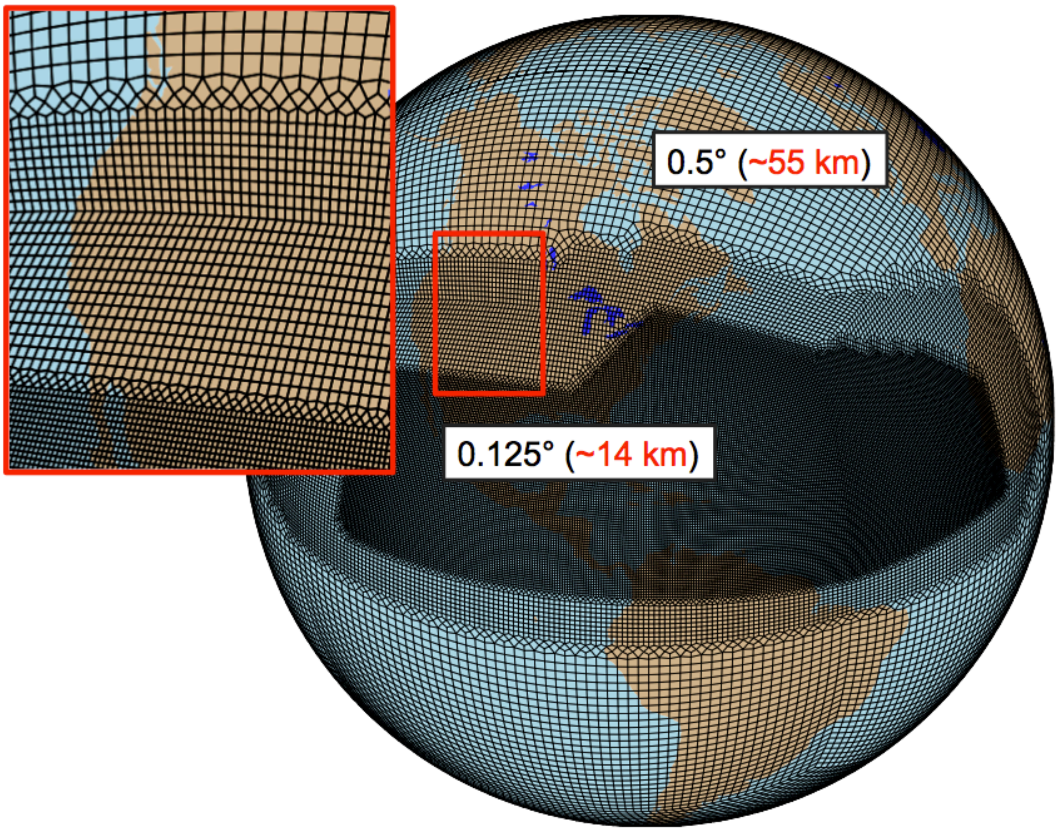

Figure 1. Example of a non-moving variable-resolution mesh in the model CAM-SE

6.4.3 Adaptive mesh refinement

Dynamic adaptivity of the mesh (AMR) has been a topic of interest for many years and progress has been made towards the development of global models that can track objects and refine resolution as the objects develop smaller scales. Many 2D adaptive mesh refinement algorithms for e.g. the shallow-water equations on the sphere and x-z non-hydrostatic slice models in Cartesian geometry have been documented in the literature. Examples are the AMR shallow water articles by Jablonowski et al. (2006), Läuter et al. (2007), St-Cyr et al. (2008), Weller (2009), Chen et al. (2011), Blaise and St-Cyr (2012), Marras et al. (2015), Aechtner et al. (2015) or McCorquodale et al. (2015). Furthermore, adaptive x-z slice model configurations were explored by Skamarock and Klemp (1993), Müller et al. (2013) or Kopera and Giraldo (2014). A comprehensive review of AMR techniques for atmosphere and ocean models has been provided by Behrens (2006). The 2D AMR assessments have served as an idealized test bed for adaptive 3D model developments. Very few 3D AMR models in spherical geometry have been developed so far, and this research field might become an emerging trend for future-generation GCMs. Among the adaptive 3D AMR approaches are the weather prediction model OMEGA (Bacon et al. 2000; Gopalakrishnan et al. 2002), the anelastic adaptive moving mesh model of Kühnlein et al. (2012), the dynamical core AMR developments by Jablonowski et al. (2009) and the non-hydrostatic cubed-sphere Chombo-AMR model that is currently under development at DoE's Lawrence Berkeley National Laboratory and the University of Michigan.

6.4.4 Model adaptivity

Another type of model adaptivity, where the model changes locally in a region of the domain, will also play an important role in future computing. It will be most effective when combined with hierarchical adaptive mesh and algorithm refinement techniques. These models can describe the same physics at different levels of fidelity at the same location or can describe different physics. Model adaptivity can potentially exploit different levels of parallelism, asynchrony, and mixed precision and can minimize communication across layers. Model adaptivity (as well as AMR) could be tied to error control and uncertainty management to apply the finer-grained models only in those regions where the extra expense improves the solution accuracy. There are clearly opportunities in developing scalable adaptive algorithms, but more research is needed.

6.5 PHYSICAL PARAMETERIZATIONS

Currently, all subgrid-scale parameterizations only operate in vertical columns. In the future, more horizontal coupling becomes necessary, especially for increasing resolution as already mentioned for gravity-wave drag. More properties, like rainfall, will need to become prognostic variables instead of diagnostic quantities. It will also be possible that multi-dimensional radiation schemes are needed that interact more realistically with cloud properties. Improving the representation of deep convection in the so-called “grey zone” (with grid spacings between 2-10 km where deep convection becomes partially resolved) as well as an improved representation of orographic and turbulent flow interactions are of continued importance for global simulations of weather and climate.

Numerical discretizations in physics routines are often of low-order and not consistent with the numerical discretization in the dynamical core. Physical parameterization packages also do not converge at their expected order when time steps are reduced (Dubal et al. 2006, 2005, 2004; Staniforth et al. 2002a, 2002b; Wan et al. 2015). Typically, the physics packages and dynamical cores are coupled in a first-order operator-split way. Within the physics package a time-split approach is used which makes the results dependent on the order of the operations. In view of the smaller time steps chosen in CFL-limited dynamical cores, much efficiency can be gained by operating different physical parameterizations at different time steps, performing differently in different regions (e.g. stratosphere and troposphere, day and night areas in chemical calculations) and in computing these parameterizations asynchronously or on accelerator-type processors. More research is needed to assess the splitting error with such approaches and solve associated load-balancing problems.

Another emerging issue is the question whether the dynamics and physics grids should be different. For example, Lauritzen et al. (2014a) found numerical noise and grid imprinting signatures in the vertical velocity field when the physical parameterizations were computed on the gnomonic cubed-sphere computational grid of the CAM-SE dynamical core. The gnomonic grid tends to slightly cluster the SE collocation points towards the edges of each spectral element as e.g. depicted in Dennis et al. (2012). The grid imprinting was reduced after the dynamics and physics grids were split. The new physics grid consisted of an equidistant distribution of the inner grid points in each spectral element, and the forcing tendencies were projected back onto the collocation points of the dynamics grid. The total number of physics and dynamics grid points stayed the same (Lauritzen et al. 2014a). However, this also raises the interesting question whether the grid spacings of the dynamics and physics grids should be different. The physics tendencies could be e.g. sub-sampled on a finer grid and averaged back onto the coarser dynamics grid scale. This mimics the idea behind the so-called super-parameterization (Grabowski, 2004), which has gained popularity in recent years. A contrasting viewpoint is that the effective resolution of the dynamical core is a multiple of the grid spacing. Therefore, it can also be argued that the physics grid should not be refined since the dynamical information at the grid scale is uncertain. One can even claim that the grid point information should even be horizontally averaged before calling the physical parameterizations. Such physics-dynamics coupling questions are areas of active research.

6.6 COMPUTATIONAL ASPECTS

Concerning computing, the key figure is the electric power consumption per floating point operation per second (Watts/FLOPS) or, eventually, the total power cost for producing a forecast. In order to reach “exascale” performance the need to include highly parallel computing concepts into GCMs and the data post-processing stream is paramount. Despite ambitious targets being set for model resolution, complexity and ensemble size, today the bulk of the calculations are not performed with configurations that utilize the maximum possible number of processors. Initially, substantial efficiency gains can be obtained from a rigorous utilization of the Message Passing Interface (MPI) and the Open Multi-Processing (OpenMP) techniques which are distributed-memory and shared-memory programming paradigms, respectively. These can be further enhanced by Partitioned Global Address Space (PGAS) programming models that are either part of existing languages, such as Fortran, or higher-level standards, such as the Partitioned Global Address Space Programming Interface (GASPI).

A source of uncertainty at present is the inconsistent support of compiler directives for hardware accelerators (e.g. Open Accelerators (OpenACC), OpenMP4, Govett et al. 2003, 2014), Fortran language features such as Coarray Fortran (CAF), and vectorization constructs across compilers. In addition, new programming language extensions like CUDA-C or CUDA-Fortran are now available for vendor-specific General-Purpose Graphical Processing Units (GPGPUs). This “Compute Unified Device Architecture” (CUDA) programming framework is able to fully utilize the power of GPU hardware accelerators. However, CUDA codes become non-portable and will not work on hardware platforms of other vendors. Dynamic task parallelism represents an interesting feature but it could impose load imbalance on the calculations. At present, limited experience exists with this feature in our community. Compiler development is an important interface between science and industry, ultimately aiming for a lower level of hardware awareness in science codes. However, these enhancements are applied to existing science codes and do not require fundamentally different scientific and numerical solutions.

Performing calculations in single precision presents obvious efficiency gains in runtime and memory allocation, and can be applied to selected code components where the loss of accuracy does not affect scientific performance or numerical stability. Efficiency enhancement at the expense of precision can be further exploited towards inexact hardware (Düben et al. 2013).

Given that modern computer architectures are heterogeneous and consist of shared- and distributed-memory CPUs as well as various types of accelerators like GPGPUs or the “Many Integrated Core” (MIC) architecture the best numerical algorithms are those that are easy to localize (domain decomposition with good load balance) and compute intensive but require little data communication. Examples are spectral element, finite element and discontinuous Galerkin methods, or even parallel-in-time algorithms. Several examples of the parallel scalability of the NCAR Community Earth System Model (CESM) model are depicted in Dennis et al. (2012) who coupled the CAM spectral element atmospheric component to land, ocean and ice models at high resolutions (between 11-28 km grid spacings). The coupled climate model scaled reasonably well up to about 100 000 processors and more. Note that the scaling of CESM was highly impacted by the choice of the computing architecture. Alternative parallel scaling curves for the spectral transform NWP model IFS are provided in Mozdzynski et al. (2015). They show that the scaling of IFS greatly benefits from the use of Coarray Fortran constructs. With a 10 km global grid spacing reasonable scaling was achieved on up to 40 000 processors.

Error resilience becomes an issue with increasing relevance on future exascale systems. Fault tolerant algorithms and techniques to compensate for missing calculations and data need to be developed. Failure detection is an important component and has a strong dependence on hardware and compilers. Ensembles are less critically affected since ensemble statistics can be derived from fewer than nominal members.

It is recognized that bit-reproducibility for a fixed processor configuration is of crucial importance for code debugging and operational error tracing, and the only means for distinguishing between hardware differences and code issues. However, reduced or part bit-reproducibility may be crucial for operating on future architectures with acceptable fault tolerance and, e.g. for running large ensembles stably over long time periods.

While scientific choices differ quite substantially between individual models a more coordinated effort to develop common tools, e.g. libraries or workflows, between GCM model developers and computational scientists is required in the future. This also implies an enhanced level of flexibility with respect to the choice of numerical methods through shared libraries containing calls to highly optimized kernels that serve different applications. Efficiency gains from refactored code run on accelerators can be substantial (Shimokawabe et al. 2010; Lapillonne and Fuhrer, 2014) but require a trade-off between gains and code refactoring and maintenance effort.

In general, code development and maintenance becomes a problem going towards extreme parallelism and heterogeneous machines. A solution could be offered by machine-generated code from a high-level language. This has already been exploited with the finite-element formalism for the solutions of partial differential equations on the sphere (Rognes et al. 2013).

6.7 CONCLUSION

This chapter has reviewed the current state of the research in global weather and climate modelling. The emerging challenge is to take advantage of future computing resources via modern numerical and computational techniques in order to fully exploit the power of exascale-type computer generations. The chapter highlighted the intersections between the physical, mathematical and computational viewpoints, and thereby provides pointers to future high-performance and high-resolution GCM research.

There are many opportunities for GCM modellers, applied mathematicians and computational scientists to come together and foster the progress in the numerical design of atmosphere and ocean models. Examples are the regular “Partial Differential Equations (PDEs) on the Sphere” Workshops (e.g. see Lauritzen et al. 2014c), the bi-annual ECMWF Workshop on High Performance Computing in Meteorology, dedicated workshops and long programs like the 2012 “Isaac Newton Institute Programme on Multiscale Numerics for the Atmosphere and Ocean” or the recent 2015 “Workshop on Galerkin methods with applications in weather and climate forecasting”, as well as special sessions at the American Geophysical Union (AGU) Fall meeting, the European Geosciences Union (EGU) General Assembly and many other conferences like the 2014 World Weather Open Science Conference.

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CHAPTER 7. CHALLENGES CONFRONTING OUR UNDERSTANDING OF THE RELATIONSHIPS BETWEEN CLOUDS, RADIATION, PRECIPITATION AND EARTH'S ENERGY BALANCE

Graeme L. Stephens

Abstract

Cloud-radiative effects and the feedbacks associated with these effects are not anymore considered of second-order for short-term numerical weather prediction. As the lead time of weather forecasts increases, there is time for radiative impacts to accumulate influencing diabatic processes and in turn important dynamical phenomena. The four main science questions posed under the climate sensitivity grand challenges of the World Climate Research Programme are briefly described. It is recognized that an important step for in progress on these climate grand challenges require advances in cloud treatment in weather prediction.

7.1 INTRODUCTION

For short-term numerical weather prediction, cloud-radiative effects and the feedbacks associated with these effects have traditionally been considered of second-order. This topic is now beginning to attract new attention for the following reasons:

(i) First, forecasting with kilometer-scale models highlights importance of local effects and feedbacks such as local-scale radiative forcing at the surface influencing convection and its diurnal cycle.
(ii) As the lead time of ensemble forecasts increases, there is time for radiative impacts to accumulate. A key to predicting weather systems beyond the first few days is an accurate representation of Rossby wave trains and other tropopause- level potential vorticity features. Errors in forecasting these features trace to errors in diabatic processes (e.g. Davies and Didone 2013).
(iii) There is a growing realization that cloud processes play an important role in the development of major storm systems (e.g. Bony et al. 2015) and that the relation of the coupling of the diabatic processes associated with clouds to the larger scale on the short timescale represents the foundation for understanding cloud influences on the longer climate time-scale.

Water and energy intimately couple in the Earth's climate system (e.g. Stevens and Bony, 2013) and it is these couplings that establish the important diabatic processes that shape our weather systems and influence our climate. The purpose of this chapter is to highlight some of the important ways these connections are realized, describe some consequences of them, and the challenges confronting us in developing a quantitative understanding of the relationships that connects one, water, to the other, energy.

These challenges are introduced first in terms of the global energy balance, and then systematically in terms of finer and finer scales of interactions. There are a number of aspects of the global energy balance that are still not well understood and the limitations of our understanding are discussed in Section 7.2. One particular aspect that has received relatively little discussion is introduced in Section 7.3 and concerns the largely unmeasured far-infrared (FIR) emission that contributes significantly to the outgoing longwave radiation (OLR). The energy emitted at these wavelengths is considerable and is a result of the absorption and emission by water in the coldest regions of Earth. This FIR emission is central to important and sensitive climate feedbacks (e.g. Harries et al. 2008).

After highlighting the hemispheric character of the energy balance in Section 7.4, discussion focuses on processes where the science challenges identified under the Clouds, Circulation and Climate Sensitivity Grand Challenge of the World Climate Research Programme (WCRP) are introduced. Discussion about how high clouds might affect convection and precipitation is emphasized there not because the ideas are new but more because this is becoming a recognized area of growing importance. Section 7.6 follows with a discussion on how our view of clouds and precipitation is beginning to change, both with respect to observations and modelling. Joint cloud and precipitation observations are now providing a more integrated view of moist physics and new insights on the precipitation formation process globally. The chapter concludes with discussion of the aerosol influences on clouds and precipitation mostly as a reminder that cloud microphysics will continue to represent areas of great challenge particularly as we move into an era of more fully resolved cloud dynamics in global models.

7.2. CHALLENGES IN UNDERSTANDING AND CLOSING THE EARTH'S ENERGY BALANCE

Earth's climate is determined by the flows (fluxes) of energy into and out of the planet and to and from the Earth's surface. Geographical distributions of these fluxes are particularly important since latitudinal variations in the top of the atmosphere (TOA) fluxes establishes one of the most fundamental aspects of Earth's climate determining how much heat is transported from low latitudes to high latitudes via the Earth's main weather systems and ocean currents.

Despite the fundamental relevance of the energy balance to our understanding of climate and climate change, there remain many challenges in quantifying it globally and in understanding its behaviour regionally. There have been a number of depictions of our global mean energy balance over the past decade (Stevens and Schwartz, 2012, Wild et al. 2013; Trenberth et al. 2009; Stephens et al. 2012). Current depictions of the surface energy balance (e.g. Stephens et al. 2012) indicate that uncertainties attached to our best depiction of the net surface energy balance are an order of magnitude larger than the small imbalance of $0.64\pm0.43Wm^{-2}$ inferred from the ocean heat content (OHC) changes (e.g Llovel et al. 2014). Although the intrinsic uncertainty in TOA fluxes is larger than the inferred OHC imbalance, both Wong et al. (2006) and more recently Loeb et al. (2012) demonstrate that changes to TOA net fluxes generally track the changes in OHC. It is for this reason that the OHC is used as a constraint on the TOA balance measured by Earth-orbiting satellites (e.g. Loeb et al. 2009). The TOA Clouds and the Earth's Radiant Energy System (CERES) fluxes that are adjusted to the OHC are referred to as the Energy balance Adjusted Fluxes (CERES EBAF). No attempt has yet been made to examine the extent that surface energy balance changes also track OHC changes.

At present, the global mean energy balance requires adjustments to our best estimate of the individual fluxes either measured or independently observed. The TOA fluxes are typically adjusted by a few Wm^{-2} to the OHC whereas the surface energy balance requires adjustments to our best-estimate of surface fluxes that are an order of magnitude larger. To date these surface adjustments have been ad hoc following two main philosophical approaches. One introduced by Kiehl and Trenberth (2007) and later by Trenberth et al. (2009) assume the most uncertain flux at the surface is the downward longwave radiation (DLR) and apply adjustments principally to this flux. No error estimates of fluxes are given to support this assumption. A second approach was introduced by Stephens et al. (2012) in which turbulent fluxes of sensible and latent heating are adjusted based on estimated errors on all fluxes given in that study. Trenberth et al. adjust the global-mean downward longwave radiative flux (DLR) by more $10Wm^{-2}$ below our current best estimate of this flux and outside the uncertainty attached to these estimates. Stephens et al. adjust the combined latent and sensible heat fluxes upward by more than $10Wm^{-2}$ increasing the latent heat flux which is outside the range suggested by available information on global precipitation (Behrangi et al. 2014). As there is no compelling evidence to support one approach over the other, two basic questions then follow. What might be the unaccounted for sinks of radiation that could explain why radiant energy incident on the surface is less than our best estimate of these fluxes? Conversely, what might be the sources of enhanced precipitation missing from current data records? Addressing these questions represent one of the main challenges that confronts the climate science community.

Figure 1 is our most current depiction of the annual and global mean energy budget for the first decade of the 21st century based on various datasets that are described in L'Ecuyer et al. (2014)

and combined through an optimal method weighted by uncertainties. Since a different adjustment has been applied to the CERES TOA fluxes than has been applied to produce the CERES EBAF 2.7 fluxes, both sets of TOA fluxes are included offering some sense of the sensitivity of the TOA fluxes to the adjustment process itself. As a result, the net imbalance also differs (0.64 versus 0.45 Wm^{-2}). For similar reasons the CERES EBAF 2.7 surface radiative fluxes (e.g. Kato et al. 2011; 2013) are contrasted against the adjusted fluxes of L'Ecuyer et al. Another set of adjusted surface fluxes is also provided where one of the fluxes (the DLR) is constrained more tightly than is perhaps justifiable to the Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) value that is based on a combination of satellite and surface data (Stackhouse et al. 2011) and is practically identical to the CERES EBAF flux value. Comparison of the values given offers some measure of the sensitivity of the remaining surface fluxes to assumptions about the degree of adjustment to any given fluxes.

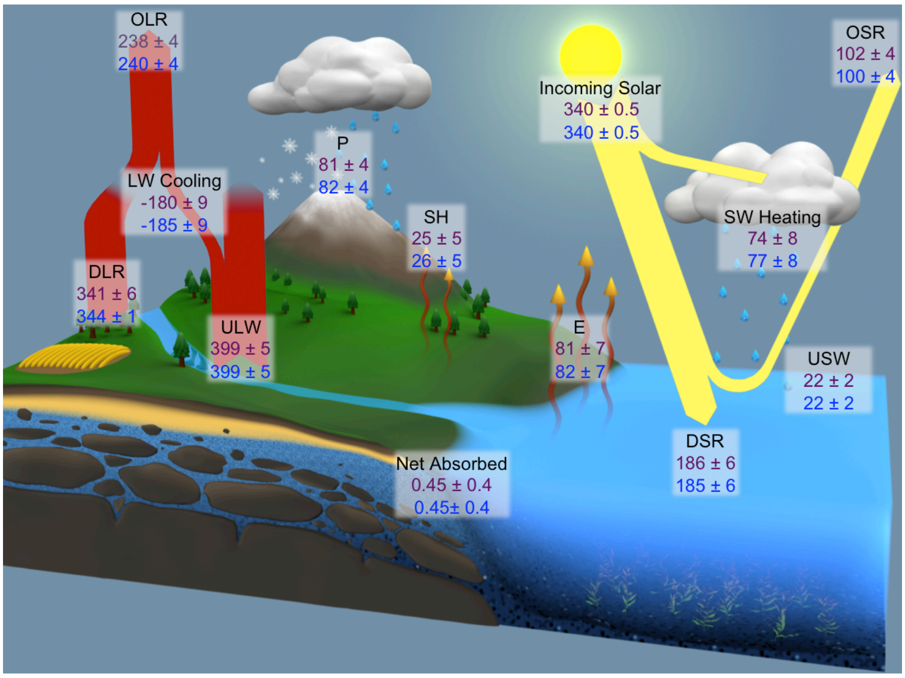

Figure 1. The global and annual mean Earth's energy balance derived from various sources of data that have been optimized to define closure (Stephens and L'Ecuyer, 2015). Two versions of energy balance are provided as an indicator of how the balance can change under different optimization assumptions. All quantities are fluxes in units of Wm^{-2}. The grey numbers are the optimized fluxes after L'Ecuyer et al. 2014. The fluxes in blue are from second optimization where the TOA fluxes are more tightly constrained to the CERES EBAF version 2.7 fluxes that in turn are constrained to independent OHC information. The surface fluxes in blue are also more tightly constrained to the GEWEX surface radiation flux product (note the DLR flux difference between the different estimates). Legend: OSR=outgoing shortwave radiation, OLR=outgoing longwave radiation, DLR=downward longwave radiation, ULR=upward longwave radiation, DSR=downward shortwave radiation, USW =upward shortwave radiation, P=precipitation, E=evaporation/evapotranspiration, S=sensible heat.

7.3 THE CHALLENGE OF THE FAR-IR

While we have broadband observations of the OLR, and spectral OLR measurements with wavelengths less than 15μm, it is remarkable that there are no global observations of a large portion of one of the OLR at wavelengths longer than about 15μm (the FIR, e.g. refer to Harries et al. 2008 for review). Emission at these wavelengths is not directly measured and the knowledge of the properties that shape this emission is scant. This is significant because approximately 49% of the global mean TOA energy emitted to space occurs at FIR wavelengths and this contribution increases to over 60% in polar regions due in part to the shift in the maximum of the blackbody emission to longer wavelengths at colder temperatures. The increased FIR fraction both from the surface to the TOA and poleward underscore the importance of FIR radiative processes in the cold dry regions of the planet typified by high latitudes, regions of elevated topography, and the low-latitude upper troposphere. Critical climate feedbacks play out in these cold, dry regions of the planet and the FIR emission is central to them.

Figure 2 adapted from Turner and Mlawer (2010) offers important context for why better information on the emission in the FIR and the properties that shape this emission is so relevant to understanding connections between energy and water. The figure offers this perspective in the form of three panels. The lower panel (c) is the spectral clear-sky radiative cooling rate of the atmosphere showing how all the radiative cooling of the upper troposphere arises from the emission in the FIR. This cooling in turn is central to our understanding of the connections between water and radiant energy in the upper troposphere and feedbacks related to this connection, such as exemplified in the hypothesized feedbacks between convection and high clouds (e.g. IPCC, 2013 and Section 5 below). The second panel (b) is the total atmospheric column transmission calculated for three different atmospheres and the upper panel (a) is an expanded view of the far-IR portion of this transmission. The transmissions of the three atmospheres in this example are characterized by the values of 0.2,1.5 and 15 mm of column water, characteristic of extremely dry wintertime polar, polar and mid-latitude column water vapour contents. This transmission information emphasizes how FIR contributions become more dominant in cold, dry regions of the planet such as in polar regions, high elevation regions and in the low latitude upper troposphere as emphasized.

The absorption-emission of the atmosphere under dry conditions is governed by FIR continuum absorption about which little is also known (e.g. Tobin et al. 1999). No global data exist to test how the FIR transmittance changes over the ranges of humidity that are observed globally as in Figure 2. Furthermore there are very few measurements of the radiative properties of high clouds in the FIR, and the measurements that do exist are limited to a few aircraft flights over thin cirrus (Cox et al. 2010). Thus to represent these important radiative processes in models, we are typically left to resort to extrapolation of properties from the mid-IR region which is problematic (e.g. Feldman et al. 2014).

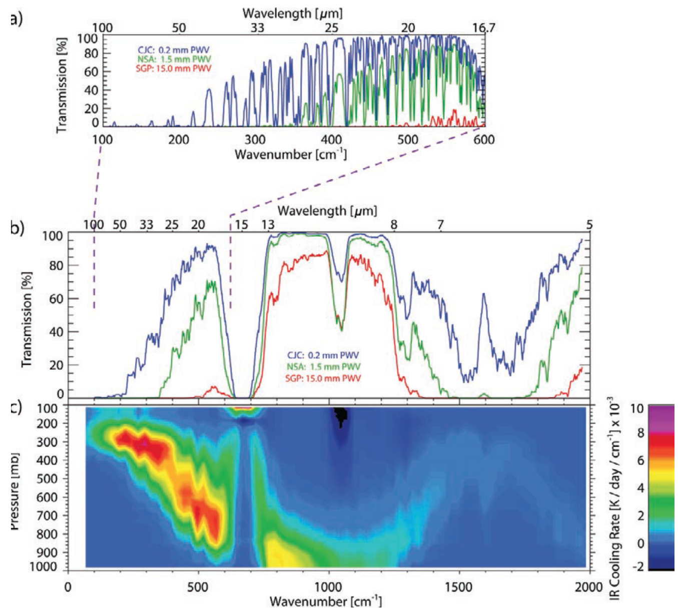

Figure 2. (a) A fine resolution depiction of the FIR spectral transmission for three different column water vapour (CWV) values, (b) The coarse-band depiction of the IR transmission of an atmospheric column, (c) The spectral IR radiative cooling rate as a function of altitude. The relation between the spectral OLR and changing amounts of water vapour in different climate regimes is essential to understanding important feedbacks that are determined by radiation-water processes.

Source: Turner and Mlawer, 2010

7.4 THE MYSTERY OF THE HEMISPHERIC BALANCE

A remarkable and as yet not fully understood aspect of the Earth's energy balance is the hemispheric symmetry it portrays. The symmetry in hemispheric reflected flux and albedo has in fact been noted since the time of the early satellite observations (VonderHaar and Suomi, 1969) and is discussed further in recent studies of Voigt et al. (2013). Broader aspects of the symmetry are discussed in Stevens and Schwartz (2012) and further in Stephens and L'Ecuyer (2015) and Loeb et al. (2015). The nature of this symmetry such as it occurs in current observations is summarized in Figure 3 (taken from Stephens and L'Ecuyer, 2015). Figure 4a is also adapted from Stephens et al. (2015) and shows the NH-SH differences in just one component of the TOA r[energy balance, the reflected flux and the contributions of this reflected flux by atmospheric scattering processes and surface reflection processes for both all-sky and clear sky fluxes. The details of how these component contributions are determined are introduced by Donohoe et al. (2011) and reviewed in Stephens et al. (2015). It is remarkable that the larger surface reflection of the NH is precisely offset by the increased scattering from the SH atmosphere. The latter is a consequence of the greater amounts of cloudiness that exist in the SH, an inference supported by the hemispheric differences of cloud amount taken from 4 years of CloudSat- Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar/radar data (Mace et al. 2009).

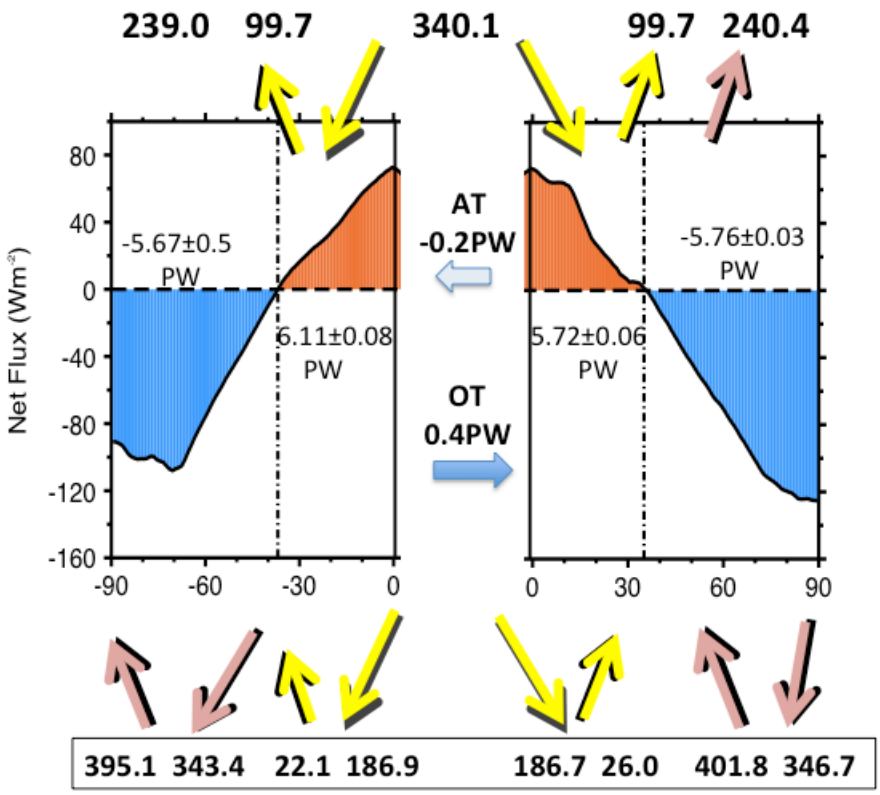

Figure 3. The annual-hemispheric mean energy balance of Earth. Unless specified otherwise, all TOA and surface numbers are in Wm^{-2}. Fluxes of sunlight entering and leaving the TOA and surface are in yellow and infrared fluxes are red (Stephens and L'Ecuyer, 2015). Our best estimate of the cross equatorial heat transport by atmosphere (AT) and oceans in PW (OT) are also given.

A similar analysis is presented for the OLR and shown in Figure 4b. This figure presents the NH-SH OLR difference for all sky, clear sky and the longwave cloud radiative effect (CRE). A larger clear sky OLR from the NH is a consequence of the warmer NH compared to the SH but the clear-sky emission differences are offset by a larger NH CRE due to fact that on average clouds are both higher and thus colder in the NH compared to the SH (e.g. Kang et al. 2014). This interpretation of the hemispheric difference in CRE is again supported by the hemispheric differences in cloud top height obtained from CloudSat/CALIPSO observations. These observations show the NH clouds to be over 1 km higher than SH clouds.

The results of Figure 4 show how the near hemispheric symmetry in TOA energy balance as depicted in Figure 3 is established by hemispheric differences in cloud properties that work to reduce the asymmetries that are apparent in surface and clear-sky fluxes. The fundamental importance of this cloud regulation of the energy balance between hemispheres to our understanding of the climate system is not fully known but we can infer that is its likely to be important when contemplating the heat transported from low latitudes to high latitudes. The degree to which the hemispheres are symmetric or not fundamentally dictates how much heat and moisture is transported across the equator from one hemisphere to another. Current climate models do not reproduce the degree of symmetry observed. Although the differences with the observed hemispheric fluxes are a few Wm^{-2} (Stephens et al. 2015) the recent study of Haywood et al. (2015) show dramatic sensitivity of the monsoonal precipitation of one model from a series of climate model experiments where symmetry in reflected sunlight is imposed.

Energy-based explanations for the movement and position of the Inter Tropical Convergence Zone (ITCZ) have come to the fore offering important insights on the relation between these convergence regions and planetary energetics and how processes at higher latitudes influence these zones (e.g. Frierson and Hwang, 2012; Frierson et al. 2013; Kang et al. 2008. Bischoff and Schneider, 2014; Voigt et al. 2013). Schneider et al. (2014) offer a review of these studies and illustrate how an energy-based theory for the position and movement of the ITCZ can be supported with observations such that the mean position of the ITCZ in the NH is linked to the atmospheric energy transport, which is directed from the warmer northern hemisphere into the cooler southern hemisphere and the ocean transport northward primarily by the Atlantic's meridional overturning circulation (AMOC) that transports energy northward, up the mean temperature gradient. The resulting net northward transport across the equator amounts to 0.4 PW in the zonal mean (Figure 3; also Marshall et al. 2013). Some of this ocean energy transport across the equator is compensated by the southward (down-gradient) atmospheric energy transport, primarily accomplished by a Hadley cell with ascending branch and ITCZ north of the equator.

The global mean position of the ITCZ also shifts on geological timescales (e.g. Haug et al. 2004) with the tendency to shift to the differentially warmed hemisphere and away from the cooled hemisphere (e.g. Chiang and Friedman, 2012). This general pattern of shift has also been reproduced in modelling studies (e.g. Broccoli et al. 2006). An indication of these shifts over the past 100 years is provided in Figure 5 taken from Schneider et al. (2014). It shows a centennial time series of the change of the NH minus SH temperature anomaly of the extra-tropics (poleward of 24 degrees latitude) versus the anomaly in Sahel precipitation (see caption). This figure shows how the precipitation of the Sahel moves southward as the NH-SH temperature differences decreases, i.e. as the SH warms relative to the NH.

Stephens and L'Ecuyer (2015) revisited the analysis of Riehl and Simpson (1979) and similarly argue that the climatological mean position of the ITCZ is largely determined by planetary energetics. They suggest, however, the hemispheric differences in seasonal solar insolation is the determining factor in setting the NH climatological position of the ITCZ. The SH winter season experiences significantly more energy loss than the corresponding NH winter owing to comparative decreased incident solar radiation on the winter SH. This differentially cooled SH compared to the winter NH requires greater amounts of heat transported from the NH toward the SH winter pole thus setting the region of low level atmospheric convergence, the tropical trough zone as referred to by Riehl and Simpson, northward. This explanation for the current NH position of the ITCZ due to seasonal insolation changes is consistent with the paleo-climate evidence for shifts in the ITCZ away from the differentially cooled hemisphere to the differentially warmed hemisphere.

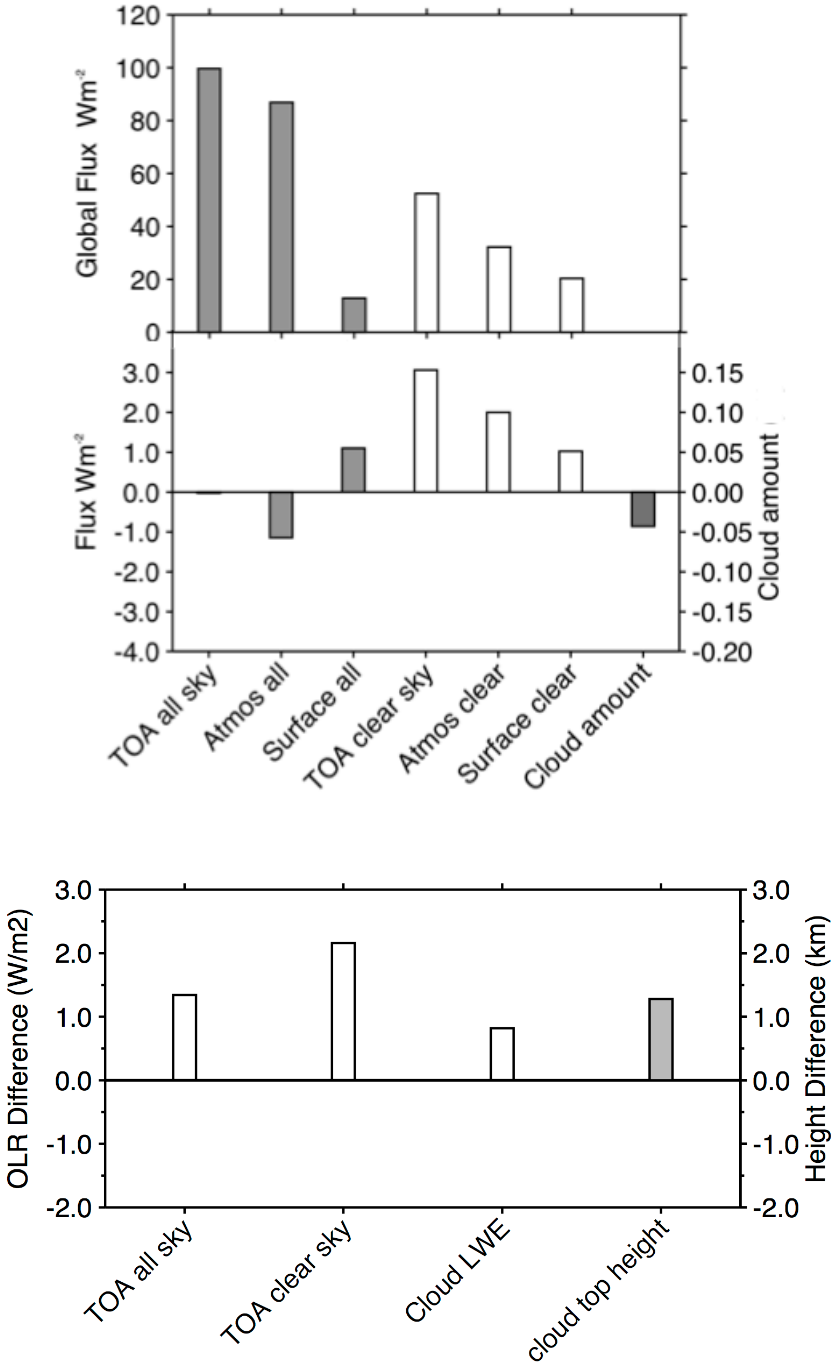

Figure 4a. (upper) The all-sky and clear-sky global, annual mean reflected fluxes (upper) separated into the two main components. The lower panel of (a) shows the difference between hemispheric annual mean all and clear-sky reflected fluxes and the individual components that comprise these fluxes. These hemispheric differences are defined as the NH minus SH and the all-sky difference is 0.05Wm^{-2}. Also presented for reference is the hemispheric difference in cloud amount (expressed in absolute units). (b) The NH-SH difference in clear sky and all sky OLR (in Wm^{-2}). The NH being warmer emits more radiation than the SH but this is compensated for by less emission from clouds as indicated by the positive NH-SH difference in cloud longwave effect (Cloud LWE). The NH-SH difference in hemispheric mean cloud top height (in km) based on 4 years of CloudSat-CALIPSO data is also shown for reference

Source: adapted from Stephens et al. 2015; Stephens and L'Ecuyer, 2015

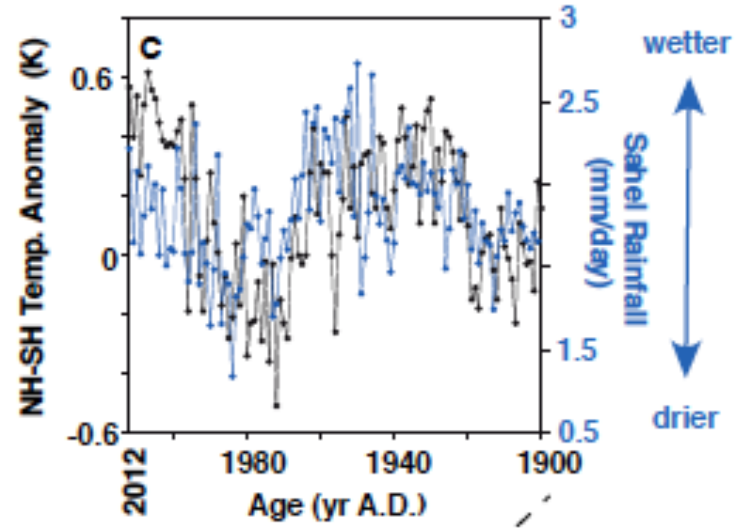

Figure 5. Temperature contrast between northern and southern hemisphere extra-tropics (poleward of 24°N/S) based on instrumental data (black), and average daily rainfall over the Sahel (12°-18°N, 20°W-35°E) during June-October based on land station data (blue). All temperatures and temperature contrasts are given as anomalies relative to the 1960-91 annual mean.

Source: adapted from Schneider et al. 2014

7.5 CHALLENGES IN UNDERSTANDING CLOUDS, RADIATION AND PRECIPITATION FEEDBACKS

So far the discussion has been broadly based centring on the topic of planetary energetics. As we move from this broad energy perspective to one with a focus on the water cycle we need consider how one, energy, connects to the other, water. On the global scale, the relation between global precipitation and the global energy balance has been discussed extensively (e.g. Allen and Ingram, 2002; Wild and Liepert, 2010; O'Gorman et al. 2012, Stephens and Hu, 2010; among others). As the planet warms, the resulting increase in global precipitation is controlled by the changes to the emission from the atmosphere that results when the atmosphere is warmed and moistened. More fundamental though are the processes that build these connections. These processes are the focus of the Clouds, Circulation and Climate Sensitivity Grand Challenge of the World Climate Research Programme as described in Bony et al. (2015). That Grand Challenge is constructed around four basic questions:

What controls the position, strength and variability of storm tracks? Although considerable progress has been made recently on understanding the interaction between diabatic processes and extratropical weather systems such as extratropical cyclones and upper-level Rossby wave trains (see Chapter 5) , the roles of the large-scale coupling of clouds with storm tracks on longer timescales is only now beginning to be appreciated. Approximately half of the poleward transport of energy within storm tracks is accomplished by latent heating, meaning moisture is vital in setting the temperature gradients upon which storms grow. It is now clear that as the clouds embedded within the storm tracks shift, there are systematic implications or the radiation budget and its influence on the temperature gradients that give rise to the storms in the first place (e.g. Grise et al. 2014; Ceppi et al. 2014).

What controls the position, strength and variability of the tropical rain belts? A number of papers have recently addressed this question exploring interactions on various scales. Mesoscale convective circulations appear to influence the poleward extent of the monsoon in ways that are just starting to be understood, and planetary scale circulations connect the rain belts to processes in distant extra-tropical locations. Newly developed energetic frameworks have proven to be a useful way to understand these connections as discussed above.

What role does convection play in cloud feedbacks? Convection influences so much of the climate system. Deep convection produces the many of high clouds of the tropics, and is a main source of upper tropospheric moisture, both with significant effects on climate energetics and the hydrological cycle. Feedbacks established by the connections between high clouds and convection have long been thought to be important. Feedbacks involving height changes to high clouds detrained from deep convection that rises higher in a warmed climate has received more attention under the so-called "fixed anvil-temperature" mechanism (Hartmann and Larson, 2002) and variants on this idea (e.g. Zelinka et al. 2011). A positive cloud altitude feedback results because the temperature difference between the cloud and the surface increases, increasing the cloud's greenhouse effect without necessarily affecting its albedo. However there is more to this feedback than has been generally considered. Changing the heating of the upper troposphere by high clouds, largely a function of this cloud-to-surface temperature difference, provides a feedback on convection. A number of papers have hinted at the importance of radiation as an organizing influence in radiative-convective feedbacks (e.g Tompkins and Craig, 1998a) and a few mechanisms have been hypothesized as important to such feedbacks. In addition to the general and understood control of convection by large-scale radiative cooling (e.g Dudhia, 1989), three of the more commonly discussed mechanisms deal with radiative effects of high clouds on convection. These mechanisms are: (i) Destabilization of cloud layers by intense cloud top cooling (Webster and Stephens, 1980; Tao et al. 1996; Xu and Randall, 1995); (ii) Secondary circulations forced by differential horizontal radiative heating between cloudy and clear regions (Gray and Jacobson, 1977; also Mapes, 2002 and Sherwood, 1999); and (iii) the stabilizing effects of upper tropospheric radiative heating by cirrus detrained from convection (Stephens et al. 2003, Fu et al. 1995; Lebsock et al. 2009 and Stephens et al. 2008). In a series of radiative convective equilibrium experiments, Stephens et al. (2008) demonstrate how mechanisms (ii) and (iii) operate together to regulate convection, organize it and fundamentally govern the state of Radiative Convective Equilibrium (RCE) reached in the experiments reported.

What role does convective aggregation play in climate? The propensity of convection to aggregate and organize into larger entities has long been though important. In the tropics, the Madden Julian Oscillation and monsoonal storm systems are an aggregate of convective processes organized into mesoscale convective systems (MCS's) that cluster into a large-scale envelope of storm activity. MCS's are also a major mode of storminess over mid-latitude regions producing much of the severe weather over continental USA including tornadoes and hail in spring [Maddox et al. 1986; Houze et al.1990; Tollerud and Collander, 1993]and 30 to 70% of the warm season (growing season) rainfall (Fritsch et al. [1986]). While the role of MCS's on short timescales is clear, their role in reducing medium-to-extended range predictability and in the climate system is much less clear and less well understood.

The four questions posed above present an ideal opportunity for collaboration between scientists working from a climate and a weather perspective. In particular, the expertise in WWRP on the impact of diabatic processes associated with clouds, precipitation and radiation on atmospheric dynamics is essential to understand the interaction between clouds and circulation on timescales of days to months.

7.6 THE OBSERVED JOINT CHARACTER OF CLOUDS AND PRECIPITATION

One of the main challenges confronting progress on the questions posed above lies in the need develop suitable observational diagnostics to test hypotheses and build understanding. In the case of precipitation falling weather systems, it would appear trivial to suggest that a necessary step toward the successful modelling of precipitation requires realistic treatment of clouds. However, much of the observing system strategy of the past has been based on the artificial practice of observing and analyzing clouds and precipitation as separate entities. Even traditional approaches to the parameterization of convective precipitation have typically had little connection to cloud physics. This situation is changing as has been noted, both with respect to observations and modelling. Convective permitting global models now couple convection to cloud physics explicitly, and with the emergence of observations from the A-Train (Stephens et al. 2002), the opportunity to develop a more unified approach to observing both clouds and precipitation properties jointly has now emerged. This more integrated view of moist physics is beginning to offer new insights on the precipitation formation process. Here just a small sample of this progress is presented and much more is still to be done.

7.6.1 Cloud-precipitation macroscopic structures

Masunaga et al. (2005) were perhaps the first to provide a joint histogram analysis of observations of (convective) clouds and precipitation. They used the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) echo-top height and Visible and Infrared Scanner (VIRS) infrared brightness temperature as a proxy of precipitation top height (PTH) and cloud top height (CTH), respectively. This analysis was subsequently used to tune the microphysics of the NICAM global cloud model (Satoh et al. 2008). Another way to derive CTH and PTH information was devised by Stephens and Wood [2007], who defined two echo-top heights with different dBZ thresholds applied to 94-GHz radar reflectivity. Following these studies, Masunaga et al. (2008) developed joint histograms of CTH and PTH constructed individually from both TRMM and CloudSat observations as well as the corresponding parameters synthesized from the NICAM global cloud resolving model. An example of their analysis, applied to the wet and dry phases of the MJO, is provided in Figure 6. Panels a and b of this figure highlights basic differences in the cloud-precipitation structures of the MJO wet phase and dry phases. The wet phase of the MJO is characterized by cold cloud tops (or high CTHs) with high PR echo tops, while shallow cumulus dominates in the dry phase. The CloudSat CPR histogram (panels c and d) shows prevailing high clouds near the tropopause and an increase in shallow cloud population from the wet phase to the dry phase is also evident. A majority of histogram peaks fall in the upper triangle away from the diagonal line, indicative of a significant gap between CTH and PTH, particularly where PTH is higher than the freezing level. The portions with CTH>PTH can be attributed either to the absence of large ice particles detectable by the PR Cloud Profiling Radar (CPR) above the 19-dBZ (10-dBZ) threshold or mid-level clouds such as cumulus congestus overlapped with cirrus clouds (Stephens and Wood, 2007). In the synthesized 14-GHz histogram from the NICAM experiment (panels e and f), the TRMM observation is reasonably reproduced except for the over-production of very high PTHs (10 km or higher).

Figure 7 is another example of how cloud observations and precipitation might be jointly put together. The figure is drawn from CloudSat observations and shows the fraction of both the total amount of precipitation falling in the defined latitude regions as a function of cloud top height and the fractions falling within the indicated ranges of precipitation rate. The data are a composite of 2008 data of CloudSat and CALIPSO where the cloud top height comes from the CloudSat 2B-GEOPROF-lidar product (Mace et al. 2009) and the precipitation information is from the 2C-PRECIP-PROFILE product (Lebsock and L'Ecuyer, 2011). Representation of cloud information on one axis, versus precipitation on the other, as in this example, with insight into the structure of precipitating cloud systems and hints for how these systems might heat the atmospheric vertical column. The figure highlights statistics for two problematic regions of the planet. One panel of Figure 8 shows the cloud top structures of tropical precipitation and the other two panels express seasonal relationships for southern ocean cloud systems. Also included in these figures as insets are the cumulative fractions of total precipitation as a function of cloud-top height.

While a number of obvious and expected features emerge from these figures, such as the heavier precipitation typically falls from deeper clouds in the tropics, there are also aspects of the clouds that are less expected. For example, significant amounts of the precipitation for all three cases come from clouds with tops below 8 km.

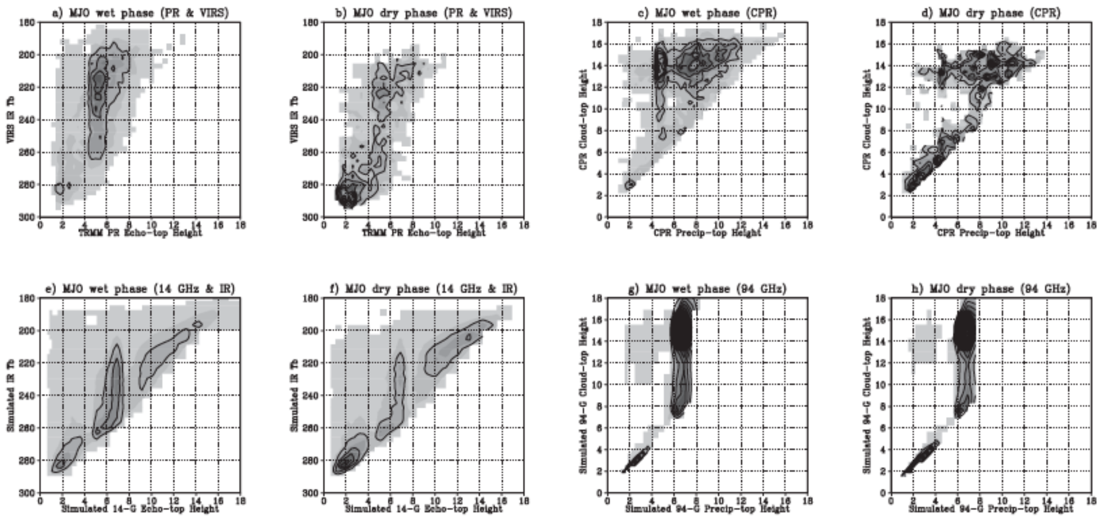

Figure 6. Joint histograms of precipitation top height (PTH, abscissa) and cloud top height (CTH, ordinate): a) TRMM PR and VIRS histogram for the MJO wet phase, b) Same as (a) but for the MJO dry phase, c) Same as (a) but CloudSat CPR histogram, d) Same as (b) but CloudSat CPR histogram, e)-h) Same as (a)-(d) but synthesized from the NICAM simulation. The histograms are shaded and contoured in linear spacing.

Source: Masunaga et al. 2008

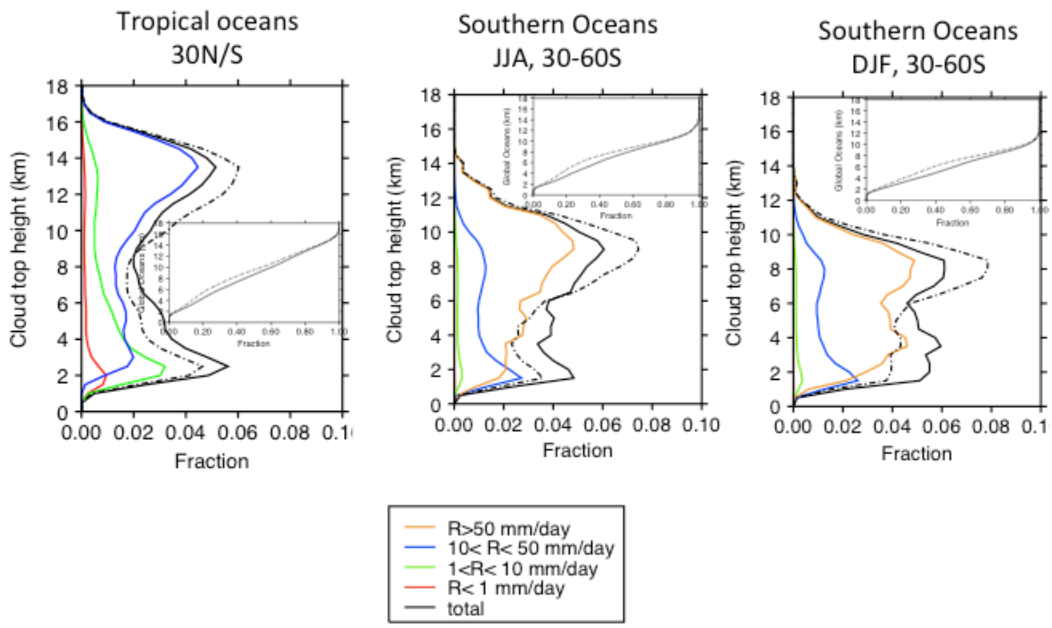

Figure 7. The fraction of oceanic precipitation as a function of cloud top height presented for different precipitation thresholds. The total fractional precipitation is shown as a function of two different measures of cloud-top height. The solid applies to the highest cloud top height detected and the dashed to the lowest loud top height from which precipitation falls. The difference is an indication of the presence of multiple layered clouds.

7.6.2 Microphysical properties

While Figures 6 and 7 provide some indication of the macrophysical structures of precipitating cloud systems, and much is still to be learned from these sorts of analyses, more explicit and quantitative information about specific rain formation processes has been abstracted from combinations of observations from the sensors of the A-Train constellation of satellites. In a series of papers, Suzuki et al. (2008,2015) introduce a novel way of relating the density of occurrence of vertical profiles of radar reflectivity (Z_e) re-scaled as a function of in-cloud optical depth (ICOD) in the form of the contoured frequency by optical depth diagram (CFODD) as shown in Figure 9. It can be shown that this analysis reveals explicit information about the collection processes that produce warm rain. CloudSat data composited into the 2-dimensional CFODD format reveals the formation of warm rain which can be classified according to cloud-top effective particle radius. Figure 8 presents such an analysis of data binned for droplet radii of 5-10µm, 10-15µm, and 15-20µm deduced from the Moderate Resolution Imaging Spectroradiometer (MODIS) reflectance data (Figures 8a-c). This reveals how precipitation progresses as particle size increases with the coalescence process becoming increasingly more efficient as particle size increases. Four different representations of the auto-conversion process are also cast into the CFODD format in Figures 8d-g. These simulations reveal how methods (the Tripoli-Cotton and Berry methods) depart greatly from the observations, with drizzle forming even for clouds composed of droplets in the smallest particle range considered. This sort of analysis provides a powerful and unique way of constraining processes that are parameterized in models and that have not been testable before the availability of these observations.

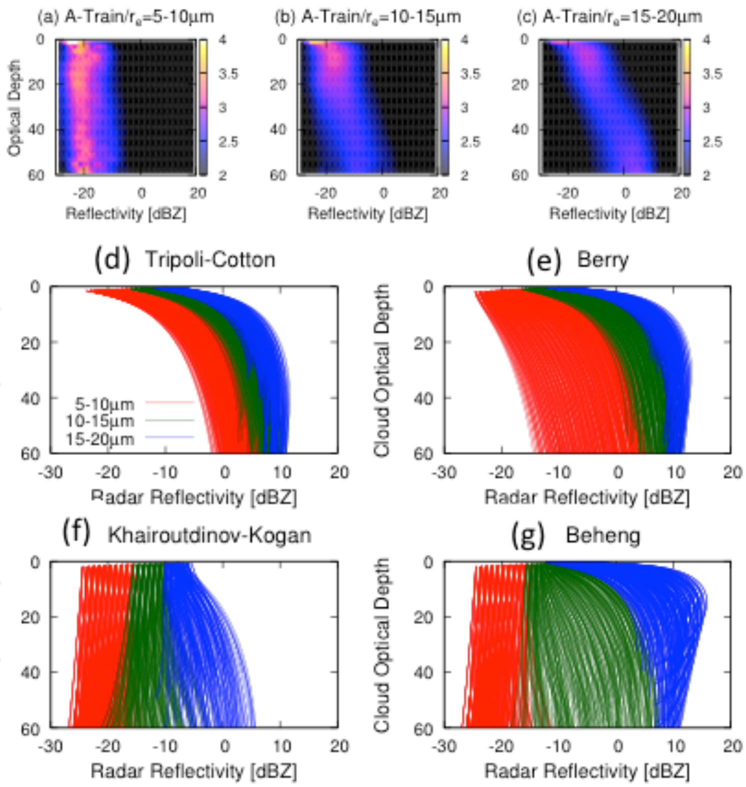

Figure 8 (a)-(c). A-Train-based CFODD representation of CloudSat and MODIS data grouped by 3 different ranges of MODIS effective radius. Evidence of drizzle appears in the 10-15 μ m radius range at bottom of clouds as indicated by reflectivities > -10 dBZ. Figure 8 (d)-(g) CFODDs derived from a steady-state solution to the single-column cloud model with 4 different auto-conversion schemes typical of those used in model parameterizations. This is a clear example of how the data are being used to evaluate specific components of operational models and identify which schemes are more realistic Suzuki et al. 2014).

7.7 CHALLENGES OF MICROPHYSICS AND AEROSOL EFFECTS ON MOIST PHYSICS

The influence of the microphysical properties of clouds looms large in importance especially with global models now beginning to resolve the bulk movement of water on meso- and cloud-scales. Much has been written on the importance of microphysics via the topic of aerosol indirect effects and the more this topic is examined the more we are left to conclude aerosol influences in clouds are highly buffered (e.g. Feingold and Stevens, 2009). When the early ideas of these aerosol effects were first proposed by Twomey (1976) for warm clouds, he had not lost sight of the fundamental role of the macroscopic water budget of clouds in understanding the net effects of aerosol on cloud albedo. While the importance of this budget is inherent to concepts such as the so-called second indirect effect with aerosol affecting water content via influences on drizzle and cloud lifetimes (Albrecht, 1989), much of the focus has been fixated primarily on the microphysical changes of clouds and the importance of the water budget has mostly been overlooked. Early representations of these indirect effects in models, for example, were based on a simple direct inverse relationship between cloud particle size and aerosol (e.g. Boucher and Lohmann, 1995) with the result that the strength of indirect effects has been grossly overestimated.

There is a vast amount of literature on indirect effects, mostly focusing on low clouds (e.g. IPCC, 2013). Study of ship tracks, a natural analogue to study these indirect effects, serves to remind us of the fundamental role of clouds macrophysics in determining indirect effects and how these macroscopic effects buffer the more direct microphysical changes. Figure 9 highlights this point showing a distinct relationship between the changes in cloud albedo of ship tracks as a function of change in water path. These data are from a catalogue of low cloud ship tracks sampled by the A-Train as described in Christensen and Stephens (2011). In all ship tracks sampled, the cloud particle size was reduced as indicated by the inset histogram diagram, yet contrary to the gross way these effects are parameterized, the albedo did not always increase. In about 30% of the cases examined the ship tracks were darker than the surrounding cloud and the so-called Twomey effect, which implies negligible change in cloud water, occurred in only about 30% of cases (Chen et al. 2013). Chen et al. (2014) further extended this analysis globally and demonstrated how the free troposphere humidity, a factor that influences the water budget through dry air entrainment, is an important factor in determining the net response of marine clouds aerosol through its influence on the cloud water path. These effects resulted in a greatly reduced estimate of the global indirect radiative forcing of low clouds.

It is possible that aerosol effects on clouds might be more important to other types of clouds and other processes than to the marine boundary layer clouds and cloud albedo. Christensen et al. (2014) for example provide the first observational study of ship tracks in mixed phased clouds and found that adding yet more degrees of freedom by which clouds can adjust to aerosol perturbations dilutes aerosol effects even further. More recent emphasis has been placed on possible aerosol effects on precipitation and convection, both from modelling and (e.g. Seifert et al. 2012) and observational perspectives and has been reviewed by Tao et al. (2012). Several studies (Andreae et al. 2004; Khain et al. 2005; Koren et al. 2005; van den Heever et al. 2006; van den Heever and Cotton, 2007; Lee et al. 2008; Rosenfeld et al. 2008; Lebo and Seinfeld, 2011; van den Heever et al. 2011; Storer and van den Heever, 2013) all suggest that increased aerosol concentrations lead to the invigoration of deep convective storms but the issue is far from settled. It is generally established that in a polluted environment, or one which contains higher concentrations of aerosols that can act as cloud condensation nuclei (CCN), collision and coalescence in deep convective systems will be less effective due to the increased numbers of smaller cloud droplets, thus leading to a reduction in warm rain production. This leaves higher amounts of water in cloud that can be lofted to form ice, providing an additional source of latent heating that increases the buoyancy of an updraft. These changes are hypothesized to lead to stronger storms with higher cloud tops, more ice, and heavier surface precipitation. There is still no clear consensus on this effect, as summarized in Tao et al. (2012) with contrasting conclusions drawn from modelling and observational evidence for such intensification is scant (e.g. Storer et al. 2013).

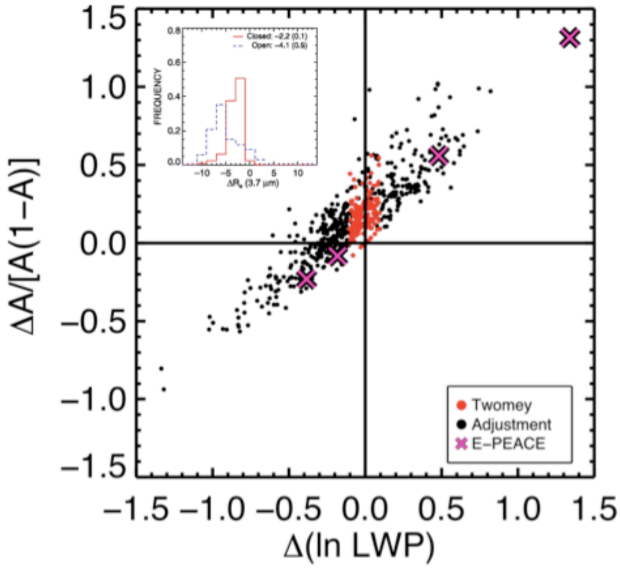

Figure 9. A clear example that emphasizes how the albedo of low clouds is highly buffered though processes that govern the water balance of clouds. The proportional change in the albedo of ship track portions of clouds contrasted against nearby clouds versus the change in liquid water path of the ship tracks. These data are from compilations of ship tracks observed by A-Train data as reported by Christensen and Stephens, 2011. The regime of the Twomey effect is noted in red and data from an airborne ship-track campaign (E-PEACE) are also noted. The inset shows the cloud particle size decreases for all ship tracks regardless of how the data are binned (modified from Chen et al. 2012).

7.8 CLOSING COMMENTS

This chapter attempts to highlight some of the challenges, and thus opportunities, that confront us in understanding how radiation, clouds and precipitation link together to shape our planet's water cycle and energy balance. The chapter focuses on the important ways water and energy connect, describe some consequences of them, and the challenges confronting us in developing a quantitative understanding of the relationships that connects one to the other.

Unmet challenges are introduced first in terms of the global energy balance, and then systematically in terms of finer and finer scales of interactions ending with a discussion of cloud microphysical influences within the context of cloud-aerosol interactions. The four main science questions posed under the climate sensitivity grand challenges of the WCRP are briefly described. Since we know long-term climate model biases typically develop from short term errors in weather-related processes that involve clouds and convection, an important step for in progress on these climate grand challenges require advances in cloud treatment in weather prediction.

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CHAPTER 8. LAND-ATMOSPHERE INTERACTIONS AND THE WATER CYCLE

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Abstract

The land surface and the atmosphere are interactive through the global water cycle and can act in tandem to modulate the severity of extreme events both on the dry and wet end of the scale. The societal impacts of extreme events, such as droughts and floods, motivate considerable attention to understand the mechanisms that control land-atmosphere interactions at local to continental scales. Land surface processes can influence weather and climate, in addition to the partitioning and distribution of water for agriculture, industry, and nature. This paper aims to review some of the recent advances in representing land-atmosphere coupling in Earth system models used for weather and climate prediction.

8.1 INTRODUCTION

The land and atmosphere are intimately linked through exchanges of water via precipitation and evaporation, and via the energetic, thermodynamic, dynamic and hydrologic processes associated with those water exchanges. The upward branch of the feedback loop from land to atmosphere is relevant to weather and sub-seasonal timescales as a pathway for predictability and prediction skill arising from the slowly-varying surface (Figure 1). This pathway is in effect when three characteristics are present. Each is a necessary condition, but only when all three are present is there a sufficient and complete linkage from the land surface back up to the atmosphere. These characteristics are coupling, variability and memory. They are also in effect for the downward side of the loop, and are far less subtle in their manifestation, where they are highly relevant for weather and climate impacts on surface and subsurface hydrology. However, the focus here is on the feedback from land to atmosphere, which affects predictability and prediction for meteorology, hydrology, and many other concerns. The schematic representation of the hydrological cycle in Figure 1 indicates the many pathways by which the land surface receives and redistributes water to the atmosphere the deep soil and the oceans.

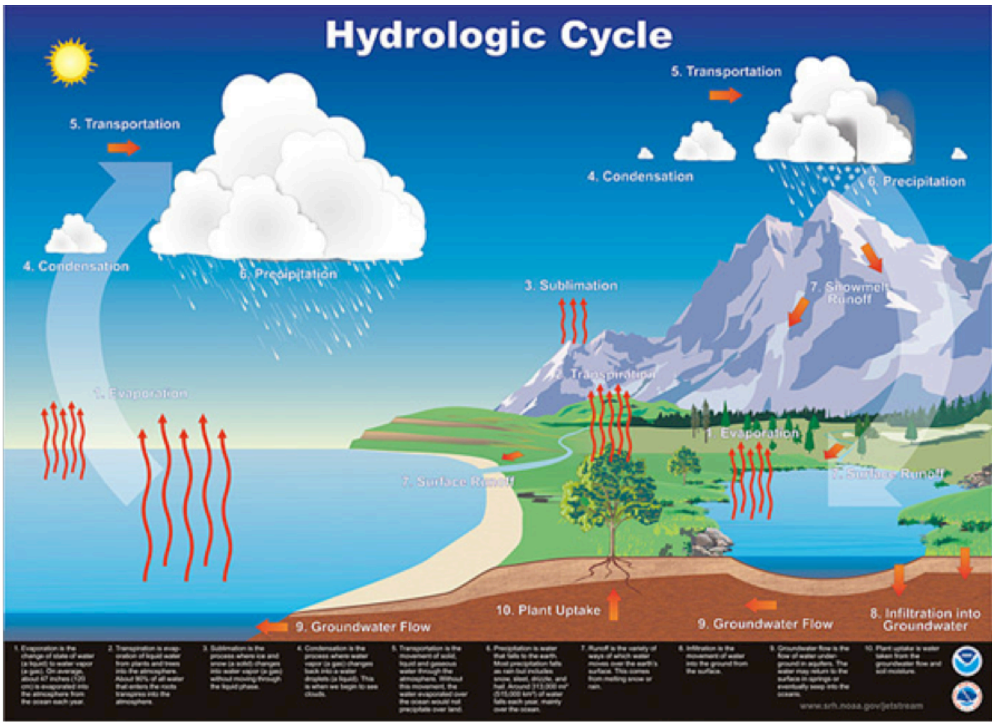

Figure 1. Schematic of the water cycle *(Source:* NOAA)

Enhanced weather and climate predictability can arise because the land surface states vary more slowly than do the atmospheric states. This slow manifold has some effect on the weather time-scales, but appear to peak in the range of one to several weeks, indicated schematically in Figure 2. This time scale is significant because it lies between the deterministic time scales of classical weather forecasting, and the fully probabilistic seasonal scales where ocean states (particularly the tropical oceans) can have global impacts. Thus, the land surface holds promise as a source of predictability and prediction skill in the gap between traditional weather and climate time scales.

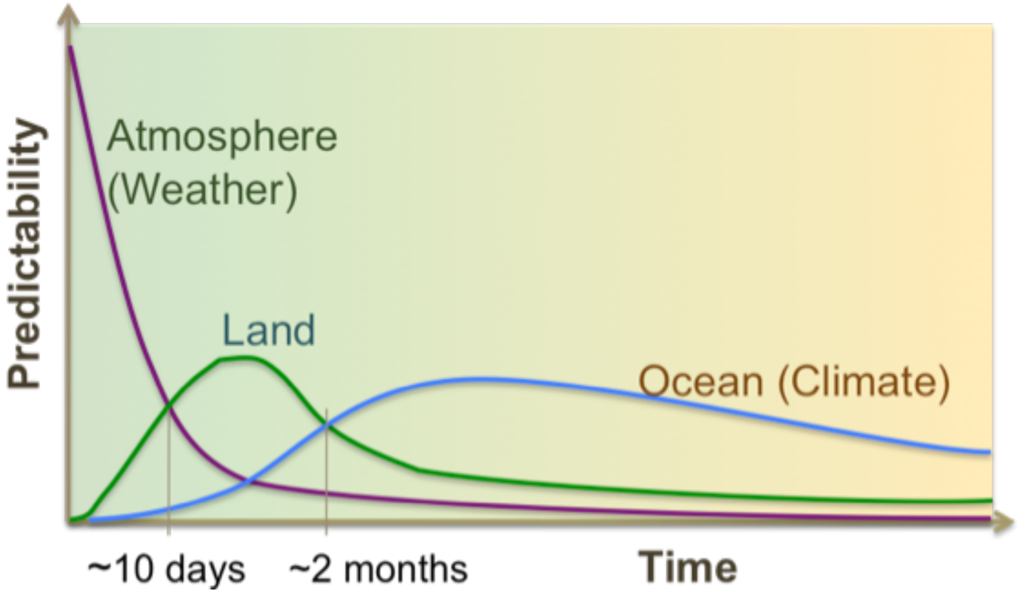

Figure 2. Schematic of the time scales associated with predictability originating from the initial states of atmosphere, land and ocean

It should be evident that this feedback is a coupled process between land and atmosphere. Thus theoretical, observational and modelling studies of land-atmosphere interactions must necessarily be conducted in a coupled land-atmosphere framework. Furthermore, the water cycle is intimately connected to the energy cycle (via the correspondence between latent heat flux and evapotranspiration) and the carbon cycle (through the vegetative controls on transpiration and carbon uptake through the process of photosynthesis). Process-level investigations often lead one into these related areas.

Below we describe coupling, variability, and memory as sub-themes to the main theme of "Land-Atmosphere Interactions and the Water Cycle", with particular focus on their representation in Earth system models and their various components.

8.2 COUPLING

The characteristic of coupling between land and atmosphere implies the existence of a significant correlation between land states and surface fluxes, as well as between surface fluxes and atmospheric properties and processes. Furthermore, to be meaningful such correlations must exist for a phenomenological reason - a process by which the lower state or flux affects the next level above. For example, over many locations significant correlations exist between soil moisture anomalies and latent heat flux anomalies. A positive correlation occurs in a moisture-limited situation, where the availability of soil moisture is a controlling factor for evaporation. In such situations, actual evaporation rates are well below the potential evaporation rate. There may also exist significant negative correlations (anti-correlations) between soil moisture anomalies and latent heat flux anomalies where the environment is energy limited. In those locations, moisture is plentiful and evaporation rates are near the potential rate. When net radiation is large, evaporation increases and soil moisture is drawn down; when net radiation is small the opposite occurs. In this situation, the land surface state does not control the flux, but rather the flux controls the soil moisture level, and the feedback loop is broken.

Feedbacks from land to atmosphere are quantifiable on a range of scales, but it can be argued that all feedback originates within the diurnal cycle, which serves as a gateway to process-level understanding of coupled system behaviour. Therefore, the diurnal cycle is a handy domain on which to understand land-atmosphere coupling.

Furthermore, all coupling begins locally - if the evolution of vertical exchanges and interactions between land and atmosphere within the diurnal cycle are not properly represented in models, then effects at larger space and time scales will suffer. The “Dooge rosette” shown in Figure 3 (Dooge, 1992) proposes a simple mechanism to characterize the soil-atmosphere control in water exchange depending on the water content in each reservoir and the active processes.

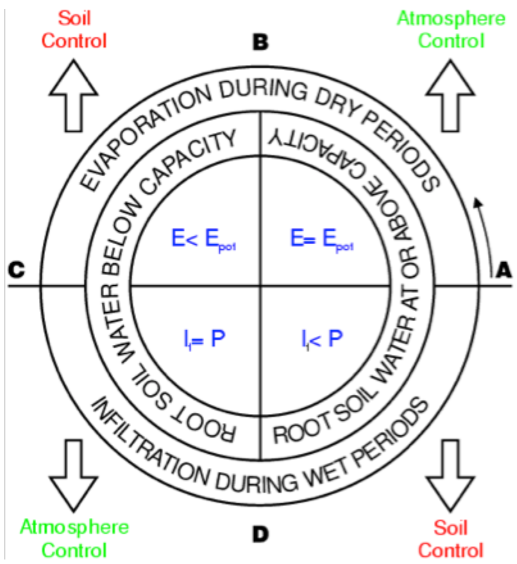

Figure 3. Schematic representation of soil and atmosphere control, P, precipitation; E, evapotranspiration; Epot, potential evapotranspiration and I_t rate of downward infiltration of water.

Source: Dooge, 1992

Local feedbacks can be decomposed into evaporative vs. non-evaporative processes, or soil moisture controlled versus other processes, but ultimately all sides are linked regardless of the subsets. At the land surface, strong coupling means there is a large response in surface latent and sensible heat fluxes to the atmosphere for a given change in land state (e.g. perturbation in soil moisture). However, this relationship necessarily depends on near-surface atmospheric states, turbulence, net radiation, vegetation and soil processes.

The most important land surface coupling to the atmosphere on weather to seasonal climate time scales is that which impacts precipitation. Depending on the vertical stability of the atmospheric profile and the land surface partitioning of available energy between latent and sensible heat flux, cloud formation may be favoured over either a wet or a dry surface (Taylor et al. 2012, Ek and Holtslag, 2004; Gentine et al. 2013; Tawfik and Dirmeyer 2014). The chain of linkages that communicate land surface conditions to the cloud base depend on relationships that may be considered strictly within the domain of land surface models (LSMs; e.g. the soil moisture controls on stomatal resistance), wholly in atmospheric models (e.g. turbulent exchanges of heat and moisture at the top of a growing boundary layer), or a product of both land and atmosphere (e.g.

rates of latent and sensible heat flux). Error is most likely to depend on the weakest link in the chain - if one model or component is highly accurate but others are seriously flawed, the overall simulation of land-atmosphere feedback will be poor (e.g. Dirmeyer 2001). Effects on other atmospheric states such as near surface humidity may be more strongly dependent on the land surface model, but secondary atmospheric processes such as cloud formulations can have as much impact on near-surface temperature errors as the land surface parameters.

Our theoretical understanding of the processes that link land and atmosphere is growing. There are still many situations where statistical approaches can outperform physically-based models (Abramowitz, 2005), but ultimately the more physically realistic models will provide the most potential for improvement. For prediction, physically-based models are more apt to portray extreme events or elements of a changing climate, as one would expect a statistical model calibrated on only unexceptional past data to be less able to encompass unprecedented occurrences. Similarly, while optimal tuning of model parameters can minimize targeted errors (e.g. Gupta et al. 1999, Santanello et al. 2007; Santanello et al. 2013), a paradigm of Earth system modelling has been that there is more accountability for maintaining parameters in a realistic physics space.

For vegetated regions, the strongest surface coupling occurs where the soil is dry (moisture limited, strong stomatal control) and turbulence is strong (e.g. high surface roughness such as a forest, strong communication of surface fluxes into the atmosphere), while weak coupling happens with wetter soils and weak turbulence (van Heerwaarden et al. 2010). Diagnosis of coupled forcing of the atmosphere by the land surface has concentrated on places and times when there is strong net radiation: at low latitudes, middle latitudes during summer, and during daytime. These relationships can change in regions with very weak radiative forcing, over ice, in complex topography, or in regions where there is strong advection from contrasting surfaces such as sea-breeze regimes. For instance, Betts et al. (2014) have shown that the onset of snow cover in high latitudes acts as a climate switch to change land surface-cloud coupling and feedbacks from shortwave to longwave cloud forcing in winter.

In the presence of vegetation, the type of land cover can affect the land surface feedbacks to the atmosphere. Teuling et al. (2010) showed mid-latitude forests and grasslands respond very differently to heat waves. Forests tend to put the extra net radiation into sensible heat flux, grasses into latent. Analysis metrics from Stap et al. (2014) that describe the strength of boundary layer versus surface resistance feedbacks as a function of soil moisture and radiation suggest offsetting compensations between the two. An "uncoupled" simulation cannot represent the full suite of feedbacks, meaning a model component calibrated offline may fail in a coupled framework.

Ultimately, a proper understanding of the coupled land-atmosphere system and especially how anomalous land states are likely to perturb weather and climate will provide a means to improve forecasts on sub-seasonal time scales. The land surface state is a source of potential predictability that has not been tapped, although experiments like the second Global Energy and Water Cycle Experiment (GEWEX) Global Land-Atmosphere Coupling Experiment (GLACE2; Koster et al. 2011) suggest some models are already capable of capitalizing on realistic soil moisture initialization to improve forecasts. Tawfik and Dirmeyer (2014) have explored how atmospheric pre-conditioning determines the amount of moistening versus surface warming needed to trigger daytime convection at the top of a gradually heated boundary layer. Without assumptions about parcel properties, the diurnal evolution can be explored to see what range of evaporative fractions and available energy will or will not trigger cloud.

To validate such theoretical approaches and model developments, observational data at high time resolution are needed to resolve the diurnal cycle of near surface meteorology, surface fluxes including radiation and lower tropospheric profiles. Such measurements must be co-located and quality-controlled, preferably at a range of locations sampling different vegetation and soil types, climate regimes and synoptic situations. Fifteen years ago there was almost no such data. A few field campaigns had unevenly collected a subset of the necessary measurements, usually focused on only a part of the coupled system. As described in the Introduction, today the quality, quantity and completeness of observations are passing a critical threshold of usefulness, but more are needed. In most locations such as FluxNET (fluxnet.ornl.org) sites the missing ingredient is the lower troposphere, but low-cost LIDAR sounders are becoming available that can sample temperature and humidity profiles in the lowest few kilometres of the atmosphere with sufficient accuracy and resolution (Wulfmeyer et al. 2011). Deployment of LIDARs co-located with flux towers, surface radiation and meteorology stations and soil moisture probes could jump-start coupled land-atmosphere model development right away.

8.3 VARIABILITY

In the upward branch of the feedback loop from land to atmosphere, sufficient variability in the forcing (lower) term is necessary for there to be a consequential reaction in the response (upper) term, even if correlations are large. Expanding on the coupling example, there are very high correlations between soil moisture anomalies and evaporation in hot deserts such as the Sahara. Moisture from a rain shower raises soil moisture, which then quickly evaporates. However, there is typically so little water falling so infrequently that anomalies, and thus overall variability, in both the forcing and the response is small, and there is typically little consequence in the strong coupling for the water cycle in such areas.

Land surface models (LSMs) are developed using very little observation data for calibration and validation, and function largely as conceptual models that are expected to perform at a range of spatial scales and across a large range of surface conditions for many ecosystems, climates and terrains. While there is scientific merit in pursuing model development based on conceptual representations of nature, has the drive to add ever more spatially-sensitive processes into LSMs led to intractable modelling systems with inherently poor performance (Abramowitz 2012)? In the end, an LSM should represent accurately how elements of the land surface vary in time and space, so as to provide an accurate and realistic lower boundary in forecast models.

An ongoing problem is that LSMs coupled to weather and climate models must represent conditions over tens, hundreds or thousands of square kilometres (the resolution of the atmospheric model). However, observations used for calibration and validation are typically at the point scale (in situ measurements such as meteorological stations or flux towers) or area averages that are smaller (e.g. satellite pixel) or larger (e.g. basin runoff from stream gauges) than the model grid cell. Temporally, validation is typically performed on daily means or instantaneous values (e.g. a weather map at some hours of forecast lead), which may also mask problems that are exhibited within the diurnal cycle (see previous section). Data assimilation is increasingly being applied to land surface states, particularly using satellite observations, which both helps constrain LSMs to a more realistic range of variability and provide clues as to the nature and source of model errors.

Most LSMs use tiling to account for sub-grid heterogeneity in land surface cover, and in some cases processes like carbon dynamics or surface hydrology. They implicitly assume time variations scale with spatial variations, as LSMs do not intrinsically have a specific spatial scale while they are integrated at specific time step intervals. In nature, heterogeneous surfaces lead to heterogeneous heating of the convective boundary layer and the formation of secondary circulations on a spectrum of time scales that greatly affect bulk transport, the surface energy balance, and cloud formation (Pielke et al. 2011). The scale of the heterogeneities determines the strength and character of secondary circulations (van Heerwaarden et al. 2014). This is not accounted for in most coupled land-atmosphere models. Any heterogeneity of fluxes due to tiling is removed as area-weighted averages are delivered from the LSM to the atmospheric model on the coupled model's time step, and in return the LSM "sees" a uniform atmosphere over all land surfaces in a grid box.

Topographic variations also drive convective organization (e.g. Lowman and Barros, 2014), and urban areas above a certain size have an impact on storm-level precipitation (Schmid and Niyogi, 2013). Contrasts between "dry" land and open water or wetlands is another common source of small-scale heterogeneity (Balsamo et al. 2012), where the vastly different heat capacities of land and water introduce new time scales of variability. Transient heterogeneity, such as when snow cover obscures some ground in forested areas (Viterbo and Betts, 1999), can also induce area mean changes and small-scale lateral circulations that models struggle to capture.

Land use change and agricultural practices like crop rotation, fallow farming, and irrigation (Ozdogan et al. 2010) introduce another time-varying component to spatial heterogeneity that also needs to be accounted for. This is particularly important, as there is a global correspondence between "hot spots" of land-atmosphere coupling and the locations of major agricultural areas.

Independent of the feedbacks with the atmosphere, LSMs still do a poor job of simulating the impacts of sub-grid heterogeneity of the land surface and subsurface on the water cycle. LSMs struggle to partition precipitation properly between evaporation and runoff, largely because LSM development has neglected the runoff side of the system (Koster and Mahanama), which has fast (Horton and Dunne surface runoff processes) and slow (Darcy subsurface runoff) modes. Runoff estimates in model inter-comparison projects typically show the greatest variations and errors (Boone et al. 2004). LSMs have not been properly developed and calibrated for hillslope runoff processes, endorheic processes (e.g. ponding), sub-grid lateral transports, dry season transpiration of groundwater by deep-rooted plants, and inter-basin exchanges. Furthermore, runoff heterogeneity is strongly controlled by precipitation heterogeneity - a characteristic poorly represented in coupled models. Even in flat terrain with relatively homogeneous vegetation, subtle variations in topography can have large consequences for surface water behaviour.

Likewise, parameterizations for atmospheric processes such as cloud microphysics, the development of convection, and radiative transfer in the presence of hydrometeors and aerosols, remain riddled with biases and errors that percolate into the simulation of land-atmosphere interactions. Often a poor representation of temporal variability in land states and fluxes in coupled land-atmosphere models can be directly traced to poor variability in downward fluxes of energy and water from the atmospheric model.

There remains a strong need for more observational data to inform model development at finer scales, and parameterization of processes at the sub-grid scale, that are transferable to any region of the globe. Operational centres push for the best skill scores while scientists seek fundamental understanding. In the realm of coupled land-atmosphere modelling, this results in two unsatisfactory extremes - the best answers for the wrong reasons (compensating errors in unrealistic parameterizations), and the wrong answers for the right reasons (good physics with insufficient calibration).

8.4 MEMORY

Finally there is the characteristic of memory, which means the degree of persistence of anomalies in the forcing term. The degree to which the atmosphere "feels" an anomaly at the lower boundary is compounded over time, provided the anomaly remains strong and in place. A large perturbation to the land surface state in a region of demonstrated strong coupling that only lasts a day will have much less impact on weather and climate than one that persists for many days or weeks.

Inertia in the land surface component of the earth system provides a potential source of predictability throughout and beyond the "deterministic" time scales of weather forecasting. As shown in Figure 2, the slow manifold of land and ocean are the primary sources of atmospheric predictability on sub-seasonal to seasonal time scales.

Land surface memory relevant to weather and climate time sales is typically defined based on anomalies of soil moisture. Memory is both a property of the land surface (e.g. clay soils have more memory than sand) and climate that forces soil moisture variability (e.g. monsoon regions exhibit long memory during the dry season when there rainfall events that might change soil moisture anomalies, but little memory once the rainy season returns and saturates the soil).

A straightforward way to estimate the memory of a quantity is to calculate the lagged autocorrelation of its time series. This is been done for soil moisture from models (Schlosser and Milly 2002; Dirmeyer et al. 2009; Lo and Famiglietti 2010) and observations (Vinnikov and Yeserkepova 1991; Seneviratne and Koster 2012). The memory can be quantified as either the correlation at a given lag or the time required for the autocorrelation to drop below a threshold value. Results will be sensitive to whether the time series consists of instantaneous values or time-averaged data, and the time interval in the series (e.g. daily versus monthly) and will vary with season and location. In modelling experiments, the declining signal-to-noise ratio where initial land states differ between sets of experiments can also be used as a memory metric. For forecasting purposes, memory may be defined by the temporal extent of improved skill when realistic land surface initial conditions are used in a model, versus climatological or other initial states not representative of the observed situation. If this measure is based on the skill of atmospheric variables like temperature or precipitation, it implicitly includes the effect of the feedbacks of the land surface on the atmosphere.

Because the coupling between land and atmosphere can vary in time, memory in the form of soil moisture anomalies may lurk dormant until such time as surface fluxes become sensitive to the land surface state. An apparent rebound in predictability can ensue days to weeks after initialization, as demonstrated in retrospective model forecasts (Guo et al. 2011, 2012). Actually the predictability is there all along, locked in the land surface states. Memory in the form of a delayed realization of predictability can also occur when winter snow cover anomalies become spring and summer soil moisture anomalies (e.g. Xu and Dirmeyer 2013).

Positive feedbacks between land and atmosphere can exacerbate or prolong climate anomalies such as droughts, providing a form of coupled memory. The role of the land surface in modulating drought has long been established in modelling studies (e.g. Dirmeyer 1994; Fennessy and Shukla 1999, Seneviratne et al. 2006, Zaitchik et al. 2013). For this reason, the understanding and quantification of land surface memory is important for the forecast of extremes, as well as a general means to improve sub-seasonal prediction skill.

As observational records of soil moisture and other land surface states grow in length, they become ever more useful for quantifying memory in nature in a statistically dependable way. These data are also necessary to validate this aspect of weather and climate models. Much more can be accomplished in terms of understanding by the use of models in carefully designed experiments. Case studies of climate extremes likely to be influenced by land surface states, most notably droughts, need to be examined in carefully designed modelling experiments in a multi-model framework. (e.g. World Climate Research Programme (WCRP) 2011, Mariotti et al. 2013). Such a project could advance understanding of the role of the land surface in extreme events through the exercise of attribution, as well as accelerate model improvement.

8.5 SUMMARY AND OUTLOOK

Coupling, variability and memory are identified as the ingredients of land-atmosphere interactions that can contribute to enhanced predictability in Earth system models. Progress in the understanding and simulation of key processes in these areas would be facilitated by an improved and expanded observational capability to characterize these properties for different biomes, land-use situations and climate regimes. We are on the verge of having sufficient observational data to begin to address these problems, although scale differences persist. Furthermore, a consistent set of diagnostics and metrics that can highlight the difference between the model and the real-world will further advance the potential for enhanced land surface contribution to prediction skill.

The memory inherent in land surface water reservoirs such as soil, snow and lakes can extend the quality of medium range prediction beyond the classic deterministic limits, especially in the presence of significant pre-existing anomalies. However, this ingredient alone is not sufficient without the other two components (realistic coupling and sufficient variability), which demands evaluating models over extensive periods of time such as those covered by modern era reanalyses and the period of continuous satellite remote sensing. Predictability can be converted to forecast skill with high-quality land surface initial conditions consistent with the land surface model (cf. Koster et al. 2009). Innovations need to be incorporated into operational prediction models in a timely fashion. We are at an exciting time when major progress in exploiting the predictability in land- atmosphere feedbacks is likely in the coming decade.

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CHAPTER 9. OCEAN-WAVES-SEA ICE-ATMOSPHERE INTERACTIONS

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Abstract

Research is beginning to demonstrate that coupling between the atmosphere and other climate systems can improve short-range weather forecasts. Furthermore, as our understanding of the Earth system increases, so the interactions with additional physical processes have become recognized. In this chapter interactions between the atmosphere, the ocean, ocean surface waves, sea ice and snow are analyzed.

9.1 INTRODUCTION

Climate modelling and seasonal forecasting have long recognised how interactions between the atmosphere and other elements of the Earth system introduce new long-timescale feedbacks, which provide the potential for predictability on seasonal and longer forecast lead times. Research is beginning to demonstrate that coupling for example between the atmosphere and ocean can improve short-range weather forecasts for example by improving the diurnal cycle. Furthermore, as our understanding of the Earth system increases, so the interactions with additional physical processes have become recognised. For example, over the past 15 years or so there has been a growing recognition of the key role played by ocean surface waves in driving the marine atmospheric boundary layer and in deepening the ocean surface boundary layer. Also, sea ice is obviously important in a changing climate, but has also been shown to play a role in the short range, for example for seasonal forecasting. Coupling amongst Earth system components is also an area that can benefit from the seamless approach, with improvements in climate modelling leading to benefits in weather modelling and vice versa. Finally, there is a move for short-range forecasts to aim to predict a range of environmental variables beyond the traditional weather, for example Arctic Sea ice extent: We are moving from weather prediction towards environmental prediction.

In this chapter, we consider interactions between the atmosphere, the ocean, ocean surface waves, sea ice and snow. Firstly, we identify some physical processes that have recently been identified that require parameterization into large-scale models. What are the new phenomena that are likely to yield improvements to weather and climate prediction? How complicated do the representations of these processes need to be and what kind of coupling is necessary and feasible? With the advent of larger super-computers we also consider some of the benefits of higher temporal and spatial resolution on the coupling between these Earth system processes. Where are the likely big jumps going to come as resolution increases? Finally the technical challenges associated with coupled modelling should not be under-estimated. Universal couplers do exist, but are they adequate and can they be used at the timescales that are required by the underlying physics of the problem? These questions are addressed in this chapter.

9.2 OCEAN COUPLING

The ocean plays an important role across the range of timescales from weather to climate variability and change due to its ability to sequester and transport heat and freshwater. On the large scale, the ocean acts to dampen atmospheric variability (e.g. Hasselmann 1976), whereas at the oceanic mesoscale the wind, clouds and precipitation in the atmosphere respond to ocean mesoscale eddies (e.g. Chelton and Xie, 2010, Frenger et al. 2013). So, maritime weather and climate prediction may require oceanic coupling even for short- to medium-range predictions to determine variability at the scale of a hundred or so kilometres. This need is reflected in current research: the importance of including coupling to the ocean has long been recognised in climate modelling and seasonal prediction, particularly in the tropics. Effort is now focussed on the role of ocean coupling at mid-latitudes from weather to seasonal forecasting timescales. With the move to coupled ocean-atmosphere models for prediction on shorter timescales, the priority is moving towards better understanding, representation and resolution of the rich range of phenomena, from mesoscale, submesoscale through to three dimensional turbulence dynamics, particularly in the ocean, where their role and significance is only just emerging.

At the basin scale, higher-resolution, eddy permitting, ocean models have been shown to substantially improve atmospheric circulation and prediction out to seasonal timescales. For example, in the Atlantic, there is a body of evidence that suggests that ocean surface temperature in the extra-tropical Gulf Stream region could affect large-scale atmospheric circulation near Europe in data (e.g. Ratcliffe and Murray 1970) and in models (Minobe et al. 2008, Brayshaw et al. 2009, Scaife et al. 2011). The higher ocean resolution provides sharper sea surface temperature gradients, which improves the mean state of the atmosphere and blocking statistics (Scaife et al. 2011). There is evidence that the strength of coupling between the atmosphere and ocean within models is weaker than in nature on seasonal time scales (e.g. Rodwell and Folland 2002). The response appears to be sensitive to resolution with the model response reducing as the resolution of the SST gradients is degraded (Minobe et al. 2008), leading to reduced low frequency variability in the atmosphere (Feliks et al. 2011). With these new-generation models skill has started to emerge in seasonal prediction of the winter North Atlantic Oscillation (Scaife et al. 2014), although the predicted signal seems to have a weaker amplitude than in observations (Eade et al. 2014). If it is the case that the strength of the ocean-atmosphere coupling is underestimated, addressing the underlying causes is an important challenge for the future.

At the ocean mesoscale, the ocean imprints patterns upon the atmosphere, and the importance of spatial model resolution can be demonstrated by comparing modelled and observed correlations between Sea Surface Temperature (SST) and wind patterns. The observed correlation between ocean and atmosphere (Chelton and Xie 2010), only starts to appear in coupled ocean-atmosphere models when the ocean resolution reaches ~1/4 degree with further improvements as the ocean resolution reaches the ocean mesoscale (e.g. Bryan et al. 2010; McClean et al. 2011; Delworth et al. 2012; Demory et al. 2014).

At finer scales, there are the motions that control evolution of the ocean surface boundary layer (OSBL). For example, Large and Crawford (1995) show evidence of rapid deepening when there is resonance between wind turning in mid-latitude weather systems and inertial oscillations in the OSBL, which maintains the surface wind stress aligned with the surface currents, enables substantial energy and momentum exchange. The physics of the deepening process remains an important parameterization problem (Grant and Belcher, 2011). Jochum et al. (2013) argue that this process should be greatly improved by mesoscale-permitting resolutions. However, there are a host of other phenomena that remain unresolved and will need to be understood and then parameterized. The primary questions of exchange between atmosphere and ocean have generally been modelled using vertical-gradient-only, one-dimensional or “pencil” models of oceanic mixing. This approximation assumes that the horizontal scales of oceanic motion are much larger than the vertical scales and that the oceanic response is slower than the mixing timescale. However, recent research has demonstrated the importance of a new class of motions at the oceanic sub-mesoscale, which have horizontal scales of order 100 m-10 km. These motions have been thought to be a passive continuation of the small end of the mesoscale eddy spectrum, but recent work (e.g. Boccaletti et al. 2007) has shown that dynamics at the sub-mesoscale can behave quite differently from both larger and smaller scales. Many of the structures that inhabit the sub-mesoscale exist predominantly within shallow surface or bottom boundary layers where the stratification is weak and their effective depth is the boundary layer depth. Thus, the effective deformation radius for these flows is much smaller than in the oceanic pycnocline (Boccaletti et al. 2007). Thus, the timescale of the sub-mesoscale motions of fronts (Capet et al. 2008), their interaction with wind (D’Asaro et al. 2011), and their instabilities are fast enough to compete with the diurnal cycle and seasonal changes to the OSBL, systematically affecting both regional and global physical balances (Fox-Kemper et al. 2008, 2011; Thomas and Taylor 2010; Hamlington et al. 2014) and biology (Taylor and Ferrari 2010; Mahadevan et al. 2012). Unlike smaller-scale boundary layer turbulence and related phenomena, these phenomena are fundamentally three-dimensional, depending sensitively on the horizontal gradients of density and other properties, and cannot be represented with pencil models. Complete understanding and reliable parameterization remain important challenges.

It has been recognized for some time that for effective parameterization of air-sea exchange both the cool skin (a very thin layer near the surface less than 1mm thick) and the diurnal warm layer (up to a few meters deep) have to be taken into account. The cool skin layer has negligible heat capacity, but is important for assimilation of remotely sensed observations, and its representation has become a standard component of state-of-the-art air-sea interaction algorithms (Fairall et al. 2003). The amplitude of the diurnal cycle can be up to a few degrees at very low winds, and requires high frequency coupling with the atmosphere. Experience at the European Center for Medium-range Weather Forecast (ECMWF) with a simple bulk approach for the warm layer (Zeng and Beljaars 2005; Takaya et al. 2010) is that it has a modest but positive impact on the Madden Julian Oscillation (MJO) forecasts.

The drive to continuous improvement of forecasts on seasonal and weather timescales is leading towards an enhanced interest in ocean-atmosphere coupling. This brings with it the opportunity of exciting advances in resolution and process parameterization. We have focussed here on ocean processes: to reap many of the benefits will also require improvements in processes and resolution in atmospheric models (dealt with elsewhere in this volume). With the prospect of seamless modelling with the same coupled ocean-atmosphere model being employed over the full range of timescales, there is also the prospect of potential improvements on climate timescales as understanding on the shorter timescales develops.

9.3 WAVE COUPLING

The surface gravity waves on the interface between the atmosphere and ocean are being increasingly recognised as critically important in shaping the coupling between the atmosphere and oceanic boundary layers. The roughness of the surface plays a role in air-sea transfer of momentum, gasses, sea-spray aerosols, bubbles, etc. (Cavaleri et al. 2012; Sullivan and McWilliams 2010), and therefore these waves must play a role in coupled modelling.
While there are many potential effects of waves on climate and weather (Cavaleri et al. 2012), the ones thought to be most important and currently receiving the most attention are: sea-state effects on drag between the ocean and atmosphere, ocean mixing driven by waves, transport of ocean properties by Stokes drift or Stokes-induced forces, and radiative effects through sea-spray aerosols or droplet/bubble induces air-sea gas transfer.

A key tool in process understanding of these effects is Large Eddy Simulation of either the atmospheric or oceanic boundary layer or both. This class of simulation resolves explicitly the large sale boundary layer turbulence and so removes many of the uncertainties in general circulation models and their boundary layer parameterizations, but difficulties remain. Generally, assumptions are made limiting the kinds of waves that are present, or how and whether they evolve during a simulation, etc. Generally, the equations of motion used are not the Navier-Stokes equations, but rather an approximate set such as the Wave-Averaged Equations (e.g. Lane et al. 2007). Thus, it is critical to continue observations and development of diagnostic techniques in situ, where the consequences of such assumptions can be evaluated (e.g. Fairall et al. 2003; Edson et al. 2007; D'Asaro et al. 2014).

The effects of sea state on momentum to forecasting and climate modelling have been recognised for some time (Janssen, 1989). There remain difficulties at high and low wind speeds over the ocean. At hurricane wind speeds a large fraction of the surface waves are breaking and observations are sparse. In this regime there is a spread between different treatments of wave effects (e.g. Chen et al. 2007; Moon et al. 2007). At low winds there is often remotely generated swell present (Hanley et al. 2010). There is observational and modelling evidence that with low winds and swell the boundary layer turbulence collapses completely (Smedman et al. l999, Edson et al. 2007, Hanley and Belcher 2008) sometimes with the momentum flux changing sign so that the transfer is from the waves into the atmosphere (Grachev and Fairall 2001). These behaviours are not currently represented in models and the consequences for weather and climate are not known.

Upper ocean boundary layer turbulence and mixing is sensitive to sea state. In the 1930s, Langmuir observed windrows in the ocean, and in the last 15 years the theoretical basis of the substantially increased upper ocean mixing due to enhanced turbulence due to Stokes forces (Langmuir turbulence) and wave breaking has grown, see for example the reviews by Sullivan and McWilliams (2010), Belcher et al. (2012) and D'Asaro (2013). Belcher et al (2012) showed that the effects on the OSBL are likely to have global significance and could help fix the current substantial biases in modelled OSBL depths. Observational evidence for the increased turbulence is beginning to accumulate (Sutherland et al 2014, D'Asaro et al. 2014). Parameterizations of these processes for their representation into weather and climate models are at an early stage of development. And so the wider implications of these wave-driven processes in coupled ocean-atmosphere will need to be an important focus.

The final major wave effect in coupled modeling is the effect of the Stokes forces on the mean momentum balance of the ocean, and thereby on the advection of sea surface temperature and other properties important for weather and climate. The Stokes-Coriolis force and the Stokes-vortex force perturb the ocean momentum balances when waves are present (Polton et al. 2005, Lane et al. 2007). These forces can be substantial due to the large shear in the Stokes drift, and they can exhibit effects on surprisingly wide regions up to the scale of the wave packet (hundreds of kilometres). The Ekman layer, fronts, filaments, and instabilities of those features are all affected (e.g. Polton et al 2005, McWilliams et al. 2012; McWilliams and Fox-Kemper 2013; Hamlington et al. 2014), sometimes at leading order in the momentum balance or at a higher order than other more familiar complexities such as advection of momentum (McWilliams and Fox-Kemper 2013). It is important to recognize that because of these perturbed force balances, the Stokes drift does not simply add to the transport by the ocean currents as early models attempted. Instead, a two-way interaction governs the different flows and their advection properties. The two-way interaction is stronger for smaller-scale phenomena, especially so for sub-mesoscale features and Langmuir turbulence, but it can also affect larger scales. These interactions can be modelled in a coupled atmosphere-ocean-wave model but a full accounting of their effects in a sub-mesoscale-resolving, coupled wave-ocean nonhydrostatic model is still unknown.

It has long been the working assumption that these waves are in equilibrium with the winds, and therefore the wave state, and any other properties that may depend on it, is simply determined from the wind. However, recent global analyses of wave conditions (Hanley et al. 2010; Carrasco et al. 2014; Webb and Fox-Kemper 2011, 2014) show that often waves are not fully developed nor even aligned with the wind. So, the effects of waves on climate variability and weather are distinct from the effects that can be captured from the local wind alone. Consequently, there is a need to couple wave models into weather and climate models. Skill at wave forecasting has improved considerably (e.g. Janssen 2008), and numerical weather prediction benefits from including the sea state are notable at ECMWF and elsewhere.

9.4 SNOW-ATMOSPHERE INTERACTION

Snow exhibits unique physical properties that vary very rapidly over time and strongly impact the heat and vapour fluxes between the atmospheric boundary layer and the continental surfaces. Snow physical properties contribute to a cooling of the atmospheric boundary layer (Armstrong and Brun 2008): in terms of radiation, snow has a high albedo and a high emissivity; in terms of thermal properties, snow exhibits a very low thermal capacity and conductivity, especially when snow density is low, leading to an almost complete decoupling between the atmosphere and the ground beneath the snow as soon as snow depth is larger than a few tens of centimetres; during the melting period, snow surface temperature remains colder than 0°C. Consequently, for a given meteorological situation, snow surface temperature is colder than any other continental surface, which generally induces a very stable boundary layer. For these reasons, heat fluxes over snow are often poorly simulated in Numerical Weather Prediction and climate modelling systems and large temperature and humidity forecast errors occur frequently (Holstag et al. 2013).
Detailed numerical snow models have been developed during the last decades, mainly for snow and avalanche research (Essery and Etchevers 2004). When run in off-line mode from reanalysis, these models represent reasonably well the evolution of snow depth, snow water equivalent,

surface temperature, density, snow grain size and albedo (Brun et al. 2013). Intermediate complexity snow models have been developed to be run within meteorological and climate models. At least 5 numerical snow layers are necessary to correctly simulate snow depth, albedo, temperature and density (results presented at the World Weather Research Programme and THe Observing system Research and Predictability Experiment Workshop on Polar Prediction 2013). As snow ages, albedo can be reduced by increasing grain size, as well as exposure of underlying surfaces or the presence of deposited aerosols on the ice. This can lead to a snow-albedo feedback whereby increased warming accelerates the loss of snow, reducing albedo and increasing warming (Bony et al. 2006). Multilayer snow models, which include snow aging and densification (e.g. Best et al. 2011), have been shown to improve the simulation of atmosphere and soil temperatures. Since physical properties of snow differ significantly from other surfaces, the heterogeneity of snow covered surfaces needs to be represented properly, especially in forested areas. A multi-energy balance approach describing explicitly radiation transfers through the canopy is therefore recommended to properly represent soil/snow/vegetation interactions in Numerical Weather Prediction (NWP) systems along with the implementation of intermediate complexity snow models coupled to relatively complex soil models representing freezing processes.
The near-real-time initialization of the state of snow characteristics (for example, cover, depth and temperature) raises specific issues. Remote-sensed observations of snow depth are not yet possible while near-real-time snow cover retrievals from optical sensors and snow water equivalent retrievals from micro-wave still suffer from strong deficiencies. In situ snow depth observations are still a key source of snow information in NWP systems but they are unevenly distributed and they suffer from discrepancies in observation practices. In contrast, skin temperature is well observed in clear sky conditions from satellite. Fréville et al. (2014) have demonstrated the high quality of Moderate-Resolution Imaging Spectroradiometer (MODIS) skin temperatures over Antarctica. It is recommended to support the ongoing Global Cryosphere Watch initiative for improving the observation of and the access to near-real-time observations of in situ snow depth. The evaluation of the potential of using off-line near-real-time simulations of snow cover characteristics as an alternate source or a complement to snow observations in NWP systems is strongly encouraged.

9.5 SEA ICE-ATMOSPHERE INTERACTION

Sea ice plays an important role at the interface of the ocean and atmosphere; the ocean surface absorbs most of the incoming solar radiation, while the high albedo of sea ice means that it reflects 50-70 % of the incoming solar radiation. In climate change simulations, the differing albedos of ocean and sea ice can lead to a feedback (Winton 2006; Perovich et al. 2007) whereby sea ice melts allowing the ocean to absorb more heat and subsequently melt more ice is an important mechanism in determining the rate of loss of sea ice cover. Aside from its high albedo, sea ice also acts as a blanket to the ocean, reducing the oceanic loss of heat, while the freezing and melting of sea ice leads to salt and freshwater fluxes in the ocean which can drive variations in the large-scale thermohaline circulation.

Historically, the main focus for coupled models including sea ice has been long-term climate simulations. However, with increasing interest in seasonal predictions of Arctic sea ice minima (Merryfield et al. 2013; Peterson et al. 2014) and the potential for routing ships through the Arctic (Stephenson et al. 2011), coupled sea ice simulations from short-range to centennial timescales are now of increasing interest. The Polar Prediction Project (http://www.polarprediction.net/) and the Year of Polar Prediction can be anticipated to lead to improvements in the use of coupled models for short-to-medium range forecasting. Given the large seasonal cycle in sea ice, the seamless approach to coupled modelling can be shown to have potential for improving models on all timescales (Hewitt et al. 2015).

In coupled models, the choice has generally been made to use an identical grid for ocean and sea ice components. This is a prudent choice given that 1) the ocean and the ice interact on short timescales and 2) the choice of grids to avoid a singularity on the North Pole (currently focussed around the tripolar grid) is well-suited to both ocean and sea ice. An ongoing debate with sea ice coupling is in determining the most appropriate place for the interface to exchange coupling fields between the sea ice and the atmosphere; most current models place the interface either at the surface of the sea ice or at the first interior level of the sea ice, with the latter approach similar to the coupling of land surface components described by Best et al. (2004) which allows the sea ice surface temperature to be implicitly calculated with the thermodynamic surface fluxes (e.g. Hewitt et al. 2011). Determining the relative importance of the two approaches is a challenge for the future.

The thermodynamics associated with sea ice is crucial to the interaction with both atmosphere and ocean; multilayer thermodynamics (Bitz and Lipscomb 1999) is generally included in many models (although issues with implicit coupling have led groups to maintain the zero layer thermodynamics). Multilayer sea ice enables the salinity profile to be modelled through the depth of the ice (Vancoppenolle et al. 2006); brine release occurs as ice forms and ice becomes fresher as it ages. There is also ongoing research to represent the ice microstructure and small-scale processes occurring inside the ice cover, such as brine pockets evolution and gravity drainage (Turner et al. 2013) which in turn affect the ice properties (Semtner 1976). State-of-the-art sea ice models typically model sea ice using an ice thickness distribution (Thorndike et al. 1975) so that the ocean surface is effectively tiled with either open water or a sea ice thickness category (where 5 categories are often used for climate modelling following Bitz et al. 2001). One of the advantages of a multi-category sea ice scheme is that it allows thin ice to respond quickly to changes in the surface fluxes. In regions where ocean/sea ice and atmosphere grids are misaligned, conservation of fluxes over so many tiles can be problematic.

To accurately represent the seasonal cycle of ice albedo (for example, as observed in the Surface Heat Budget of the Arctic Ocean project; Perovich et al. 2002), sea ice models need to represent the properties of both snow and meltponds. Prior to the start of the melt season, snow (with its high albedo and low thermal conductivity) can strongly impact the heat balance at the surface. Most of the existing models simulate crudely the evolution of the snow cover; often with only one vertical layer and snow density being fixed in space and in time. Including sophisticated snow models over sea ice (similar to those being employed over land) is a future aspiration for coupled models (Best et al. 2011). During the melt season, as ponds form at the surface, the surface albedo can be significantly smaller than either bare ice or snow covered ice. Keen et al. (2013) showed that this effect was important in the simulation of the long-term thinning of sea ice over the historical period. Many models however, parameterize the effect of melt ponds on the surface albedo by having an albedo that depends on the surface temperature. Given the likely importance of this process, models which explicitly represent the evolution of melt ponds are now being introduced (Flocco et al. 2010). The explicit inclusion of melt ponds is expected to lead to improvements in the simulation of the melt season.

Satellite observations of sea ice velocity gradients reveal that the Arctic sea ice cover is characterized by quasi-rigid plates separated by long narrow zones of large deformations (Kwok et al. 2008). Correctly simulating the deformations of the sea ice cover is crucial as they are very important for atmosphere-sea ice-ocean interactions and for determining the ice mass balance and the ice thickness field on the geophysical scale. When convergence occurs, the ice thickness increases locally due to rafting and ridging. When there is divergence, the sea ice cover opens up and there is formation of a lead. Leads absorb solar radiation in summer and can be the sites of large latent and sensible heat exchanges between the relatively warm polar ocean and the cold atmosphere in winter (Maykut 1978). Most models currently represent the sea ice rheology based on a viscous-plastic formulation (Hibler 1979) using the elastic-viscous-plastic method (Hunke 2001; Lemieux et al. 2012; Bouillon et al. 2013) which assumes that the ice cover is isotropic and can only resist small tensile stresses (Coon et al. 1974) and was developed for models with spatial resolution O(100 km). These assumptions are being called into question in an active debate over sea ice rheology: some authors claim that the Hibler approach cannot represent adequately the statistics of sea ice deformations (Girard et al. 2011) and that a different rheology is required. Different approaches have been proposed such as anisotropic models (Schreyer et al. 2005; Tsamados et al. 2013) and an elasto-brittle rheology (Girard et al. 2011). Much work is needed to evaluate these new developments and the requirements for representing the ice rheology as models move towards higher resolution. Improved numerical algorithms will be required at high resolution to address numerical issues that have been identified with the solvers (e.g. Lemieux et al. 2010; Lipscomb et al. 2007; Lemieux et al. 2014). In addition to the ice rheology, the sails and

keels of pressure ridges are important topographic features that affect the air-ice and ice-ocean stresses. Sea ice models have generally only considered the skin drag and neglected the form drag due to topographic features (e.g. Hibler 1979; Losch et al. 2009) but new air-ice and ice-ocean stress formulations have recently been developed (Lupkes et al. 2013; Tsamados et al. 2014) to address these issues which will require evaluation in coupled models.
Wave-ice interactions is an area of research that needs to be addressed to account for better representing atmosphere-ice-ocean interactions in the marginal ice zone (e.g. Williams et al. 2013). Waves propagating in ice infested waters are damped, with more attenuation for waves with short-wavelength. Waves can in turn affect the sea ice cover in many ways: they can break floes therefore modifying mechanical properties of the ice, increasing lateral melting and impacting the formation of frazil ice. Waves breaking can also potentially alter the surface albedo by depositing sea water at the floe surface.

9.6 COUPLING STRATEGIES

In order to build a model from atmosphere/ocean/wave/sea ice components, there are both technical and scientific considerations to take into account. Clearly, given limited computing resources it is important to build an efficient system but these considerations need to be balanced by technical solutions which ensure the scientific integrity of the model in terms of allowing components to interact on the most appropriate timescale and by preserving conservation of freshwater and energy.

Technically the most efficient strategy needs to be determined in terms of how to arrange the components and where to exchange fluxes between the components. For example, in some cases, it may be more efficient to couple components into a single executable and allow coupling to take place on the timescale of the component time step, while in other cases it may be more efficient to allow a coupler to deal with the exchange of data between components. As model resolution increases and further components are added, for example the inclusion of ocean surface waves or ice sheets and ice shelves, it is likely that coupling strategies will also need to be re-examined. Ultimately, weather and climate science needs both flexible and high-performance coupling. Both have become crucial in the last few years as new challenges arise due to the need to couple an increasing number of constituents, to support diverse scientific objectives, and to maintain multiple configurations, with these trends expected to continue in the future.

Coupling technologies link component models together by managing data exchange between components and controlling the execution of the components. The component model data must be re-gridded and passed between the component models whilst respecting constraints such as conservation of physical quantities, stability of the flux exchange numerics, and consistency with physical processes occurring near the component surface. As described by Valcke et al. (2012) there are two common approaches: the “integrated strategy” (for example the Earth System Modeling Framework (http://www.earthsystemmodeling.org; Hill et al. 2004), the new coupler at the National Center for Atmospheric Research - CPL7 (Craig et al. 2012), the Flexible Modeling System (http://www.gfdl.noaa.gov/fms)), where a driving layer explicitly calls the components and coupling is realised via arguments passed through the component interface which typically involves compiling all constituent models into a single binary and the “multiple executable” approach (e.g. Ocean- Atmosphere-Sea Ice-Soil (OASIS) coupler (https://verc.enes.org/oasis; Valcke 2013), OpenPALM (http://www.cerfacs.fr/globc/PALM_WEB/), GOSSIP developed by Environment Canada (http://collaboration.cmc.ec.gc.ca/science/rpn/)) where binary independence of the components and synchronization is ensured via specialized communication calls flexibly placed in models with minimal intrusion into the coding architecture. Because they address different needs, both strategies need to be maintained and further developed for the foreseeable future. Besides these two general coupling approaches, other approaches are also emerging, such as the ability to couple components through web services. Indeed, in some cases, when the component models are so different that they should not even be executing on the same platform, heterogeneous computing should be considered. This may be particularly beneficial for integrating models from different communities with different drivers and constraints, for example the land surface or hydrology communities.

Improving scientific productivity will continue to be the main driver for decisions about the future of coupling technologies. Most of the gains in the last decade came from hardware improvement with faster processors, increased memory parallelisation, and faster communication algorithms. However, in order to combine improved performance and reduced power consumption, future platforms are likely to be based on heterogeneous system architectures composed of orders of magnitude more processors, with less and slower memory. Moving into the exascale era will require, for coupling technology as for other software, both finding additional opportunities for parallelism and better overlap of communication with computation.

Collaboration presents opportunities for the geosciences community both in terms of qualitative comparison, or benchmarking, of the performances of the different coupling technologies and in some unifying of the different coupling approaches. An example of an ongoing activity is the Infrastructure for the European Network of Earth System Modeling (IS-ENES2) EU project (verc.enes.org/ISENES2), which is participating in the International Working Committee on Coupling Technologies (earthsystemcog.org/projects/iwcct/; Valcke and Dunlap 2011; Dunlap et al. 2014). The performance of some coupling tasks, such as generation of interpolation weights, parallel exchange of coupling data, and re-gridding, are easy to compare between the different technologies, while other aspects such as user-friendliness, flexibility or intrusiveness of coupling technologies are less tangible and therefore harder to define and measure. However, the community will benefit from a general assessment of the different coupling technologies. While there are significant barriers to sharing infrastructure, there are potential benefits of unifying coupling approaches, particularly in terms of sharing development costs. The recent merge of OASIS3 and the Modeling Coupling Toolkit (MCT) into OASIS3-MCT is an example of a successful collaboration. There is also on-going research in generative programming, which explores potential ways to unify the different coupling approaches (e.g. BFG; Armstrong et al. 2009). As future partnerships emerge, we expect the geoscience communities to reap the benefits of a new generation of robust, efficient, and high-quality coupling technologies.

9.7 CONCLUSIONS

In this chapter we have reviewed some of the emerging themes in the interactions between the atmosphere with oceans, ocean surface waves, snow and sea-ice, and the computational strategies for coupling. Higher model resolution, particularly in the ocean, looks likely to pay dividends. There are tantalising clues that there is greater predictable signal on seasonal timescales from ocean-atmosphere coupling than current models have, and it may be that proper resolution of oceanic mesoscale eddies will help. Sub-mesoscale circulations in the ocean have recently been recognised as playing important roles in re-stratifying the surface layers of the ocean and will need to be parameterized. Ocean waves are now recognised as shaping the structure of the marine atmospheric boundary layer and probably dominate mixing in the ocean surface boundary layer. There is an urgent need therefore to couple wave forecasting models and to properly parameterize the processes driven by the waves. Models of the role of snow on the surface energy balance have improved substantially over the past 10 years, and it is now recognised that multi-layer models are essential to represent the rich range of processes. For Numerical Weather Prediction and seasonal prediction there is a need to initialise snow properties, which drives a need to improve observations of snow cover and depth. We highlighted the need for sea ice models to represent fluxes from the wide range of conditions that occur, such as ageing ice, melt ponds and snow. As we move towards higher model resolution, the representation of ice rheology and wave-ice interactions needs to be addressed. Finally, we reviewed briefly the technical strategies current employed to facilitate coupling between different Earth system components. These technologies will require substantial investment if we are to reap the rewards of exascale computing.

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CHAPTER 10. CHALLENGES FOR SUB-GRIDSCALE PARAMETERIZATIONS IN ATMOSPHERIC MODELS

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Abstract

The quality of weather and climate predictions is hugely sensitive to the representation of unresolved processes. Higher resolution has benefitted many applications, but the uncertainties in representing processes continue to be large, and despite weather and climate models moving toward ever-higher resolutions, challenges remain since many of the key atmospheric processes are still unresolved (or only partially resolved).

Future improvements in the representation of sub-gridscale processes and their interaction with larger-scale phenomena will rely on more and better convective and smaller-scale observations, high-resolution virtual laboratories, and a system of parameterization test beds with a range of complexities. It is suggested that the development of physically-based parameterizations that are scale-aware, non-local, non-equilibrium, and stochastic should offer the optimum forward path. This is especially true for convection, but there is also an urgent need for improvements in sub-grid turbulence schemes, the representation of sub-grid orography, the representation of cloud microphysical processes and of land and ocean surface interactions, especially as shorter-range forecast models (and the highest resolution regional climate models) move towards sub-kilometre resolutions.

10.1 INTRODUCTION

Representing physical processes that occur on spatial and temporal scales that are not explicitly resolved is an outstanding challenge for weather and climate prediction models. For global models, atmospheric convection continues to be one of the most notable of these (e.g. Sherwood et al. 2014). Convection interacts with the larger-scale dynamics in ways that remain poorly represented in global models. Errors in representing convection contribute to errors in many parts of the climate system, including cloud radiative properties, diurnal-to-inter-annual variability, and the global water cycle (Stevens and Bony, 2013). Short-range forecasts of global convection also remain poor. Convection is often crucial for forecasts of severe windstorms, flooding, and drought, which in turn have fundamental impacts on human safety, agriculture, and the biosphere.
With the expected increase in computing power, the next ten years will see global operational modelling systems for weather and climate using atmospheric grid lengths ranging from a few kilometres to around a hundred kilometres. On the other hand, for some problems requiring very long integration times, large forecast ensembles, or significant additional complexity (e.g. detailed atmospheric chemistry and/or ocean biogeochemistry), a hundred kilometre grid length may still be too expensive. Hence for the foreseeable future, the overwhelming majority of weather and climate forecasts will continue to use grid lengths where convection needs to be fully or at least partially parameterized, and therefore the understanding of convective processes and how to parameterize them across these scales is a fundamental and urgent requirement.
Although there is often emphasis on convective processes (as reflected in the balance of submissions to the World Weather Open Science Conference, WWOSC-2014), it should be noted that the parameterization challenges of clouds in general and the associated microphysical, turbulence and land surface processes are also extremely important. Additionally, while it has become almost obsessional to focus research on moist physics, it is well-known among global modellers in particular that representing drag/dissipation processes accurately can play as important a role in accurately modelling the large-scale circulation, with model performance extremely sensitive to the (relatively uncertain) representation of drag. (See Section 10.2.2).

For regional models, many of the parameterization issues remain as for global models: e.g. boundary layer turbulence and cloud microphysics remain fully parameterized even in models with resolution of around one kilometre. However, these models do start to explicitly represent deep convection (convection-permitting rather than truly convection-resolving), and hence convection parameterizations are typically significantly modified in this 'grey-zone' such that deep convection is either turned off or at least significantly turned down; however, there remain many open questions as to how to handle shallow convection at these resolutions since it will be barely, if at all, represented explicitly. Some changes often involving the addition of extra complexity are also usually made to other schemes (e.g. microphysics and land surface) in models where detailed prediction of local weather is the goal.

10.2 KEY QUESTIONS AND CHALLENGES

10.2.1 The parameterization of convection in global models

It is now possible to represent deep convection (order 1 km grid spacing) in model domains of global scale, and to resolve large eddies (order 10 m grid spacing) in model domains containing small numbers of individual clouds, and this represents a unique opportunity to make more rapid progress in convection research. The following discussion in this section of the challenges and opportunities in the next decade relies substantially on input from the report of a recent UK workshop (Holloway et al. 2014).

The key challenges we currently face are:

1) What is the best way to represent convection in the "deep convection grey zone", i.e. at grid scales that are similar to the scales of a typical deep convective cell? (Clearly shallow convective clouds continue to need parameterization at these scales). This question also arises because conventional quasi-equilibrium closure ideas break down at these scales (and have significant deficiencies even at coarser grid scales). The importance of this question has been recognized by the existence for several years of the ongoing Global Energy and Water Cycle Experiment (GEWEX) Atmosphere System Study (GASS)-Working Group on Numerical Experimentation (WGNE) 'Grey Zone Project', an international collaboration activity.
2) To what extent will realistic convective organization and scale interactions emerge simply by moving to models with higher resolution (and explicit convection), and to what extent is it necessary to parameterize aspects of organization?
3) How can the modelling of phenomena that involve convection and interactions across a large range of scales be improved? Examples of these phenomena include the Madden-Julian Oscillation (MJO), monsoons, extra-tropical and tropical cyclones.

To address these challenging questions, efforts should focus on progressing the development of physically based convective parameterizations that are:

- Scale-aware: adapting automatically to changes in grid length and in updraught area fraction.
- Non-local: simulating realistic spatial and temporal structure, with representations of memory and interactions between grid points.
- Non-equilibrium: with closures that take account of triggering mechanisms, particularly sub-cloud environment variability at both resolved and sub-grid scales.
- Stochastic: with the parameterization at one time step and grid point representing a single realization of convection taken from a probability density function (PDF) given the larger-scale conditions (and assumed spatial and temporal correlations of the convection), rather than the mean of this PDF.

Parameterizations already exist that incorporate one or more of the above qualities, and examples can be found in Arakawa and Wu (2013), Plant and Craig (2008), Mapes and Neale (2011), Brown and Grant (1997), Rio et al. (2013), Park (2014) and Bechtold et al. (2014). However, it should be recognized that major, concerted research efforts are likely to be required to develop schemes that incorporate them all. A global model using super-parameterized convection, in which a 2-D Cloud-system Resolving Models (CRMs) is embedded in each large-scale grid cell, has also shown promising results e.g. Khairoutdinov and Randall (2001) and Randall (2013). Global CRMs are also beginning to increase the understanding of large-scale convectively coupled phenomena (e.g. Satoh et al. 2012). Work on the effects of non-deterministic statistics of convection is helping to show the benefits of stochastic parameterizations, especially at higher resolution (e.g. Berner et al. 2012; Peters et al. 2013). Several of the parameterization features proposed above, including scale awareness and stochasticity, are recommended (or at least discussed as possible ways forward) in a chapter of a recent World Climate Research Programme (WCRP) volume on research, modelling, and prediction priorities (Sherwood et al. 2013), highlighting agreement within the broader scientific community.

It seems likely that mass-flux based convection parameterizations will continue to be useful in the foreseeable future over a range of model grid lengths, although there are merits in other types of schemes, such as super-parameterization. If so, the total mass flux will probably be separated into updraught fraction and updraught velocity (required for aerosol-cloud interactions); likewise, parameterizations will need to do proportionately less of the work as the updraught fraction becomes larger.

In developing and evaluating new parameterizations, the convection community will make use of new simulations that represent macroscale convective dynamics (triggering, updraughts, downdraughts, and cold pools) in domains that capture large-scale circulations such as monsoons. Results from the *Cascade* project (e.g. Marsham et al. 2013) have shown the power of these simulations in describing interactions between convection and dynamics that could not previously be observed or modelled. Global convection-permitting simulations are now becoming possible, and there will be increased use of such simulations to connect process studies (observations and Large-Eddy Simulation [LES] models) with global dynamics and the parameterization problem. High-resolution models (with order 1 km grid length or smaller) remain a key tool for supporting parameterization development and there is still a need for a comprehensive evaluation of the resolution dependence of simulations with these models for a range of environments and phenomena. In particular, an evaluation of the appropriateness of current sub-grid parameterizations of turbulence and microphysics at different resolutions is required. Convective-scale observations will be needed to evaluate and develop LESs and CRMs, and these will require improved instrument capability to provide measurements of in-cloud quantities such as vertical velocity, mass flux, temperature, entrainment rate, detrainment rate, and heating rate. Higher moments (variability) of in-cloud and environmental properties will also need to be measured, along with surface properties over land (such as vegetation and soil moisture).

To develop the new parameterization schemes envisaged above will require substantial dedicated resources and new data sources from observations and LES, together with new methods for analyzing such data and assessing the resulting parameterizations. Investing significant high-performance computing in pursuing an LES “virtual laboratory” approach with small horizontal grid lengths (order 10-100 m) combined with large domain sizes (order 100-1000 km) will provide sub-cloud process information (e.g. entrainment, detrainment, and in-cloud vertical velocities) as well as interactions between sub-cloud scales and larger scales. This is somewhat analogous to a much higher-resolution version of the UK Cascade project, which used limited-area simulations at CRM grid lengths (1.5-12 km) of tropical domains several thousand kilometres across to study convective interactions with larger-scale phenomena such as the West African Monsoon (Marsham et al. 2013), the MJO (Holloway et al. 2013), and the diurnal cycle of precipitation in the Maritime Continent (Love et al. 2011). Another ongoing example is the German research programme ‘High definition Clouds and Precipitation for Advancing Climate Prediction’ (HDCP2). Such simulations then provide a means of comparing coarser-resolution model simulations (CRMs and general circulation models [GCMs]), observations, higher-resolution process models, and theories of convective coupling. Ideally, a hierarchy of model configurations for parameterization development is required which will build on existing models with various degrees of complexity, from single column models and idealised 3-D simulations through to implementation in the full GCM. These simulations should include large-domain idealised cases and realistic case studies using both explicit convection and parameterized convection at the desired operational resolution. Much of this research plan and the necessary protocols and groundwork for this are laid out in the ongoing GASS-WGNE ‘Grey Zone Project’, and it is expected that significant improvements in convective parameterizations over the next 5 to 10 years will result, with concomitant improvements in global weather and climate predictions.

10.2.2 Other model parameterizations in global models

With the availability of more computer power, the resolution of global models is increasing to the point where convection is partially resolved (as discussed above), orography is better represented, and the land characterization can have more details. Also, data assimilation is expected to make better use of satellite observations that are affected by clouds, precipitation and land surface. The observations will not only help to define the state variables of the atmosphere, but will also inspire and inform parameterization development. All these aspects will raise new parameterization issues and will require extensive research. In principle, some of these issues are already addressed now in the context of high-resolution regional models (see Section 10.2.3). However, the requirements of global models put a much stronger constraint on sub-grid schemes as they have to work adequately in different climate regimes.

Clouds

At a recent European Center for Medium range Weather Forecasting (ECMWF) workshop on cloud parameterization (ECMWF, 2013), it was concluded that the following areas require more attention: (i) microphysics, (ii) the representation of sub-grid variability, and (iii) the use of observations. Bulk microphysics schemes will be necessary at all resolutions, but it is by no means clear what complexity is optimal at what resolution. The representation of microphysics needs to be, as much as possible, resolution independent or resolution aware. Current complexity in global models appears appropriate with prognostic variables for cloud water, cloud ice, rain and snow, but in future additional variables for number concentrations may be beneficial. The interaction of aerosols with microphysics still requires more research before conclusions for parameterization can be drawn.

Regarding the representation of sub-grid variability of clouds, various approaches are in use e.g. through a PDF scheme with prognostic variables for higher order moments (Golaz et al. 2002) or simply cloud cover (Ahlgrimm and Forbes, 2014). At this stage it is not clear what the optimal approach is and at what resolution an all or nothing scheme will suffice. It should be noted that cloud/radiation interaction is highly non-linear and therefore a representation of cloud heterogeneity is likely to remain an important aspect at all resolutions. The ECMWF workshop concluded that a hybrid formulation based on the use of a cloud cover variable and assumptions about in-cloud PDF's may be a suitable research direction for many years. The role of LES models is believed to be important as these models can provide sources and sinks for the prognostic equations and information about the PDF's in various cloud regimes. Another major issue is the role and behaviour of mixed phase clouds, because the way these clouds are maintained is still very uncertain (Shupe et al. 2008). Observations and verification will play a key role in all aspects of the cloud parameterization research. At this stage only a small fraction of the available passive microwave and active radar/lidar observations has been explored (Illingworth et al. 2015), so it is expected that further exploitation will lead to many improvements in cloud and precipitation formulations of global models.

Radiation

Radiation is probably the least controversial of all model processes and is well supported by line-by-line computations. However, it still poses major parameterization issues. Current radiation schemes can compute clear sky radiation to a high level of accuracy, but such computations tend to be expensive and the available codes make compromises between accuracy and efficiency, e.g. by limiting spectral, spatial and temporal resolution. This will remain an active area of research also in view of changing computer architectures (highly parallel and/or supported by dedicated accelerator processors). Cloud optical properties and the representation of cloud heterogeneity will remain an important topic (Hogan and Illingworth, 2000). Also, the representation of 3D effects will become increasingly relevant at high resolution (Hogan and Kew, 2006), (Wissmeier et al. 2013).

The two way interaction between cloud dynamics and radiation, e.g. through cloud top cooling, will become more important, and might require high frequency coupling between the radiation and cloud schemes.

The planetary boundary layer

Parameterizations of the boundary layer and shallow convection are still needed even when deep convection is reasonably resolved at e.g. 500 m resolution. The boundary layer parameterization problem will only be alleviated when another order of magnitude resolution increase can be achieved, e.g. 100 m resolution. In all cases an appropriate 3D sub-grid model will be required, but the expectation is that the sensitivity to the representation of sub-grid turbulence becomes less dominant in LES where the sub-grid model is in the isotropic turbulence cascade regime (at least for convective boundary layers). Simulations at LES resolution of 100 m can already be performed over considerable domains and will help to address the parameterization issues at resolutions between 20 km and 1 km resolution, which will be the resolution of many global models over the coming 10 years. Current boundary layer schemes tend to use a combination of diffusion for dry turbulent transport and a mass flux approach for cloudy boundary layers. Some of them are supported by a turbulent kinetic energy equation. Interestingly, many traditional issues with boundary layer, and boundary layer cloud, representations in large scale models are still unresolved: notable examples are the lack of wind turning (Brown et al. 2006), the lack of response of surface wind speed to stability (Chelton et al. 2001), the excessive diffusion in stable situations and the associated underestimation of nocturnal jets (Holtslag et al. 2013), the uncertainty in cloud forcing in climate models (Bony and Dufresne, 2005), the difficulties with the transition from cumulus to stratocumulus, and the lack of understanding of the physics of mixed phase clouds (Shupe et al. 2008). Another issue is the representation of the surface boundary condition for momentum over heterogeneous terrain.

The need for excessive diffusion in the stable boundary layer, often formulated by so-called long-tail stability functions, is probably one of the more pressing and poorly understood issues as it hinders the introduction of Turbulent Kinetic Energy (TKE) formulations. The strong diffusion affects surface drag, the thermal coupling with the underlying surface (particularly at high latitudes) and the amplitude of the diurnal cycle for temperature. It is very well possible that the underlying reason for the excessive diffusion in the stable boundary layer is the lack of shallow vertical shears in large scale models which might be due to unresolved mesoscale variability, e.g. variability related to inertial and gravity waves over land and topography. Many of the issues listed above can be studied by making use of LES simulations over a large domain. It is important of course to verify whether the fine scale simulations and the derived parameterizations show the correct dependence on forcing parameters as observed. Examples of such critical dependencies are the relation of boundary layer cloud cover with inversion strength (Klein and Hartmann, 1993) and the dependence of the amplitude of the diurnal cycle on wind speed and radiation (Betts, 2006).

Land momentum issues and sub-grid orography

It is well known that numerical weather prediction models respond strongly to the formulation of various surface drag formulations (Sandu et al. 2013). Drag at the surface is exerted by the resolved orography, sub-grid orography schemes and the boundary layer scheme, and the relative magnitudes of these contributions depend on model resolution. None of these contributions can be evaluated from observations on a routine basis, and experimental campaigns over heterogeneous terrain are extremely rare and often limited (e.g. Bougeault et al. 1997). The basic concepts to represent the different types of drag are well established: i) empirical tables to link surface roughness to vegetation type; ii) effective roughness (Grant and Mason, 2006) or turbulent orographic form drag (Beljaars et al. 2004); iii) flow blocking by sub-grid orography (Lott and Miller, 1997); and iv) gravity wave generation by sub-grid orography (Miller et al. 1989). However, these schemes are often developed with idealized topography in mind, they are difficult to connect to real terrain characteristics and they have many empirical constants. Because direct verification is difficult or impossible, the drag representation is uncertain, and considerable optimization/tuning is necessary on the basis of forecast experiments. In a recent WMO/WGNE initiative, different operational Numerical Weather Prediction (NWP) models were compared and it was concluded that surface drag is rather different in the models. The differences are particularly large for the individual components and for the diurnal cycle, illustrating that the modulation of drag by stability is completely different in different models. The main difficulty in models is, on the one hand, to characterize the land surface in terms of heterogeneity (from vegetation cover to complex orography) and on the other hand, to have formulations that use the land information and convert it into reasonable drag values dependent on wind speed and stability. Most of the theory and schemes have also been developed for uniform flow and stability whereas in reality wind and stability vary with height. To progress in this area of research, more comprehensive use should be made of simulations over real terrain. Routinely run limited area models could be used to try and diagnose resolved drag for topography and provide “ground truth” over a limited area for the global parameterized models. However this in itself needs careful study as these models are not using ‘real’ orographies and will have biases in boundary layer characteristics. Similar simulations could be performed at much higher resolutions by LES models with the purpose of developing parameterizations of drag for heterogeneously vegetated terrain (or effective roughness including stability dependence). This has to be accompanied by activities to map and characterize heterogeneous terrain e.g. from space (lidar) observations.

Land surface schemes

The main role of a land surface scheme in atmospheric models is to provide a surface boundary condition for heat and moisture fluxes (see Balsamo et al. (2014) for a review). The more comprehensive versions of these models also handle carbon, aerosols and other tracers. State-of-the-art land surface schemes in large-scale models are necessarily highly empirical as it is currently impossible to describe the relevant processes in all their complexity and detail. However, these complex processes, occurring over a wide range of spatial and temporal scales, govern the energy and water cycles at global scale, and the large-scale budgets are obviously a priority in global models. The water budget is a clear example, as precipitation falls on the ground in a non-uniform way, some of it is intercepted by the vegetation and evaporates again, and another part falls through and can either run off on the surface or infiltrate into the soil. Soil texture, being highly heterogeneous, affects vertical transport and horizontal water transport to rivers. Evaporation is another important component of the water budget. It is linked to the available energy, but is also highly regulated by vegetation through root distribution and plant physiological processes. The consequence of all this complexity is that it is difficult to build a land surface scheme from the smallest scale of individual leaves and plants and the smallest elements of soil heterogeneity and to integrate such a description to effective scales of the order of 10 km. A related difficulty is that it is impossible to characterize the surface vegetation and soil with sufficient accuracy over the whole globe since accurate datasets to support such characterization do not presently exist. This is the reason that a bulk parameterization of land surface processes is necessary and inevitably there are strong elements of inverse modelling (i.e. parameters have to be optimized on the basis of the results). Having observational information strongly related to the processes that are modelled is important; otherwise the introduction of compensating errors is very likely. Major challenges for the coming years are: i) to achieve consistency between model components e.g. between carbon uptake by vegetation and transpiration (Boussetta et al. 2013a); ii) to represent all the time scales, e.g. from the fast evaporation from plant-intercepted water to the diurnal and seasonal time scales (Gentine et al. 2011); iii) to avoid compensating errors e.g. between bare soil evaporation and transpiration (Lawrence et al. 2007); iv) to integrate as much as possible all available observations e.g. skin temperature and vegetation observations (Trigo and Viterbo, 2003; Bousetta et al. 2013b); and v) to develop a comprehensive benchmarking system e.g. covering the full water budget from precipitation and evaporation to runoff (Hirschi et al. 2006; Blyth et al. 2011). Integrating diverse observational sources will require a more holistic approach to parameterization testing, and should be combined with innovative applications of data assimilation techniques extending parameter space. Improved understanding of surface process mechanisms will rely on the combination of optimal estimation techniques and modelling, to identify optimal parameters and also to better identify certain limits within the existing schemes.

10.2.3 Parameterization issues specific to convection-permitting models

In the last decade, many meteorological centres have implemented operational regional NWP systems based on non-hydrostatic convection-permitting models (Weiss et al. 2008; Lean et al. 2008; Baldauf et al. 2011; Seity et al. 2011). In such models, the spatial resolution is supposed to be sufficient to resolve convective systems. The horizontal resolution was increased from 3-5 km in the earlier versions to 1-3 km at present with a forecast lead time up to 1-2 days. It is however clear that these resolutions are not really sufficient to resolve deep convective cells well but are able to resolve the macrosystem, and hence these models have proved able to provide skilful guidance for operational forecasting of high-impact weather at the mesoscale, such as heavy convective rainfall, fog, mid-latitude storms or tropical cyclones. They produce more realistic convective precipitation structures compared to lower resolution models using parameterized convection. New approaches have been developed for high resolution model verifications, oriented towards weather elements and severe weather events (Gilleland et al. 2010; Roberts and Lean, 2008; Mittermaier, 2014; Ebert and McBride, 2000), which confirm some benefits of convection-permitting models compared with global models. Very recently these models have started to be applied to downscale climate models (e.g. Kendon et al. 2014), with the improved representation of convection leading to different conclusions about likely changes in heavy convective rainfall in a future climate.

Convection permitting models typically do not include deep convection parameterization despite the fact that their resolution is still insufficient to resolve deep convection very well. Generally they also do not include orography-induced gravity wave parameterization but they often have similar physical parameterizations to global models for turbulence, shallow convection, micro-physics, radiation and surface processes, the physical processes operating at these scales being mostly the same. This strongly supports the concept of seamless prediction of weather and climate which consists of developing models that can be used in a more or less continuous way over a wide range of spatial and temporal scales. However, there are still specific issues regarding physical parameterizations in convection-permitting models. For instance, micro-physical processes which are crucial for the explicit evolution of deep convection are often parameterized in a more detailed manner, and the inclusion of extra species also helps with the assimilation of radar data. Several physical processes cannot be neglected any longer at kilometric scales and physics/dynamics coupling plays a bigger role because of shorter time scales (See later discussion on coupling. The following section will focus on key questions specific to physical parameterization in convection-permitting regional models.

Microphysics

The micro-physical scheme is a key component in convection-permitting models because of the role of dynamics-microphysics-radiation interactions in the evolution of convection (Grabowski and Moncrieff, 1999; Petch and Gray, 2001). Micro-physical schemes vary widely in complexity, differing in the number of prognostic parameters used to describe condensed water particles covering a wide range of sizes and shapes (for ice crystals) and in depicting micro-physical interactions. Though 'bin' micro-physical schemes (size distribution discretised into bins) are quite successful, they are too expensive to be used operationally. Hence 'bulk' micro-physical schemes are used in convection-permitting models. The distribution of hydro-meteors is represented by several classes of particles, each class being represented with a specified type of size spectrum (e.g. exponential, gamma, log-normal, etc.) and a small number of predicted parameters, generally the first moments of the distribution (mass, number concentration, reflectivity, etc.). Micro-physical schemes within convection permitting models include generally more classes than within global models for solid condensates, such as graupel and sometimes hail. Ice micro-physics has a particularly important impact on the evolution of the convection (Liu et al. 1997; Bryan and Morrison, 2012). The use of a one moment bulk micro-physics scheme and a very basic aerosol representation has been widely used in convection-permitting operational models. There is now a clear orientation towards the development of more detailed multi-moments and multi-species schemes with aerosol coupling to improve the representation of size distributions and hence micro-physical process rates (Seifert and Beheng, 2006a,b; Phillips et al. 2007). However, the understanding of physical processes such as the conversion parameters (snow to graupel, liquid and ice auto-conversion...) and of ice particles (nucleation, shape, diffusional growth, aggregation, breakup, riming, density changes) is as yet unsatisfactory, although the work of Morrison and Milbrandt (2015) and Sulia et al. (2014) is promising. Further research is strongly needed to improve the understanding of these physical processes and their parameterization in NWP kilometric scale models. Better consistency should be achieved between micro-physics and radiation schemes for modelling cloud optical properties with precipitating particles (rain, snow, graupel, etc.) still often ignored by radiative transfer schemes despite evidence that they play a significant role (Petch, 1998).

Convection and turbulence

Some sort of parameterization of convection is still needed in kilometre scale models, which explicitly resolve only deep convective systems. Most of the convection is not explicitly resolved, for instance thermals in the PBL, shallow and medium convection in the troposphere, but also non-organised deep convective clouds. The triggering and the evolution of explicit convection rely very strongly on a consistent treatment of turbulence and thermals (dry and moist) in PBL. Some progress has been achieved in recent years for high resolution and global models with the developments of eddy-diffusivity and mass-flux “EDMF” schemes (Hourdin et al. 2002; Siebesma et al. 2007; Pergaud et al. 2009) and higher-order closure turbulence schemes (Bogenschutz et al. 2010). The inclusion of physically-based stochastic elements in PBL schemes seems promising for the representation of the sub-grid spatial heterogeneity and the onset of explicit convection. The modelling of the convection at grey zone resolutions (around 5 km for deep convection and around 500m for shallow convection) is a growing research topic both for global and regional models. The GASS-WGNE Grey Zone project has been undertaken to gain an insight and understanding of the behaviour of models in the grey zone and to provide guidance and benchmarks for the design of new scale-aware convective parameterizations that can operate in the grey zone. The use of LES simulations on large geographical domains is promising to help diagnose the proportion of resolved and parameterized turbulence according to spatial resolution (Honnert at al. 2011) and to develop scale aware physical parameterizations.

The representation of turbulence in stable conditions (polar regions, nocturnal inversions, the free troposphere, the tropopause etc.) is also an important issue for high resolution models. The modelling of turbulence over orography or at the edge of convective clouds warrants more attention in convection permitting models than in global models. The representation of 3D turbulence will become important in mountain regions with further increases in model resolution. Research is needed to develop and improve 3D turbulence parameterization and demonstrate its utility for hectometric resolutions.

Radiation and surface processes

Similar radiation schemes are used in low and high resolution models. However, radiation-cloud-aerosol interactions, generally not computed every time-step because of their computational cost, should be parameterized more frequently in convection permitting models which simulate shorter time scales. Radiation schemes with an intermittent level for computation of gaseous transmissions coupled with a radiation-cloud interaction at every time-step look promising. Some radiative orographic effects such as slope, shading and sky view factor need to be parameterized in kilometre scale models (Müller and Scherer, 2005). Since full 3D radiation schemes are very demanding in computational resources and will not be affordable for many years, there is a need to parameterize some 3D radiative effects in a simple way (for instance cloud shading at the surface). Surface processes also warrant some specific adaptations for kilometre scales models. Available climatological databases for physiography and soil properties at kilometric scales are not of uniform quality and still contain significant errors. Research is needed to improve these databases and to develop new ones at much higher resolutions (~100 m). The assimilation of satellite observations should be promoted to provide real-time surface parameters, such as albedo, vegetation fraction or leaf area index. There is also a need for improved orographic databases at very high resolutions (~30 m) for computing sub-grid orographic parameters such as orographic roughness, slope, standard deviation, non-isotropic properties derived from the tensor of orographic gradient correlation, sky-view parameters, etc. The implementation of urban schemes has been found to be very positive in improving the simulation of surface fluxes over large cities and the diurnal cycle of the surface temperature, although recent inter-comparison studies have shown that relatively simple schemes may perform as well in many respects as more complex ones (Best and Grimmond, 2014). Many aspects (urban moisture, momentum fluxes, town gardens, etc.) of these schemes, including the availability and standardisation of urban parameters (a major issue), are in dire need of further study. The use of kilometre-scale, and soon sub-kilometre-scale, models opens the way to simulate snow-pack and hydrology over mountains. The snow parameterization should be improved to describe the time evolution of the physical properties of the inner snow-pack (thermal conduction, radiative transfer) based on the time evolution of the morphological properties of the snow grains along with snow metamorphism. A parameterization of blowing snow will be important as well. The coupling with hydrological models is needed to forecast flash-floods. There is a continuing trend for increasing the vertical resolution near the ground to improve the simulation of radiation fog, but this is in contradiction with the blending height hypothesis. Research is needed to improve coupled land-atmosphere modelling systems.

Coupling

Physics/dynamics coupling is very important in convection permitting models, because explicit convection results from a complex feed-back between the buoyancy force (dynamics) and the condensation/evaporation (physics). The order (sequential or parallel) of computing physical parameterizations (ranging from slow to fast processes) matters significantly. The way physics and dynamics are connected also has some importance, such as the location of physics tendency computations in models using a semi-Lagrangian trajectory. The tendencies computed in the physics have to be projected into the dynamical equations in a consistent way to assure the conservation of mass, momentum and energy. Implicit and explicit numerical diffusion have also a significant impact in convection permitting models (Piotrowski et al. 2009, Langhans et al. 2012). For all these reasons, a better understanding of physics/dynamics coupling is strongly needed in these models. This should bring modelling experts working on physics and dynamics closer.

10.3 CONCLUSIONS

The problem of representing unresolved physical processes in numerical models of the atmosphere remains a crucial one and has been discussed here at some length. The ever-decreasing grid lengths of atmospheric forecast models has helped resolve some aspects of the problem but raised new challenges also. Of particular note is the difficulty in representing convection at ‘Grey Zone’ resolutions. The importance of using large domain LES-type integrations as a surrogate for the real atmosphere has been emphasised and what might be expected from such an approach considered. It is recognised that as well as convection, challenges exist for many other processes that are parameterized in global models. The additional requirements posed when shorter and shorter space and timescales are introduced (such as in sub-kilometre limited-area models) were also reviewed and similar grey zone issues at sub-kilometre resolutions with regard to boundary layer circulations discussed.

This paper did not set out to answer these challenges but rather to identify them and indicate possible pathways forward. Collectively the scientific problems outlined in this paper will require a vast amount of research and development in the coming decade; work that is essential if our forecast systems are to continue their rapid progress.

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CHAPTER 11. STOCHASTIC FORCING, ENSEMBLE PREDICTION SYSTEMS AND TIGGE

Thomas M. Hamill and Richard Swinbank

ABSTRACT

Many operational NWP centres now produce global medium-range (≤ 14 day) and higher-resolution, limited-area, shorter-range (≤ 3 day) ensemble forecasts. These provide probabilistic guidance and early warning of the likelihood of high-impact weather. There are two main challenges in the design of ensemble prediction systems: (1) properly simulating the initial condition uncertainty, including the definition of the initial ocean, land, and sea-ice states, and (2) properly simulating the uncertainty due to inadequate representations of physical processes in Numerical Weather Prediction (NWP) models.

Post-processing the output from the ensemble prediction systems using past forecasts and observations/analyses can dramatically reduce systematic errors in forecast products and improve skill and reliability. The generation of products from multi-model ensembles (facilitated by the THe Observing system Research Predictability EXperiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) database, sharing global operational ensemble forecasts) has also been shown to frequently improve the skill and reliability of ensemble predictions.

11.1 INTRODUCTION

From the earliest days of weather forecasting, there has been an appreciation that there are inevitable uncertainties in weather prediction. Admiral FitzRoy, the founder of the UK Met Office, wrote in a letter to the *British Times* newspaper some 150 years ago that “forecasts are expressions of probabilities - and not dogmatic predictions.” However, only in the last two decades has it become computationally feasible to apply methods that objectively calculate the state-dependent uncertainties in weather forecasts. Prior to this, forecast guidance typically consisted of one model integration, and forecasts were expressed deterministically. Now, while some deterministic models are often run at higher resolutions, an increasing role is played by ensembles of forecasts that are integrated from sets of slightly different initial conditions, and employ methods to simulate the uncertainty of the forecast model itself. The intent is to make sharp (specific) yet reliable state-dependent probabilistic forecasts (Gneiting et al. 2007) directly from the ensemble guidance.

The penetration of probabilistic concepts throughout the forecast process is not yet complete. Customers of weather forecasts still generally expect deterministic expressions for upcoming forecasts, even though in many cases more appropriate decisions could be made when leveraging probabilistic information (Zhu et al. 2002). Although ensemble prediction is becoming increasingly important at operational NWP (numerical weather prediction) centres, prediction systems are still commonly evaluated with deterministic verification methods. As discussed by Palmer (2014), this can lead us to inappropriate conclusions about whether we have improved our prediction systems. Common deterministic verification metrics include root mean square (RMS) errors, anomaly correlations, and threat scores (Wilks 2011, Joliffe and Stephenson 2012). Unfortunately, such measures often penalize the forecasting of small-scale features if they are not predictable; a smoother forecast lacking such scales of motion is assessed as providing higher skill. The existence of smaller-scale phenomena is of course realistic and consistent with a continuous energy spectrum across scales (Nastrom and Gage 1985). In contrast, the use of probabilistic verification metrics such as the continuous ranked probability skill score (CRPSS; Wilks 2011, Chapter 7) suffers no such consequences, though observation errors should be accounted for (Candille and Talagrand 2008). A forecast is rewarded for accurately predicting the probability as specifically as possible, subject to their being reliable. If an ensemble of forecasts is missing small scales present in the analysis, it will be penalized for this lack of variability.

Despite such impediments, over the last decade ensemble predictions have matured, in part from better and higher-resolution prediction systems afforded by larger computers and in part from a more thorough understanding and codification of the underlying theoretical concepts stimulated by research. This research has included collaborative studies facilitated by WMO's THORPEX (The Observing System Research and Predictability Experiment) programme and its shared TIGGE (The International Grand Global Ensemble, formerly known as THORPEX Interactive Grand Global Ensemble; Bougeault et al. 2010) database. This chapter reviews the current state of the science of ensemble prediction and suggests fruitful areas for further research. In Section 11.2, we touch upon the advances in construction of initial conditions; the operational centres now have as many similarities in their methods as differences, thanks to advances in ensemble-based data assimilation. We also discuss uncertainty in the state of the lower boundary (ocean, land, ice). Section 11.3 focuses on a current key development in ensemble prediction, the use of stochastic forcing methods to treat model uncertainty. Those techniques are at an earlier stage of the development cycle than initial-condition uncertainty. Section 11.4 describes various practical methods to address systematic errors in ensemble predictions, both by combining predictions from different centres' systems and by using more objective statistical methods that correct today's forecast based on discrepancies noted between past forecasts and observations/analyses. Finally, in Section 11.5 we discuss some applications of ensembles to produce risk-based weather forecasts, particularly as they enable improved forecasts of high-impact weather events. Some related material on ensemble design and post-processing is also available in the chapter "Global Environmental Prediction."

11.2 ENSEMBLE INITIAL CONDITIONS

11.2.1 Introduction

At the dawn of operational ensemble prediction in the early 1990s, the scientific debate about ensembles focused largely on the method of construction of the ensemble of initial atmospheric model states, meant to sample the uncertainties in the initial conditions. On the basis of trying to provide a medium-range ensemble that explained as much as possible of the forecast error, ECMWF (European Centre for Medium-range Weather Forecasts) scientists proposed the use of "singular vectors" (Buizza and Palmer 1995, Molteni et al. 1996), perturbations that grow the fastest in time given the chosen initial and final norms for measuring perturbation size. For both times, ECMWF chose the dry total-energy norm. In more recent years, ECMWF has blended in tropical singular vectors (Barkmeijer et al. 2001, Puri et al. 2001) and perturbations generated by running parallel, reduced-resolution 4D-Var cycles that assimilate perturbed observations. They refer to the latter as "*ensembles of data assimilations*," or EDA (Bonavita et al. 2012; Lang et al. 2014).

Under the assumption that the most critical initial-condition errors would be inherited from the background forecast in the data assimilation process, NCEP (the US National Centers for Environmental Prediction) initially used the "bred vector" method (Toth and Kalnay 1993, 1997). Initially random perturbations were repeatedly forecast forward in time to the next assimilation cycle, then rescaled and adjusted in amplitude to be generally consistent with a climatological estimate of analysis uncertainties. Analysis uncertainties were described by a "mask," i.e. a field of spatially varying analysis variances. Over the last five years, NCEP has used a modified version of the breeding technique known as "ensemble transform with rescaling," or "ETR" (Wei et al. 2008). This procedure added ortho-normalization so that pairs of perturbations did not result in forecasts with as highly correlated forecast errors.

The Canadian Meteorological Centre (CMC) initially used the "perturbed observations" method to quantify the effect of observation errors on the uncertainties in the initial state (Houtekamer and Derome 1995). Parallel 3D-Var data assimilation cycles were conducted, with each member cycle updated with perturbed observations consisting of the control observations plus realizations of random noise consistent with observation-error statistics. In recent years, CMC has migrated to the use of an ensemble Kalman filter, or "EnKF" (e.g. Evensen 1994; Houtekamer and Mitchell 1998, Burgers et al. 1998, Hamill 2006) whereby the ensemble provides background-error statistics for the data assimilation, and the update produces an ensemble of analyses consistent with draws from the implied analysis-error covariances. In 2015, NCEP will also migrate to using initial perturbations from 6-hour forecasts generated from EnKF analysis perturbations. The UK Met Office uses a related technique known as the ensemble transform Kalman filter, or ETKF (Wang and Bishop 2003, Bowler et al. 2008).

There actually is a theoretical basis for the optimal choice of initial condition perturbations, outlined in Ehrendorfer and Tribbia (1997). Under assumptions of Gaussianity, linearity of error growth, and the choice of final time's norm, analysis-error covariance singular vector initial perturbations will provide the maximum amount of explained forecast error variance at the chosen final time. Restated, these are perturbation structures that are initially consistent with analysis-error statistics while growing most quickly. With this theoretical result in mind, we have the ability to understand the various approximations used by the various centres. While ECMWF's total-energy singular vector perturbations grow quickly, their singular vectors are sub-optimal due to the choice of total energy rather than analysis-error covariance as the initial norm. Their singular-vector perturbations may have too low amplitudes near the tropopause and the surface relative in comparison to singular vectors computed using an initial analysis-error covariance norm (Barkmeijer et al. 1998, 1999, Hamill et al. 2002b). This may result in unrealistic perturbation amplitudes in very short-range forecasts. ECMWF's more recent EDA technique will encounter sampling error from the limited number of perturbed data assimilations conducted and uses an initial covariance that is not flow-dependent (note: this will change to a fully flow-dependent cycling in the next model cycle; personal communication, F. Rabier, 2015). These perturbations are not optimized to grow as quickly as possible, either.

Bred and ETR perturbations only approximately are consistent with the daily varying analysis error statistics; they are not explicitly estimating the state-dependent analysis-error covariances from data assimilation cycle. Further, the procedure only rescales (and in the case of ETR, orthogonalizes) the forecast perturbations. Thus, they cannot account for the randomization effects from observation assimilation (Hamill et al. 2002a), and they are optimized for past forecast error growth rather than future growth.

CMC's and NCEP's EnKF approach are conceptually appealing, in that the resulting initial perturbations are more closely designed to represent analysis-error statistics. In practice, the realism of these perturbations may be limited by several factors. These include the fidelity of model-error representations used in the generation of the ensemble (Mitchell et al. 2002, Zhang et al. 2004, Hamill and Whitaker 2005, 2011, Anderson 2009, Whitaker and Hamill 2012), the underlying assumption of Gaussian error statistics, and the limited ensemble size (sampling error) which requires the introduction of ad-hoc procedures like "covariance localization" (Houtekamer and Mitchell 2001, Hamill et al. 2001) that can introduce additional imbalance. The initial perturbations are typically random rather than computed to explain the maximum forecast error, as with singular vectors. The Met Office ETKF represents a low-dimensional approximation to the EnKF that doesn't involve a full assimilation cycling and covariance localization (Bowler et al. 2008, Bowler and Mylne 2009). Consequently, the rescaling and rotation process of the ETKF strips out too much variance from the prior forecast ensemble, and hence perturbations must be dramatically scaled up in size before use.

In general, limited computational capacity requires making simplifications of one sort or another. The choice of which simplification to apply has varied between the operational centres. Still, over the past two decades the various centres have evolved toward using methods that are increasingly consistent with the theoretical ideal outlined by Ehrendorfer and Tribbia (1997), producing sets of analyses that are consistent with the state-dependent analysis uncertainty.

11.2.2 Underpinning research

While methods for initializing ensembles of atmospheric states are becoming more similar in their underlying approaches, the ensemble prediction systems continue to have too little spread near the earth's surface. This is likely because the uncertainty in the land, water, or ice state is currently not treated at all or is treated sub-optimally. Addressing this is an important direction for future research in the design of ensemble prediction systems.

Consider the land state. As outlined in Sutton et al. (2006), near-surface temperature forecasts and precipitation forecasts can be sensitively dependent on the initial state of soil moisture, and furthermore the analyses of soil moisture are often quite error-prone. The soil moisture states are commonly estimated through the offline cycling of a land-surface model forced by analysed temperatures, humidities, and precipitation, though some centres update their soil moistures with scatterometer data (Scipal et al. 2008, Naemi et al. 2009) and surface relative humidity (de Rosnay et al. 2013). These soil moisture analyses can be highly imperfect, and the land-surface model itself can have significant imperfections, such as mis-specifications of model constants such as soil hydraulic conductivity or surface roughness length. Various centres have recently introduced some methods for increasing near-surface variability, such as by perturbing soil moisture in some form (e.g. Lavaysse et al. 2013, Tennant and Beare 2014). Still, there is much room for improvement. Research is needed into improved ways to simulate the range of model structural and initial-condition uncertainties near the surface (e.g. Hacker et al. 2007, Hacker and Rostkier-Edelstein 2007), thereby providing more realistic ensembles of near-surface temperatures and humidities as well as ranges of initial soil states.

There is also increasing demand for the medium-range ensemble predictions to be extended to sub-seasonal timescales. For these longer-lead predictions, the spread of the atmospheric ensemble will usually grow to near its climatological variability. What predictive skill remains may be in only a few low-frequency modes of oscillation, some related to ocean-state oscillations such as El Niño. Hence, for these extended-range predictions, it may be necessary to quantify the initial uncertainty of the ocean state and how that uncertainty evolves through the duration of the forecast. Ideally, there would be numerical consistency between atmospheric perturbations and ocean perturbations; for example, in a member of the ensemble that has larger wind speeds than average, there might be greater vertical mixing in the ocean state for that ensemble member. Since synoptic-scale variability peaks at O(1 week) while ocean variability peaks at O(1 year), this discrepancy of timescales makes the direct coupling of ocean and atmospheric initialization via methods such as the EnKF potentially problematic, and in need of further exploration (e.g. Yang et al. 2009, Ueno et al. 2010). Relatedly, ensemble predictions out to sub-seasonal timescales may be sensitively dependent on the initialization of sea-ice areal coverage and thickness (Juricke et al. 2014) as well as land snow cover (Jeong et al. 2013).

A common approach for providing spatially detailed forecasts at short leads is to use a higher-resolution, limited-area ensemble prediction system (Hamill and Colucci 1997, 1998, Frogner et al. 2006, Bowler et al. 2008, 2009, Bowler and Mylne 2009, Aspelien et al. 2011, Romine et al. 2014) commonly with lateral boundary conditions provided by a global ensemble prediction system. There are a host of challenges associated with the use of limited-area ensemble prediction systems with one-way interactive nests, many outlined in Warner et al. (1997). The one-way nesting prohibits scale interactivity, whereby developing features inside the limited-area domain can affect the larger scales of motion outside the domain. If the limited-area prediction is carried out in a very small domain, the ability to predict detailed features may be overwhelmed by the "sweeping" in of lower-resolution information from the global model. In an ensemble context, it is also important to provide lateral boundary conditions with appropriate variability (Nutter et al. 2004, Torn et al. 2006).

There are complicated ensemble initialization challenges associated with very high-resolution, shorter-range forecasts as well. The shorter-range, convection- permitting models have the ability to provide forecasts with detail at the scale of individual thunderstorms (e.g. Hohenegger et al. 2008, Clark et al. 2009, 2010, Schwartz et al. 2010, 2014, Johnson and Wang 2012, Duc et al. 2013). For example, the German Weather Service is initializing its regional ensemble with an ETKF (Harnisch and Keil, 2014). However, data assimilation systems like the ETKF or EnKF have underlying assumptions such as Gaussian error statistics (Lawson and Hansen 2004) - assumptions that may be more frequently unrealistic at the convective scale. One would not a priori expect Gaussian ensemble error statistics of cloud liquid water, for example, in the region of a thunderstorm; they might have two dominant modes, no cloud water (with no thunderstorm) and ample cloud water (with thunderstorm). The optimal methods for data assimilation and ensemble initialization in the presence of such non-Gaussian error statistics are not clear. Further, methods are desired that simultaneously perform a high-quality analysis and initialization of both the larger and smaller scales of motion. There are some suggestive directions; there is much research into particle-filter methods as a potential solution (e.g. Gordon et al. 1993, Doucet et al. 2001) but there are also concerns that the "curse of dimensionality" may make such methods impractical with the very-high dimensional systems common in weather prediction (Snyder et al. 2008). Other new directions to address non-Gaussianity include the rank-histogram ensemble filter (Anderson 2010, Metref et al. 2014) and methods that deal with position errors by performing the data assimilation in two steps, a correction for position errors followed by a correction for amplitude errors (Ravela et al. 2007, Nehrkorn et al. 2015).

11.2.3 Linkages and requirements

Several WMO-sponsored projects will help address many of the research questions identified here. For example, the Sub-seasonal to Seasonal (S2S) prediction project (WMO 2013, see Chapter 20) will facilitate coordinated explorations of issues related to prediction at these timescales, including methods for initializing coupled models and how to generate ensembles. WMO is also developing a programme for improving forecasts of high-impact weather (Jones and Golding 2014) that will facilitate further exploration in the design of ensemble prediction systems.

The availability of ensemble prediction data through via the TIGGE project (Bougeault et al. 2010, Swinbank et al. 2015) has greatly facilitated research in these areas. Buizza et al. (2005) carried out an inter-comparison of three of the prediction systems in the TIGGE dataset, but more inter-comparisons to understand the evolving relative strengths and weaknesses of various ensemble methodologies are still needed.

Despite the widespread interest in short-range, high-resolution ensemble prediction, collaboration between prediction centres on this avenue of research has been more difficult; each centre naturally chooses a more limited region of interest driven by their country's need and the tight production timelines for short-range forecast guidance. Still, given the success with global multi-model ensemble prediction (see Section 11.4 below), there may be significant benefit in future coordination between prediction centres (Paccagnella et al. 2011). For example, were each centre in Europe to enlarge the domains of their high-resolution ensemble forecasts to a general common domain while decreasing their ensemble size, it may be possible to have a neutral impact on computational expense at each centre. Exchanging the data between centres would enable each centre to use a larger multi-model ensemble, leveraging the advantages of the multiple dynamical cores, initialization methods, and parameterizations. This may result in ensembles that do a better job of spanning the forecast uncertainty. Such approaches would require rapid exchange of large amounts of prediction data, entailing greater coordination between the prediction centres, and may prove impractical for operational forecasting.

The validation of high-resolution ensemble prediction systems, especially key forecast variables such as precipitation amount and wind strength, is hampered by challenges in the sharing of observational and forecast data. In Europe, this has been addressed by the creation of a TIGGE-LAM (Limited-Area Models; Paccagnella et al. 2011) dataset hosted by ECMWF. Following the example of the global TIGGE dataset, regional ensemble forecasts over Europe from (currently) nine NWP centres are now available for scientific research, though on somewhat different computational domains. In most cases, the data are available from the first half of 2014 to the present. In the US, the Hazardous Weather Testbed project has been running for more than a decade during the spring season, comparing experimental ensemble forecasts run at 4-km resolution across the central USA (Clark et al. 2012).

11.3 STOCHASTIC FORCING

11.3.1 Introduction

Finite grid spacings result in many meso- and microscale phenomena being unresolved in atmospheric models. In such cases the effects of the unresolved scales upon the resolved scales are typically “parameterized,” that is, estimated with closure assumptions that depend on the resolved-scale weather parameters. Parameterization schemes may be developed in several ways (Craig 2014). One way is to base parameterizations on process models that are based on theory developed independent of the atmospheric model. A prediction of mean effects is produced, and sometimes higher moments are estimated as well. Another approach is to use systematic truncations of equations in high-resolution. A third approach is to use ad-hoc formulations to produce a desired effect in the model (for example, hyperdiffusion to control grid-scale noise).

Commonly, these parameterizations have been deterministic; two grid boxes with identical grid-scale states will have the same parameterized tendencies diagnosed for each box, even though the sub-grid scale details may vary between them. Where the model grid size is large, it is assumed that the phenomena being parameterized is likely to be much smaller than the size of the grid box, and its mean statistical properties of the sub-grid effects can be estimated with reasonable approximation (Figure 1a). As models are run using finer grid spacings, two challenges become increasingly apparent. First, note that Figure 1a suggests a simplification that commonly is not valid, that the unresolved phenomena has one characteristic scale that is clearly smaller than the grid scale. Much more commonly, there is a spectrum of motions across scales (Figure 1b); for example, not all convective systems are in fact the same size. Second, there may no longer be a clear scale separation between the phenomena in question and the size of the grid box; the spread of estimates of sub-grid effect between grid boxes with nearly identical large-scale states can be of comparable magnitude to the mean estimate (Plant and Craig 2008). A consequence of neglecting this in the parameterization design is that the ensemble predictions may be unduly similar to each other. This deficiency of spread leads to over-confident probabilistic forecasts.

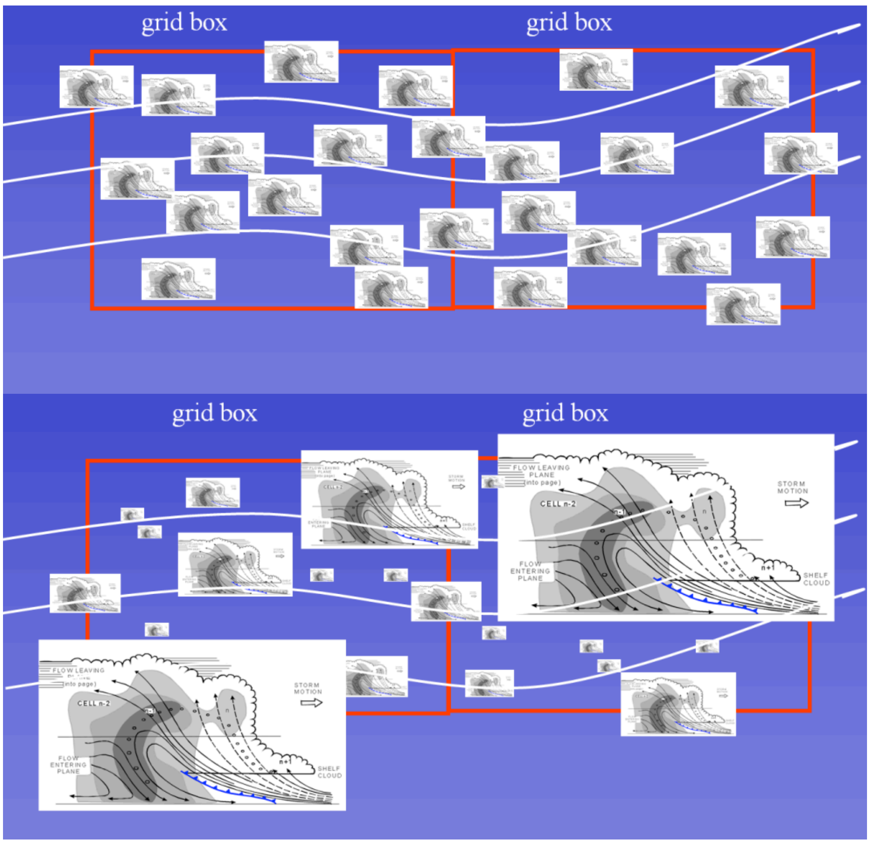

Figure 1. a) Schematic showing clear scale separation between resolved flow and sub grid-scale convection.
b) schematic of a more realistic situation where there is no scale separation.

Source: courtesy of Tim Palmer, Oxford University

Apart from the issue of scale separation, there are several other sources of uncertainty in parameterizations. The grid-scale effects of some subgrid-scale processes may depend on unknowable sub-grid details, not just on the grid-scale details. An example of this is the effect of greatly variable cloud droplet size spectra on the reflection, absorption, and transmission of short-wave radiation. Some details of grid-scale characteristics may be mis-estimated and should be treated as random variables. For example, a mis-estimation of soil characteristics could lead to errors in energy balance affecting surface-temperature forecasts and convective initiation (Sutton et al. 2006).

11.3.2 Underpinning research

A variety of methods have been used to simulate model uncertainty. One of the simplest methods is to estimate probabilities using multi-model ensembles. Since weather prediction centres tend to have developed their models and parameterizations suites somewhat independently, the combination of several ensembles may account for some of the knowledge uncertainty. Multi-model ensembles will be discussed in more detail in Section 11.4 below.

A related approach is to use multiple parameterizations amongst the ensemble members (e.g. Charron et al. 2010, Berner et al. 2011). For example, member 1 may use a Kain-Fritsch deep convective parameterization, member 2 a Tiedtke parameterization, and so on. Experimentally, many have noted significant increases in spread and some improved skill with the use of such approaches. Still, there are significant drawbacks to the multi-parameterization approach. It becomes necessary to maintain a library of multiple parameterizations rather than one, increasing software maintenance expense. Also, should one of the parameterizations be improved significantly, it would be desirable to use that one consistently, so that its improvement affects all ensemble members, rather than retaining out-of-date parameterizations for the sake of diversity. Finally, there can be a loss of “exchangeability,” the desirable property that all ensemble members have identical error statistics.

In a class of schemes referred to as “perturbed parameters,” a number of key parameterization constants are identified whose values are uncertain but which have a significant effect on the model tendencies (e.g. Bowler et al. 2008, Charron et al. 2010, Gebhardt et al. 2011). A range of plausible but different parameterization constants are used across the ensemble members to represent the uncertainty in those parameter values. In some versions of this approach the perturbed parameters are held constant for a given ensemble member, while in other versions, including the “random parameters” scheme used operationally at the Met Office (Bowler et al. 2008) they are varied with time. Such methods are defensible to the extent that parameters are perturbed consistent with their uncertainty and are fully tested in combination with other parameterization constants; without rigorous testing and randomizing the values of the constants over times, it’s possible that specific combinations of perturbed parameters will result in members with non-exchangeable statistics and growing systematic errors.

A very promising approach to representing model uncertainties is the use of stochastic forcing methods, i.e. changing the design of parameterizations that are known to have uncertainties so that they provide stochastic rather than deterministic estimates of the sub-grid effects. One of the earliest methods is “stochastically perturbed physical tendencies” (SPPT; Buizza et al. 1999, Palmer et al. 2009, Bouttier et al. 2012). SPPT is a somewhat ad-hoc method that multiplies the total parameterised tendency by a random number that fluctuates in time and space. These methods have been shown by several centres to increase ensemble spread to be more consistent with mean error.

Realistic representation of model uncertainties requires an understanding of the relevant physical processes. Stochastic kinetic energy backscatter (SKEB; Shutts 2005, Berner et al. 2008, Tennant et al. 2011) attempts to take account of the unphysical energy loss that typically occurs in models as a consequence of numerical diffusion, mountain drag, and deep convection. This method has had the practical effect of making the model energy spectra in ensemble members look more like -5/3 spectral slope expected by theory for the mesoscale (Nastrom and Gage 1985), thus notably increasing spread in the smaller scales of motion. Both SKEB and the previously discussed SPPT schemes are quite widely used in operational ensemble prediction systems.

These considerations have stimulated significant new research into physically based stochastic parameterizations, whereby stochasticity is incorporated into the parameterization in physically realistic ways. Examples of research into stochastic parameterization for deep convection include Lin and Neelin (2000, 2003), Majda (2007), Tompkins and Berner (2008), Plant and Craig (2008), Teixeira and Reynolds (2008), Frenkel et al. (2012), Peters et al. 2013, Grell and Freitas (2014), and Keane et al. (2014). Stochastic parameterization concepts touching on cloud microphysics includes Posselt and Vukicevic (2010), and van Lier-Walqui et al. (2012).

A further consideration is that models need to take into account the uncertainties in the forcing of the atmosphere from the lower boundary. Work addressing the uncertainties in land-surface processes includes Lavaysse et al. (2013) and Tennant and Beare (2014); ocean-atmospheric uncertainty has been studied by McClay et al. (2012).

A longer list of reading material on this subject is available from the 2011 WMO- and ECMWF-sponsored workshop on model uncertainty (ECMWF, 2011).

11.3.3 Linkages and requirements

The 2011 workshop mentioned above provided a succinct summary of the necessary research. The summary stated:

> "*the stochastic parameterization paradigm needs further development at the process level, and hence needs to be incorporated as part of general parameterization development. Key tools will include sophisticated analyses of observational datasets, output from cloud resolving models, and analyses from objective data assimilation. Data assimilation techniques themselves will benefit from better representations of model uncertainty*."

The development of physically based stochastic parameterizations at the individual process level will proceed more rapidly if the scientists involved in the parameterization development and the ensemble system development collaborate. The parameterization methods need to be consistent with the physical laws while faithfully replicating the statistics of the processes. For some parameterizations, the entire formulation might be cast probabilistically, such as the representations of the sub-grid distributions of vertical velocity, temperature, and cloud liquid water as joint PDFs, (e.g. Larson and Golaz 2005, Larson et al. 2012, Bogenshutz and Krueger 2013). With such a formulation, generating a realistic range of parameterization outputs for the ensemble is somewhat more straightforward.

Determining the space- and time-dependent relationships of the PDFs will require further study. Parameterization inputs may have correlated errors; for example, a microphysics parameterization may infer a different drop-size distribution in the presence of few vs. many aerosols, and the aerosol concentration likely is correlated from one grid cell to the next. Stochastic parameterization outputs should also have appropriately correlated structures. For example, the parameterization of convection should be "non-local" in many circumstances, with communication of information between adjacent grid boxes; the organization of convection is important for the realistic simulation of mesoscale convective systems and their influence on larger-scale phenomena.

Modern ensemble-based data assimilation methods provide one useful way of evaluating whether changes in simulating model uncertainty are realistic. With an improved model uncertainty method, the space-time background-error (first-guess) covariances should become more realistic, resulting in a more appropriate adjustment of the background forecast(s) to the observations. Over time, then, the statistics of the mean absolute error of observations minus the forecasts[a] should decrease. There are other novel methods (e.g. Scheuerer and Hamill 2015) for evaluating relationships between forecast state elements and whether they resemble the relationships between observed states.

As noted earlier in this section, parameterization originally relied on the large separation of scales between resolved and unresolved scales. As model resolutions improve further the scales of some physical processes start to overlap the grid-scales. For example, kilometre-scale models are now explicitly resolving some aspects of deep convection, although they may also need to parameterize shallow convection. The regime where processes are partially resolved is often referred to as the grey zone. In this regime, it is a particular challenge to represent turbulent transport of heat, moisture and momentum. At the convective scale it is particularly important to properly represent physical processes in order to represent the uncertainties in the initiation of convection, and the formation of fog and low cloud.

The problem is addressed in part by the WMO “Grey Zone” project which is coordinated by the Global Atmospheric Systems Studies (GASS) within the WMO World Climate Research Programme (WCRP) and the Working Group on Numerical Experimentation (WGNE). Many scientists are contributing to the development of cloud-resolving model simulations that can be coarse-grained and used to provide some ground truth for the development of stochastic parameterizations (e.g. Shutts and Palmer 2007, Palmer et al. 2009). One important issue is the initiation of convection due to unresolved sub-grid-scale fluctuations. Leoncini et al. (2010) showed that small random temperature perturbations could be added in the boundary layer to represent the effects of unresolved fluctuations. A similar stochastic approach has recently been employed in the Met Office, for both deterministic and ensemble convective-scale forecasts, to improve the spatial realism of convective showers (personal communication, A. Lock).

Another international project providing valuable data to support the development of stochastic parameterizations is the Protocol for the Analysis of Land-Surface Models (PALS), organized by the WMO/WCRP Global Energy and Water Cycle Exchanges Project (GEWEX). This project provides data sets suitable for testing and evaluating land-surface models, and can be leveraged to test land-surface models that incorporate physically based stochastic parameterizations.

The WWRP (World Weather Research Programme) has recently instituted a new working group on Predictability, Dynamics and Ensemble Forecasting (PDEF). One of the main scientific challenges that the group will address is the representation of model uncertainty using stochastic techniques. The working group will support the WWRP projects, including the three THORPEX legacy projects on Sub-seasonal to Seasonal prediction (S2S), Polar Prediction Project (PPP, see Chapter 19) and High-impact Weather (HIWeather). Extending the data available from TIGGE, the S2S project will collect ensemble forecasts out to a range of several months, suitable for the inter-comparison of operational methods for simulating model uncertainty and the uncertainty associated with coupled-state interactions. The WMO’s Polar Prediction Project (PPP) will collect databases of Arctic conditions that can be used for the refinement of stochastic parameterizations in the Arctic. Both HIWeather and PPP, plus a range of other research work, will continue to be supported though the provision of ensemble prediction data via TIGGE and TIGGE-LAM, which will continue under the oversight of the PDEF working group.

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[a] *processed through the data assimilation system’s “forward operator.”*

11.4 MODEL COMBINATION AND STATISTICAL POST-PROCESSING.

11.4.1 Background

Although much effort has been applied to reduce systematic errors in NWP models, given past history they are likely to be large enough to be of consequence for decades to come. Deterministic NWP output may often exhibit systematic mean error, and ensembles may also be under-dispersive, i.e. they tend to produce over-confident forecasts. Although the spread deficiency of ensembles has been significantly improved for many variables in recent years (e.g. Gagnon et al. 2014), some customers are requesting reliable, unbiased probabilistic guidance right now for all variables. Hence, other methods such as multi-model or multi-centre ensembles and statistical post-processing are commonly applied to improve forecast reliability and skill.

Multi-centre ensemble combinations exhibit improved skill and reliability of the forecasts (Swinbank et al. 2015 and references therein), especially at the larger scales of motion that are within the predictive capacity of these systems. The different systems commonly exhibit varying systematic errors, and hence their combination provides some increased spread and reduction of error through cancellation. Multi-centre combinations are now a regular part of the post-processing used by weather forecasting centres. Indeed, the North American Ensemble Forecast System (NAEFS; Candille, 2009) has been established by the weather services of the USA, Canada and Mexico to provide multi-model ensemble forecast products as an operational counterpart to the TIGGE research project. The benefit of combining predictions from different ensembles also extends to cyclone track predictions (e.g. Yamaguchi et al. 2012). The applications section below continues the discussion of multi-model techniques.

Beyond simple model combination, many statistical post-processing methods may be applied that address the systematic errors of ensemble predictions. The general approach is to adjust current model guidance using relationships between past forecasts and observations/analyses. Many approaches have been proposed in the last several years, including Bayesian Model Averaging (BMA; Raftery et al. 2005, Wilson et al. 2007, Sloughter et al. 2007, Hamill 2007, Fraley et al. 2010) and related techniques (Wang and Bishop 2005, Glahn et al. 2009, Unger et al. 2009), non-homogeneous Gaussian regression (NGR; Gneiting et al. 2005, Hagedorn et al. 2012), logistic, extended logistic, and heteroscedastic extended logistic regression (e.g. Hamill et al. 2008, Wilks 2004, Roulin and Vannitsem 2012, Messner et al. 2014), analog methods (Hamill and Whitaker 2006, delle Monache et al. 2013), and many other methods (e.g. Hamill and Colucci 1998, Eckel and Walters 1998, Cui et al. 2012, Flowerdew 2013, van Schaeybroeck and Vannitsem 2014, Scheuerer 2014, Scheuerer and König 2014). For the calibration of uncommon events such as heavy precipitation or for longer-lead forecasts where the signal is small and errors are large, a large amount of training data may be needed. One approach to provide extra sample sizes is to run many forecasts of historical cases with a current NWP system (often referred to as reforecasts; Hamill et al. 2006, 2013, Hagedorn 2008, Fundel et al. 2010, Fundel and Zappa 2011). Another approach to increasing sample sizes may be to compose training data across many locations (e.g. Charba and Samplatsky 2011ab, Hamill et al. 2008, 2015).

Statistical post-processing methods are commonly applied independently for each forecast point and lead time. Some applications such as hydrological prediction can benefit from additional information on the joint probabilities between many locations, information which can be lost when processing the data independently. One particularly useful approach for providing correlative information may be through “ensemble copula coupling” (ECC, Schefzik et al. 2013 and references therein). Figure 2 shows how the ECC technique can be used to restore the spatial structure in ensemble members that have previously been calibrated using BMA. Flowerdew (2013) also used a similar approach to ensure spatial coherence of the calibrated ensemble members as part of his reliability-based ensemble calibration method. A complementary approach where multivariate relationships are set using climatological data is known as the “Schaake Shuffle” (Clark et al. 2004). Wilks (2014) provided a comparative evaluation of two.

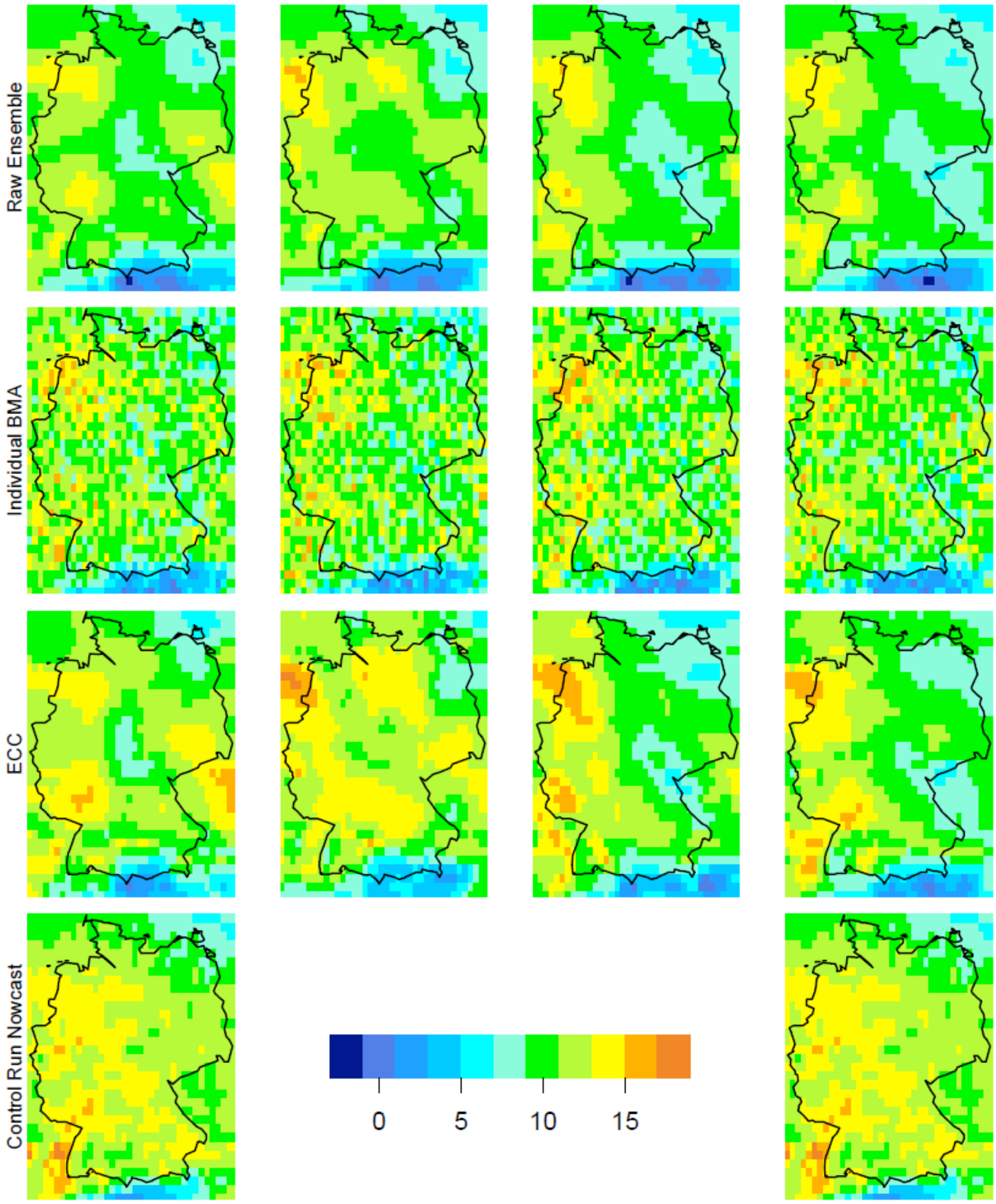

Figure 2. Demonstration of the ability of ECC to recover spatial structure in calibrated ensembles. Top row shows raw 24-hour temperature forecasts (degrees C) valid on 22 April 2011, from four members of the ECMWF ensemble. Second row shows the results of post-processing the ECMWF forecasts with BMA. Post-processing with BMA generates a calibrated PDF, and the grid-point values are generated using random draws from the PDF. Third row shows the samples of calibrated forecasts which have been re-ordered using ECC processing. The bottom picture shows the corresponding nowcast temperature field (control run; the same field is plotted twice).

Source: courtesy of Roman Schefzik

11.4.2 Underpinning research

Despite the proliferation of methods for statistical post-processing, it appears that continued research is needed into improved methods. Methods that may be optimal for one forecast problem (e.g. heavy precipitation) may not be optimal for another (e.g. precipitation type forecasting). Hence, continued research into the development of improved algorithms is desired, especially for variables related to high-impact weather (tropical cyclone intensity, precipitation type, tornado probability, calibration of joint probabilities, and so forth). Methods that facilitate exploratory data analysis for the very high-dimensional data common in post-processing would be helpful; we need to identify predictors and classes of methods that will work adequately from dry to moist locations, from tropical to extra-tropical.

In many situations now, the differences in skill between several credible post-processing algorithms may not be as large as the differences in skill for one algorithm for small vs. large training data sets. Extensive reforecast data sets are expensive to compute, so additional research would be helpful to inform how best to construct the reforecasts. For example, which provides the most useful data across a range of post-processing applications: is a ten-member, twice weekly reforecast spanning ten years preferable to a five-member, twice weekly reforecast over 20 years? What about a five-member, four times weekly reforecast spanning ten years? Should reforecast samples be more frequent for shorter-lead forecasts than for longer-lead forecasts, or vice versa? Hamill et al. (2014) provides some guidance behind possible choices, but more research is needed.

Another challenge with reforecasts is that their statistical characteristics should resemble those of the current operational forecast model. Ideally, this would mean that they would be initialized with reanalyses and ensemble initialization methods that were the same as used operationally; the same forecast model at the same resolution, the same data assimilation methodology. Extensive reanalyses may be impractical for every operational centre to compute for each forecast model. This then raises the practical question as to whether the reanalyses from a different modelling system can be used with or without some modification for reforecast initialization. This is a very new area of research and is currently being pursued at the Canadian Meteorological Centre (personal communication, N. Gagnon, 2014) and at Météo-France (personal communication, M. Boisserie).

11.4.3 Linkages and requirements

The current literature is replete with the testing of large varieties of methods for statistical post-processing. Unfortunately, there are no standardized test data sets that have been published, so it is often difficult to know whether a proposed new methodology is better than an older one, since they likely were not tested with the same data. The development of some standardized forecast and observation/analysis data sets would be helpful.

Since post-processing is dramatically improved with large samples, should the operational centres embrace the reforecast methodology, they will also need dramatically enlarged disk space to make the data accessible to in-house and external developers. Such costs should be incorporated when soliciting bids for future high-performance computing systems or cloud computing and storage.

Finally, post-processing skill will only be as good as the data used to train the method. High-quality, shared analyses of high-impact variables are needed, including precipitation and precipitation type, surface temperature, winds, and humidity, and so forth.

11.5 APPLICATIONS

11.5.1 Introduction

A major motivation for running ensemble prediction systems is to provide better predictions of the risk of high-impact weather. The THORPEX Global Interactive Forecast System (GIFS)-TIGGE working group fostered the development of multi-centre ensemble-based products to support this goal using the TIGGE dataset.

An initial focus of this work was on the developments of experimental products to support tropical cyclone forecasting. Most of the weather prediction centres that participated in TIGGE provided forecasts of tropical cyclone tracks, and in some cases additional data including intensity. Those were exchanged using a new XML-based format (known as CXML, see http://www.bom.gov.au/cyclone/cxmlinfo/), to support the THORPEX Pacific Asian Regional Campaign (T-PARC) and subsequent forecast demonstration projects. With the help of TIGGE data, several different types of products have been developed to support forecasts of tropical cyclones. A simple approach is to plot the individual tracks from each ensemble member. Another approach that has been widely adopted is to calculate a “strike probability” map, showing the probability that the cyclone with pass within a set distance (normally 120 km) of any point (van der Grijn et al. 2004). Figure 3 shows an example of this type of plot for typhoon Hagupit that struck the Philippines in early December 2014. Other useful products include ellipses (Hamill et al. 2011) and graphs showing time series of various measures of the forecast cyclone intensities (e.g. central pressure, maximum wind speed, or vorticity, such as Figure 3 of Hamill et al. 2012).

As noted above, objective verification scores indicate that combining ensembles together is generally beneficial, especially giving improved measures of the uncertainties in cyclone track forecasts, (e.g. Yamaguchi et al. 2012). With the exchange of cyclone forecast information by TIGGE partners, it has been straightforward to use those data to produce strike probabilities and other products based a multi-model grand ensemble. Indeed, the examples shown in Figure 3 are based on the combination of three ensembles.

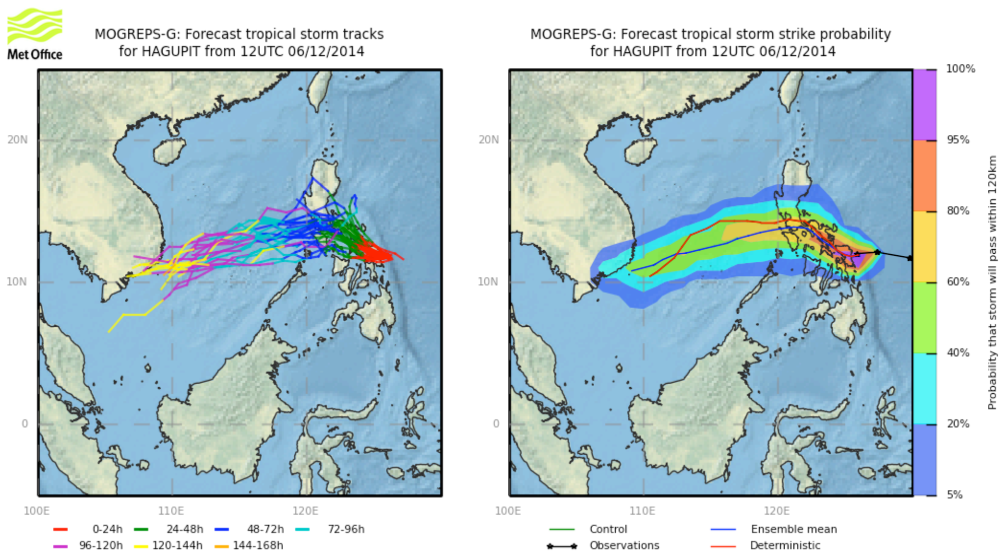

Figure 3. Example of tropical cyclone forecast products for a forecast of typhoon Hagupit from the intial time of 12 UTC 6 December 2014. Left plot: individual track forecasts from each ensemble member. Right plot: summary plot showing strike probability and key tracks.

Source: courtesy of Piers Buchanan

TIGGE has also been used more recently to highlight the risks of heavy rainfall, strong wind and extreme temperatures. Using TIGGE data, Matsueda and Nakazawa (2014) developed a prototype suite of ensemble-based early warning products for severe weather events, using both single-model (ECMWF, JMA, NCEP, and Met Office) and multi-model grand ensembles. These products estimate the forecast probability of the occurrence of heavy rainfall, strong winds, and severe high/low temperatures, based on each model’s climatology. The procedure attempts to calibrate the products by using the climatological probability density function from each ensemble to determine appropriate thresholds for severe weather events. Objective verification of the products confirms that the combination of four ensembles improves the forecast (both statistical reliability and skill) compared with the equivalent product based on a single ensemble. In another initiative developed using TIGGE data, forecasts of humidity are being used to help forecast meningitis outbreaks in the “meningitis belt” south of the Sahara (Hopson, 2014).

With the sophistication of modern NWP systems, unless data is shared, there is now potentially large gap between the forecast information available in the most highly developed countries and that available in less developed countries. Since developing countries are often particularly vulnerable to severe weather events, it is important to address that gap. The WMO has established a Severe Weather Forecast Demonstration Project (SWFDP) that enables some of the less-developed regions of the world to benefit from state of the art numerical predictions. This is achieved by global NWP centres supplying graphical products tailored to support regional SWFDP initiatives. The SWFDP also includes training, to help forecasters interpret and use the new products. Some of the products developed from the TIGGE data are now being rolled out for use in the SWFDP.

The SWFDP was first established in Southern Africa, and following its early success, the initiative was extended to more countries. The SWFDP was then established in a second region - the South Pacific, and has since been extended to South-east Asia and East Africa. It would be very beneficial to extend it to other regions, as funding allows.

11.5.2 Underpinning research

In recent years there has been considerable improvement in the skill of tropical cyclone track forecasts, and ensembles have contributed a lot to quantifying the uncertainties in the track forecasts. However, the skill of forecasts of cyclone intensity has not improved at the same rate. One factor leading to this poor skill could be that global NWP models, in particular those used for ensemble forecasting, are still relatively coarse in resolution compared with the size of storm's inner core. Some recent studies have shown very encouraging results using very high-resolution, limited-area models to simulate the evolution of tropical cyclones (Gall et al. 2013 and references therein). However, it should be noted that environmental factors such as vertical wind shear and humidity are also very important for tropical cyclone formation and intensity changes, so relatively coarse resolution models also have the potential to predict them. The initialization of mesoscale structures is hindered by challenges with data and assimilation methodologies, including the relative paucity of inner-core data in many circumstances as well as other challenges such as substantial position errors and non-Gaussian error statistics (Chen and Snyder 2007, Geer and Bauer 2011, Nehrkorn et al. 2015; and Section 11.2 of this chapter). Continued research on assimilation methods and high-resolution modelling of tropical cyclones is warranted.

While it has proved feasible to provide high-quality forecasts of tropical cyclones tracks a few days ahead, the next challenge is to look further ahead, which entails forecasting cyclone formation as well as evolution. Recent work using the TIGGE ensembles shows that it is now becoming possible to give probabilistically based forecasts of the likelihood of tropical cyclone formation, and an indication of their future tracks, as shown in Figure 4. There are obvious societal benefits from further improvements to both cyclone intensity forecasts and the extension of the forecast range. Given that tropical cyclone formation is sometimes over- or under-forecast in models, the use of reforecasts to assess the deviations of genesis from their climatological probabilities may be helpful (e.g. Figure 4 from Hamill et al. 2012).

Ensembles provide a wealth of information, but this information needs to be synthesized into products that are most useful for decision makers. There is still a significant role for social scientists to play in helping meteorologists determine the best ways to convey probabilistic information (e.g. Joslyn and Savelli 2010, Savelli and Joslyn 2013, Novak et al. 2014, Ash et al. 2014).

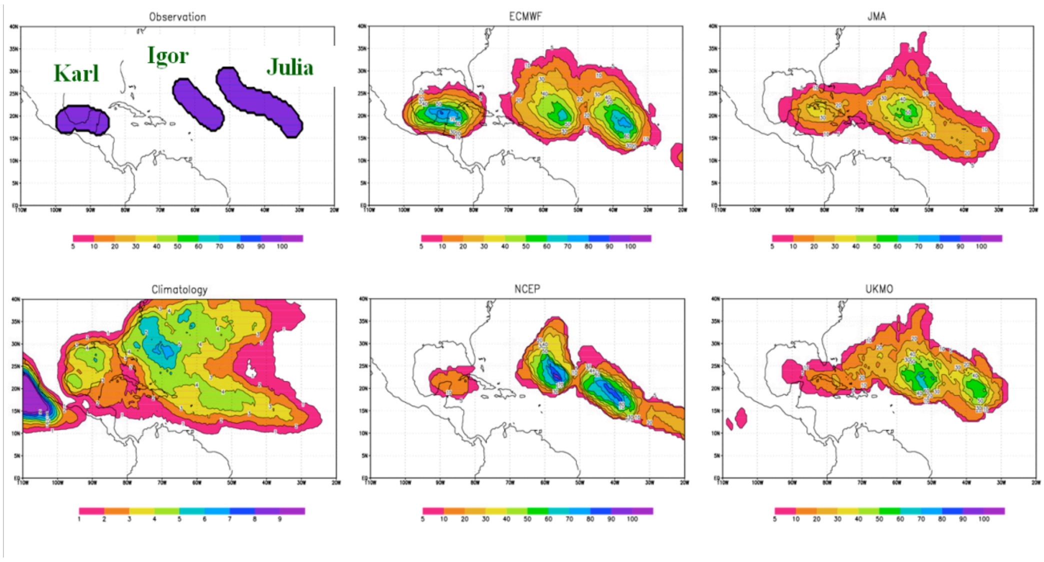

Figure 4. Ensemble forecasts of tropical cyclone activity at a range of 6-9 days, from initial conditions at 12UTC on 9th September 2010. Three tropical cyclones occurred in this period: hurricane Igor formed about a day before the start of forecast, Julia about 3 days after the start and Karl about 5 days afterwards. Top left plot: areas affected by the three hurricanes. Bottom left plot: climatological hurricane activity. Remaining plots: forecasts of activity from four ensemble systems, ECMWF, JMA, NCEP and UKMO.

Source: Yamaguchi (2014)

11.5.3 Linkages and requirements

The WMO/WWRP High-Impact Weather (HIWeather) project is laying out a research and development agenda that includes the development of applications for using ensemble and multi-model ensemble data. The goal is to:

> "*Promote cooperative international research to achieve a dramatic increase in resilience to high-impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications*."

The reader is encouraged to consider the implementation plan (Jones and Golding, 2014). This programme will coordinate the activities of physical scientists and social scientists to address major high-impact weather phenomena, including urban flooding, wildfire, localised extreme wind, disruptive winter weather, and urban heat waves/air pollution. The TIGGE databases of regional and global weather ensembles and the S2S database of intra-seasonal ensembles will continue to be very helpful in the research and development of experimental forecast products.

11.6 CONCLUSIONS

In the past two decades, considerable progress had been made in quantifying uncertainties in weather forecasts using ensemble prediction systems. Ensemble prediction systems need represent both the uncertainties in the initial conditions, and how those uncertainties evolve during the course of the forecast. The quantification of initial errors is closely linked to the data assimilation problem. The problem of representing the effect of model errors in a physically reasonable and yet statistically correct manner remains a major challenge, requiring the deployment of sophisticated stochastic modelling techniques. The challenge is magnified as model resolutions increase, so that physical processes are partly (but not fully) resolved - the so-called "grey zone" problem. Stochastic forcing methods will remain a key area for further research and development in the coming decades.

The next part of the challenge is the translation of ensemble output to create probabilistic weather forecasts - and particularly to alert people to the risks of severe weather events. Especially using TIGGE data, there have been considerable developments in recent years on using both statistical methods and the combination ensembles to reduce systematic errors and provide reliable probabilistic forecast products. The communication and application of such probabilistic forecasts is a further challenge, addressed by the User, Applications and Social Science component of this conference.

11.7 ACKNOWLEDGEMENTS

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CHAPTER 12. SEAMLESS METEOROLOGY-COMPOSITION MODELS: CHALLENGES, GAPS, NEEDS AND FUTURE DIRECTIONS

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Abstract

Aiming at eventually migrating from separate meteorology and chemistry-transport modelling systems to seamless meteorology-composition-chemistry models (SMCM) has several advantages: It allows the consideration of two-way interactions (i.e. feedbacks), the consistent treatment of, e.g. water vapour in chemistry and meteorology, and ensures synergies in research, development, maintenance and application. This paper offers a review of the current research status of seamless meteorology and atmospheric chemistry modelling (or seamless meteorology-composition models (SMCM) for short) and recommendations to evolve from separate to seamless meteorology-composition models to address limitations in weather, climate and atmospheric composition fields whose interests, applications and challenges are now overlapping. SMCMs describe the relevant processes to investigate long-standing scientific questions on the interactions between atmospheric constituents and atmospheric processes and support the creation of new environmental prediction services. "Seamless" is introduced in the paper in relation to two aspects: 1) at the process-scale where it refers to the coupling within a model of meteorology and composition processes to represent for example the two-way interactions between composition and radiative processes or microphysics, or the consistent treatment of water vapour; and, 2) in terms time and space where it refers to the absence of discontinuities in model behaviour when used at multiple temporal or spatial resolutions to have for example consistent treatment of black carbon for air quality and climate applications. Starting with a survey of relevant processes responsible for the interactions between atmospheric physics, dynamics and composition, the paper highlights the challenges of this evolution towards seamlessness and presents priority areas for research to further this path.

12.1 INTRODUCTION

'meteorology' is used as the generic terminology that encompasses both weather and climate

During the last two decades or so, some major research initiatives have independently investigated the role of atmospheric composition in weather forecasting (Grell and Baklanov, 2011; EuMetChem; ICAP; WGNE), the real-time forecasting of air quality (Baklanov, 2010; Kukkonen et al. 2012; Zhang et al. 2012 a&b), the generation of chemical analyses through the assimilation of composition data (Monitoring Atmosphere Composition and Climate (MACC): Hollingsworth et al. 2008; Bocquet et al. 2015) and the interactions between atmospheric composition and climate (Alapaty et al. 2012; Liu et al. 2013; World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM)). These different projects have converged towards similar approaches by coupling meteorology and composition-chemistry models in order to better address the different model application problems, resulting in seamless models (SMCMs) where the treatment of meteorology, composition and composition-meteorology interactions is combined in one model through either an online integrated or online access coupling. Online integrated models simulate meteorology and chemistry over the same grid in one model using one main timestep for integration while Online access models use independent meteorology and chemistry modules that might even have different grids, but exchange meteorology and chemistry data on a regular and frequent basis (Baklanov et al. 2014).

Online integrated models are not new. They recently became available in the mainstream meteorological and atmospheric composition and chemistry research community. This is catalysed by ever increasing computing power and permits new forays into long-standing scientific questions on the interactions between atmospheric constituents and atmospheric processes. It also allows the implementation of new operational environmental prediction services (e.g. Copernicus in Europe: http://atmosphere.copernicus.eu/; Air Quality Health

Index (AQHI) in Canada: AQHI, 2013; Stieb et al. 2008). The level of coupling, the processes represented and the level of complexity of their representation, amongst other things, vary widely between models. While different applications can commend different choices, dedicated efforts are needed to address the challenges that are encountered in seamless models. This also extends to considerations of spatial and temporal scales as it is to be expected of modelling systems to produce consistent responses across all scales. Multi-scale capable models will have to be seamless. Discussions held at the World Weather Open Science Conference (WWOSC-2104) took stock of the current status, gaps and challenges of this integration and explored the needs and future research requirements towards a seamless representation of the atmosphere for the full range of atmospheric modelling systems.

12.2 EXISTING EXPERIENCE, MAIN TRENDS AND MOTIVATION

National Meteorological and Hydrological Services (NMHS) are now looking at bringing representations of atmospheric composition into different parts of their operational forecasting systems resulting in a wide range of efforts for various applications and as many levels of complexity in the representations. NMHSs have invested in the following areas: Volcano ash forecasting, warning and impacts; Sand and dust storm modelling and warning systems; Wild fire impact on atmospheric pollution, health and visibility; Chemical weather / air quality forecasting and reanalyses; Numerical Weather Prediction (NWP) for precipitation, visibility, thunderstorms, etc; Urban and environmental meteorology; High-impact weather and disaster risk management; Effects of short-lived climate pollutants; Earth system modelling and projections; Data assimilation for air quality and NWP; Weather modification and geo-engineering. The SMCMs developed have reached different levels of maturity and are at varying stages of operational implementation. Climate services are an additional application area of SMCMs.

Several major research and development projects have been initiated to support these new interests. In recognition of the rapid development of coupled meteorology and composition modelling, the Action ES1004 (EuMetChem) in the European Cooperation in Science and Technology (COST) Framework was launched in February 2011 to develop a European strategy for coupling air quality (AQ) and meteorology modelling (www.eumetchem.info). The Action aimed to identify and review the main processes coming into play in the coupling and to specify optimal modular structures for SMCMs to simulate specific atmospheric processes. The COST Action developed recommendations for efficient interfacing and integration of new modules, keeping in mind that there is no one best model, but that the use of an ensemble of models simulations is likely to provide the most skilful result (Baklanov et al. 2014, 2015).

Other collaborative efforts are ongoing at the international level. The Air Quality Model Evaluation International Initiative (AQMEII), coordinated by the European Commission Joint Research Centre (JRC) and the US- Environmental Protection Agency (EPA), primarily addresses the fundamental issue of model evaluation through collaboration between the European and North American regional scale air quality communities. In the first phase of AQMEII (2010-2012), uncoupled chemical transport models (CTM) were extensively evaluated (Galmarini et al. 2012), while the models participating in Phase 2 (2013-2014) were online coupled meteorology-composition-chemistry models (Galmarini et al. 2014).

In the operational aerosol prediction community, the International Cooperative for Aerosol Prediction (ICAP, http://icap.atmos.und.edu/) initiative was set to address common challenges among operational centres related to the prediction of aerosols at the global scale, including their interactions with other Earth system's components. Its latest work proves the benefit of using a multi-model ensemble approach for the near-real-time production of aerosol forecasts based on the latest generation of models (Sessions et al. 2015).

On the European Union side, one major effort is the Copernicus Atmosphere Monitoring Service (CAMS) that will start in fall 2015. CAMS will consolidate many years of preparatory research (Global and regional Earth system Monitoring using Satellite and in situ data (GEMS), MACC, MACC-II and MACC-III projects) and development and deliver a large set of operational services.

Among them, there is the provision of daily forecasts and analysis of air composition (reactive gases and aerosols) at the global scale (http://www.gmes-atmosphere.eu/) and provision of boundary conditions for the regional prediction of air quality at the European level. For this a tropospheric chemistry scheme and an aerosol scheme is coupled with the Integrated Forecast System (IFS) that is used for the operational NWP at the European Centre for Medium-range Weather Forecasts (ECMWF). Further, work is underway to explore the benefits of a multi-model ensemble approach based on three state-of-the-art tropospheric/stratospheric schemes, taking into account scientific and computational cost issues. More generally, CAMS integrates all the components (emissions, observations, assimilation and forecasts systems both at global and regional scales, verification, data access, and documentation) needed to generate atmospheric composition products accessible to a large variety of worldwide users (policy users, solar energy and commercial applications and research). At the regional scale, a state-of-the-art multi-model ensemble approach is used for air quality operational forecasts over Europe. In this case, separate meteorology and chemistry-transport modelling systems are used.

In addition, several programmes and initiatives of the World Meteorological Organization (WMO) are moving towards seamless modelling, such as the WMO Working Group for Numerical Experimentation (WGNE), the GAW (Global Atmosphere Watch) Urban Research Meteorology and Environment (GURME) project (http://mce2.org/wmogurme/), the Sand and Dust Strom Warning Advisory and Assessment System (SDS-WAS), and the WCRP Chemistry-Climate Model Initiative (CCMI, Eyring et al. 2013). In particular, the WGNE recently initiated a specific online integrated modelling case study on Aerosol Effects on NWP (see: http://www.wmo.int/pages/prog/arep/wwrp/new/documents/03_Freitas_Aerosols.pdf/ and Arlindo daSilva's WWOSC-2014 presentation at: https://www.wmo.int/pages/prog/arep/wwrp/new/wwosc/presentations.html).

Most of the above-mentioned programmes are approaching the issues with the seamless meteorology-composition modelling approach since they are interested in 2-way interaction mechanisms with a focus on aerosol feedbacks. Direct processes and feedback relevant to meteorology, composition and chemistry have been reviewed in detail by Zhang (2008) and Baklanov et al. (2014).

The potential impacts of aerosol feedbacks can be broadly explained in terms of four types of effects: direct, semi-direct, first indirect and second indirect. For example, the reduction due to aerosols in solar radiation reaching the Earth's surface is an example of a direct effect (Jacobson et al. 2007). Changes in surface temperature, wind speed, relative humidity, clouds and atmospheric stability that are caused by this reduced radiation due to absorbing aerosols are examples of the semi-direct effect (Hansen et al. 1997). A decrease in cloud drop size and an increase in cloud drop number as a result of more aerosols in the atmosphere are named as the first indirect effect (Twomey, 1977). These changes might enhance cloud albedo. An increase in liquid water content, cloud cover and lifetime of low level clouds and suppression or enhancement of precipitation are examples of the second indirect effect (Albrecht, 1989). However, this simplified classification is insufficient to describe the full range of two-way chains and loops of interactions between meteorological, composition and sometimes chemical processes in the atmosphere. For example, clouds modulate boundary layer outflow/inflow by changes in the radiative and turbulent fluxes as well as alterations of temperature profiles and thereby vertical mixing and the water vapour modulates radiation. The vertical temperature gradient also influences cloud formation and controls turbulence intensity and the evolution of the atmospheric boundary layer (ABL). Similar feedback mechanisms exist for altered chemistry impacts on chemistry. On a more general level, a number of chains and loops of interactions take place and should be properly simulated in a seamless model.

The relative importance of the seamless meteorology-composition modelling and of the priorities, requirements and level of details necessary for representing different processes still varies with the applications and communities (AQ forecasting, AQ assessment, NWP, climate and Earth system models). Against the backdrop of the separate development of meteorological models (MetMs) and CTMs together with the continued increase in computing power, a more detailed modelling description of physical and chemical processes and their interactions calls for a strategic vision. Such a vision will help to provide shared goals and directions for the research and operational communities in this field, while still having a multiple model approach to respond to diverse national and institutional mandates.

The next 10 years will need to see a much higher level of meteorology-composition models as multi-scale models will be more widely used to better describe the atmospheric processes. However, combining two modelling systems for operational applications, each of which has high CPU time and memory requirements, poses many challenges in practice. An assessment of the challenges, gaps and requirements is presented below. In the following Sections 12.3-12.7, the main sub-themes that need to be considered for further developments of SMCMs are discussed. Each sub-theme is structured as background info, underpinning research, main linkages and requirements for further research and realisations.

12.3 MAJOR CHALLENGES AND NEEDS FOR INTERACTING PROCESSES AND FEEDBACK MECHANISMS

Background

Numerous feedbacks exist between the dynamical and thermodynamic state of the atmosphere and gaseous and particulate compounds. Although most feedbacks have been identified for a long time several of them are yet not well quantified or characterised. In addition, their relative importance for seamless meteorology-composition forecasting and predictability are not quantified yet. Tables 1 and 2 summarize these feedback processes.

Table 1. The impact of atmospheric variables and processes on trace gases and aerosols

Temperature	Modulates chemical reaction and photolytic rates
	Modulates biogenic emissions (isoprene, terpenes, dimethyl sulphide, etc.)
	Influences biogenic and anthropogenic emissions (isoprene, monoterpenes, VOCs from solvents and fuel)
	Influences the volatility of chemical species
	Determines aerosol dynamics (coagulation, condensation, nucleation) Determines atmospheric stability, turbulence and mixing potential
Temperature and humidity	Affect aerosol thermodynamics (e.g. gas-particle partitioning, secondary aerosol formation) Influence pollen emissions
Water vapour	Modulates OH radicals, size of *hydrophilic aerosol*
Liquid water	Determines wet scavenging and aqueous phase chemistry
Wind vector	Determines horizontal and vertical transport of trace gases and aerosols
	Influences dust-, sea-salt-, and pollen emissions
Atmospheric turbulence	Determines turbulent diffusion of trace gases and aerosols
ABL height	Influences concentrations
Radiation	Determines photolysis rates Determines biogenic VOC emissions
Cloud processes	Affect in-cloud scavenging of aerosols and trace gases
Precipitation	Determines the wet removal of trace gases and aerosol
Surface-vegetation-atmosphere exchange processes (depending on soil type, vegetation cover, soil moisture and leaf area)	Affect natural emissions (e.g. dust, sea salt, pollen, nitrogen compounds, biogenic VOCs, CO_2, water vapour) and dry deposition
Lightning	Contributes to natural NOx emissions

Table 2. Impacts of trace gases and aerosols on atmospheric variables and processes

Aerosols	Modify radiation transfer (SW scattering/absorption, LW absorption, LW scattering by large particles like dust)
	Affect ABL meteorology (temperature, humidity, wind speed and direction, stability)
	Affect haze formation and atmospheric humidity
	Modify physical properties of clouds (size distribution, extinction coefficient, phase function and single scattering albedo)
	Influence cloud droplet and ice crystal number concentrations
	Influence precipitation (initiation, intensity)
Soot	Influences surface albedo (e.g. ice surfaces)
Trace gases	Modify radiation transfer

These feedback processes show that seamless meteorology-composition model systems can improve the current state of knowledge and the capability of future seamless prediction atmospheric models. The relative importance and necessity of seamless meteorology-composition models and the related level of detail required for representing different processes and feedbacks vary greatly between the three application fields: NWP, air quality and chemical weather forecast, and climate/Earth system modelling, as was also confirmed in an expert poll conducted among the members of the EuMetChem COST Action (Baklanov et al. 2014; Kong et al. 2014).

Emissions and deposition interact with the meteorological part within online coupled models. The most interesting emissions are those which depend on meteorology as they can be treated more accurately and consistently than in offline coupled models. Natural emissions (e.g. isoprene, terpenes and pollen) strongly depend on meteorology and are in general already calculated online even in offline models using the meteorological input driving the CTM model. Sea spray is the dominant aerosol source over the oceans and therefore, its proper quantification is highly relevant for simulating chemical reaction in offshore and coastal areas and thus is more realistically to be calculated in a seamless meteorology-composition-model. Wind-blown dust refers to particles from a broad range of sources. Due to their direct relationship with meteorology, such emissions must be calculated with the seamless approach.

A large variety of chemical mechanisms are currently in use in SMCMs. Nevertheless, the most commonly-used mechanisms have converged in terms of the state of the science included in their formulation. Modifications of the chemical mechanisms, which not only affect gas phase chemistry but also the coupling with aqueous-phase and aerosol mechanisms, have faced practical difficulties in the past. Methods of updating chemical mechanisms make updates much easier as illustrated in the MECCA module (Sander et al. 2005).

In comparison to conventional weather forecasting models, SMCMs may require huge computational efforts depending on the involved processes. Therefore, one main challenge will be identifying the degree of representativeness and complexity required with respect to 3D-composition fields, chemistry, aerosol dynamics and aerosol chemistry, and the feedbacks between gaseous compounds, aerosols, clouds and radiation for the next generation of seamless meteorology-composition models. Nevertheless, these needs and challenges are scaled by the differing degree of requirements of the various applications and users with as the main aim to improve forecasting skills for all meteorological parameters and relevant concentrations.

Underpinning research

Although it is the final goal of seamless meteorology-composition model systems to include all relevant processes describing the feedback between atmospheric composition and weather and climate one might think of intermediate steps.

In case of air quality model systems that include mineral dust and biomass burning aerosol would be an improvement of the current situation. This requires research in the fields of the emission of mineral dust, the emission of biomass burning aerosol, and of plume rise models.

Mineral dust is one of the most abundant aerosols. Mineral dust particles strongly modify atmospheric radiation. Taking this effect into account would be relevant step for seamless prediction. The calculation of the optical properties of aerosols is required to simulate the impact of mineral dust on the radiative fluxes. The refractive index is a crucial input parameter for such calculations. The refractive index depends on the chemical composition. Improved wavelength dependent measurements of the optical properties of mineral dust particles are needed. The nonsphericity of the mineral dust particles, often neglected needs further attention.

As long as bulk schemes are used in numerical weather forecast models to treat cloud microphysics an improvement would be including aerosols in a simplified way in such schemes. An example would be the process of auto-conversion which transfers cloud droplets to rain droplets. This transfer depends on the number concentration of cloud droplets which depends on the number of cloud condensation nuclei. In-cloud and below-cloud scavenging, sedimentation and deposition at the surface could be taken into account by such models. As sea salt and mineral dust are the most abundant aerosol particles in many regions of the world the simulated number concentrations of those particles could serve as an input to drive the auto conversion in microphysical bulk schemes. This requires the development of parameterizations.

A further step forward would be the replacement of bulk microphysical schemes by more sophisticated ones as for example two moment schemes and the inclusion of secondary aerosol particles as sulphate and nitrate or secondary organic compounds. Several aerosol processes such as nucleation, coagulation, condensation, and evaporation should then be included. The interactions of aerosols with gas phase chemistry and their impacts on radiation and cloud microphysics depend strongly on their physical and chemical properties. Although several models are available in the research community there is still a strong need for research before such model systems can be transferred into seamless meteorology-composition forecast models. Accurate parameterization of the ability of aerosol particles to act as ice nuclei and the quantification of their relevant freezing processes within clouds are needed. A quantification of the level of complexity which is needed in case of atmospheric chemistry is required; this can be achieved by performing sensitivity studies and comparisons with observations. Disentangling the role of aerosols for cloud formation and precipitation needs further research efforts, before the level of complexity that has to be included in SMCMs is clear. This has to be done focussing on different cloud types (low level, mixed phase, deep convective) and weather systems.

Linkages

The strategy to advance on the research topics listed above requires an understanding of the atmospheric processes as a whole. For this, it is necessary to promote close collaborations at the international level between the different research areas involved: meteorology, atmospheric chemistry, and aerosol science. Interdisciplinary basic research projects towards this goal should be promoted with dedicated observing and modelling strategies depending on the specific meteorology-composition process and feedbacks to be studied.

Requirements

Migration from offline to seamless and, more specifically, to online integrated modelling systems is recommended for many applications as this approach can guarantee a consistent treatment of processes and allow two-way interactions of physical and chemical components of SMCMs, particularly for chemical weather forecasting (CWF) and NWP communities. In particular, the following steps should be taken:

- A challenge for most SMCMs is the adequate treatment of indirect aerosol effects. Its implementation with affordable computational requirements and evaluation against laboratory/field data would greatly facilitate the transition to seamless meteorology-composition models.

- The understanding and therefore the parameterization of aerosol-radiation-cloud-chemistry interactions is still incomplete and further research on the model representations of these interactions is needed.
- Key aerosol properties (size, phase, hygroscopicity, mixing state, optical properties) and processes (chemistry, thermodynamics for SOA and dynamics) need to be better represented for seamless meteorology-composition-chemistry forecasts.
- Cloud properties (droplet number concentrations, size distribution, optical properties), processes (microphysics, dynamics, wet scavenging, aqueous phase chemistry) and cloud-aerosol interactions for all types of clouds need to be better represented.
- As more meteorological and chemical variables are assimilated into a model, one must be cautious about possible diminishing returns and possible antagonistic effects due to the interactions between meteorological variables and chemical concentrations. Consequently, the development of optimal methods for data assimilation is warranted, including the estimation of model and observation uncertainties.
- Create a unified central database of chemical mechanisms, where mechanism owners can upload relevant codes and provide updates as necessary.
- Enable interfacing of this database using, e.g. the Kinetic Pre-Processor (KPP) to develop a set of box model intercomparisons including evaluation against smog chamber data and more comprehensive mechanisms and moreover an analysis of the computational cost.

12.4 SEAMLESS COMPOSITION REPRESENTATION

Background

As presented in Hurrell et al. (2009), “the global coupled atmosphere-ocean-land-cryosphere system exhibits a wide range of physical and dynamical phenomena with associated physical, biological, and chemical feedbacks that collectively result in a continuum of temporal and spatial variability”. This recognition, which implies that the traditional boundaries between atmospheric, oceanic and earth sciences are by and large artificial, sparked a new area of research for seamless weather, composition and climate predictions, which was actively discussed at the WWOSC-2014. Within the same conference, many scientists recognized that the concept extends beyond weather and climate prediction to chemical weather and chemical climate. As it is the case for physical and dynamical processes, there is a continuum of chemical phenomena and interactions with the physical and dynamical state of the atmosphere across all time and spatial scales. Models need to aim for numerical representations whose results are consistent across those scales. This is a particularly difficult challenge with chemistry where hysteresis is frequent, yet even more important to avoid divergence in the predictions of atmospheric constituents.

The representations of atmospheric composition in each of the three main atmospheric disciplines (weather, climate and air quality) are constrained by the associated cost of such representations and have different priorities. As a result, the heterogeneity and different levels of maturity in each field are major challenges to overcome in order to evolve towards a seamless framework. Recognizing that the atmospheric community at large aims to model the same chemical phenomena and can leverage each other’s advancement is key to the development of a next generation of models where the simplest to the more explicit representations of composition provide the same consistent scientific results. In doing so, the community will need to revisit the computing performance of chemical representations and take advantage of the upcoming computing capacities, an area that has seen a lot less attention compare to their dynamic and physic counterparts.

Finally, the spatial transitions cannot be forgotten as numerical models are bound to achieve sub-kilometre resolutions on an operational basis within the next two decades. To stay in step with this trend, the chemical community will need to participate in emerging research efforts focusing on scale-independent and scale-aware parameterizations (Grell et al. 2014), and understand how these concepts extend more broadly to chemical composition.

Linkages

It is fairly evident that to expand the seamless framework to atmospheric composition, synergistic efforts are required within the communities currently dedicated independently to weather, air quality and climate. Overarching initiatives such as the CCMM symposium (http://eumetchem.info/ccmm/Agenda_CCMM.pdf) are developing to gather and foster a scientific dialogue across the disciplines; this needs to be further supported through dedicated joint research efforts. Likewise, a similar integration is required in data assimilation and is further discussed in Section 12.7 and in Chapter 3.

Requirements

- The chemical modelling and climate research communities are evolving rapidly towards adopting SMCMs as the tool of choice for development in the next decade. The NWP community is not requiring implementation of full chemistry and mostly needs the implementation of aerosol interaction processes. Using common platforms is a critical component to establish an engaged dialogue across weather, climate and air quality modellers and facilitate the harmonization of the chemical composition representations.
- Scale-independent and scale-aware parameterizations are examples of the new concepts that emerge from pushing the scientific thinking beyond the artificially established boundaries; research efforts along the same concepts need to be fostered and applied broadly to chemical composition.
- Accelerating developments that address the seamless challenges will require the support of joint research initiatives with international recognition and participation; the benefits of modelling experts of different background working alongside will extend well beyond the objectives of the initiatives as it pushes each party to reassess their working assumptions.

12.5 NUMERICAL AND COMPUTATIONAL ASPECTS

Background

With the increase of computational resources, more complex numerical models are becoming feasible, and an increase of the spatial resolution is affordable. Consequently, SMCMs are experiencing closer attention. Key points in such models are (i) the numerical schemes (especially those for the transport of composition species), (ii) the seamless treatment of the coupling or integration between meteorology and chemistry, (iii) the role of initial and boundary values and (iv) the efficient performance of the system in a specific high performance computing (HPC) environment.

Underpinning research

A number of different numerical techniques have been used and proposed for the transport of aerosols and other chemical species in seamless meteorology-composition-models. Some of them are able to maintain consistency of the numerical methods applied for both meteorological and chemical variables, while others apply different transport schemes for meteorology and chemistry species, partly because the transport requirements for chemical species are stronger than those for hydrometeors in NWP (see overview in Baklanov et al. 2014; model inventory at mi.uni-hamburg.de/costmodinv). This may be a relevant deficiency when explicitly treating aqueous phase chemistry. Rasch and Williamson (1990) listed the following desirable properties for transport schemes: accuracy, stability, computational efficiency, transportability, locality, mass conservation and shape-preservation (positive definiteness, monotonicity, etc.). The last two are of particular interest in composition modelling. It is important also to mention the so-called wind mass inconsistency problem, which turns out not to be trivially resolved in SMCMs.

Among technical aspects, one should also consider the basic structure of the code. When using SMCMs the number of prognostic variables in the model increases dramatically. To make sure that the code is still efficient, the numerical schemes must be highly multi-tracer efficient (Lauritzen et al. 2010).

The current state of online coupled models is that they are run on state-of-the-art supercomputers and are written in a mixture of Fortran 2008/2003/95/90/, C and C^{++} and some Fortran 77. The mixture of different languages is a result of the enormous efforts needed to develop a robust code, which easily extends more than 100 man-years. The models are using either Message Passing Interface (MPI), Open MultiProcessing (OpenMP), or a combination of the two for the parallelisation of the code. Both methods have advantages and disadvantages, but by combining the two methods, one can ideally optimize the code for use on all types of machine architectures.

Linkages

The numerical and computational aspects for seamless meteorology-composition models are also extremely important and common to AQ, NWP and climate modelling communities, so this work should be done together and involving numerical mathematics experts and computer scientists.

Requirements

The most relevant properties to be considered when developing integrated models and especially for considering feedback mechanisms are mass conservation, shape-preservation and prevention of numerical mixing or unmixing. Eulerian flux-based schemes are suitable for mass conservation. Recently, several semi-Lagrangian schemes have been developed that are inherently mass conservative. Such schemes are applied in some integrated models.

- A detailed analysis of the numerical properties of SMCMs is recommended. A particularly relevant set of tests has been described by Lauritzen and Thuburn (2011), which shifts the focus from traditional, but still important, criteria such as mass-conservation to the prevention of numerical mixing and unmixing. Not maintaining the correlations between transported species is similar to introducing artificial chemical reactions in the system.
- A clear trend towards seamless meteorology-composition model development is becoming perceptible with several modelling systems that can be considered as online integrated models with main relevant feedbacks implemented. Complementing those, there are several ones that are built using an online integrated approach, but some major feedbacks are not included yet. A third group of models, the online access models, is characterised by applying an external coupler between meteorology and composition/chemistry. All the information is passed through the coupler. Depending on the approach used, wind and mass consistency problems may arise in the last case. In this sense, online integrated models are desirable to avoid inconsistency problems.
- Numerical performance is an important issue for SMCMs. The current parallelisation is based on well-established MPI and OpenMP programming models. Beyond these approaches, there is no clear trend towards new parallelisation paradigms, even though supercomputers are experiencing a huge increase in computing power achieved mainly through an increase in the number of computing units rather than an increase in clock frequency. New processor types such as GPU’s and MIC’s are only beginning to be explored.
- To adopt newer technologies, a conversion programme that transfers existing code to the new technology would be advantageous. The transferred code would need to be still

readable and maintainable. This would be very useful since a seamless meteorology-composition-chemistry model takes several decades of work to develop, and without software based support, transfers can take years to be completed reliably.

12.6 EVALUATION OF COUPLED MODELS

Background

There is a crucial need for more advanced evaluation of methodologies and output data. Model validation and benchmarking are important elements of model development as they help identify model strengths and weaknesses. Model validation has a long tradition in the NWP and AQ modelling communities, and many concepts can be applied to SMCMs as well. The MetM community has the necessary tools, for example, to analyse whether including certain feedbacks has a positive effect on weather forecast skill. Demonstrating these benefits however, requires running a model with and without feedbacks and specific combinations of feedbacks over extended periods of time - rather than for selected episodes - in order to draw statistically significant conclusions. Furthermore, reliable comparison data need to be available, at least for the most relevant processes.

Underpinning research

Evaluating whether relevant feedback processes are treated accurately by a model is challenging. The effects of aerosols on radiation and clouds, for example, depend on the physical and chemical properties of the aerosols. Thus, comprehensive measurements of aerosol size distributions, chemical composition, and optical properties are needed. Such observations should ideally be collocated with detailed radiation measurements (e.g. WMO GAW, AERONET), with aerosol lidars probing the vertical distribution and with radiosondes providing profiles of temperature and humidity. Evaluating indirect aerosol effects on clouds and precipitation is even more challenging and requires additional detailed observations of cloud properties such as cloud droplet number concentrations. Measurements from polarimetric radars, disdrometers, and cloud particle imagers can provide information on hydrometeor phases and size distributions but are only sparsely available. SMCMs can also be beneficial for AQ modelling. Surface-based observational networks are available for the validation of classical air pollutants such as O_3 or NO_x and satellite observations (column values) of NO_2, O_3, SO_2 and CO, and the aerosol optical depth (AOD). Note that surface networks are not uniformly distributed around the world, with very sparse observations in the southern hemisphere and over the oceans. Aircraft data also represent an important resource for observations of trace gases and aerosols for evaluation and possibly data assimilation.

Linkages

To advance the aforementioned research objectives it will be necessary to promote synergetic work between NWP, climate, and chemistry communities in order to define new strategies for model evaluation of all its components as a whole.

Requirements

For SMCMs, the evaluation can no longer be conducted for meteorology or composition separately. Interacting processes will need specific attention to avoid the situation where the “right” results are obtained for the wrong reasons. In this regard, efforts should focus on conducting dynamic evaluation to establish the models’ credibility in accurately simulating the changes in weather and air quality conditions observed in the real world. To achieve this, attention should be given to:

- An international test bed for evaluation of urban, regional and global SMCMs. The first step in this direction has been taken by the AQMEII consortium for the regional scale, but extension to higher resolution models is important. At the European level, model evaluation activities are currently conducted for AQ under the FAIRMODE initiative. Involving the meteorology community in such activities could help to ensure that model results are right for right reasons.

- Overall evaluation methodologies for model application objectives outside the European AQ directives (EC, 2008) as suggested by Schlünzen (1997) and updated by Schlünzen and Sokhi (2009) are needed to ensure that relevant meteorological targets (e.g. very high temperatures, extreme precipitation) are also simulated correctly for the right reasons. Dynamic as well as diagnostic evaluation as defined by Dennis et al. (2010) should be considered.
- The quality measures used for evaluation need to be reconsidered in order to include uncertainty of the comparison data in them (Schlünzen et al. 2015).
- A target specific evaluation concept using operational data should be developed and applied globally to be able to compare (and exchange) model results.
- Extending quantitative evaluation approaches developed for meteorology to climate models (Schoetter et al. 2012) is an additional necessary extension of current evaluation attempts.
- Non-standard variables (e.g. shortwave and longwave radiation, photolytic rate of NO_2, AOD, Cloud Optical Thickness (COT), Cloud Condensation Nuclei (CCN), Cloud Droplet Number Concentration (CDNC), precipitation) should be included routinely into model evaluations for SMCMs. Reliable measurements are needed on a routine basis.
- Routine, long-term measurements of aerosol size distributions, chemical composition and optical properties in operational ground-based networks are urgently needed to verify meteorology/climate-composition-chemistry feedbacks.
- Ground-based and satellite remote-sensing measurements of aerosol and cloud properties (e.g. optical depths, CCN, CDNC and shortwave and longwave radiation) are very important to study aerosol indirect effects and should be included for validation of meteorology chemistry feedbacks.
- Last but not least, there is a need to evaluate routinely the atmospheric mixing processes in models, in particular within the Atmospheric Boundary Layer (ABL), using measurements on fluxes of meteorological parameters and chemical species in all three directions. These data need to be gained, evaluated and provided for evaluation.

12.7 DATA NEEDS AND ASSIMILATION

Background

Experience with chemical data assimilation (CDA) in SMCMs is still limited but it has become subject of much investigation (see an overview in Bocquet et al. 2015). Most applications of CDA use CTMs, rather than SMCMs, to improve the simulated concentration fields or model parameters such as emissions. Initial efforts have been made with integrated systems (IFS-MOZART and Weather Research and Forecasting Model (WRF)-Chem) to assimilate composition and meteorological observations in SMCMs. There is some evidence that CDA can also improve the assimilated meteorological variables, for example the assimilation of ozone can have a positive effect on the assimilated wind fields (Semane et al. 2009).

Underpinning research

CDA will be beneficial in SMCMs if it improves the realism of the composition/concentration fields which are used to simulate the interaction between atmospheric composition and meteorology. The most common approach is the adjustment of initial conditions through CDA in a manner similar to meteorological data assimilation. Optimal interpolation, variational approaches, Ensemble Kalman filter (EnKF) or hybrid techniques combining the advantages of both variational and EnKF techniques are all applicable. Other methodologies such as inverse modelling of emission fields appear as a promising technique to improve the skill of SMCMs and may have a stronger impact for short-lived pollutants than CDA has on initial conditions. However, it is debatable whether the results of inverse modelling should be used directly to correct emission fields or only to provide insights for the development of improved emission inventories.

Linkages

An important aspect of seamless composition modelling has been the development of data assimilation systems that include also chemical species and particulate matter. Several global and regional models currently provide analysis of gases and aerosols. As an example, among others, the global MACC system incorporates retrieved observations of ozone, CO, SO_2, NO_2 and aerosol optical depth in its analysis to provide initial conditions for the prediction of these species. Currently, the emissions are not part of the analysis but are specified either from established inventories or from satellite observations as it is the case for the emissions of biomass burning aerosols, CO and other species from wild fires (Global Fire Assimilation System (GFAS), Kaiser et al. 2012). Estimation of emissions through data assimilation will be the next step for global models. This has already been successfully tried by regional models (e.g. Elbern et al. 2007) and in off-line models (i.e. Huneeus et al. 2012).

Requirements

Several data assimilation techniques are currently used in the analysis of atmospheric constituents such as 3D and 4D-Var, EnKF and Optimal Interpolation. More research is needed for the correct definition of the background error covariance matrices for the chemical species, including errors deriving from the incorrect specification of the emissions. Hybrid 4D-Var/EnKF systems could be used for CDA and research towards that end is definitely encouraged. There is also the need to invest in research related to the inclusion of the full tangent linear and adjoint of the chemical processes in variational methods. In most current systems, these processes are not included in the minimization and this may limit the impact of the assimilation. Independent of the specific assimilation framework, some general recommendations related to data assimilation observational needs can be made:

- Observations of key variables have to be timely and accurate. In particular, especially for chemical weather forecasting and air-quality applications, the data to be fed in the assimilation system need to be in near-real-time (NRT), with correct timing and have a characterization of the observation errors at the pixel level.
- More research is needed to make full use of raw products such as satellite radiances. This involves the development of higher-complexity observation operators. The benefits will be the more efficient exploitation of the observations, and the lower dependency on a priori assumptions external to the system.
- Several data sources are needed to ensure resilience of the system and wealth of observation-based information. Currently most centres rely on satellite data for the analysis of the atmospheric composition. The next generation of satellite measurements is designed to provide more information on the vertical distribution of gas pollutants and of their precursors, in particular in the lower troposphere, which will be most useful. Efforts are also under way to use ground-based (CO_2, PM, etc.) and aircraft measurements.
- Accurate measurements to verify the model prediction are also needed. These could have longer data latency than the data to be used for assimilation. However it is important that these observations are also delivered timely, to ensure the possibility of a routine verification of the chemical model prediction. Validation datasets are mostly those coming from ground-based observing networks such as GAW, Aerosol Robotic Network (AERONET), European Aerosol Research Lidar Network (EARLINET), Micro Pulse Lidar Network (MPLNET) (www.iagos.fr) etc. Aircraft data also provide invaluable independent observations for validation. High quality, validated datasets are essential also for the verification of the SMCMs run in climate configuration.
- Observations have to be available in a format that is easily accessible, and should also be as compatible as possible with model fields. To this end, close collaboration between data providers and modellers is encouraged to make the process of data acquisition and assimilation more efficient and successful.

12.8 WHAT DO NMHSS NEED FOR SPECIFIC APPLICATIONS AND SERVICES?

In this section, we address the aspect that research is needed on the SMCM systems to have consistent representation of composition constituents regardless of application.

It is clear that the seamless modelling approach is a prospective way for future single-atmosphere modelling systems, providing advantages for all three communities: meteorological modelling including NWP, AQ modelling including CWF, and climate modelling. However, there is not necessarily one seamless modelling approach/system suitable for all communities.

Comprehensive SMCM systems, built for research purposes and including all important mechanisms of interactions, will help to understand the importance of different processes and interactions and to create specific model configurations that are tailored for their respective purposes.

Regarding CWF and atmospheric composition modelling**,** the SMCM approach will certainly improve forecast capabilities as it allows a correct way of jointly and consistently describing meteorological and chemical processes within the same model time steps and grid cells. This also includes harmonised parameterizations of physical and chemical processes in the ABL. There are many studies and measurements supportive of this conclusion (Grell et al. 2004; Grell, 2008; Zhang, 2008; Korsholm et al. 2009; Grell and Baklanov, 2011; Forkel et al. 2012; Saide et al. 2012; Zhang et al. 2013). In particular, due to the strong nonlinearities involved, separate models for meteorology and atmospheric composition can lead to inaccuracies in composition simulations.

For meteorological modelling, the advantages of SMCM approaches are less evident and need to be further investigated and justified. The results of process studies with very detailed comprehensive SMCM systems will serve as a benchmark for reducing physical and chemical processes. Operational forecast centres will rely on the results of those efforts to decide on the practical usage of such next generation seamless prediction models. Here a strong interaction with academia and operational forecast centres is required (e.g. Bangert et al. 2012; Rieger et al. 2014; Vogel et al. 2014). The main improvements for NWP that are possible through an online integrated approach will be related to improvements in (i) meteorological data assimilation (first of all remote sensing data, radiation characteristics, which require detailed distributions of aerosols in the atmosphere) and (ii) description of aerosol-cloud and aerosol-radiation interactions, yielding improved forecasting of precipitation, visibility, fog and extreme weather events and radiation (including Ultraviolet). While these improvements might not be statistically significant as averaged over longer periods of time, it is clear that for specific episodes and high-impact weather events (e.g. aircraft icing, dust storms, vegetation fires, clear summer skies) there are large potential benefits. In summary, meteorology modelling including NWP should benefit from including such feedbacks as aerosol-cloud-radiation interactions and aerosol dynamics.

For climate modelling, the feedbacks (forcing mechanisms) are the most important and the main improvements are related to climate-chemistry: Greenhouse Gas (GHG)/aerosol-radiation and aerosols-clouds interactions. However, the online integration approach is not strictly necessary for all purposes in this field. Many GCMs or RCMs use an offline approach (separate meteorological and chemical composition models) for describing GHG and aerosol forcing processes (by chemistry/aerosol parameterizations or prescription or reading outputs of CTMs). For climate studies, in the EU project MEGAPOLI (http://megapoli.info), a sensitivity study compared the seamless versus offline approaches and showed that for long-lived GHG the seamless approach did not give large improvements (Folberth et al. 2011). On the other hand, for short-lived climate pollutants, especially aerosols and for regional or urban climate, the outcome was very different, with online integration modelling being of substantial benefit. The seamless approach for climate modelling is mostly important for studies of short-lived climate pollutants, which represent one of the main uncertainties in current climate models and are in particular at the core of political and socio-economic assessments of future climate change mitigation strategies. It will be impossible to answer the main questions about aerosol short-lived climate pollutants and mitigation strategies

without employing SMCM systems that include aerosol dynamics and feedbacks.
Proceeding from the above analysis and results of several overall publications (Zhang, 2008; Grell and Baklanov, 2011; Kukkonen et al. 2012; Zhang et al. 2012a,b; Baklanov et al. 2011, 2014, 2015), we suggest aiming at eventually migrating from separate MetM and CTM systems to integrated SMCM systems. Only this type of model allows the consideration of two-way interactions (i.e. feedbacks) in a consistent way. The integration has not only the advantage of a single-atmosphere model, for instance where water vapour and other atmospheric gases are no longer treated numerically differently, simply because of historical separation of the different disciplines. Furthermore, the integration has the advantage of saving computational resources, since several processes (e.g. vertical diffusion) have to be described in both MetMs and CTMs. It will also reduce the overall efforts in research and development, maintenance and application leading to cost savings for both types of models. However, adding new components (chemistry, detailed aerosol for instance) in NWP for operational applications still raises the issue of timeliness for product delivery when running a more complete and therefore computationally costly model.

To achieve the objective of seamless meteorology, composition and chemistry simulation in forecast models some specific aspects should be considered:

- National weather centres should consider progressively including aerosol-composition interactions into NWP systems which will lead to potential improvements and extending them to CWF using SMCMs for cross evaluations, benefitting both disciplines.
- The seamless approach is well suited for applications where frequent feedbacks/communication/interactions between meteorology and composition-chemistry models are required to properly account for the effects of mesoscale events in high-resolution CTMs.
- The online integration of meteorology, physics and emissions and their accurate representations are essential for CWF; the implementation of aerosol feedbacks is important mostly for specific episodes and extreme cases.

Administrative problems might hinder progress of CWF models. On a national level environment and meteorology are often handled in separate ministries, which might hinder merging Meteorological and Composition data sets as needed in the future. Thus, different regional and national data centres might have to be used.

Last but not least, the further development and use of SMCMs needs deep-rooted experts. Thus, universities should extend and update their education programmes to be tailored for the future needs of seamless modelling. The basic education in physics, (numerical) mathematics and atmospheric sciences has to be extended and include chemistry and computing knowledge in order to be able to create and maintain SMCMs. Since most programme codes are developed and used over decades, a good education of the future scientists is essential.

12.9 CONCLUSION

The paper presented a synthesis of advances in atmospheric dynamics and composition modelling and provided recommendations to evolve from separate to seamless meteorology-composition models to address limitations in weather, climate and atmospheric composition fields where interests, applications and challenges are now overlapping.

Seamless modelling is a prospective way for future single-atmosphere modelling systems with advantages for applications at all timescales of NWP, atmospheric composition and climate models.

A variety of SMCM systems is needed for different applications. Different model versions should contribute to different targets with respect to temporal as well as spatial scales, but also to processes under focus. The relative importance of online integration and of the priorities, requirements and level of details necessary for representing different processes and feedbacks can greatly vary for these related communities.

For NWP: full scale gas chemistry is less important, chemical mechanisms can be simplified focusing mostly on chemistry influencing aerosol formation and cloud interactions; aerosol feedbacks improve ABL characteristics and precipitation in very polluted episodes or over cities. Statistically the effects are not strong in average, but significant for specific episodes. NWP might not depend on detailed chemical processes but considering the cloud and radiative effects of aerosols can be important for fog, visibility and precipitation forecasting.

For AQ: the SMCM approach improves AQ forecasting, and an extended chemistry is needed; aerosol feedbacks effects are not always relevant, they need to be studied further. For AQ forecasting, the key issue is usually the ground-level concentration of pollutants, whereas for weather and climate studies model skill is typically based on screen level temperature, wind speed and precipitation. For chemical weather forecasting and prediction of atmospheric composition, the seamless meteorology-composition modelling definitely improves AQ and chemical atmospheric composition projections.

For climate studies: suitable only for understanding the forcing and feedback mechanisms, it is still too expensive to include the full chemistry in climate runs. Chemistry is important, the models need to be optimised and simplified. For climate modelling, feedbacks from GHGs and aerosols are extremely important. However in some cases (e.g. for long-lived GHGs on global scale), fully online integration of full-scale chemistry and aerosol dynamics is not critically needed, but SMCMs should include composition change projections.

Remaining gaps: Understanding of several processes e.g. aerosol-cloud interactions are poorly represented and need further research; data assimilation in SMCMs still needs to be developed to avoid over-specification and antagonistic effects; model evaluation for SMCMs needs more (process) data, long-term measurements and a test-bed.

Several applications are likely to benefit from seamless modelling though they do not clearly fall under one of the three above-mentioned main communities, e.g. forecasting of bio-weather (e.g. pollen concentration), monitoring and forecasting plumes from volcano eruptions, forest fires, oil/gas fires, nuclear explosions or accidental releases, wind and solar energy production assessments and forecasting, weather modification and geo-engineering techniques that involve changes in the radiation balance, etc.

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WMO WGNE: WMO JSC/CAS Working Group on Numerical Experimentation, http://www.wmo.int/pages/about/sec/rescrosscut/resdept_wgne.html

WCRP WGCM: The World Climate Research Programme Working Group on Coupled Modelling, http://www.wcrp-climate.org/index.php/unifying-themes/unifying-themes-modelling/modelling-wgcm

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CHAPTER 13. CONTINENTAL CONVECTIVE SYSTEM

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Abstract

This chapter is intended to provide an overview of the research on convection over continental locations in the middle and subtropical latitudes. The pressing societal need to reduce property damage, save lives and minimize injuries drives this research. There is a societal need for improved prediction of convective weather events for times ranging from minutes to days and even seasons. The basic research is challenging due to the non-linear dynamics of deep moist convection. However, the future holds promise thanks to new theoretical understanding of how to model convection, to growing modelling and observational capabilities and to a community research interest in complementing case studies with the statistical use of large-data sets in order to grasp a more complete view of the problem.

13.1 INTRODUCTION

An accurate treatment of atmospheric convection is one of the primary obstacles preventing improvements in the prediction of weather and climate (e.g. Rodwell et al. 2013; Sherwood et al 2014). The importance of convection to the prediction of weather events and the climate system, together with the varied impacts of convective events on society, have resulted in an extensive scientific literature on convection and convective processes. From within the community's extensive research portfolio on convection, this chapter will concentrate on research related to the prediction of convective events themselves and only briefly touch on the role of convection within the context of the general circulation. While convection takes place worldwide, including over polar regions (e.g. Granerød 2011), this chapter will focus on convection over the middle and subtropical latitudes, particularly over continental locations. Tropical convection is treated in Chapters 14 and 15 of this book and Chapter 19 deals with polar processes.

In order to further limit the scope of this chapter, the text will focus on research relevant to the subset of those convective weather events that result in significant impacts on society, the environment and the economy. For example, numerous hazards that lead to fatalities, injuries, property damage, economic disruptions, and environmental degradation are associated with convection. Such hazards include hail, lightning, damaging "straight-line" winds, tornadoes and heavy rainfall leading to flooding. Furthermore, their impacts are typically greater over continental locations. While examples of the destructive power of convection and convectively driven hazards are too numerous to list, a few examples are provided here. In 2014, three of the five largest natural catastrophes in the world as defined by overall economic losses were associated with two severe weather events in the United States and one event that affected France, Belgium and Germany[a]. The losses from these three events totalled 9 billion in US dollars (US$). In 2013, the five most costly natural disasters, as measured in insured losses, were associated with warm season flooding, hail and tornadoes events across North American and Europe, totalling about 30 billion US$ in economic losses (Swiss RE 2014). As these numbers illustrate, the largest economic losses typically take place in the developed world. Convection also takes human toll among developed nations as, for example, hundreds of casualties occur each year in the US alone due to convective storms (e.g. Schoen and Ashley 2011). On the other hand, the largest numbers of fatalities and injuries from weather and climate events are often associated with hydrometeorological events in the developing world (World Meteorological Organization 2014). These disasters can results in 10,000's of fatalities each year with tropical cyclone, droughts and flooding from convective rainfall taking a large toll.

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[a] *See Insurance Information Institute at http://www.iii.org/fact-statistic/catastrophes-global with the original source the 2015 Munich Re, Geo Risks Research, NatCatSERVICE*

The losses discussed thus far are associated with the direct impacts of storm systems. However, convective events, such as heavy rainfall, hail and damaging winds, can also have a wide variety of detrimental secondary effects. These include negative impacts on health through water-borne and mosquito-borne illnesses brought about by flooding (e.g. Tall et al. 2014), civil unrest caused by hydrometeorological disasters in societies with insufficient resiliency (e.g. Nel and Righarts 2008) and food shortages from either convective hazards or from a lack of convective rainfall leading to drought (e.g. Haile 2005).

The beneficial role of convective systems in hydrological applications, such as agricultural and water management, are also important drivers of convective research. For example, the occurrence of rainfall associated with warm season convection can be critical to agricultural success. Conversely, the hazards associated with convective weather can negatively impact agriculture. A good illustration of this point is the classic map of agriculture areas and the tornado activity produced by Fujita (Figure 1). A similar relationship between damaging convection and agricultural areas is indicated by the comparison of the global composite of hail days from Court and Griffins (1986) shown in Figure 2 with the location of the major agricultural areas presented in Figure 1.

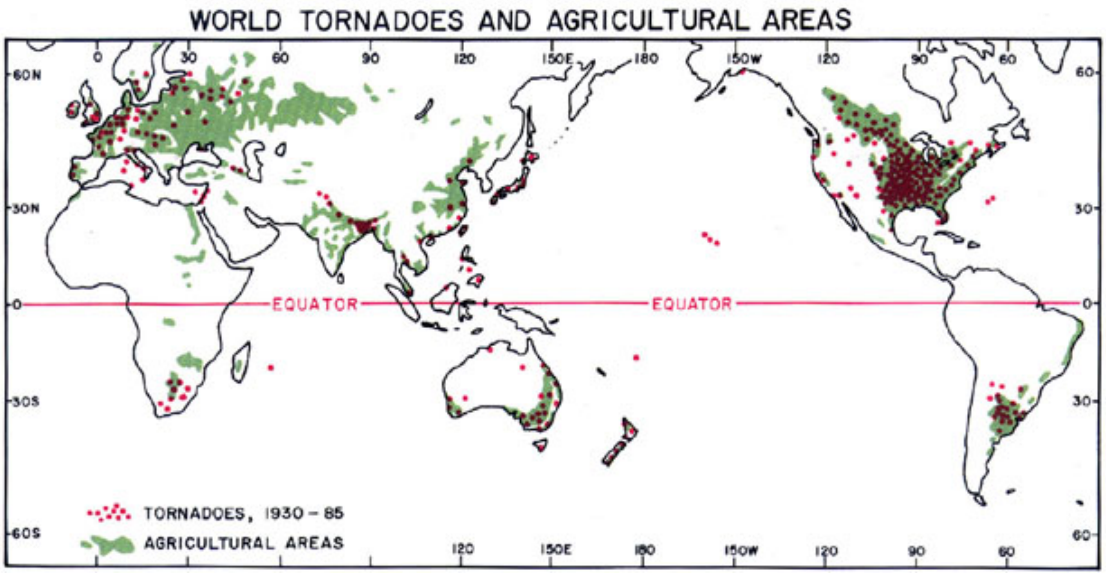

Figure 1. Tornado occurrence and agricultural areas as produced by T. Fujita (2000) from the University of Chicago and made available at http://www.windows2universe.org/earth/Atmosphere/tornado/agri_map.html&edu=mid

Given the clear need for accurate and timely predictions of high-impact convective events and their secondary effects, this chapter will examine the phenomena of deep convection from two different viewpoints. Specifically, Section 13.2 will present the current status and future vision for research oriented directly towards improving forecasting of convection and related hazards. On the other hand, Section 13.3 will focus on the innovative aspects of convective research, stimulated by the development of new observational technologies and the advancement of large-scale computing.

13.2 PREDICTING CONVECTIVE WEATHER

This section provides an overview of some of the critical issues associated with predicting convective weather and embedded hazards. Distinctly different approaches are required, since the time-scales of prediction range from minutes to days and even months. Our discussion begins with the shortest predictive time-scale where observations rather than numerical models currently constitute the basis for providing public warnings of convective hazards.

13.2.1 Observational-based nowcasting

The accurate prediction of convective weather and its associated hazards has some very specific challenges. For example, convective storms are relatively small-scale and short-lived phenomena. Individual convective cells typically have a lifetime of ~15 to 30 minutes prior to reaching their dissipation stage, and a diameter of ~10 km or less (e.g. Byers and Brahams 1949). The short time-scale and small spatial extent impose inherent limitations in the prediction of individual convective cells in numerical models. For example, very high resolution is required to represent these features (Bryan et al. 2003). In addition, convection is non-linear and predictions for lead times of just a few hours means that the forecast extends over numerous lifecycles (e.g. eddy turnover times) of a convective cell, and thus the predictive skill of such a forecast is limited. The fact that more severe convective cells termed supercells are longer lived during their mature stage (e.g. Browning 1965) and that convection can organize up-scale into mesoscale convective systems (MCSs) (Simpson et al. 1967) provides some glimpse of hope for longer-term predictions (Carbone et al. 2002).

Moreover, the embedded hazards for which the society desires accurate forecasts occur at even smaller spatial scales than that of individual convective cells. On such hazard is hail, which frequently produces damage across portions of China, North America, Central and Eastern Europe, India and other locations (Figure 2). Mountainous regions are particularly prone to hail, as evident by the prevalence of certain mountain ranges, such as the Andes and Alps in the frequency maps in Figure 2. This connection to orography is long known and is understood to be associated with the role of elevated terrain in generating convective instability, regional circulations and ascent (e.g. Smith and Yau 1993) The reduced time that graupel and hail have to melt before reaching the surface in elevated terrain can also add to the frequency of reported hail occurrence (e.g. Knight and Knight 2001). Another extreme example of an embedded, small-scale hazard is the tornado with a spatial scale that ranges from tens of meters to several kilometres, producing damaging surface winds lasting from seconds to over an hour. The most extreme and relatively rare tornadoes are associated with surface winds exceeding 400 km/h (see Wurman et al. 2012 and references within). Another example of an intense small-scale feature that is embedded within a convective cell is the downburst (e.g. McCarthy et al. 1982), with damage producing, surface winds that can be in excess of 200 km/h.

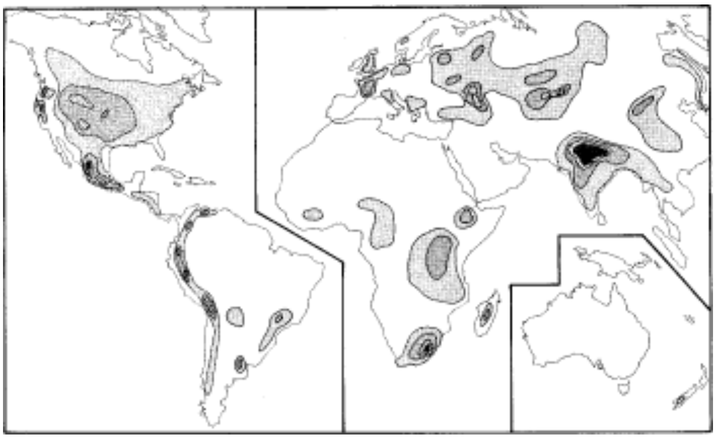

Figure 2. World composite of hail days reproduced by Court and Griffiths (1986). The shading indicates 1, 3, 6 and 9 days per year, respectively.

The small-scale and short-lived nature of convective cells and embedded hazards means that these hazards are often “nowcast” using observations rather than predicted using numerical weather prediction (NWP) systems. Summary articles on the history and evolution of nowcasting can be found in (Wilson et al. 1998; Mass 2012; Sun et al. 2014). These papers focus on radar-based approaches, since radar has proven an effective mechanism for detecting and tracking hazardous phenomena embedded within storms, thus allowing warnings to the public. The use of advanced radar systems have been particularly effective, such as Doppler radars that measure both radar reflectivity and the radial velocity associated with the advection of hydrometeors by the horizontal wind. For example, Doppler radar observations have been utilized to detect vortices in the wind field (for a review of approaches see Potvin 2013) that, in combination with the other measurement systems, storm spotters and knowledge of storm behaviour has resulted in improvements in warning the public before a tornado forms and reaches the surface (For example, the lead time in the US is currently 13 minutes as described in Broztge et al. (2013).

Another advanced radar technology utilized in the nowcasting convection is the dual-polarization approach. This radar technique provides information on the shape of hydrometeors and other scatters of radar energy, allowing insight into microphysical processes within a storm and detecting the debris produced by high surface winds. Dual-polarization techniques have proven useful for nowcasting convective phenomena, such as hail, tornadoes, aircraft icing and heavy rainfall (e.g. Scharfenberg et al. 2005). While radar-based nowcasting is effective for detecting hazards and extrapolating the movement of convective cells, combining radar data with satellite, upper-air and surface observations can result in improved nowcasts (e.g. Mueller et al. 2003). For example, Preston and Fuelberg (2015) combined lightning data with polarization radar observations to develop accurate guidelines to predict the cessation of lightning in isolated cells. In addition, satellite data has the potential advantage of identifying the development of new convective cells prior to producing precipitation. Nowcasting based on the use of satellite techniques is in itself a critical path forward, particularly in areas of the developing world that lack advanced radar systems. Another critical need identified by community vision documents (NRC, 2009; 2010) is the need to represent local and mesoscale variations in thermodynamic variables within the boundary layer and lower troposphere, as such variations impact storm formation, evolution, structure and intensity. Radar obstruction can also be beneficial in this sense. For example, effort has been dedicated to developing and improving radar refractivity retrievals, which contain information about low-level temperature and moisture variations (Weckwerth et al. 2005).

The observational approach of nowcasting convective weather hazards has had some spectacular successes in terms of delivering positive benefits to society. One dramatic example of success is associated with downbursts as discussed in Smith (2014). A critical point in this success was when Fujita and Brahams (1977) proposed that a new type of wind shear hazard called “downburst” could be the cause of the weather related crash of Eastern Airlines Fight #66 in New York in June 1975. The paper sparked a major debate in the atmospheric sciences, with discussions on the strength of convective downdrafts and on the depth and intensity of the corresponding strong divergent signal near the surface. The phenomena subsequently became a focus of the weather research community, cumulating in a field experiment called JAWS (Joint Aircraft Weather Studies; McCarthy et al 1982). The observational data set collected during JAWS and subsequent cloud modelling studies revealed that downbursts were a relatively common phenomena. Research showed that downbursts ranged from the expected strong downdrafts associated with heavy rainfall to the “so-called” dry microbursts driven by evaporation of precipitation from small and relatively weak convective cells. This evaporation produces large negative buoyancy in the presence of deep well-mixed boundary layers. The dry microbursts represent a unique phenomenon for forecasters and aviation safety, as they are not typically associated with high values of radar reflectivity and with the visible curtain of heavy rain that pilots can easily avoid on take-off or landing. These research studies quantified the magnitudes of vertical and horizontal winds expected from microbursts and also solidified how aircraft were impacted by the downdraft and outflow (Figure 3).

The data collected and the knowledge gained from this research allowed microbursts and downbursts to be incorporated into pilot and air traffic controller training, including the flight simulators utilized by the commercial pilots. Observational capabilities were also improved to deal with these hazards, including arrays of surface stations surrounding airports and automated processing of Doppler radar measurements. These changes had a positive effect. Prior to this research and to the transfer of this knowledge to the forecasting and aviation community, downbursts had a terrible impact on commercial aviation (for example, nine commercial flights crashes in the US alone in the 1970s’ and early 1980’s were likely due to wind shear associated with strong downdrafts; Smith, 2014). As a result of this research and the resulting operational changes, the last crash of a commercial aircraft caused by a downburst in the US was over twenty years ago!

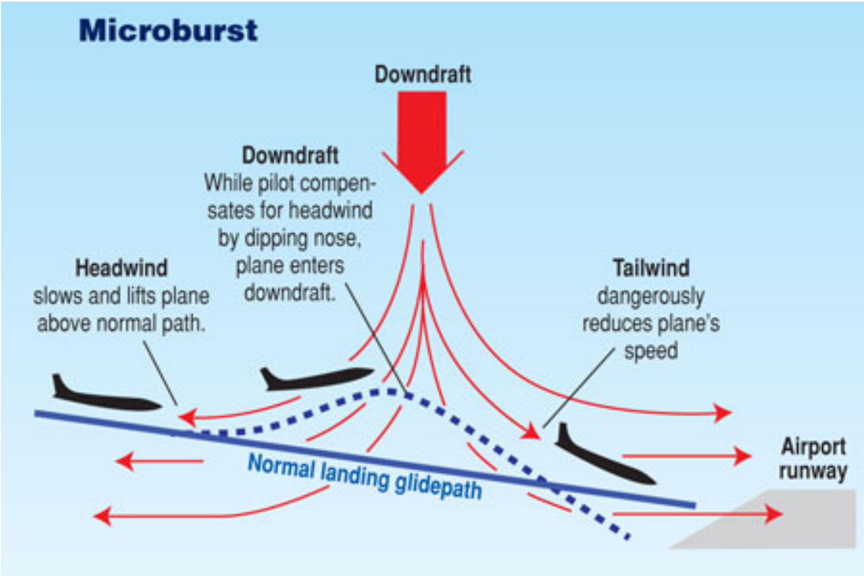

Figure 3. A schematic of how a microburst detrimentally impacts an aircraft on approach.

Source: From an article in Professional Pilot by Shein, 2013

The downburst is just one example of numerous successes of nowcasting research and of the transfer of knowledge to operational practice. Research questions posed from a likely continued reliance on observations for prediction of hazards at short time-scales include:

- How can observational systems and measurement networks be designed to help improve the prediction and understanding of rapidly evolving convective features, while also providing usable information to initialize numerical weather prediction models?
- How can surface meteorological stations and satellite remote sensing data be utilized to save lives and prevent injuries from convective hazards in developing nations that lack advanced observational infrastructure, such as weather surveillance Doppler radars?
- How can the flow and content of information to the public, the media, the decision makers and the emergency response teams be tailored so that the desired responses minimize fatalities, prevent injuries and protect property?
- Can fundamental research answer the wide range of questions often posed by forecasters and needed by society, such as why does one storm produce a tornado, while neighbouring storms do not?
- Can conceptual models and guidelines resulting from research and forecaster experience be incorporated into automated systems and algorithms that process observations, leading to providing accurate and timely warnings of convective hazards?
- How can non-linear processes, such as the initiation of new convective cells, be incorporated into nowcasting approaches and how does one bridge the gap between observations-based nowcasting and numerical weather prediction methods?

13.2.2 Prediction of convective hazards utilizing deterministic predictions from non-hydrostatic models

While observation-based nowcasting will continue for certain hazards, the limitation of such an approach is that nowcasting works well for extrapolation of convection cells, but often cannot forecast the initiation of new cells. Thus, nowcasting approaches tend to become increasingly less effective with time and are generally limited to several hours (Germann et al. 2006). This limitation leads to an increasing focus on blending nowcasting systems with products from NWP models for short-term prediction, and on using NWP models to predict convection and convective hazards at longer time-scales (e.g. Mass 2012; Sun et al. 2014). Optimism for forecasts based on NWP is that researchers have established that certain convective features, such as supercells and MCSs, have lifetimes that span several hours, thus implying a greater degree of inherent predictability relative to ordinary convective cells. Such systems would seem good candidates for an NWP approach. For example, large Mesoscale Convective Complexes (often referred to as MCCs) observed in the warm season have cold cloud shields covering over 100,000 km^2 and lifetimes in excess of 12 h (Maddox 1980). Not surprisingly, these large convective complexes are often associated heavy rainfall and flooding, due to either the repeated effects of individual convective cells moving over a location or watershed, or due to features related to the mesoscale organization of convection, such as the intense line of heavy precipitation with trailing stratiform rainfall occurring in squall lines. These convective structures can also generate their own hazards through mesoscale circulations that can produce high winds at the surface (e.g. Davis et al. 2004 and references within). Particularly damaging long-lived features are derechoes, a type of long-lived MCS associated with damaging “straight-line” surface winds in excess of hurricane strength and impacting the surface for ~6 hours or more (e.g. Johns and Hirt 1987).

Unfortunately, given current computational technologies, convection must be parameterized as a subgrid-scale process in current global NWP systems, which means that such global models are not well suited to predict convective modes and the details of convective organization (with the arguable exception of the largest mesocale convective systems). Given that the parameterization of convection has proven a vexing problem for the atmospheric sciences (e.g. Stevens 2013), directly resolving convection is the desirable approach for predicting the behaviour of convection on the time-scales of hours. NWP models with kilometre-scale horizontal grid spacing, which permit convection to occur rather than attempting to parameterize convection as a subgrid-scale process are limited in their spatial domain by current computing technology (domains generally covering 100s to 1000s of kilometers). Thus, convective permitting models are typically driven by lateral boundary conditions generated by global prediction systems. These models are often termed as “limited area” or “mesoscale” models, and have shown great promise in providing information on the mode and structure of convective events that is not obtainable from coarser grid models.

These convective permitting models have been utilized extensively to advance knowledge of convective and mesoscale dynamics. The community is currently in the midst of a paradigm shift towards operational use of non-hydrostatic NWP models with kilometre-scale horizontal grid spacing. Operational meteorological centres around the world now run either deterministic of probabilistic convective-allowing systems, such as the AROME model in France, the UKV model run by the Met Office in U.K., the High-Resolution Rapid Refresh in the US Saito et al. (2007) describes the early history of the operational use of non-hydrostatic models in Japan. Within Europe, the Mesocale Alpine Project (MAP) and its subsequent Demonstration Project (MAP D-Phase) showed strong justification for the use of high-resolution, non-hydrostatic models to predict heavy rainfall in Alpine regions, by comparing the relative value of an impressive variety of modelling approaches (Rotach et al. 2009). Forecasters also find these convection permitting models useful in predicting hazards, since the models provide information on the mode of convection hours and even days in advance (e.g. Clark et al. 2012). For example, output from these models can be processed to obtain information on the rotation in simulated storms and to forecast tornado pathlength (Clark et al. 2010, 2013, Kain et al. 2010), Such information is not available from coarse models with parameterized convection.

The community focus on the use of convective permitting model extends over a wide range of activities, from simply using convective permitting models to down-scale predictions from a global NWP model, to storm-scale predictions that attempt to advance modern data assimilation approaches to make predictions beyond the scale of nowcasting. Aspects of this later problem are summarized in Gao et al. (2014) and the reader is referred to that article and references therein. For example, storm-scale data assimilation can consist of combining radar observations of the precipitation associated with a convective storm with a previous model forecast (background) to obtain an analysis that is then used to initialize another forecast. As the initial conditions contain information about the storm, the new forecast is expected to better simulate the evolution of the small-scale hazards related to that storm. Such research is exciting as modern data assimilation techniques that can estimate the flow dependent nature of the background error covariance could contribute to improving forecasts at the convective-scale as such approaches did for larger-scale flow. Aspects of the problem of storm-scale data assimilation is dealt with in Chapter 5.

Despite the growing operational use of these systems, a wide variety of basic and applied research questions remain, including:

- What horizontal and vertical resolution is required to accurately simulate convective systems and their interaction with large-scale circulations, especially when these non-hydrostatic approaches are eventually applied to global prediction systems?
- With kilometre or sub-kilometre grid spacing, what changes must occur in the treatment of other physical processes in models (e.g. turbulence, microphysics, boundary layer schemes)?
- What observational systems, measurement strategies and data assimilation techniques are best suited for kilometre-scale, non-hydrostatic approaches where convection is the phenomena of interest and diabatic processes are part of the initial state?
- What verification approaches are best suited to identify systematic problems in initial conditions and model physics that lead to forecast failures?
- Are systematic difficulties in accurately representing certain phenomena, such as nocturnal convective events, due to deficiencies of the modelling system or to limited inherent predictability?

13.2.3 The use of convection permitting ensembles

Unfortunately, accurate predictions of continental convection utilizing NWP remain a significant challenge for many reasons. One difficulty is that convective instability is essentially a local vertical instability, which translates into sensitivity to small changes in the vertical profile of thermodynamic properties and, for some processes, in wind speed and direction. For example, as illustrated in Crook (1996) for a continental location, variations in the initial conditions of temperature and moisture within the boundary layer of only 1°C and 1 g kg^{-1}, respectively, can result in the model simulating intense convection and no storms at all. The implications of this finding for prediction can be evidenced in several ways. For example, as discussed in Flentje et al. (2007), the absolute calibration of most of the water vapour measurements assimilated into the European Center for Medium Range Forecasts (ECMWF) global model currently have an absolute calibration error in humidity in excess of 10%. This error magnitude means that the criteria discussed by Crook (1996) would generally not be satisfied.

The spatial variability of water vapour measurements in the atmosphere raises the issue of the representativity of observations. For example, Weckwerth et al. (1996) showed that local variations in water vapour within a convective boundary layer reached 1.5 to 2.5 g kg^{-1} , most likely due to boundary layer rolls. This uncertainty from spatial variations also exceeds Crook (1997)'s criterion for accuracy in the water vapour field. In addition to this sensitivity to thermodynamic variables, data assimilation experiments suggest that predictions of convection can be even more sensitive to the inclusions of mesoscale circulations in the ambient environment (e.g. Guo et al. 2000). The evolution and structure of a convective system also depends on the initiation mechanism, which is difficult to accurately predict given that these predictions rely, on the treatment of surface characteristics (e.g. soil moisture, terrain, and land-use), boundary layer processes and large-scale flow features such as fronts, drylines and other boundaries (e.g. Weckwerth and Parsons 2006).

Once initiated, the subsequent evolution of convection is highly sensitive to how models represent key aspects of the storm structure. For example, the upscale growth of an MCS is maintained through the lifting of the storm's inflow by a pool of cold air produced by melting and evaporation of hydrometers. The slope of the lifting of the warm unstable air at the leading edge of the cold pool (e.g. Rotunno, et al. 1988) and the depth and magnitude of this lifting (Parsons 1997) are influenced by a balance between the vertical shear of the horizontal wind in the warm air mass and the characteristics of the cold pool itself. The nature of the cold pool is strongly sensitive to the microphysical parameterization, and to how mixing and entrainment are handled within the model (e.g. Bryan and Morrison, 2012, and references therein). Obtaining the correct vertical shear depends on the accurate representation of the large-scale flow and on the boundary layer parameterizations.

The nature of convection and the wide range of sensitivities of predictions to the initial conditions and to model physics present significant obstacles to obtaining accurate simulations of convection. This situation calls for an ensemble approach to the prediction of convective events and their associated hazards (e.g. Fritsch and Carbone 2004; Clark et al. 2008; 2011; Duda et al. 2014). This section introduces some of the issues and questions associated with ensemble predictions of convection. However, we limit the discussion to ensembles using such horizontal and vertical resolution that convective motions are permitted to occur rather than parameterized. For a more complete treatment of the subject of ensemble prediction of convection, the reader is referred to the excellent recent review of the status and challenges of parameterized and resolved convection in numerical models by Holloway et al. (2014).

This chapter will only touch on a few of the numerous important efforts related to convective permitting ensembles. One focused effort on convective permitting ensembles is NOAA's programme to extend the warnings of weather hazards beyond the time range of observational nowcasting through the "Warn on Forecast" programme (e.g. Stensrud et al. 2009; 2013). This ambitious effort intends to produce a probabilistic convective-scale ensemble analysis and forecast system that assimilates in-storm observations into a high-resolution convection-allowing model. One foundation for this effort is the annual Hazardous Weather Testbed Spring Experiment at the National Weather Center in the US, which brings together operational forecasters with the research community for approximately one month of interaction each year. The Testbed began in 2000 as described in Kain et al. (2003) and the exchanges are beneficial in two ways: by exposing researchers to operational needs, and by allowing operational forecasters to work with recent advances of the research community, including experimental modelling systems. In 2007, the University of Oklahoma's Center for the Analysis and Prediction of Storms (CAPS) provided the first convective permitting ensemble to the Spring Experiment activities (e.g. Xue et al. 2007; Kong et al. 2007). Since 2007, the use of convective permitting ensembles has continued throughout the years and according to Clark et al. (2012) the CAPS ensemble guidance has become the cornerstone of prediction. The configuration of the ensemble varied from year to year, the 2010 ensemble being a 26 member, multi-model system with a 4 km grid spacing (Clark et al. 2012).

Europe is also a centre of activity regarding convective permitting ensembles. For example, the COPS (Convective and Orographically-induced Precipitation Study) international field campaign in 2007 included convective permitting ensembles (Wulfmeyer 2011; Barthlott et al. 2011). Another field campaign, the HYMEX project, also focused on the use of convective permitting ensembles for heavy rainfall (e.g. Ducrocq et al. 2014). Another effort is the use of the COSMOS-DE in a convective permitting ensemble including attempts to gain insight into the predictability of convective systems (Keil et al. 2014). Within the United Kingdom, the Met Office has an operational ensemble system with a 2.2 km horizontal grid spacing with their Met Office Global and Regional Ensemble Prediction System (MOGREPS) modelling system (e.g. Dey et al. 2014). The use of post-processed information from this ensemble system in severe weather forecasting is discussed in Neal et al. (2014), and the use of this system for the London 2012 Olympics is discussed in Golding et al. (2014). A unique aspect of limited area ensemble prediction over Europe is the establishment of an open sharing of ensemble products within the TIGGE LAM (THORPEX Interactive Grand Global Ensemble - Limited Area Model) archive at the ECMWF established under the GEOWOW project (see https://software.ecmwf.int/wiki/display/TIGL/Home for more information).

A number of research questions remain regarding convective permitting ensembles including:

- What observational systems, measurement strategies and data assimilation techniques are best suited for convection permitting ensembles?
- What are the implications of permitting, rather than resolving convection, as many of the convective ensembles are implemented with horizontal grid spacing of ~3-4 km?
- What is the optimal design of convective permitting ensembles (e.g. how many members, how can one capture the range of uncertainties in the lateral boundary conditions, initial conditions and parameterization of dynamical and physical processes)?
- What are the inherent limits of predictability for convective storms, and can these be taken into account in developing ensemble systems?
- How can the uncertainty in the prediction be characterized and effectively communicated to the public?

13.2.4 Early warning guidance for convective outbreaks

While the inherent nature of deep convection prevents the prediction of precisely where and when convective storms will form in the medium range, global ensemble modelling systems are growing increasingly important in providing early warnings of convective hazards. A growing capability is perhaps expected given the foundation of steady improvements in global modelling (e.g. Shapiro et al. 2010). However, the challenge is significant as it is well known that the skill of convective parameterized models in predicting convective rainfall in the warm season is lower than for cool season rainfall (e.g. Fritsch and Carbone 2004). In addition, Buizza et al. (1999) and Mullen and Buizza (2001) showed that the accuracy of precipitation forecasts decreases with increasing rainfall threshold, making the prediction of events such as heavy rainfall and flooding even more difficult. Recently, Hamill (2014) showed the limitations of global ensembles relative to high-resolution predictive models in predictions of the Front Range floods of September 2013. This result is consistent with the earlier findings from MAP campaigns that revealed the need for higher resolution modelling in complex terrain.

While part of the difficulty is the inherent non-linear nature of convection, another problem is accurately parameterizing convection as a subgrid scale process. Despite improved schemes and numerous advances, this topic remains a major, unsolved problem in the atmospheric sciences. As evidence of the magnitude of the community effort on improving convective parameterization, a Web of Science keyword search on the topic of convective parameterization in meteorology and the atmospheric sciences yields nearly 580 publications and over 14,000 citations with over 2,000 citations in 2014 alone!

Despite challenges in the accurate prediction of hazardous, convective events during the warm season, operational forecasters make use of medium range predictive tools in predicting hazards. For example, NOAA's Storm Prediction Center in the US has a 4 to 8 day outlook for convective weather that is readily available to the public. Petroliagis and Pinson (2014) discussed early warnings from the ECMWF Extreme Forecast Index including the successes, difficulties and challenges associated with predicting convective events. While the focus of the ECMWF extremes index is on the early medium range, the system includes alarm bells/signals extending into the late medium range based on the deterministic and/or ensemble results. The Met Office issues a National Severe Weather Warning Service (NSWWS) out to five days that warns the public and emergency planners of the possibility of severe weather with the warnings based both on the likelihood of the event and the potential impact. The ECMWF and Met Office warnings are not limited to convection, but include other types of weather events. Medium range prediction is also utilized to drive hydrological models, as discussed in Schumacher and Davis (2010) and references therein.

While medium range warnings of hazardous events, including convective storms, are being issued at various centres, researchers have investigated the potential of ensembles for early warnings of heavy precipitation. One promising result by Lynch and Schumacher (2014) is shown in Figure 4. This precipitation event was associated with a record precipitation of over 480 mm of rainfall in central Tennessee, associated with persistent heavy rainfall that occurred from 1 to 3 of May 2010 across the Ohio and Mississippi River valleys. While the results were promising, variations among the members resulted in large differences in rainfall, again illustrating the need for an ensemble approach to the prediction of convective systems.

One tool utilized in these studies is the archive of global ensembles of TIGGE (THORPEX Interactive Grand Global Ensemble) (Bougeault et al. 2010). The TIGGE archive consists of deterministic predictions from all the ensemble members of ten ensemble forecast systems produced by the major global forecast centres. Research with the TIGGE data set includes the Weigand et al. (2011) study, which showed that an event on the south side of the Alps could be predicted with a four-day lead time. Another study suggests the advantages of downscaling TIGGE using high-resolution ensembles with lateral boundary conditions driven by global ensembles members of TIGGE (Xu et al. 2012). More recently, Liu and Xie (2014) utilized the TIGGE archive to develop heavy precipitation prediction tools for the Hiaihe Basin. Hamill (2012) explored both calibrated and multi-model ensembles constructed from TIGGE forecasts. He showed that the skill of multi-model estimates of rainfall fields exceeds the improvement obtained by applying the multi-model approach to other model parameters (such as, for example, 2 m temperature forecasts). Although Hamill (2012) cautions that their conclusions are based on a limited data set, the results are encouraging enough to explore the multi-model approach for global ensemble-based prediction of heavy convective rainfall.

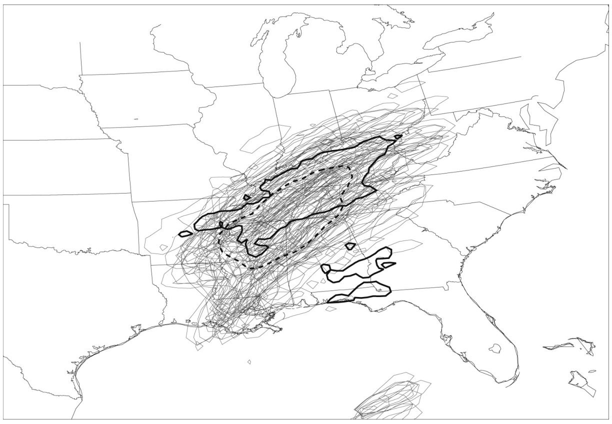

Figure 4. A "spaghetti plot" showing the predicted 100 mm rainfall contour for the time period from 1200 UTC 29 Apr to 1200 UTC 4 May 2010 from each ensemble member in gray. The forecast system used was the ECWMF ensemble system. The observed 100 mm contour from 1200 UTC 29 Apr to 1200 UTC 4 May 2010 is shown in thick black. The ensemble mean 100 mm contour is shown in thick dashed black. Initialization time is 1200 UTC 29 Apr 2010. The agreement for the large-scale precipitation pattern is worth noting, as is the difficulty in predicting the smaller-scale features to the southeast of the main system.

A number of research questions exist regarding medium range warnings of convective hazards including:

- Can the probability of hits and false alarms for specific convective events directly predicted by ensembles, such as high winds and heavy rainfall, be quantified as a function of lead time in the medium range?
- Can fields predicted by the global ensembles (e.g. convective available potential energy, (CAPE), convective inhibition (CIN), low-level helicity, height of the melting level and magnitude of the surface to mid-tropospheric vertical wind shear) be utilized to provide probabilistic predictions of the type of convective hazard that might occur (e.g. large hail, tornadoes, long-lived derechoes etc.)?
- What improvements in the post-processing of ensembles, including calibration and the use of multi-model systems, are likely to improve the prediction of convective hazards in global modelling systems?

- How can the parameterization of convection and convective processes in global models be improved and how can the uncertainty in the treatment of convection be better quantified?
- Can systematic shortcomings in the ensemble modelling system, including problems in characterizing the uncertainty in predictions, be identified and remedied in order to improve forecasts and/or identify situations where forecasts are particularly unreliable?
- How can the early warnings be effectively communicated in order to obtain the desired response from the public and emergency managers?

13.3 RESEARCH OPPORTUNITIES

The previous sections laid out a wide range of challenges closely related to improving the prediction of continental convection and associated weather hazards. The close relation of these research problems to operational prediction does not mean the challenges are any less formidable, nor that the research is meant to be only the focus of operational centres. The challenges discussed so far represent a fraction of the vexing problems faced in the quest to advance the knowledge and the prediction of high-impact convective systems. The stakes are high in solving these problems for reasons of public safety, but also due to the importance of these convective systems for the broader atmospheric science.

These challenges are significant, however as the reader will subsequently discover, a theme to this section is that the study of convective systems is fortunately moving into a period of unprecedented research opportunities that will advance our understanding of continental convective systems and their hazards. In a sense, the potential exists for a “golden age” of convective research that affords the possibility of improvements in predictions of convective events and the better understanding of our forecast failures. These new opportunities are built upon a foundation of the well-documented improvements in the skill of numerical weather models, which have resulted into a more accurate representation of the necessary conditions for continental convection, thus allowing better insight into how convective systems are initiated and how the large-scale flow influences the structure and evolution of these storms.

The reasons for the optimism for a golden age are varied and include new technological advances, such as the growing computing power, which is allowing new problems to be tackled through global modelling at convection permitting scales, and through very high resolution simulations. Other technological advances are related to observational capabilities, from satellite remote sensing of soil moisture, cloud fields and other parameters, to advanced ground-based radars that could revolutionize nowcasting of tornadoes and other convective hazards. Another opportunity for convective research includes access to “long-term” archives of radar data, reanalysis products, and data sets from global and even convective-permitting ensembles. These large data sets allow a statistical approach to understanding convection, convective hazards and linkages to the large-scale flow. Finally, another reason for optimism is the substantial efforts of the research and observational community dedicated to particularly vexing problems in prediction, such as improved prediction of nocturnal convection, and flash floods in mountainous terrain.

The opportunities afforded by these research areas are illustrated in the following subsections. In these subsections, the examples are selected from the scientific literature and from presentations at the World Weather Open Science Conference. The examples and literature presented are not meant to provide an in-depth overview and heavily reflect the ideas exchanged at the conference and the author’s own research knowledge. The author notes that numerous other examples of research frontiers could have been selected to convey the general point that new and/or growing research opportunities will accelerate the advances in our knowledge, leading ultimately to improving predictive skill.

13.3.1 An example of the promise of new technology

Earlier in the text, a brief history of how research increased our knowledge of downbursts, ultimately decreasing the grave threat these phenomena posed to commercial aviation safety, was presented. This section describes the possibility for another breakthrough observation and modelling opportunity that will advance our understanding of the processes leading to the formation of tornadoes, and their subsequent evolution[b]. While science cannot eliminate all damage associated with tornadoes, the potential to increase the lead time of warnings over a large number of cases could save numerous lives and prevent injuries to an extent similar to the downburst example presented earlier. This research is built, in part, upon rapid-scan radar technology, achieved through a variety of approaches, including phased array technology (Bluestein et al. 2010), rapid scanning radar dishes with pulse compression and frequency hopping waveforms (e.g. Pazmany et al. 2013) and imaging technology (Isom et al. 2013). This new technology would allow a storm to be scanned repeatedly at an interval of 10-20 seconds rather than the 7 minutes scans of conventional operational systems. Evaluations of forecasters' warning decision-making showed that rapid radar scans allow forecasters to more rapidly recognize weather hazards, given the increased number of views of the structure and evolution of a particular phenomena (Heinselman 2013; Bowden 2014). Even without prolonged training, forecasters exposed to this technology were able to increase the lead time of warnings of severe weather by ~5 minutes. As the current lead time for tornado warnings is currently 13 minutes, the 5 minute gain represents an important and potentially lifesaving achievement.

Testing of this technology in a forecast environment is continuing. In addition to increasing lead time for warnings, there is also the potential to decrease false alarm rates, which have a long-term detrimental effect on public response. The ability to obtain the desirable public response when minutes matter is itself a critical aspect of the tornado warning problem. Hence, how warnings are communicated to the public represents another research frontier with great potential for public benefit, especially for the shorter time-scales of minutes and tens of minutes. An initiative in this direction, termed Weather Ready Nation (Brotzge and Donner 2013) has been put forth in the US built upon a partnership between social and physical scientists. This type of partnership is a strategy in which the World Weather Research Programme (WWRP) has been a pioneer since the 1990s.

However, perhaps the most important potential use of the rapid scan radar is in advancing our scientific understanding of the formation and evolution of tornadoes. Currently, forecasters and automated systems are hindered in their attempts to extend warning lead times and to reduce false alarms by the lack of a clear understanding of how tornadoes form in the atmosphere, and a clear conceptual model of why one storm becomes tornadic while another does not. A clearer understanding of the genesis process may allow forecasters to relate early genesis to signatures in radar measurements of Doppler winds, reflectivity and dual polarization parameters. In the past, much of the focus on detecting tornadoes was concentrated on mesocyclones in the lower troposphere, since tornadoes are often associated with supercell storms (e.g. Smith et al. 2012). The hypothesis was that tornadoes are a downward extension of the mesocyclones associated with supercells. More recently, a growing body of evidence is focusing on processes near the surface and in the lower troposphere (e.g. below 3-5 km above the surface), including the formation of low-level vortex sheets along gust fronts as discussed in Markowski et al. (2014). Recently, French et al. (2014) utilized rapidly scanning Doppler radar data to show that the formation of several tornadoes was associated with rotation rapidly evolving in the lower troposphere, rather than with a downward extension of the mid-level mesocyclones (Figure 5). From the rapid update cycle measurements of French et al. (2014), one might speculate that the past data sets that relied on far less frequent updates misinterpreted the genesis process. The link between mid-tropospheric rotation associated with supercells and low-level vorticity associated with the developing tornado may be due to the temporal aliasing of the data set. However, it is also possible that different tornadic storms have different formation mechanisms. Additional information on tornadic signatures can be obtained from dual polarization measurements (e.g. Van de Broeke and Jauernic 2014; Wang and Yu 2015 and references within), which can detect changes in microphysics and even the debris associated with tornadic storms.

[b] *Unfortunately due to an unavoidable cancelation of an invited presentation at the conference, this topic was not covered in this meeting*

To complement new insights into storm dynamics provided by advanced radar, numerical simulations that can produce features resembling tornadoes have been undertaken (e.g. Schenkman et al. 2014; Xue et al. 2014). The hoped-for outcome is that forecasters may eventually be able to numerically predict the probability of tornadic storms through “tornado-resolving” ensembles initialized by radar data, thus greatly increasing the current lead time for a tornadic storm. Unfortunately, technology currently limits us to deterministic simulations on these scales, since ensembles on such fine grids are very computationally expensive. For example, the simulation analyzed by Xue et al. (2014) had a 25 m horizontal grid spacing, a 20 m vertical grid spacing, nearly a third of a billion grid cells and took 24 hours of processor time on today’s supercomputers to simulate 1 hour of storm evolution. For now, a fruitful approach could be combining the findings from new rapid-scanning, multi-parameter radar and other observational capabilities with “tornado-resolving” simulations. Such research avenues are unprecedented and have the potential to improve conceptual models of tornadogenesis and to advance the knowledge of how the storm-scale and regional-scale environment affect the genesis, strength, size and intensity of such features. With these advances, a new framework for identifying precursor signals of these dynamic events within the radar data can be developed to be coupled with deterministic modelling approaches. This approach can also be extended to understand other convective hazards such as large hail and extreme surface winds.

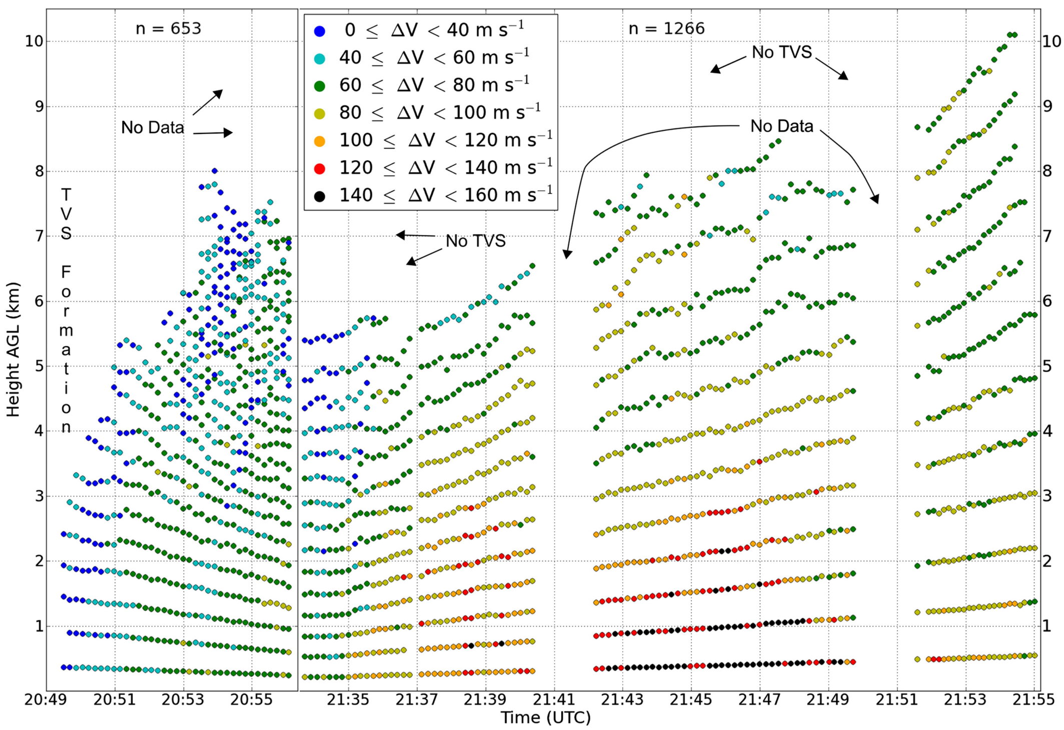

Figure 5. Observations of a tornado vortex signature (TVS) from rapid-scan Doppler radar as presented in French et al. (2015). The vortex first appears in the lowest ~3 km and subsequently extends upward in depth. The intensity of the TVS is denoted by the colour scale. The reader is referred to French et al. (2015) for further details.

13.3.2 Resolution, physical parameterizations and the problems of Terra Incognito and the Grey Zone

The growing computing capability has allowed simulations for research that were difficult to imagine a generation ago. For example, early efforts on the Earth Simulator in Japan allowed global simulations with large portions of the domain at convective permitting scales (e.g. Desgangé et al. 2006). Models with sophisticated grid designs (e.g. Skamarock et al. 2012) hold the promise of exploring and predicting the relationship between convection and the large-scale flow by allowing convective permitting grids over continental and even global regions. This strategy is promising not only for downscaling convection processes, but also for improving the representation of the effects of convection on global circulations (e.g. upscaling). For example, the potential of exploring the interplay between convection and the large-scale flow, such as diabatic heating near the presence of the Rossby wave guide, sets the stage for exciting decades of research. Aspects of the diabatic processes and Rossby wave dynamics are discussed elsewhere in this book such as Chapter 5.

However, the effects of increasing the horizontal resolution also raise a number of problems that need to be addressed. An important aspect is that as mesoscale models use finer grid spacing, the circulations resolved within the models begin to inadvertently represent motions and processes that are intended to not be resolved, but instead to be treated by boundary layer parameterizations. For example, simulations with horizontal grid spacing of 500 m would likely begin to resolve rolls and cells that arise from a heated boundary layer. Wyngaard (2004) coined the term “terra incognita” for simulations that range from large eddy simulations to mesoscale model simulations at sufficiently fine horizontal resolution that the model utilizes boundary layer schemes, but also begins to directly resolve these turbulent scales.

The invited presentation in this conference by Rotunno (2015) explored the terra incognita. The reader is referred to Rotunno’s presentation and Ching et al. (2014) for a full description of this study[c]. Their study was guided by established turbulent theory (Rayleigh 1916) and included both large eddy simulations and simulations with mesoscale models that include boundary layer parameterizations. The findings presented by the Rotunno (2015) presentation include: i) High-resolution mesoscale models (~500-1000 m mesh size) produce convective structures that are sensitive to both the grid resolution and the boundary layer parameterization scheme; ii) The convective structures are driven by classical convective instability of the parameterization-produced super-adiabatic temperature profiles; iii) Accurate and grid independent representation of structures, such as rolls or cells, requires grid meshes in the inertial subrange of turbulence. The research also presents evidence that inaccurate energy spectra of vertical motion and heat flux may be due to the existence of these artificial structures.

Based on these results, Ching et al. (2014) and Rotunno (2015) call for the development of advanced boundary layer schemes that can prevent these resolution-dependent artificial circulations, perhaps through mitigating the development of the super-adiabatic lapse rates and/or by filtering the resulting artificial convective structures. These results argue for a research focus to improve the representation of the convective boundary layer. To prioritize this research question from an operational point of view, there is a need to quantify the effect of these theoretical shortcomings on forecast parameters of interest to the public. This task is a research challenge in itself.

Still, given the sensitivity of simulated convection to the boundary layer parameterization scheme, it is expected that properly treating boundary layer processes would positively impact forecasts of convective activity. Thus, work on overcoming the problems of the terra incognita should benefit predictions of convection and its subsequent evolution. The development of boundary layer parameterizations that can solve the terra incognita is challenging. For example, consider the effect of the diurnal cycle of solar heating on the development of a deep convective event. The scale of the boundary layer circulations that form in response to diurnal heating changes as the boundary layer deepens, as explained by Rotunno et al. (2014). Eventually, the boundary layer circulations intensify so that deep convection develops. The parameterization for turbulence must be able to represent entrainment and other turbulent mixing processes associated with convective clouds and with the penetration of cold pools in the boundary layer. Finally, the turbulent/boundary layer parameterization needs to accurately depict the development of the nocturnal boundary layer and the interaction of these stable layers with negatively buoyant downdrafts from convection.

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[c] *All the presentations from the WWOSC-2014 conference are available online at* *https://www.wmo.int/pages/prog/arep/wwrp/new/wwosc/presentations.html*

The challenges of terra incognita become more complex as simulations incorporate other physical processes. The impacts of variations in physical parameterizations and different treatments of land surface processes at relatively high resolution (2 km grid spacing) were illustrated in a presentation by Hodur and Jakubiak (2014) at this conference. A main finding of their study is that “some precipitation events are simulated quite well, others pose problems for all parameterizations”. This result illustrates the need for systematic and detailed studies to determine whether this sensitivity is related to model deficiencies (i.e. the inability of model physical parameterizations to represent certain physical processes), or to intrinsic predictability limitations (as indicated by numerous studies such as Hohenegger et al. 2006, Melhauser and Zhang, 2012, etc.).

Another problem arises as to the effect of grid spacing for accurately representing the dynamical and microphysical processes associated with deep convection. The range of scales for which the horizontal grid spacing is too large to accurately represent deep convection, but small enough so that convective parameterizations are typically not utilized is called the “grey zone”. The research problem of the *grey zone* has been undertaken as a priority project of the WMO-CAS/WCRP Working Group on Numerical Experimentation (WGNE)(http://www.knmi.nl/samenw/greyzone/). A first case study for the Grey Zone project is a cold-air outbreak event observed during the CONSTRAIN field campaign. While this event is not associated with continental convective systems, the result of this study may be applicable to convection in general. In actuality, the grey zone and terra incognito occur over similar spatial scales.

Several presentations explored aspects of the relation between physical parameterizations and model resolution. Hohenegger et al. (2014) explored the response of convective circulations and the resulting shallow cloud field to idealized mesoscale variations in surface properties. The horizontal grid spacing in the simulations ranged from 400 m to a convection-permitting 2.2 km spacing, to a 11 km for which convection was parameterized. Following Rotunno et al. (2014) and Ching et al. (2014), the finer grid is likely to lie within the terra incognita. The mesoscale circulations were driven by differences in surface properties due to a land-sea difference in a simulation initialized by a sounding from the North Sea coast during summer. The results were interpreted within the context of fluxes of sensible and latent heat being representative of the strength of the mesoscale circulation. The greatest differences in the mesoscale circulation were between the coarse grid simulation (11 km grid spacing), and the other two simulations. Smaller differences were observed between the 400 m and 2.2 km simulations. The results indicate the importance of resolution, but also the complexity of separating the different effects of resolution (e.g. treatment of turbulence, characteristics of surface properties, not properly resolving clouds) on convection as simulations become more realistic.

The study by Gantner et al. (2014) was motivated by the need to improve the representation of clouds and precipitation within climate models, and was realized through the analysis of large eddy simulations. A range of simulations with a horizontal grid spacing of 100 m and different treatments of land surface parameterizations were performed for their study. The forecasts were then compared to observations from Doppler lidar and other instruments, which included estimates of vertical motions and cloud fraction. The results of Gantner et al. (2014) showed relatively weak sensitivity to the model configuration when the modelled vertical velocities and cloud fields were similar to the observations. The comparison between forecasts and observations was also discussed, such as large differences in the spatial and temporal evolution of boundary layer parameters.

The paper in the conference by Lean et al. (2014) conducted simulations within this range of the grey zone and terra incognita through examination of the resolution dependence of convective simulations over horizontal grid spacings from 100 m to 4 km. These simulations were compared to statistics of storm parameters from 40 days of observations collected during the DYMECS (Dynamical and Microphysical Evolution of Convective Storms) with the Chilbolton research radar. A key issue from this study is how simulations represent the size of convective cells. At 100 m grids, the models have a tendency to produce too many small cells with a behaviour very sensitive to the subgrid-scale mixing, and not enough large storms as depicted by the radar.

Marsham et al. (2014) explored the multi-day prediction of convection associated with the West African Monsoon using convection-parameterized and convection-permitting model simulations. The study illustrated the problems in representing the initiation of convection by local processes in convection-parameterized models, as well as errors in soil moisture gradients for these coarse-grid simulations. The study also presents parameterizations of convection that better capture the storm initiation, storm structure, the diurnal cycle of convection and the rainfall intensities, thus showing that there still is room for improvement in convective-parameterization schemes.
The need to explore the grey zone and the terra incognita, represents a focal point for future research on how to improve the accuracy of numerical modelling from research and operational simulations utilizing limited area models at high resolution to climate models. There is a clear need for systematic exploration of how resolution impacts the representation of continental convection. It is necessary to characterize the effect of model resolution separately for different physical processes (e.g. boundary layer circulations, deep convection, representation of variations in surface properties, and mesoscale circulations) and to explain why such effects exist. Research opportunities related to these problems clearly exist. Such opportunities are at the intersection of studies of continental convection itself and other fundamental research issues facing our field, such as how to optimally design future weather and climate models.

13.3.3 New research opportunities afforded from long-term archives

Another opportunity to advance convective research is the existence of easily accessible archives that contain multi-year data sets that allow statistical investigations of continental convective systems. These data sets include long-term archives of radar mosaics at continental scales, archives of satellite data, reanalysis, operational modelling and even ensemble forecasts from convective permitting models assembled from the research community. The combined use of long-term model and observational data sets allows insight that complements and extends beyond the conclusions that can be drawn from case studies and special observing periods.

One early example of this approach is the work by Carbone and colleagues (e.g. Carbone et al. 2002). These studies revealed the tendency for convection east of the Rockies to propagate as ‘episodes’ that originate over high terrain and then propagate to the east over large distances (~1000 km) and long times (~12 h), thus indicating enhanced predictability of warm-season precipitation. This apparent propagation, which in fact is a combination of storms moving eastward and a decay-initiation cycle of storms, is associated with a nocturnal daily maximum of precipitation over the Great Plains. The research on this “continental” organization and propagation of convection systems was subsequently extended to Australia, North Africa and east Asia (e.g. Wang et al. 2004; Keenan and Carbone 2008; Liang et al. 2008; Levizzani et al. 2010).

The approach of utilizing continental archives of radar data was subsequently expanded through the incorporation of information from nowcasting and numerical weather prediction systems as revealed in the invited presentation by Zawadzki et al. (2014) and the companion presentation by Surcel et al. (2014). These large-data efforts complement modelling efforts aimed at understanding the inherent predictability of convection (e.g. Zhang et al. 2003). The research approach by Zawadzki, Surcel and colleagues includes a focus on the scale dependence of predictability of warm season precipitation, as revealed by continental-scale radar mosaics and numerical models (Germann and Zawadzki 2002, 2004; Turner et al. 2004; Germann et al. 2006; Radhakrishna et al. 2012). According to the first paper in this series by Germann and Zawadzki (2002) the intent of this research was to “(i) determine the scale-dependence of predictability; (ii) set a standard against which the skill for quantitative precipitation forecasting by numerical modelling can be evaluated; (iii) extend nowcasting by optimal extrapolation of radar precipitation patterns.” The results obtained from analyzing the predictability of precipitation from radar allowed the formulation of probabilistic nowcasting based on Lagrangian persistence of radar precipitation (Germann and Zawadzki, 2004). The results from this approach were subsequently used to refine nowcasting approaches (Turner et al. 2004) and was further extended to nearly 6000 radar composites taken over 1424 hours (Germann et al. 2006), thus yielding information about predictability of warm-season rainfall.

Subsequently, Radhakrishna et al. (2012) examined the scale dependence of the growth and decay of continental-scale, warm season precipitation systems. This research also provided insight into the inherent predictability of convective precipitation by estimating how quickly observed reflectivity pattern becomes decorrelated. They found that the growth and decay of precipitation may be predictable by statistical methods for up to about 2 h for horizontal scales larger than 250 km. This study is a broad look at the predictability of convection that considers many different types of convective systems together. The predictability estimates for individual events such as long-lived derechoes and supercells may be larger than this averages estimate.

The series of papers by Surcel et al. (2010) and Berenguer et al. (2012) extended the approach of utilizing large and detailed convective data sets to the evaluation of NWP models with a focus on the diurnal cycle of continental convection. For example, Surcel et al. (2010) used the continental radar composites to evaluate the Canadian GEM (Global Environmental Multi-scale) model separately for the spring and summer of 2008. This work provided insight into the seasonal, temporal and spatial variations in the behaviour of observed convective systems and the ability of the GEM model to predict these variations. It was found that the GEM model was unable to predict the continental scale propagation of convective systems during the summer as mentioned earlier by Carbone et al. (2002).

Surcel et al. (2014) built upon these previous studies through research investigating the observational data together with forecasts from the McGILL Algorithm for Precipitation Nowcasting by Lagrangian Extrapolation (MAPLE) nowcasting system (Turner et al. 2004) and the output from the CAPS convective permitting ensemble (Xue et al. 2007; Kong et al. 2007) run during National Oceanic and Atmospheric Administration (NOAA) 2008 Hazardous Weather Testbed Spring Experiment. Specifically, this study quantified the limits of predictability of precipitation as a function of spatial scale and forecast lead time and noted the rapid loss of predictability at scales smaller than 200 km. Their methodology, further formulated in Surcel et al. (2015) was based on determining at what scales precipitation forecasts from the CAPS ensemble become fully decorrelated. Other than providing precipitation predictability estimates for different forecasting methods, this work also explored the importance of radar data assimilation for convection-permitting forecasts and the impact of various perturbation methodologies (e.g. initial and boundary conditions, and model physics perturbations) for storm-scale ensembles.

The use of other archives, such as regional and global reanalysis supports the movement of convective research beyond the case study approach. For example, in this conference Ganai et al. (2014) utilized 5 years of cloud congestus and rainfall products from Tropical Rainfall Measuring Mission (TRMM), the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis and models at various resolutions to explore the diurnal cycle of clouds, cloud microphysics and precipitation over central India during the Indian summer monsoon. This approach allowed insight into both the climatological diurnal variation of convection and model biases, and illustrates the potential for using archives of satellite measurements that have become available in recent decades. In another example from this conference, Dyson (2014) utilized the thirty years of sounding data from Gauteng, South Africa and applied the concept of self-organizing maps to create a climatology of the thermodynamic profiles associated with heavy rain. This type of approach cannot only improve forecasting, but also helps the understanding of processes leading to heavy rainfall.

Rodwell et al. (2012) applied the large data set approach to medium range prediction through utilizing the ERA-Interim to explore medium range ‘busts’ in the 6-day forecasts over Europe for the 1989 to 2008 time period. In this work, a bust is defined as forecast of 500-hPa heights over Europe having a root mean square error greater than 60 m and an anomaly correlation coefficient less than 40%. This study found the mean pattern associated with forecast busts to be associated with a high likelihood of occurrence of continental convection over North America (Figure 6). A clear advantage of this approach is the large number of events that can be investigated (the ERA-Interim data used here resulted in 587 bust cases). Recently, Lillo (2014) examined these ECMWF bust events in more detail through Principal Component Analysis followed by a cluster analysis of the resulting patterns (Figure 7). Lillo (2014) found that each of the derived clusters had seasonal tendencies and were associated with the generation and/or amplification of Rossby wave trains initiated by diabatic processes. The amplification and the potential for Rossby-wave breaking modified the large-scale pattern including, in some instances, changing the North Atlantic Oscillation. While results are preliminary, it seems that the different clusters were associated with different synoptic regimes. Therefore, in addition to continental convection over North America, the extratropical transition of tropical cyclones and intense cyclogenesis were also likely sources of forecast busts.

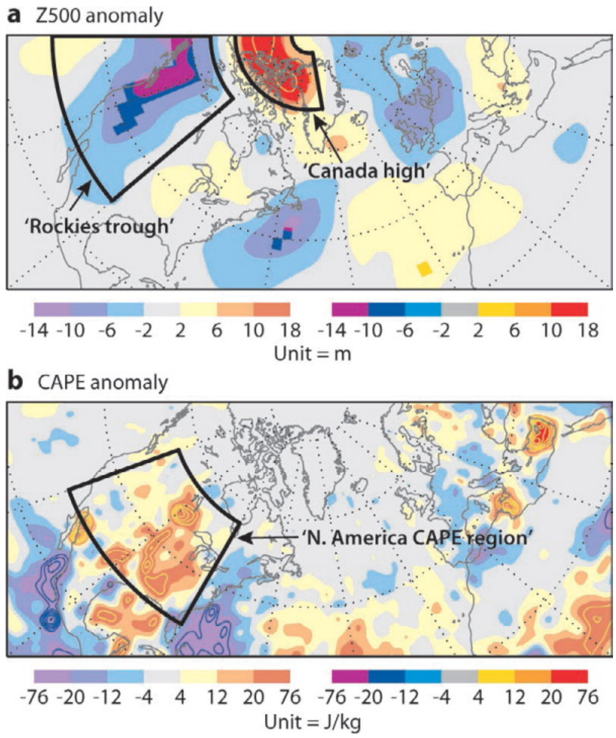

Figure 6. The mean initial condition anomalies of (a) 500 hPa heights and (b) the maximum CAPE in a 6 hour forecast associated with forecast busts identified in Rodwell et al. 2013. The anomalies are calculated relative to the ERA-Interim climatology for 1989-2008. Statistical significance at the 5% level is indicated with bold colours. Throughout this article, the analyzed CAPE is actually a 6-h forecast, since this is what is archived.

Source: Rodwell et al. 2013

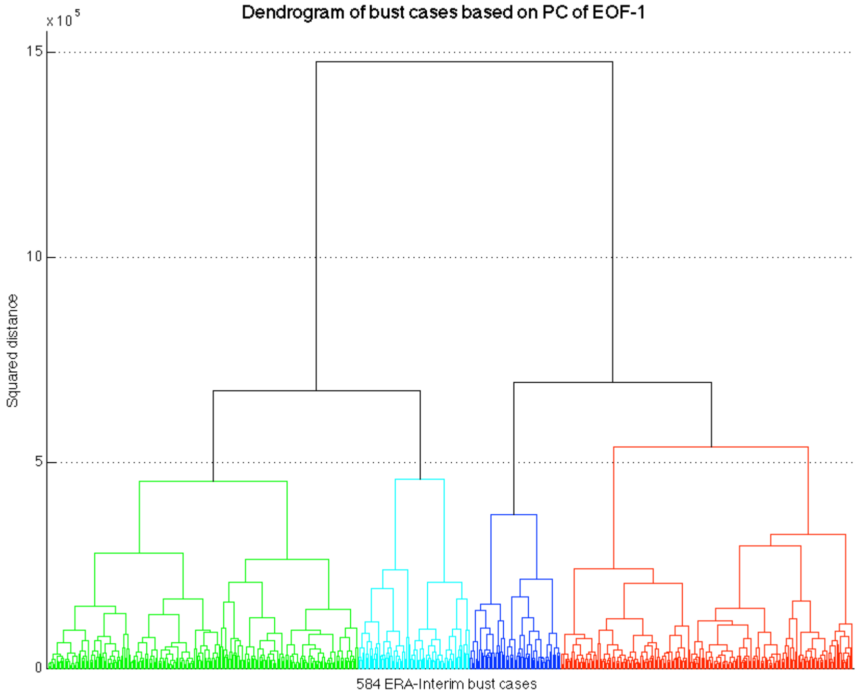

Figure 7. A dendrogram based a cluster analysis of the bust cases identified by Rodwell et al. (2013). The clustering was based the Principal Component Analysis scores of the first Emperical Orthogonal Function yielding different phenomena and large-scale wave patterns.

Source: From Lillo (2014)

The powerful potential of utilizing long-term reanalysis to understand convective systems and how these systems depend on the larger-scale environment is also illustrated by the presentation in this conference by Allen et al. (2014). This study used data during the period from 1979 to 2014 from both the National Climatic Data Center's Storm Data and the North American Regional Renalysis to derive a hail 'index'. This index describes the monthly climatological likelihood of severe hail over the United States. Allen et al. (2014) then explores how the climate system is influenced by the seasonality, spatial distribution and frequency of occurrence of large hail. This study illustrates the potential of understanding severe weather within the context of global circulation, thus showing the possibility of extending severe weather forecasts into the monthly and seasonal range through increasingly detailed, accurate, and accessible long-term archives. The study, for example, shows a strong dependence of hail on the phase of the El Niño/Southern Oscillation (ENSO) cycle. The presentation by Abiodun et al. (2014) at this conference addresses the predictability of convective rainfall at even longer time-scales by employing nine different regional climate models driven by different global climate models in order to better understand extreme rainfall patterns over South Africa, and the ability of climate models to accurately replicate these patterns. Such work is critical for assessing the uncertainty of projections by global and regional climate models about heavy rainfall under future climates.

The presentation by Wapler et al. (2014) in this conference illustrates the ability to explore how convective events link to their societal impacts. This study examined a severe convection event over Germany on 22 June 2011 that included 3 tornadoes, large hail, heavy rainfall and widespread occurrence of strong surface wind gusts. This presentation utilized the European Severe Weather Database (Dotzek et al. 2009) to explore the relative economic impacts of a weather event on the scale of convective cells. This database provides a web-based access to detailed information on storm impacts based on information that range from insurance loss data to eye witness reports. The observational data set was also compared to operational weather warnings at various lead times, which gives the possibility to understand how forecast skill affects storm damage.

Another example of these valuable research archives created in recent years is the TIGGE (Bougeault et al. 2010) and TIGGE LAM archive of data from ensemble systems. Research utilizing TIGGE to investigate early warnings of warm season convection was discussed earlier. However, an examination of TIGGE publications on other topics suggests that work on the early warnings of convective hazards using long-term archives is underrepresented, thus suggesting several areas for research on the use of global models for predicting the large-scale conditions that are known to lead to heavy rainfall, damaging straight line winds, and even tornadic activity. These research areas again show the value of long-term reanalysis, data and modelling archives that are growing in both quality and length of record.

13.3.4 Community research focii

A number of research topics have been the focus of major community efforts. Such efforts are driven by the fundamental desire to advance both knowledge and prediction skill. These efforts often take the form of studies focused around large data archives or field experiments and tend to include a wide range of participants from the academic community, research laboratories and the operational community, and a range of approaches - observational, theoretical and modelling. These focused efforts can sometimes result in tens to hundreds of papers in the refereed literature. The international efforts are sometimes large enough to be organized under the WWRP. As expected, these campaigns address the critical areas identified elsewhere in this chapter including the design of convective permitting ensembles, questions of resolution and the novel use of state-of-the art instrumentation.

Several of the presentations at this conference are representative of the research themes associated with these major campaigns. For example, the paper presented at the WWOSC-2014 by Diongue-Niang et al. (2014) is research conducted under the THORPEX Africa (WWRP, 2008). The THORPEX Africa programme is an ambitious effort with goals that include advancing the understanding of the physical and dynamical processes associated with high-impact weather over the continent, capacity building, improvements in observational capacity, advances in prediction systems and better use of weather information by society and the economy. The Diongue-Niang et al. (2014) presentation discussed a case study of a West African heavy rainfall event that led to flooding in many Sahelian countries. This study, aspects of the THORPEX Africa programme and the earlier mentioned presentation by Marsham et al. (2014), were all built upon the major community effort associated with the AMMA (African Monsoon Multi-disciplinary Analysis) project (e.g. Redelspeger et al. 2006). This project focused on the West African Monsoon and included Significant efforts related to convection in West Africa. AMMA was motivated in part by the knowledge that model performance was relatively poor in West Africa, and that the path to model improvements was uncertain given that the difficulty of model evaluation due to the lack of appropriate observations. The region strongly relies on rainfall for agriculture. Hence, accurate predictions of hazards and seasonal predictions of monsoon rainfall could yield significant societal benefits. AMMA had numerous scientific and practical successes through building research capabilities in Africa (e.g. forecaster training, dramatic improvements in the number of PhDs from nations in West African, instrumentation). These advances, particularly those related to human resources and expertise may result in the West African Monsoon being an area of enhanced future activities. AMMA represents a unique model of cooperation on a research and operational level between developed and developing nations to improve prediction of convection and related phenomena, and attempts should be made to replicate this success.

Within Europe, the challenges of predicting heavy convective rainfall in the presence of significant orography has been the focus of several major efforts including the Mesocale Alpine Experiment (MAP) and the follow-on Forecast Demonstration Phase (MAP D-Phase) (e.g. Rotach et al. 2012). This project demonstrated the relative meteorological benefits of high-resolution, convective-permitting simulations in Alpine regions. The presentation by Martynov et al. (2014) illustrates how the link between Alpine orography and severe weather, such as hail, continues to be an active area of research. This investigation included examination of how different microphysical schemes, resolution and domain size impacted forecast accuracy leading to an optimal domain configuration.

In another related European effort, which also included North African countries, was the HYdrological Cycles in the Mediterranean Experiment (HYMEX). This major project was dedicated in part to understanding heavy rainfall in the presence of significant orography in the vicinity of the Mediterranean (e.g. Ducroq et al. 2014). HYMEX has a number of other successes, such as advancing knowledge of physical processes that lead to heavy rainfall, and the refinement and testing of hydrological, atmospheric and oceanographic coupled models at high resolution over the Basin. The presentation by Richard et al. (2014) revealed the role of HYMEX in evaluating and improving convective permitting ensembles with further details available in Hally et al. (2013). Another exploration on the topic of advancing knowledge of and predictive skill for heavy rainfall in the Mediterranean Basin was presented by Corsmeier et al. (2014) in their observational and modelling study of the factors leading to heavy rainfall over Corsica. The Convection and Orographic Precipitation Study (COPS) (Wulfemeyer et al. 2011) represents yet another major European research effort. This project examined the problem of convection and orography, but with a greater focus on convective initiation and the pre-convective environment.

A main focus of the long-term European interest in convection over regions of significant orography has been to utilize the scientific and operational insight gained from research to illustrate the societal benefits of improved forecast skill. This approach was evident in the MAP D-PHASE and HYMEX projects and is a hallmark of the WWRP. The Integrated Nowcasting for Central Europe Area (INCA-CE) as described in Kann et al. (2012) continued this trend and resulted in implementing a transnational weather information system designed to reduce risks of major economic damage across different socio-economic sectors and loss of life caused by severe weather. The project includes a web-based platform for outreach to different socio-economic sectors and the production of a compact guideline for policy makers. The end-to-end path from convective research to operations to quantifying the public safety and economic benefits for different users is a mode of operation that should be replicated elsewhere.

Heavy rainfall and mountainous terrain is also the focus of basic research in other regions of the globe as described, for example, by the presentation of Luo and Wang (2014). This presentation discussed the structure of mesoscale convective systems and the ambient environmental conditions during the Southern China Monsoon Rainfall Experiment (SCMREX). In another presentation on Asian rainfall at this conference, Zhao (2014) discussed a case study of an unusual heavy rainfall event that formed north of the Tibetan Plateau. Another region of the world where orographic influences strongly affect convection is the mid-latitude region of South America. According to parameters such as storm depth and lightning flash rate, these storms are some of the strongest in mid-latitudes. In a presentation by Sailo and Vidal (2014), the orographic influences on the triggering of these intense storm systems were discussed. The presentation by Nesbitt et al. (2014), described the scientific motivation for a major field campaign and associated research effort to study these storms in more depth. The motivation included detrimental societal impacts, relatively poor predictive skill in model forecasts and the lack of understanding of the structure and lifecycle of these storms. The proposed field campaigns are called the RELAMPAGO (Remote sensing of Electrification, Lightning, And Meso-scale/micro-scale Processes with Adaptive Ground Observations) and ARM-DOE SAME-PACE (South American Multiscale Extreme Precipitation-Aerosol-Cloud Experiment).

These South American storm systems form in the lee of the Andes Mountains. During the summer in North America, the convective episodes that often originate over the higher terrain in the vicinity of the Rocky Mountains and drift over the Great Plains of North America cause a nocturnal maximum in rainfall. This propagation of convective systems is also poorly predicted by models (Surcel et al. 2010). The mechanisms explaining the envelope of convection discussed in Carbone et al. (2002) and other studies are also subject of debate. The presentation by Haghi and Parsons (2014) showed that these nocturnal convective systems are often associated with waves in stable layers rather than with long-lived density currents, suggesting a different mechanism for maintaining these systems than ascent generated at the leading edge of gust fronts. Haghi and Parsons (2014) also discussed a major field and modelling campaign called the PECAN (Plains Elevated Convection at Night Experiment) that will take place in June and July of 2015. Since such envelopes of convective propagation exist in locations other than North America, the problem of understanding and predicting these nocturnal convective events will likely remain an area of future research.

13.4 SUMMARY

This chapter is intended to provide an overview of the research on convection over continental locations in the middle and subtropical latitudes. The pressing societal need to reduce property damage, save lives and minimize injuries drives this research. There is a societal need for improved prediction of convective weather events for times ranging from minutes to days and even seasons. Relative to other topics in this book, the nature of convection and our current prediction systems are such that prediction strategies for convective events are more focused on nowcasting using observations than for the prediction of other phenomena. Thus, the prediction systems and research problems discussed here range from observational-based nowcasting to deterministic models to convective permitting ensembles. The basic research is challenging due to the non-linear dynamics of deep moist convection. However, the future holds promise thanks to new theoretical understanding of how to model convection, to growing modelling and observational capabilities and to a community research interest in complementing case studies with the statistical use of large-data sets in order to grasp a more complete view of the problem. The link between convective research and seasonal prediction and large-scale atmospheric modes was evident in this chapter. Research activities oriented in this direction are also sure to further develop in the future. Exploration of societal impacts, demonstration of societal and economic benefits and the involvement of social scientists in the communication of warnings will broaden convective research into a multi-disciplinary field.

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CHAPTER 14. TROPICAL CYCLONE INTENSIFICATION: PREDICTION AND MECHANISMS

Chris Davis and Johnny Chan

Abstract

Presentations related to tropical cyclones at the World Weather Open Science Conference (WWOSC-2014), Montreal, Canada, 16-21 August 2014 focused on the problems of tropical cyclone intensity prediction, including the prediction of tropical cyclone formation. Observational studies presented revealed the importance of the spatial distribution of convection more than its intensity in determining genesis and intensification. Both environmental and convective-scale perspectives on the importance of vertical shear, surface entropy flux and convection organization revealed the complexity of intensity change process and why probabilistic intensity prediction is essential. Finally, the forefront of intraseasonal (and longer) prediction of tropical cyclone was shown to contain windows of opportunity, but advancement is still impeded by model error.

14.1 INTRODUCTION

In this chapter, we explore the subject of tropical cyclone (TC) intensity change based on the recent work presented at the WWOSC-2014 (http://wwosc2014.org/).Tropical cyclone intensity generally refers to the maximum sustained (one minute or ten minute) wind at 10 m elevation. This parameter is notoriously difficult to predict, especially in cases of rapid intensification, defined as an increase in the maximum winds of 30 knots or greater in 24 hours. The hazard posed by a TC undergoing rapid intensification before landfall is exemplified by the case of Super-typhoon Haiyan in 2013. Many of the factors affecting TC intensity have been identified, but some conditions may still be unknown, especially those responsible for rapid intensity change. Similarly, while environmental conditions favouring TC formation and intensification are generally recognized, the mesoscale details, including the essential behaviour of convection, are still not clear. The work presented at the conference, collectively suggests that, in addition to high ocean heat content and weak vertical wind shear, the coverage and radial location of convection are more important than the intensity of convection for determining rapid intensification. The coverage of deep convection is closely related to enhanced tropospheric relative humidity. Furthermore, predictive skill for tropical waves and intraseasonal oscillations appears to have increased, as have the advances in convective scale models. However, the intensification of weak disturbances in moderate vertical shear appears inherently unpredictable.

14.2 MECHANISMS OF TC FORMATION AND INTENSIFICATION DEDUCED FROM OBSERVATIONS

14.2.1 Large-scale aspects

While we typically think of large-scale conditions as determining whether or not a cyclone will occur or where it will track, rather than details about its intensity, there is an important link between intensity and the large-scale. It is widely believed that TCs will reach extreme intensity, at least to their maximum potential intensity (MPI) (Emanuel 2003), or greater (Bell and Montgomery 2008), unless impeded somehow by the environmental conditions in the atmosphere and ocean. Thus, given that both formation and maximum intensity are strongly constrained by environmental parameters, it should not be surprising that environmental parameters also influence hurricane intensity change.

It is well established that equatorial waves generate environments favourable for tropical cyclogenesis. Roundy (WWOSC-2014) used an extended dataset and performed a similar analysis to that of Frank and Roundy (2006). In Figure 1 are shown composites for the Western Pacific several days before genesis. These represent the well-known patterns associated with tropical waves (Kiladis et al. (2009), the Madden-Julian Oscillation (MJO, Figure 1a), and equatorial

Rossby waves (Figure 1b) (mixed Rossby-gravity waves not shown), foremost in the outgoing longwave radiation (OLR) but also in the shear and the surface wind anomalies. As day zero approaches, the negative OLR anomalies become coincident with the TC genesis location (TS symbol). Evidence was shown for the importance of Kelvin waves (Figure 1c). Kelvin-wave modulation of genesis in the Atlantic basin was also found, where it has traditionally been assumed that Kelvin waves had little effect on TC formation.

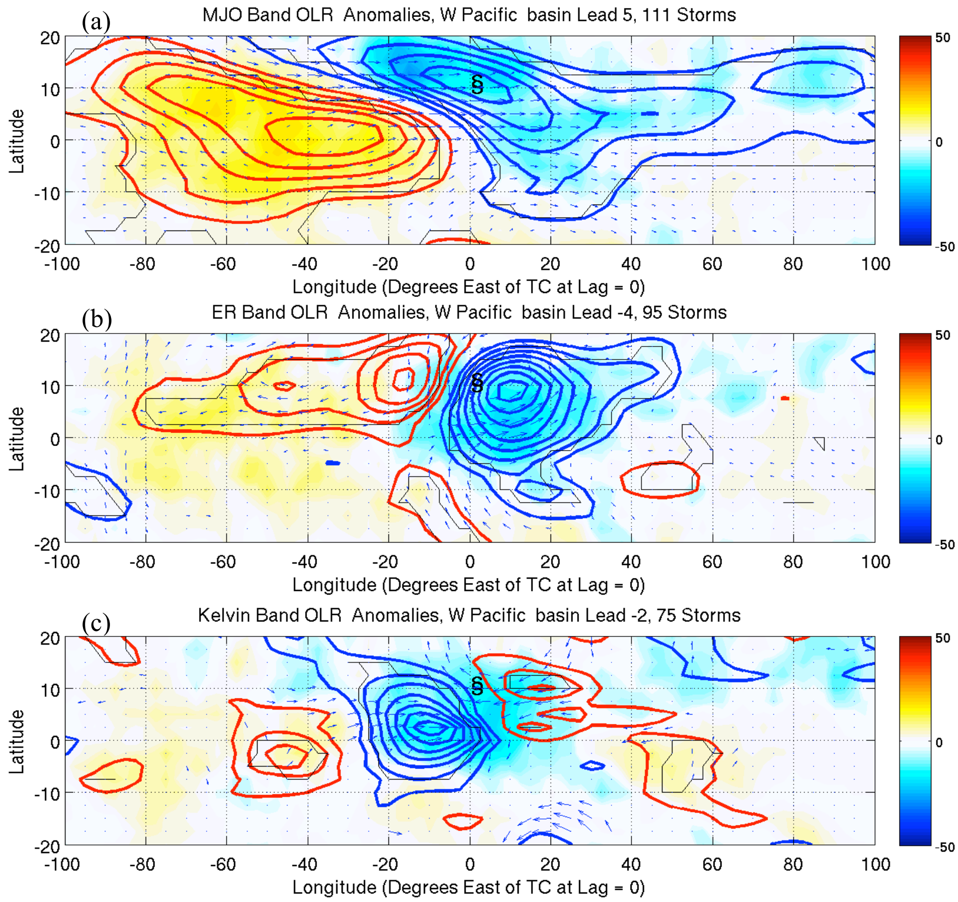

Figure 1. Time lagged composites of unfiltered OLR anomalies (shading, Wm^{-2}) and filtered OLR anomalies (Contours, plotted every 2.5 Wm^{-2} with negative in blue and positive in red, with the zero contour omitted). Composite wind anomalies are plotted at 850 hPa. Composites are based on averaging fields of data shifted to centre on the longitude of the tropical cyclogenesis event located at hurricane symbol. The latitude of the symbol is the mean latitude of genesis over the set of included events. The time lag noted in the title is the number of days since the genesis event.

Source: Adapted from figure provided by Paul Roundy

The Atlantic and Eastern Pacific also feature westward-moving easterly waves that are known to initiate tropical cyclones, albeit with a modest 20% efficiency in the Atlantic (Frank 1970, Dunkerton et al. 2009). It has recently been shown that named storms in the Atlantic and eastern Pacific basins are almost all associated with a cyclonic Kelvin cat's eye of a tropical easterly wave critical layer, located equatorward of the easterly jet axis (Dunkerton et al. 2009). Based on spatially and temporally filtered fields from the ECMWF ERA-Interim 6 hourly reanalyses for the 1998-2001 hurricane seasons, and idealized barotropic simulations, Asaadi et al. (WWOSC-2014) showed that the nonlinear evolution of instabilities associated with critical layers play a significant role in generating coherent cyclonic vortices with spatio-temporal structures consistent with tropical cyclogenesis analysis.

However, most waves, especially in the Atlantic, feature some vertical wind shear. While it is generally accepted that low shear is more favourable for genesis, it has recently been suggested (Nolan and McGauley 2012) that TC genesis occurs more often in easterly shear whereas, given a favourable thermodynamic environment and easterly surface winds, their numerical simulations indicated that westerly shear is more favourable than easterly shear. Galarneau and Davis (WWOSC-2014) used the ERA Interim reanalysis and the Hodges tracking algorithm (Hodges 1995, 1999) to identify developing and non-developing disturbances in the four basins of the Northern Hemisphere. Tracking was applied to the 800–5000 km band-pass filtered 700-hPa relative vorticity field. Maxima in filtered vorticity were tracked above a threshold of 2.0×10^{-5} s^{-1}. Galarneau and Davis stratified the sample to remove dry disturbances that occur frequently in westerly shear by requiring the total precipitable water to exceed 50 mm during the 2 days leading up to genesis (or maximum intensity in the case of non-developers). Figure 2 shows the efficiency of genesis in different flow configurations in different basins. Of note is that counter-aligned shear is generally not more favourable than other configurations. But westerly surface winds and easterly shear are quite favourable in the Pacific, and very unfavourable in the Atlantic. At higher latitudes and over the western Atlantic, westerly shear and easterly surface winds are particularly favourable and it appears that the left-of-shear- maximum in surface latent heat fluxes contributes substantially to developing cases.

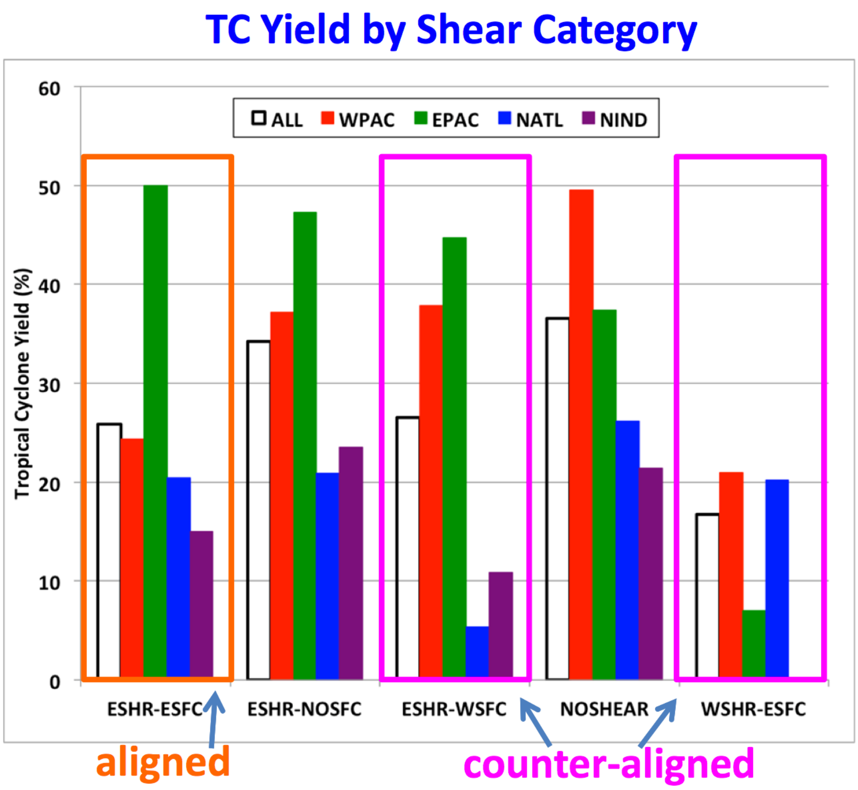

Figure 2. Histograms of the yield of tropical cyclones in each basin, defined as the number of tropical cyclones divided by the total number of tracked disturbances. White bars: total for each flow configuration; red for Western Pacific; green for Eastern Pacific; blue for Atlantic; and purple for Northern Indian Ocean. ESHR=easterly shear (850-200 hPa) greater than 2.5 m s^{-1}; WSHR=westerly shear; ESFC=easterly surface greater than 1.0 m s^{-1}; NOSFC=surface winds weaker than 1.0 m s^{-1}; NOSHEAR=shear less than 2.5 m s^{-1}. Environmental flows are computed after removal of the vortex.

Source: Adapted from figure provided by Tom Galarneau

Oceanic cyclones exhibiting properties of both tropical and extratropical systems have been categorized as subtropical cyclones (STCs) since the early 1950s. The synoptic-scale characteristics of STCs were examined by Bentley et al. (WWOSC-2014) and found to agree with earlier results (Evans and Guishard 2009; Guishard et al. 2009) concerning the seasonal occurrence and synoptic-scale environment. Of note was that anticyclonic wave breaking, accompanied by a PV streamer plunging as far south as the tropics, was a key for STC formation.

For South Atlantic STCs, in addition to the "PV streamer" genesis, there is also a second region of development downstream of the Andes in years when the Brazil Current extends further southward (Evans and Braun, 2012).

14.2.2 Storm-scale and inner-core aspects

Herein we summarize results concerning aspects of intensity change that involve processes within the storm. As stated by Zipser et al. (WWOSC-2014), "There has been a long-standing debate about the requirements for tropical cyclogenesis, and for rapid intensification of tropical cyclones, once formed. One school of thought, stimulated by the original "hot tower" hypothesis from the Riehl-Malkus era, can be framed as "the more intense the convection, the better"." Both Zipser et al. (WWOSC-2014) and Davis and Ahijevych (WWOSC-2014) challenged the idea that more intense convection was better for tropical cyclone formation. The former examined 12000 overpasses of tropical cyclones from 16 years of data from the Tropical Rain Measuring Mission (TRMM) satellite. Zipser et al. concluded, "While there is no doubt that intense convection in the eyewall or in rainbands can contribute to deepening, the more important requirement seems to be a greater degree of symmetry in the convection, and in latent heat release in the inner core of the storm."

Davis and Ahijevych (WWOSC-2014) inferred a similar result from the thermodynamic structure of pre-genesis disturbances in which a mid-tropospheric vortex is accompanied by only marginal convective instability owing to the warm anomaly above the vortex and cool anomaly below. Their conclusion, based on the study of Karl prior to genesis, was that having parcel buoyancy limited in depth would contribute to a "bottom heavy" mass flux profile (Raymond et al. 2011), and would be consistent with a mix of cumulus congestus and deep convection (Wang 2012). There was also evidence of a precession of a weaker surface vortex around the mid-tropospheric vortex that ultimately favoured vertical alignment of a coherent vortex.

For an existing storm, a leading question is what causes rapid intensification (RI) in some cases. While the influence of the synoptic-scale environment is well established, processes operating on scales smaller than the environmental scale also contribute to intensity change (Hendricks et al. 2010). Convection and its role in RI have focused primarily on the role of convective bursts (CBs). The exact role that CBs play has been tied to warming from upper-level subsidence around the periphery of the bursts and to the stretching and subsequent axisymmetrization of low-level vorticity collocated with the updraft in vortical hot towers.

Using composites of airborne Doppler measurements, Rogers et al. (2013) compared the vortex- and convective-scale structure of hurricanes that intensify with those that remain steady-state. On the convective scale, the primary difference was a higher concentration of CBs inside the low-level radius of maximum wind (RMW) for intensifying hurricanes, consistent with the theoretical efficiency with which diabatic heating released within the storm core, where inertial stability is high, is converted into an increase in the kinetic energy of the storm (Vigh and Schubert 2009). Rogers (WWOSC-2014) showed a contrast of two cases: Earl (2010) and Gustav (2008) (Figure 3). Earl was rapidly intensifying at this time, 12 UTC 30 August, whereas Gustav was near a steady intensity at 00 UTC 1 September 2008 (Rogers et al. 2013). It is apparent that CBs in Earl occurred at or within the RMW, whereas many CBs occurred beyond the RMW in Gustav. Furthermore, CBs in Earl were found azimuthally closer to the upshear side of the storm, that is, the intense convection wrapped farther around the vortex. The difference in the radial distribution of CBs is further illustrated in Figure 3c, which shows a peak in CB distribution between 0.75 and 1 x RMW for Earl, and between 1 and 1.25 x RMW for Gustav.

Research on RI has focused on two modes of radial inflow: a deep, relatively weak inflow that converges absolute angular momentum above the boundary layer, where it is conserved; and strong inflow in the lowest 1 km that also converges angular momentum and creates super-gradient flow as the inflowing air converges absolute angular momentum at a rate that exceeds its dissipation to the ocean surface via friction (Montgomery and Smith 2014). The importance of super-gradient flow is that it results in outward acceleration of the radial wind, creating a region of low-level convergence that can potentially lead to primary and secondary eye wall formation

(Huang et al. 2012). An analysis of the structure and forcing of eye wall convection observed during the rapid intensification of Hurricane Rita (2005) from the RAINEX/IFEX field campaign was able to approximately quantify the structure and magnitude of the a-gradient wind (Bell et al. WWOSC-2014). However, the presentation also showed how difficult it is to obtain reliable estimates of the pressure gradient in the boundary layer from aircraft at the usual penetration altitude of 2.5-3 km. This implies that deducing the mechanism of secondary eye wall formation will rely partially on numerical simulations (Section 14.2) provided that such models use boundary layer schemes that are not too diffusive (Montgomery and Smith 2014).

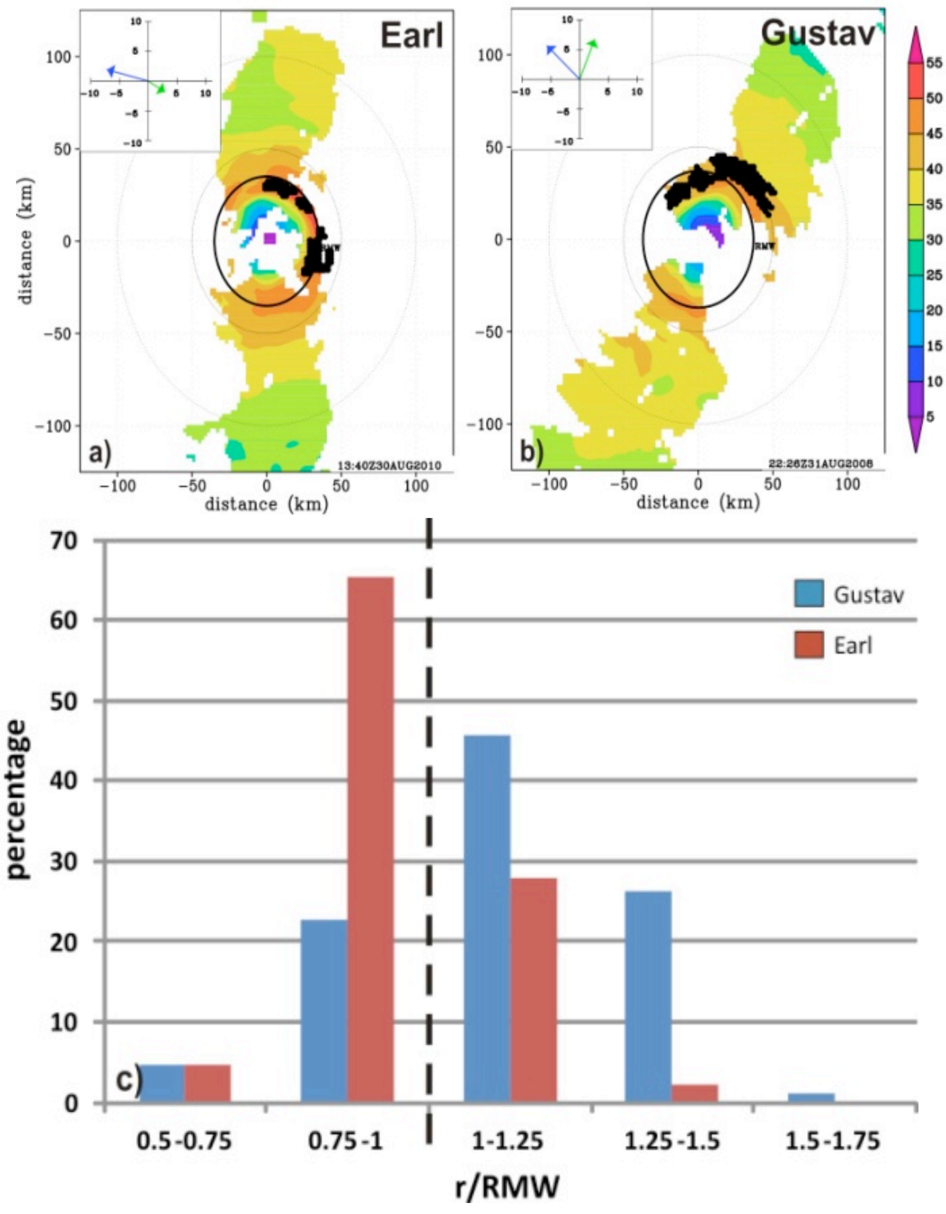

Figure 3. (a) Storm-relative wind speed (shaded, m s^{-1}) at 2 km altitude for pass centred at 1340 UTC from mission 100830H1 in Hurricane Earl; (b) As in (a), but for pass centred at 2226 UTC from mission 100831H1 in Hurricane Gustav; (c) Normalized radial distribution of convective bursts for all passes from the missions in Earl and Gustav from (a) and (b). Dashed line in (c) denotes location of RMW. Insets on (a) and (b) show the Statistical Hurricane Intensity Prediction System (SHIPS)-derived shear vector (green arrow, m s^{-1}) and storm motion vector (blue arrow, m s^{-1}) for the 6 hour time nearest to the mission.

Source: Adapted from figure provided by Robert Rogers

Simultaneously a product of the "environment" and the storm itself is the interaction of the upper ocean to the passage of a tropical cyclone. Over the past two decades, upper ocean impacts on intensity have received considerable attention including the cold wake structure and the negative feedback over quiescent oceans. Persistent western-boundary currents represent deeper mixed layers (higher oceanic heat content) that respond much less to the passage of a TC. During the hurricane Earl case, Jaimes et al. (2015) showed elevated enthalpy fluxes, deduced from more than 500 GPS dropsondes, were aligned with these deeper pools of high OHC just prior to rapid intensification. Shay (WWOSC-2014) and Lin (WWOSC-2014) noted that this trend in the vicinity of the western boundary currents, perhaps coupled with its more rapid translation, was a factor that allowed Haiyan to achieve its remarkable intensity (Lin et al. 2014). With intensity peaked at 170 kts, supertyphoon Haiyan devastated the Philippines in November 2013. In addition to the western boundary-current limit on mixing, Pun et al. (2013) discovered that the region where Haiyan developed has undergone significant subsurface warming. As compared to the early 1990s, upper ocean heat content has increased by 15%. Lin et al. (2013) and Lin (WWOSC-2014) showed that a new ocean coupling potential intensity (OCPI) index accounts for the subsurface ocean condition and can possibly identify the potential for exceptionally intense storms. The new index replaces SST by a pre-cyclone ocean temperature averaged from the surface to the expected depth of the TC-induced mixing. With little interference from unfavourable environmental conditions, including the state of the upper ocean, Haiyan was able to achieve intensity unmatched for a landfalling storm.

In summary, the observational studies presented at the WWOSC-2014 generally described necessary conditions for TC formation and intensification. The examination of environmental factors benefits from having more cases but causality is still difficult to establish. Storm-scale studies benefit from detailed reconnaissance data and an abundance of microwave data, but generally lack the time continuity to resolve the relevant processes. Large uncertainty remains in documenting convective processes, including the spatial distribution of heating (horizontally and vertically) relative to the structure of the vortex, which theory tells us should strongly affect intensity change. As a result, numerical models provide an important framework within which theoretical ideas are evaluated.

14.3 MODELLING OF TC INTENSIFICATION

Intensity changes of tropical cyclones (TCs) remain a significant forecast challenge. One roadblock to improved forecasts is our incomplete understanding of the governing processes. An important environmental contribution to intensity change is vertical shear of the environmental winds. Various shear-related mechanisms have been proposed to explain the deleterious effects of wind shear on storm intensity. These include filamentation of the upper-tropospheric piece of the PV monolith (Frank and Ritchie (2001), ventilation of the mid-troposphere (Gray 1968; Tang and Emanuel 2013), subsidence induced over the low-level centre of a tilted vortex (DeMaria 1996) and ventilation of the boundary layer inflow (Riemer et al. 2010).

Riemer et al. (WWOSC-2014) summarized a conceptual model for the interaction with vertical wind shear based on idealized numerical experiments (Riemer et al. 2010, 2013; Riemer and Montgomery, 2011). In this model, vertical shear is prone to excite a persistent downdraft pattern tied to the tilt of the TC vortex in shear. The persistent downdrafts flush the inflow layer with low-entropy air. It is hypothesized that surface fluxes do not compensate for this entropy decrease completely and air within the inner-core updrafts rises with reduced entropy values. Air masses from above the boundary layer but at low levels (approx. 1.5-3 km height) are brought into the frictional inflow layer of the TC, thus diluting the TC's heat engine and providing the thermodynamic reason for intensity decrease. Figure 4 illustrates schematically the three-dimensional interaction between the rotational flow and the thermodynamic influence of dry air. The helical primary precipitation band initiates mainly downshear from the centre and ascends as it rotates around the centre. Beneath this rather strong updraft are downdrafts enhanced by the import of dry air as storm-relative trajectories of environmental origin in the lower troposphere make their closest approach to the eye wall.

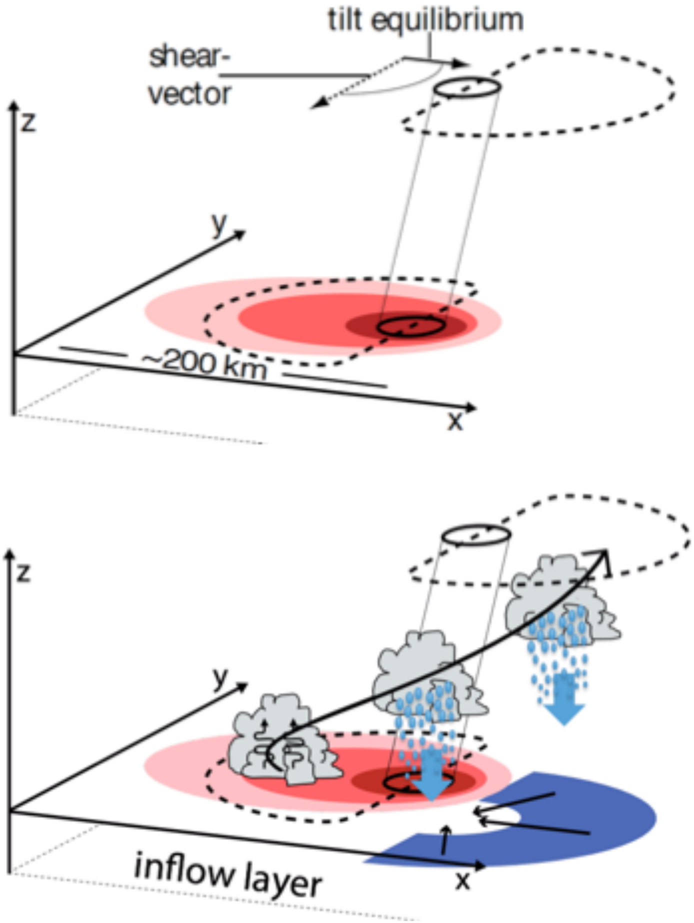

Figure 4. Schema of a tilted vortex in vertical shear, with the tilt to the left of the shear vector. Due to the shear interaction, the distribution of high-entropy “vortex” air at lower is highly asymmetric (red colours, top). Bottom panel shows the consequences for the distribution of convection, precipitation, and downdrafts. Convection is forced in the high-vorticity, high-entropy region to the right of the shear vector and ascend on a helical path within the primary rain band (long black arrow). Precipitation falls into unsaturated air below and ensuing downdrafts (blue arrows) bring low-entropy air into the frictional inflow layer (blue shading).

Source: Adapted from figure provided by Michael Riemer

Further work on the importance of environmental moisture in the lower troposphere in shear was presented by Rios-Berrios and Torn (WWOSC-2014) who used a five-day, 96 member ensemble forecast for Hurricane Katia (2011) produced by the Advanced Hurricane Weather Research and Forecasting (AHW) model. Hurricane Katia posed great challenges for operational prediction and consistent with this difficulty, the ensemble showed an anomalously large spread of intensity after 4 days. All members were initialized with a moderately strong environmental vertical wind shear, but the weakest members had a drier environment than the strongest members. A water vapour budget confirmed that the strongest members had more water-vapour flux convergence at low levels and less water-vapour divergence at the mid levels. The result was greater water vapour through a deep layer in the strongest members. Consequently, the strongest members had more area-averaged deep convection and condensational heating, indicative of more active convection. It is hypothesized that a feedback between low-level water vapour, low-level convergence, and deep moist convection aided in vortex stretching that helped to spin up the strongest members. It is also possible that the additional water vapour at low levels offset the dilution of boundary-layer moist entropy discussed by Riemer et al. (WWOSC-2014).

While vertical shear can suppress intensification through the induced thermodynamic response mentioned above, it can also invigorate convective updrafts. Nguyen and Molinari (WWOSC-2014) examined the asymmetric rapid intensification of Tropical Storm Gabrielle (2001) using the

Weather Research and Forecasting (WRF) model with 1 km grid spacing. As the simulated tropical cyclone intensified, intense convective cells with associated cyclonic vorticity anomalies developed preferentially downshear. One particularly strong mesovortex developed initially downshear-right, revolved cyclonically around the TC centre for several hours, and subsequently aligned with the vortex in the mid-troposphere. This case provides an example of transient development in shear. Presumably, if the shear is maintained past a period of initial intensification, the storm will subsequently struggle to become an intense tropical cyclone owing to the otherwise negative effects of shear on intensity.

The asymmetric vorticity dynamics, often related to vertical shear, were examined in a highly idealized context by Menelaou and Yau (2014) who used a "dry" thermally forced model to conduct numerical experiments starting with a weak vortex forced by a localized thermal anomaly. They found that the response of the vortex was dominated by the radiation of a damped sheared vortex Rossby wave (VRW) that accelerated the symmetric flow through the transport of angular momentum. An increase of the kinetic energy of the symmetric flow by the VRW was shown also from the eddy kinetic energy budget.

A limiting case of outer convection bands is the formation of a secondary eye wall, a process that often drastically modulates storm intensity. The exact mechanism of secondary eye wall formation remains a matter of controversy. Wu et al. (WWOSC-2014) outlined several possible mechanisms, including vortex Rossby waves (Menelaou et al. 2014); β-skirt axisymmetrization formation hypothesis (Terwey and Montgomery 2008), unbalanced dynamics near the top of the boundary layer (Huang et al. 2012; Wang et al. 2013; Abarca and Montgomery 2013, Bell et al. WWOSC-2014), the balanced response to diabatic heating within an elevated inertial stability region (Rozoff et al. 2012), and friction-induced updraft via an Ekman-like process over a region with radial vorticity gradient. The super-gradient mechanism was explored by Wu et al. (WWOSC-2014) through an extension of simulations of Typhoon Sinlaku (2008) by Huang et al. (2012). Based on momentum budget analyses, it was shown that the tangential wind field broadens prior to the formation of a secondary wind maximum and the forcing of positive radial wind (Figure 5) moves outward as well, establishing a region of convergence near 75 km radius. It is also true that the expanded vortex has greater inertial stability at a larger radius, so that the heating from the convection that develops in response to this outer convergence more efficiently generates vorticity at a larger radius than prior to the expansion.

As is well known, the approach to land generally causes a weakening of the tropical cyclone. Furthermore, proximity to land can induce asymmetries that change the motion of the storm, as explored by Chan et al. (WWOSC-2014). It was found that differential friction results in a tropical cyclone drifting towards the rougher surface through the development of (a) a pair of counter-rotating gyres generated by changes in the relative vorticity budget and (b) asymmetric diabatic heating. In the presence of topography, the induced upslope and downslope flows also lead to the development of a set of counter-rotating gyres that tend to cause the tropical cyclone to move towards the location of onshore flow. Topography at a large distance away from the tropical cyclone could also have an effect of its track as well through a similar mechanism. While it is intuitive that more precipitation will occur on the upslope side in the presence of topography, whether stronger convection occurs on the onshore or offshore side depends on moisture availability as well as the vertical wind shear, generally occurring downshear-left with respect to the shear averaged within 400 km of the vortex (Li et al. 2015). Ultimately, hydrological considerations also determine the local flooding potential associated with landfalling TCs near complex terrain.

It is clear from the modelling studies discussed above that the influence of vertical shear varies from case to case. The proliferation of idealized simulations in the last several years has allowed progress into the basic dynamical response of deep convection to vertical shear within a strong vortex. The recent studies have focused on the combined influences of shear on the vorticity and on the moisture transport relative to the vortex thereby providing information on the thermodynamic consequences of vertical shear as well as the dynamical strain on vortex coherence.

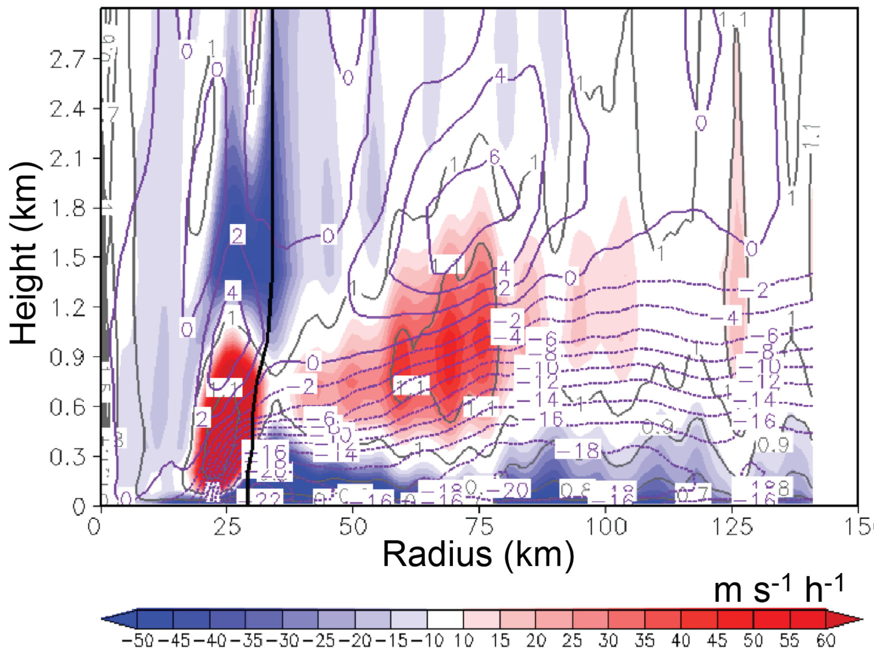

Figure 5. Radius (km) vs. Height (km) plot of azimuthal mean radial wind (contours) and a-gradient forcing (shaded) for the period 1-3 hours prior to secondary eye wall formation. Heavy black line denotes the location of the radius of maximum wind.

Source: Adapted from figure provided by Chun-Chieh Wu

14.4 PREDICTION AND PREDICTABILITY

Despite rapid advances in numerical weather prediction (NWP) models and ever-increasing computational capability, our ability to accurately predict various severe weather phenomena including tropical cyclones in the short-to-medium range remains limited. In particular, Zhang (WWOSC-2014) summarized the recent studies of Zhang and Tao (2013) and Tao and Zhang (2014) who used a series of convection-resolving ensemble experiments with varying magnitudes of vertical wind shear, each initialized with an idealized weak TC-like vortex, to examine predictability limitations. It was found that predictability is most limited for storms with environmental shear within the range of 5 to 7.5 m s^{-1} under moderately warm sea surface temperature (SST) of 27°C (Figure 6). With the imposition of random noise, the error growth from differences in moist convection first alters the tilt amplitude and angle of the incipient tropical storms, which leads to significant differences in the timing of precession and vortex alignment. The tropical cyclone intensifies immediately after the tilt and the effective local shear reach their minima. In some instances, small-scale, small-amplitude random noise may also limit the intensity predictability through altering the timing and strength of the eye-wall replacement cycle, which is to a certain extent similar to the upscale error growth processes that limit the intrinsic predictability of winter snowstorms and moist baroclinic waves discussed in Zhang et al. (2003, 2007). Further increasing SST to 29°C will lead to the largest intensity uncertainty for shear magnitude around 10-12.5 m s-1 since warmer SST will allow the storms to resist stronger shear (Tao and Zhang 2014). Limited predictability for moderately sheared storms may at least partially contribute to relatively larger operational forecast error under suboptimum conditions (Y. Zhang et al. 2014).

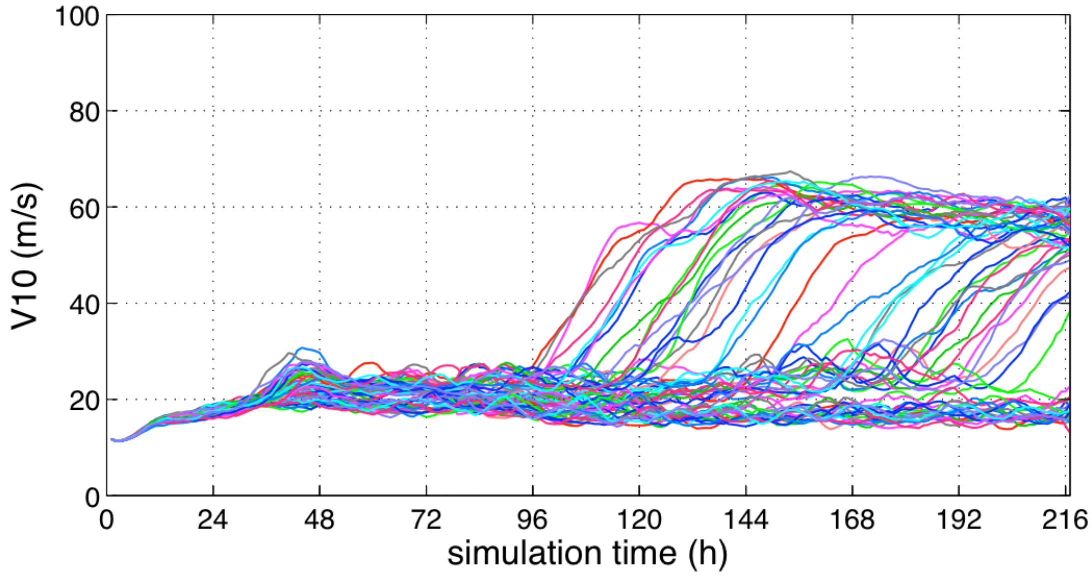

Figure 6. Maximum wind at 10 m for idealized simulations with 5, 6 and 7.5 m s^{-1} shear. All simulations are initialized with the same vortex and same environment (apart from the shear) with the addition of small random noise.

Source: Adapted from figure provided by Fuqing Zhang

Although tropical cyclone (TC) intensity change is fairly well understood under idealized scenarios, the predictability of TC intensity and structure under more realistic conditions is not as well known. In particular, it is unclear how the combination of errors associated with the vortex structure, near-storm environment and lower boundary condition (i.e., sea surface) limit intensity predictability. Torn (WWOSC-2014) determined the relative importance of different error sources using multiple sets of Advanced Hurricane WRF (AHW) ensemble forecasts of 20 Atlantic TCs over 35 initialization times during 2008-2011. Each set of ensemble forecasts was characterized by a different source of uncertainty, which included the atmosphere, ocean, and physical processes (i.e., surface layer physics, microphysics). The results from these experiments suggest that the uncertainty from the atmosphere has the greatest impact on intensity, with small TCs showing greater probability of large error growth compared to large TCs. By contrast, errors from the ocean or physical processes have lower error growth and more consistent error growth from one case to another.

Another source of systematic error is improper treatment of the upper ocean response to the TC. Ito et al. (WWOSC-2014, 2015) performed 281 3-day forecasts with the Japan Meteorological Agency (JMA) non-hydrostatic atmospheric model and the atmospheric model coupled to a simple upper ocean model. They found a 29% improvement in the minimum sea-level pressure forecasts using the coupled model. Most of this improvement was the removal of bias by the inclusion of the wind-driven mixing and upper-ocean cooling beneath the storm.

Given the variations in predictability from case to case that results from atmospheric flow dependent error growth, more useful forecasts might be obtained if one could predict whether a particular model forecast will be more or less skillful than average. Bhatia and Nolan (2013) studied the relationship between synoptic parameters, TC attributes and forecast errors, and found that certain storm environments are inherently more or less difficult for individual models to forecast. Bhatia and Nolan (WWOSC-2014) extended this work by using storm-specific characteristics as well as parameters representing initial condition error and atmospheric stability to predict both the absolute error (AE) and the actual error (bias). Error predictions were applied to 12-120 hour intensity forecasts for the Logistic Growth Equation Model (LGEM), Decay Statistical Hurricane Intensity Prediction Scheme (DSHP), Hurricane Weather Research and Forecasting Interpolated Model (HWFI), and Geophysical Fluid Dynamics Laboratory Interpolated Hurricane Model (GHMI). The methodology for the development of the error prediction models was very similar to that used for SHIPS (DeMaria and Kaplan 1994). The standard “cross-validation” approach was used, whereby all but one of the years from 2007-2013 were used as the training data, and then the excluded year was used for validation; this was repeated for all years. An example of very good correlation of predicted AE versus true AE is shown in Figure 7. The general trend is for better predictions of forecast errors for the longer intervals (96h, 120h).

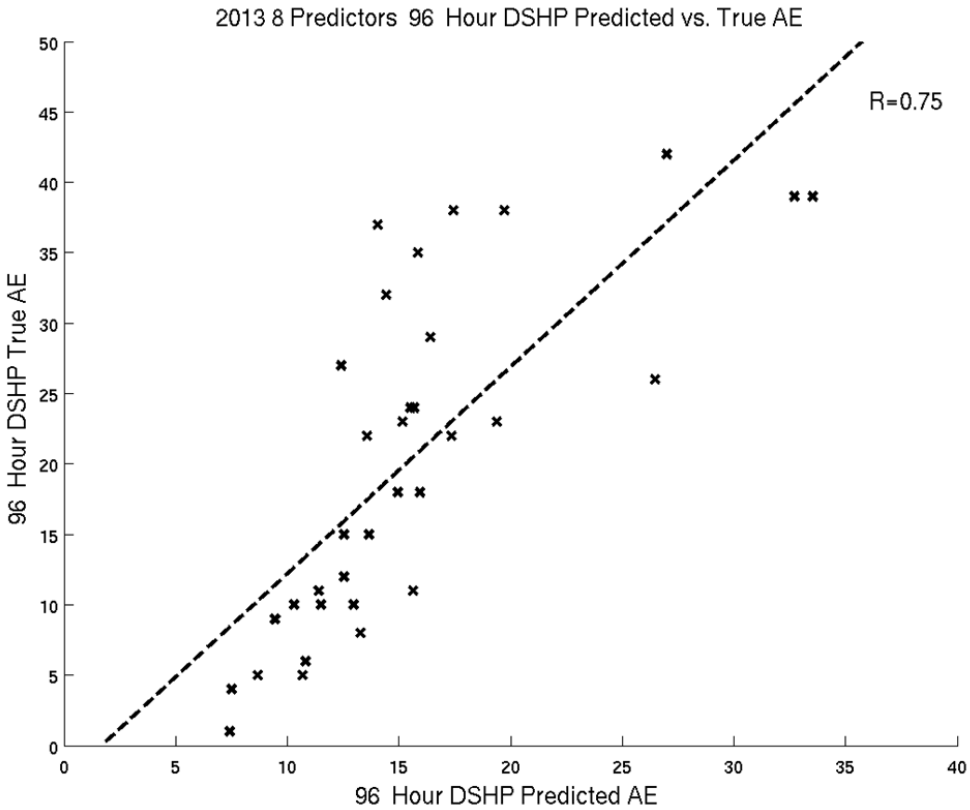

Figure 7. Predicted absolute error (AE) versus actual error for 96 hour forecasts for the Decay-SHIPS (DSHP model during the 2008 hurricane season).

Source: Adapted from figure provided by Kieran Bhatia

Although ensemble forecasting is gaining popularity for TC structure and intensity, the full information content of ensemble forecasts is not yet realized. The practical use of ensembles for prediction was explored by Evans and Kowaleski (WWOSC-2014) in the case of hurricane Sandy. They were able to derive track-based clusters in the ensemble that each represented not only a different track group, but also different structures of the storm for different tracks. Deriving scenarios from the ensemble in this way retains physical characteristics of the storm that are often lost through simple ensemble averaging. For example, it was shown that leftward-turning tracks, similar to the track of the observed storm, featured a realistic warm-core seclusion.

There is increasing emphasis on extended range predictability of tropical cyclones, even as far out as 1 month. Clearly on these time scales, it is essential to predict intraseasonal variability that constrains tropical cyclone formation. Nakano et al. (WWOSC-2014) conducted 31 extended-range (30-day) forecasts initialized on each day of August 2004 using 14 km-mesh Nonhydrostatic ICosahedral Atmospheric Model (NICAM). The formation of Megi, Chaba, Aere, and Songda were found to be predictable up to two weeks before their geneses.

There are also signals in observations of even longer-term relationships between atmosphere-ocean modes of variability and tropical cyclone formation. Camargo et al. (WWOSC-2014) examined successively longer-time-scale connections between TCs and large-scale variability. Beyond tropical waves and the MJO, which have pronounced influences on TC formation (see subtheme 1), there is the El Niño/Southern Oscillation (ENSO). The improved ability of coupled models to predict ENSO has led to improvements in numerical seasonal prediction (Vecchi and Villarini 2014). Beyond that, there are decadal oscillations that also modulate TC activity. The phase of the Atlantic Meridional Mode has a profound influence on the number of storms and the recurvature characteristics of these storms (Kossin et al. 2010). The ability of models to correctly simulate this mode of variability has clear implications for long-term investments in infrastructure along the eastern U. S. coast.

Although the potential influence of climate change on TCs has been the subject of number of recent studies, it is still difficult to confidently assess the magnitude of future changes in storm intensity. Although the resolution of climate models is increasing to the point where they are starting to resolve tropical cyclones, intensity prediction in climate models is not yet reliable. However, Lee et al. (WWOSC-2014) presented a new statistical-dynamical downscaling system to study the influence of climate on TCs. Using a multiple-linear regression model they found that monthly data from global models with only the most essential predictor, the difference between storm intensity and potential intensity, might be sufficient for us to understand the response of hurricane intensity to a changing climate from a statistical perspective.

It is apparent from the collection of studies presented at WWOSC that ensembles are indispensable for understanding the processes that affect hurricane intensity and quantifying the predictability of the results of those processes. It is clear that uncoupled models have significant biases that render their application in ensemble studies somewhat questionable. Furthermore, there still remain some important questions about the errors inherent in convection-permitting simulations. To better understand the response of convection to vertical shear, it may now be necessary to proceed to ultra-high, turbulence resolving simulations of hurricanes in shear.

14.5 CONCLUSIONS

The dominant theme among all the papers on tropical cyclones at the WWOSC-2014 was the subject of TC intensity and intensity change, with an emphasis on both mechanisms and prediction. It should be apparent from the foregoing discussion that intensity prediction has a large stochastic element. Observations are involuntarily subject to this stochasticity through the case-to-case variability that dilutes the signal in composites of genesis and intensification. This also means that deterministic forecasts of intensity are not fully justified. This may explain why purely statistical models do about as well as dynamical models concerning genesis and rapid intensification of TCs. Nonetheless, errors in models remain obstacles to modelling the correct probability distribution of tropical cyclone intensity change. Because there may be long lead times (months) for certain large-scale patterns, it is important that models are improved so that reasonable probabilities are derived as these states change. This underpins all efforts to capture the long-term climate change signal in tropical cyclones. Detailed observations have been used in recent years to make numerous improvements in hurricane models, but there is a long way to go in terms of faithful modelling of convective-scale atmospheric-ocean coupled system.

14.6 ACKNOWLEDGEMENTS

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CHAPTER 15. ORGANIZED CONVECTION AND THE YOTC PROJECT

Mitchell W. Moncrieff and Duane E. Waliser

Abstract

The World Climate Research Programme (WCRP)/World Weather Research Programme (WWRP) - THe Observing System Research and Predictability EXperiment) (THORPEX) Year of Tropical Convection (YOTC) project addresses organized tropical convection and its multiscale interactions up to the weather-climate intersection (sub-seasonal) timescales. Organized convection has been extensively studied in observational, numerical and theoretical respects yet little progress has been made with its parameterization. A reason for this state-of-affairs is the fundamental incompatibility between the dynamical coherence of organized convection and the assumptions that underpin cumulus parameterizations. The nascent era of climate models with mesoscale-permitting computational grids calls for serious attention to organized convection. Progress will benefit from a paradigm shift in the approach to parameterization that represents organized convection as a multiscale coherent structure in a turbulent base state and approximates it by multicloud parameterization. This approach is illustrated by utilizing two iconic categories of propagating organized convection: mesoscale convective systems and multiscale organized convection in convectively coupled tropical waves and the Madden-Julian Oscillation. The chapter concludes with a summary of the collaborative activities of the YOTC project, and plans for the continuance of such activities under other programmatic banners.

15.1 INTRODUCTION

Tropical convection and its multiscale interactions are fundamental to Earth's weather and climate. Supplying most of the rainfall, tropical convection crucially affects the heat, moisture and momentum budgets of the entire tropics. The latent heat released and absorbed during phase changes of water, together with the transport of momentum by convection, drives the large-scale tropical circulation, modulates the global water cycle, and initiates planetary-scale atmospheric waves that influence weather and climate worldwide.

Moist convection is observed to evolve upscale into long-lived multiscale systems usually referred to as organized convection. In the midlatitudes that includes squall lines, mesoscale convective systems, severe storms and frontal rain-bands. The multiscale organization of tropical convection, notably the Madden-Julian oscillation (Madden and Julian, 1972), is an integral part of the large-scale tropical circulation that affects the global circulation through planetary-wave teleconnection. It will be shown later in this chapter that the vertical shear is key to organized convection dynamics and is manifested as an upscale cascade of energy and a counter-gradient transport of momentum. These basic aspects are distinct from the dissipative and turbulent character of traditional cumulus parameterizations. We consider that organized convection parameterization supplements rather than replaces subgrid cumulus parameterization. The formulation of reliable parameterizations as a function of grid-size is part of the issues higher resolution and the explicit representation of organized systems, a focus of this chapter. It seems disingenuous to expect that the variability of convective weather in a changing climate can be understood without due attention to organized convection and, more broadly, mesoscale physical and dynamical processes.

The above aspects distinguish organized convection from cumulus convection which has occupied the attention of parameterization development since the early days of atmospheric modelling and prediction. However, the parameterization of organized convection has proven to be a formidable scientific and practical challenge. Despite valiant efforts (e.g. Donner 1993, Donner et al. 2001, Mapes and Neale 2011) organized convection is not reliably parameterized in any global climate model. The reasons for this state-of-affairs are described by Moncrieff et al. (2012a). Besides the distinction between organized convection transport and classical simple turbulence, mesoscale convective organization contradicts the assumption of a scale-gap between cumulus and the synoptic-scale motion that underpins cumulus parameterization.

Global observations show that organized convection is physically significant. Figure 1 shows the fraction of rainfall from precipitation features of size 100 km or more in horizontal scale calculated from rainfall retrievals from the Tropical Rainfall Measuring Mission satellite data. A large fraction of the surface rain derives from the stratiform cloud decks of mesoscale convective systems, the dominant rain producers in the tropics and subtropics. More information can be found in Schumacher and Houze (2003), and to quote Nesbitt et al. (2006) "mesoscale convective systems are responsible for more than 50% of rainfall in almost all [tropical] regions with average annual rainfall exceeding 3 mm day". A large faction of the stratiform rain is in regions where climate models experience difficulty, e.g. the InterTropical Convergence Zone, sub-Sahel Africa, and over the tropical oceans in association with intraseasonal variability, and the monsoon regions. The absence of organized convection is at least partly to blame for the rainfall bias in contemporary climate models.

In view of the tardy progress noted above, addressing the organized convection challenge calls for a paradigm shift in that gives due attention to moist convection dynamics and the key role of vertical shear. This is particularly salient for the emerging era of weather and climate models with O(10 km) mesoscale-permitting computational grids that, for the next 5-10 years or so, will pace operational global weather prediction and global climate modelling. In that respect the 10 km grid is a threshold for addressing mesoscale processes in the climate context.

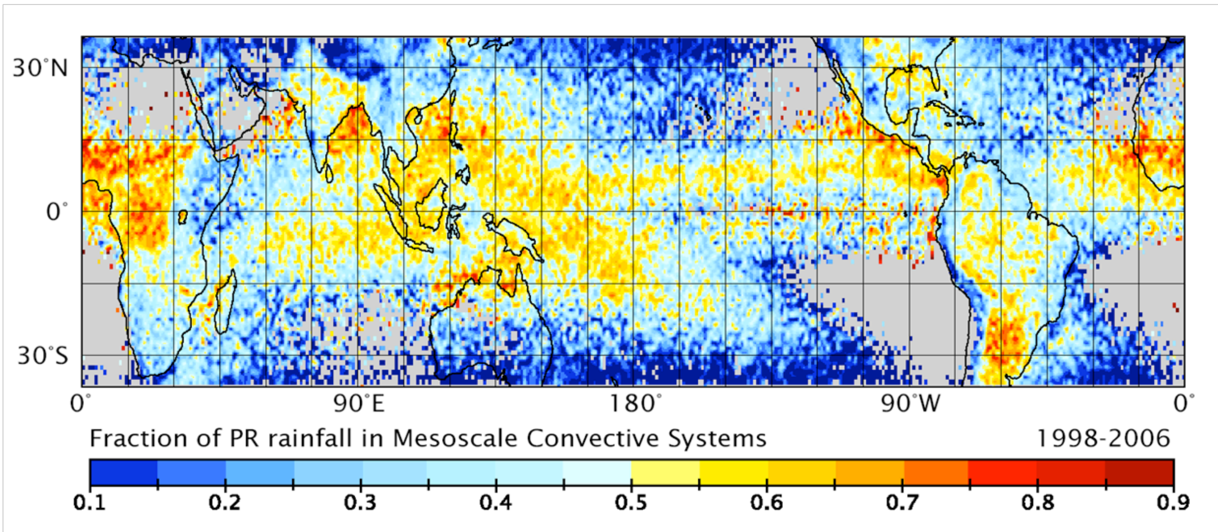

Figure 1. Fraction of estimated rainfall from precipitation features of order 100 km in maximum dimension calculated from TRMM precipitation radar measurements from January 1998-December 2006.

Source: Tao and Moncrieff (2009)

The need for serious attention to organized tropical convection motivated the 2006 international workshop WCRP Organization and Maintenance of Tropical Convection and the Madden-Julian Oscillation (MJO), co-sponsored by the WWRP/THORPEX. Moncrieff et al. (2007) summarized the proceedings of this ground-breaking workshop which was hosted by the International Centre Theoretical Physics (ICTP) in Trieste, Italy. The formation of the WWRP-THORPEX/WCRP Year of Tropical Convection (YOTC) project followed a recommendation by the workshop participants, recognizing that the organized convection is a crucial bridge between weather and climate. Waliser et al. (2003) showed that ensembles of twin-predictability experiments suggest that successful dynamical forecasts of the Madden-Julian oscillation may be an avenue for bridging the gap between medium- to long-range weather forecasting and short-term climate prediction. In summary, the YOTC project is viewed as an actionable way to address the seamless prediction grand challenge (Dole, 2008; Hurrell et al. 2009; Palmer et al. 2009; Shukla et al. 2009; Brunet et al. 2010).

The motivations and objectives of the YOTC focus on organized tropical convection are described by Moncrieff et al. (2012a), and the main meteorological events during the YOTC virtual global field campaign are described by Waliser et al. (2012). The website http://yotc.ucar.edu contains a wealth of information. Additional information on YOTC can be found in Zhang et al. (2013) and Parsons et al. (2015). In order to minimize repetition, we focus on some selected aspects. The multiscale coherent structure paradigm for organized convection is introduced in Section 15.2, followed by two iconic examples of organized convection that severely challenge global models: propagating orogenic convection in Section 15.3, and the Madden-Julian oscillation in Section 15.4. The collaborative activities of the YOTC project and its follow-on activities are summarized in Section 15.5. The chapter concludes in Section 15.7.

15.2 THE MULTISCALE COHERENT STRUCTURE PARADIGM

The paradigm shift is based on the fundamental property of coherent structures whereby organized convection is approximated as a multiscale coherent structure; specifically, by slantwise layer overturning introduced in Section 15.2.1. Figures 2a and 2c distinguish a field of unorganized cumulus from multiscale coherent structures in a field of cumulus (Figures 2b and 2d). Figure 2b shows the entraining plume model of cumulus characterized by single-column updrafts and downdrafts where the effects of vertical shear are assumed negligible. Figure 2d illustrates a coherent system in a sheared environment which is approximated as slantwise layer overturning (Moncrieff, 2010; Houze, 2004).

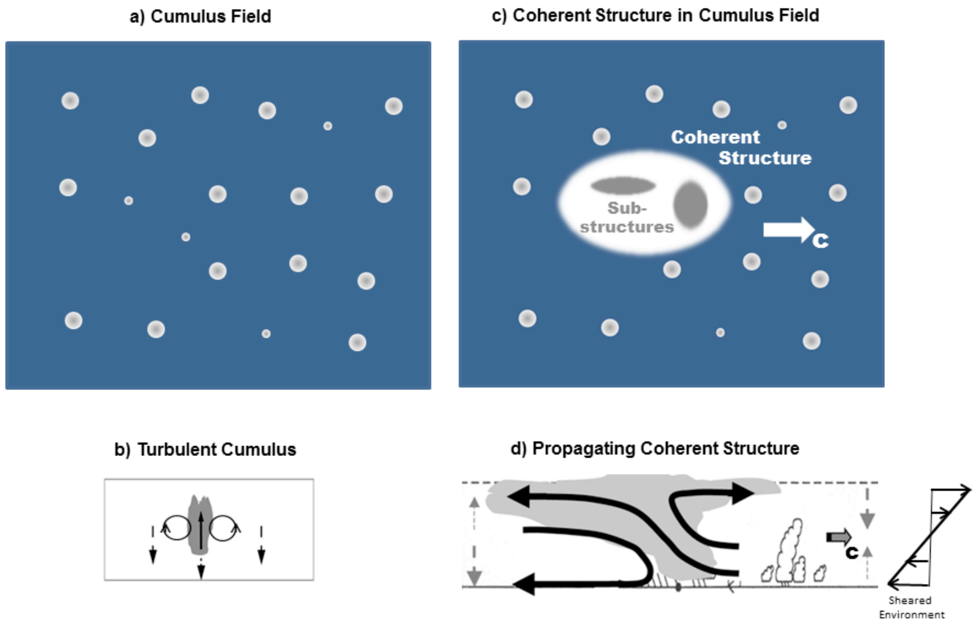

Figure 2. Idealization consisting of: a) field of cumulus; b) cumulus parameterization with anentraining plume, single-column updrafts and downdrafts, and compensating descent; c) multiscale coherent structure with embedded sub-structures in a field of cumulus; d) propagating slantwise layer overturning featuring a trailing stratiform region, an overturning ascent and a mesoscale downdraft.

15.2.1 Slantwise layer overturning in the vertical plane

It has long been observed that vertical shear has an organizing effect on atmospheric convection (Ludlam, 1980), excellent examples being severe convective storms (Browning and Ludlam, 1963) and squall lines (Newton and Newton, 1959). The early numerical simulations and dynamical models of squall lines (Moncrieff and Green 1972; Moncrieff and Miller, 1976; Thorpe et al. 1982) demonstrated the effects of shear on mesoscale circulations, kinetic energy generation, and counter-gradient momentum transport. These processes are missing from traditional cumulus parameterizations.

Cloud-system resolving models defined by O(1 km) computational grids have, for decades, reliably simulated the organizing effects of wind shear on moist convection. For instance, the numerical simulation in Figure 3 captures transitions among weakly organized non-squall clusters, highly organized squall lines, and a field of unorganized cumulus as the shear varies within a synoptic-scale tropical easterly wave observed for 1-7 September, 1974 during the Global Atmosphere Research Programme (GARP) Atlantic Tropical Experiment (GATE) Intensive Observation Period.

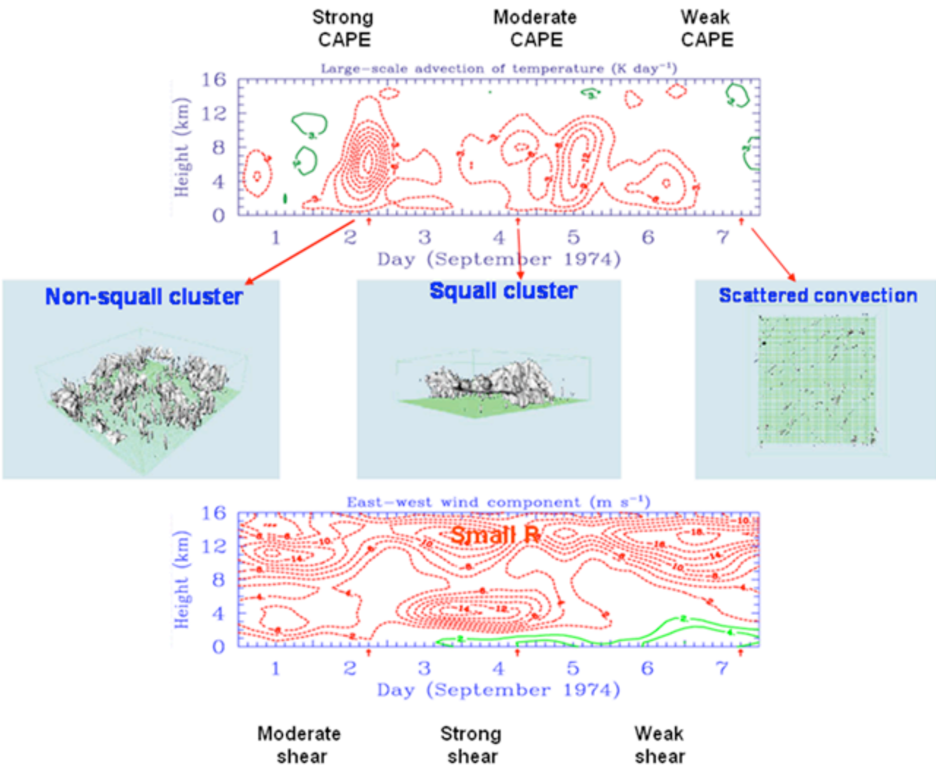

Figure 3. Simulated organized convection in a (400 km x 400 km x 26 km) computational domain and 2 km grid. Upper: Large-scale advection of temperature identified with the distribution of convective available potential energy (CAPE). Middle: the mixing ratio of water for non-squall, squall cluster, scattered cumulus. Lower: Zonal wind component

Source: Grabowski et al. (1998)

The slantwise layer overturning in Figure 4 characterizes the effects of wind shear on mesoscale convective systems. As well as the convective available potential energy (CAPE) associated with all moist convection, slantwise layer overturning involves kinematic forms of energy: i) the kinetic energy available from vertical shear and propagation, AKE = $\frac{1}{2}(U_0 - c)^2$ and ii) the work done by the pressure gradient, WPG = $\frac{\Delta p}{\rho}$. Collectively rather than each on their own, CAPE, AKE and WPG control the organization of moist convection via the convective Richardson number R = CAPE/AKE and the Bernoulli number E = WPG/AKE. In the limit of CAPE → 0 slantwise layer overturning reduces to the minimalist archetypal model (Moncrieff, 1992). Despite its maximal simplicity, this purely hydraulic form of slantwise overturning faithfully approximates propagating systems across scales: O(1 km) density currents (Moncrieff and So, 1989); O(10 km) frontal rain bands (Moncrieff, 1989); O(100 km) squall lines and mesoscale convective systems (Moncrieff and Miller 1976; Moncrieff 1992); O(1,000 km) tropical superclusters (Moncrieff and Klinker 1997). The scale-invariance of vertical slantwise layer overturning flows is consistent with the Mapes (1993) results. Note that Section 15.4.3 presents horizontal slantwise layer overturning in the context of O(10,000 km) convectively coupled equatorial waves and the Madden-Julian oscillation.

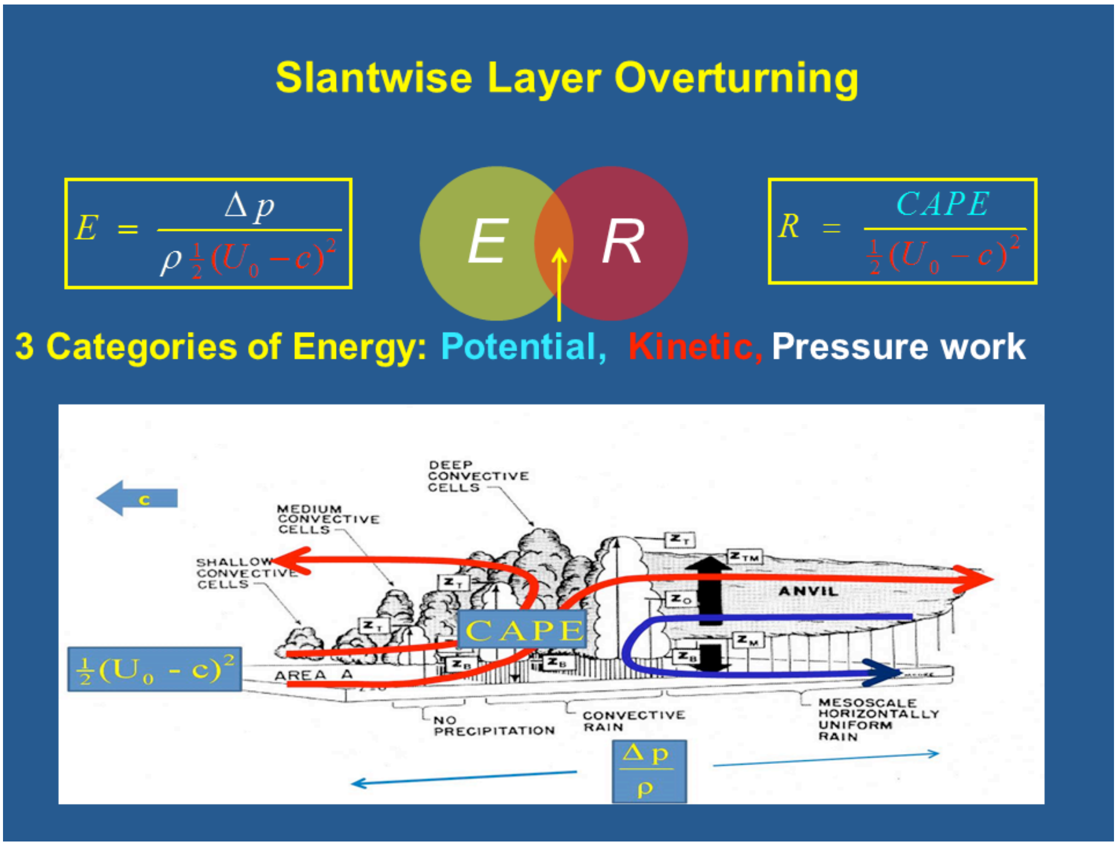

Figure 4. Slantwise layer overturning featuring a jump up-branch, an overturning up-branch, and overturning down-branch overlying the standard model of a mesoscale convective system.

As detailed in Moncrieff (2010), two-dimensional slantwise layer overturning in the vertical plane is governed by the integral-differential vorticity equation:

$$\nabla^2 \psi = G(\psi) + \int_{z_0}^{z} \left(\frac{\partial F}{\partial \psi}\right)_z dz \qquad (1)$$

where z_0 (Ψ) is the inflow height of the streamfunction in the vertical plane (ψ) defined by ($u = \partial\Psi/\partial z$, $w = -\partial\Psi/\partial x$), and $F(\Psi, z)$ is the buoyancy measured along trajectories in steady flow. The first term in Eq. 1 is the vorticity along trajectories, the second term is the environmental shear, and the third term is the vorticity generated by the horizontal gradient of buoyancy by latent heat release and the absorption of heat during evaporation. Equation 1 is an almost exact integral of the fully nonlinear vorticity equation (Moncrieff, 1981). The single approximation is that the latent heating along trajectories is proportional to the vertical velocity and that is valid for moist adiabatic motion.

15.2.2 Vertical transport of momentum

The organizing effects of vertical shear is apparent in the mesoscale transport of horizontal momentum in the vertical direction (Moncrieff and Green, 1972; Moncrieff and Miller, 1974; LeMone et al. 1984; Wu and Yanai, 1994). The generation of mean-flow kinetic energy is comparable to generation of convective available potential energy (Wu and Moncrieff, 1996). Nevertheless, the organized transport of momentum is not represented by any traditional convection parameterization.

The vertical transport of horizontal momentum by convection can be explained in fundamental terms. For a vertically bounded channel, the vertical integral of the momentum flux divergence is zero. Therefore, in an atmospheric column momentum can be vertically redistributed but the column-average momentum remains unchanged. Both up-gradient and down-gradient transport of momentum occurs because, should shear increase in some layer it must decrease in another layer. Figure 5 shows that for slantwise layer overturning in the vertical plane, the sign of the momentum transport is opposite to the propagation vector.

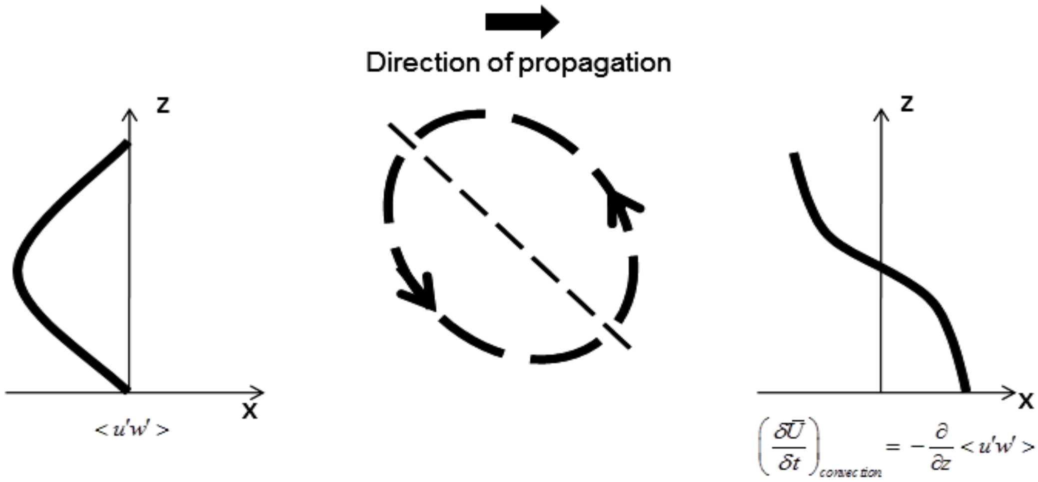

Figure 5. Momentum transport (left), mean-flow acceleration (right) due to a tilted eddy

These fundamental properties have been verified by field-campaigns, e.g. Kingsmill and Houze (1999), Houze (2004) and Schumacher and Houze (2003). Tung and Yanai (2002a, b) showed that for the Madden-Julian oscillation, on the average, convective momentum transport is a downscale process that damps the large-scale motion. The fluctuations can be as large as the mean value and intense bursts of upscale transport can amplify the large-scale motion. In the westerly wind burst behind the Madden-Julian oscillation, the characteristic upscale transport in the deep convection region is usually followed by downscale transport.

Numerical simulation provides significant verification of the above theory. The Nonhydrostatic Icosahedral Atmospheric Model (NICAM) global model simulates the organization of convection on scales ranging from the mesoscale to the planetary scale (Satoh et al. 2008). Miyakawa et al. (2012) derived the momentum budget for tropical squall lines utilizing about 13,000 sections within an MJO event in the tropical western Pacific simulated by NICAM with a 7 km computational grid. The simulated rainfall was verified using Tropical Rainfall Measuring Mission retrievals. The acceleration of lower-tropospheric westerly environmental flow and the upper-tropospheric easterly flow in this simulation are consistent with the classical momentum transport signature in Figure 5.

15.3 PROPAGATING MESOSCALE CONVECTIVE SYSTEMS OVER US CONTINENT

The above discussion is pertinent to propagating mesoscale convective systems over the midlatitude continents during the warm season, and in the tropics throughout most of the year. Propagation communicates the effects of mesoscale systems up to the continental scale. In association with the midlatitude and subtropical jet stream regions, mesoscale convective systems are initiated over orography and propagate great distances (Laing and Fritsch, 1997). It has been estimated that orogenic propagating systems account for up to 70% of the warm-season precipitation in the region from the Rocky Mountains to the Mississippi (Fritsch et al. 1986). That the contribution to rainfall is even larger in midsummer identifies mesoscale convective systems as a defense against drought in the United States mid-west. For additional information we refer to Chapter 10 of this book.

Although a 100 m grid is needed to adequately resolve mesoscale convective systems (Bryan et al. 2003), a cloud-system resolving model with a 3 km grid reliably simulates mesoscale features such as tilted circulations, leading and/or trailing stratiform regions, and evaporation-driven mesoscale downdrafts. The Moncrieff and Liu (2006) three-dimensional simulations of propagating convection over the continental United States were initialized and forced at the lateral boundaries by the National Centers for Environmental Prediction global analysis. The precipitation patterns of explicit propagating convection on 3 km and 10 km grids, and the hybrid representation (explicit + parameterized cumulus) on the 10 km grid are verified by the Carbone et al. (2002) analysis (Figure 6). Resolved mesoscale circulations provide most of the precipitation, but will be compromised unless the grid is 10 km, or preferably finer. The morphology of the airflow for the 3 km and 10 km grids is similar, whereas 30 km grid loses the vertical tilted circulation and, most importantly, the mesoscale downdraft. Loss of the cool downdraft warms the lower-troposphere by a few Kelvin. The above simulations show that a 10 km grid global model is a reasonable threshold for the explicit organized convection.

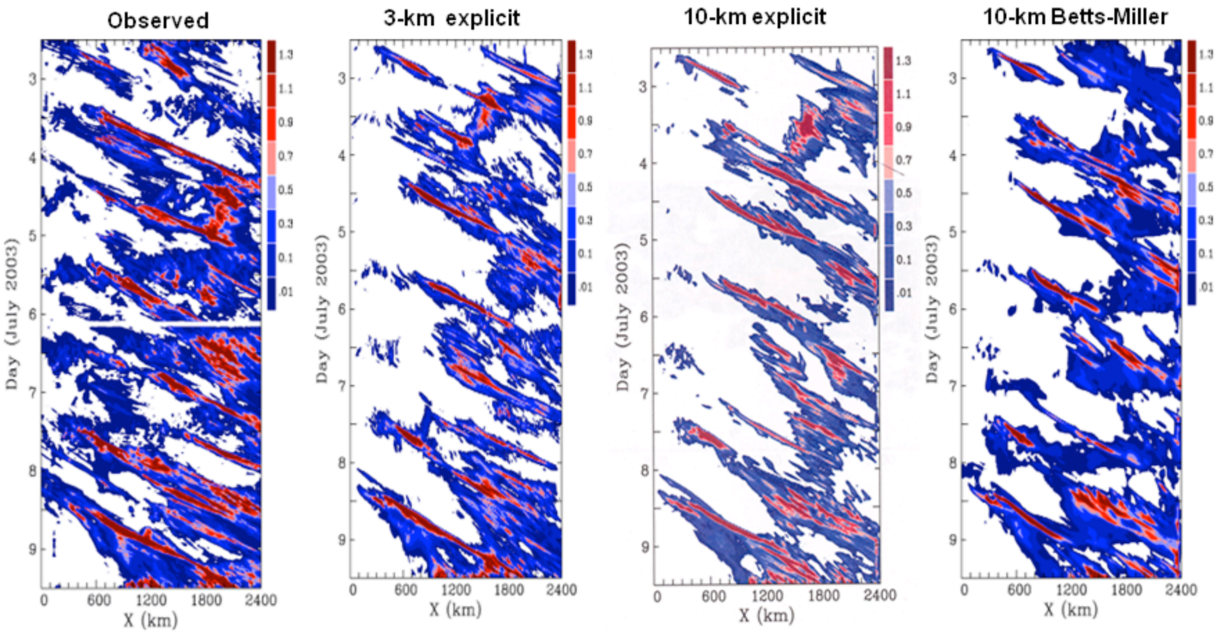

Figure 6. Precipitation rate in mm left-to-right: Next Generation Weather Radar analysis, 3 km grid simulation, 10 km grid simulation, and 10 km grid simulation with the Betts-Miller convective parameterization.

Source: Moncrieff and Liu (2006)

Propagating mesoscale systems are missing from global climate models because traditional cumulus parameterizations do not represent these systems and the model resolution is inadequate to simulate them. When the parameterizations of convection and the planetary boundary in the National Center for Atmospheric Research (NCAR) Community Climate Model (CAM) were replaced by order 1 km grid cloud-system resolving models (super-parameterization) propagating systems were simulated (Pritchard et al. 2012). However, systems that propagate across the climate grid are not simulated by the cloud-resolving models because the periodic lateral boundary conditions on these models confines the systems to their domain of birth. Instead, the systems that propagate across climate grids are organized by the action of vertical shear on the climate grid on the latent heating by the cloud-system resolving models. The mechanism involves the slantwise layer overturning shown in Figure 4. Recalling the Moncrieff and Liu (2006) 30 km grid simulation, these under-resolved systems will be distorted, especially the mesoscale downdrafts. Note that the convective systems that propagate across the climate model grid will more realistic at higher-resolution. This is consistent with Grabowski (2006) who suggested that super-parameterization in a 10 km grid climate model is more effective than in a 100 km grid model[a].

[a] *An analogous principle applies to MJO-like systems simulated by super-parameterization*

Impressive improvement in the representation of propagating mesoscale convective systems has recently been achieved by the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS), in addition to the previous improvements in the diurnal cycle of rainfall demonstrated by Bechtold et al. (2014). The Hovmoeller diagram in Figure 7 shows propagating mesoscale convective systems over the United States predicted by the 16 km grid IFS as a concatenation of daily 12-36 hour forecasts. These forecasts include an assimilation of a six hour accumulated rainfall. The forecasts compare excellently with the hourly rainfall as observed by the Tropical Rainfall Measuring Mission (TRMM) (Bechtold, private communication). These results are consistent with Moncrieff and Liu (2006) in that the propagating systems are generated by grid-scale circulations. This gives grist to the 10 km grid being a reasonable threshold resolution for the mesoscale convective organization.

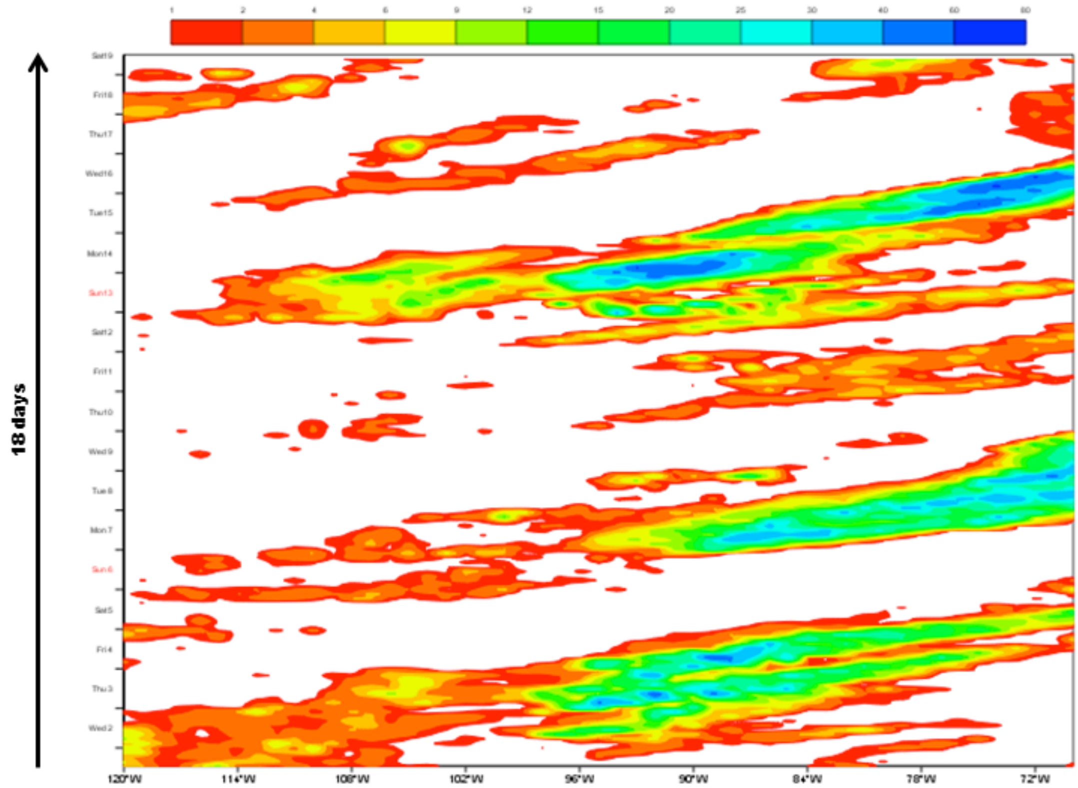

Figure 7. Propagating mesoscale convective systems over the US continent predicted by the 16 km grid ECMWF Integrated Forecast System as concatenations of 12-36h rainfall forecasts that assimilate accumulated rainfall.

Source: Peter Bechtold, ECMWF

Figure 8 shows a serious lower-tropospheric warm bias in global climate models over the continental United States during the warm season, consistent with the absence of propagating mesoscale convective systems in these models. The absence of cool mesoscale downdrafts from propagating convection can, on its own, explain about half the warm bias (Moncrieff and Liu, 2006). A new model intercomparison project, Clouds Above the United States and Errors at the Surface (CAUSES), is presently underway with the objective of quantifying the physical processes responsible for the warm bias over the US continent. More information can be found on the http://portal.nersc.gov/project/capt/CAUSES website.

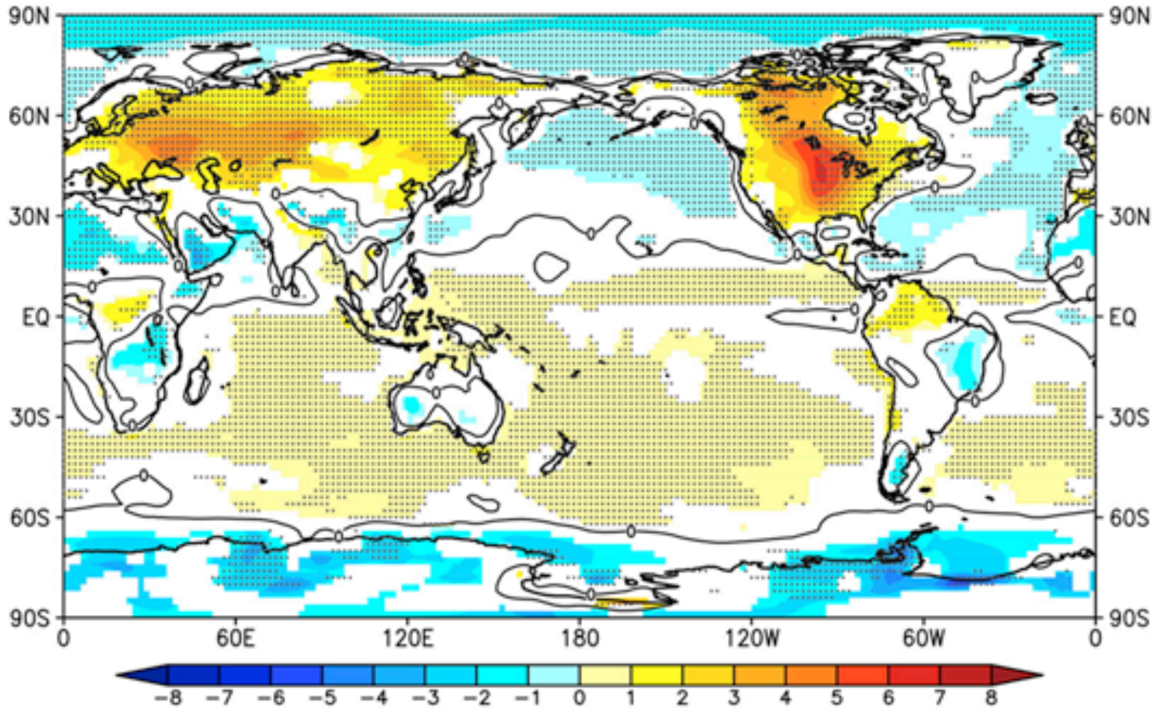

Figure 8. June-August CMIP5/AMIP multimodel mean 2 m temperature (K) for forecast day 5, with contours indicating zero bias. Coloured regions are ensemble mean biases statistically significant at the 95% confidence level. Stippled regions are where 80% of models have biases of the same sign.

Source: Ma et al. (2014)

15.4 MULTISCALE COHERENT STRUCTURES FOR THE MADDEN-JULIAN OSCILLATION

Figure 9 illustrates multiscale tropical convection in the Intertropical Convergence Zone, over the sub-Sahel region and West Africa, and large-scale MJO-like organized convection over the Indian Ocean. The Madden-Julian oscillation has been a focus of the YOTC project since its inception (Moncrieff et al. 2012a; Waliser at al., 2012) in view of its pronounced effects on global climate and weather (Zhang 2005; Lau and Waliser, 2011; Zhang et al. 2013), and as a potential source of predictability on intraseasonal time scales (Waliser et al. 2003; Waliser, 2011; NAS, 2010). In this section we focus on dynamical aspects in recognition of their critical implications for the weather-climate intersection.

Majda and Stechmann (2009a) developed a nonlinear oscillator model that represents the intraseasonal and planetary scales of the MJO. This "skeleton model" explains the slow eastward phase speed of about 5 ms-1, the unusual dispersion relation, and the horizontal quadrapole vortex structure in terms of neutrally stable interactions between planetary-scale, lower-tropospheric moisture anomalies and the convection-wave envelope. Majda and Stechmann (2011) showed that MJO events often begin as standing oscillations and then propagate slowly eastward, akin to actual MJOs. The skeleton model reproduces significant features, such as the spatial and temporal variability and large-amplitude fluctuations of the Madden-Julian oscillation.

Observations are reasonably consistent with the skeleton model. For example, Tromeur and Rossow (2010) examined tropical weather states using a cluster analysis of the International Satellite Cloud Climatology Project (ISCCP) cloud-top pressure/optical thickness, and an MJO index based on upper-level wind anomalies. They showed that MJO-like events exist almost all the time. Instead of an event being associated with on-off deep convection, it is characterized by weaker and stronger episodes of mesoscale convective organization.

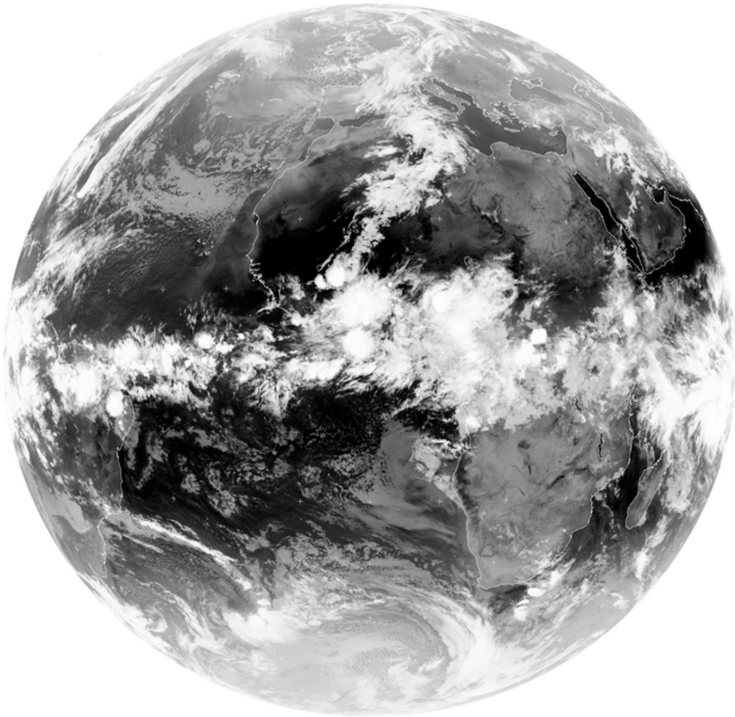

Figure 9. Multiscale organization of tropical convection

Source: Dundee Satellite Receiving Station, Scotland

15.4.1 Scale-selection

The multiscale coherent structure concept in Figure 2 implies the need for a scale-selection principle to set the concept onto a firm dynamical basis. The presence of a maximum growth-rate for small-amplitude perturbations at the smallest possible scale has forever plagued classical theories of moist convection. While mechanisms have been proposed for tropical cyclones, none seem applicable to mesoscale convective systems (Smith, 1997). The classical perturbation theory (e.g. Miles 1961; Kuo, 1963) shows that two-dimensional shear-perpendicular lines have maximum growth rate at finite horizontal scale (a few times the depth the convection). However, Moncrieff (1978) showed that these lines are tilted downshear in contrast to the upshear tilt of the mesoscale convective system. For a thermodynamically unstable state and unsheared environment, the fastest-growing three-dimensional shear-parallel perturbation has vanishingly small horizontal scale. The following paragraph suggests that the needed principles exist.

Yano et al. (1995) evaluated five categories of convective parameterization in a simple model with a passive subcloud layer and a dynamically active one-layer troposphere. A prognostic convective life-cycle scheme for convective systems with mesoscale downdrafts generated westward-propagating clusters or mesoscale convective systems embedded in eastward propagating superclusters. Linear stability analysis by Yano et al. (1998) showed scale-selection at about the 400 km cloud-cluster scale. Moreover, the mesoscale downdrafts generated westward-propagating meso-synoptic features embedded in large-scale eastward-propagating MJO-like cloud envelopes. This multiscale structure is consistent with the Nakazawa (1988) analysis of satellite observations of the MJO. However, the one-layer troposphere precludes the rearward-tilted slantwise layer overturning that is characteristic of mesoscale convective systems.

We shall return to scale-selection principles in Section 15.4.3 in the context of convectively coupled waves and the Madden-Julian oscillation.

15.4.2 Slantwise layer overturning in the horizontal plane

The meridional transport of zonal momentum importantly affects the large-scale tropical circulation and can cause super-rotation where the vertically averaged zonal flow exceeds the Earth's rotation speed. Moncrieff (2004) demonstrated scale-invariance between slantwise overturning in the vertical plane and slantwise overturning in the horizontal plane, as follows. Firstly, there is an equivalence between the convective Richardson number (R) for the vertical overturning and the inverse Rossby number, Ro = $\beta L^2/U_0$ for the horizontal overturning, with β the latitudinal gradient of the Coriolis frequency, and L the meridional width of the β-channel. Secondly, the horizontal vorticity equation (Eq. 1) for slantwise overturning in the horizontal plane is

$$\nabla^2 \varphi \;=\; H(\varphi) + \int_{y_0}^{y} \left(\frac{\partial C}{\partial \varphi}\right)_{y'} dy' \qquad (2)$$

where here the streamfunction, φ, is defined by (u = - ∂φ/∂y, v = ∂φ/∂x), C is the difference between the vertical vorticity of the MJO circulation and the planetary vorticity, and H the far-field vertical vorticity. The similarity of equations 1 and 2 demonstrate the fundamental nature of slantwise layer overturning. The following analysis of momentum transport in a global model with explicit organized convection further supports the scale-invariance aspect.

Moncrieff (2004) explained the momentum transport by two categories of large-scale organization in global-scale simulations by Grabowski (2001), the inauguration of super-parameterization. Firstly, the momentum transport by eastward propagating wavenumber-4 convectively coupled waves was explained as superclusters (i.e. giant mesoscale convective systems). This is consistent with the large-scale organization observed in the Tropical Convection Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE). Tung and Yanai (2002a, b) showed that quasi-two dimensional squall lines at the leading part of a supercluster accelerates the large-scale zonal flow by upscale kinetic energy transfer, and maintains vertical wind shear by upgradient momentum transport. In other words, the acceleration of the lower-tropospheric zonal flow at the leading part of the eastward-propagating envelope maintains the westerly wind burst of the Madden-Julian oscillation. Secondly, the eastward-propagating MJO-like system and equatorial super-rotation was explained in terms of the meridional momentum transport of zonal momentum in terms of slantwise layer overturning in the horizontal plane that represents asymmetric Rossby gyres (Moncrieff, 2004; Figure 9a).

The role of momentum transport is consistent with Biello et al. (2007) who showed MJO-like organization is driven by synoptic-scale heating fluctuations with vertical and meridional tilts. Super-rotation occurred when the planetary-scale flow due to the vertical upscale momentum flux from synoptic scales reinforced the horizontally convergent flow arising from the planetary-scale heating.

Majda and Stechmann (2009b) showed interactions between the zonal mean flow and convectively coupled gravity waves associated with organized momentum transport. An intraseasonal oscillation of the mean flow and convectively coupled waves involve upscale and downscale convective momentum transport. The waves first weaken, and change propagation direction, and then strengthen as the mean flow oscillates. In an investigation of the westerly wind burst phase of the Madden–Julian oscillation, convective momentum transport accelerates the westerly wind aloft followed by a deceleration on the intraseasonal time scale.

The key role of organized momentum transport across scales is at odds with its low profile in global climate models. A parameterization of organized momentum is needed, which is an issue addressed in the following section.

15.4.3 Multicloud parameterization of slantwise layer overturning

The multicloud parameterization (Khouider and Majda, 2006, 2008) based on the first two baroclinic vertical models of diabatic heating is a viable parameterization from slantwise layer overturning. The multicloud parameterization represents the total diabatic heating (Figure 10) as the collective effect of the three cloud types observed by Johnson et al. (1999) to dominate the heating field of the Madden-Julian oscillation: cumulus congestus, deep convection, and stratiform cloud. In the multicloud model these three cloud types are systematically represented by: i) a half-sine profile that heats the whole troposphere (deep convection); ii) a full-sine profile that heats the lower troposphere by cumulus congestus and radiatively cools the upper troposphere; iii) a full-sine profile that cools the lower troposphere by evaporative downdrafts and heats the upper troposphere by stratiform latent heating and infrared absorption. Together, these heating profiles force the 1st and 2nd baroclinic modes of vertical motion. The multicloud parameterization represents the meso- and synoptic-scale circulations in Figures 2c and 2d. Figure 10 illustrates the relationship between to slantwise layer overturning and the multicloud parameterization. The step-like distribution of the three cloud types (buff colour in Figure 10) is mirrored in front-to-rear and overturning ascent regions and mesoscale descent regions in Figure 4.

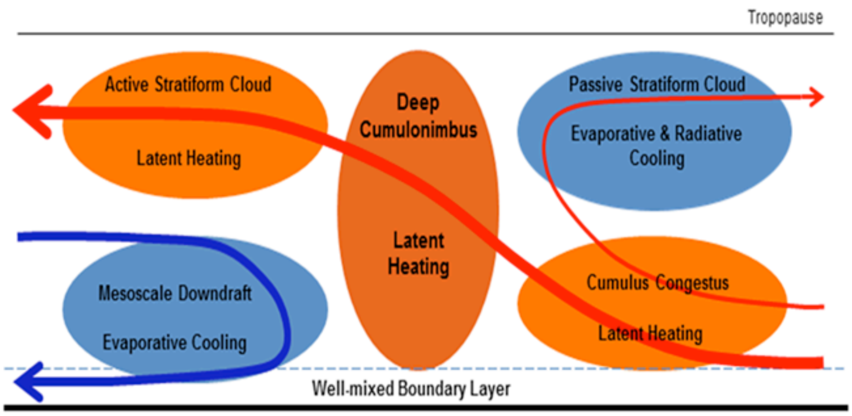

Figure 10. Multicloud parameterization adapted from Figure 6 of Khouider and Majda (2006). i) Brown hues represent warming tendencies by cumulus congestus, deep convection, and stratiform cloud. ii) Blue hues represent cooling by mesoscale downdrafts and radiation. The overlying curves show the 3-branch slantwise layer overturning in Figure 4 herein mapped onto the multicloud parameterization.

Khouider and Majda (2006) showed spontaneous convective instability at a wavelength of about 400 km resembling actual mesoscale systems. Khouider and Majda (2008) identified synoptic-scale convectively coupled gravity wave packets moving westward at 15-20 embedded in planetary-scale envelopes that move eastward at about six with features resembling actual convectively coupled waves and Madden-Julian oscillations. The slow-moving planetary-scale cumulus congestus category is reminiscent of the skeleton model.

Applying the multicloud model as a parameterization of slantwise layer overturning, Khouider et al. (2011) and Ajayamohan et al. (2013) successfully simulated MJO-like systems in the High-Order Methods Modeling Environment (HOMME). Figure 11 shows the Hovmoeller (longitude-time) diagram of the 200 hPa zonal wind precipitation averaged over the equatorial belt S-N as a series of MJO-like events that form over the warm pool and propagate eastward at a realistic. Upon their demise at the eastern end of the warm pool, the MJO-like systems trigger wind disturbances that continue to move eastward at about 25, resembling a second-baroclinic dry Kelvin wave.

In a recent paper addressing organized convection in the Intertropical Convergence Zone (ITCZ), Khouider and Moncrieff (2015) have identified new meso- and synoptic-scale instabilities that support the scale-selection principles noted in Section 15.4.1. The above success with MJO-like system simulation and the discovery of new dynamical instabilities on scales ranging from the meso- to the planetary-scale, encourages an application in a full global climate model of multicloud parameterization for slantwise layer overturning.

The remainder of this chapter is devoted to the virtual global field campaign and collaborative activities spearheaded by the YOTC project.

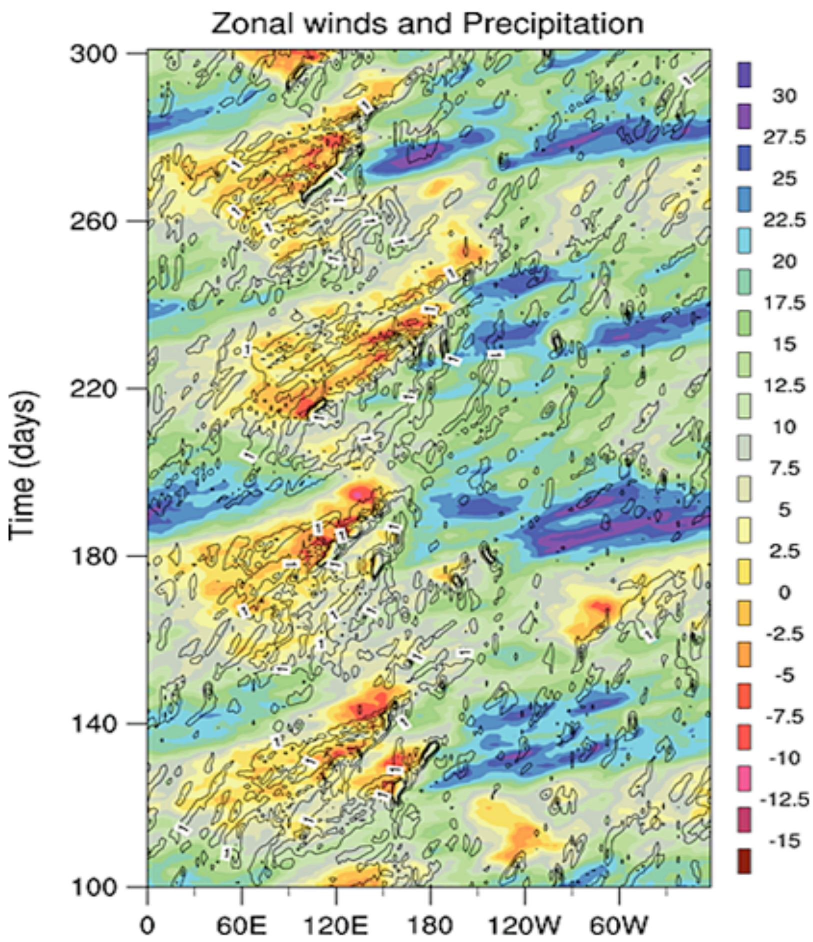

Figure 11. Longitude-time plot of 200 hPa zonal wind (colour) and precipitation averaged for (contour) for MJO-like systems simulated by the High-Order Method Modeling Environment (HOMME).

Source: Ajayamohan et al. (2013)

15.5 YOTC COLLABORATIVE ACTIVITIES

Figure 12 summarizes the main activities of the YOTC project which began subsequent to the Trieste Workshop (Moncrieff et al. 2007). The YOTC Planning Group led to the YOTC Science Plan (Waliser and Moncrieff, 2008), followed in 2009 by the Implementation Plan published online at http://yotc.ucar.edu. The YOTC Project Office opened soon after. About a dozen YOTC-focused sessions have been convened at the American Meteorological Society and American Geophysical Union meetings. The 2011 YOTC International Science Symposium was hosted by the China Meteorological Administration in Bejing (Moncrieff et al. 2012b). The YOTC sessions at the 2014 World Weather Open Science Conference in Montreal, Canada led to this book chapter.

YOTC has made substantial contributions to the THORPEX objective of making operational products more readily accessible to the research and application communities as a focal point for international collaboration on tropical convection, and focused attention to the weather-climate intersection interests of the THORPEX (Parsons et al. 2015). A highlight of the operational contribution is the virtual global field campaign for the two-year period, May 2008 - April 2010. “Virtual” means that sub-synoptic to planetary scale 'observations' are provided by the global analyses, forecasts and subgrid data of the ECMWF Integrated Forecast System that assimilates tens of millions of observations each day. Over 30 subgrid tendencies allow researchers to delve deeply into the treatment of the physical and dynamical processes than would be possible with other reanalysis archives and actual field campaigns, by way of high-resolution hindcasts and other studies.

YOTC has improved access to satellite data by providing ways to subset, visualize, and access data from multiple space-borne sensors. Firstly, the efficient web-based satellite data analyses facility, the YOTC Giovanni System (YOTC-GS) developed by the NASA Goddard Earth Science (GES) Data and Information Service Center (DISC), see http://disc.sci.gsfc.nasa.gov/giovanni. Secondly, a multi-sensor satellite data set based on the A-train constellation of satellites (Stephens et al. 2002). The A-train provides a comprehensive, multivariate view of convection, clouds, aerosol, radiation and surface conditions. The YOTC-NASA Giovanni satellite data dissemination system is available via a web-based application developed by the National Aeronautics and Space Administration (NASA) Goddard Earth Science Data and Information Service Center, see http://giovanni.gsfc.nasa.gov for details.

A literature survey shows that nearly 100 papers refer to the YOTC project (see yotc.ucar.edu for a complete list). That include a comparison of different indices for tracking the MJO (Kiladis et al. 2014); tropical cyclogenesis (Xu et al. 2013); evaluation of potential improvement in tropical cyclone track predictions by a model initialized with ECMWF analyses (Yamaguchi et al. 2012); predictability of the Indian monsoon (De and Sahai, 2013); multi-model comparison of forecast skill for the boreal summer inter-seasonal oscillation (Fu et al. 2013); controls on tropical low-level cloud cover by utilization of the YOTC analysis and A-Train satellite data (e.g. Kubar et al. 2011); structure of thermodynamic profiles and wind profiles in the lower troposphere over the southern oceans (Hande et al. 2012); utility of the YOTC database for extra-tropical research focused on turbulent heat fluxes in the Drake Passage (Jiang et al. (2012); and skill of medium-range forecasts during YOTC (Chakraborty, 2010).

The collaborative activities of YOTC with other national and international efforts on Figure 12 are now summarized.

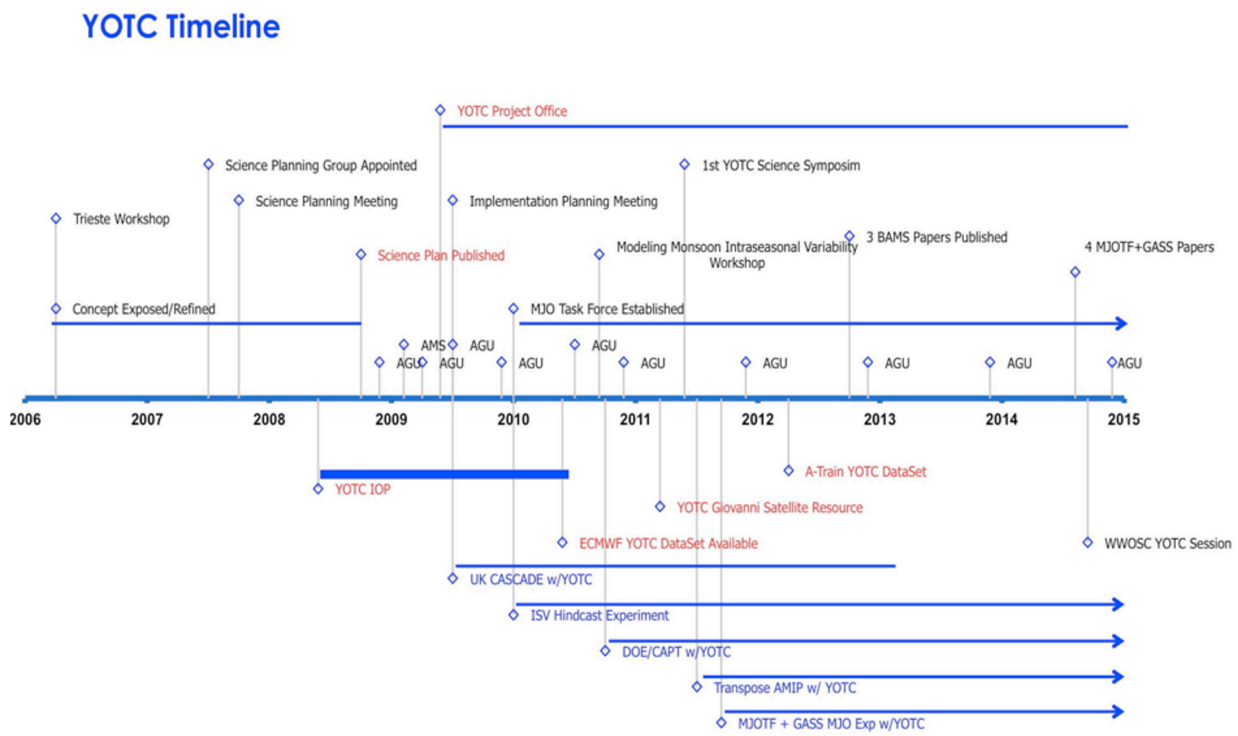

Figure 12. WCRP/WWRP-THORPEX YOTC project timeline

15.5.1 Cascade

The UK Cascade project simulated the MJO and the organization of tropical convection in the Maritime Continent and the Indo-Pacific Warm Pool regions using the limited-area version of the Met Office Unified Model (UM; Davies et al. 2005; Holloway et al. 2012). Initial conditions were provided by the YOTC-ECMWF analysis, and the sea-surface temperature distribution was held at the initial value. The simulations were updated at the lateral boundaries by YOTC-ECMWF analysis, started at 0000 UTC 6 April 2009 and run for 10 days for the early April 2009 MJO (Case D, Waliser et al. 2012). A 4 km grid explicit convection simulation using advanced subgrid mixing in the vertical and horizontal directions resulted in the most realistic MJO. The vertical motion and the horizontal wind are shown in Figure 13. Explicit convection with a 12 km grid is an improvement on the 12 km simulation with parameterized convection. In general, the better MJOs feature a more realistic relationship between lower-tropospheric moisture and precipitation suggests that moisture-convection feedback is key to MJO propagation. This is consistent with the Grabowski and Moncrieff (2004) conclusions on the role of moisture-convection feedback in the tropics. We refer to Holloway et al. (2013) for a complete description of the Cascade simulations.

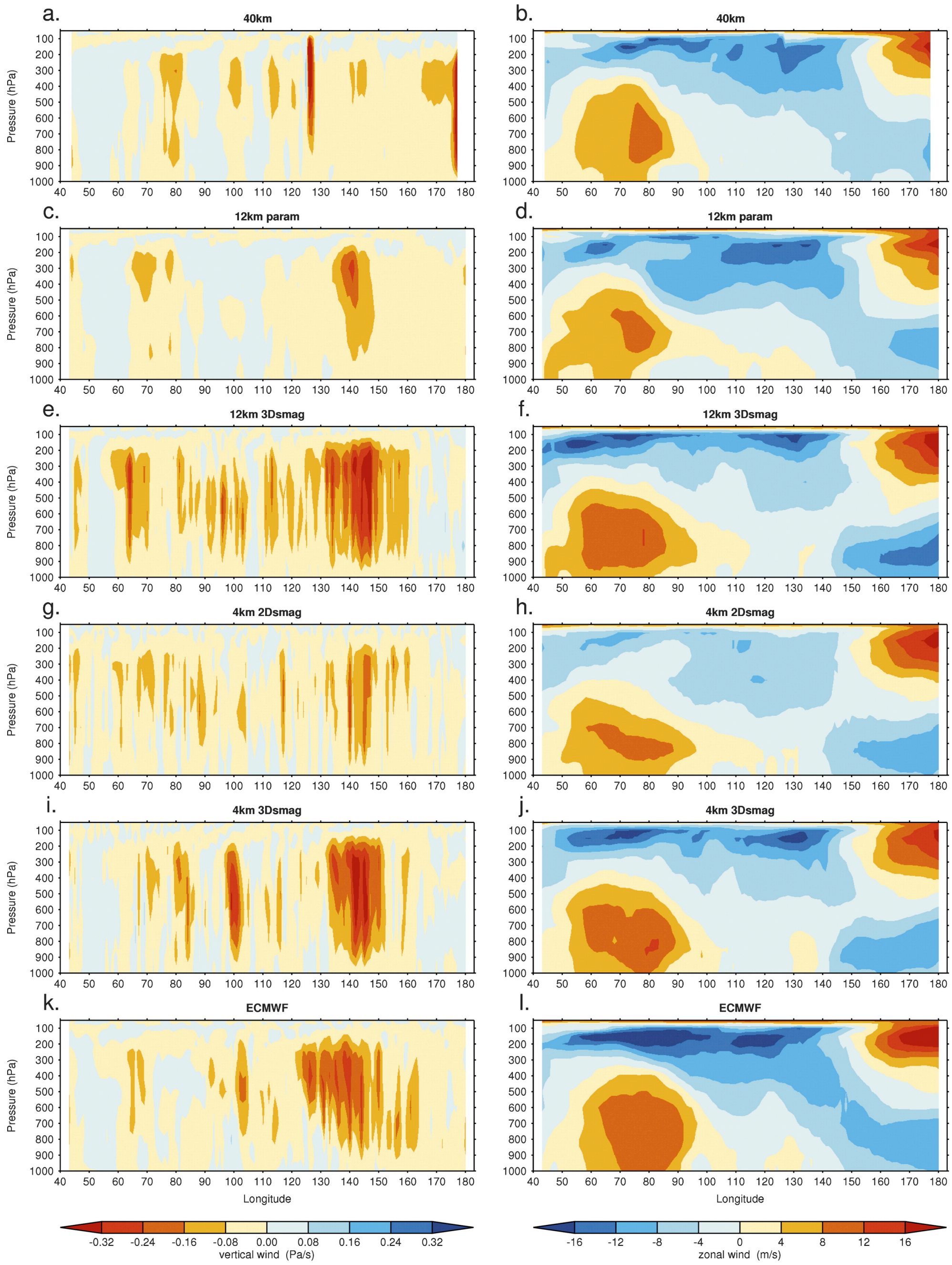

Figure 13. Vertical motion ($\mathrm{Pa\,s^{-1}}$) and zonal wind ($\mathrm{m s^{-1}}$) for the Cascade simulations and the YOTC-ECMWF global analysis for April 15 2009, averaged over onto a grid.

Source: Holloway et al. (2012)

15.5.2 MJO Task Force

Under the auspices of YOTC, the WCRP-WWRP MJO Task Force (MJOTF) was formed to continue the activities of the US CLIVAR MJO Working Group (e.g. Waliser et al. 2009; Gottschalck et al. 2010). Under the efforts of the YOTC MJO Task Force, operational forecast metrics have been developed for boreal summer intraseasonal variability (Lee et al. 2015). Process-oriented diagnostics and metrics for global model representations of the MJO have been developed (Kim et al. 2014). Model performance metrics have been developed for the Working Group on Coupled Models (WGCM) and the Working Group on Numerical Experiment (WGNE) joint Climate Metrics Panel (Sperber and Kim, 2012).

Diabatic heating in the MJO and the challenge of reducing deficiencies in MJO simulation require investigation in GCMs, in comparison with observations, and evaluation against forecasts, reanalysis, and satellite data retrievals. Transitions of the vertical heating structure associated with the MJO, ranging from shallow, to deep, to stratiform cloud systems (Johnson et al. 1999), should be reflected in the vertical structure of diabatic heating but reanalysis products and satellite observations struggle to capture this transition. The ERA-Interim, CFS-R, Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis imply a tilted heating distribution in the eastern equatorial Indian Ocean and the western Pacific due to the transition from shallow to deep heating (Jiang et al. 2011; Ling and Zhang 2011). However, a tilted heating profile was not seen in the Mirai Indian Ocean Cruise for the Study of the MJO-Convection Onset (MISMO) field campaign data (Katsumata et al. 2009). Tropical latent heating is estimated from satellite data retrieval (Tao et al. 2006). TRMM-based estimates exhibit a weak or no vertical tilt (e.g. Morita et al. 2006; Jiang et al. 2009; Jiang et al. 2011).

The above uncertainties related to latent heating, and vertical structure of the MJO more generally (Sperber and Waliser, 2008) led to a focused analysis effort. Sponsored by the WCRP and the WWRP-THORPEX and coordinated jointly by the MJO Task Force (MJOTF) and GASS, the GEWEX Atmospheric System Studies[b] (Petch et al. 2011), the experimental design for the MJO Vertical Structure and Physical Processes project has three components: i) 20 year climate simulations to characterize model representations of the MJO and explore interactions with tropical cyclones, monsoons, and ENSO; ii) 2 day lead time hindcasts over a near-equatorial Indian Ocean/Western Pacific Ocean domain to investigate heat, moisture and momentum budgets and the physical processes; iii) 20 day lead time hindcasts to reveal model performance in representing MJO evolution.

The 2 day and 20 day hindcast experiments were focused on the two MJO events for El Niño conditions for October 2009-February 2010 during YOTC identifies systematic weaknesses in the physical processes in models responsible for their intrinsic variability which, in turn, have negative impacts on MJO forecast skill. The outcomes of this experiment and the implications are described in three papers, one on each component, and a synthesis paper (Jiang et al. 2015, Xavier et al. 2015, Klingaman et al. 2015a,b).

The November 2011 MJO observed in the Dynamics of the MJO (DYNAMO) field campaign is the next case study to be undertaken by the Task Force. DYNAMO is the US component of the international Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011 (CINDY2011) which is focused on the initiation of the MJO as detailed in http://www.eol.ucar.edu/projects/dynamo/. We refer to Yoneyama et al. (2013) for an overview.

15.5.3 Transpose-Atmospheric Model Intercomparison Project

A joint activity between the Working Group on Numerical Experimentation (WGNE) and the Working Group on Coupled Models (WGCM), Transpose-AMIP runs climate models retrospectively in weather forecast mode. These hindcasts enable a detailed evaluation of fast physical processes, such as moist convection, in the context of specific meteorological events.

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[b] *Formerly called the GEWEX Cloud System Study (GCSS)*

Assessing how biases evolve from the initial state provides insight on the cause of the biases and ways to improve the models.

The Transpose-AMIP Phase I, the Cloud-Associated Parameterization Testbed (CAPT) focused on the US Southern Great Plains ARM site, and the Community Atmosphere Model (Boyle et al. 2006). Centred on the four MJOs that occurred for La Nina conditions during the first year of the YOTC project, Transpose-AMIP II examined the correspondence between short- and long-term systematic errors in five atmospheric models. Specifically, sixteen 5 day hindcast ensembles from Transpose-AMIP II for July-August 2009 were compared to climate simulations from the Coupled Model Intercomparison Project, Phase 5 (CMIP5) and the Atmospheric Model Intercomparison Project (AMIP) for the June-August mean conditions for 1979-2008 to investigate the origin of the model errors. Ma et al. (2014) showed that the systematic errors in precipitation, clouds, and radiation processes in the long-term climate runs are present by day five. Figure 14 shows the amplitudes of short-term 2 day and 5 day model errors. Because the large-scale atmospheric states remain close to observations during the first few days, these systematic errors are assumed to be rooted in the physical parameterizations. This is further evidence of the similarity between systematic errors in hindcasts and long-term integrations of the Community Atmospheric Model shown by Xie et al. (2012).

Phase II of Transpose-AMIP II contributed to the Coupled Model Intercomparison Project 5 (CMIP5) with the YOTC period as the hindcast focus. The correspondence between hindcasts and climate simulations, and cloud and related biases in the southern Ocean and the Arctic was examined (e.g. Barton et al. 2014; Ma et al. 2014). Work from the DOE Cloud-Associated Parameterization Testbed systematically examined the correspondence between hindcasts and climate simulations with NCAR's Community Atmospheric Model version 4 (CAM4) and 5 (CAM5) during YOTC (Xie et al. 2012; Ma et al. 2012).

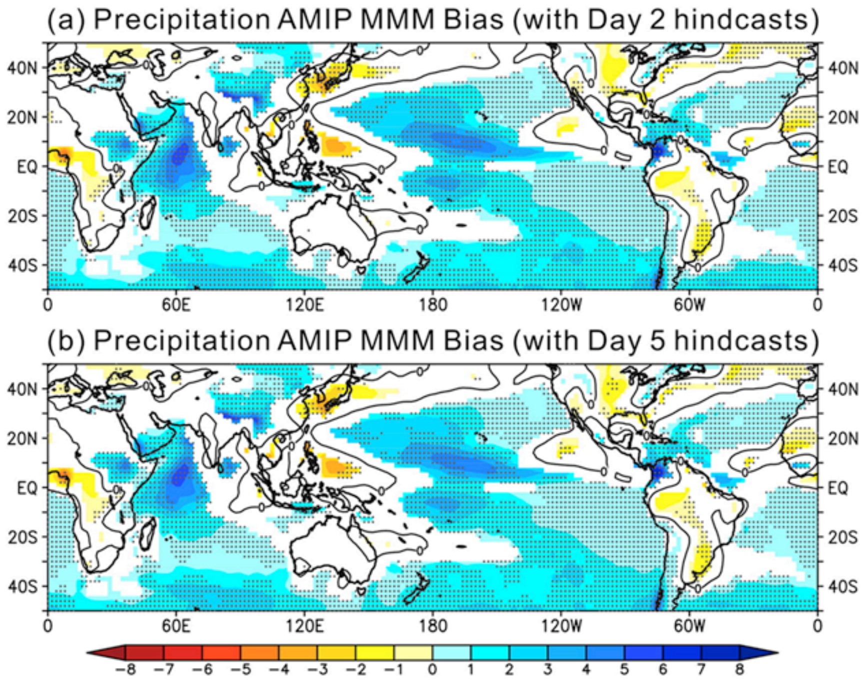

Figure 14. June-August CMIP5/AMIP multimodel mean 2 m temperature biases (K; colour), with contours indicating zero bias. Regions where ensemble mean biases are statistically significant at the 95% confidence level are colour shaded. Stippled regions are where 80% of models have bias of same sign: a) day 2; b) day 5.

Source: Ma et al. (2014)

15.5.4 Intraseasonal Variability Hindcast Experiment

The Intraseasonal Variability Hindcast Experiment (ISVHE) is the first multi-model experiment that studies prediction and predictability questions associated with the MJO and other categories of intraseasonal variability. ISVHE is jointly sponsored by the Asian Monsoon Years project and by the Asian-Australian Monsoon Panel of the WCRP-Climate and Ocean: Variability, Predictability and Change (CLIVAR) project. Research has led to updated predictability assessments of the MJO (Neena et al. 2014) and boreal summer intraseasonal variability (Lee et al. 2015), and the first such assessment for eastern Pacific intraseasonal variability (Neena et al. 2014).

15.6 CONCLUDING DISCUSSION

This chapter provided an overview of the role of organized convection in the climate system. Because other aspects have previously been described by Moncrieff et al. (2012), Waliser et al. (2012), Zhang et al. (2013), Parsons et al. (2015), about 100 other publications, and http://yotc.ucar.edu , we focused on unifying themes across scales and phenomena, current limitations on representing organized convection in climate models, and pathways toward progress. As summarized in Figure 15, the paradigm shift represents organized convection as multiscale coherent structures in the form of slantwise layer overturning (Moncrieff, 2010) as an observationally verified model of mesoscale convective systems (Houze, 2004). The Khouider and Majda (2006) multicloud parameterization approximates slantwise overturning in global models. Intended to supplement rather than replace convection parameterization, this opens the issue of convective organization as a vital process, especially for higher resolution models.

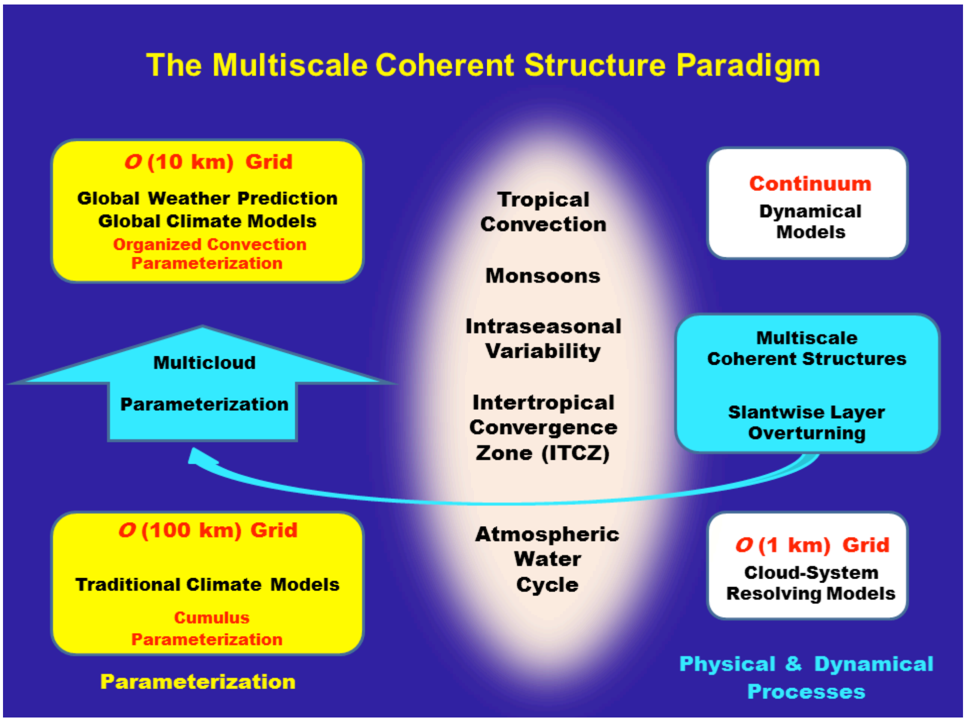

Figure 15. Center: Examples of meteorological phenomena that feature organized convection. Yellow boxes: Traditional global climate models with *O*(100 km) grids and cumulus parameterization, and the next generation of global climate models and global weather prediction models with *O*(10 km) grids requiring organized convection parameterization. White boxes: Explicit dynamical models and cloud-system resolving models with *O*(1 km) grids. Blue boxes show multiscale coherent structures (slantwise layer overturning) and their approximation by multicloud parameterization.

The resolution of global climate models has increased by almost an order of magnitude in a remarkably short time as a result of sustained exponential increases in computer capability. We are now entering a new era of mesoscale permitting climate models where mesoscale processes, including organized convection require a higher profile. Mesoscale physics and dynamics are critical for getting the right type, intensity and distribution of precipitation and representing the key effects of vertical shear. Without in-depth comprehension of mesoscale interactions in global models, it will surely be difficult to comprehend how weather events will vary in a changing climate. The ECMWF global weather prediction system will soon implement a 10 km grid. Such capabilities will engage improved knowledge of organized convection gleaned over past decades from observational, computational and theoretical approaches.

In the next 5-10 years we can look forward to significant progress at the weather and climate intersection. In that context, we draw attention to the Athena Project (Kinter et al. 2013), a coordinated effort to evaluate 10 km grid global models. Inspired by the 2008 World Modelling Summit (Shukla et al. 2009) and made possible by a unique availability of high-end computing resources, Athena investigated the sensitivity of climate simulations to spatial resolution and subgrid processes by utilizing two global modelling frameworks: the ECMWF's Integrated Forecast System and Japan's Nonhydrostatic Icosahedral Atmospheric Model. While many aspects of the mean climate are similar between the frameworks, the magnitudes and structure of regional effects differ substantially, including the systematic behaviour of intraseasonal tropical variability.

The YOTC project was completed on 31 December 2014 at the same time as the parent THORPEX programme (Parsons et al. 2015). However, organized convection aspects spearheaded by YOTC will continue as part of other strategic weather-climate intersection efforts, notably the Sub-seasonal to Seasonal (S2S, see Chapter 20) prediction project which, like YOTC, is joint between WWRP and WCRP (Vitart et al. 2012). In conjunction with the MJO Task Force, the S2S contains an activity devoted the Madden-Julian oscillation and the Maritime Continent (http://www.s2sprediction.net). A virtual global field campaign will be part of the WWRP Polar Prediction Project (PPP, see Chapter 19). The ECMWF will provide to PPP a complete global analysis, forecasts and subgrid data for mid-2016 to mid-2018 on a 10 km grid. Based on our YOTC experience, we anticipate that this 2nd virtual global field campaign will be widely utilized.

15.7 ACKNOWLEDGEMENTS

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CHAPTER 16. GLOBAL ENVIRONMENTAL PREDICTION

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Abstract

Over the past 30 years the skill of global numerical weather predictions has significantly improved: high-resolution global forecasts now routinely exceed a defined useful level of skill up to ~6½ days ahead, with particular forecasts extending considerably further. The rate of improvement continues at about one day per decade of research and development. Weather forecasts involve accurate and reliable ensembles of numerical predictions defining the range of likely future weather outcomes or scenarios with a quantitative measure of the confidence that can be placed on them. This white paper considers how this progress has been made and it provides a picture of future scientific opportunities by covering the: importance of resolution, physics, and coupling; use of ensembles/reforecasts; tropical aspects, and assessment of performance.

16.1 INTRODUCTION

The advances in global Numerical Weather Prediction (NWP) made in the past decades have arisen from scientific developments that have:

- Reduced numerical errors through more accurate and efficient numerical methods and increased spatial resolution, enabled by increasing supercomputer capacity.
- Improved the quality of the initial conditions by developing data assimilation methods that optimally combine the increasing number and variety of observations with prior information from forecasts.
- Improved the representation of physical processes, using fundamental meteorological research on: clouds, convection, sub-grid scale orographic “drag”, surface interactions, aerosols.
- Enabled the design of reliable ensemble predictions through the inclusion of initial condition and model uncertainties such that probabilities can be inferred.

Numerical weather prediction is now based on the underpinning concept of estimating the initial-time probability density function and predicting its evolution by using an ensemble of realizations of the system. A state of the art global forecasting system in 2015 operates with around 20-50 ensemble members and a horizontal resolution in the range 13 to 50 km with of order 100 vertical levels. The initial ensemble spread of the 500 hPa geopotential height for the northern hemisphere is about 2.5 m (or only about 3% of the variability) with an initial exponential growth rate of the spread in the forecast of about 1 day^{-1}. On average by 10 days into a forecast this spread has grown to around 70 m.

Looking forward, the prospect for global NWP is that it will further approach kilometre-scale resolutions. We can aspire to predict large-scale weather patterns and regime transitions out to a month or more ahead and high-impact events, such as tropical cyclones, out to two weeks ahead both accurately and reliably. There are good indications that, under certain conditions, global anomalies could exhibit predictable signals on seasonal timescales.

It is now apparent that many components of the Earth system (e.g. atmosphere, oceans, composition, land surface, cryosphere) are influential for medium-range weather predictions. Also analyses and predictions of these components, on a range of timescales, have societal significance and so numerical weather prediction is evolving into numerical environmental prediction. Coupling the components of the Earth system, including the data assimilation, is becoming a major aspect of the future science that is needed.

In this chapter, we provide an overview of environmental predictions systems with a focus on global medium-range prediction, as well as tropical prediction aspects. Section 16.2 provides an overview of the development of these environmental prediction systems. The use of ensembles and reforecasts for medium range prediction has been of growing importance in the community and is presented in Section 16.3. The progress in NWP in the last several decades has been remarkable and the performance of global environmental prediction systems is summarized in Section 16.4. Because of their critical importance to global forecasting, the tropical aspects of global medium-range forecasting will be described in more detail in Section 16.5. Opportunities for collaboration are indicated in Section 16.6. The summary and conclusions can be found in Section 16.7.

16.2 DEVELOPMENT OF ENVIRONMENTAL PREDICTION SYSTEMS

Background

Dramatic progress in the performance of global numerical weather predictions is reported elsewhere in this document. As noted in the introduction, improved observational coverage, observation quality and data assimilation algorithms have been important contributors to these improvements. In addition, developments to the models themselves have also been crucial. These have included both resolution (horizontal and vertical) and improvements to the representation of physical and dynamical processes. Balanced judgments have been made on a regular basis about the best use of resources (e.g. trade-offs between the computational costs of resolution, ensemble size, model complexity and data assimilation) in order to obtain such improvements.

The ability of higher horizontal resolution models to have smaller truncation errors and to better represent processes, weather systems and surface forcing (e.g. better resolved topography) has consistently been found to improve performance. A fundamental aspect to the skill of numerical weather predictions is the size of the initial condition error; this has been apparent since the pioneering work of Lorenz on chaos and sensitive dependence on initial conditions. Higher horizontal resolution enables more of the information from the observations to be utilized and thus helps to reduce the initial condition error. As horizontal resolution increases, previously unresolved physical processes will be able to be explicitly simulated thereby reducing the uncertainties associated with parametrizations. Severe weather is often associated with small-scale features embedded within larger scale systems. Higher horizontal resolution enables these high-impact features to be resolved and thus predicted more accurately. The numerical approximations to the underlying partial differential equations are increasingly accurate as horizontal resolution increases. Finally the description of the energy spectrum is known to be imperfect for horizontal scales smaller than about five to ten mesh lengths. Hence even with a mesh length of, say, 1 km it is to be expected that the effective horizontal resolution is closer to perhaps as much as 10 km; this provides a strong motivation for a much higher horizontal resolution than is used today in global weather models.

Models have also improved their representation of the vertical structure of the atmosphere, both by raising the tops of the models (often now located between 0.1 and 0.01 hPa, i.e. between about 65 and 80 km altitude) and by increasing the number of vertical layers. One of the key benefits of the former is that more accurate profiles in the stratosphere allow better use of satellite data and hence improve the quality of the analysis (and hence the forecast). There is also some evidence that a better representation of the stratosphere can directly improve tropospheric forecasts (Roff et al. 2011, Shaw and Shepherd, 2008, Tripathi et al. 2014), although assessing the relative importance of this on different timescales is still an area of active research. Increasing vertical resolution in the troposphere has often proved a difficult change for operational centres to successfully make, requiring some retuning of model physics in order to achieve satisfactory performance. In part this may indicate undesirable resolution sensitivities of the physics schemes, but in part it may simply be indicative that the vertical resolution remains insufficient to properly represent important processes and phenomena (e.g. relatively shallow layer clouds and sharp boundaries such as associated with inversions or cloud-no cloud interfaces).

Improvements to the representation of physical processes have also been important in part because of their influence on the large-scale circulation patterns but also in representing critical fluxes of heat, moisture and momentum from unresolved to resolved scales of motion and in determining precipitation rates, the growth of boundary layers, the interaction with the underlying surface etc. In global numerical weather prediction models there are representations of the following physical processes: convection, radiation, turbulence, gravity waves, cloud microphysics, surface transfers of heat, moisture and momentum, cloud cover and so on. An example of the importance of how these processes are represented is provided by the surface frictional properties. For example the accuracy of NWP forecasts is strongly sensitive to the (still relatively uncertain) representation of surface drag, and errors in the representation of convection can have significant remote influences in the medium-range.

A key aspect of the global models that are being used for NWP is that they are increasing in complexity in the sense that there are other components of the Earth system that are included in addition to the atmosphere. These include the oceans, the land surface, hydrology, atmospheric composition, sea-ice, etc. This is motivated because research is indicating that these other components contain sources of weather predictability, e.g. long-lived anomalies in soil moisture, sea-surface temperature, and sea-ice. It is also motivated by the fact that society and decision-support agencies require analyses and predictions of aspects of these components, e.g. atmospheric composition for air quality and greenhouse gas monitoring, ocean state, and flooding. The growth of Earth system science and a holistic approach to the natural environment has developed most strongly in the climate science community, but is growing rapidly in weather prediction also. It means that many scientific disciplines other than meteorology now are involved in the scientific and modelling developments that are needed. These include: atmospheric chemistry, oceanography, hydrology, glaciology and sea-ice science. The interactions between the weather and the physical, chemical and biological properties of the system can lead to complex inter-connections. For example, there is evidence that the evolution of hurricanes on timescales of 3-7 days can be significantly influenced by the presence of a coupled ocean in numerical prediction models. It has also been shown that accurate treatment of aerosols in an NWP model can affect wind speeds via the radiative forcing and this in turn can affect weather phenomena such as heavy rainfall within the Indian summer monsoon. Another potential example is a link between the rapidly changing sea-ice coverage of the Arctic basin which is believed to have a role in affecting the northern hemisphere circulation and so the predictability of European weather. This has led NWP centres to add interactive components such as a coupling to an ocean circulation model even from day zero in weather predictions. This will present increasing and exciting scientific challenges such as devising coupled ocean-atmosphere data assimilation methods and ways to represent the complexity of tropospheric chemistry without prohibitive computational cost.

An example of global environmental prediction systems driven from a societal need is provided by the Canadian Global Ice Ocean Prediction System (GIOPS, see Smith et al. 2014). Marine traffic in the Arctic is increasing significantly, and the demand for atmosphere-ocean-ice forecasts is being amplified by the increased economic activities in this region. GIOPS comprises ocean and ice assimilation systems, and provides 10 day forecasts of ocean-ice conditions at a grid spacing of 0.25°. Currently, a one-way coupling with the atmosphere is operational at the Canadian Meteorological Centre, but a fully coupled atmosphere-ocean-ice system is in development and should become operational within a few years.

Underpinning research and requirements

Looking forward, the steady progress that has been made over the past decades to reduce horizontal mesh sizes is expected to continue to reap the associated benefits. In order to do this, there are specific science challenges that will need to be addressed. These include how to transfer from parameterized to explicitly resolved processes, such as those associated with deep convection, i.e. how to address the grey zone where key processes may only be partially resolved. Also, data assimilation will have to transition to become fully multi-scale/multi-parameter schemes for the various components of the future coupled system.

In order to make progress, significant developments in many aspects of the model representation of physical processes are required. For example, although an 'old' problem, representation of the stable boundary layer remains problematic, with challenges to achieve realistic near-surface temperatures while at the same time achieving good synoptic behaviour. In part at least the latter may be related to issues with the drag parameterizations. Current work co-ordinated by Working Group on Numerical Experimentation (WGNE) has revealed that while different leading operational centres typically have very similar zonal mean drags (as scores degrade very quickly if this is not optimized), they achieve this through very different combinations of boundary-layer and orographic drag, suggesting a fairly arbitrary tuning of schemes against each other. A real challenge is to try to come up with techniques to better disentangle compensating errors (both in drag and more widely). The use and detailed analysis of errors in short forecasts e.g. day 1 (or even in the limit the first time-step) can certainly help in this process as errors remain more linear and closer to source. However, further assessments of and direct constraints on individual schemes (e.g. from observations or from using high resolution models as surrogate truth) are also required.

The representation of tropical convection is another area that remains particularly challenging, with most global models struggling with convective organization and the diurnal cycle, although some progress is being made. Indeed it seems plausible that making significant progress may require challenging some of the traditional paradigms for parameterization (such as treating each column individually), with future schemes likely to have to represent organization across multiple columns, have memory and an in-built representation of uncertainty (Holloway et al. 2013). They will also have to be scale-aware and able to cope with the problem of convection becoming partially resolved (an area that is undergoing active current research such as via the WGNE grey-zone project). Partially resolved explicit convection is achieved by global nonhydrostatic models which are being developed in many research groups (e g Satoh et al. 2014 and references therein) and are being used at NWP centres such as the Met Office. A global simulation with the horizontal mesh size around sub kilometres have been performed and it shows that deep convective cores become resolved when the mesh size is less than 2 km (Miyamoto et al. 2013).

Other areas worthy of increased attention include the numerics of many of the physics schemes (e.g. microphysics), and the coupling together of the physics and dynamics. Furthermore, many operational models show spectra that tend to fall-off more rapidly than observed at scales a surprisingly long way above the grid scale (e.g. six to eight times the mesh size). The reasons for this are not fully understood, and there are certainly implications for the physical schemes.

The development, over the last 20 years, of initial condition and model error uncertainty, has allowed mean ensemble spread to approach ensemble mean error for upper-air parameters. The challenge for the future is to do this on a flow-dependent basis. In order to do this, an important area of research is to utilise our knowledge of the uncertainties in individual physical processes to generate the model uncertainty component of ensemble design. Today there is usually either no link or limited connectivity between the physical parameterizations and the representation of model uncertainty via the variety of schemes used in operational prediction systems that are sometimes referred to as "stochastic physics". Indeed the whole area of model uncertainty is one where substantial progress is needed if this vital element in generating forecast errors and unreliability is to be properly addressed. Another example of the large effective resolution issue referred to earlier is that current stochastic physics schemes have to use long correlation space scales in order to impact the ensemble spread appropriately.

A continuing and important area of research is regarding the sources of predictability in the Earth system. To use terminology that Vilhelm Bjerknes would have recognised in 1904 - predicting future weather really is a battleground with the forces of predictability pitched against those of unpredictability. The sources of predictability include: large-scale forcing of smaller–scale weather; surface forcing; teleconnections or the chain of predictability; long-lived coherent structures. The sources of unpredictability include: upscale energy propagation and instabilities injecting chaotic "noise"; errors in numerical and physical approximations; insufficient number and poor use of observations. The outcome of this battleground could be described in terms of noise growing during the forecast and thereby leading to limits to predictability. The conventional wisdom might suggest that the limit is around two weeks ahead. But we need to ask what are the predictable signals and on what timescales - is there music lurking within that noise? Coherent long-lived phenomena (and propagating Rossby waves) provide predictability and space-time averaging isolates predictable signals. This has been referred to as “predictability in the midst of chaos”. It suggests that the concept of a limit to predictability be replaced by the concept of a seamless predictive capability on a wide variety of temporal- and spatial-scales (see Hoskins, 2012). Appropriately defined space-time average properties exhibit much longer predictable timescales. Prospects over the next decades might be characterised as: global NWP at kilometre horizontal resolution by 2030; accurate and reliable prediction of high-impact weather out to 2 weeks ahead; prediction of large-scale weather patterns and regime transitions out to a month or more ahead; prediction of global circulation anomalies out to a year ahead.

One of the biggest challenges in the coming years will be coping with significantly different supercomputer architectures. In the past, developments have been primarily science driven, with algorithm optimization following. However, computational efficiency needs to be taken into account much more upfront in the choice and design of algorithms, and this will require much closer working between scientists and computational specialists. Many centres are already looking into this in the context of dynamical core design (e.g. choices of grids; choices of implicit versus explicit methods, choices of advection methods), but similar considerations will need to be taken across all aspects of our modelling systems - the term “scalability” has been coined for this variety of critical aspects of the NWP-computer system. Given the scale of the challenges here, almost certainly too large for any one centre to tackle alone, there is a need to consider how international co-ordination can help e.g. through sharing experiences, through jointly developing algorithms and in interacting with supercomputer vendors.

16.3 USE OF ENSEMBLES AND REFORECASTS

Background

Most weather prediction centres now routinely generate regional and/or global ensemble predictions, with multiple realization or “scenarios” being generated for each forecast to span the uncertainty space. The regional systems are now commonly generated at grid spacings < 10 km and up to 1-2 days, with several using forecast modelling systems employing convection-permitting models and resolutions < 5 km. The regional models are relied upon for providing situational awareness of the likelihood of high-impact weather at the mesoscale, such as heavy rainfall leading to flooding, severe local storms, and tropical cyclone track and intensity. Global ensemble prediction systems are routinely run into the medium range (< 2 weeks). In 2014, most employ grid spacings of ~20-80 km. A state-of-the art system will have tens of ensemble members. These models are used to provide estimates of the synoptic-scale uncertainty, as well as to provide probabilistic guidance on high-impact events such as tropical cyclones. Some regional and global models have also been coupled to other components of the Earth system, such as to ocean models to predict wave heights and to hydrologic models to provide probabilistic estimates of streamflow.

Most current ensemble prediction systems under-estimate the forecast uncertainty except for the larger-scales; their spread (the standard deviation of the ensemble about its mean) is smaller than the ensemble-mean error, though the two should be consistent in magnitude on average. The two underlying reasons for forecast uncertainty are: (1) the rapid growth of forecast errors from initially small errors due to chaos (Lorenz 1993), and (2) the uncertainty contributed by the use of imperfect, and frequently deterministically formulated prediction systems. The aim for an ensemble forecast is to be both accurate (in the sense that a measure of forecast error is small) and reliable (in the sense that the predicted frequency of occurrence matches the observed frequency of a given event).

Since users expect ensemble guidance to provide useful estimates of the situation-dependent uncertainty, and since there are substantial challenges to designing ensemble prediction systems to correctly address (1) and (2) above, users have tried some other conceptually simpler methods for achieving more reliable probabilistic predictions. One method is multi-model combination;

ensemble prediction data is shared between operational centres, and products are derived from combined guidance (e.g. Figure 1). This data sharing occurs operationally between the US and Canada through the NAEFS (North American Ensemble Forecast System), and the World Meteorological Organization (WMO)/THe Observing System Research and Predictability EXperiment (THORPEX) has promoted experimental product development of multi-model products through its TIGGE (THORPEX Interactive Grand Global Ensemble) project (Bougeault et al. 2009). Global ensemble forecasts are available, with a two-day delay, from web sites at the US National Center for Atmospheric Research (NCAR), from the European Centre for Medium-Range Weather Forecasts (ECMWF), and from the China Meteorological Administration (CMA). The TIGGE database can conveniently provide data to those scientists wishing to understand the merits of multi-model vs. single-model ensemble prediction systems (e.g. Hagedorn et al. 2012, Hamill 2012). Regional multi-model collaboration has also been facilitated by the WMO through the TIGGE-LAM (Limited-Area Model) project. Though multi-centre ensemble combinations have been demonstrated in many circumstances to improve skill and reliability, they are ensembles of convenience. They have not been explicitly constructed to simulate all the sources of initial-condition and model uncertainty from first principles. Further, their improvement depends on the improvement of the constituent ensemble prediction systems.

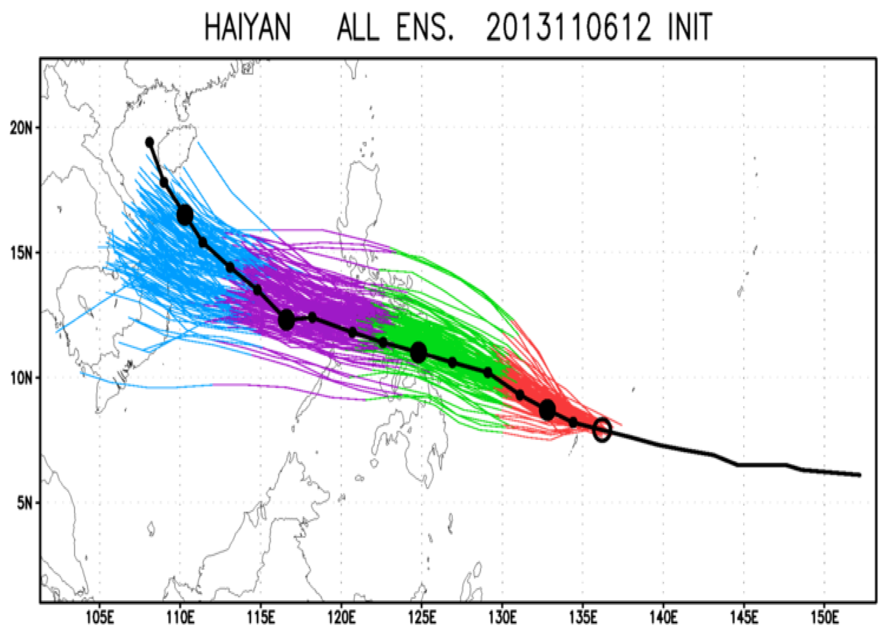

Figure 1. Illustration of multi-model track forecasts using models from the TIGGE data set, here for forecasts of Typhoon Haiyan, initialized at 12 UTC on 6 November 2013

Another method for improving forecast reliability of existing ensemble prediction systems is through statistical post-processing. Past forecasts and associated observations or analyses may be used to determine statistical adjustments to apply to the current forecast. For some fields such as 2 meter temperature at short forecast lead times, a relatively modest sample of a few months provides enough data to substantially improve upon the forecast. For other variables such as heavy precipitation, severe weather, or longer-lead temperature forecasts, one typically notices that the statistical post-processing can be improved by having a much larger training sample. When an assimilation/forecast system is frozen and past forecasts are generated using that frozen system, these are commonly called “reforecasts,” or “hindcasts” in the climate community. Many operational centres have experimented with the generation of reforecasts, including the US National Weather Service, ECMWF, Météo-France, and the Canadian Meteorological Center. Logistically, reforecasting can present challenges; the computational and personnel expense of reforecasts and associated re-analyses is significant. Freezing the operational model and/or data assimilation system to avoid reforecast re-generation can unacceptably slow the rate of improvement of the raw forecast guidance, but an older reforecast data set that is statistically inconsistent with the new real-time guidance is of little value. The improved skill and reliability from reforecasts, however, is so substantial (e.g. Figure 2) that many centres are attempting to provide them despite the logistical hurdles.

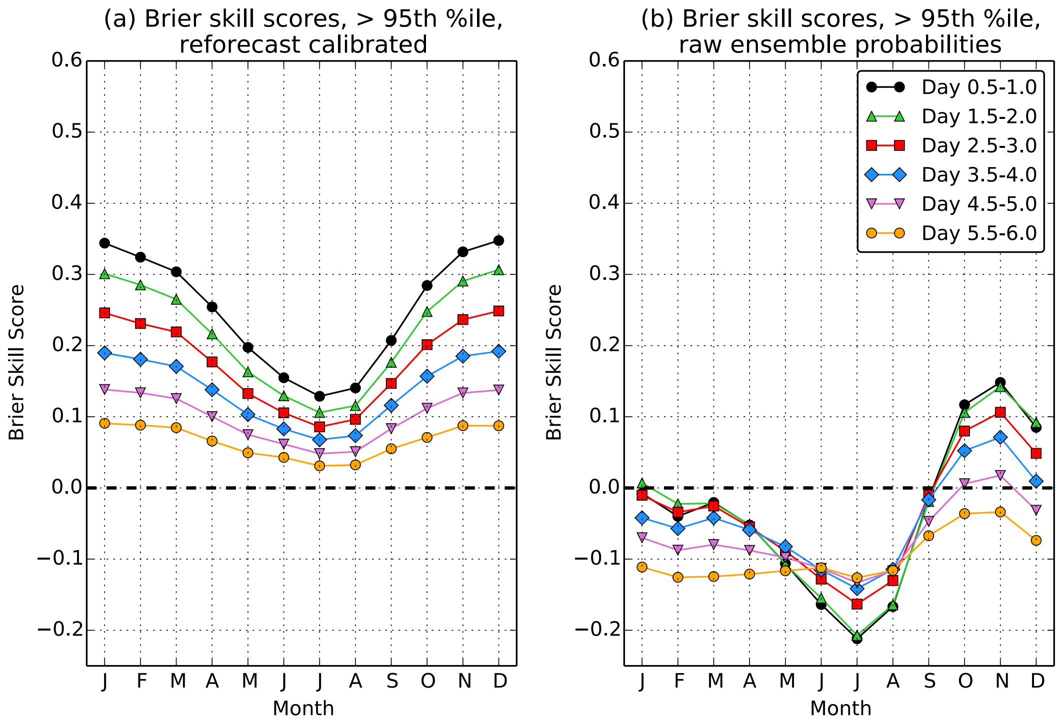

Figure 2. An example of the increased skill provided by post-processing numerical guidance using reforecasts. Brier skill scores for exceeding the 95th percentile of the climatological distribution are shown, calibrated and validated using 2002-2013 1/8-degree precipitation data over the CONUS. (a) reforecast analog-calibrated probabilities using the second-generation global ensemble reforecast data set of Hamill et al. (2013), and (b) raw ensemble probabilities from the 11 member US global ensemble.

Underpinning research and requirements

Were we able to produce reliable, skillful ensemble guidance, there is bountiful evidence that improved user decisions could be made based on this probabilistic information (e.g. Zhu et al. 2002). There are several hurdles to realizing these improved decisions. First, the ensemble prediction systems do not routinely generate sufficiently reliable forecast guidance, and this problem is worse for high-impact weather elements such as heavy precipitation than it is for commonly referenced mid-tropospheric elements like 500 hPa geopotential height. Hence, research to improve the ensemble prediction systems such that they properly simulate the uncertainty related to both initial condition errors and the model uncertainty are critical, especially methods that realistically simulate the uncertainty related to these high-impact events. Statistical post-processing methods could be improved as well. In particular, it would be helpful to employ post-processing methods that are efficient for the given amount of training data, i.e. that produce reliable guidance even when using only a modest number of past reforecasts.

Many users and even some forecasters are not yet comfortable with making decisions based on probabilistic guidance; they are more comfortable with more definite guidance (“cloudy, with a high of 18C tomorrow”). Education is needed for forecasters and users: what causes forecast uncertainty, how to interpret ensemble guidance, how to make improved decisions based on that guidance. In many cases, too, the ensemble information is yet not synthesized in such a way as to be maximally useful to the forecaster or decision maker. Hence, research and development is also needed into how to present ensemble information in convenient ways to the end user, so as to best facilitate their particular decision-making process.

The US Hazardous Weather Testbed may provide a useful paradigm for making progress on several of these research fronts simultaneously. During the US spring tornado season, several modelling groups contribute high-resolution, storm-resolving forecast guidance to scientists and forecasters gathered at the US Storm Prediction Center (SPC). The scientists and forecasters evaluate ensemble predictions and use them to make experimental forecast guidance of severe-storm potential. They evaluate their prior forecasts, learning how they could have improved on their communication of forecast risk, and they also provide feedback to model developers on the strengths and weaknesses of the modelling systems from the perspective of their ability to simulate the severe weather and its uncertainty. Programmes like this thus serve the dual purpose of educating forecasters on how to best leverage the (yet somewhat unreliable) forecast data, while model developers get practical feedback on model performance in aspects that are of greatest societal relevance.

Hirschberg et al. (2011) provides more requirements for further research and development to fully utilize data from ensemble prediction systems. Though oriented around US ensemble prediction deficiencies, the plan provides a convenient outline of the many components needed to realize effective usage of uncertainty information. These include a necessity to better understand forecast uncertainty, doing the research to quantify predictability related to high-impact phenomena and to identify the societal needs and best methods for communicating forecast uncertainty information. Another requirement is to generate improved forecast uncertainty data, products, and services. To achieve this, we will need to do the research and development to improve the ensemble prediction systems, the post-processing, the verification. Particular attention should be paid to the development of methods that unify the data assimilation and initial condition generation (e.g. ensemble Kalman filters and their hybridization with variational assimilation methods). Developing physically based methods of estimating the model uncertainty are also very important. The supporting infrastructure, should be upgraded, including improved high-performance computing as well as the storage space needed for the archival of forecast, observational, and analysis data, and the bandwidth to transmit this data to forecasters and users. The methods for displaying the much more voluminous and complicated ensemble information will need to improve. Finally, there is a need to communicate forecast uncertainty information effectively. This will involve reaching out to, informing, educating, and learning from users, training atmospheric scientists in uncertainty quantification and how to communicate this, and developing products that tailor the ensemble-related information to be maximally useful for making improved decisions.

16.4 PERFORMANCE OF GLOBAL ENVIRONMENTAL PREDICTION SYSTEMS

Background

In the last twenty years, progress in Numerical Weather Prediction has been tremendous, as illustrated for example in Figure 3 for the ECMWF model. As mentioned earlier, this progress was driven by various factors. Improvements in models (resolution and description of physical processes) and in significant initial condition error reductions via progress in data assimilation methods are documented to be the main factors (Magnusson and Kallen, 2013). The changes in the available observations (quantity and quality) also contribute, to a lesser extent. Although it is relatively easy to evaluate these improvements over long time-series, the year-to-year improvement is more subtle and performance depends not only on improvements in the forecasting system but also on the intrinsic predictability and degree of activity of the atmosphere in specific regions. It is thus particularly relevant to compare the actual operational performance at a given time with that of a reference system, which is fixed over a few years. This can be achieved by running forecasts as part of a reanalysis system, and comparing those with the operational forecasts, as shown in Figure 4.

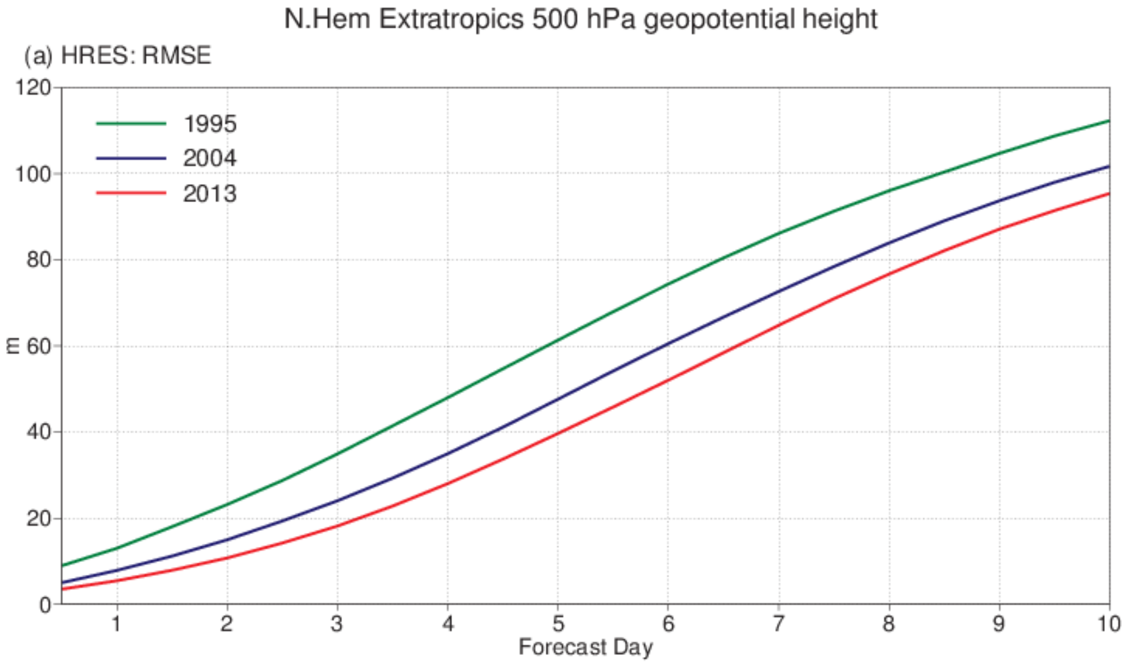

Figure 3. ECMWF's forecast Z500hPa extra-tropical error growth over the last two decades

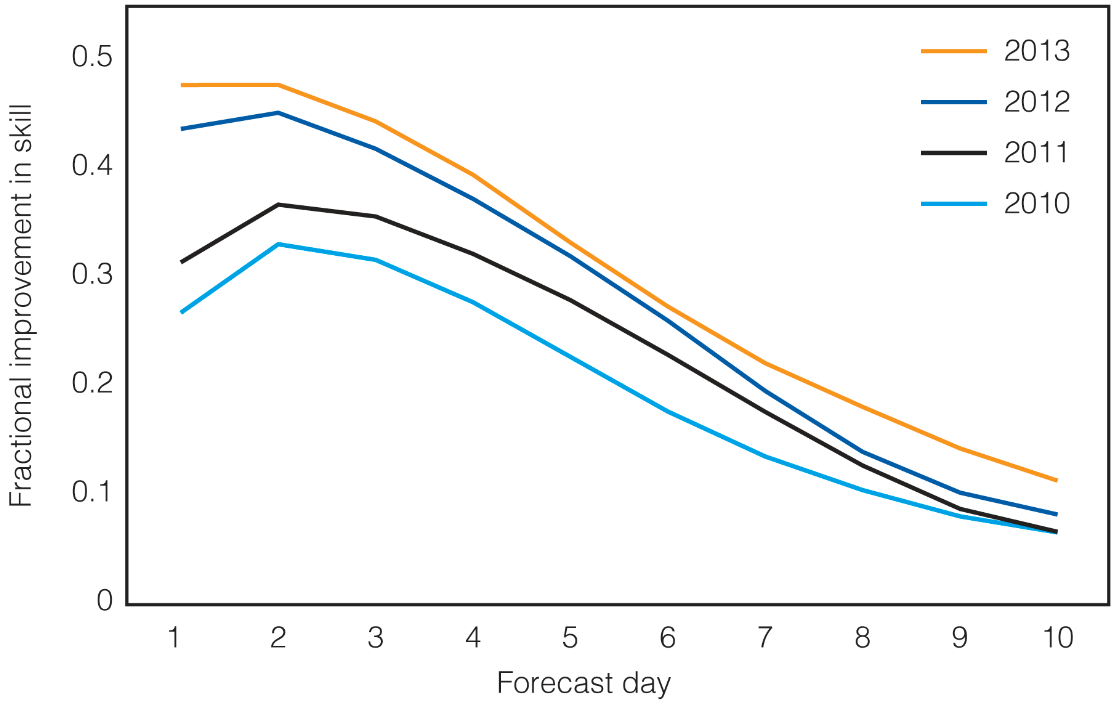

Figure 4. Fractional improvement in the anomaly correlation coefficient at 500 hPa in the extratropical northern hemisphere for the ECMWF high-resolution forecasts compared with those made using the forecasting system of 2006 (ERA-Interim) for calendar years 2010, 2011, 2012 and 2013.

As increasingly forecasters rely heavily on probabilistic forecasts, the performance measures refer to the performance of the ensembles. These are sometimes difficult to interpret as they depend on the improvements in the underlying data assimilation and model and on the enhancements of the ensemble system itself through a better representation of uncertainties. In this situation too, a reference system with respect to which one could compare the performance would be needed. At the moment, as re-forecasts are not computed with the full-fledged system (same number of ensemble members in particular), one uses instead the TIGGE archive to compare between various centres.

Measuring average performance is important but evaluation of individual forecasts during case studies of extreme events is also crucial. For example, in 2012, Hurricane Sandy hit the eastern coast of the USA with major disruption and casualties. Such cases are the ones for which the quality of the forecast can make the difference in public response and mitigation of weather-related impacts. For this reason, they are investigated in great detail in major NWP centres (Magnusson et al. 2014). In this case, as in many other severe event situations, the probabilistic information brought by the ensemble systems proved to be crucial for decision-making in forecasting offices. Diagnostics obtained on these cases of extreme weather are useful to understand better how the forecasting system behaves “under pressure”, and how the different components fit together. Extreme weather often includes small-scale structures, rapid development and large departures between model and observations. Investigations of the system during extreme situations might highlight deficiencies that also impact normal weather, but are enhanced in these extreme conditions. Case studies can also inform us about ensemble forecast deficiencies, particularly in cases of small spread and large error.

As systems get more coupled/integrated, the overall performance is also increasingly measured through the impact of the various components (hydrology, ocean, land, cryosphere, atmospheric composition). For example, flood forecasting can reveal deficiencies in the precipitation amounts produced by the weather forecast, or ocean forecasting deficiencies in surface fluxes.

Underpinning research and requirements

Evaluation of the forecast performance is generally performed on a few main parameters, verifying against own analyses or observations. This is extremely useful as these standardized scores are exchanged globally and give a broad description of the main operational systems at any given time.

The verification against an analysis has many advantages. Namely, the analysis is an optimal combination of all the available information (observations and model), with generally high accuracy. Furthermore, the analysis is global, at the same resolution as the model forecast. However, the use of its own analysis to verify a forecast has some caveats, as the analysis depends on the forecast model itself, and in particular on its biases. The performance of the forecast at short lead times can be over-confidently assessed in regions where the analysis is not sufficiently constrained by the observations, such as the stratosphere, the polar or tropical regions. Research is needed on the use of other analyses such as a consensus analysis or analyses randomly drawn from a set of different systems.

Verifying against observations is a very relevant approach. However, the radiosonde coverage is too inhomogeneous to be globally representative and one should consider relying on other observations such as the satellite measurements. In particular, progress is needed on verification with respect to satellite measurements for cloud and radiation evaluation. There is also a need to add to large-scale parameters such as geopotential at 500 hPa or temperature at 850hPa, and each centre verifies a whole range of weather parameters such as precipitation, surface temperature or wind gusts. As resolution increases, the observations needed on the global scale will need to be much more numerous than the ones currently exchanged internationally, both for verification and data assimilation.

Ensemble verification is also an area which will benefit from research and development to quantify all aspects of reliability (agreement between forecast probability and mean observed frequency), sharpness (ability to forecast probabilities which are not clustered around the mean) and resolution (ability to resolve the set of sample events into subsets with characteristically different outcomes). Research is very active in this area to establish fair and proper scores (Ferro, 2014, Christensen et al. 2014).

For extreme events, as these are rare, many of the scores degenerate to non-meaningful values. In Ferro and Stephenson (2011) the symmetric extremal dependence index (SEDI) was introduced, which does not have this property and research needs to be pursued in this area, together with the investigation of individual cases.

Although the general forecast performance has significantly improved in the last decades, there are still occasional forecast busts. For example, Figure 5 shows anomaly correlation time series of 500hPa geopotential height over Europe at a lead time of 6 days for single forecasts started at 0000 and 1200 UTC by several of the world's weather prediction centres. In general, scores fluctuate about the 80% level, but between 7 and 10 April 2011, there was a strong drop in performance. The frequency of these busts has decreased in parallel with forecast improvement. However, even a low level of busts causes problems for users of NWP products and motivates dedicated investigations in order to understand the potential issues associated with them. Research on how to best perform these investigations is active. One approach used by Rodwell et al (2013) is to make a large composite of several hundred bust events in order to identify common features. Composites of ensemble (rather than single) forecasts also allow us to estimate predictability and to relate this to forecast error.

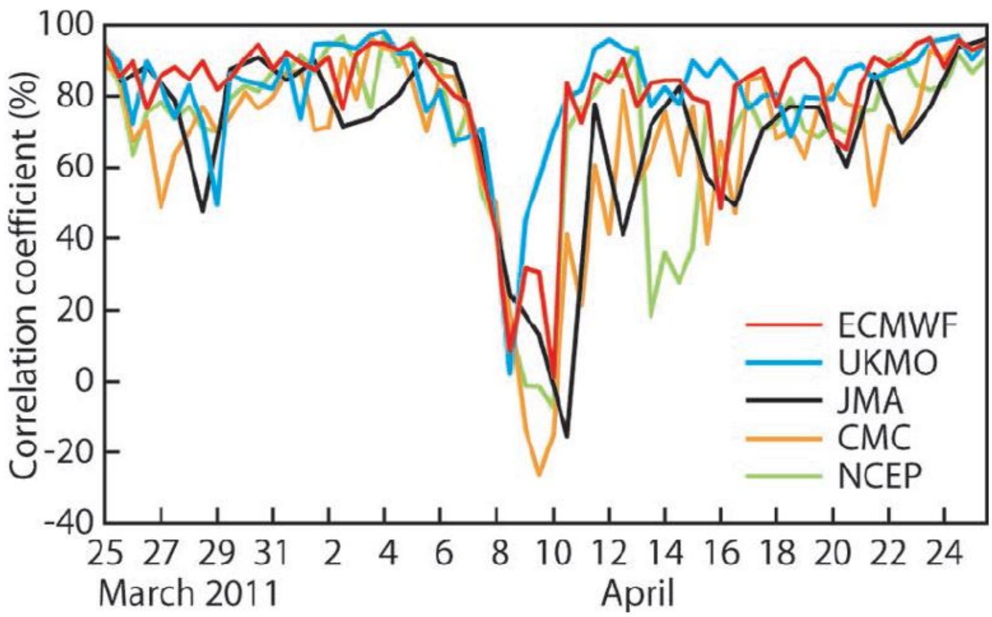

Figure 5. Time series of day 6 forecast skill over Europe from some of the world's NWP centres (within the TIGGE programme): Met Office (UKMO), Japan Meteorological Agency (JMA), Canadian Meteorological Centre (CMC), and NCEP. The dates correspond to the start of the forecast. The score shown is the spatial ACC of Z500. Europe is defined in this article as the region 35°-75°N, 12.5°W-42.5°E.

An area where users would benefit from improvements in the forecast is the prediction of changes in weather regime at the medium to extended range. The forecast performance has to be diagnosed in relation to these weather regimes in order to identify specific deficiencies in the forecasts such as the under-prediction of blocking situations for example. This can raise awareness at the user level and can also be used to diagnose which deficiencies in the model can be responsible for poor performance. Other aspects are the understanding of the processes and interactions between scales, and the identification and diagnostics of the processes that are relevant to forecast performance.

Verification is used to set performance targets and therefore plays a major role in system development. It is essential that scores are devised that guide development in the "right" direction by, e.g. being resistant to hedging, and that score uncertainty is minimized for a given sample size.

16.5 TROPICAL GLOBAL ENVIRONMENTAL PREDICTION SYSTEMS

Background

The prediction of tropical weather, convection, and the complex multi-scale interactions that take place among the rich palette of tropical phenomena is a long-standing challenge for global numerical weather prediction. Major challenges remain in predicting prominent phenomena of the tropical atmosphere such as the tropical cyclones, the Madden-Julian Oscillation (MJO), monsoons and their active/break periods, intertropical convergence zone (ITCZ), tropical and subtropical clouds, organized deep convection, air-ocean interaction, and even fundamental aspects of the diurnal cycle.

The destructive potential of high winds, heavy precipitation, and storm surges associated with tropical cyclones is well known, and the demand for more accurate prediction of their track (or position), strength (or intensity), and structure (e.g. distribution of high winds) is greater than ever. Medium-range forecasts of tropical cyclone tracks from global NWP models have shown remarkably steady improvement over the last several decades due to improved data assimilation methods and more realistic representations of physical processes in the tropics. For example, the official US National Hurricane Center forecasts, which are largely based on the leading global NWP models, have shown steady improvement over the past several decades for lead times of 24-120 h (Figure 6). With the steady improvements of global NWP models, recent studies have shown considerable promise for tropical cyclone genesis prediction (e.g. Halperin et al. 2013). Additionally, NWP models have been demonstrated recently to predict the genesis or occurrence of tropical cyclones at the intraseasonal time range (Vitart et al. 2010). The MJO can have a profound impact on tropical cyclone activity, along with other sources of predictability at the intra-seasonal time scale such as equatorial Rossby waves, mixed Rossby gravity waves, easterly waves, extratropical waves, and equatorial Kelvin waves. The boreal summer intra-seasonal oscillation (BSISO) also affects tropical cyclogenesis and its predictability is closely related to the medium range forecast skill of tropical cyclones (Nakano et al. 2014). Prediction of tropical cyclone intensity remains a formidable challenge for global NWP models, in part because resolutions at convective permitting scales may be required for reliable prediction.

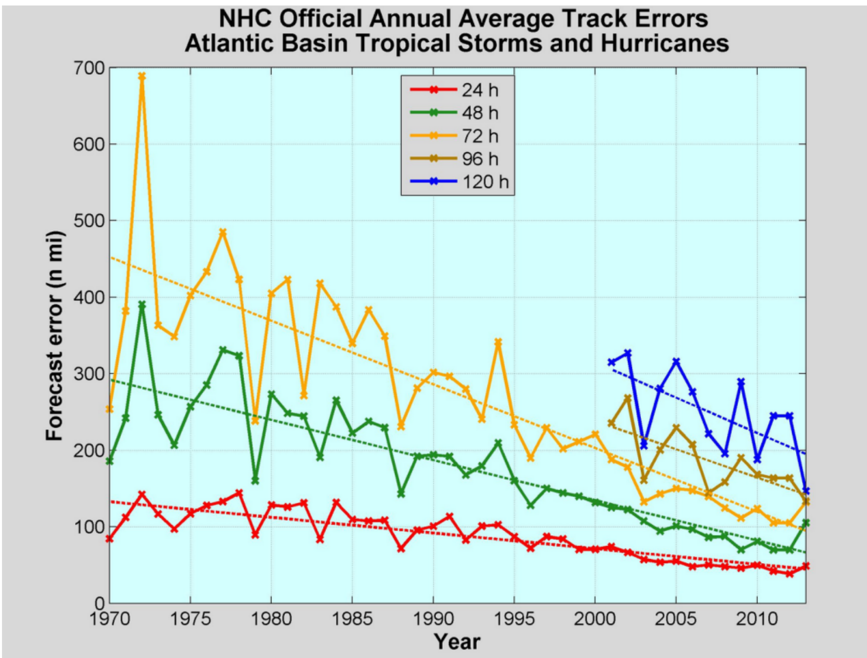

Figure 6. The official annual average track errors for the Atlantic basin for tropical storms and hurricanes for 1970-2013

The MJO is of substantial importance for global weather prediction because it is the primary mode of intraseasonal variability in the tropics (see review article by Zhang, 2005). In turn, the MJO has been shown to influence many different tropical and extratropical phenomena, including the onset and break of the Asian and Australian Monsoons, precipitation in different regions of North and South America, the development of tropical cyclones in different tropical basins, and has also been linked to ENSO through impacts of westerly wind bursts on the equatorial Pacific thermocline (Waliser et al. 2003 and references therein; Zhang 2005 and references therein). More recently it has been linked to the Arctic and Antarctic oscillations (Flatau and Kim 2013, and many others) and North American temperature forecasts (Rodney et al. 2013; Johnson et al. 2014). Given its influence on so many weather phenomena around the world, and the intraseasonal timescales on which it varies, improving forecasts of the MJO are considered a vehicle for improving global weather forecasts on the weekly to monthly time scale.

Several challenges exist for the proper simulation of the MJO. Many current weather and climate systems have difficulty simulating MJO initiation and propagation through the maritime continent. Many prediction systems also tend to dampen the amplitude of the MJO during forecast integrations and have incorrect propagation speeds (e.g. Kim et al. 2014b, see Figure 7). However, given the broad scientific effort to address these problems, there is cause for optimism that successful MJO forecasts are achievable within the next several years should these efforts be maintained or increased. One direction is toward the use of higher resolution global model with explicit convective processes to realistically simulate statistical effects of deep convection (Miyakawa et al. 2014).

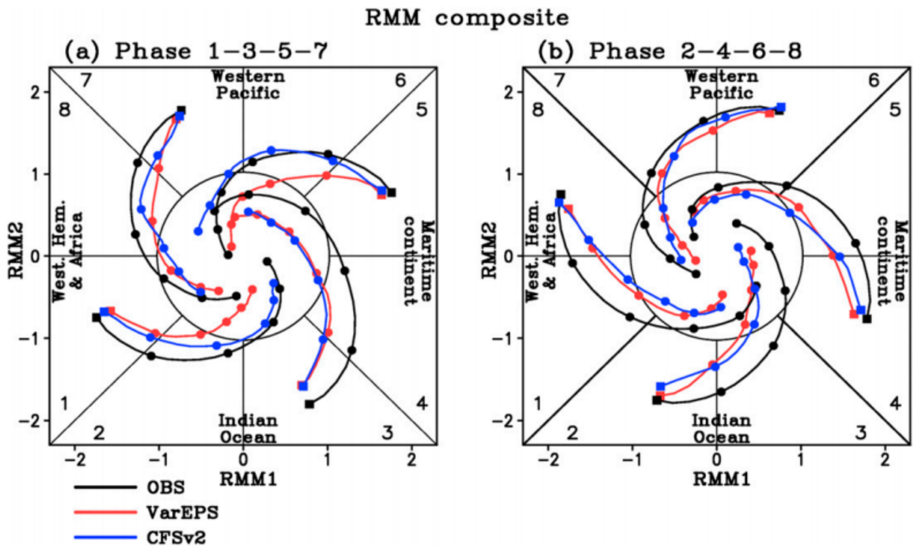

Figure 7. Wheeler-Hendon Multi-variate MJO index (RMM) composite phase–space diagram for observation (black) and the ensemble mean of ECMWF Variable Resolution Ensemble Prediction System (blue) and NCEP Climate Forecast System, version 2 (red) hindcasts initialized in strong MJO phases. The dots represent every 5 days from the forecast starting date (square).

Source: From Kim et al. 2014b

In many countries the summer monsoon is critical for replenishment of the waterways, supply of water for agriculture, and many other economic concerns, and thus accurate prediction of the active and break periods of the monsoon is crucial. The mean prediction skill over the global tropics and Southeast Asia for current operational and research global models is approximately 1-2 weeks for Asian-summer-monsoon-related rainfall (Fu et al. 2013), and more focus is needed to extend the predictive skill for monsoons. The tropics features a multitude of other phenomena that are important for global NWP, and many of these pose significant challenges for predictability on medium-range time scales.

The review article by Zhang (2005) highlights many challenges associated with simulating MJO and more generally most other tropical phenomena, including a strong sensitivity to the physical parameterizations, especially the convective parameterization, sensitivity to model resolution, sensitivity to biases in the time-mean state, and air-sea coupling. Studies that find sensitivity to the physical parameterizations include Benedict et al. (2014), who find a strong relationship between MJO simulations and gross moist stability as influenced through the treatment of moist convection, and tropical cyclone studies that point to strong sensitivity to the surface flux and convective parameterizations. Kim et al. (2014a) find a robust relationship between the amount of lower-tropospheric humidity increase needed for transitioning from weak to strong precipitation and MJO simulation skill in climate models. Holloway et al. (2013) find that explicit convection produces much better MJO simulations in the Met Office Unified Model than parameterized convection, but only when Smagorinsky sub-grid mixing in the vertical is used in place of a conventional boundary layer scheme. An explicit convection approach via the multi-modelling framework (e.g. the super-parameterized Community Atmospheric Model; SP-CAM) and a global cloud-resolving model (e.g. the Nonhydrostatic Icosahedral Atmospheric Model; NICAM) shows general improvement of the MJO predictability, suggesting that statistical effects of model resolved convection naturally reproduce favourable dynamics of the MJO (Benedict and Randall 2009; Miyakawa et al. 2014). Recent studies finding sensitivity to ocean coupling include that of Benedict and Randall (2011), who find that the implementation of an idealized slab ocean model to SP-CAM resulted in improved space-time structure and propagation of the MJO through an improved relationship between precipitation and SSTs. Likewise, Seo et al. (2014) find that the SST diurnal cycle strongly influences the onset and intensity of MJO convection in the Scripps Coupled Ocean-Atmospheric Regional Model. Many studies show the importance of ocean coupling for tropical cyclone forecasts, particularly for intensity. Bauer et al. (2014) come to somewhat different conclusions in an examination of the skill of the ECMWF model in predicting MJO events during the DYNAMO time period. They found that global measures of MJO forecast skill are more optimistic than local measures. They also found that the main source of error or skill in convective initiation is not localized to the Indian Ocean or very sensitive to tropospheric humidity or tropical SST. Rather they find that the MJO forecast skill is influenced by the analysis in broader regions as well as the model's ability to represent teleconnections.

Underpinning research and requirements

Because multi-scale convectively coupled processes are drivers of large-scale tropical phenomena such as the MJO and linked to other prominent phenomena such as tropical cyclones, the need to reach convective-permitting resolutions for NWP models in the tropics, along with the required computational resources, is particularly acute. In addition, accurate coupling of different geophysical components (atmosphere, ocean, land-surface, hydrology) will become increasingly important as resolution increases and as the community aims to improve forecast skill in the medium range. Therefore, there is a strong requirement for interdisciplinary research in building integrated systems in which the individual components are consistent with each other in, for example, their treatment of fluxes, or the construction of ensemble initial perturbations.

Data assimilation in the tropics has a set of issues that are in some ways distinct from that in the mid-latitudes. These include the importance of assimilation of cloudy radiances and of moisture variables, weak geostrophic balance constraint, lack of in-situ observations over much of the tropical domain, and the importance of model uncertainty. Challenges remain to properly initialize various tropical phenomena; for example, the intensity of tropical cyclones. Research in tropical data assimilation and model development will need to be closely linked to adequately address these issues.

16.6 OPPORTUNITIES FOR COLLABORATION

WGNE is very active in bringing together modelling centres, sharing progress and running projects to tackle problems of common interest (e.g. current studies include drag comparison; grey-zone; assessment of impact on forecasts of different levels of aerosol complexity). It also provides a vehicle to link to climate expertise that is becoming increasingly valuable to the NWP community (as well as vice versa). For example, as NWP models move towards coupled oceans there is clearly much to be learned from experiences with coupled seasonal and climate models. Also as the top of NWP models have been raised, further assessment of their performance in the stratosphere - and of how best to represent non-orographic gravity waves - can be best (and is increasingly being) done in close collaboration with the active climate community.

The THORPEX legacy “High-Impact Weather” (HIWeather) project is oriented around issues such as have been discussed here, facilitating the use of forecast guidance for making improved decisions related to high-impact weather and to further improving the ensemble guidance that is used in making these predictions. There are other WMO-sponsored programmes that address particular forecast challenges. Forecasting problems related to Arctic and Antarctic prediction, for example, are addressed through the collaborative R&D facilitated by the WMO’s Polar Prediction Project (http://polarprediction.net/) and Sub-seasonal to Seasonal Prediction Project (http://www.wmo.int/pages/prog/arep/wwrp/new/S2S_project_main_page.html). Improving predictions and predictive skill of severe weather forecast capacity in developing nations is addressed through the WMO’s Severe Weather Forecast Demonstration Project (http://www.wmo.int/pages/prog/www/swfdp/).

The WWRP/THORPEX/World Climate Research Programme (WCRP) joint research project Sub-seasonal to Seasonal Prediction (S2S, see Chapter 20) has the goal of improving forecast skill and understanding on the S2S timescale, with specific attention on extreme weather including tropical cyclones and monsoon precipitation. Work that will improve weather prediction on these time scales will certainly be relevant to predictions on shorter time scales. Links with the WCRP/WWRP-THORPEX YOTC MJO Task Force (formally the US CLIVAR MJO Working Group, reformulated in 2013 as the WGNE MJO Task Force) are essential given the MJO focus. Specifically, lessons learned from the “Vertical Structure and Diabatic Process of the MJO: A Global Model Evaluation Project” will be particularly relevant for weather forecast system development. Links with CINDY/DYNAMO (Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011/ Dynamics of the Madden-Julian Oscillation) and the coming YMC (Years of the Maritime Continent) will provide a wealth of observations relevant to the problem, and access to intensive research on MJO physical processes, simulations, and predictability.

An active physics community is already co-ordinated through GEWEX (Global Energy and Water Exchanges Project) Global Atmospheric System Studies (and Global Land/Atmosphere System Study for the land surface), which runs numerous projects typically bringing together observations and process models (e.g. cloud resolving models) and using them to try to understand and improve the performance of operational models. Although hosted under WCRP, the fast physics issues are almost entirely common for weather and climate models, and hence this grouping serves the ends of both the weather and climate communities. Many of these projects do successfully involve the academic community, although there remain challenges in truly getting academia actively involved in model development (as distinct from model evaluation or process research). In part these challenges are technical, and need to be overcome through close partnership working between individual centres and academia, but there are wider issues (being considered by the WCRP Modelling Advisory Council) including whether career paths in academia really encourage individuals to get involved in detailed model development.

There should be a link of NWP centres with WMO/CBS for the exchange of scores, extending them to surface parameters. The WWRP/WGNE Joint Working group on Forecast Verification Research (JWGFVR) is an important forum for international collaboration on all aspects of verification research.

The societal benefits from the Earth system or environmental approach are substantial. In Europe a major new programme involving several billion Euros of funding is being supported by the European Union - it is the Copernicus programme. This is to provide a single authoritative source of quality-controlled information on the state of the global natural environment for policy-makers and businesses. This is a continental and therefore multi-national collaborative response to a burgeoning environmental information service industry that is developing. A backbone of the

Copernicus programme is a European addition to the global observing system - the Sentinel satellites - adding to the other weather and climate measurements made routinely and for special purposes. Copernicus is the major contribution by the European Union to the GEO (Group on Earth Observations) programme.

16.7 CONCLUSIONS

It is over 110 years since Vilhelm Bjerknes and Cleveland Abbe outlined the paradigm that underpins numerical weather prediction (Bjerknes 1904 and Abbe 1901). Global NWP has already been a hugely successful scientific and technical enterprise with substantial societal benefits arising from the resultant weather forecasts. The scientific, observational and computational advances that have been needed to realise this paradigm show no sign of letting up so that we can be optimistic that further progress can be expected.

So where will this progress come from? Assuming that the computational capacity and capability is available then there would appear to be every reason to suppose that we are heading for kilometre horizontal mesh sizes in global models. At that resolution we can expect some of the physical parameterizations, such as for deep convection, to be no longer necessary so that those physical processes are described explicitly, although it is not envisaged that all applications up to the extended range will be at that stage in the coming decade. This will also greatly reduce truncation errors associated with the way the underlying partial differential equations are solved numerically. We can expect huge opportunities for improved weather predictions from increasing the number of processes that are represented in our models within the Earth system, such as the oceans, land surface, sea ice, and composition. This implied increase in complexity will require the science behind coupling of the components, including the data assimilation, to be advanced. To go along with the increasing resolution we can expect a further expansion of the number and type of observations shared internationally to initialize models that will come from novel instruments and platforms. It is expected that re-analyses and re-forecasts will become increasingly useful to perform accurate verification and calibration of the forecasts.

These scientific opportunities have to be matched by the ability to solve the equations efficiently on supercomputers and this is likely to require new ways to code on massively-parallel machines with potentially millions of cores. The energy consumption (watts per flop) will become a significant challenge. The NWP process has to be viewed end to end in a holistic way with the computer being a critical and fundamental part along with the governing laws. In parallel, the fine-scale information produced in real-time will have to be provided to the users with large increases in data volumes. Data handling and dissemination will be revised to accommodate this new situation. Compression of the information might be needed to communicate only the relevant signal to the users. How will this come about? The key is to think holistically and address the scalability challenge by using novel mathematical solutions and computing techniques. It is no longer good enough to only focus on individual parts of the process.

What can we expect from the forecasts themselves? They will continue to be fundamentally ensemble based with a prediction that defines a most likely state and the confidence one has in that being quantified via a set of scenarios. They are likely to be increasingly seamless in the sense that the same model is used in a more-or-less continuous way over a full range of timescales out to a year or more ahead. And we can expect to be predicting not just the weather but also many other aspects of the atmospheric, oceanic and land-surface environment. Indeed, the use of global models to provide a consistent and complete analysis and prediction of the key attributes of the Earth system can be used to prevent loss of life, reduce damage and provide economic opportunities. All of this requires an Earth system approach that in many respects has been pioneered by the weather and climate science and prediction community. Finally the process has to fully engage with the users of these forecasts because society’s needs have to be factored into the way the system is developed.

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CHAPTER 17. REGIONAL ENVIRONMENTAL PREDICTION SYSTEMS

Stephane Belair

Abstract

Short-range regional environmental forecasting is considered an operational priority in many national prediction centres. Forecasts from regional prediction systems are normally produced at higher frequency and higher spatial resolution than those from global systems used for medium- or longer-range forecasting. Regional operational suites typically include both a deterministic component as well as an ensemble component. Recently implemented deterministic systems have grid spacing on the order of 1-4 km, compared with 2-20 km grid spacing for ensemble systems. Research and development on deterministic models is mostly focused on the representation of physical processes. For ensemble systems, the emphasis is essentially on the methods used to represent the uncertainty of the initial conditions and forecasts. The next generation of regional short-range prediction systems is likely to include subkm-scale deterministic models together with km-scale ensemble systems. More complex suites of coupled models are also expected to become more widely used for operational production.

17.1 INTRODUCTION

Regional short-range forecasting systems are typically integrated at greater horizontal resolution and frequency than global forecasting systems. More than the fact that regional forecast products are often available earlier than their global medium- or longer-range counterparts, the value of regional systems lies in the enhanced quality of their environmental forecasts. This added value is related to the greater horizontal resolution that is possible at the regional scale which allows for more physical and realistic representation of processes such as clouds, precipitation, radiation, and turbulence, as well as for more detailed and accurate modelling of the impact of the surface on the atmosphere.

It is often argued that recent advances in global forecasting systems are continuously challenging the motivation for having regional systems. The main questions examined in this chapter are thus related to how today's regional systems contribute to better environmental forecasts. This is discussed in the context of the recently implemented deterministic and ensemble prediction systems, as presented in the next two sections. The next generation of even higher-resolution systems expected for implementation in the next decade is discussed in the last section. Although the word “environmental” is part of this chapter's name, most of the emphasis is on the atmospheric or weather component. But the transition towards truly environmental systems, highlighted by the recent progress on coupled systems that include more complex models for components like oceans, sea-ice, hydrology, chemistry/air quality, and cities, is briefly discussed at the end of the chapter.

17.1.1 Deterministic systems

One of the important evolutions in national prediction centres is certainly related to a more widespread use of km-scale atmospheric models for deterministic weather forecasts. In this chapter, “km-scale” is referring to models with grid spacing of about 1 to 5 km. For example,

- Environment Canada (EC) has been using a series of limited area models (LAM) over several regions of the country with 2.5 km grid spacing for nearly a decade (Erfani et al. 2005, Mailhot et al. 2010). More recently, in 2014, EC has implemented its national version of this 2.5 km system, which covers about two-thirds of North America.
- In the United States of America (USA), runs produced with the High-Resolution Rapid Refresh (HRRR) system are launched hourly since 2014 at the National Centers for Environmental Prediction (NCEP), with 3 km grid spacing. An experimental version of this system has been run in real-time since 2010 at the Global System Division (GSD) of the

National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL).

- In 2012 the Japan Meteorological Agency (JMA) has updated the configuration of its local forecasting system, with the implementation of a 2 km grid spacing version of their nonhydrostatic model (JMA-NHM) (Saito, 2012). This system is currently launched every hour, for 9 h forecasts. It is accompanied by a lower-resolution system with 5 km grid spacing and launched every 3 hours for 39 h forecasts.
- In the United Kingdom (UK), a variable-resolution version of the Met Office Unified Model (UKV) has been used in the last few years for short-range forecasting, with runs every 3 hours and with 1.5 km grid spacing (at its core) (Lewis et al. 2015). With this approach, the Met Office is able to directly drive the high-resolution regional model with lateral boundary conditions provided by its global numerical weather prediction (NWP) model (Tang et al. 2012).
- In France, Météo-France intends to implement a 1.3 km grid spacing version of their model called Application of Research to Operations at Mesoscale (AROME-France) (Seity et al. 2011, 2014).
- In other European countries, km-scale versions of the Consortium for Small-scale Modeling (COSMO) model have been running at several centres, such as the 2.8 km grid spacing version used at the German weather forecasting centre (Deutscher Wetterdienst, DWD) and the 2.2 km version at MeteoSwiss.

For all these implementations, it was generally found that the use of km-scale atmospheric models leads to a more realistic representation of mesoscale meteorological features, including local surface circulations, clouds structure, and precipitation extent and intensity (e.g. Seity et al. 2011), compared with forecasts from lower-resolution models with grid spacing on the order of 10 km or more. These improvements are often highlighted using subjective evaluation. But recently a study by Lewis et al. (2015) demonstrates that objective scores of surface weather phenomena from the newly-implemented 1.5 km UKV system has substantially greater skill than their global forecasting systems. Other studies have provided evidence of the modelling quality that can possibly be attained with km-scale models (e.g. Ikeda et al. 2013).

Of great interest is the possibility offered by km-scale models with their increased horizontal resolution (and sometimes vertical resolution) to represent phenomena which until now have not been systematically well predicted. This includes the modelling of fog (or low-level clouds in general), the initiation, intensification, and motion of intense summertime convective activity, the influence of detailed orography on precipitation, and the complex precipitation structures often produced by winter systems, involving transition from rain to snow (and vice-versa) as well as the production of freezing rain.

17.1.2 Underpinning research

Although all modelling aspects have been researched and developed in order to implement km-scale deterministic atmospheric systems, including dynamical, numerical, and physical components, most recent gains have been mostly based on improvement of physical processes. Among these processes, the representation of cloud microphysics along with its associated precipitation and its interactions with atmospheric radiation has received considerable attention. Several microphysical schemes of relative complexity, most often based on bulk microphysics with several hydrometeors categories represented with two or three moments, have been developed and used in km-scale atmospheric models. Many studies have emphasized the crucial role played by these schemes in the numerical prediction of summertime and wintertime precipitation events (e.g. Thompson et al. 2008, Frick et al. 2012, Iguchi et al. 2012).

A representative example is provided by Bryan and Morrison (2012) who showed that the use of a two-moment microphysical scheme led to more realistic representation of the leading convective line and trailing stratiform regions of a squall line. There is also the promising new approach presented in Morrison and Milbrandt (2015) in which all ice-phase particles are represented by a single category for which several physical properties evolve freely in space and time. This new scheme, called Predicted Particle Properties (P3) was shown in Morrison et al. (2015) to representation reasonably well clouds and precipitation for a squall line case as well as for orographic precipitation, and this at a reduced computational cost compared with other microphysics schemes.

Another aspect that favours km-scale deterministic regional systems with respect to lower-resolution models is related to the role and impact of the surface. As horizontal resolution increases, surface features such as orography, vegetation, roughness, fractional coverages of land and water, and the presence of cities could be responsible for the development and structures of low-level small-scale circulations.

For instance, when achieved together with the use of complex microphysics, increasing of horizontal resolution has been shown to be particularly effective in regions of complex orography. In these conditions, km-scale models have been shown to successfully represent orographically-forced precipitation. One such example is discussed in Milbrandt et al. (2008) who describes 1 km and 4 km simulations of a winter storm over the USA West Coast with a triple-moment scheme (Milbrandt and Yau, 2005). Based on a larger number of cases, Smith et al. (2015) shows that using the newly-implemented operational UK Unified Model (MetUM) with 1.5 km grid spacing leads to more realistic spatial variability of precipitation over mountainous regions of the UK, and to a significant reduction in precipitation biases compared with lower-resolution versions of the MetUM.

Coastal areas, with their sharp contrast between water and land surfaces also have a great influence on small-scale circulations produced by km-scale regional models. Many studies have confirmed the ability of km-scale models to represent sea and ocean breezes, and their effect on urban conditions in cases of coastal cities (Cai and Steyn, 2000, Dandou et al. 2009, Chen et al. 2011). Of particular interest is the density current nature of sea breezes with the production of relatively large upward velocity at their leading edge which has an impact on transport and diffusion of pollutants and potentially on the formation of clouds (Thompson et al. 2007, Leroyer et al. 2014).

More evidence based on observations and numerical modelling has been published in the last decade concerning the impact of urbanized areas on the spatial variability and intensity of precipitation (Miao et al. 2011, Souma et al. 2013, Kusaka et al. 2014). These aspects related to coastal areas, lakes, and cities are now better resolved in km-scale operational regional systems, presenting new possibilities for short-range weather forecasting.

17.1.3 Linkages

The atmospheric models used for deterministic regional weather forecasts can be considered as the central component for most of the emerging environmental prediction systems. This is true for instance for air quality applications, in which chemical processes along with representation of aerosols and surface sources have been added into regional atmospheric models (see Gong et al. 2012 for the Global Environmental Multi-scale - GEM Air quality system, Grell et al. 2005 for the Weather Forecasting and Research - WRF/Chem system, and Baklanov et al. 2014 for a more exhaustive list of meteorology chemistry models in Europe). Regional models are also providing the meteorological support for dispersion modeling at the continental and urban scales (e.g. Bourgouin et al. 2012, Kanda et al. 2013). Likewise, they are closely coupled with several types of surface systems, from land data assimilation systems (Belair et al. 2003, Mitchell et al. 2004), hydrological forecasting systems (Deacu et al. 2012), as well as ocean and ice prediction systems (Smith et al. 2012, Lemieux et al. 2015). Regional NWP models are of importance for several other applications, including transportation as well as wind power and solar energy management.

17.1.4 Requirements

Even though the recently implemented km-scale systems generally represent an improvement over previous operational systems, there are still several aspects of short-range weather forecasting that are poorly represented and require particular attention (e.g. Hong and Dudhia, 2011). Not surprisingly, precipitation still continues to represent a challenge, both in warm and cold seasons. In general, precipitation's spatial and temporal variability requires improvements with km-scale models. The fact for example that convective activity is only partially resolved at these scales can lead to precipitation cells often predicted as too large and too intense in summertime, with a strong and undesired diurnal cycle for precipitation biases (Seity et al. 2014). The localization in space and time of small-scale severe convection is another important problem with dramatic impact on hydrological forecasting for small catchments. In winter, the precipitation phase (rain, snow, ice pellets, and freezing rain) still remains an ambitious problem (Iguchi et al. 2014). Other weather elements that remain difficult even at the km-scale include fog and all visibility aspects related to clouds, as well as boundary-layer mixing in stable and near-neutral situations.

Some of these difficulties could be related to poor initial conditions (upper-air and surface) and to the loss of predictability for small-scale phenomena (an important challenge for high-resolution NWP), but improvements to physical process modelling is still expected to lead to substantial gain. Much of the emphasis on physics development in km-scale models remains on cloud microphysics which obviously plays an important role in the representation of clouds and precipitation in these models (e.g. Iguchi et al. 2012, Morrison and Milbrandt, 2015). In addition to continuous fundamental research on these schemes, new aspects related to aerosols, chemistry, and electrification are coming to the forefront (Shi et al. 2014).

Maybe less frequently investigated, but also of great importance, are the role and impact that subgrid-scale clouds (also called implicit clouds) have on km-scale regional forecasting. Indeed, km-scale models do not resolve convective clouds, although they are often referred to as “convection-permitting”, “convection-allowing”, or even “convection-resolving” models. Small cumulus clouds and stratocumulus clouds at the top of the boundary layer require a special treatment (usually as part of the turbulent boundary-layer scheme), as does overshooting shallow convection (see Belair et al. 2005). The necessity of including a deep convection parameterization in km-scale models has not been widely accepted one way or another, even though it is clear that this type of clouds could be misrepresented in purely explicit km-scale models, and even though their absence could explain the problem described earlier concerning the overestimation of the size and intensity of convective cells. Implicit representation of deep convection is also likely to improve the diurnal signal for summertime precipitation biases.

The advent of km-scale atmospheric systems provides an opportunity to better simulate the impact that surface features such as water, vegetation, and cities can have on weather. This involves all aspects related to surface modeling, including first and foremost the specification of land surface characteristics at the appropriate scales. Parameters and properties associated with orography, fractional water coverage, soil texture, vegetation, and urban areas represent a requirement for proper representation of surface impact on the atmosphere and meteorology.

Ideally, initialization of surface variables over water and land surfaces should be achieved with surface data assimilation systems, and not through the use of climatological fields (often prepared at lower resolutions). Although much of the effort concerning surface assimilation systems has been for lower-resolution global forecasting systems (Rodell et al. 2004, Reichle et al. 2007), several systems have been developed and used to initialize surface variables at the regional scale. Those include the North American Land Data Assimilation System (NLDAS, Mitchell et al. 2004), the National Center for Atmospheric Research (NCAR) high-resolution land data assimilation system (Chen et al. 2007), and the Canadian Land Data Assimilation System (CaLDAS, Carrera et al. 2015). It has been found for example that land surface initial conditions provided by CaLDAS for the Canadian national 2.5 km forecasting system resulted in substantial improvements for near-surface forecasts of air temperature and humidity, both in summer and winter. In coming years, the use of km-scale LDAS should become more widespread. Inclusion of high-resolution space-based remote sensing data to initialize surface variables such as water temperature, snow cover and depth, land surface temperature, and soil moisture, should be emphasized. Upcoming satellites such as the Soil Moisture Active Passive (SMAP, Entekhabi et al. 2010) will provide some of the km-scale observational data necessary for this effort.

17.2 ENSEMBLE SYSTEMS

In complement with deterministic prediction systems, regional ensemble prediction systems (REPS) are now routinely used to provide probabilistic forecasts and information on the uncertainty of short-range regional numerical predictions. Although they are integrated at lower resolution than their deterministic counterpart, the statistical diagnostics of these ensemble runs (such as the spread) can be used to provide probabilistic information on uncertainty, in spite of the fact that each member of these ensembles could be of lesser quality in average than the control high-resolution deterministic run.

One of the earliest operational implementation of a REPS was NCEP's Short-Range Ensemble Forecast system (SREF, Stensrud et al. 1999, 2000). Since then, and especially after the World Weather Research Programme (WWRP) Research and Demonstration Project (RDP) for the 2008 Beijing Olympics, many other REPS systems have been operationally implemented in national centres (Duan et al. 2012). With grid spacing on the order of 2-20 km, and ranges of 2 to 4 days, these include (among others) the Canadian REPS (Li et al. 2008, Charron et al. 2010), the UK Met Office Global and Regional Ensemble Prediction System (MOGREPS, Bowler et al. 2008), Japan's Meteorological Institute (MRI) and JMA's Mesoscale Ensemble Prediction System (MEPS, Saito et al. 2006), the Prevision d'Ensemble ARPEGE (PEARP) system at Météo-France (Descamps et al. 2014), the COSMO-DE Ensemble Prediction System at DWD (Gebhardt et al. 2011), and the Aire Limitee Adaptation Dynamique Developpement International – Limited Area Ensemble Forecasting (ALADIN-LAEF) at the Austrian national centre (Zentralanstalt fur Meteorologie und Geodynamik – ZAMG, Yang et al. 2011). Implementation of these systems has been shown to provide useful information on the probabilistic nature of weather events and on their uncertainty.

17.2.1 Underpinning research

Similar to deterministic NWP, the quality of the probabilistic forecasts obtained from REPS systems directly depends on the quality of the initial conditions and of the environmental system modelling. But another aspect which could be argued to be of even greater importance relates to the ability of REPS systems to represent the distributions of possible meteorological events with its ensemble properties. To achieve this, recent research and development that led to the operational implementation of REPS mainly focused on these ensemble properties, such as the spread-skill relation. Items examined in this context are perturbations to initial conditions, perturbations to lateral boundary conditions (LBCs), and perturbations to the model(s).

Several methods have been used to include the effect of uncertain initial conditions in regional ensemble modeling. One of the simplest approaches is to directly use initial conditions from a lower-resolution global ensemble prediction system (GEPS), with perturbations. This method known as downscaling has been found to underestimate the spread of the ensemble, especially in the initial forecast hours which are regarded as important for short-range forecasting. More advanced methods have achieved better results in this regard. They include breeding methods (Descamps et al. 2014), ensemble data assimilation, such as localization in an Ensemble Transform Kalman Filter (ETKF, Bowler et al. 2009), singular vectors (Li et al. 2008), and blending methods (Wang et al. 2014).

The uncertainty associated with LBCs obviously depends on the quality of the spread provided by the lower-resolution GEPS that is used to drive the REPS systems, as well as on the perturbations that are applied on these LBCs. The spread characteristics of the most widely-used GEPS are relatively well known, or at least have been examined in some details (e.g. Buizza et al. 2005). For REPS systems, it is found that LBCs have a more substantial contribution to the ensemble spread in later stages of the short-range forecasts (beyond 12h), as shown for example in Vie et al. (2011).

Perturbations to atmospheric initial conditions and to LBCs are often not sufficient to adequately represent the broad range of possible meteorological events. To improve on this, perturbations to the model itself are done. Several approaches have been used and developed for this, based on stochastic kinetic energy backscatter (Bowler et al. 2009, Charron et al. 2010, Shutts, 2005), on stochastic perturbations of model physical tendencies (Bouttier et al. 2012, Charron et al. 2010), or on a multi-model or multi-physics approach (Descamps et al. 2014, Duda et al. 2014, Keller et al. 2011).

17.2.2 Linkages

International initiatives such as the Beijing 2008 RDP (Duan et al. 2012, Saito et al. 2011) and the THe Observing system Research and Predictability EXperiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) for Limited-Area Models (TIGGE-LAM) have helped the development, research, and implementation of REPS worldwide. The scientific exchanges as part of these international activities have contributed to focus and guide the research and development required to improve current systems and prepare for the next generation of REPS, with km-scale grid spacing.

Short-range REPS are expected to be able to provide information on forecasts uncertainty which should be useful for several applications. At this point studies are under way to use REPS outputs as atmospheric forcing to other components of environmental prediction systems such as land surface forecasts and assimilation systems, hydrological systems, and precipitation analyses.

17.2.3 Requirements

The quality of the probabilistic forecasts produced by REPS directly depends on the quality of each member run, so REPS systems de facto benefit from any improvement that comes with better initial conditions (e.g. addition of new types of data, new assimilation methods) and with better forecast models (atmospheric, land surface, oceans, lakes). Moreover, as noted in Bowler et al. (2009), Vie et al. (2011), Descamps et al. (2014), and Wang et al. (2014), most REPS systems suffer from an underestimation of the uncertainty (spread) near the surface, most likely due to a lack of perturbations of surface conditions. This effect has been investigated by Lavaysse et al. (2013) who showed that perturbations to surface characteristics and variables have indeed a positive impact on near-surface spread in REPS, although they do not completely resolve the problem.

Several prototypes of local EPS with km-scale grid spacing and which could be considered as representative of the next generation of REPS are currently being developed and tested. Such examples are described in Vie et al. (2011), Leoncini et al. (2013), Bouttier et al. (2012), and Schumacher and Clark (2014). An important question is related to the added value of going to these scales, especially considering that global EPS are approaching the horizontal resolution of current regional EPS.

Other aspects that are of interest in order to improve the performance of REPS systems include the impact and role of perturbations on biases (Charron et al. 2010), the impact of data assimilation on the ensemble spread (Vie et al. 2011), and methods to extract useful information from ensembles (especially at km-scale grid spacings) (Dey et al. 2014).

17.3 NEXT GENERATION OF REGIONAL FORECASTING SYSTEMS

New modeling systems which will be responsible in the coming years for the production of numerical guidance for regional short-range forecasts are now being developed and tested over local areas for more targeted applications. Some of these systems, presented below, include subkm-scale models, km-scale ensemble systems, and coupled environmental systems.

17.3.1 Subkm-scale deterministic systems

Atmospheric systems with grid spacing on the order of a few hundred meters have been more widely examined in the last few years. Often used in mountainous and urban environments, they are an important facet of the next generation systems for regional short-range forecasting systems. National centres as well as other research institutes have run them for special events and for case studies. Their performance until now is promising, and reveal potentially substantial improvements for near-surface meteorology (related to a better representation of surface processes) and high-impact summertime weather (related to a better resolution of convective clouds).

A few examples of subkm-scale atmospheric systems include the 333 m grid spacing model that was used by the UK Met Office during the London 2012 Olympic Games (Golding et al. 2014), the 250 m grid spacing version of GEM and the 600 m grid spacing version of WRF that were used during the 2014 Olympic Games in Sochi, Russia. In Canada, a 250 m model is currently run in a real-time mode over the region of southern Ontario in preparation for the 2015 Pan American (summer) Games in Toronto. For nowcasting applications, a 500 m version of the French AROME model has been used over the Paris Charles de Gaulle airport (Hagelin, 2014).

Although benefits have been observed when using subkm grid spacing for atmospheric modeling, many aspects of the model forecasts require substantial improvements, leaving research and development associated with these themes wide open. One of these aspects that requires further and continuous improvements, still at these scales, concerns the representation of clouds and precipitation. At this resolution, the grid-scale condensation scheme (microphysics) is able to resolve in a more decisive manner the deeper convection and its organization into mesoscale convective systems, ruling out the need to parameterize these clouds. But the smaller convective clouds, such as the boundary layer cumulus and stratocumulus clouds, and even the overshooting shallow convective clouds, are still not likely to be resolved in a satisfactory manner even with grid spacings on the order of 100-200 m. There is little doubt that the schemes used to represent this subgrid-scale contribution (e.g. Belair et al. 2005) are not appropriate for these models, requiring at the very least further testing and adjustments, and very likely complete re-engineering.

Microphysical or grid-scale condensation schemes are on the other hand most appropriate at these scales. Research concerning the three-dimensional aspects of these clouds, related for instance to their interactions with atmospheric radiation (e.g. Ham et al. 2014) and with atmospheric turbulence (Bartello et al. 2010) are key questions with a potentially vast influence on the quality of numerical forecasts produced by these models.

Increasing the horizontal resolution opens up opportunities related to the representation of the surface and its interactions with the atmosphere. At subkm-scale, features related to orography, water-land fractional coverages, vegetation, and cities generate local circulations that are better resolved and sustained by the atmospheric models. These circulations include breezes, outflows, orographic flows, and thermal contrasts between different types of surfaces (e.g. water and land, rural and urban, slope effects). These opportunities are in effect putting even more stress on the specification of surface geophysical features. Based on quality and resolution, new and better databases may have to be ingested to specify the land surface characteristics. For example, databases such as CanVec (Natural Resources of Canada), the USA National Land Cover Database (NLCD, Jin et al. 2013), and the global OpenStreetMap can be used to specify urban geometric and thermal characteristics.

Another challenge is related to the proper initialization of surface variables over land and water at the appropriate resolution. At this time, land surface and ocean data assimilation systems based on variational or ensemble approaches are not typically used to produce analyses at the subkm scales. Downscaling of the surface analyses produced by systems such as CaLDAS (Carrera et al. 2015) or NCAR's high-resolution land data assimilation system (Chen et al. 2007) could be achieved based on high-resolution (subkm-scale) integration of offline surface systems such as the Canadian GEM-Surf (Bernier et al. 2011) or Météo-France's externalised surface system called SURFEX (Météo-France).

A difficulty of subkm-scale atmospheric model is the much talked-about “terra incognita” for atmospheric turbulence, as presented by Wyngaard (2004). In short, atmospheric models with grid spacing greater than a few kilometres do not resolve atmospheric turbulence. Their subgrid-scale convective boundary-layer turbulence is mostly produced by one-dimensional vertical thermal plumes. In Large Eddy Simulation (LES) models, with grid spacing of a few tens of meters, most of the thermal plumes are resolved on the model grid scale leaving smaller-scale, three-dimensional, and isotropic turbulent motions to be parameterized. The challenge with atmospheric models having grid spacing a few hundreds of meters is that they only partially resolve the larger boundary-layer turbulent eddies, making the problem of representing subgrid-scale atmospheric turbulence more difficult conceptually (Ching et al. 2014). Some recent studies have examined the scales at which atmospheric models should start using three-dimensional diffusion scheme, mostly based on the boundary-layer depth (Honnert et al. 2011, Honnert and Masson, 2014). Many others have proposed alternative (transition) methods for “gray zone” models, often involving hybrids between 1D and 3D types of turbulent schemes (Boutle et al. 2014, Shin and Hong, 2014, Zhou et al. 2014). At this point, the definitive solution for this problem has yet to be determined. The same could be said about this problem's real impact on the numerical prediction of high-impact weather.

In addition to all the physical aspects described above, there are a few numerical and dynamical aspects that have to be considered for subkm-scale atmospheric models. As it is always the case, but maybe more so for subkm-scale models, computational efficiency is crucial for these models to run in an optimal manner on large computers in order to provide their solution with a reasonable latency (Saito et al. 2012). Because of the resolution, orographic slopes in areas with complex terrain can be substantial sometimes causing crashes when it is greater then 40-50 degrees (Vionnet et al. 2015).

Finally, increase in vertical resolution should be expected in subkm-scale models. Of particular importance is the vertical resolution near the surface, and the location of the lowest atmospheric level. Having the first atmospheric level very near the surface (about 2 m) has real advantages in the solution of nighttime inversion layers, but causes difficulties both conceptual (related to the use of similarity theory for such a shallow layer) and practical (related to numerical stability). Furthermore, increase in vertical resolution near the surface can allow new approaches for coupling the land surface and the atmosphere. For instance, vertical levels could “intersect” with the vegetation canopy, allowing physical tendencies on temperature, humidity, and momentum for a set of near-surface levels instead of having the land surface impact rely solely on the provision of the lower boundary conditions to the vertical diffusion scheme (Masson and Seity, 2009, Husain et al. 2013)

17.3.2 Km-scale ensemble systems

In a way similar to their deterministic counterpart, regional ensemble prediction systems are also attempting to exploit newly-available computational power by increasing their horizontal resolution. In the last few years, a relatively large number of studies have presented widely varying approaches to optimize the benefits of using ensembles of km-scale runs (e.g. Gebhardt et al. 2011). These studies obviously benefit from the recent research and development on the numerical, dynamical, and physical aspects of km-scale atmospheric models (as described in a previous section). But the main difficulties (again) with km-scale ensemble systems remains in the methods and approaches that are required to estimate the uncertainty of short-range km-scale forecasts, including aspects related to near-surface meteorology, clouds, and precipitation.
A major difficulty regarding this objective is that currently available computational power does not allow to have km scale ensemble prediction systems that cover spatial areas as large as what is typical of operational regional forecast systems. And it limits the number of members which is usually small compared with what is used in operational REPS with grid spacing of 10 km or more. Nevertheless, positive results have been achieved in several research centres and institutes compared with km-scale deterministic systems (e.g. Bouttier et al. 2012, Schumacher and Clark, 2014). Except for a few exceptions, the perturbed initial conditions in these studies are obtained from a downscaling approach, i.e. from analyses performed at lower resolutions (Schumacher and

Clark, 2014, Duda et al. 2014, Schwartz and Liu, 2014, and Kuhnlein et al. 2014). Also, the multi-model or multi-physics approach is mostly used to represent the modeling aspect of forecast uncertainty (Leoncini et al. 2013, Schumacher and Clark, 2014, Duda et al. 2014). At this time, this approach might be the most appropriate due to the small number of members. But as computing power continues to increase in the coming years, making possible the use of a greater membership, and questions regarding the possible use of stochastic methods, such as what is presented in Bouttier et al. (2012) for instance, are likely to be of greater interest to the research and operational community.

17.3.3 Coupled systems

Through their numerical solving of dynamical fluid equations together with the use of complex parameterization schemes, current NWP systems already represent a wide range of processes going from atmospheric dynamics, to atmospheric physical processes such as turbulence, clouds, and radiation, and finally to surface processes over land, water, sea-ice, cities, and glaciers. In what might be called "traditional" NWP, the treatment of these processes is typically done in-line within the same code, with the same time step for all components (except maybe when methods such as time splitting are used), and on the same computational grid (same spatial resolution). Furthermore, these parameterization schemes are designed to optimize their impact on meteorological forecasts.

In the last decade or so, traditional NWP has been slowly transitioning towards more modular and more general numerical environment prediction (NEP) which integrates other complex models together with atmospheric models. These other models could be for atmospheric dispersion, oceans with sea-ice, waves, forest fires, hydrology, hydrodynamics, lakes, cities, and land surface. In NEP systems, distinct codes and executables could be run simultaneously and coupled (one-way or two-way). The models can be run on different computational grids with different time steps. And each model is designed for its own purpose (e.g. ocean models setup to best represent ocean circulations and variables, instead of being calibrated to minimize atmospheric errors), often with its own assimilation system.

This view of coupled modeling systems has been adopted for some time for long range applications (climate and seasonal) with the use of coupled atmospheric and oceanic models at the global scale (Palmer et al. 2004, Saha et al. 2014). It is less common however for regional or local scales. One such example is from Pellerin et al. (2004) which showed the benefits of two-way coupling between a limited-area atmospheric model and a sea-ice model over the Gulf of St. Lawrence in Canada. New coupled systems with several models running in parallel and communicating throughout their integrations are to be expected in the coming years.

17.4 CONCLUSIONS

The current status of NWP for short-range regional forecasting has been discussed in this chapter, along with the research and development themes that define these systems as they are now used operationally in several national centres, and as they are evolving into more general, more modular, and more complex NEP systems.

Research and development to improve the deterministic, ensemble, and coupling aspects of regional short-range forecasting is vibrant, as it should be for this important problem. Even with the fast evolving global forecast systems, there remains a rationale for higher-resolution (km-scale and subkm-scale) regional systems which focus on high-impact weather for certain regions of interest. As these systems move into uncharted territory, significant effort is required to optimize the benefits of representing features at these small scales.

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CHAPTER 18. URBAN-SCALE ENVIRONMENTAL PREDICTION SYSTEMS

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Abstract

Weather, climate, water and related environmental conditions, including air quality, all have profound effects on cities. A growing importance is being attached to understanding and predicting atmospheric conditions and their interactions with other components of the Earth System in cities, at multiple scales. We highlight the need for: (1) development of high-resolution coupled environmental prediction models that include realistic city-specific processes, boundary conditions and fluxes; (2) enhanced observational systems to support (force, constrain, evaluate) these models to provide high quality forecasts for new urban services; (3) provision of meteorological and related environmental variables to aid protection of human health and the environment; (4) new targeted and customized delivery platforms using modern communication techniques, developed with users to ensure that services, advice and warnings result in appropriate action; and (5) development of new skill and capacity to make best use of technologies to deliver new services in complex, challenging and evolving city environments. We highlight the importance of a coordinated and strategic approach that draws on, but does not replicate, past work to maximize benefits to stakeholders.

18.1 INTRODUCTION

From now until 2050 most population growth is expected to occur in cities and towns, especially in Asia and Africa. Urban environments are particularly sensitive to weather, air quality, climatic conditions and their variability, all of which have profound impacts, direct and indirect, on activities within cities (e.g. transportation, energy demand, construction, school access, tourism etc.) and beyond (especially if the city is of regional, national or global economic importance). Impacts also relate directly to human health and well-being, both acute (e.g. epidemics) and chronic (e.g. respiratory). Cities are also focal points for innovation driving economic and societal progress, locally, regionally and globally. Thus cities provide huge potential for mitigation and adaptation to changing atmospheric conditions, and sites where some of the greatest benefits will accrue from enhanced prediction through smarter models, data and climate services.

While urban areas range from extensive conurbations (e.g. the Pearl River Delta, Tianjin-Beijing, Yangtze River Delta, New York-Boston) to megacities (e.g. Tokyo, Sao Paulo, Jakarta, Manila, Los Angeles, Lagos) to large cities (e.g. London, Hanoi, Bangalore) to smaller urban areas, these settings have important features in common: dense populations, impervious built surfaces, significant emissions of pollutants, heat and waste, etc. However, atmospheric conditions and forcing factors vary significantly, within as well as between cities, and the needs of various stakeholders (e.g. private, public and third sector) for services, advice and warning, in terms of information and tools, differ considerably too. These factors must be recognized in the development of weather, climate, water and related environmental services in cities.

A number of recent reports have considered what is needed to enhance predictive capabilities for urban areas (e.g. Fisher et al. 2005, Martilli 2007, Hidalgo et al. 2008, Baklanov et al. 2009, Grimmond et al. 2010, 2013, 2014, National Research Council 2010, 2012, Zhu et al. 2012/2013, Dabberdt et al. 2013, Pelling and Blackburn 2013). This chapter, informed by these recommendations, considers the needs to improve model development and predictive capability.

18. 2 MODELLING PHYSICAL PROCESSES IN THE ATMOSPHERE

18.2.1 Background

Operational mesoscale numerical weather prediction (NWP) models in many national meteorological services are now being run at grid lengths of the order of a few km. At this scale, urban effects of larger cities can be seen, albeit crudely. For example, operational forecasts are run at 5 km (Japan Meteorological Agency (JMA), Japan), 3 km (National Centers for Environmental Protection (NCEP), continental USA), 2.8 km (Deutscher Wetterdienst (DWD), Germany), 2.5 km (Météo-France; Danish Meteorological Institute (DMI), Denmark; Environment Canada (MSC) Canada (south-west region)), and 1.5 km (Met Office, UK); with some including urban land surface schemes (e.g. Masson 2000, Best 2006, Mahura et al. 2008, Seity et al. 2011, Lane 2014).

Cities influence atmospheric flow, its turbulence regime, and create distinct microclimates which modify the transport, dispersion, and deposition of atmospheric constituents, both within and downwind of urban areas. Key urban features include the:

- Distribution and shape of roughness elements (notably buildings and trees) which affect the turbulence regime, speed and direction of the flow, as well as radiative and thermodynamic exchanges between different surface elements and the atmosphere.
- Extensive surfaces of impervious materials, with these and the concurrent reduction of vegetation and exposed soils affecting the hydro-meteorological regime and aerosol deposition.
- Release of anthropogenic heat by human activities (e.g. from vehicles and buildings) which affect the thermal regime.
- Release of pollutants (including aerosols) which affect radiation transfer, formation of clouds, and precipitation within the city and beyond.

The net result is a series of distinct urban weather, climate and related environmental features. The most well-known of these is the urban heat island - warmer urban canopy air temperatures than in nearby rural areas - that are most pronounced a few hours after sunset. Such thermal differences can influence regional air circulation.

Some of the features listed above are included in current numerical weather prediction models, but with higher resolution coupled systems the challenge is to greatly improve the precision and scope of predictions.

18.2.2 Underpinning research

NWP models make use of a wide range of urban land surface models (ULSM). These ULSM are undergoing rapid development and enhancement, and have been the focus of recent systematic evaluations (Grimmond et al. 2010). While existing ULSM include very different levels of complexity, currently no one scheme performs best for all surface exchanges, so significant scope for improvement remains (Grimmond et al. 2011, Best and Grimmond 2015).

Inclusion of ULSM in mesoscale models has improved performance both experimentally (e.g. Mahura et al. 2008, Porson et al. 2010, Trusilova et al. 2013, Leroyer et al. 2014) and operationally (e.g. Best 2006, Lane 2014). The challenge of modelling urban canopy processes is complicated by the increasing resolution of atmospheric models. Current research involves mesoscale models being run at greater spatial resolution than the operational scales (e.g. Chen et al. 2011, Bohnenstengel et al. 2012, Loridan et al. 2013, Masson et al. 2013, Schoetter et al. 2013, Leroyer et al. 2014, Lean et al. 2015). These models are capable of simulating obstacles and meso-scale features (Martilli et al. 2007, Baklanov and Nuterman 2009, Schlünzen et al. 2011). Routine experimental runs include the UK Met Office's 300 m model for Greater London (Boutle et al. 2015) and Environment Canada's 250 m NWP for Greater Toronto (Leroyer and Bélair 2014).

18.2.3 Linkages

Higher resolution numerical prediction models are being applied to applications such as air quality (AQ), chemical dispersion, urban hydrology and ocean models (for coastal cities). For example, the 250 m Environment Canada NWP model may contribute to the 2.5 km grid AQ forecasts for Greater Toronto in the context of the PanAm 2015 games.

By modelling at ≤1 km scale, models will require more detailed surface fluxes and will resolve more atmospheric physical processes, which will result in different requirements for sub-grid parameterizations. At such scales, more advanced microphysics schemes may be required and deep convection schemes may be deactivated, although that does not mean convection is perfectly represented (Stein et al. 2014). A fundamental issue is the need to better understand the behaviour of high-resolution NWP models as they start to resolve turbulence (the so called grey zone) so that the complementary role of sub-grid scale vertical mixing schemes may be revised (Honnert et al. 2011). In this regard, many lessons can be learnt from the LES (large eddy simulation) community. An example of the issues that may be encountered is the serious spin-up effects often observed as air enters the domain of ~100 m resolution models and spin up turbulence (Munoz-Esparza et al. 2014).

Evaluation of new models need to draw on observations, from the real world and laboratory studies (e.g. wind tunnel, water tunnel), and from higher resolution and more detailed numerical studies (e.g. DNS - direct numerical simulation). Consequently, different research communities need to work closely together to ensure that these data are collected appropriately and used effectively. Data mining of such rich data sets will be necessary to improve the understanding of the processes that are modelled.

18.2.4 Requirements

Careful analysis of all elements in integrated forecasting systems is required to define their importance, priorities, and needs for different applications. More research on the resolution required to provide suitable descriptions of urban effects for different applications (e.g. urban weather, pollution, climate comfort) is necessary.

Higher resolution NWP, combined with the presence of more tall buildings in many cities, challenges the limits of current understanding. Key questions that need attention include: do buildings need to be directly resolved in these models? What simplifications are appropriate to make the computations tractable in realistic modelling time? At what scale can the current land surface schemes and model physics be applied? When does the model type need to be changed and the traditional RANS (Reynolds Averaged Navier Stokes) models be replaced by LES models?

Higher resolution models will also require a great deal of development of the representation of the urban surface. Given current projections of computer power, it will still be many years before models can resolve buildings (i.e. be equivalent in resolution to current street scale CFD/LES/DNS modelling (computational fluid dynamics/large eddy simulation/direct numerical simulation)) for any reasonable sized city. This means that a key challenge moving forward will be the "building grey zone" (analogous to the often discussed convection grey zone) where buildings are not resolved but the assumption, in lower resolution surface schemes, that there are many in each grid-point also breaks down.

To improve model evaluation, a wider range of laboratory and CFD/LES/DNS studies are needed with structures that more closely resemble cities rather than idealized homogenous arrays. These are needed particularly to inform model development for urban Roughness Sub-Layer (RSL) turbulence. Higher resolution models will also mean that the vertical extent of buildings will have to be considered, with schemes correctly distributing effects of buildings on heat fluxes, drag etc. over the lower parts of the boundary layer (e.g. Masson 2000, Martilli 2007, Baklanov et al. 2008, Chen et al. 2012, Santiago et al. 2013, Husain et al. 2013), in conjunction with a number of other processes.

There is also a need to improve understanding of dynamically changing land cover for model parameters. Cities are dynamic, new structures are built and there is ongoing repair and regeneration of older buildings (e.g. new roofs, painting or resurfacing of walls, roads, green infrastructure), as well as growth and management of vegetation etc. These all affect the micro-scale features of the surface. Methods need to be developed to gather this information in a routine manner, ingesting the spatially explicit parameters appropriate to models.

Research is required to advance coupled models that simulate the feedback between human activities (e.g. energy use in buildings, traffic) and urban environmental conditions (e.g. air quality, anthropogenic heat fluxes). Multi-scale modelling will allow more thorough investigations into the effects of large-scale atmospheric turbulence on the neighbourhood or micro-scale turbulence below the canopy levels. These tools need to be more thoroughly developed for a wide range of applications (e.g. the interaction between natural and built areas; human comfort; building energy consumption; and urban design).

Furthermore, research is needed to better understand the air quality weather feedbacks at urban scales, and how sensitive predictability is to the complexity of the representations of these feedbacks. Research is also needed to further develop and evaluate data assimilation methods to support coupled prediction systems.

18.3 CHEMICAL MODELLING IN THE ATMOSPHERE

18.3.1 Background

Cities emit significant amounts of pollution into the atmosphere which can result in poor air quality and large negative impacts on human health (notably in megacities, such as Beijing and Delhi). The pollutants usually result from urban transport, power generation, industry, and various cooking and heating activities. They have effects on the environment and are harmful to health. However, this pollution is not confined by city boundaries but is transported over large distances and contributes to regional and even hemispheric background pollution (Anenberg et al. 2014). Many of these pollutants, along with greenhouse gases like CO_2, can also influence weather and climate directly and indirectly.

Urban air pollution involves both primary and secondary pollutants, and can occur throughout the year. Meteorology and emissions play important roles, which are not fully understood. For example, the rise in winter haze events in east China is thought to be influenced by changes in emissions and trends in temperature and relative humidity (Wang et al. 2014).

Due to the large impacts of urban air pollution on human health, and disruptions to transport and other services during haze episodes, more and more cities around the world are expanding their air quality forecast services. The demand for, and diversity of, services using air quality prediction systems (including health alerts and emission reduction management planning) are placing increased requirements for more model products and at higher spatial resolution. In addition, the need to also address climate services expands the scope of the prediction systems to include greenhouse gases and radiative forcing due to greenhouse gases and short-lived climate pollutants (e.g. black carbon).

18.3.2 Underpinning research

A number of recent international studies have been initiated to explore these issues[a]. These aim to assess the impacts of megacities and large air-pollution hotspots on local, regional and global air quality; to quantify feedback mechanisms linking urban air quality, local and regional climates, and global climate change; and to develop improved tools for predicting air pollution levels in cities. The sources and processes leading to high concentrations of the main pollutants, such as ozone, nitrogen dioxide and particulate matter, in complex urban and surrounding areas are not fully understood. This limits our ability to forecast air quality accurately. Air quality prediction is strongly dependent on the estimates of emissions. Emissions impacting urban environments include those related to transportation, power generation, industrial, and cooking, heating and cooling. But wind-blown particulates and smoke from forest and agricultural fires also need to be considered. Air

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[a] *See MILAGRO (www.mce2.org), MEGAPOLI (http://megapoli.info/), CityZen (wiki.met.no/cityzen/start), ClearfLo (www.clearflo.ac.uk), WISE (Seoul), and SUIMON (Shanghai). A comprehensive worldwide overview of impacts of megacities on air pollution and climate and corresponding projects is available at WMO/IGAC (2012).*

quality forecasting activities place additional demand on the emission estimates, including representing near-real-time estimates of the contributions from fires and dust outbreaks. Substantial work has been done in recent years on emission estimates (e.g. Vermote et al. 2009, Kaiser et al. 2012). Comparison of three major global emissions inventories, alongside two city-level inventories, showed that the sources and degrees of emissions vary hugely between megacities, in particular, by geographical region (van der Gon et al. 2011). For example, much of the megacity emissions in Europe and the Americas are associated with traffic and road use, whereas in Asia and Africa the output currently largely stems from residential energy use.

Secondary air pollutants (e.g. ozone, and secondary inorganic (e.g. sulphate) and organic aerosols) can be major components of air pollution in urban environments. Improving the understanding of secondary aerosol formation has been an active research area, and improved treatments are now being incorporated into air quality models (Tulet et al. 2006). But more work is needed. Other research relates to aerosol interactions with clouds and radiation, data assimilation that includes chemical and aerosol species, dynamic cores with an efficient multi-tracer transport capability, and the general effects of aerosols on the evolution of weather and climate. All of these areas are concerned with an optimal use of models on massively parallel computer systems.

The numerical models most suitable for integrated operational urban weather, air quality and climate forecasting systems are the new generation of limited-area models with coupled dynamic and chemistry modules (so called Integrated Meteorology-Chemistry Models, IMCM). These models have benefited from rapid advances in computing resources, along with extensive basic science research (Zhang 2008, Baklanov et al. 2014).

Current state-of-the-art IMCMs encompass interactive chemical and physical processes, such as aerosols-clouds-radiation, coupled to a non-hydrostatic and fully compressible dynamic core that includes monotonic transport for scalars, allowing feedbacks between the chemical composition and physical properties of the atmosphere. These models are incorporating the physical characteristics of the urban built environment discussed earlier. Recent studies have shown that the effects of the built environment, such as the change in roughness and albedo, the anthropogenic heat flux, and the feedbacks between pollutants and radiation, can have significant impacts on the air quality levels (compare Yu et al. 2012, 2014).

However, simulations using fine resolutions, large domains and detailed chemistry over long time durations for the aerosol and gas/aqueous phase are computationally demanding given the models' high degree of complexity. Therefore, IMCM weather and climate applications still make compromises between the spatial resolution, domain size, simulation length and degree of complexity for the chemical and aerosol mechanisms.

A typical model run at the weather scale for an urban domain uses a reduced number of chemical species and reactions because of its fine horizontal and vertical resolutions, while climate runs generally use coarse horizontal and vertical resolutions with more detailed chemical mechanisms (Barth 2007). There are initiatives to expand the air quality related services of large forecast centres. For example the MACC-II - Monitoring Atmospheric Composition and Climate - Interim Implementation - project[b] served has the pre-operational atmosphere service on the global and European scale, which is now being transitioned to operations. This activity could be extended and downscaled to megacities and urban agglomerations. This approach has successfully been applied in the research community and shows very local impacts within hot spots. However, a seamless prediction from global to local scales has not been achieved.

Large uncertainties remain in the predictions of air quality. Multi-model ensembles show promise in improving prediction skill (Zhang et al. 2012).

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[b] http://www.gmes-atmosphere.eu/

18.3.3 Linkages

The incorporation of urban effects into air pollution models is generally carried out through the "urbanisation" of meso-meteorological or NWP models (which act as driver models), or using special urban meteo-pre-processors to improve non-urbanised NWP input data. This is also the case in air pollution assessment studies following, for example, European directives (e.g. BMU, 2002).

The increasing resolution in NWP models allows more realistic reproduction of urban air flows and air pollution, and triggers interest in further experimental and theoretical studies in urban meteorology.

18.3.4 Requirements

Modelling air quality and chemical dispersion in the urban area will require improved modelling of the bio-geophysical and chemical features of the land surface and consequent exchanges of heat, moisture, momentum, radiation (the surface energy balance) and pollutants with the urban boundary layer (UBL). Research with CFD/LES/DNS codes jointly with physical modelling (wind tunnel experiments) will allow improved understanding of wind and pollutant transport in regimes other than skimming flow and with combined effects of wind and buoyancy. Research is needed so more realistic air pollution chemistry mechanisms can be incorporated into the models.

Of particular importance is the need to better represent local, time-dependent pollutant emissions. There are currently large uncertainties in urban-scale emissions that increase at higher resolutions. Additional demands are placed on the emissions inventories for use in forecasting activities, as such applications require up-to-date daily emissions. Emission inventories available for use in forecasting are typically produced using a bottom-up approach relying on statistics that are several years out of date. Continued efforts are needed to improve emission estimates needed by air quality prediction systems, and increased efforts are needed to design and incorporate emissions modelling/forecasts (especially those that are weather dependent) as a component of seamless prediction. The use of observations from satellite to rapidly update emissions is an area of active research (Streets et al. 2013).

Computational constraints have led to meteorological models being run at higher resolutions than chemical composition models. In the future, higher resolution chemical composition runs need to be evaluated. Some tests suggest resolutions below 1 km do not show clear improvements (e.g. Saide et al. 2011). This could relate to the dynamical model which was not built for such high-resolution. Investigations are needed to achieve better performance at fine resolutions.
Different levels of chemistry sophistication are needed for different applications of urban integrated service modelling systems, e.g. for urban air quality, NWP and climate studies. Building on the tools and ongoing studies at different scales, often by distinct communities (weather/chemistry /AQ/Climate), studies are needed to provide guidance on the level of application awareness required at different scales, given the cost of including chemistry and aerosols in models. Likewise, guidance on prioritization of what is feasible, in what timeframe and within the context of regional issues (e.g. China vs Europe/North American AQ levels) would also be valuable. Further coordination between ongoing activities such as those taking place in ICAP (International Cooperation fore Aerosol Prediction), where real-time comparison of global models and ensemble forecasts with aerosol representation are being undertaken, and the WGNE (Working Group on Numerical Experimentation) aerosol project are relevant examples.

Air quality services are being established in cities around the world, often stimulated by high-profile events (e.g. Olympics, Expos, etc.). Increased efforts to support and transfer knowledge gained from these efforts are needed so that lessons learned can be applied to other cities as they plan to initiate or expand urban-related services. The establishment of formal test-beds and legacy projects are possible mechanisms to support knowledge exchange.
Satellite retrievals of atmospheric constituents at urban scales are becoming available (e.g. 1 km, Lyapustin et al. 2011) and are being used (e.g. Hu et al. 2014). However, they are not yet assimilated into models to improve predictions.

18.4 MODELLING URBAN HYDROLOGY

18.4.1 Background

A majority of the world's major cities are situated adjacent to water - either the sea or a major river or both. The building of cities disrupts the normal hydrological cycle of the land surface, creating impervious surfaces and culverted drainage networks, and modifying larger water courses through straightening, dredging, enclosing and damming. Cities depend on water for drinking, hygiene, manufacturing, power generation, waste disposal, heating and cooling and many other services. When there is too much or too little water the consequences can be very serious.

Floods are a recurrent hazard in many cities. Urban flooding may arise from windstorms that generate storm surges and storm waves. In October 2012, Superstorm Sandy raised a storm surge of up to 3 m along the eastern seaboard of the USA. This was sufficient at high tide to raise the sea level above the height of the sea defences, so that the waves of up to 6m, generated by the onshore winds, could run straight over the land, demolishing buildings and infrastructure for many km inland (Alves et al. 2015, Sullivan and Uccelini, 2013). Considerable damage was caused in New York from this combination of ocean surge and waves. The threat from storm surges is not confined to open ocean coastlines. Some of the most damaging surges have occurred on coastlines bordering semi-enclosed seas such as the North Sea between the Netherlands and the UK (Heaps, 1983). Cities on lakes with no tides may be built with little protection, so that a change in wind climate could lead to frequent damaging floods.

River flooding is a recurrent threat to a large proportion of major cities in all climates. Large rivers gather water from vast areas of land through networks of tributaries. Floods may be caused by unusually large amounts of rainfall or snowmelt in distant places, may be the result of unusual phasing of more modest amounts from multiple sources, or may occur due to extreme precipitation in the region of the city itself. In August 2011, flooding in rural areas of Thailand produced a massive flood that propagated down the Chao Phraya river inundating Bangkok for a period of several months (Nabangchang et al. 2015, Trigg et al. 2013). In 2009 torrential rain in Ouagadougou, amounting to a quarter of the annual average rainfall, produced a huge flood in the river destroying a dam in the reservoir in the city and forcing more than 100,000 residents to flee.

In the case of locally intense rainfall, smaller water courses and surface water flooding may be as important as the main river (Falconer et al. 2007). Whereas it may be clear which areas are at risk of flooding from major rivers, enabling defences to be constructed, flooding from local extreme rainfall will occur wherever the local natural and/or artificial drainage channels are overwhelmed, leading to flash flooding and landslides in steep topography and ponding of water in low areas, including underground shopping malls and transport corridors.

18.4.2 Underpinning research

Current hydrological forecasting capabilities depend on the use of a large number of tools developed for specific requirements (Sene, 2008). In the future there will be a move towards modelling the water cycle as an integrated whole, including water in ice, liquid and vapour phases, in the atmosphere, on the land surface, under the land surface and in the ocean. Climate models already deal with many parts of the cycle, but this integration is currently not well developed for weather forecasting timescales. In the atmosphere, the most intense rainfall is associated with convective storms, either in isolated forms or embedded in fronts and tropical cyclones. The latest generation of km-scale NWP models is able to reproduce the observed convective rainfall intensity on timescales of relevance to flood forecasting (Lean et al. 2008). However, the details of location, timing and intensity of such predictions are highly sensitive to details of the initial state, model parameterizations and representation of the surface topography, so that probabilistic prediction appears to be essential. Development of km-scale probabilistic prediction schemes is at an early stage and much more work is needed on all its aspects (Clark et al. 2010, Vie et al. 2011, Peralta et al. 2012).

Modelling the run-off in urban areas is an area of hydrology that needs considerable development. Conventional rainfall-runoff models are designed for rural land surfaces and do not take account of the routing of water by gutters, buildings or drains. Surface inundation models are designed mainly for prediction of flooding from river overtopping or breach and need further development for use with direct rainfall inputs. Drainage models deal with the highly important sub-surface water flows, but often with only a crude representation of the surface. In all of these models, the representation of sediment and detritus washed from flooded land upstream is excluded. There are major challenges to developing flood models that can include an affordable and consistent level of complexity across these different aspects (see e.g. Butler and Davies, 2010, Hedonin et al. 2013). Modelling coastal flooding from storm surges and waves has a long history in many susceptible locations. However, achievable resolutions have until recently limited such predictions to offshore conditions, from which the risk to the coastline must be inferred. New developments in variable grids, and improved physics, coupled with increased computation power are now allowing such models to forecast conditions in the surf zone, enabling a much more direct assessment of the risk of overtopping and breach of coastal defences (Alves et al. 2015). Models have been developed that integrate surge, waves and inundation across the coastline (e.g. Li et al. 2014). Achieving this in real-time forecasting will permit assessment of impact and hence of risk to be much more effective and localised.

Bringing all of these advances together so as to be able to predict the risk to inhabitants of a megacity will take many generations of modelling systems and new capabilities in observing and monitoring.

18.4.3 Linkages

Predictions of flooding from ocean surges and waves depend on detailed modelling of the interaction of ocean with coastal bathymetry. In many areas of the world the bathymetry changes as currents move sediment around the sea floor, especially during storms. Similarly, beaches and dune systems are an important component of the coastal defences of large areas of land, but these change with human activity and with waves action, especially in storms. In both areas there are requirements both for monitoring and updating of the models and for representation of the dynamical interactions during storms.

Predictions of flooding from rivers depends on knowledge of the upstream river network - the cross-section of the river, the sediment in its bed and carried in the stream, the vegetation etc. These change through the seasons, due to human activity, and due to storm water flows. A concern in many rivers is the likelihood that the river will change channel or create a new channel during a storm, leading to dramatic changes in the areas at risk from overtopping.
Predictions of flooding from surface water, piped drainage and minor water courses depend critically on the (three-dimensional) topography of the urban landscape, which can change extremely rapidly. The presence of obstacles in gulleys or culverts can instantly divert water streams, while collection of detritus will modify the conveyance by piped drainage or water courses. These effects are not predictable and nor are they completely observable, so a stochastic approach to their representation seems likely to be needed.

Interactions between the different types of flooding are important. Tides and surges raising water levels in estuaries are a key contributor to flooding by rivers due to the restriction of outflow. This is well illustrated by the Thames Barrier which is more often used to restrict upstream propagation of a surge during high river flow conditions for this purpose than it is to protect London directly from a storm surge (Mikhailov and Mikhailova, 2012). Both surges and high river conditions can cause back flows in minor water courses and restrict outflows from sewers, leading to upstream flooding. These effects can only fully be dealt with in a completely coupled flood prediction system.

18.4.4 Requirements

Flooding and related land slippage is one of the most disruptive natural hazards in urban areas. City management requires fore-knowledge of the area likely to be affected, the level of impact, and its duration, so as to be able to plan resources allocations and to prioritise responses so as to enable the continued functioning of the city as a whole (e.g. Speight et al. 2015). Individuals need to know the threat to them, their property and the infrastructure they depend on, so as to choose appropriately between evacuating, protecting and riding out the storm. In the case of some infrastructure impacts, such as roads, power and water supply, the flooding may not be local to those affected, making the communication process particularly difficult. An extreme example is the need to deter evacuation from low risk areas that on evacuation routes through areas of high flood risk.

The risk posed by flooding depends primarily on its depth, the water speed, and the duration of its stay. Water speed is the primary determinant of fatalities, not only due to drowning of individuals, but to vehicles being swept into water courses, and due to undermining and destruction of occupied buildings. Duration is significant in cutting people off from the resources needed to keep them alive - particularly, food, water and heating - and due to the growth and spread of disease. Advanced knowledge of the locations where the risk from such impacts is highest can enable both self-protection activities, such as sand bagging entrances and stocking up on food, as well as deployment of central city resources, such as pumps, boats, water tankers, generators, satellite communications etc, that might be difficult to move through the streets once floodwater has flowed through them carrying vehicles and other detritus with it.

The timescales for such deployments are critical for the usefulness of forecasts. Having sufficient staff resources to deploy will generally depend on a forecast before the end of office hours the day before the flood, while accessing equipment and getting them to the right places will require several hours. In the event of a major disaster, if support from outside the city will be required, several days warning of that level of impact will be needed. In contrast to these needs, the precise location and intensity of convective precipitation is currently predictable for only an hour ahead at best, while totals from organized bands of precipitation may be reliably predictable up to 12 hours ahead. While improvements to these capabilities will not doubt be achieved, the discrepancy indicates that decisions will need to be made predominantly on probabilistic information. This has major implications for the focus of development of prediction tools as well as in challenging the communication of information so as to achieve the most effective responses.

18.5 OBSERVATIONS TO SUPPORT URBAN-SCALE ENVIRONMENTAL PREDICTION SYSTEMS

18.5.1 Background

To evaluate model performance, improve model algorithms and provide data for forcing or assimilation, observational data are needed. Operational urban networks (within and around a city) need to be installed with attention to the optimal balance between resolution, resources and practicality. Such observational networks need surface-based instrumentation (e.g. soil moisture and air/soil/surface temperature, rainfall) and vertical profiles (from within the deep urban canopy layer to the top of the boundary layer) of temperature, humidity, wind, turbulence, radiation, air quality (gases and particles, precursors and secondary), reflectivity and refractivity.

As urban areas become larger, buildings often become taller. This is particularly the case in rapidly urbanising Asia. In Shanghai, for example, in 2012 there were >100 buildings taller than 30 stories, with one building (the second tallest building in the world) > 630 m tall (Tan et al. 2015). Such tall buildings, individually or clustered together, have implications both for the measurement of atmospheric variables and for the contexts for which the data are needed (e.g. the ability to predict conditions at a range of heights; a fire and smoke at floor 15 of at 30+ storied building disperses differently to a fire on floor 2 of a 3 storey building). As a consequence, new technologies are needed to gather observations in places where currently measurements are challenging or not possible at all. Investments are needed in conventional instrumentation, alongside high density sensor networks, mobile platforms, new remote sensing techniques and other data sources (e.g. real-time information from mobile phones and on-board computers in cars etc.), to enable improvements in technology to observe places and processes that currently are difficult. This also needs to include design and better integration of satellite observing systems.

Observations of the spread of flood water pose particular challenges in an urban environment. Flood extent is often monitored with aerial photography, but the urban canopy severely restricts the view and sub-surface flooding is not accessible to such approaches. Flow and level cam be monitored in drainage pipes, but these measurements rarely give good information once flooding starts. The potentially widespread nature of urban flooding makes it difficult to adequately monitor a city with in situ instrumentation, though developments in the "Internet of Things" make cheap ubiquitous sensing a possibility for the future (e.g. Holler et al. 2014). Alternatively, crowd sourcing of flood information may provide the information required.

18.5.2 Underpinning research

Detailed guidance for observations, based on theoretical knowledge and experience gained from past studies, is available for standard urban surface observations (WMO 2008, see Chapter 11, https://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html). However, numerous challenges exist in undertaking observations in the urban environment in many real world settings (e.g. Grimmond 2006, Barlow 2014) and using hardware models (e.g. Kanda 2006).

With an air quality focus, extensive field experiments in cities have provided highly resolved airborne and ground-based measurements (e.g. http://discover-aq.larc.nasa.gov/, Discover-AQ in Baltimore-Washington, California, Texas, Colorado). These studies have posed challenges to existing models, which are not able to resolve much of the fine structures measured nor to accurately predict pollution formation mechanisms. Future work needs to be undertaken utilizing these existing high-resolution datasets to keep advancing urban-scale models.

Satellites data are an important source of information for urban areas providing information on land use and other attributes (e.g. Jensen and Cowan 1999, Yang et al. 2003), population density (e.g. DeSherbinin et al. 2001) surface temperatures (e.g. Dousset and Gourmelon 2003), hydrology (e.g. Weng 2014) and atmospheric composition (Streets et al. 2014). Satellite derived data provide an effective way to track dynamic changes in the form (e.g. addition of taller buildings, Gamba et al. 2006) and materials (e.g. change in cladding, use of cool materials etc, e.g. Kotthaus et al. 2014) of cities. However the data often remain coarse and data at the building scale rarely are available. With a number of geostationary satellites set to launch in the next few years, the potential enhancement for a wide variety of purposes including AQ and chemical forecasts (Saide et al. 2013, Streets et al. (2014).

Most current urban observational networks fall into two groups: long-term measurements for a very limited number of variables or stations and short-term (or specific event) measurements of multiple variables for a large number of stations extending across an urban area. The former provides better data for model evaluations across seasons; the latter insights into spatial heterogeneity of urban influence and a better understanding of relations between meteorological variables. Short-term field experiments and wind tunnel studies also have been used successfully (Klein et al. 2007, 2011; Wood et al. 2009, Leitl et al. 2014). Very few urban areas are equipped with 4D measurement networks. Exceptions, include combinations of in situ surface and mast observations with radar in Hamburg (Wiesner et al. 2014), Light Detection and Ranging (LiDAR) in London (Bohnenstengel et al. 2015), and both in Shanghai (Tan et al. 2015) and Helsinki (Wood et al. 2013). More of these are needed for research within an operational context as only the latter two examples are run by meteorological agencies.

Evaluation of meteorological models using observations traditionally has been conducted in two modes: off-line (i.e. stand-alone ULSM) and on-line. In off-line mode, observations or an operational or coarser meteorological model provide the atmospheric forcing. Evaluations require verification of the urban surface description used as model input and the representation of physical processes (Leroyer et al. 2010, 2011, Grimmond et al. 2011). Analyses for several locations and variables provide the best insights into compensations of model errors or hidden meteorological features. Assessments of the performance of models does depend on the variables considered (e.g. Loridan et al. 2013) and model resolution (e.g. Leroyer et al. 2014), with differences being related to different physics in the schemes (e.g. convection representation Leroyer et al. 2014). This highlights the importance of nested observations of physical and chemical variables to ensure that complete urban environmental prediction systems are evaluated as well as components models.

18.5.3 Linkages

Improvements of urban observational networks need to be closely linked to those in the region; the greatest benefits will come from coordinated nesting of observations (Dabberdt et al. 2013). Attention needs to be directed to the full range of modelling work that needs to be undertaken (and addressed elsewhere in this document); *viz*, improving physical, chemical and other application models, engaging the full suite of stakeholders and end-users. Given the difficulties of obtaining urban observations, collaborative data collection and mining (e.g. site provision, combined data systems) should aid all partners.

Another key linkage involves connecting the research community and citizen scientists. The research community are driving forward many model improvements that are needed (see other sections in this chapter), while citizens are becoming important providers of meteorological information (crowd-sourced data). For example, the Weather Observations Website (WOW) (http://wow.metoffice.gov.uk/), the Weather Observer Program (CWOP, http://www.wxqa.com/), and the Community Collaborative Rain, Hail and Snow CoCoRaHS network for precipitation (http://www.cocorahs.org/) all gather data, both currently and historically, that can be used to enhance modelling skill. Similarly, data from less traditional sources (e.g. mobile phones, Overeem et al. 2013) are likely to permit data collection in places not possible previously. These new data sources present major challenges for those involved in gathering and managing data. The use of this potentially transient data, with appropriate quality control, will yield useful data only through the combination of new data-mining techniques but also a good understanding of urban meteorology and atmospheric chemistry. If this expertise does not draw upon much of the rich history of study and understanding (which extends back at least over two hundred years e.g. Howard 1818) there will be unnecessary reinventing, relearning, and missed opportunities.

18.5.4 Requirements

To enhance seamless predictions in urban areas it is widely accepted that there is a need for long-term, multi-site urban observation networks reporting traditional meteorological variables, fluxes, and the vertical state of the physical and chemical properties of the atmosphere (e.g. Grimmond et al. 2010, National Research Council 2010, 2012). Advances are needed to develop methods and frameworks to analyse atmospheric data measured above and within complex urban surfaces. This needs to include attention to measurement source areas to ensure representative results and meaningful comparisons with models. Much more needs to be known about the outer layer of the urban boundary layer (UBL), the atmosphere above the ISL (inertial sub-layer). Further research is needed on the relation between urban morphology and flow (and exchanges) within the canopy, directly above, and with the UBL. Research is also needed to better understand the coupling of surface and air temperatures. Similarly, there is a need to improve our understanding of ventilation and pollutant removal mechanisms (vertically and laterally) for three-dimensional street canyons.

Design of observation networks, for multiple-scales of interest from a larger region to the key areas of particular interest will be essential to improve model prediction times for extreme events. Research is needed on appropriate densities for such networks, including provisions for redundant information. Both the physical and chemical characteristics of the atmosphere need to be considered. Risks associated with exposure (e.g. to air quality, heat, intense precipitation) need to be better understood and taken into consideration in providing climate services. This needs to be explored as part of network design. Given network expansion and operations can be costly, these need to optimally designed.

Given the potential range of new measurement approaches and the diversity of settings for siting of such instruments, appropriate metadata and protocols must be developed and reported. This will enable the data collected to be used appropriately for wide-ranging applications (e.g. the needs of those interested in wind loading on a building are markedly different to data to force operational weather models). Smart protocols, to address data quality control, siting and metadata, can help to ensure all users are served well with the potential wealth of urban data. Better information on the urban surface is needed to provide site metadata for observations and as input for urban models. Improved methods are needed to determine key urban surface characteristics; for example, material radiative (e.g. albedo, emissivity), thermal (e.g. heat capacity) and water (uptake and storage) properties. Soil characteristics and ground water conditions need to be known along with vegetation types and their biophysical status. Remote sensing techniques need to be developed so that additional data sets for modelling urban areas are available (e.g. time dependent leaf area index, soil moisture for dense urban areas, Ye et al. 2011). In addition, enhanced spatial resolution and/or improved algorithms to deal with the challenges of the range of urban materials found in small areas, combined with their complex geometries (e.g. creating shadows, mixed pixels) are needed. Given the rapid changes that occur in many urban settings (associated with development and redevelopment), methods to facilitate timely updates also are important. Current activities associated with the WMO Integrated Global Observing System (WIGOS[c]) and WMO Information System (WIS[d]) could be of assistance in supporting urban-related data needs and management.

Methods need to be developed and evaluated to enhance the suite of variables that are directly modelled and directly observed (e.g. surface “temperatures”, structure function parameters). This requires advances in both modelling and observations. These variables need to be measured over extensive spatial domains (e.g. remotely sensed) and address assumptions to yield the “observed” or ‘modelled’ data, given the challenges and complexity of the urban surface.

The impact of the patchwork of changing densities and heights of buildings (and trees) across the city needs to be much better understood. This requires advances in measurements of the mean and turbulent characteristics of the urban atmosphere in such settings. For example, Doppler LiDAR misses the lowest 90-100 m; SOnic Detection And Ranging (SODAR) is too noisy in urban areas. Attention is also needed to how to model the processes occurring within and above tall urban surfaces. DNS and LES currently require too much computational resources to undertake realistic simulations for extensive areas, i.e. to yield realistic surface temperature forcing, stabilities, and there are minimal data for evaluation of model results (e.g. extensive atmospheric and surface measurements of radiation, temperature, wind, chemical concentrations, horizontally and vertically within tall urban canyons). Moreover, instrumentation needs to be developed and deployed to sample this environment at rates that are compatible with the modelling.

Observations are needed for a larger range of urban land uses (morphologies) to establish universal flow and flux characteristics. Existing long-term measurement stations need to be preserved to enable broader spatial representativeness of frequent, rare and extreme urban phenomena. Simultaneous measurements of flow properties at various sites/levels are needed to better understand coherent structures and intermittent ventilation processes within the RSL.

To improve the understanding of air quality and greenhouse gases, measurements of fluxes of greenhouse and other gases and particles need to be undertaken. These need to be combined with isotopic and chemical fingerprint analysis to determine not only the magnitudes of these fluxes but also to identify emission sources (e.g. background concentration, gasoline combustion, natural gas combustion and respiration).

Anthropogenic gas, heat and moisture emissions need to be better quantified by improved measurement and estimation techniques at a range of scales. The individual building scale permits closure of budgets (e.g. energy) for a control volume and is the scale for much decision-making. For applications and future model development, model evaluation and integration of physical and chemical processes at this scale will need nested observations down to this scale. Given the immense size and variations in tall buildings in cities, there are many challenges that need to be overcome.

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[c] http://www.wmo.int/pages/prog/www/wigos/index_en.html
[d] http://www.wmo.int/pages/prog/www/WIS/

Hydrological processes, including precipitation patterns, soil moisture, evaporation rates and runoff are spatially variable across a city. Enhanced knowledge of these patterns, as precursor conditions for intense rainfall events, is needed to enhance the provision of weather and climate services to predict and respond to hydro-meteorological events that can be life threatening (e.g. intense precipitation, flooding). The influence of cities on precipitation patterns has been (e.g. Lowry 1998) and remains an area of intense research need (e.g. Han et al. 2014).

People spend a large amount of their daily lives indoors, yet the interaction of atmospheric conditions indoors and outdoors is poorly understood. Ingested air impacts the comfort, health and operations of the buildings. Greater knowledge of actual in situ conditions can reduce energy usage and CO_2 emissions. Consideration of external emissions with building openings and air-intakes also is important and if better known could reduce resource use and improve the health of those internally and outside. Thus many would benefit from improved predicative capability of well evaluated and routinely run models that capture these interactions.

In addition to physical and chemical processes of the urban atmosphere, are human behaviours (individually and collectively) impact emissions (e.g. atmospheric pollutants, energy, water, heat) and these need to be observed and incorporated into modelling. Many end-users (e.g. street vendor, outdoor sports person, car driver, etc.) would like tailored products. Human response on mass (e.g. mode of transport used) have important feedbacks on urban environmental prediction systems. The more seamless methods to capture these controls and feedbacks, the more effective predictive models will be.

Data assimilation (DA) in the urban environment is another area that needs extensive exploration and should be considered as part of new observational network design. Current DA techniques for atmospheric and chemical models rely on traditional meso-net observations. With the recent availability of large urban observational networks, it may become possible to provide higher resolution analysis that integrates urban climate. Forecasting over urban areas will then benefit from improved initial conditions. The 4-D nature of physical, chemical, and human processes/states is needed for the wide range of models continuously operated to maintain city operations. Consideration initially is required to assess what variables, at what scale and with what error will be beneficial for DA. Data assimilation in coupled models is in its early stages and applications are illustrating the co-benefits to improved forecasts that are possible by assimilation of both meteorological and atmospheric composition observations (Saide et al. 2012, 2013, 2014; Bouquet et al. 2014). Given the elementary nature of the capabilities at the moment, development of the human capacity and observations in focussed areas may be the essential starting point.

18.6 INTEGRATION AND APPLICATIONS

18.6.1 Background

Success in improving predictive capabilities for urban areas depends on a set of issues including: initiation of integrated urban weather, climate, water and related environmental services, databases and data sharing (e.g. socio-demographic data, observations), modelling and prediction, applications, communications and outreach, evaluation, research and capacity development. Seamless prediction of weather and air quality and projection of climate in urban areas necessitates integration of complex elements of the Earth system drawing on advances which historically have been reached almost independently. With increasing computational power in operational and research centres, and increasing amounts of available data, the logical trend is to build comprehensive coupled systems to serve megacities, agglomerations and smaller urban areas.

Applications are, however, becoming wider, and the list of potential end-users increasing (e.g. NRC, 2012). As highlighted above, the main applications concern NWP, air quality (prediction and assessment), flooding and climate (projection and assessment of adaptation measures). Public health agencies also are requesting more and more derived products as the potential for seamless predictions in urban areas increases.

These tools are needed not only for short events but also long-term operations of cities. Urban planners require the scientific background for pertinent strategies to both mitigate and adapt their city to climate change (Lemonsu et al. 2014). Tools needed to be generic, but also capable of taking into account site characteristics and local geographical, historical and social features and impacts (Masson et al. 2014). Cultural and social behaviours, in a governance context, modify people's behaviour. This interacts with, and feedback to, the urban climate increasingly (e.g. the urban heat island). Thus seamless weather prediction in the urban context extends from meteorological and chemical processes to include hydrological, economic and social dimensions. The services need to cross multiple scales, from the individual (e.g. exposure) to the city (e.g. urban planning), supporting decisions at times scales from short term (e.g. fire related, energy use) to those that impact for hundreds to thousands of years (e.g. urban planning). With it the dissemination of raw or derived products has to support the wide range of end-users (e.g. from specialized operational requirements to the public or non-specialists).

18.6.2 Underpinning research

Understanding of the interactions between urban/social processes and heat/pollutant emissions needs to improve and current basic and applied knowledge in these disparate fields needs to be drawn together (Grimmond 2013). The World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) project[e] has helped enhance capabilities of some national meteorological services to handle meteorological and related aspects of urban pollution and urban extreme weather.

Some operational centres already provide services that use integrated models (e.g. Tan et al. 2015). This is helpful, but will benefit from future research and development of coupled models. As already noted research on basic physical and chemical processes, and the development of numerical models and tools are integral components to reliable and accurate forecast products and services. As operational personnel cannot be fully responsible for all the research and development activities, strong and long-term partnerships need to be established and sustained between researchers and internal and external operational groups. These partnerships should promote the development of methods to measure improvements in forecast skills and benefits.

Cities exist within the context of other globally changes. The impact of this on cities needs to draw upon the understanding of the large-scale and long-term processes (e.g. ocean temperature and currents, sea-level rise, changes in land cover, slow-changing atmospheric variables). These changes can produce climate fluctuations that potentially are predictable at seasonal and inter-annual timescales. Targeted prediction products, of temperature, rainfall and high-impact events (e.g. heat waves (several days), floods (minutes to several days)) can refine regional downscaling of integrated climate-chemistry or Earth system models. Concurrently improvement to global models and bias corrections associated with downscaling also are needed (e.g. Schoetter et al. 2012).

18.6.3 Requirements

In cities there are extensive ranges of specialized end-users, and often there is a mismatch between availability of tools and demands. As new tools are developed to support end-users, it is important that due attention is given to the dynamic changes (e.g. data availability, communications) to benefit research intensive situations and those in operational situations that may be data poor. Thus, for example, emergency response situations with minimal real-time data (e.g. winds from the nearest airport) can benefit from new tool development incorporating the essential urban 3-D urban morphology (GIS) data if gathered. It is critical that new tools are made 'openly' available, to reduce duplication of effort and to focus attention on improvements. In some cases developing web-based interfaces to run the models may greatly enhance usage, as will simple tools to improve provision of data.

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[e] *http://mce2.org/wmogurme/*

Many policy-makers, in different governance structures, along with community groups are actively engaged in proposals and discussions to enhance urban sustainability and resilience. These may involve changes to the local buildings/infrastructure in terms of urban greening through tree planting; repaving/replacing roads/pavements with high(er) albedo or low-emissivity materials, , Sustainable Urban Drainage Systems (SUDS: see e.g. Butler and Davies, 2010) or investing in multi-function solutions. Tools are needed that allow such stakeholders to consider competing and unintended impacts of suggested changes. For example, green infrastructure introduced with the intent of reducing air temperatures, will increase humidity and change the air quality. Stakeholders need to be able to consider the net benefits to health and comfort in the context of their city. To achieve this goal, limit values for heat and moisture exposure as well as for wind load need to be developed. Different considerations will come into play if the concern is with day-to-day management versus extreme events. Who the stakeholders and end-users are needs to be explored, with the intent of engaging these evolving communities with the applications of interest to them, with attention to the scale of interventions needed. Such needs assessments should inform research developments to address those with greatest demand and potential benefit. The breadth of these stakeholders and end-users, and how they vary between and across cities, also needs to be recognized.

Enhancing two-way communication between the meteorological community and those operating city services is essential in ensuring the tools developed are usable and beneficial to residents/occupants of cities. High profile special events (e.g. Olympics or other sports events, political meetings, etc) have been catalysts in developing collaborations with stakeholders and end-users to develop early warning systems (e.g. Beijing London, Shanghai, Toronto, Glasgow). However, many improvements are needed and learning from these events/settings needs to be generalised.

Knowledge of what information, what form it needs to be presented in, and with what lead times needs to be gathered. For example, a number of public health warnings could be improved by providing more tailored forecasts (e.g. heat waves, cold, air quality, pollen, flooding). Consideration, through collaborations with stakeholders and end-users, is needed as to what improvements of weather products will be of greatest benefit to the end-users. It is critical to develop appropriate and effective ways to communicate data and warnings, both through conventional means and current (and evolving) electronic media.

18.7 CONCLUSIONS

Weather, climate, water and related environmental conditions have profound effects on cities and their residents. The majority of the world's population is now urban and city dwellers. Worldwide cities are growing, particularly in Asia and Africa. Increasing attention is being directed to the predictions of atmospheric conditions and its interaction with other components of the Earth System at the scale of cities, in the context of better understanding the risk and resilience of urban environments. Recognition is also emerging of important variability across large conurbations and the effects of the cities and their residents on atmospheric processes and local conditions. This summary highlights that much remains to be done and the importance of a coordinated and strategic approach to maximize benefits to stakeholders and to best draw on research capacity. The key areas where investment is particularly important, identified also by others, are highlighted in terms of observations and metadata; frameworks for analysis; models; tools; and communication. Specific recommendations are made about: (1) development of high-resolution coupled environmental prediction models that include realistic city specific processes, boundary conditions, and fluxes of energy and physical properties; (2) enhanced urban observational systems to determine unknown processes and to force these models to provide high quality forecasts to be used in new urban climate services; (3) understanding of the critical limit values for meteorological and atmospheric composition variables with respect to human health and environmental protection; (4) new, targeted and customized delivery platforms using an array of modern communication techniques, developed in close consultation with users to ensure that services, advice and warnings result in appropriate action and in turn inform how best to improve the services; (5) the development of new skill and capacity to make best use of technologies to produce and deliver new services in complex, challenging and evolving city environments.

An overall challenge moving to higher resolution and taking into account the considerations highlighted here, is to ensure that a balanced effort across all aspects occurs, rather than striving for disproportionate accuracy in one part of the model while gross errors remain in other parts.

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CHAPTER 19. THE WWRP POLAR PREDICTION PROJECT (PPP)

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Abstract

Mission statement
"Promote cooperative international research enabling development of improved weather and environmental prediction services for the polar regions, on time scales from hours to seasonal".
Increased economic, transportation and research activities in polar regions are leading to more demands for sustained and improved availability of predictive weather and climate information to support decision-making. However, partly as a result of a strong emphasis of previous international efforts on lower and middle latitudes, many gaps in weather, sub-seasonal and seasonal forecasting in polar regions hamper reliable decision making in the Arctic, Antarctic and possibly the middle latitudes as well.

In order to advance polar prediction capabilities, the WWRP Polar Prediction Project (PPP) has been established as one of three THORPEX (THe Observing System Research and Predictability EXperiment) legacy activities. The aim of PPP, a ten year endeavour (2013-2022), is to promote cooperative international research enabling development of improved weather and environmental prediction services for the polar regions, on hourly to seasonal time scales. In order to achieve its goals, PPP will enhance international and interdisciplinary collaboration through the development of strong linkages with related initiatives; strengthen linkages between academia, research institutions and operational forecasting centres; promote interactions and communication between research and stakeholders; and foster education and outreach.

Flagship research activities of PPP include sea ice prediction, polar-lower latitude linkages and the Year of Polar Prediction (YOPP) - an intensive observational, coupled modelling, service-oriented research and educational effort in the period mid-2017 to mid-2019.

19.1 INTRODUCTION

Interest in the polar regions has been increasing considerably in recent years, largely because of concerns about Arctic. There has also been an increasing economic interest (e.g. shipping and tourism) in the polar regions, especially in the Arctic. Record low Arctic summer sea ice in recent years for example, has opened new shipping routes, which have shortened routes between Europe and East Asia substantially (Schøyen and Bråthen, 2011). The ongoing and projected changes in polar regions and increases in economic activities also lead to concerns for indigenous societies and northern communities (e.g. increased exposure to risks associated with industry). Finally, through scientific research and monitoring of polar regions, we are just beginning to appreciate the connectivity between polar atmospheric, oceanic, and cryospheric processes and those in lower latitude regions. While this connectivity has always existed, its ramifications are only now being understood.

The context of development pressure coupled with significant socio-cultural, technological and environmental changes translates into great potentially for demand of weather and environmental prediction and related services - essentially 'more' of the polar regions are becoming exposed to environmental hazards, and that which is exposed may become more sensitive. This is also true for research activities in polar regions whose success crucially depends on availability of efficient logistics which in turn depend on reliable predictions. In summary, there is growing need for sustained and improved availability of environmental predictions across a wide range of time scales to support decision-making.

Partly as a result of a strong emphasis of previous international efforts on lower and middle latitudes, many gaps in weather and environmental forecasting in polar regions hamper reliable decision-making. There are certainly gaps, for example: in data availability, our understanding of how good current environmental polar predictions actually are, and where the limits of predictability lie for features such as high-impact polar weather phenomena, blowing snow, and ice coverage in the Northwest Passage. Furthermore, important parts of every forecasting system, such as the numerical model, the data assimilation system, and the methods to generate ensemble predictions are yet to be thoroughly evaluated and customized for the polar regions. It will be crucial, for example, to consider coupled atmosphere-sea ice-ocean-hydrology models in relatively short 'weather-timescale' prediction systems, which have traditionally been carried out using atmospheric models only.

19.2 RESEARCH GOALS AND KEY ACTIVITIES

In the following an overview of the main research goals of PPP (Figure 1) will be given and plans for a Year of Polar Prediction (YOPP) will be outlined.

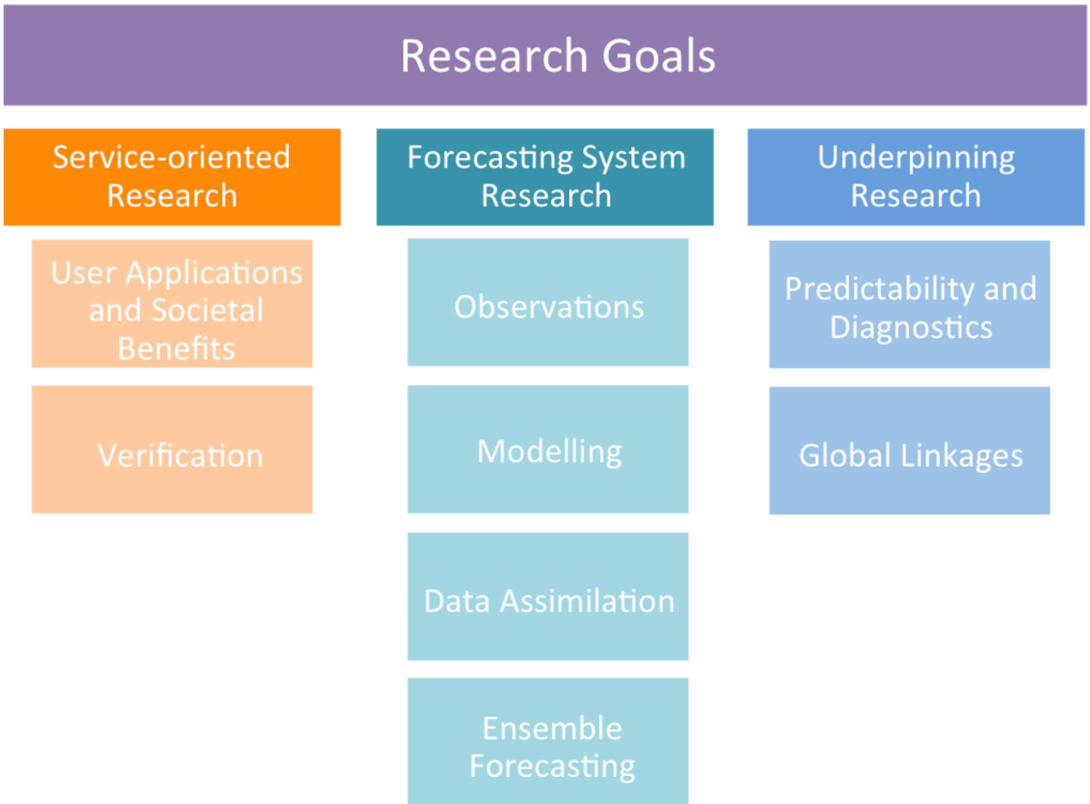

Figure 1. Grouping of research goals in the WWRP Polar Prediction Project

19.2.1 User applications and societal benefit

Background

Societal and Economic Research and Applications (SERA) is synonymous for research conducted into user applications and societal benefit. SERA draws from a variety of social science disciplines, including economics, sociology, psychology, anthropology, political science, human geography, and communication studies, and is chiefly concerned with explaining human behaviour. Applied to the polar prediction theme, this involves exploring how individuals, groups and organizations seek, obtain, perceive, share, comprehend and use weather and related risk information in making decisions. In particular, SERA aims to understand how changes in the attributes of the information and knowledge (for example accuracy, precision, or the manner in which it is communicated) and the characteristics and situational context of the user (who might be a weather forecaster, resident of an Inuit community, or mineral exploration engineer) affect decision-making processes, associated behaviours, and particular outcomes of interest (safety, health, prosperity, etc.).

The methodological domain of SERA encompasses both qualitative and quantitative approaches. Ethnographic field research, whereby the subject participants are observed in their natural settings or through direct interaction with researchers, is an example of the former (e.g. examination of social constructions of a severe weather event in northern Canada; Spinney and Pennesi 2012). A statistical analysis of questionnaire survey data is representative of the latter (e.g. tourist perceptions of weather in Scandinavia, Denstadli et al. 2011).

Blending results from studies adopting qualitative and quantitative approaches will be necessary but difficult for this project (given respective roots in interpretive/critical and positivistic perspectives). The extent to which even quantitative study findings can be aggregated and generalized across polar regions is questionable and a targeted series of independent case studies, demonstrations or applications may be a more achievable objective. Given the sparse population of the Arctic and limited activity in the Antarctic, the availability of large secondary social and economic data sets directly relevant to the use of polar weather forecast information is likely very limited. It will be necessary to invest in original research and data collection, though it may be possible to borrow from recent studies and projects that have examined adjustments to current and potential climate change impacts.

Development of a SERA research framework, including the establishment of linkages with verification and other natural science components of the Polar Prediction Project, will be essential to rising to the challenges noted above. Such a framework must explicitly treat the teleconnections between improvements in the prediction of hydrometeorological processes and phenomena in polar and extra-polar regions, as this may be the greatest source of economic benefit. It must also acknowledge and account for the important role of indigenous and local knowledge concerning weather-related risks and the interactions of such wisdom with scientific sources of information.

Key challenges

- Estimation and analysis of historic and current use and interpretation of polar prediction products
- Communication of risk, opportunity and uncertainty across user types
- Investigation of perceptions and adapted measures of communities in response to polar prediction products
- Methods to evaluate and integrate 'dislocated' and within-region costs and benefits

Selected activities

- Carry out literature review, inventory and evaluation of current (historic) weather-related hazards/impacts, prediction services, information requirements, and user experiences in applying information in decision making
- Organize social and interdisciplinary science workshops (Weather and Polar Society) to elaborate on pressing research and application gaps, issues, and needs and begin formulating a formal research framework
- Publish societal benefit assessment, experiences and best practices, and development of a capacity-building initiative targeted to National Meteorological and Hydrological Services (NMHSs) and groups of users

These activities will be further developed by a newly-formed PPP-SERA sub-committee composed of social and interdisciplinary scientists (PPP-SERA 2015), working in close coordination with the PPP Steering Group WWRP-SERA working group and the Executive Council Panel of Experts on Polar Observations, Research and Services (EC-PORS).

19.2.2 Verification

Background

Verification is a process to provide users with information about forecast quality to guide their decision-making procedure, as well as providing useful feedback to the forecasting community to improve their own forecasting tools. Forecasts are typically compared against actual, measured or observed values (or phenomena), and various scores and measures are then used to assess the \`goodness\` of forecasts. Results are often compared against a \`standard\`, which represents a minimal level of forecast skill (e.g. climatology or persistence).

Traditionally, forecast verification has focused on weather variables that are of little direct value for most users of weather information, such as the 500 hPa geopotential height. The diversity of verification measures has been relatively limited with a strong emphasis on basic statistical measures like root-mean-square error and correlation metrics. Standard verification has moreover mostly concentrated on mid-latitude and tropical regions. Relatively little is, therefore, known about the skill of current operational forecasting systems in the polar regions (e.g. Jung et al. 2007). Some of the biggest challenges in forecast verification relate to the quality and quantity of observations. In fact, representative observational data are the cornerstone behind all successful verification activities. Given the notorious sparseness or even complete lack of conventional observations in the polar regions, progress in quantifying and monitoring the skill of weather and environmental forecasts will hinge on the availability of additional observations.

Forecast verification against analyses, which are influenced by the model itself during the data assimilation process, is still a common - but questionable - practice. This will be especially harmful in parts of the world, including the polar regions, where the sparseness of high-quality observations leads to a very strong influence of the model's first guess on the analysis. New methods need to be devised, such as verification in observation space (e.g. satellite data simulators), to reduce issues associated with verification against analysis.

In recent years, there has been a shift in how verification is perceived. It has been widely recognized that verification activities should focus more strongly on user relevant forecast aspects, that more advanced diagnostic verification techniques are required, and that the usefulness of verification depends on the availability of sufficient high quality observational data. These developments need to be strengthened and put forward in the coming years to advance the field of polar forecast verification.

Key challenges

- Raising awareness of the need for comprehensive forecast verification in the polar regions
- Establishment of optimal observational networks and access to reference data sets for verification purposes
- Verification of high-impact weather and climate events in polar regions

Selected activities

- Review existing state-of-the-art verification methods to see how applicable they are to polar regions
- Define an observation strategy to meet forecast verification requirements, particularly for YOPP
- Define verification metrics for use as key polar-relevant performance measures to monitor progress during the 10 year period of the project
- Verify existing forecasting systems in the polar regions for reference information
- Develop forecast verification in observation space using, for example, satellite data simulators
- Devise methods that can be used to verify user-relevant key weather and climate phenomena in polar regions (e.g. visibility, sea ice deformation, polar lows)

It is anticipated that these activities will be carried out primarily by, and in close coordination with, the Joint Working Group on Forecast Verification Research (JWGFVR).

19.2.3 Observations

Background

The polar regions are among the most sparsely observed parts of the globe by conventional observing systems such as surface meteorological stations, radiosonde stations, and aircraft reports. Figure 2 illustrates the situation: contrast the dense network of surface stations (SYNOPs/purple dots) over Scandinavia with the sparse network over the rest of the Arctic; or compare the coarse but arguably adequate network of radiosonde stations (TEMPs/yellow dots) over Eurasia with the handful of stations over Antarctica. The polar oceans are also sparsely observed by the Argo array of automated profiling floats, implying problems for coupled atmosphere-sea ice-ocean forecasting.

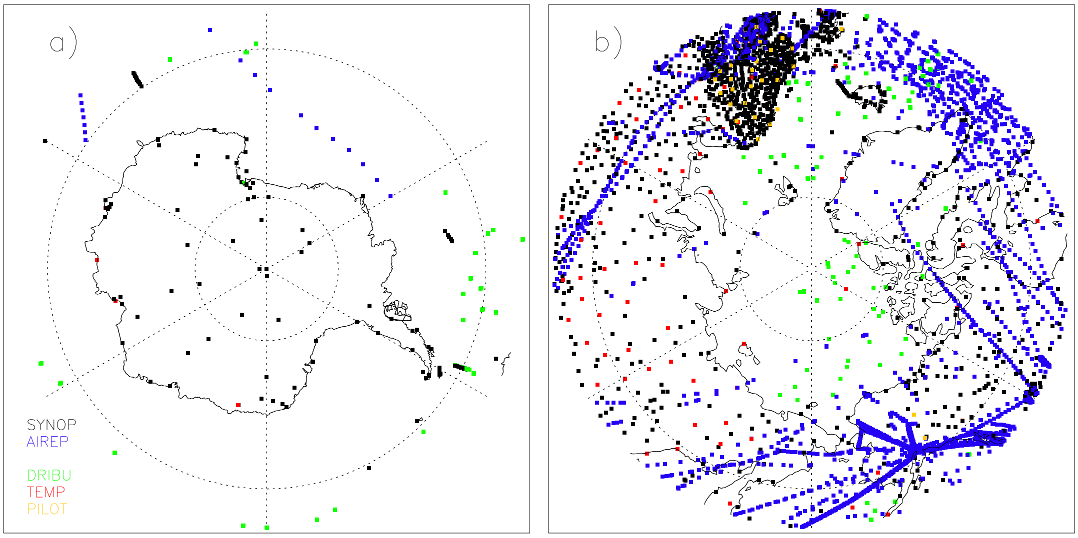

Figure 2. Polar data coverage of conventional observations in the ECMWF operational analysis at 00 UTC on 1 January 2012 (21-09 UTC window) for (a) southern polar region, and (b) northern polar region. SYNOPs are surface reports from land stations; AIREP are in-flight reports from aircraft; DRIBU are surface drifting buoys; TEMP are upper air balloon soundings; PILOT are upper air winds from tracked balloons.

The polar regions are barely sampled by geostationary satellites, but generally have a denser sampling by polar-orbiting satellites, providing the potential for improvements in satellite sounding (e.g. the Infrared Atmospheric Sounding Interferometer (IASI) sounder), or sea ice thickness (e.g. from Cryosat). Using satellite-based observations of the polar surface is challenging partly due to the ever-changing and highly heterogeneous sea-ice, which prohibits observations of ocean surface temperature and salinity, colour, altimetry/wave height, surface winds, precipitation, etc. Differentiating between snow and ice-covered surfaces and clouds in the atmosphere has also been a long-running challenge. Making better use of existing and new satellite-based observations is a must for improving forecast initialisation and verification.

The relative remoteness and harsh environmental conditions of the polar regions is always going to provide a barrier to enhanced observations. With improved technology and power systems the barrier is becoming more limited financially than logistically: improved observations of the polar regions are possible but are they worth the cost? To answer this, Observing System Experiments (OSEs) are required with a particular focus on user-requirements for these regions. To carry out these kind of experiments a sustained observing period is required - a Year of Polar Prediction (YOPP, see below). In addition, periods of intense process-focussed field campaigns are required to provide comprehensive observations of processes that are poorly represented in current forecasting systems.

Key challenges

- Lack of observations due to remoteness, harshness and cost of operating in the polar regions
- A need for optimization of the observing system and international collaboration
- Constraining small-scale processes characteristic for the polar regions (e.g. shallow boundary layers, leads and river run-off)
- Supplying pertinent observations for data assimilation for regional model forecasts to constrain initial conditions
- A need for continual availability of adequate observations in near-real-time

Selected activities

- Devise new and cost effective means for taking observations in the polar regions (e.g. voluntary observing ships)
- Use techniques such as adjoint sensitivity to quantify the importance of different components of the polar observing system to analysis and forecast quality
- Perform data denial and Observing System Simulation Experiments (OSSEs) to understand the potential benefit of enhanced observation capabilities, and to optimise the overall observing system

19.2.4 Modelling

Background

Numerical models of the atmosphere, ocean, sea ice, land and rivers play an increasingly important role in prediction. For example, models are used to carry out short to seasonal range weather and environmental forecasts; they form an important element in every data assimilation scheme (state estimation); they are used as a numerical laboratory to carry out experiments devised to understand the functioning of the climate system; and they can aid design of future observing systems (e.g. satellite missions) through so-called Observing System Simulation Experiments (OSSEs).
Although numerical models have come a long way, even state-of-the-art systems show substantial shortcomings in the representation of certain key processes. For example, skilful model simulations of stable planetary boundary layers and tenuous polar clouds remain elusive (e.g. Bromwich et al. 2013). The shallowness of stable planetary boundary layers in the polar regions, the smaller spatial scale of rotational systems (e.g. polar cyclones) due to the relatively small Rossby radius of deformation along with the presence of steep topographic features in Greenland and Antarctica. All these points raised above suggest that polar predictions will benefit from increased horizontal and vertical resolution. However, while some of the existing problems may be overcome by increased resolution accessible via the projected availability of supercomputing resources during the coming 10 year period, it is certain that the parameterizations of polar subgrid-scale processes will remain an important area of research for the foreseeable future.

Most existing short-range and medium-range global prediction systems are coupled atmosphere-land surface models. The ocean, sea ice and snow as well as parts of the hydrological cycle (e.g. rivers) are still treated rather simplistically. Although it is well established that sub-seasonal and seasonal predictions require the use of models of the fully coupled system, it is increasingly recognized that the same is true for shorter ‘weather’ forecasts. The expected increase in shipping traffic in the Arctic will require new kinds of forecast products, such as those for sea ice pressure, which require the use of dynamic-thermodynamic sea ice models. Furthermore, the common practice of persisting sea ice during the course of short-term forecasts can lead to substantial errors in near-surface temperature predictions, especially at times when sea ice is changing rapidly.

The increasing importance of sea ice-ocean models for polar predictions will require critical review of the strength and weaknesses of existing models (e.g. Guemas et al. 2014). Most sea ice models, for example, still employ rheologies that were developed in the late 1970s. While these rheologies have been successfully applied in coarse resolution models, for which they have been developed, future increases in resolution raise the question whether the underlying assumptions for the existing formalisms remain valid. Furthermore, until now, interactions between the sea-ice model and the atmosphere and ocean models have been relatively simple in many forecasting systems, with even more simplified interaction when models are used within data assimilation systems in terms of albedo and turbulent heat and momentum exchange at the surface. These interactions also require critical review.

The strong emphasis of the Polar Prediction Project on the improvement of models in polar regions should help to alleviate some of the existing longstanding model biases. The anticipated model improvements will help improve the skill of predictions across a range of time scales in the polar regions and beyond.

Key challenges

- Improvement of the representation of polar key processes in atmosphere, ocean, sea ice, land surface and river-systems through enhanced model formulation and increased horizontal and vertical resolution
- Development of coupled model systems for short-, medium- and extended-range predictions

Selected activities

- Assess accuracy of polar processes and feedbacks simulated by currently used models (“gap analysis”)
- Improve representation of atmospheric processes of particular relevance for polar regions - e.g. stable boundary layers, aerosol and cloud microphysical properties
- Improve parameterizations for river flow, lakes, permafrost and other relevant high-latitude terrestrial processes
- Assess alternate sea-ice rheologies to account for future increases in horizontal resolution and improved sea ice parameterizations and interactions
- Use process models (e.g. “large eddy simulations”) to guide developments for global and regional models
- Explore grey zone issues for the Arctic and Antarctic - i.e. the validity of parameterizations when the horizontal resolution of models is increasing and the possible use of scale-aware parameterizations
- Develop stochastic parameterization schemes for polar regions and processes to account for model uncertainty and up-scale effects from subgrid-scale processes

19.2.5 Data assimilation

Background

Data assimilation systems are used to derive the best possible estimate of the state of a geophysical system valid at a certain time and over a defined area. This is called the analysis. In numerical weather prediction, these systems are based on the numerical model that is also used for forecasting and observations, with an optimization algorithm that combines the model and the observations such that a physically realistic estimate is derived that matches the model prediction and observations within their respective error margins. The analysis also serves for initializing the forecast model. The quality of the analysis is of fundamental importance for forecast skill since weather forecasting is, to a large extent, an initial value problem. Generally, the sensitivity of forecasts to the analysis changes between short, medium and extended range from smaller-scale and fast processes (e.g. turbulence, clouds, convection) to larger-scale and slow processes (e.g. planetary waves, ocean and sea-ice dynamics).

Modern global weather forecasting employs data assimilation systems that use time integrations of the three-dimensional model at 15-25 km resolution and 50-100 vertical levels ($O(10^9)$ grid cells) together with $O(10^7)$ observations resulting in very large numerical optimization problems. Ensemble analysis systems aim at additionally specifying the uncertainty of the analysis that is required for deriving the above mentioned model error margins but also serve as initializations for ensemble forecasts.

Over polar areas, shortcomings in all three main data assimilation components, namely model, observations and assimilation algorithm, contribute to sub-optimal state estimates with detrimental impact on forecast skill from the short to extended range. During atmospheric conditions in which boundary layer processes and atmosphere-surface interaction - particularly with variable sea-ice coverage - are dominant, small scale cyclonic systems (polar lows) and the interaction of the flow with extreme orography are currently not well resolved in global models, and even less well resolved in data assimilation systems. Observations are sparse and mostly lacking over sea-ice and the Antarctic continent. Satellite data are more difficult to interpret due to, for example, little optical contrast between the surface and atmosphere. The specification of model and observation uncertainty, required to balance the contributions from observations and the model in the analysis, becomes a key issue.

The Polar Prediction Project aims at addressing models, observations and data assimilation methods, emphasizing polar-specific aspects, such as the crucial model processes, atmosphere-surface interaction and spatial resolution, enhanced surface-based observational networks and satellite data exploitation, assimilation methods more optimally tuned to high-latitude conditions and coupled atmosphere-ocean-sea ice data assimilation at regional and global scale.

Key challenges

- Representation of model uncertainty
- Data assimilation with coupled atmosphere-ocean-sea ice-land models
- Data assimilation in the vicinity of steep orography (e.g. Greenland and Antarctica)

Selected activities

- Evaluate existing analysis and reanalysis data sets from a consolidated Polar Prediction Project point of view
- Develop automated retrieval/data assimilation algorithms for sea ice observations from satellite - e.g. ice concentration and thickness from Synthetic Aperture Radar and Cryosat data, respectively
- Develop flow-dependent error covariance matrices for the polar regions (e.g. error covariance matrices appropriate to typically shallow boundary layers and sharp sea ice boundaries)
- Develop coupled data assimilation systems for the polar atmosphere-ocean-sea ice-land system

19.2.6 Ensemble forecasting

Background

Ensemble forecasting is an approach to reliably quantify uncertainty of weather or climate forecasts. An ensemble prediction system (EPS) is designed to account for the fact that inevitable errors in the initial conditions and inaccurate model formulations affect forecast skill differently from day to day (flow-dependent error growth). The EPS is implemented by running multiple forecasts in parallel - so-called ensemble members - using slightly different initial conditions that are all plausible given the past and current set of observations. Some EPSs also represent model uncertainty by running different ensemble members with slightly different model formulations. For a well-designed EPS, a relatively low ensemble spread (i.e. different members give similar results irrespective of the existing uncertainties) implies a high level of confidence in the forecast; in contrast, a high ensemble spread implies that the forecasts are uncertain.

Existing operational EPSs have been primarily designed with processes in the tropics, sub-tropics and mid-latitudes in mind. For example, atmospheric singular vectors, which are use to generate initial perturbations, tend to target baroclinic instability in mid-latitudes, whereas stochastic convection schemes are most effective in the tropics in representing model uncertainty. In contrast, ensemble forecasting in the polar regions has attracted relatively little direct attention, a situation the Polar Prediction Project aims to address.

Because of a previous focus on non-polar regions, relatively little is known about the quality of ensemble forecasts, including the associated probability forecasts in polar regions. In fact, a lot of progress in the provision of environmental information can be made by raising awareness of the importance of polar ensemble forecasting and by applying existing ensemble verification techniques to the polar regions.

The main challenge when designing EPSs lies in the proper representation of initial conditions and their errors and model inaccuracy to obtain reliable estimates of prediction uncertainty and probability forecasts. Most operational EPSs employ optimal perturbations to represent initial condition uncertainty. In the atmospheric mid-latitudes, baroclinic instability dominates the early stage of forecast error growth; in the tropical atmosphere, on the other hand, convective instability plays the dominant role. Although it can be anticipated that baroclinic instability has some role to play in the polar regions, research needs to be carried out to identify other more polar-specific sources of perturbation growth - for the atmosphere, as well as for other components of the polar climate system such as the ocean and the sea ice.

Given the limitations of state-of-the-art models to represent some of the key processes in the polar regions, it will be imperative to properly represent model inaccuracy in operational ensemble forecasts from hours to seasonal time scales. Different approaches have been suggested including multi-models and stochastic parameterizations. Given that most of the existing schemes were built for the tropical, subtropical and mid-latitude atmosphere, it will certainly be important to carry out a separate assessment of the various stochastic techniques for the polar regions and different time scales. Furthermore, given that routine weather forecasts are likely to be carried out with coupled models by the end of this decade, as they are already used for sub-seasonal and seasonal forecasting, the representation of model uncertainty in sea ice, ocean, land surface, and land-based hydrology will also need to be addressed in the Polar Prediction Project.

In summary, there are two ways in which the Polar Prediction Project can contribute to the improvement of operational ensemble forecasting. Firstly, substantial progress can be made by applying well-established NWP methodology (e.g. standard verification scores) in a polar context. Secondly, improving ensemble forecasting systems by taking polar-specific aspects such as sea ice into account provides scope for further improvements in probabilistic forecasts in the polar regions and beyond.

Key challenges

- Identification of forecast relevant instabilities in the polar regions, especially those leading to high-impact events
- Improvement of initial perturbation techniques to realistically represent initial condition uncertainty in polar regions
- Development of techniques to represent model uncertainty in polar regions
- Development of ensemble techniques for sea ice, ocean, land and hydrology models and fully coupled systems
- Verification of probabilistic forecasts in polar regions using observations

Selected activities

- Assess performance of existing global and limited area EPSs in the polar regions
- Exploit existing and future special ensemble forecast data sets - e.g. TIGGE, CHFP (Climate System Historical Forecast Project), WMO Lead Centre for Long-Range Forecast Multimodel Ensemble and the Sub-seasonal to Seasonal data base - and provide feedback to operational institutions
- Improve techniques to represent initial condition and model uncertainty in coupled ensemble prediction system
- Assess the benefits of using stochastic parameterizations versus multi-model methods
- Explore the growth of uncertainty and its flow-dependence

19.2.7 Predictability and forecast error diagnosis

Background

Predictability research is primarily concerned with the mechanisms that potentially influence forecast skill at different time scales. The predictability of a system is determined by its instabilities and nonlinearities, and by the structure of the imperfections (analysis and model error). In forecast error diagnosis, possible weaknesses of different components of forecasting systems can be unravelled through detailed and systematic diagnosis of actual forecast failures and through carefully designed numerical experimentation.

The unique feature of the polar regions is the presence of vast areas of snow and ice. Due to its relative persistence or stability, sea ice anomalies are usually considered a potential source of predictability, especially on sub-seasonal and seasonal time scales. Relatively little is known at present, however, about its role in operational forecasting and how the atmospheric circulation and hence “remote” regions such as Europe and Australia respond to sea ice anomalies. It is also not straightforward to realize the potential predictability associated with sea-ice and snow cover, because of their strong interactions with the atmosphere and the ocean. These interactions constitute very important feedback mechanisms. Additionally, given the remoteness of the region, in situ ocean and ice data needed for model initialization are sparse, which may limit the predictability that can be realized.

The presence of sea ice, snow and ice in the polar regions in conjunction with mid-tropospheric inflow of relatively warm air from the mid-latitudes leads, at times, to the development of relatively shallow and stably stratified planetary boundary layers (PBLs) in the interior of the Arctic and Antarctic during wintertime.

On the other hand, extreme temperature contrasts across the ice edge can lead to very unstable PBLs and turbulent surface heat fluxes in excess of 1000 W/m^2 over the adjacent open ocean regions. Depending on the dynamical conditions associated with the outflowing air masses, very strong, hurricane-like vortices with diameters typically of a few hundred kilometres (polar lows) may develop within a period of a few hours under the influence of sensible and latent heating from the open ocean. These polar lows are responsible for some of the most dangerous weather in the Arctic, due to strong winds, heavy snow fall, and icing on ships and installations. Furthermore, their predictability is highly variable, because of the fast development over areas with sparse observations, and their small scales. It is also likely that some aspects of model formulations pertinent to these systems are inadequate.

The polar atmosphere is often characterised by relatively small-scale features. This can be explained by relatively weak planetary wave activity, the existence of relatively sharp horizontal gradients (e.g. sea ice edge), high and steep topography, a relatively small Rossby radius of deformation, the low height of the tropopause and relatively high tropospheric stability during the winter darkness.

In summary, the particular characteristics of the polar regions change the relative importance of different dynamical and physical processes compared to that in the lower latitudes, which implies that our process understanding gained in the lower latitudes is often not directly transferrable to the polar regions.

Predictability research in the Polar Prediction Project will advance our understanding of those key dynamical and physical processes in the polar regions that determine its predictability. This knowledge will be used to explore the limits of polar predictability across all time and space scales considered in the Polar Prediction Project. This improved process understanding will be exploited in diagnostic research activities to identify key problems of operational forecasting systems in order to guide future developments.

Key challenges

- Improving predictions of polar high-impact weather and climate events (e.g. polar lows, blizzards, etc.)
- Understanding the role of the polar ocean, sea ice and stratosphere in medium-range and extended range prediction
- Identification of key sources of forecast error in the polar regions to guide future model development

Selected activities

- Carry out coordinated studies on inherent polar predictability
- Evaluate the role of sea ice, ocean and stratosphere for all forecast ranges
- Characterize the role of model parameterization uncertainty, and of model resolution
- Characterize the influence of initial condition uncertainty
- Establish priorities for model development and observing system design
- Develop efficient diagnostics techniques
- Employ initial tendency diagnostics to unravel key model short-comings

19.2.8 Global Linkages

Background

In order to get a comprehensive understanding of polar predictability it is necessary to go beyond a purely polar perspective and also consider possible linkages with the lower latitudes. There is evidence, that the evolution of polar weather is partly determined by what is happening in the mid-latitudes. On the other hand, recent research indicates that the reduction of summer-time sea ice in the Arctic leads to an increased frequency of occurrence of high-impact weather events in the mid-latitudes suggesting that the polar regions play an important role when it comes to prediction across the globe (e.g. Jung et al. 2014).

Compared to tropical-extratropical interactions, for which a vast body of literature is available, relatively little is known about the dynamics of polar-lower latitude linkages, especially for the atmosphere. For shorter time scales (short-range and medium-range forecasts) it seems likely that atmospheric baroclinic waves will play a crucial role in linking the polar regions with the mid-latitudes and that this link is strongly mediated through the presence of planetary-scale Rossby waves. On longer sub-seasonal and seasonal time scales, lower latitude-polar linkages are probably established through teleconnections to patterns such as the Arctic Oscillation (AO) and Southern Annular Mode (SAM). While these teleconnection patterns are well studied phenomena, there is little quantitative knowledge about their role in transferring forecast skill (or uncertainty) from the polar regions into the mid-latitudes and vice versa. Furthermore, our understanding of the role of polar processes in influencing large-scale atmospheric teleconnection patterns remains limited.

It is therefore expected that research on global linkages will enhance our understanding of the role of the polar regions in the global climate system, both is terms of the underlying dynamics and in terms of predictability on time scales from days to seasons.

Key challenges

- Improved understanding of two-way linkages between the polar regions and the lower latitudes and their flow-dependence on time-scales from days to seasons
- Obtain better understanding of possible polar origins of predictive skill and forecast failures in lower latitudes in order to guide future forecasting system development

Selected activities

- Revisit teleconnections from a prediction perspective
- Carry out relaxation and data denial experiments to understand the influence of improved polar predictions on lower-latitude forecast skill
- Determine flow-dependence of interactions between polar regions and lower latitudes using reanalysis and reforecast data sets
- Determine mid-latitude response to sea ice anomalies

19.2.9 The Year Of Polar Prediction (YOPP)

YOPP is one of PPP's flagship activities. Its mission is to "Enable a significant improvement in environmental prediction capabilities for the polar regions and beyond, by coordinating a period of intensive observing, modelling, verification, user-engagement and education activities".

YOPP will be carried out in close collaboration with the Polar Climate Prediction Initiative (PCPI) of World Climate Research Programme (WCRP) and other related initiatives. YOPP encompasses four major elements: an intensive observing period, a complementary intensive modelling and forecasting period, a period of enhanced monitoring of forecast use in decision making including verification, and a polar prediction focussed educational effort. YOPP is structured in three phases: the preparation phase, central YOPP and the consolidation phase (Figure 3).

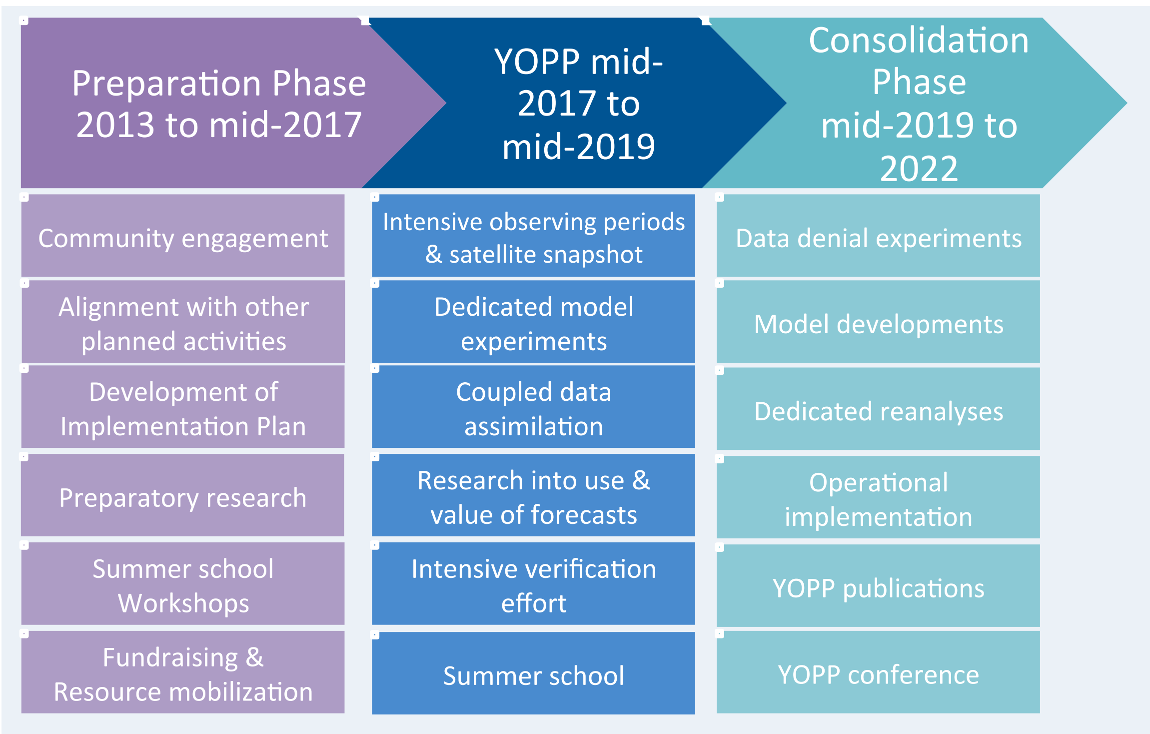

Figure 3. Three stages of YOPP, including the main activities for each stage

The preparation phase of YOPP covers the period from 2013 to mid-2017 and is characterized by the following key activities: community engagement, coordination with other planned activities, preparatory experimentation, preparation of observational and modelling strategies, development of implementation plan, organisation of summer school and workshops, liaison with funders. YOPP itself extends over the period from mid-2017 to mid-2019 and comprises periods of intensive observations, dedicated model experiments, research into the use and value of forecasts and intensive verification efforts. A consolidation phase marks the end of the YOPP decade. Data denial experiments, model development, dedicated reanalyses, operational implementation and YOPP-specific publications are its main features.

Specific objectives of YOPP are to:

- Improve the polar observing system to provide good coverage of high-quality observations in a cost effective manner. Gather additional observations through field programmes aimed at improving understanding of polar key processes.
- Develop improved representation of polar key processes in uncoupled and coupled models used for prediction, including those which are a particular hindrance to high-quality prediction for the polar regions, such as stable boundary layer representation, surface exchange, and steep orography.
- Develop improved data assimilation systems that account for challenges in the polar regions such as sparseness of observational data, steep orography, mesoscale polar systems (e.g. polar lows), model error and the importance of coupled processes (e.g. atmosphere-sea ice interaction).
- Explore the predictability of sea ice on time scales from days to a season.
- Improve understanding of linkages between polar regions and lower latitudes and assess skill of models representing these.
- Improve verification of polar weather and environmental predictions to obtain quantitative knowledge on model performance, and on the skill of operational forecasting systems for user-relevant parameters; and efficiently monitor progress.
- Improve understanding of the benefits of using existing prediction information and services in the polar regions, differentiated across the spectrum of user types and benefit areas.
- Provide training and educational opportunities for early career scientists to develop expertise in polar prediction related issues.

19.3 CONCLUSION

The ten year (2013-2022) World Weather Research Programme (WWRP) Polar Prediction Project (PPP) is one of three THORPEX legacy projects that will help to enhance prediction capabilities in the polar regions and lower latitudes. PPP will address the increasing needs for reliable forecasts in parts of the globe that have attracted relatively little attention in previous international research programmes.

There are many gaps in our knowledge and understanding of key processes in polar regions of how best to improve computer models and prediction systems, how to optimize the observing system, and what services should be provided. Polar research is an extremely resource-demanding endeavour requiring large-scale infrastructure. Coordination of research activities at an international level is therefore especially important for generating the knowledge required to improve prediction capabilities for the polar regions and beyond.

As a result of the Project, many who live in, or visit, the polar regions, where activities related to transportation, tourism and resource development are on the rise, will benefit from improved predictions. However, the expected benefits will go beyond the provision of more accurate predictions on various time scales (hourly to seasonal) in the two regions (Arctic and Antarctic). Improvements anticipated in the representation of polar processes in coupled numerical weather models will help to narrow uncertainties in regional climate change projections. Furthermore, improved environmental predictions in the polar regions will result in more accurate predictions for non-polar regions, especially in the middle latitudes, through atmospheric linkages.

PPP is an international effort that aims to provide advanced prediction capabilities in two regions that are becoming increasingly important, but which, thus far, have attracted relatively little attention from the forecasting community. The Steering Group has developed science and implementations plans and strategies in collaboration with partners from the research community and operational centres (see *http://polarprediction.net*). PPP may become a crucial WMO contribution into an emerging International Polar Partnership Initiative, which will unite efforts of many agencies and organizations in achieving socially important objectives in the polar regions.

Ultimately, the success of the Polar Projection Project will depend on support from WMO Members through contributions to the Polar Prediction Trust Fund to ensure proper international coordination, on in-kind support from operational centres, research institutions and universities, and on an enhanced level of interest in polar prediction by national and international funding agencies.

19.4 ACKNOWLEDGEMENTS

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CHAPTER 20. SUB-SEASONAL TO SEASONAL PREDICTION: LINKING WEATHER AND CLIMATE

Frédéric Vitart, Andrew W. Robertson and S2S steering group

Abstract

Recent research has pointed to potential sources for improving predictability in the sub-seasonal to seasonal timescale. Identifying windows of opportunity to increase forecast skill could be the basis for enhanced, actionable forecasts. Specific attention is paid to the risk of extreme events, including tropical cyclones, droughts, floods, heatwaves and the waxing and waning of monsoon precipitation. From the end-user perspective, the sub-seasonal to seasonal timescale is a very important one as many management decisions in agriculture and food security, water disaster risk reduction and health fall into this range. Improved weather-to-climate forecasts tailored to key social needs promise to be of significant socio-economic value.

20.1 INTRODUCTION

Demands are growing rapidly in the operational prediction and applications communities for forecasts that fill the gap between medium-range weather forecasts (up to two weeks) and long-range or seasonal ones (3-6 months). Ten years ago, few operational centres produced forecasts at the sub-seasonal time range. Today, at least ten operational centres are issuing sub-seasonal to seasonal forecasts routinely.

To bridge the gap between medium-range weather forecasts and seasonal forecasts, the World Weather Research Programme (WWRP) and World Climate Research Programme (WCRP) have recently launched a joint new research initiative, the Sub-seasonal to Seasonal Prediction Project (S2S). The main goal of this project is to improve forecast skill and understanding of the sub-seasonal to seasonal timescale, and to promote its uptake by operational centres and exploitation by the applications communities (http://www.s2sprediction.net). For instance, evidence of this growing interest is already apparent in several new US initiatives, such as the North-American Multi Model Ensemble (NMME) seasonal forecasting system funded by NOAA, and a multi-agency (Navy, National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF)) effort to develop and implement an Earth System Prediction Capability (ESPC) on time scales from a few days, to weeks, months, seasons and beyond. The intensified research attention on sub-seasonal predictions has been triggered by growing needs from applications, and inspired further by significant progress in medium-range forecasting and improvements in simulations of key sources of predictability for sub-seasonal to seasonal prediction, like El Niño Southern Oscillation (ENSO), the Madden Julian Oscillation (MJO) and their teleconnections (e.g. Lin et al. 2009, Vitart 2014).

Sub-seasonal forecasting is at a relatively early stage of development, bridging a gap between the more mature weather and climate prediction communities. To make progress in this area, many scientific and technical issues remain to be solved. In addition, coordination among forecast producers must be improved before the full potential of sub-seasonal prediction can be realised. Tantalizing glimpses now exist of potential predictability well beyond the range of normal numerical weather prediction (NWP) (~10 days), but the many processes influencing S2S predictability are still not yet fully understood. There is good evidence that predictive skill will be higher in certain windows of opportunity (e.g. as shown for Australia by Hudson et al. 2011, or in the US in Dole et al. 2014), but how to identify these opportunities in advance is still unclear. Relevant science issues ranging from sources of predictability, forecasting systems design, forecast quality assessment (verification) and services for user applications, are reviewed in this article.

20.2 RELEVANT PHENOMENON FOR SUB-SEASONAL TO SEASONAL PREDICTIONS AND PREDICTABILITY

The sources of sub-seasonal predictability are associated with various phenomena and processes in the atmosphere, ocean and land surface. This section describes briefly the main relevant areas of current research.

The Madden Julian Oscillation

The MJO is the dominant intraseasonal mode of organized convective activity in the tropics. It has large impacts in the middle and high latitudes as well, and is a major source of global predictability on the sub-seasonal time scale (e.g. Waliser 2011). Considerable efforts have been made on the prediction of the MJO, leading to the development of several empirical and statistical models (e.g. Waliser et al. 1999; Lo and Hendon 2000; Wheeler and Weickmann 2001; Mo 2001; Jones et al. 2004; Maharaj and Wheeler 2005; Jiang et al. 2008; Kang and Kim 2010). Useful predictive skill of the MJO from these empirical models extends out to about 15–20 days. Regarding dynamical models, ensemble prediction systems (EPS) have shown remarkable improvements in MJO forecast skill in recent years (see example in Figure 1). About 10 years ago, the actual forecast skill of the MJO by all the dynamical models was considerably lower than that of the empirical models (e.g. Chen and Alpert 1990; Jones et al. 2000; Hendon et al. 2000). In general these studies using dynamical models found some MJO skill only out to about 7-10 days. Recently, skilful MJO forecasts have been reported beyond 20 days (e.g. Kang and Kim 2010; Rashid et al. 2010; Vitart and Molteni 2010; Wang et al. 2014). This progress can be attributed to model improvements and better initial conditions, as well as the availability of historical reforecasts to calibrate the forecasts. However, limitations persist. In particular, the Maritime Continent is perceived to be a natural predictability barrier for the MJO. This is exacerbated in models by inadequate physical understanding and by limitations in model representations of MJO - Maritime Continent interactions. Several modelling studies (e.g. Vitart and Molteni 2010, Weaver et al. 2011) have shown that numerical models have difficulties propagating the MJO across the Maritime Continent.

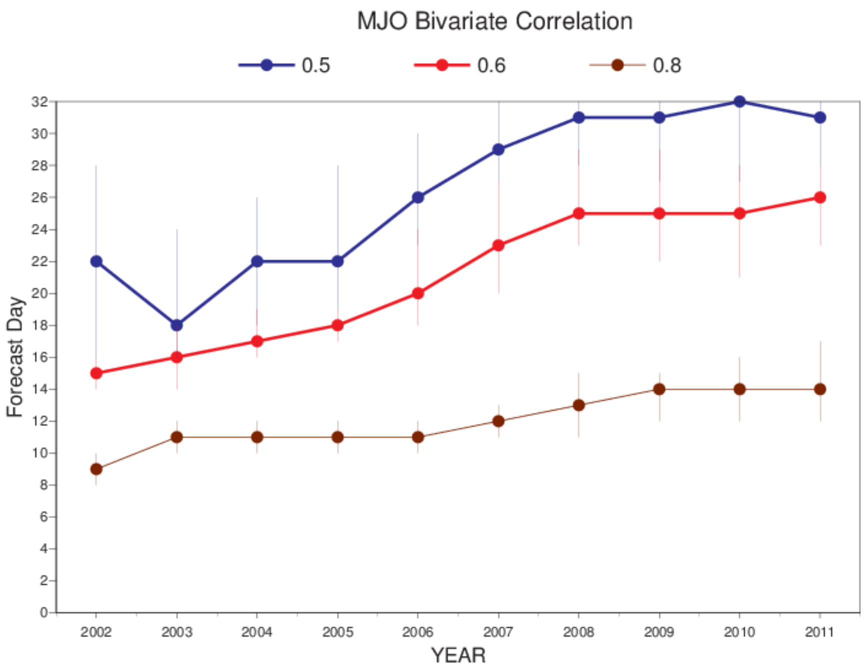

Figure 1. Evolution of the MJO skill scores (bivariate correlations applied to the Wheeler and Hendon Index (Wheeler and Hendon, 2004) in the European Centre For medium range Weather Forecasts (ECMWF) sub-seasonal forecasts since 2002 as indicated by the days when the MJO bivariate correlation reaches 0.8 (brown curve), 06 (red curve) and 0.5 (blue curve). The MJO skill scores have been computed on the ensemble mean of the ECMWF re-forecasts produced during a complete year. The vertical bars represent the 95% confidence interval computed using a 10,000 bootstrap re-sampling procedure.

ENSO

While ENSO has an interannual timescale, it plays an important role on the S2S scale for several reasons. It provides a large source of equatorial Pacific SST memory that is important in its own right as a source of sub-seasonal predictability, despite the shorter averaging periods (one to several weeks) relevant to sub-seasonal forecasts, as opposed to typically three months used in seasonal forecasting. Weather noise will be less attenuated by these shorter averaging periods, but can still result in an important source of precipitation skill for sub-monthly forecasts (Li and Robertson, 2015). In addition, the ENSO background state (ENSO phase) may impact the nature of the MJO and sub-seasonal anomalies (Yoo et al. 2010), and MJO-related westerly wind bursts are well known to have an impact on ENSO (Kessler et al. 1995; Vitart et al. 2001). ENSO conditions may also affect MJO teleconnections and their impacts, such as by shifting the probability distribution function (PDF) of daily weather, such as heat extremes or flood potential (Riddle et al. 2013, Robertson et al. 2015). The interplay between ENSO and MJO teleconnections raises the prospect of enhanced “windows of opportunity” for skilful sub-seasonal to seasonal predictions when and where these teleconnections are active and interacting (Johnson et al. 2014). Hudson et al. (2011) found that sub-seasonal forecast skill of the Predictive Ocean Atmosphere Model for Australia (POAMA) seasonal forecast system was enhanced over Australia when ENSO, the Indian Ocean Dipole and the Southern Annular Mode are active, while the MJO was not found to contribute skill in that case. Targeted forecasts of opportunity for situations of high conditional skill- perhaps in terms of spread-skill relationships- would be a departure from current seasonal forecasting practice where skill estimates are averaged across all reforecasts for a particular season and start date.

Soil moisture

Memory in soil moisture can last several weeks, influencing the atmosphere through changes in evaporation and the surface energy budget. These changes can affect sub-seasonal variability and forecasts of air temperature and precipitation in certain areas and seasons, as demonstrated by the Global Land-Atmosphere Coupling Experiment (GLACE) experiment (Koster et al. 2010). The GLACE experimental protocol consists in comparing an ensemble of model integrations where the land has been properly initialized with a second ensemble where the land initial conditions have been randomized. Three different studies have focused respectively on the United States, Europe and the global domain as documented in Koster et al. (2009), van den Hurk et al. (2012), Koster et al. (2010), respectively. The three studies showed the added value from realistic initialization of the soil moisture, measured in terms of predictability gain of 2 m temperature and precipitation on US and Europe with forecast lead times ranging from 16 to 60 days. The continental US has generally higher potential predictability that is also mirrored in retrospective forecast skill. It is remarkable that for temperature at 2 m over Europe the predictability gain obtained from better soil moisture initial conditions during the warm season, extends significantly beyond the ranges typically considered in NWP (and up to 16-30 days ahead), leading to increased lead times for anticipating extreme events such as summer 2003 (e.g. Weisheimer et al. 2011).

Snow cover and sea ice

The radiative and thermal properties of extensive snow cover anomalies can significantly modulate local and remote climate over monthly to seasonal time scales (e.g. Yang et al. 2001; Sobolowski et al. 2010; Lin and Wu 2011). Sea ice cover could also provide a source of memory that may enable some predictive skill at longer time scales in polar and midlatitudes (Holland et al. 2011). The degree to which sea ice anomalies influence the atmosphere locally and remotely in the mid-latitudes is not yet fully understood. Modelling results do suggest that sea ice anomalies can influence the atmosphere, especially in the sea ice margin zones of the Labrador Sea and Greenland-Icelandic-Norwegian seas (Deser et al. 2007), with potential effects on synoptic storm activity in surrounding regions (e.g. Bader et al. 2011). Progress in sub-seasonal to seasonal polar prediction hinges on significant improvements to the polar observing system, initialization of (coupled) models and representations of key polar processes such as stable boundary layers, mixed phase clouds, surface fluxes and sea ice are represented in numerical models. A further challenge is representing initial and model uncertainty in the polar regions, which may require modifications to the techniques that have been successfully used in the lower latitudes. Observational data is particularly limited in polar regions, leading to a large reliance on satellite observations. While satellite observations provide a useful characterization of some atmosphere and sea ice conditions, they provide little information on the underlying ocean. Issues with observational data sparseness, incompleteness, and bias are a critical challenge in terms of adequately initializing coupled model forecasts. Furthermore, satellite data are usually not sufficient when it comes to improving models at the processes level.

Stratosphere-troposphere interaction

Changes in the polar vortex and the Northern Annular Mode/Arctic Oscillation (NAM/AO) are often seen to come from the stratosphere, with the anomalous tropospheric flow lasting up to about two months (Baldwin et al. 2003). Perturbation experiments also reproduce negative NAO/AO in response to weakened stratospheric winds on both seasonal and longer timescales (for example, Boville 1984, Norton et al. 2003, Scaife et al. 2005, Scaife and Knight 2008). Jung et al. (2010) found that relaxation of the extratropical stratosphere to the observed state leads to forecast error reductions in the high latitude and European troposphere, but that the tropical stratosphere has no systematic impact. They caution against over-interpretation of these results, however, as the troposphere strongly influences the NH stratosphere, and other studies show a tropical QBO influence on the extratropical surface climate (Boer and Hamilton 2008, Marshall and Scaife 2010).

Ocean conditions

Sea surface temperature (SST) anomalies lead to changes in air-sea heat fluxes and convective heating, which affect atmospheric circulation. Studies show that tropical intraseasonal variability (ISV) forecast skill is improved when a coupled atmosphere-ocean model is used (e.g. Woolnough et al. 2007; Fu et al. 2007). The time scale of sub-seasonal prediction is such that the influence of atmospheric initial conditions on the predictability is decreasing while the contribution from slowly evolving oceanic conditions is increasing. For this intermediate range, realistic representation of ocean-atmosphere coupling can be important for at least two reasons. It is possible that as the contribution of atmospheric initial conditions on the prediction skill goes down, the relative contribution of including a realistic ocean-atmosphere coupling on prediction skill increases. However, the potential contribution of realistic ocean-atmosphere coupling on prediction skill relative to initial conditions, and how this contribution changes with lead time, has not been quantified. This primarily depends on the role of ocean-atmosphere coupling in constraining atmospheric variability. The correct representation of ocean-atmosphere coupling may be important for some specific phenomena, e.g. prediction of intensity and tracks of hurricanes, Madden Julian Oscillation etc., but of lesser importance for atmospheric variability in high latitudes, at least on synoptic time scales.

Tropics-extratropics teleconnections

There is great potential gain in sub-seasonal forecast skill in mid-latitudes if the model can realistically capture the atmospheric teleconnections associated with MJO. However, many scientific questions remain to be answered. For example, what is the relative importance of tropical convection in generating teleconnections in comparison to other dynamical processes such as interactions with synoptic-scale eddies? What are the processes involved in the initiation of tropical convection by Rossby wave-trains propagating from the extratropics into the tropics? There has not been a systematic assessment of how the current models perform in simulating global teleconnections on the sub-seasonal time scale, especially for those related to tropical-extratropical interactions. How the models differ and what determines a model's ability to accurately capture the teleconnections remains unclear.

20.3 EXTREME EVENTS

Extremes are of great interest to the weather, climate and user communities, for both climate attribution and real-time early warning. There have been several predictability studies on the 2010 Russian heat wave (Matsueda 2011; Dole et al. 2011) and simultaneous Pakistan floods (Webster et al. 2011; Lau and Kim 2011). It was suggested that the 2010 Russian heat wave was predictable up to 9 days in advance (Matsueda 2011), and the Pakistan rainfall was predictable out to 6-8 days (Webster et al. 2011). Both of the extreme events were related to an extraordinary strong and prolonged extratropical atmospheric blocking event, and excitation of a large-scale atmospheric Rossby wavetrain spanning western Russia, Kazakhstan, and north western China/Tibetan Plateau region. A connection with the monsoonal intraseasonal oscillation was also found (Lau and Kim 2011). The extremely warm March 2012 over US is a good example of how conditional information on different time scales enters into the prediction problem. Dole et al. (2014) showed that probability for extreme warmth evolved dynamically as different phenomena became predictable across time scales from climate (Pacific Decadal Oscillation (PDO) and ENSO) to MJO and weather, necessitating a seamless approach.

The predictability of extreme events at the sub-seasonal time scale often originates from the modulation of extreme events by the large-scale circulation (e.g. Marshall et al. 2013; White et al. 2013). For instance, White et al. (2013) showed that the increased skill of the POAMA sub-seasonal to seasonal coupled model prediction system to predict extreme heat in the winter months over northern Australia comes mainly from La Nina periods and over eastern and south-eastern Australia from El Niño periods, highlighting the impact of ENSO events on sub-seasonal forecasts. Identifying such windows of forecast opportunity requires a reforecast set that spans a sufficiently long period, particularly when associated with low frequency variability such as ENSO. Numerous studies have also shown the impact of the MJO on the probability of extreme events, like tropical cyclones (TCs). The modulation of TC numbers by the phase of the MJO has been quoted to be as high as 4:1 in some locations (e.g. Hall et al. 2001; Maloney and Hartmann 2000a). Statistical and dynamical models have been developed to predict the genesis or occurrence of TCs at the intraseasonal time range (Leroy et al. 2004; Frank and Roundy 2006; Leroy and Wheeler 2008, Vitart et al. 2010). Recently, the skill of the ECMWF monthly forecasting system for predicting tropical storm modulation of TC activity has been demonstrated, prompting a comparison of the skill and reliability of the statistical and dynamical models (Vitart et al. 2010). The MJO also modulates other extreme events such as the occurrence of tornadoes in spring in the United States (Thompson and Roundy 2013; Barrett and Gensini 2013), which can lead to skillful sub-seasonal to seasonal forecasts of severe weather activity (Figure 2).

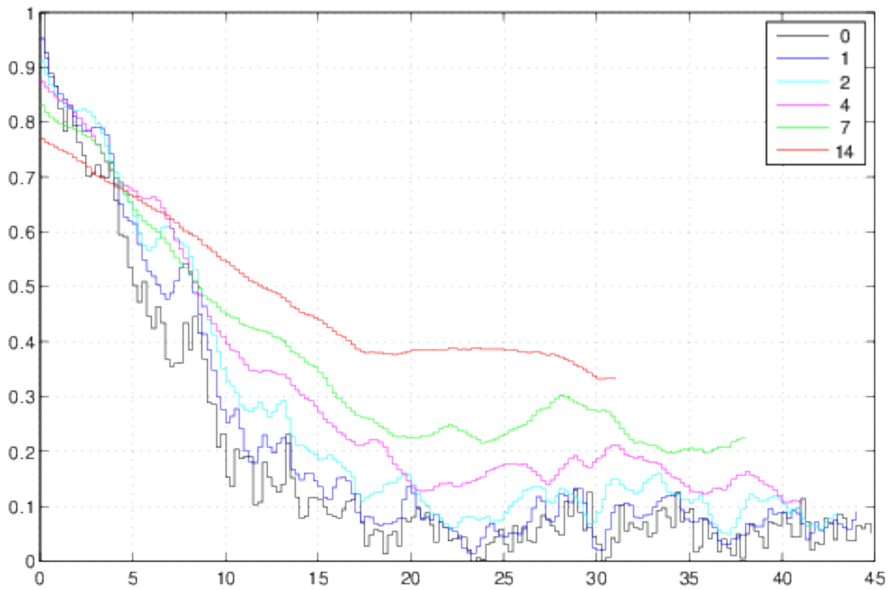

Figure 2. Correlation of a tornado environment index (TEI; Tippett et al. 2012) with CFSv2 forecasts during 2013 for averaging windows ranging from 6 hours to 14 days

Heat waves and cold waves are amongst the weather events which have the strongest societal impact. This is particularly true for the heat waves during the warm season and the cold waves during the cold seasons. For instance, the 2003 summer heat wave over Europe was particularly intense. Its overall impact on society was exceptional, with severe disruption of activities and heavy loss of life in many European countries. Health authorities estimated that because of the soaring temperatures about 14,000 died in France alone, and thousands more casualties were reported in other countries. The prediction of the evolution of such an extreme event (onset, maintenance, decay) a few weeks in advance would be particularly useful. Blocking diagnosis and the use of daily circulation regimes in forecasts and observations can be used to help understand sub-seasonal to seasonal predictability of weather extremes in mid-latitudes through tropical-extratropical teleconnections, as well as flow dependent predictability. Prediction systems with demonstrated skill can also help diagnose causes with implications for climate change attribution of extreme events.

20.4 DESIGN OF FORECAST SYSTEMS

20.4.1 Initialization

The approach for medium-range forecasting to date has been to use the most accurate initial conditions possible for the atmosphere and largely ignore the more slowly varying ocean conditions. For seasonal prediction, the initial conditions of the coupled system are important, particularly the upper ocean, and the rapidly varying components of the atmosphere are often less well predicted and initialised. Requirements for the sub-seasonal timescale probably lie somewhere in between. Forecasts on this timescale are influenced by initial conditions of both the fast (i.e. atmosphere) and slow (i.e. ocean, land and cryosphere) components of the coupled system. A major challenge for data assimilation and initialisation of sub-seasonal forecasts is to address these different time and space scales of the atmosphere and ocean to exploit information from both the fast and slow components.

The most common approach is to analyse and initialise the atmosphere and ocean components separately. Quite sophisticated schemes are generally used to analyse the atmospheric state, typically using four-dimensional variational (4d-var) or Ensemble Kalman Filtering (EnKF) data assimilation methods. Ocean analysis techniques tend to be less sophisticated but EnKF and 4d-var techniques are being developed. However, it is unclear whether uncoupled initialisation is optimal. Coupled data assimilation is often identified as a challenging but potentially more optimal alternative, such that observed information in one component is used to correct fields in the other coupled components. Research and development for coupled data assimilation are still in their infancy. No operational fully coupled data assimilation systems currently exist, although weakly coupled schemes, e.g. assimilation into each component of the coupled model separately, but evolving the background states using the coupled model, are being developed or, in the case of NCEP, already implemented. Ideally, coupled assimilation should include land surface conditions and sea ice to provide a balanced initial state for the whole coupled system.

Initial conditions are required not only for real-time forecasts, but also back in time (reanalyses e.g. ERA-Interim) for initialising the reforecasts needed for calibrating the real-time forecasts. This raises a number of issues:

- What observations of the coupled atmosphere-land–ocean system are needed for capturing details of the initial conditions for successful sub-seasonal predictions? For example, how important are correct stratospheric initial conditions?
- How important is it to have consistency between the initial conditions of the reforecasts and real-time forecasts?
- There are differences between reanalyses used to initialise reforecasts. How accurate are these reanalyses in describing sub-seasonal variability in the real-world? Are some reanalyses better than others and, if so, where and why?

20.4.2 Initial perturbations

The representation of uncertainty in initial conditions has been approached by using random sampling, singular vectors, breeding schemes or lagged averaging. The representation of uncertainty in model formulation has been approached by using multi-model, stochastic physics or perturbed parameters ensembles, although so far the latter has only been used in climate change and multi-annual forecast experiments. Some studies (e.g. Weisheimer et al. 2014) have shown that stochastic physics has a positive impact on the representation of the MJO in sub-seasonal forecasts. Lee et al. (2009) have also shown that sub-seasonal MJO forecasts produced by a multi-model ensemble were more skillful than the MJO forecasts produced by each model separately. The impact of stochastic physics or multi-model ensemble on other sub-seasonal skill scores in the Extratropics as well as in the Tropics needs to be investigated.

Alternatives need to be explored to optimize sampling uncertainty in the initial conditions. So far very few studies have tried to address this issue for sub-seasonal to seasonal prediction. Waliser et al. (2014) have shown that all current operational models display a spread in MJO predictions that is too small relative to the RMS error. It is not clear if, for instance, the singular vectors used in some operational centres to perturb the initial conditions are appropriate for sub-seasonal forecasting. It is also not clear if the lagged-ensemble approach produces better sub-seasonal to seasonal forecasts than a “burst” ensemble (i.e. an ensemble starting from a single initial time as opposed to a lagged ensemble). Hudson et al. (2013) showed significant improvements to the reliability and skill of sub-seasonal forecasts through the implementation of a breeding scheme compared to using a lagged-ensemble approach. On the other hand, Kang et al. (2014) showed that the MJO prediction skills of individual perturbation methods including the breeding and lagged-average methods are all similar, and the ensemble prediction system combining all the perturbation methods has a better skill than any individual perturbation methods. Effectiveness of the perturbation methods may be dependent on the models adapted. Also the focus should be on perturbing the slow modes of the coupled system, e.g. the MJO and annular mode. Some seasonal forecasting systems perturb the ocean, but perhaps stochastic parameterizations should be extended to the ocean and land surface models to account for uncertainty in model formulation. A challenge for the community would be to produce coupled ocean-atmosphere perturbations.

20.4.3 Resolution

Current operational sub-seasonal to seasonal forecasting systems use very different horizontal and vertical resolutions. Increased model resolution is expected to improve the forecast skill by allowing more physical processes to be resolved. Although the previous statement is derived mainly from work using atmosphere-only models, it is also applicable to coupled models. For example, resolution plays an important role with respect to tropical-extratropical teleconnections (Toniazzo and Scaife, 2006) and the responses of topography and surface fluxes to sea surface temperatures. However, coupled models may require resolutions at the Rossby radius of deformation (a few tens of km) in the ocean with comparable resolution in the atmosphere, in order for the atmosphere to respond with fidelity to ocean variability (Minobe et al. 2008). The impact of horizontal resolution is likely to depend on the phenomenon considered. For instance, higher resolution is known to have a positive impact on the representation of tropical cyclones. However, some studies suggest that increasing horizontal resolution had little impact on the representation and prediction of the MJO (e.g Vitart 2014). Vertical resolution can also impact sub-seasonal to seasonal forecasts. Increased vertical resolution in the stratosphere can improve the representation and prediction of a stratospheric sudden warming (Marshall and Scaife 2010). Increased vertical resolution in the middle troposphere has been documented has having a positive impact on the representation of the MJO (Inness et al. 2001)

20.4.4 Systematic errors

Despite decades of effort devoted to model development, persistent biases exist in the coupled general circulation models (CGCMs) in e.g. tropical precipitation, low cloud cover (e.g. Randall et al. 2007) used in climate simulations and sub-seasonal and seasonal prediction. Some of these biases will arise solely from the errors in the component models and some may arise from misrepresentation of the coupling processes themselves. Further, coupled feedbacks between the atmosphere and ocean may compound existing errors in individual components or generate new biases. Several authors (e.g. Jakob 2003, Phillips et al. 2004) propose the use of initialized forecasts to diagnose the development of systematic errors in models, both through the analysis of the very short range error growth using data assimilation increments, and through analysis of the time dependent growth of the initial error over the first few days of the forecast. To date much of this work has focused on atmospheric model development, making use of the regularly initialized operational forecasts, to provide a large database of the initial model error development. The increase in operational seasonal and sub-seasonal forecasting using coupled systems allows such an approach to be extended to coupled models and the impact of the coupling on the error development to be assessed.

The identification of systematic errors requires a sufficiently large database of initialized forecasts to distinguish between random errors and systematic errors. Furthermore if error is flow dependent then sufficient similar analogues of this flow state are required. Such an analysis for sub-seasonal to seasonal forecasts relies heavily on the reforecast dataset which needs to be long enough with an ensemble size large enough to allow the estimation of systematic errors and also flow dependent errors. It also requires that the re-forecasts share the same design as the real-time forecasts, with initial conditions as consistent as possible with the real-time initial conditions.

20.4.5 Cryosphere-ocean-atmosphere coupling

As use of coupled and uncoupled prediction systems varies across operational centres, the contribution of ocean-atmosphere coupling on monthly and sub-seasonal predictions and on modifying atmospheric variability is an important question for future operational monthly prediction systems. An implicit assumption for weather predictions based on atmospheric models is that because of the slow evolution of SSTs, the skill of persisting initial SST analysis remains high (Jung and Vitart 2006). Whether this holds for the monthly time scales, and how the skill of persistence of SST forecasts compares with predictions based on coupled models remains as an open question (Kumar et al. 2011).

Several studies have documented the impact of ocean-atmosphere coupling on some specific phenomena, e.g. prediction of intensity and tracks of hurricanes, Madden Julian Oscillation etc. The vertical resolution of the ocean model, particularly in the top ocean layer, has been documented to have a significant impact on the MJO through a stronger diurnal cycle of sea surface temperature (Woolnough et al. 2007). The frequency of ocean-atmosphere coupling may also have an impact on sub-seasonal to seasonal forecasts through a better representation of the sea surface temperature diurnal cycle (Ham et al. 2012).

Some of the state-of-the-art sub-seasonal to seasonal forecasting systems already have a sea-ice model and sea-ice initialization while others systems will have a sea-ice component in the near future. When it comes to modelling sea-ice, the use of a relatively high horizontal and vertical resolution becomes crucial since both the polar atmosphere and Arctic Ocean are characterized by a relatively shallow boundary layers, steep orography (e.g. Greenland and the overflow) and narrow straits as found for example in the Canadian Arctic Archipelago, all of which need to be adequately represented. In addition, representing model uncertainty in sea-ice is expected to be important to obtain reliable spread-skill characteristics.

20.5 APPROACHES TO INTEGRATE SUB-SEASONAL TO SEASONAL FORECASTS INTO APPLICATIONS

Sub-seasonal to seasonal prediction represents a great opportunity to inform societal decision makers, for example, of changes in risks of extreme events or opportunities for optimizing resource decisions, although important challenges remain to make sub-seasonal forecasts sufficiently reliable and skillful for some applications. A great return on investment in climate science and model development is to be expected if the science of sub-seasonal to seasonal prediction can be successfully connected to societal applications. Weather-related hazards, including slow onset and chronic events such as drought and extended periods of extreme cold or heat, trigger and account for a great proportion of disaster losses, even during years with other very large geophysical events (e.g. Haitian and Chilean earthquakes). While many end-users have benefited by applying weather and climate forecasts in their decision-making, there remains ample evidence to suggest that such information is underutilized across a wide range of economic sectors (e.g. Morss et al. 2008; Rayner et al. 2005; O'Connor et al. 2005; Pielke and Carbone, 2002; Hansen, 2002). This may be explained in part by the presence of 'gaps' in our forecasting capabilities, for example at the sub-seasonal scale of prediction, and by a lack of understanding and appreciation of the complex processes and numerous facets involved in decision-making.

Weather and climate span a continuum of time scales, and forecast information with different lead times is relevant to different sorts of decisions and early-warning. Extending downward from the seasonal scale, a seasonal forecast might inform a crop-planting choice, while sub-monthly forecasts could help irrigation scheduling and pesticide/fertilizer application, by making the cropping calendar a function of the sub-seasonal-to-seasonal forecast, and thus dynamic in time. In situations where seasonal forecasts are already in use, sub-seasonal ones could be used as updates, such as for estimating end-of-season crop yields. Sub-seasonal forecasts may play an especially important role where initial conditions and intraseasonal oscillation yield strong sub-seasonal predictability, while seasonal predictability is weak, such as in the case of the Indian summer monsoon. Extending from short-range weather prediction out to a week, which is much more mature, there is a potential opportunity to extend flood forecasting with rainfall-runoff hydraulic models to longer lead times. In the context of humanitarian aid and disaster preparedness, the Red Cross Climate Centre/IRI have proposed a "Ready-Set-Go" concept to make use of forecasts from weather to seasonal, in which seasonal forecasts are used to begin monitoring of sub-seasonal and short-range forecasts, update contingency plans, train volunteers, and enable early warning systems ("Ready"); sub-monthly forecasts are used to alert volunteers, warn communities ("Set'); and, weather forecasts are then used to activate volunteers, distribute instructions to communities, and evacuate if needed ("Go"). This paradigm could be useful in other sectors as well, as a means to frame the contribution of sub-seasonal forecasts to climate service development within the Global Framework for Climate Services (GFCS).

Impacts models, such as crop, hydrologic, and epidemiological models, are often run at scales of a few km or less, which generally necessitates downscaling of Ensemble Prediction System (EPS) forecasts. For example, the S2S project forecasts and reforecasts are being archived on a regular 1.5 degree longitude-latitude grid. Downscaling studies have mostly targeted climate change projections (e.g. the WCRP CORDEX project) and seasonal climate forecasts. A large literature has developed on GCM downscaling using statistical downscaling (SD) methods, beginning with, e.g. Kim et al. (1984), and nested limited-area high-resolution models, dynamical downscaling (DD), beginning with, e.g. Giorgi (1990). Several intercomparisons of statistical vs dynamical approaches have been made in the context of seasonal forecasting (e.g. Landman et al. 2009; Ethan et al. 2012; Lutz et al. 2012; Robertson et al. 2012), showing that SD can often rival or outperform more-complex and computationally demanding regional models, although this is also a function of the applications needs (variables, gridded vs point values, etc). Since high-resolution regional models still typically exhibit significant biases, hybrid dynamical-statistical approaches have been developed (e.g. Beaulant et al. 2011; Mao et al. 2014). On the weather forecast time scale the WRF model is run routinely in many countries for real-time weather forecasts using NCEP GFS boundary conditions (http://wrf-model.org/plots/wrfrealtime.php), while SD is less utilized beyond bias correction, presumably due to the spatial complexity of rapidly evolving weather systems. The S2S time range lies in between the primarily deterministic daily evolution of weather patterns in NWP, and seasonal forecasting where the statistics of weather are predicted, a problem well suited to SD. Thus, in the S2S domain, both SD and DD methods can be expected to play important roles, but few downscaling studies have as yet been carried out for this realm.

20.6 FORECAST QUALITY ASSESSMENT

Forecast quality assessment (i.e. forecast verification) is a critical component of making forecasts useful to applications. Seamless verification will be important for the sub-seasonal to seasonal time scale. For instance, the time windows for verifying short range forecasts is not the same as for seasonal forecasts: weather forecasts are verified on a daily basis, while seasonal ones typically use 3-month averages. A time averaging window equal to the forecast lead time could be a possible approach (Zhu et al. 2014), or an approach targeted toward weather regime transitions. There is also a need to unify the verification methodology used for medium-range databases (TIGGE) and seasonal databases (Climate-System Historical Forecast project (CHFP), EUROpean Seasonal to Inter-annual Prediction (EUROSIP)). In terms of science verification questions the S2S project will provide opportunities to address the following:

- What forecast quality attributes are important for verifying S2S forecasts, and how should they be assessed?
- How should issues of short hindcast period availability and reduced number of ensemble members in hindcasts compared to real-time forecasts be addressed when constructing probabilistic skill measures? How long the reforecast period is and how many ensemble size is needed for developing a reliable probabilistic forecast system and its verification?
- How can the contributions of MJO, ENSO and other potentially predictable phenomena to S2S forecast skill be assessed (e.g. consider skill assessment conditioned on ENSO phases and try to identify opportunities for improved skill when MJO and ENSO are acting simultaneously)?
- How well do current S2S forecast systems predict active and break monsoon rainfall phases and wet/dry spells?

20.7 THE WWRP-WCRP SUB-SEASONAL TO SEASONAL PREDICTION PROJECT (S2S)

Recent publications (e.g. Brunet et al. 2010; Hurrell et al. 2009; Shapiro et al. 2010; Shukla et al. 2010, Hoskins 2012) have stressed the importance of and need for collaboration between the weather and climate communities to better tackle shared critical issues, and in particular, to advance sub-seasonal to seasonal prediction. The S2S initiative bridges the gap between the numerical weather prediction and short-term climate prediction communities. It therefore addresses a critical requirement for building a seamless prediction system for weather and climate. Weather, climate, and Earth system prediction services will greatly benefit from this joint effort. The fundamental goals of the sub-seasonal to seasonal prediction (S2S) research project are to improve forecast skill and understanding on the sub-seasonal to seasonal timescales, and to promote its uptake by operational centres and exploitation by the applications community (Vitart et al. 2012). Achieving these goals will require establishment of an extensive database that contains sub-seasonal (up to 60 days) forecasts and reforecasts (sometimes known as hindcasts), modelled in part on the THORPEX Interactive Grand Global Ensemble (TIGGE) database for medium range forecasts (up to 15 days) and the CHFP for seasonal forecasts. The research topics of the WWRP/WCRP Sub-seasonal to Seasonal Prediction project (S2S) are organized around a set of six sub-projects (Madden-Julian Oscillation, Monsoons, Africa, Extremes, Verification and Tropical-Extratropical Interactions), each intersected by the cross-cutting research and modelling issues, and applications and user needs discussed in the above. The draft science plans of each sub-project are available on line (http://www.s2sprediction.net). It is hoped that these sub-projects will provide a vehicle for broad community research engagement in S2S. The database and these six sub-projects will promote the use of sub-seasonal to seasonal forecasts in applications and also help answer important scientific questions raised in this article, such as:

- What is the benefit of a multi-model forecast for sub-seasonal to seasonal prediction and how can it be constructed and implemented?
- What is the predictability of extreme events and how can we identify windows of opportunity for sub-seasonal to seasonal prediction?
- What is the best strategy for the initializing the forecasting system, including ocean, land and cryosphere? What is the optimal way to perturb ensembles of sub-seasonal to seasonal forecasts?
- What is the impact of horizontal and vertical resolution of atmosphere and ocean models on sub-seasonal to seasonal forecasts?

- What is the origin of the systematic errors affecting sub-seasonal to seasonal forecasts?
- How well do state-of-the-art models represent tropical-extratropical teleconnections?
- What forecast quality attributes are important when verifying S2S forecasts and how they should be assessed?
- What are current S2S forecasting capabilities for daily weather characteristics relevant to agriculture, water resource management and public health, such as heavy rainfall events, dry spells and monsoon onset/cessation dates?

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CHAPTER 21. NUMERICAL PREDICTION OF THE EARTH SYSTEM: CROSS-CUTTING RESEARCH ON VERIFICATION TECHNIQUES

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Abstract

In the last decade or so the meteorological community has seen the successful development and application of new and improved forecast verification methods for numerical prediction of the Earth system. Verification methods to evaluate ensemble forecasts have become essential because of the prominent role of Ensemble Prediction Systems as sources of numerical guidance in operational centres. Moreover, coupled atmosphere-land-ocean models are now routinely run in major centres to provide operational predictions on seasonal and multi-week time frames. This chapter focus on advances in methods for evaluation of forecasts of several different types of phenomena, as well as methods for different types of forecasts and different timescales.

21.1 INTRODUCTION

Numerical Weather Prediction (NWP) model forecasts have been verified since the 1950s when they first started providing reasonable predictions. Several World Meteorological Organization (WMO) Lead Centres for forecast verification[a] now coordinate the routine production of verification results for NWP and seasonal climate predictions from major national centres. Moreover, WMO's Commission for Basic Systems (CBS) encourages the exchange of standard verification scores for NWP models. In the case of NWP, these score included bias, root mean square error (RMSE), S1 skill score, and anomaly correlation of forecast fields on selected pressure levels. Recently, verification scores for surface parameters have been added to the exchange in recognition that the accuracy of surface parameter forecasts has improved as a consequence of scientific and technical advances in NWP capabilities and increased horizontal spatial resolution of many global models, which is below 20 km in many cases.

Verification methods to evaluate ensemble forecasts have become essential because of the prominent role of Ensemble Prediction Systems (EPSs) as sources of numerical guidance in operational centres. Moreover, coupled atmosphere-land-ocean models are now routinely run in major centres to provide operational predictions on seasonal and multi-week time frames. The benefits of this coupling at shorter ranges have also been recognized, and it is being applied by some centres; for example, the European Centre for Medium Range Weather Forecasting (ECMWF) EPS is now coupled from day 1. NWP and climate models are routinely used to drive downstream impact models for emergency management, hydrology, agriculture, energy, and many other applications. These downstream developments highlight the need for users to be involved in the evaluation process.

This volume describes the many advances made in numerical prediction and the challenges to be addressed in coming years. Improvements in numerical prediction require improved methods to verify these forecasts. This has been an active area of research in the last decade or two. The World Weather Research Programme (WWRP)/Working Group on Numerical Experimentation (WGNE) Joint Working Group on Forecast Verification Research (JWGFVR) was established in 2003 to promote work in this area. This group coordinates workshops, tutorials, and verification method intercomparisons, and is the focal point for verification of WWRP Forecast and Research Demonstration Projects (FDPs and RDPs).

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[a] *The Lead Centre for Deterministic Forecast Verification is located at the European Centre for Medium Range Weather Forecasts (ECMWF), the Lead Centre for Ensemble Forecast Verification is located at the Japan Meteorological Agency (JMA), and the Lead Centres for Long Range Forecast Verification are located at the Australian Bureau of Meteorology and the Meteorological Service of Canada.*

This paper describes some of the recent successes as well as current challenges facing the verification community, as reflected in recent workshops and other presentations and papers. The following sections focus on advances in methods for evaluation of forecasts of several different types of phenomena, as well as methods for different types of forecasts and different time scales. Remaining research and challenges associated with each of these topics are also considered. The final section summarizes the current state-of-the-art in forecast verification and describes some additional challenges in verification research and applications.

21.2 SPATIAL VERIFICATION METHODS

Short and medium-range NWP models have improved considerably over the years, while they have also been evolving toward ever-higher resolution. Moreover, the prediction of surface weather parameters has greatly improved. The spatial variability and intensity distributions of model variables increasingly resemble the variability and distributions of observations, and the ability to simulate the extreme values that are very important in a forecast and warning context is also improving. Traditional verification against standard observations may suggest that high resolution forecasts are less accurate than the lower resolution ones (e.g. Mass et al. 2002). The spatial and temporal scales of the verification have a strong influence on the measured performance with finer scales more prone to the "double penalty" associated with small errors in the location and intensity of a forecast feature.

To measure the performance of high resolution forecasts in a way that is more consistent with how they are used, several new spatial verification approaches have been proposed. Gilleland et al. (2010) describe these methods as neighbourhood (crediting "closeness" in space, time, and/or intensity, often through probabilistic approaches), scale separation (quantifying error at various scales), features-based (comparing attributes of forecast and observed weather features such as their location, size, intensity, etc.), and field deformation (measuring the distortion required to make the forecast resemble the observed field). Gilleland et al. (2010) compare more than a dozen spatial verification methods and their respective ability to measure location, intensity, and structure errors, distinguish skilful scales, and verify the predicted occurrence of events. Table 1 gives a summary of these capabilities by the type of verification approach. While all methods measure intensity bias, no single method addresses all types of errors. Therefore, it is necessary to either prioritise which types of errors are most important to the user and choose the appropriate verification approach, or preferably apply more than one type of verification method. More complex verification methods could be developed that address a greater range of error types.

Table 1. Intercomparison of traditional and spatial verification methods (after Gilleland et al. 2010). A tick indicates that the method addresses the given type of error, a cross indicates that it does not.

Category	*Scales with skill*	*Location errors*	*Intensity errors*	*Structure errors*	*Occurrence (hits, misses, false alarms)*
Traditional (gridpoint)	×	×	✓	×	✓
Neighbourhood	✓	×	✓	×	✓
Scale separation	✓	×	✓	×	✓
Features based	×	✓	✓	✓	✓
Field deformation	×	✓	✓	×	×

Neighbourhood and feature-based methods are becoming mature enough to be used routinely in many NWP centres to verify high resolution models. For example, the Met Office uses the fractions skill score (FSS; Roberts and Lean, 2008) and neighbourhood Brier score (Mittermaier, 2014a) to measure the scales at which the model shows useful skill for predicting rainfall and clouds. The Method for Object-based Diagnostic Evaluation (MODE) and the Contiguous Rain Area (CRA) method are used to characterize performance of rainfall forecasts in many national centres (Ebert and McBride, 2000; Davis et al. 2009, http:/www.hpc.ncep.noaa.gov/verification/mode/mode.php - page=page-1. These methods can be applied to other parameters (for example, wind, moisture, cloud) and can evaluate timing errors, though more research is needed to explore these possibilities further.

Advanced verification methodologies have mostly focused on rainfall, due in large part to the availability of spatially and temporally complete quantitative precipitation estimates from radar. These methodologies must be tested for their ability to provide useful performance information for other variables such as wind, waves, pollutants and other hazards, as well as for more benign variables like temperature, humidity and cloud cover. The second spatial verification method intercomparison project, called MesoVICT (Mesoscale Verification In Complex Terrain; Dorninger et al. 2013) focuses on testing spatial verification methods on precipitation and wind forecasts from both deterministic and ensemble NWP, and for the first time includes ensemble analyses as reference data to simulate uncertainty associated with observation fields. Verification researchers are encouraged to participate in this project to test existing and newly developed spatial verification approaches and to explore how to account for observational uncertainty.

In light of growing reliance on high resolution NWP models for predicting high-impact weather, work must continue on characterizing location and intensity forecast errors for small scale intense features - features for which small errors can have large impacts on decision-making and impacts. It may be possible in some circumstances to correct for systematic forecast biases, particularly where intensity biases are related to model resolution. Moreover, with short-range forecasts now being used to produce graphical (spatial) warnings, there is a strong need to extend spatial verification methods to evaluate timing (lead time, onset, cessation) and intensity performance of spatial warnings.

Spatial verification approaches also have potential to provide valuable insights on the performance of longer lead time (multi-week to seasonal) forecasts through their use to evaluate anomaly predictions (e.g. for temperature and precipitation). Neighbourhood methods are used to assess the value of downscaling (De Haan et al. 2014), while features-based approaches can be used to characterize errors in anomaly or other patterns (e.g. mean, variance, extreme fields) to provide more intuitive information for users and service providers. This topic is a current area of research.

21.3 METHODS FOR EXTREME EVENTS

A strong motivation for high resolution NWP is to predict extreme values associated with dangerous weather. One challenge in verifying predictions of extremes is the limited frequency of opportunities to observe them and, thus, collecting enough forecast-observation pairs to compute meaningful and robust statistics. Thus, the accuracy of extreme event forecasts can be challenging to assess. Moreover, in cases of extreme weather the observations themselves may be less trustworthy; for example, instruments may be destroyed by floods or windstorms or measurements may be compromised by the weather conditions.

Some common categorical contingency table-based verification metrics behave badly for rare events, making them ineffective at distinguishing variations in performance among multiple forecasting systems. In particular, Ferro and Stephenson (2011) show that for imperfect forecasts, the threat score and the Gilbert, Heidke, and Peirce skill scores asymptote to zero for rare events. Many of these scores are strongly affected by the number of correct non-events and provide little useful information on the model performance for rare events. Ferro and Stephenson have proposed a new class of scores called extremal dependence scores (EDSs) that reward hits and penalize misses and false alarms, and also behave much more consistently with the forecast performance observed for less rare events. The simplest EDS is the extremal dependence index (EDI), defined as

$$EDI = \frac{(\ln F - \ln H)}{(\ln F + \ln H)},$$

where F is the false alarm rate and H is the hit rate (both of which must be non-zero). While the interpretation of the EDI is less clear cut than for the threat score, it has the strong advantage of being able to better distinguish the performance of competing models for rare binary events. Extreme value theory, widely used to analyze extremes in the climate context, offers some promise for evaluating the performance of extreme weather forecasts of continuous variables (Prates and Buizza, 2011). A threshold-weighted continuous ranked probability score (CRPS) was recently proposed by Gneiting and Ranjan (2011) as a strictly proper score for evaluating probability forecasts for extremes.

Forecasters increasingly rely on guidance from numerical predictions to issue watches and warnings for severe and high-impact weather. In contrast to routine forecast verification with fixed base times and valid times, warning verification requires the evaluation of lead time and warning duration relative to the onset and cessation of the event being warned for. Trade-offs between lead time and warning accuracy need to be assessed in order to inform user-focused studies of warning effectiveness in the face of false alarms (Wilson and Giles, 2013).

The spatial extent of a warning also influences the verification; it is easier to accurately warn for an event somewhere within a large area (e.g. a county or state) than in a small area like a town. Similar to neighbourhood verification, it may be desirable to apply "soft" criteria to warning verification - within X km, within Y minutes, within ±1 intensity category, etc., as well as "hard" criteria, to understand better the warning performance as function of scale and other factors (Neal et al. 2014). This is particularly true when observations are incomplete, as in the case of tornado sightings, in which case it may be necessary to treat observations in a probabilistic manner (Brooks et al. 1998; Hitchens et al. 2013).

With improving forecasts and warnings for extreme weather and its impacts becoming increasingly the focus of operational meteorology, greater efforts must be made to develop methods for objectively evaluating and communicating their performance in terms that users can understand. Relevant metrics might measure lead time, accuracy of predictions for "unsafe" and "all-clear" conditions, and dollars saved or losses averted relative to the no-forecast case or some other standard. Section 21.7 discusses user-oriented verification in more detail. A useful metric in this context is the relative (or potential) economic value (Richardson, 2000), which translates forecast skill into potential economic gain for users with different cost/loss ratios. It has been also found to be a useful framework for assessing the benefit of probabilistic vs. deterministic forecasts for extreme events (Haiden et al. 2014; Magnussen et al. 2014).

21.4 METHODS FOR ENSEMBLE AND PROBABILISTIC PREDICTIONS

Ensemble prediction is now being used at all scales to explicitly account for forecast uncertainty related to initial conditions and model uncertainties. EPSs can be evaluated in several different ways with the choice of approach dependent on how the forecast is intended to be used. Specifically, the ensemble members can be evaluated individually as deterministic forecasts or the ensemble can be summarized using a representative member such as the ensemble mean; they can be evaluated as probabilistic forecasts (e.g. by translating the ensemble prediction to a probability distribution or by estimating probabilities for specific events); or they can be evaluated as a distribution. While methods focused on the first two options are relatively well-established, methods for evaluation of a whole distribution are still relatively new, and improved diagnostic and intuitive approaches for evaluation of EPSs are still needed.

Traditional verification of probabilistic and distribution forecasts from EPSs is based primarily on metrics such as the Brier skill score (for probability forecasts) and CRPS (for the whole distribution), and diagnostics such as reliability and relative operating characteristic (ROC) diagrams and rank histograms, to assess spread-error consistency and reliability and discrimination of probability and ensemble forecasts. The ignorance score (Roulston and Smith, 2002) is also becoming more commonly applied as a single number to evaluate the quality of an ensemble distribution without inferring the preferences of a particular user. This measure has recently been decomposed to represent attributes that are similar to the attributes of reliability and resolution represented by the Brier Score (Weijs et al. 2010; Tödter and Ahrens, 2012).

The “spread-skill” relationship is often relied upon to determine the adequacy of the ensemble in appropriately capturing the forecast uncertainty; yet the methods for doing so are varied and the interpretations often not completely clear. A proposed new error-spread score (ES) verifies the moments of the forecast and is able to distinguish between dynamically reliable forecasts from an ensemble prediction system and the statistically reliable (but non-varying) dressed deterministic forecasts (Christensen et al. 2015). Hopson (2014) explores the nuances associated with different approaches to estimating and comparing spread and skill.

Ferro (2014) considers the “fairness” of scores such as the Brier Score and CRPS for evaluation of ensemble predictions. In Ferro’s study a score is defined to be fair if “the expectation of the score with respect to the distributions of both the ensemble members and the verifying observation is optimized when these distributions coincide”. Ferro’s work indicates that the Brier, ranked probability and continuous ranked probability scores are unfair. However, appropriately adjusted versions of these scores are fair. Meta-studies like this - related to properties of scores - provide valuable guidance for the application of the scores and the interpretation of the results. They are important contributions to the verification knowledge base as new scores gain wider use.

Spatial methods are now starting to be used to evaluate ensemble predictions - this is a promising area of research and application, especially as convection-permitting ensembles become a routine tool for high-impact weather prediction in some national centres. Neighbourhood verification methods are easily extended to include an ensemble dimension (e.g. Duc et al. 2013; Ben Bouallègue and Theis, 2014; Mittermaier, 2014a), and scores such as the FSS can be used to characterize the ensemble spread (Dey et al. 2014). Approaches for feature-based ensemble verification are still being investigated (e.g. Gallus, 2010; Johnson et al. 2013). Suggested approaches include verifying objects in probability maps, verifying the "ensemble mean" using spatially averaged forecast objects (possibly with histogram recalibration) or objects generated from average object properties, and evaluating distributions of object properties.

Because the field of ensemble verification is still relatively young, there is a continuing need for more intuitive and informative methods. This will be an important area of research in the future.

21.5 UNCERTAINTY IN VERIFICATION RESULTS

Uncertainty in verification results arises from many sources. Perhaps most importantly, observations are inherently uncertain due to measurement as well as spatial and temporal representativeness errors, and application of forecast verification to limited samples of forecasts leads to uncertainty related to sampling variability. Sampling variability is somewhat more straightforward to account for than observation-related uncertainty, and methods for estimating statistical confidence intervals have been defined for many verification measures (e.g. Jolliffe, 2007; Gilleland, 2010) and are included in at least some verification packages (e.g. the Model Evaluation Tools (MET): http://www.dtcenter.org/met/users/). These approaches generally take into account the effects of temporal correlations; accounting for the impacts of spatial correlations on the confidence intervals is somewhat more problematic and is generally not adequately addressed. Methods for applying confidence intervals to differences in performance for paired samples lead to more powerful statistical comparisons of model forecast performance.

While taking into account observation uncertainty in verification studies is still a research topic, some knowledge has been gained in recent years. However, much more knowledge and new capabilities are required. Fundamentally, as models have improved, it is no longer appropriate to ignore observation error; in fact, as models improve, the apparent error in forecasts will become closer and closer to the error in the observations. Ideally, biases in observations can be removed (when they are known) but it is more difficult to account for the random errors, which lead to poorer verification scores for deterministic forecasts. Verification results for ensemble forecasts are characterised by poorer reliability and ROC area in the presence of observation error.

A few solutions have been suggested for accounting for observation error in verification analyses to try to estimate the "true" forecast performance against perfect observations. A simple example is to include error bars in scatterplots of forecasts vs. observations. Ciach and Krakewski (1999) proposed approaches for coping with observation errors in computation of RMSE values; and Bowler (2008) considered how to incorporate observation uncertainty into categorical scores. In addition, Santos and Ghelli (2011) have looked at a version of the Brier Skill Score that accounts for observation uncertainty. A difficulty with these approaches is that in the absence of a "gold standard" of the true value of the observed parameter, the observation errors are themselves only estimates and can lead to unrealistic estimates of forecast error. Triple collocation analysis can potentially provide estimates of error variances for three or more products that retrieve or estimate the same geophysical variable using mutually independent methods; however, a recent study suggests that cross-correlation of errors causes the true random error to be underestimated (Yilmaz and Crow, 2014). Mittermaier (2014b) explored the impact of temporal sampling on the representativeness of hourly synoptic observations by considering 1 minute surface observations of temperature. Though information on the variance of the residuals can be derived, it is less clear how these should be applied, and this is an area of current research. Initial results would suggest that there may be a limit to achievable forecast accuracy.

Another area of concern is the difference in forecast performance that is apparent when comparisons are made with multiple observation sources (e.g. different analyses; gauges vs. radars) (Tollerud et al. 2014). Accounting for this variability is difficult but important. Differences in analyses provide another representation of the uncertainty associated with observations and their appropriateness for matching to specific forecasts. Gorgas and Dorninger (2012) investigated the use of an ensemble of objective analyses as verification for NWP forecasts of surface variables, to quantify the uncertainty in verification results associated with the spatial treatment of the observations. The MesoVICT project will provide an opportunity to test the sensitivity of different traditional and spatial verification methods to choice of analysis, and ways to potentially exploit this analysis variability to provide useful insights on forecast performance (see Section 21.2 for more on this project).

The wisdom of using a model's own analyses (i.e. the model state at its initial time, following data assimilation) to verify its forecasts has come under increasing scrutiny following recent findings that such results may lead to incorrect conclusions about the nature of model errors (Yamaguchi et al. 2014). Model biases carry over into the analysis from the model-based background field, especially where observations are sparse, leading to underestimates of model error and over-estimates of ensemble dispersion in the short range. Members of WGNE investigated this problem, verifying NWP models from each centre against its own and others' analyses, and found some surprising behaviours including model errors sometimes improving with lead time when verified against other centres' analyses (WGNE, 2014). As a result WGNE recommended putting greater emphasis on verification against observations.

When spatially complete observation fields are required for verification, model-independent analyses such as the Vienna Enhanced Resolution Analysis (VERA; Steinacker et al. 2000) may be used confidently where the observation density supports regular gridding. In regions where observation density is highly variable, such as Canada, it may be possible to use a modified grid. Casati et al. (2014) proposed a wavelet-based objective analysis scheme in which the size of each grid box varies according to observation support; verification is then performed at different scales according to the observation availability. Further efforts are needed to test this approach and refine it for sensitivity to observation type, network density, error characteristics, and other factors.

21.6 LONGER TIMESCALES AND SEAMLESS PREDICTION

Numerical prediction beyond the medium range requires coupled atmosphere-land-ocean modelling to account for the more slowly varying processes associated with land surface processes, ocean circulation, and sea ice evolution. Coupling may benefit the shorter ranges as well. In 2008, ECMWF introduced operational coupled ensemble prediction starting at day 11 in its variable resolution EPS system (VAREPS), and in 2014 introduced coupling starting at day 1, representing truly seamless prediction across time scales from the short- to sub-seasonal range. Other major NWP centres are expected to follow suit in due course.

Evaluation of seamless numerical prediction requires verification approaches that allow for consistent interpretation across time scales. This is tricky because short- and medium- range forecasts tend to be deterministic or ensemble predictions of instantaneous[b] "absolute" weather variables at fine spatial and temporal scales, whereas extended range forecasts are based on coarser resolution ensembles, are typically given as probabilistic predictions of weekly or fortnightly anomalies being in a particular category (e.g. highest tercile), and rely on large hindcast datasets for forecast calibration. The variables of greatest interest in the extended range include surface precipitation and temperature, features such as tropical storms and monsoon onset, and indices for modes of variability such as the Madden-Julian Oscillation (MJO).

The verification approach should reflect the way the forecasts are used. In research mode verification of extended range forecasts is generally done against independent observations from surface networks or satellite, or against the hindcast dataset using cross-validation, using standard ensemble and probabilistic diagnostics and metrics like spread-skill plots, reliability and ROC diagrams, and Brier skill score. Real-time verification may compute these metrics for the most recent set of *N* (e.g. 30) forecasts. A challenge for real-time long range forecast verification is estimating robust statistics when the number of forecasts issued in a month or season is relatively small - much smaller than for NWP. For reporting forecast quality to users, simple verification approaches such as percent correct for forecasts above/below the median are often used, but this is not sufficient for model development and improvement.

Seamless verification methods to evaluate medium and extended range models in a consistent way are in their infancy and much more research is needed. A few proposed approaches are mentioned below.

Since the coupled model starts with a set of initial conditions and integrates forward in time, it predicts weather en route to predicting climate. Therefore, verification approaches that are appropriate for weather forecasting can be applied to the shorter-range predictions from coupled models to assess the ability of the model to correctly represent processes. The Transpose-Atmospheric Model Intercomparison Project (AMIP) strategy of verifying climate models in NWP mode is an efficient way to detect errors in model processes that become apparent as biases early in the forecast period (Williams et al. 2013). Modelling centres should include this powerful approach in their programme of model evaluation activities, using as reference data not only standard meteorological observations but also satellite radiances, surface flux measurements, sea surface temperatures, and other non-standard observations.

The real-time multivariate MJO index (RMM) phase plot (Gottschalck et al. 2010) is a climate-focused verification approach that can also be applied to medium-range NWP. There is a need for additional metrics to diagnose other modes of sub-seasonal climate variability in NWP and coupled models.

A seamless approach for comparing forecasts from an extended range prediction system across time scales was proposed by Zhu et al. (2014). They verified 1 day ahead forecasts of 1 day rain accumulation, 2 day ahead forecasts of 2 day accumulation, and so on, out to 4 week ahead forecasts of 4 week rain accumulation. They computed the temporal correlation of observed and

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[b] *Rainfall is an exception; short-range quantitative precipitation forecasts (QPFs) are typically accumulated over scales of 1 or more hours*

forecast ensemble mean rainfall at each grid box and found little change in the results whether they used total rainfall or rainfall anomalies. This approach of equivalent lead and aggregation time would also be amenable to verification metrics for categorical, probabilistic, and ensemble forecasts. Depending on the chosen metric (and the verification question it addresses), one could determine the temporal scales with useful prediction skill according to that metric - this would be a promising avenue to explore.

The generalized discrimination score (GDS) described by Mason and Weigel (2009) provides a consistent verification approach across different types of forecasts. Also known as the two-alternative forced choice (2AFC) approach, this method quantifies how well the forecast correctly discriminates between the observations. It has the same meaning when applied to forecasts that are formulated as binary, multi-category, continuous, or probabilistic variables, which can be verified against observations that may be (any of) binary, multi-category, or continuous. The GDS would therefore enable model performance for deterministic short-range forecasts and probabilistic sub-seasonal forecasts of anomalies to be compared in a consistent manner.

Weather represents the rapidly varying flow within a larger scale (climate) regime. Verification of extended range predictions conditional on the climate regime has led to identification of periods of enhanced predictability associated with planetary-scale teleconnections. For example, the MJO phase of tropical convection in the initial state impacts the Northern Hemisphere conditions three weeks later (Vitart and Molteni, 2010). These "windows of opportunity" for enhanced prediction skill are not yet well understood, and require further conditional verification to quantify their benefit in predicting overall weather conditions for applications such as agriculture and water resources.

New applications for extended range prediction will require appropriate verification approaches to be developed. Some examples include windiness / storminess for renewable energy estimation, wave regimes for beach erosion and public safety, heat and humidity conditions for tourism, and so on. New user-relevant metrics will need to be developed in many cases, in close consultation with the relevant sectors.

Many thresholds may be necessary to satisfy a large range of users. For this reason, and for diagnosing and correcting errors in ensemble predictions, verification of the full distribution may be more desirable than simple metrics based on forecasts for terciles or above/below median. The probability integral transform (PIT) and rank histograms can be used to assess the calibration of probabilistic and ensemble forecasts, but research is needed on the best way to evaluate forecasts when the tails of the distribution may be more "valuable" and important to predict correctly. As noted in Section 21.3, the research on methods for verifying probabilistic forecasts of rare extreme events is still in its infancy. Advances in this area are needed to support evaluation of forecasts for extremes across all time scales.

New methods and simple metrics are needed to assess model performance in simulating the climate modes and teleconnections that enhance sub-seasonal predictability. The RMM index for verifying MJO is already in wide use, but other features that require the development and testing of verification metrics include blocking highs, land surface conditions, sea ice concentration and extent, monsoon phase, and storm track variations. Many of these features are coherent structures and may be amenable to the use of spatial verification approaches described in Section 21.2, possibly extended or modified to include the time dimension.

To focus on some of these issues, the community can make use of knowledge gained in the Climate and Ocean: Variability, Predictability and Change (CLIVAR) project and the MJO working group who have focused on the connections between larger-scale phenomena and the performance of forecasting systems. Two of the legacy projects from the WMO's THORPEX (THe Observing System Research and Predictability EXperiment) programme - namely, the Sub-seasonal to Seasonal Prediction Project (S2S, see Chapter 20) and the Polar Prediction Project (PPP, see Chapter 19) - will conduct and apply research on relevant verification methodologies and observations, which should lead to advances in the verification methodologies available for longer-range predictions. The WGNE/WGCM Climate Metrics Panel is developing and promoting a metrics toolkit for verifying the output of coupled climate models, starting with basic quantities like bias and RMSE of key state variables. Diagnostic and process-oriented verification techniques will be included in future releases; many of these techniques may be relevant for assessing extended range predictions.

Improved verification methodologies for extended range forecasts must be tested on large datasets comprising the output of seamless modelling systems, hindcast datasets for calibration and cross-validation, and well-characterized high quality global observations of precipitation, temperature, and other relevant variables. The Obs4MIPS (Observations for Model Intercomparisons) activity, which is making observational products more accessible for climate model intercomparisons, is a good source of non-real-time data (Teixeira et al. 2014). Routine verification in near-real-time (relatively speaking) should leverage current operational seasonal and NWP verification systems.

To advance these developments and applications, verification researchers will need to work with both the short-range and long-range modelling communities who are converging on extended range prediction but still tend to view the world somewhat differently. Verification systems must accommodate different data formats (e.g. GRIdded Binary (GRIB) vs. network Common Data Form (NetCDF)) and temporal/spatial aggregations. Verification of seamless modelling systems must also provide objective evidence to inform the choice that many major centres have between frequent model upgrades to incorporate improvements and boost short-range accuracy, versus freezing a model to accommodate the time consuming generation of hindcasts necessary for calibration.

21.7 ENVIRONMENTAL VARIABLES AND DOWNSTREAM PRODUCTS AND IMPACTS

Seamless prediction also refers to the coupling of weather predictions to other environmental variables such as atmospheric composition and aerosols, streamflow, water quality, and vegetation state. For many years the coupling was one way, but NWP systems such as ECMWF's Integrated Forecast System (IFS) now have the ability to carry some environmental variables directly within the model. Understanding the interfaces and identifying how error sources are propagated from one system to another is critical if predictions are to be improved. Although verification of environmental variables typically uses many of the same statistical metrics and approaches as used to verify meteorological variables, it may be preferable to develop new methodologies targeted to the problem at hand. For example, Demargne et al. (2009) describe diagnostic metrics for verifying deterministic and ensemble hydrologic forecasts that are meaningful for users in the water community.

Weather forecasts inform decision-making in a number of spheres (emergency management, energy, aviation, agriculture, tourism, and many more). A focus area for WWRP is the coupling of weather predictions to downstream impacts. Some centres are doing this automatically by using direct or post-processed NWP model output as input to impact models. An example is the Flood Forecasting Centre in the UK where model output from the variable resolution (UKV) meteorological model is fed directly to the hydrological model for predicting streamflow (Pilling et al. 2014, Lewis et al. 2014). Other examples of downstream impact models include fire spread models and renewable energy generation models.

Impact forecasting raises some interesting challenges for verification. Many of the same issues that arise with verifying warnings of extreme weather (timing, intensity) also apply to warnings of impacts associated with extreme weather. Observations of the impacts may be difficult to obtain for a variety of reasons relating to how they are collected, and by whom, how they are stored and disseminated, and whether they measure something that can be predicted and verified or are only indirectly related to the impact. In some cases that data is purposefully unavailable for commercial or national security reasons. It will be necessary in many cases to strengthen or form relationships with the organizations holding the relevant impact data in order to understand and obtain the data. The opportunities for partnering of meteorological and other agencies can lead to more effective services for the public and other stakeholders.

Communication between the meteorological and various downstream communities is often challenging, with each sector "speaking their own language" and having their own priorities for what makes a forecast useful to them. To enable the benefits of improved weather forecasting to be translated into improvements in downstream impact forecasts, it is necessary to develop and apply verification metrics that are meaningful to the downstream users. The best way to do this is through direct engagement with the users to produce “user-relevant” metrics.

The aviation industry is a heavy user of meteorological forecasts. An example of a jointly developed aviation-oriented verification metric is the flight time error, a measure of forecast upper-air wind accuracy that computes the difference between the observed flight time and the forecast flight time calculated by replacing the actual winds along the flight track with the forecast winds (Rickard et al. 2001). Other examples of user-relevant approaches include the application of spatial techniques to track the occurrence of low-pressure systems, the development of measures to evaluate wind “ramps” for the renewable energy industry, and the measurement of forecast consistency for tropical cyclone track forecasts (Hodges, 1999; Bossavy et al. 2013; Fowler et al. 2015). Methods are also needed to translate verification information into socioeconomic benefits through the application of appropriate cost-loss and other models.

Crowdsourcing and data mining of mobile phone networks, Twitter, Facebook, and other social media, are emerging and promising sources of information that may be used to infer the occurrence, coverage, and impacts of hazardous weather (Hyvärinen and Saltikoff, 2010, Muller et al. 2015). The use of these data for verification is only beginning to be explored. A 2013 study comparing crowdsourced hail observations to official hail reports and severe warning polygons in the United States suggested that, due to biases and inaccuracies related to population density and observer engagement, these crowdsourced data should only be used in conjunction with other databases in order to ensure quality (Pehoski, 2013).

The propagation of errors from the meteorological forecast into the downstream impact forecast needs to be quantified and understood. This requires sensitivity testing, including of the assumptions made by the impact model (i.e. understanding its output errors given perfect input). The longer the chain of models, the more opportunity there is to compound errors. The area that has received by far the greatest attention is the propagation of uncertainty from NWP into hydrological prediction (e.g. Zappa et al. 2010), where it has been shown that the major source of error in hydrological predictions is due to uncertainties in the predicted rainfall. Similar work is required for other hazards to allow greater understanding of the relationships in performance along the forecasting chain.

The application of meteorological verification in additional - but often related - fields also represents a challenge. Just as weather forecast verification methodologies are more advanced than the techniques applied in climate forecast evaluation, these methods are also relevant for other physical and social phenomena for which verification has not traditionally been a key activity. For example, weather forecast verification techniques are being adapted for application in areas such as ocean current and earthquake prediction. Extending our efforts into these areas will undoubtedly lead to new challenges related to users, observations, and methodologies.

21.8 LINKAGES TO OTHER ACTIVITIES

Verification is a critical component of any prediction research and application, and applies to all variables, space and time scales that can be predicted and observed. Each project of the WWRP has a strong verification component that includes both traditional approaches and new improved verification methods that may address some of the more challenging questions about forecast performance. Although the JWGFVR is a focal point for verification research and supports the WWRP in this aspect, there is great interest and innovation in verification throughout the weather and climate community. Some verification research linkages within WWRP and with other activities are noted below.

The Polar Prediction Project (PPP) aims to improve operational forecasting at high latitudes. The baseline forecast performance must first be established through increased attention to verification in the Arctic and Antarctic regions. There are significant observational challenges associated with the sparseness and quality of standard observations, especially in extreme conditions. It is likely that satellites will provide a very important source of data for verification, with model evaluation in "observations space" (simulated satellite radiances) likely to be more robust than using retrieved atmospheric variables for verification. PPP has identified sea ice prediction as one of its priorities, so methods for verifying ice extent and concentration will need to be tested and improved, for both large (basin) and very fine (seaport) scales. Spatial verification methods may prove to be quite beneficial for application to these kinds of predictions. In addition, development of user-relevant methods to verify key polar weather and climate phenomena (e.g. blizzards and fog/visibility) is an important need for this project.

The verification sub-project of the Sub-seasonal to Seasonal Prediction Project (S2S) will recommend verification metrics and datasets for assessing forecast quality of S2S forecasts, and provide guidance for a potential centralized verification effort for comparing forecast quality of different S2S forecast systems, including the comparison of multi-model and individual ensemble systems. Verification research is required to develop user-relevant metrics for sub-seasonal to seasonal forecasts and downstream applications, and to determine how to cope with short hindcast periods and the reduced numbers of ensemble members in hindcasts (compared to real-time forecasts) when constructing probabilistic skill measures. Spatial verification of coherent structures in the anomaly fields will also be explored.

The High-Impact Weather (HIWeather, see Chapter 24) project focuses on weather hazards and their impacts, including how improved high-impact weather predictions can lead to enhanced community resilience through better understanding of risk and vulnerability and more effective communication. Verification research in this project will develop methodologies for verifying predictions of hazard impacts (e.g. floods, transport delays, damage to property, injuries, etc.), and explore the use of new types of observations for verification. The potential utility of crowdsourced and third-party data from social media, sensor networks, and other new technologies is of great interest. With help from the Societal and Economic Research and Applications (SERA) working group, the translation of accuracy improvements into socioeconomic benefit (for example, increased forecast lead time leading to greater opportunities to protect assets and thereby reduce losses) will be investigated for different sectors. Verification methods for nowcasts and high resolution NWP ensembles, especially for predictions of extreme values, will also be tested in this project.

Urban meteorology is receiving increasing attention as numerical models and understanding of urban micrometeorology and atmospheric chemistry enable more accurate very fine scale prediction of weather and environmental conditions. The Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) project helps national meteorological centres deal with urban issues, especially air pollution. Traditional verification of forecast concentrations of chemical species and particulates against observations from monitoring sites could be augmented by spatial verification approaches using satellite aerosol optical depth measurements, application of new methods to verify extreme values, and development of user-oriented verification metrics for public health applications. Obtaining adequate observations in the complex urban environment poses a significant challenge for advancing urban meteorology (Carmichael et al. 2014).

Forecast and Research Demonstration Projects (FDPs and RDPs) are useful testbeds for new verification techniques, providing opportunities for verification researchers, nowcast developers, modellers, forecasters, and downstream users to interact closely to improve their respective capabilities. They have provided valuable insights on the utility of real-time verification, and further efforts in this direction should be strongly encouraged.

WGNE has a long history of promoting verification research to help the major numerical modelling centres with model evaluation and intercomparison, and to support WGNE experimentation (recent examples include the Transpose-AMIP, Grey Zone and Analysis Verification projects; WGNE, 2014). WGNE's interest in verification methodologies will remain strong as the capability of numerical modelling systems and data assimilation systems evolve, and new observations become available for data assimilation and verification. The THORPEX Interactive Grand Global Ensemble (TIGGE) dataset will continue to be an important resource for exploring new approaches for verifying ensembles and products derived from ensembles (e.g. tropical cyclone strike probability, heavy rainfall probability, storm tracks, etc.), and addressing issues related to the use of model analyses in verification.

Finally, training and education through workshops and conferences, tutorials and courses, websites, WMO documents, journal articles and other literature, are vital to promote the science and practice of verification. WMO has supported much good work in this area and it is hoped that this can continue.

21.9 SUMMARY AND PROSPECTS FOR THE FUTURE

In the last decade or so the meteorological community has seen the successful development and application of new and improved forecast verification methods for numerical prediction of the earth system; yet many challenges remain.

- Spatial verification methods are becoming mainstream and are in some cases applied operationally as well as in research settings. New research is needed to understand how well these methods apply in regions of complex terrain, for ensemble forecasts, for variables other than precipitation, and how they can be extended into the temporal domain to address timing errors.
- New scores have been developed that provide better ways to compare the ability of forecasting systems to predict extreme events; more experience with application of these scores will lead to their wider use and also to development of additional approaches for this difficult challenge, particularly in the context of ensemble and probabilistic prediction.
- Although standard approaches for evaluation of ensembles have matured and are generally applied in a consistent way, ensemble prediction is still an evolving science and new verification metrics for ensembles continue to be developed. These require testing and refinement for meteorological and downstream applications.
- The development and application of user-relevant approaches for forecast evaluation, as well as the application of methods for downstream forecasts and impacts have blossomed in the last decade; the breadth of possible applications will require some consideration and prioritization in the community, in consultation with relevant external users.
- Development of verification approaches for longer range and seamless predictions have become increasingly important to support new prediction capabilities.
- Incorporation of information about observation uncertainty into forecast verification methodologies remains one of the greatest challenges for our community.

Efforts in these areas are likely to dominate verification research over the next decade.

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CHAPTER 22. DEVELOPMENT OF APPLICATIONS TOWARDS A HIGH-IMPACT WEATHER FORECAST SYSTEM

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Abstract

The future weather forecasting and warning process of National Meteorological and Hydrological Services will focus on high impact, multi-hazard, seamless weather prediction that includes uncertainty information throughout. It will consist of several complex components including observations, ensemble-based numerical weather prediction systems, forecast applications and last but not least the human forecaster. In this context forecast applications have been defined here to be scientific and technological tools, of wide-ranging types to help deliver valuable, tailored products to customers. The overall goal for the development of those applications is to reduce the impacts of weather-related hazards.

22.1 INTRODUCTION

The forecast service in the next 10 to 20 years is envisioned to span all lead time ranges from minutes to months ahead, to convey uncertainty information throughout, and to be seamless, multi-hazard and multi-scale. Seamless refers to a vision where the different products and services are consistent regardless of the method of access or creation (push, pull, automated, human-generated) and regardless of the lead times involved. While the concept of consistent seamless forecasting may have been first introduced to help merge weather and climate models, in future it may become even more important in the field of high-impact weather forecasts.

The future weather forecasting and warning process of National Meteorological and Hydrological Services (NMHSs) will consist of several complex components including observations as well as nowcasting and ensemble based numerical weather prediction (NWP) systems (Figure 1). The human forecaster will still have responsibilities for interpreting available data, for making decisions and for creating and communicating final products to the customer, though automation will play an increasingly important role in the process (note the many arrows on Figure 1 that circumvent the forecaster).

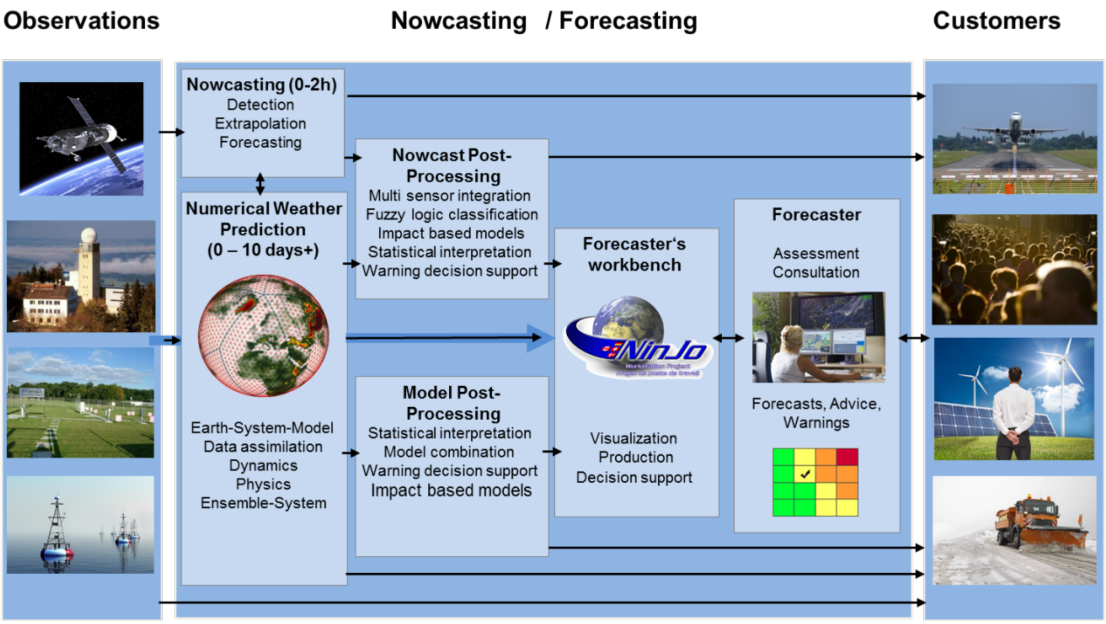

Figure 1. The weather forecasting process of the future

Although NWP will remain the central pillar of the forecasting process, further development of scientific forecast applications will be essential to successfully transpose ever increasing data volumes (‘big data’) into output that successfully meets the ever increasing requirements of users. Indeed this is the essence of ‘forecast applications’, the focal point of this chapter. Specifically, “forecast applications” are defined here to be scientific and technological tools, of wide-ranging types, that supplement or build upon NWP to help deliver valuable, tailored output to customers. Forecast applications can be especially important for translating observational data and model output into formats that are comprehensible to both the forecaster and the final customers. For example, observations and NWP systems do not know that blizzards relate to strong winds and snow on the ground, but for the customers, interested in impacts, this combination is key.

We have seen significant advances in the forecast process in the past two decades. These have been driven by advances in weather science, particularly in NWP, as well as by advances in observation technologies, forecast applications, telecommunications, internet, and high performance computing and data storage. In the near future, improved "crowd sourcing" of weather data driven by smartphones and the ubiquitous “apps” have the potential to be a game changer in the acquisition of high-density observations and impact reports, as well as in forecast dissemination. Indeed this ‘social revolution’ has already begun, providing new methods to access and interact with weather data and forecast products, and also different mechanics of interaction between and amongst forecast providers and end-users. The appetite for more of everything, for it to be faster and to be more robust is unceasing. Automation will be indispensable for parts of the future forecasting process to manage the ever-increasing amount of data.

The multi-hazard vision for the future forecast services extends the prediction science towards applications that deal with the bio-physical as well as geophysical sciences. Services will of course deal with weather, but also with safety and the economic dimensions of transportation, energy and air quality, as well as health, hydrology, drought, waves, landslides and avalanches to name but a few. The major objectives from the user perspective are to quantify the potential impact of a range of weather related hazards, in isolation or in combination, on vulnerable populations, assets and services, together with the duration of those hazards. Given such information mitigating action can then be taken, by emergency management authorities for example, to reduce the actual impact. Lives can be saved, economic losses reduced and key services maintained. To achieve these goals requires close collaboration between weather science and social science, forecasters and the relevant customers, partner agencies and stakeholders. Such collaboration fosters a much improved understanding of the full range of vulnerabilities, which in turn allows forecasts and warnings to be better tailored to societal needs.

The high-impact weather aspect is a significant paradigm shift and requires a concentrated integration of weather services and the decision-making processes of end users. There are different levels of integration at the human and the machine levels. This lies at the core of our vision of the future semi-automated (high-impact) weather forecast system shown in Figure 1.

22.2 REQUIREMENTS FOR HIGH-IMPACT FORECASTING APPLICATION DEVELOPMENT

High-impact weather has always been the over-riding mandate of the forecast system. The emphasis in recent years has been to focus attention on better use of information through improved service provision, on improvements in science including conveyance of uncertainty, on improvements in the products through enhanced development and on more engagement with end users (Bica et al. 2011), including modern mechanisms of service delivery. ‘High Impact’ requires that the forecast service provider and the decision makers understand each other’s capabilities and decision-making processes. It implies that the services and products are highly tailored and specific to the needs of the end-user.

In Figure 1, the envisioned forecast system consists of two streams. One stream (top and bottom arrows) is directed towards scientifically sophisticated users/ customers (shown on the right) who are able to use raw direct model output or post-processed output automatically without any intervention by forecasters or without interpretation by a meteorologist. They are able to handle the biases (in time, in space and in the weather variable) and uncertainties in the model. Furthermore they can take direct advantage of improvements in observations and nowcasting systems, model physics, NWP including coupled data assimilation techniques and post processing applications.

The second stream is shown in the middle of the figure where the customers rely on the expertise of meteorologists to provide oversight to the post-processed products or to create products, particularly at the challenging short time scales. An underlying requirement the forecast system is that it must be affordable, efficient and make optimal use of available resources. Automation of the service production is proffered as the way to streamline the process to save costs. In Figure 1, arrows going to the “forecaster workbench” indicate basic post-processed meteorological data to enable the forecaster analyze, diagnose and prognose the weather (Bosart, 2003; Doswell, 1986; Doswell, 2004) but they also denote automatically prepared “first guess” prognostic products that could be reviewed by the forecaster before onward transmission to the service production system. The former are envisioned to be raw observations, nowcasting and NWP output as well as post-processed data. In the latter case, the data may take various forms including point (e.g. meteograms), grid (e.g. maps) or object-oriented (e.g. location, size and attributes of radar derived thunderstorms) intermediate products that the meteorologist can review, modify, or even create afresh.

An important requirement for the forecast applications of the envisioned high-impact forecast system is that all data and products provided to the forecaster have to support situational awareness within the process, which is the ability to retain suitable judgemental skills, particularly in stressful situations where awareness and perception of details within the bigger environment is required. Lack of situational awareness is in fact a leading cause of accidents and missed weather warnings (Klein, 1999; Klein and Hoffman, 2006; Nullmeyer et al. 2005). Constant vigilance and constant cycling of the analysis, diagnosis and prognosis process are needed, whereby views of both the broad scale and finer scale developments are maintained simultaneously - the so-called “forecast funnel process” (Snellman, 1982). The meteorologist performs the analysis, diagnosis and prognosis process at each scale (global, regional, mesoscale and thunderstorm scale). It is argued that since any weather situation may be high impact the meteorologist may repeatedly go through the forecast funnel procedure in order to maintain constant situational awareness, and that cutting back on this part of forecast system will not be effective.

In Figure 1, the arrows leaving the “forecaster workbench” signify the above-mentioned intermediate products the meteorologist has reviewed, modified ore created. Conceptually these represent “the best machine-human forecast” from which the final end-user service products are generated. Depending on the system, the intermediate products have been termed weather objects (Brovelli et al. 2005), meteo-code (Verret et al. 1999), weather depiction (Greaves et al. 2001) or “modified grid” (Ruth, 2002). They are a computer representation of the expected weather sufficient to produce end-user products whether they be text, graphical or audio. Efficiency is only achieved if many end-user products can be created from a single representation of the expected “weather”. This is the core concept behind the semi-automated forecast system. Not all the details have been determined and this is an active area of forecast system development (Koppert et al. 2014; Sills et al. 2014). The distinction between “forecaster workbench” and “forecaster” is conceptual and may be embodied in a single work function.

From a technical perspective, the first-guess and forecaster-modified output are conceptually separate from the products delivered to customers. Therefore, for efficiency, system design must from the outset permit retention of both data and products. New raw and processed data/products are envisioned to be issued to a variety of independent systems and so existing World Meteorological Organization (WMO) data format standards and inter-operability need to both be extended in tandem.

The impact of weather is highly dependent on the user and their activities. Traditional warning elements are strong winds, heavy rain, heavy snow, freezing rain, hail and lightning. However, high-impact weather may be due to a combination of diverse meteorological and non-meteorological conditions. For example, non-hazardous light drizzle can result in very slippery conditions when oil has accumulated on roads after extended dry conditions. Teakles et al. (2014) demonstrated that even under clear skies and with low prevailing wind speeds, varying upslope-downslope winds over a two hour period, due to drainage flow and solar heating, had a significant impact on the ski jump event during the Vancouver winter Olympics. It is argued that all weather situations can be potentially high impact and human oversight is always required. Also, end-user requirements are always evolving and changing and so, the concept of the “routine situation" that can be fully automated is a myth.

In addition, an inadequately addressed issue is when is and how to determine that the “automated result” good enough, particularly in high-impact weather situations. Presumably, the meteorologist must go through the analysis, diagnosis and prognosis process to determine that and this does not achieve efficiencies. Combined with the need to maintain situational awareness, this is not where efficiencies will be found.

The guidance products that only provide the “answer” are insufficient. Related diagnostic products are needed to understand the “why” of the automatically produced answer and also the uncertainty in the result (Joe et al. 2003). The forecaster must be able to assess the rationale for the guidance and the system must allow the forecaster to drill down into the data, apply their cognitive skills effectively and assess and interpret the information within the ever-changing context of the ill-defined high-impact situation. Inherent in this discussion is the assumption that the high-impact weather forecaster is an expert and will be able to add value. This ability of an expert to add value has been demonstrated (Hoffman et al. 1995; Hoffman et al. 1998; Pliske et al. 1997; Pliske et al. 2004). The design of the forecast system, particularly the “forecaster workbench”, must consider the skills of the human and have to follow a “human-centred design” rather than a "designer-centred design" approach (Hoffmann, 1991, 2014). The human can absorb and process divergent and seemingly contradictory information, is flexible to adapt to changing requirements and can also create new scenarios. The high-impact forecaster not only needs to know about the weather but also about the strength and weaknesses of the automated guidance (Snellman, 1977; Stuart et al. 2006; Stuart et al. 2007). The best approach to thunderstorm forecasting is a combination of machine and the meteorologist (Wilson et al. 2004; Stern et al. 2007; McCarthy et al. 2007). However, humans can also conceptualize and infer that patterns do exist when in reality they are not actuality there (Vincente, 2006; Kahneman, 2012). The semi-automated system needs to be designed with checks and balances to safeguard against this.

Intervention tools must be developed to efficiently enable and enhance human skill sets and this is a challenge. Humans conceptualize in terms of patterns and areas. Forecasters conceptualize fronts, thunderstorms, lows, highs, vorticity maxima, jet streams and use graphical maps. Therefore, the first guesses, the diagnostic and the intervention tools need to be presented in a similar fashion, ideally in feature-based format. Point (Verret et al. 1999) and grid (Ruth, 2000; Ruth, 2002; Mass, 2003) manipulation tools have been developed. An example of a successful forecaster toolkit is the ‘field modification’ and ‘metmorph’ tools that were developed by a forecaster for forecasters (see Carroll and Hewson, 2005). Success has also been achieved by using graphical object creation and modification wherein a single representation of a weather object is able to create multiple text and graphical products (Paterson et al. 1993; Greaves et al. 2001; Sills et al. 2005; Reichert, 2013).

22.3 APPLICATIONS, TECHNIQUES AND TOOLS FOR A HIGH-IMPACT WEATHER FORECAST SYSTEM

Although forecast skill for the different components of the forecast process shown in Figure 1 will continue to improve, accurate prediction of high-impact weather will pose substantial challenges for the foreseeable future. This is for many reasons, notably:

(i) Unrepresented extraneous factors can strongly affect net impact (e.g. aircraft icing depends on the type of aircraft, soil moisture levels affect flood potential, transportation system vulnerability is elevated during a rush hour).
(ii) Weaknesses in numerical weather prediction and nowcasting applications preclude direct representation of the hazard (e.g. topographic funnelling, hailstorms, convective gusts can

suffer from resolution limitations, inadequacies in the representation of physical processes and incomplete observational coverage, to varying degrees).

(iii) Intrinsic uncertainty and predictability issues can be substantial, particularly for high-impact weather (e.g. due to elevated dynamic/convective instabilities) - consequently, the model/ensemble forecast may simply be wrong.

To address these challenges, increasing numbers of forecast applications, related to community needs, will be designed, developed and used in the weather forecasting process, to strongly advise - but not completely replace - those in a forecasting role.

For shorter lead times in the warning process high resolution rapid update regional models/ensembles and nowcasting applications will become a central pillar; indeed, in many cases, they will feed impact models and warning decision support systems. To successfully address (ii) it is expected that weather science and technology will reinforce semi-automation by both improving existing applications and developing new ones. This is, however, technically quite challenging, as one needs to somehow ‘represent the unrepresentable’ via a statistical/parametrization type of approach, heavily utilizing observations in the process. Clearly, if the relevant observations do not exist, or data or access is compromised in some way, then the output will suffer even more. Because of these various difficulties it is very likely that forecaster knowledge and experience will remain quite useful here especially in the warning context.

Successfully overcoming limitation (iii) presents an even greater challenge, and the judgment of an expert, experienced forecaster, assisted by suitable decision support applications, will arguably be even more important. Across the community, views differ on the degree to which the forecaster of the future will be able to improve upon automated guidance in this area. However the skill levels required from an automated system to be able to issue “take action” type high-impact warnings have not yet been realized. Note also that expectation levels regarding forecasts of high-impact events have been increasing and will continue to do so, as end-users appreciate and adapt to the improvements in weather science. For further discussion of such issues and the evolving role of the forecaster see Carroll and Hewson (2005), Wilson et al. (2010), Sills et al. (2014) and Novak et al. (2008) and (2014).

22.3.1 Nowcasting applications and transition from nowcasting to NWP

Numerical weather prediction is the scientific pillar of the weather forecasting process but is faced with its own predictive skill limits, as well as the intrinsic limits of predictability (see appropriate chapters of this book). Despite future advances in NWP, models will still have difficulties in providing accurate forecasts, especially for lead times from minutes to one hour ahead at smaller scales in rapidly changing high-impact weather situations. Data assimilation and NWP take a significant amount of time to execute. Sun et al. (2014) describe the limitations on NWP for nowcasting tasks that include boundary layer details, microphysics, spin-up and lack of appropriate observations.

Rapid nonlinear developments in the atmosphere frequently result in gaps between actual weather conditions represented by observations and the latest available model forecast. Commonly, these are observed in meteorologically unstable situations, which are often associated with hazardous high-impact weather (HIW) events at smaller scales. Future improvements in data assimilation and convective-scale NWP will reduce, but not eliminate, these gaps. Key customers require accurate forecasts, especially for HIW events, even for lead times of less than two hours as such events can lead to significant, expensive interruptions of business processes, damage to infrastructure and even loss of life.

To meet the challenging user requirements, applications to analyse remotely sensed observations with high temporal and spatial resolution have been implemented in countries with access to the appropriate technologies. These applications are able to nearly immediately detect the rapid, nonlinear developments in the atmosphere that lead to HIW, with a high temporal and spatial resolution. Nowcasting applications based on extrapolation of remote sensing data have been developed (Bellon and Austin, 1978; Dixon and Wiener, 1993; Wilson et al. 1998; Pierce et al. 2000;

Lang, 2001; Hering et al. 2004; Germann and Zawadski 2004; Joe et al. 2004; Joe et al. 2012; James et al. 2013).

Traditional nowcasting applications are based on observational data and provide both rapid detection with user- or impact-oriented classification, and an extrapolation of HIW events. They use pattern recognition for detection, fuzzy logic techniques for classification and extrapolation and/or trending methods to forecast the identified phenomena. Further improvements are needed in many aspects to meet the high skill levels required to make “take action” decisions particularly with longer lead times (Wilson, 2010). In the last 30 years, nowcasting applications have focused on weather elements such as thunderstorms and precipitation. There is now a growing requirement to provide nowcasting of other phenomena, such as wind speed and direction, temperature, visibility, winter weather events and even of the associated impacts.

Current operational observing networks are unable to capture all the details of high-impact weather events and clearly cannot measure the actual impact of that weather even in countries with access to modern technologies. Further developments in ground-and space-based remote sensing, data sharing and most recently, in widespread availability and usage of cell phone technology (Elmore et al. 2014; Mass et al. 2014; Moore et al. 2014; Madaus et al. 2014) are needed to provide the required information for nowcasting and convective scale NWP systems.

Figure 2 shows the uneven distribution of high-density cell phone pressure measurements in the United States and implies that observation-based nowcasting will be focused on urban environments. This technology could also be useful in countries with inadequate observation networks, but where cell phones are prevalent. Low maintenance, low infrastructure and low cost radar systems have been proposed (McLaughlin et al. 2009) that address the need to see the areal extent of “near surface” hazardous features such as tornados, microbursts and snow squalls. Weather and impact reports of citizen of the United States are gathered in the “mPING” project (Elmore et al. 2014) and are used to refine detection algorithms for precipitation type identification near the ground and thus improve the appropriate nowcasting quality. Lightning detection systems are now readily available and rely on lightning and hazard relationships for a convective nowcasting application. The business model of “selling” lightning data resolves the maintenance and infrastructure issues. Satellite and cell phone technology holds great promise for countries with less access to technology. Research is however needed to increase the observation density and to improve the quality control of the observations. The Global Humanitarian Forum (2009) states that climate change will be toughest in countries which have inadequate observation networks and less access to sophisticated tools to observe and forecast the expected changes in the weather and climate. Many countries cannot afford the luxury of radar and other observation systems. The lack of observations not only influences the observation and nowcasting of severe weather and high-impact weather systems, but also implies that less data are available for data assimilation into NWP models, which in turn affects the quality of the NWP.

It has been evident for many years, that the traditional, observation-based extrapolation techniques used in nowcasting have clear limitations in capturing significant meteorological developments. Forecasting complex meteorological developments is the domain of NWP, and in the case of very short range forecasts the human forecaster. As NWP extends to convective scales its use in nowcasting is growing, but will be restricted by the limits of predictability and will not replace observation-based-nowcasting completely. Thus future research and application development in the nowcasting sphere will focus both on improving the traditional nowcasting technologies, including forecasting techniques, and on increasing use of NWP (including data assimilation). Key customers are familiar with the limits of NWP predictive skill. They have organized their business processes to exploit observation based nowcasting applications and forecasters advice to take mitigating action in the first minutes to hours of the appropriate forecast period.

Nowcasting techniques and NWP systems have been developed independently, and often provide different results. Key customers of NMHSs require seamless predictions from minutes to days, driven by their needs for consistent, realistic and credible business scenarios over the whole forecast time range. Several blended seamless prediction systems have been developed to address these requirements bridging the gap between the actual weather occurring and the latest model predictions

(Golding 1998; Haiden et al. 2011; Kann et al. 2012. Seed et al. 2013). These techniques combine extrapolated analyses of meteorological parameters (for example precipitation rate) with forecasts from one or more NWP models. This combination can be done using simple blending techniques, with scale-selective frameworks or by exploiting the potential of ensemble based data assimilation. Further research is needed to improve the optimal combination of nowcasting and NWP systems. As weather forecasts should, from a strictly scientific perspective, all have a probabilistic format there is also a need to quantify uncertainty in nowcasting information (Germann et al. 2002, 2004, 2006b; Seed et al. 2013; Foresti et al. 2013). An area of future research is to explore whether probabilistic nowcasts can be used to initiate high-resolution models rather than through the current unbalancing schemes. The use of ensemble-based high resolution NWP (<1 km) in nowcasting applications will increase as the temporal and spatial resolution, quality and last but not least timeliness of NWP models increase. The key limitations are the lag in observation technology and the limited predictability.

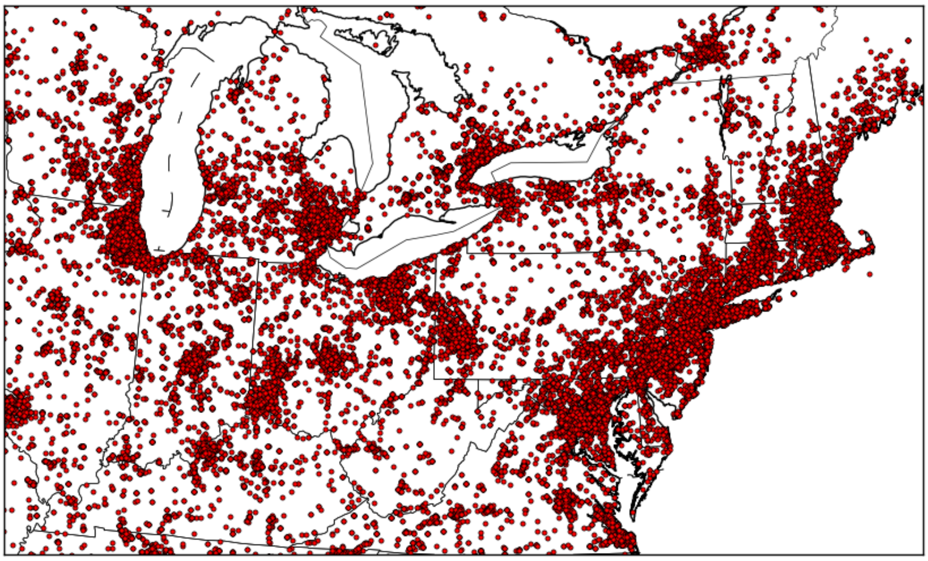

Figure 2. Pressure measurements via cell phone apps. The map shows the location of measurements in a one hour period (10-11am EDT) on 1 April 2015 in North East United States and southern Canada (48,755 observations of a total of 105,689 measurements over North America are shown). There are over 200,000 subscribers in North America. Temperature, relative humidity, signal strength and Ultra-Violet measurements can also be measured and are expected to be available in the near future.

Source: Data courtesy of Jacob Sheehy of Pressurenet.io.

In some countries NWP can be developed and run at very high resolution with the availability of supercomputers while in other countries higher resolution global NWP or ensemble prediction systems (EPS) products can merely be downloaded from the internet for local use. The WMO took the initiative to launch several Severe Weather Forecasting Demonstration Projects (SWFDP) in areas where NWP and EPS are used extensively to deal with severe weather forecasting (http://www.wmo.int/pages/prog/www/swfdp//). At the fourth meeting of the Technical Commission for Basic Systems (CBS)-SWFDP Steering Group in Geneva, 2012 (CBS-DPFS/SWFDP-SG-4/Final Report) it was recognized that one of the main challenges for the SWFDP was “the need for very short-range forecasting (including the first 12 hours) tools, to address especially the rapid onset of localized severe thunderstorms which can produce heavy precipitation and strong winds, given the absence of adequate real-time observational networks, especially weather radar coverage. The usefulness of Meteosat Second Generation (MSG) products for nowcasting purposes was recognized and it was noted that satellite based instability indices as well as satellite rainfall estimates have proven particularly useful in regions where rain gauges and radar coverage are not available. In the absence of technology, NWP, EPS and satellite can go a long way to assist basic nowcasting applications for high-impact weather (de Coning, 2013). In this way, valuable partnerships can be created between countries with more resources and countries with fewer opportunities to develop their own applications. Both partners can benefit from such initiatives - different NWP, EPS as well as satellite techniques can be tested and challenged and knowledge of local weather systems can be gained. The Nowcasting Satellite Application Facility (NWC SAF) has developed several NWP and satellite blended applications which are beneficial to countries where radar and other observation systems are not readily available. These products are used in Europe, but have also been implemented and tested in some Africa countries with great success (de Coning, et al. 2014).

22.3.2 Statistical post-processing of ensemble based NWP

Statistical post-processing refers to the development of predictive statistical relationships between the forecast output of an NWP model and observations. The direct NWP outputs can be highly biased particularly in user-oriented variables such as surface temperature, precipitation, humidity (Sun et al. 2014; Isaac et al. 2013). These relationships are built using an archive of recent model forecasts or a set of historical model runs (e.g. a reforecast dataset) that are matched to the observed weather or observed impact at the validity time of the forecast. In operations, site-specific forecasts are then calculated from the statistical equations using the most recent model forecasts (Glahn and Lowry, 1972; Balzer, 1994; Knüpffer, 1996; Wilson et al. 2003). Statistical post-processing thus improves the quality of weather forecasts and bridges the gap between the pure NWP forecasts and end-user products such as weather-related warnings for the public or impact forecasts for specific customers. Results indicate that Canadian NWP forecasts are improved by the application of statistical post-processing methods (Wilson, 2014).

Statistical post-processing methods have also been used for more than four decades to provide calibrated estimates of the probability of occurrence of various weather parameters. The advent of ensemble forecasting systems in the 1990s provided another source of estimates of uncertainty in forecasts of meteorological variables. Ensemble forecasts also need correction by statistical methods, for example bias removal (Cui et al. 2012).

The last 20 years have seen a dramatic increase in the range of deterministic and ensemble NWP model output data available in the weather forecasting process making it ever more important that applications of that output detect and highlight weather related hazards and their impacts to customers in a consistent way. Efficient tools, techniques and applications are needed to extract the relevant meteorological information to enable meteorologists and automated systems to assess, forecast and communicate weather-related hazards and their impact efficiently. This means that there needs to be a paradigm change in the use of statistical post processing techniques. Rather than emphasizing only the correction of deterministic or ensemble NWP output, statistical processing techniques of the future should also emphasize the intelligent combination of information from all available sources, leading to an optimized, calibrated probability distribution (PDF) covering all possible scenarios, including extremes. Examples of efforts in this direction are contained in Hirsch et al. (2014), Raftery et al. (2005), Swinbank et al. (2015) and Wilson et al. (2007).

Optimal statistical blending of forecasts applies for both nowcasting and longer ranges. Additionally, the availability of such optimized pdfs can then enable the uncertainty in the forecast to be mapped onto uncertainty in possible impacts, through further modelling, thereby recognising that this connection will in many meteorological situations be very non-linear. Relatively speaking, research into optimal methods of combining forecasts from different sources is in its infancy. Continued research is needed with particular attention paid to the difficult problem of optimal estimation of uncertainty in the tails of the distribution, where most high-impact weather events occur, and where observation data for validation is scarce.

Research is also needed to improve the automated production of an optimal PDF. Such a set-up will in principle streamline and simplify the workflow in the weather forecasting process and ensure that all downstream guidance products for the forecaster and end products for the user are consistent. Further systems can then simply "plug-in" to this continuously-updated, single source of optimal PDFs. This would potentially remove the requirement of these systems to manage multiple model sources on different grids, with different ensemble sizes and diagnostics, encoded using differing data formats. It would also remove the risk of inconsistent forecasts, freeing the operational meteorologists to use their expertise to provide the best guidance of extreme weather based on this forecast, rather than trying to reconcile the differences over a range of available forecasts cognitively. A significant challenge here is the frequent changes in operational models. To address this issue, there are several possible strategies. One might be to incorporate the most recent model output, whilst still also using output from the older model version to stabilize the statistical relationships. Another better but more expensive, alternative is to develop large reforecast datasets, which are always constructed using the latest model version. Only then can one actually capture the extremes (at the large scales), which are of most interest, in a reasonably reliable fashion. Such an approach was pioneered at the European Centre for Medium-range Weather Forecasts (ECMWF), and should be promulgated much more widely. Historically the lack of computer resources has been a big hurdle to overcome. In the future pragmatic decisions will need to be taken regarding whether using computer resources for the real-time running of reforecasts can bring more benefits to the community than, say, a model resolution upgrade.

Some of the challenges that remain for the future are:

(i) Combining the forecasts from multiple sources together in a way that recognizes the characteristic spatial correlations of surface weather variables, allowing the resulting blend to provide realistic representations of the spatial structures of weather phenomena.
(ii) Maintaining consistency between parameters during calibration and blending.

22.3.3 Warning decision support systems and the role of the forecaster

Forecasters are indispensable in the future high-impact forecast and warning process and will have advanced workstation systems at their disposal. These workstations facilitate the visualization, monitoring, modification and validation of increasing amounts of data and guidance products, as well as the production of forecasts and warnings (National Oceanic and Atmospheric Administration (NOAA), 1993; MacDonald et al. 1996; Koppert et al. 2004; CBS-DPFS/SWFDP-SG-4/Final Report, 2012). Such systems enable the forecaster to get a fast overview of the synoptic situation, as well as meteorological developments on the mesoscale, as befits the needs of nowcasting. The challenge for the future is to ensure that the envisioned scientific progress, in all related fields, can be successfully integrated into the operational workflow. This should be done through targeted application developments, employing “human-centred design” rather than “system-centred design” to allow human cognitive processes to be fully exploited (Hoffmann et al. 2014). To reach this target, there will remain a need for dual-role forecasters, who not only use the systems but who also help to develop them.

To help the forecaster to effectively utilize growing volumes of complex meteorological data, within the warning process, many scientific applications and warning decision support tools have been developed. As human resources will remain limited in the future and as service requirements will increase, these developments must continue, particularly for high-impact warnings. The increase in service requirements will be due to the introduction of more warning parameters and categories, the extensions to longer lead times as predictability improves, and the issuing of more warnings for low probability events, to name a few.

One acute and growing challenge within the warning process, for both forecasters and forecast applications, is coping with increasing numbers of model runs, and with the multi-scale complexity that they increasingly represent. Ever more sophisticated post-processing tools are needed to make real-time analysis and diagnosis tractable. For forecasters one strategy is to automate compaction techniques which use special algorithms to identify ‘features’ or ‘objects’ in the output of nowcasting and NWP (deterministic or ensemble) systems, specifically those that might associate with severe weather. At the nowcasting level, an example would be ‘convective features/objects/systems’ (Stumpf et al. 1998; Lakshmanan et al. 2007; Joe et al. 2005; Hengstebeck et al. 2011; Joe et al. 2012; James, 2013; Sills et al. 2014; Brovelli et al. 2005). At longer leads larger elements, such as synoptic scale features, become much more relevant. These synoptic scale features might include fronts, frontal waves, cyclones or easterly waves (Hewson, 1998; Greaves et al. 2001; Hewson and Titley, 2010; Berry et al. 2007; Young and Hewson, 2012).

Figure 3 shows an example of compaction in the form of a Dalmatian chart of forecast cyclonic centres, at 108h lead time, for a valid time of 00 UTC on 10 March 2015, from the ECMWF Integrated Forecast System (52 member ensemble). Colour denotes wind speed maxima associated with each cyclone (see legend). Note the variations in handling of a cyclone near Scotland whereby some runs show a cyclone with relatively modest winds whilst others show extreme cyclonic windstorms centred near the Faeroes. The plot has combined information from about 1300 single parameter charts.

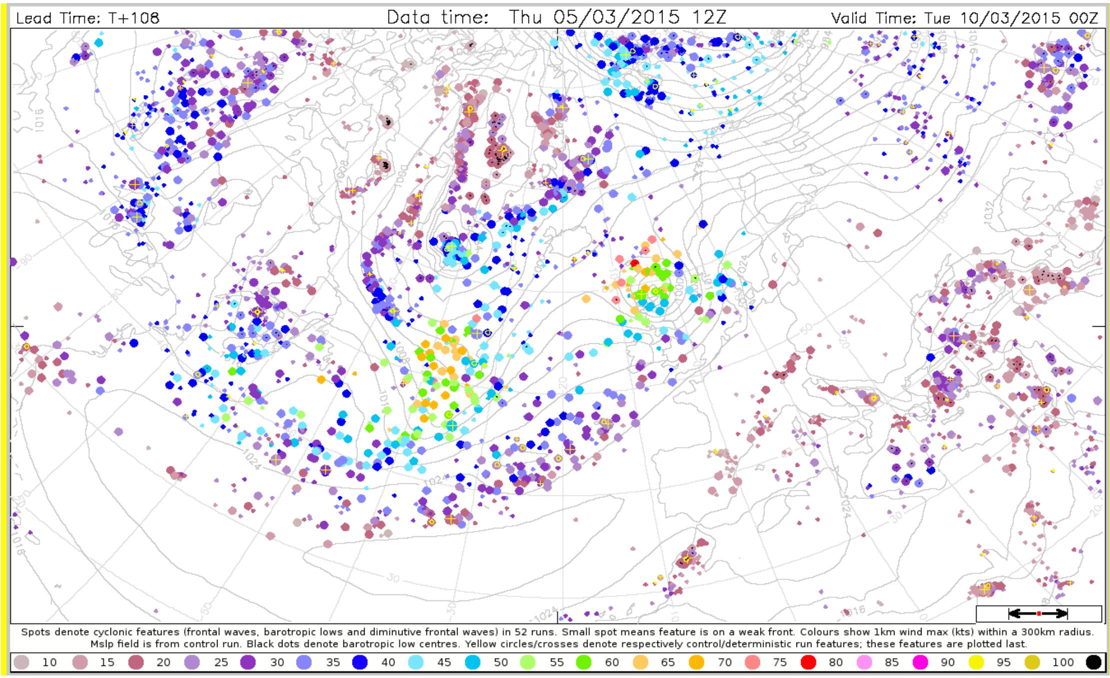

Figure 3. Dalmatian chart (see e.g. Young and Hewson, 2012) of forecast cyclonic centres

Graphical presentation, illustrated in Figure 3, has the benefit of showing the forecaster the patterns involved, thereby allowing their cognitive capabilities, based around pattern recognition, dynamical understanding and synoptic severe weather experience to more effectively come into play.

Another approach to compaction is to fully combine all calibrated ensemble and deterministic forecasts automatically, into a single ‘best’ probabilistic product for the high-impact event in question, and to accordingly provide appropriate first-guess forecast and warning guidance products to the forecaster (Hirsch et al. 2014). However, the calibration process, for extreme events, is inherently more prone to error. Appropriate diagnostic tools must be provided, to enable the forecaster to understand these guidance products. Verification results of a first prototype of an operational semi-automated warning decision support system at Deutscher Wetterdienst (DWD) highlight the advantages of such systems (Schröder et al. 2014). A problem that has only been partially solved is the integration of the machine-generated updated guidance with previously generated warnings, particularly if they are not consistent for whatever reason.

Clearly, further research is required to explore the potential and limitations of automation of different types in the forecast process, and thereby also define the optimal roles for and the expertise levels of the forecaster of the future. It is worth noting here that over the last 40 years, NMHSs have generally been over-optimistic in their estimation of the rapidity with which the increasing skill of NWP and scientific applications would remove the need for any manual intervention (Hoffmann, 2013; Persson, 2013). It does however seem very likely that the importance of model intervention, as described in Carroll and Hewson (2005), will reduce.
The future should also see a more coordinated shift across to a probabilistic framework for warnings. Historically there has been reticence to accept and use probabilistic warnings. This will

need to be resolutely addressed with cross-cutting research and demonstration projects. Concerted efforts are required to explain the benefits of acting according to potential costs and losses.

Within the warning process the typical modus operandi for dealing with a given high-impact event in the future will, as now, be to initially issue a probabilistic warning, for a large area. At shorter lead times the warning can then be updated and refined to a "definitive warning" of a high-impact weather event for a smaller area, albeit still incorporating information about uncertainty. The concept of "Forecasting A Continuum of Environmental Threats" (FACETs) provides a vision for an appropriate warning guidance (Rothfusz et al.2013). A significant component to this vision is the development of applications that provide warning decision support and allow forecasters to convert guidance information (e.g. nowcasting, mesoscale/storm-scale models) on multiple time scales (i.e. hours, minutes) into "Probabilistic Hazard Information". At both the above mentioned stages, i.e. long and short leads, the penultimate activity (prior to dissemination) is actually composing warning text/graphics and setting an alert level. The sociological issues involved (e.g. considering consistent messaging, national preparedness, customer comprehension, recent events, etc.) can be so complex and varied that it is hard to envisage scenarios where societies would benefit from full automation. Whilst computers are good at repetitive work, and automation has proved viable and usable when the scenario is straightforward, further research is needed to establish whether applications in the future really will be able to confront and adapt to complex sociological issues and environments.

From the very general perspective of providing warnings globally, we must from the outset recognize that: (a) observation network inadequacies can preclude knowledge of what is extreme, (b) such knowledge is paramount because most aspects of infrastructure and economy are vulnerable to what is extreme for a given location. Local vulnerabilities can relate directly to climatology-driven governance (e.g. local building regulations that specify gust tolerance based on return periods) or simply to an ungoverned societal appreciation of past climate (e.g. poor arid countries not installing drainage systems). So when providing weather warnings it makes considerable sense to base issue on thresholds related to local climatology.

Some extremes may be non-threatening, but still may have high impact (e.g. slight rainfall can devastate cotton crops). Through local awareness (and where available the impact models), it is incumbent upon the forecaster to disentangle such aspects to identify extreme events that are also likely to be high impact, and then warn accordingly. To gain a measure of extremeness/impacts across the world, even in data sparse regions, and thus help in the warning process, synthetic model-based climates from re-forecasts (e.g. right panel in Figure 4) may provide a useful benchmark to compare with forecasts. The "Extreme Forecast Index" (or EFI, see Zsótér, 2006) is a concept pioneered at ECMWF in which the real-time ensemble forecast distribution is compared with the model climate (e.g. Figure 4, left panel). The aim of doing this is to assess how unusual or extreme an ensemble forecast is compared to the range of outcomes ordinarily realized in the model, for that region, at that time of year (and for that lead time). Larger EFI values signify a greater difference, and so a greater likelihood of extremes, and a greater likelihood of significant impacts. The model climate distribution is constructed a priori by re-running exactly the same forecast model in re-forecast ensemble mode using starting points over the last 20 years. With this approach, biases will be present in both model climate and actual forecast and so should cancel. There are some problem areas however. For example in the tropics, in spite of error cancellation, the EFI for rainfall is not always useful. And in the extra tropics severe convective outbreaks have not yet been well served, partly because of sub-grid variability.

A key additional requirement for the future will be more accurate definition of model climate tails (or extremes). This will allow more advanced post-processing to give, for example, a direct forecast PDF of return periods for an anticipated event. Allied to this activity re-analyses, which drive re-forecasts, will need to run at much higher resolution, eventually at convective scale. This will allow for provision of forecast PDFs for lead times beyond 15 days, moving into the monthly and even seasonal time ranges.

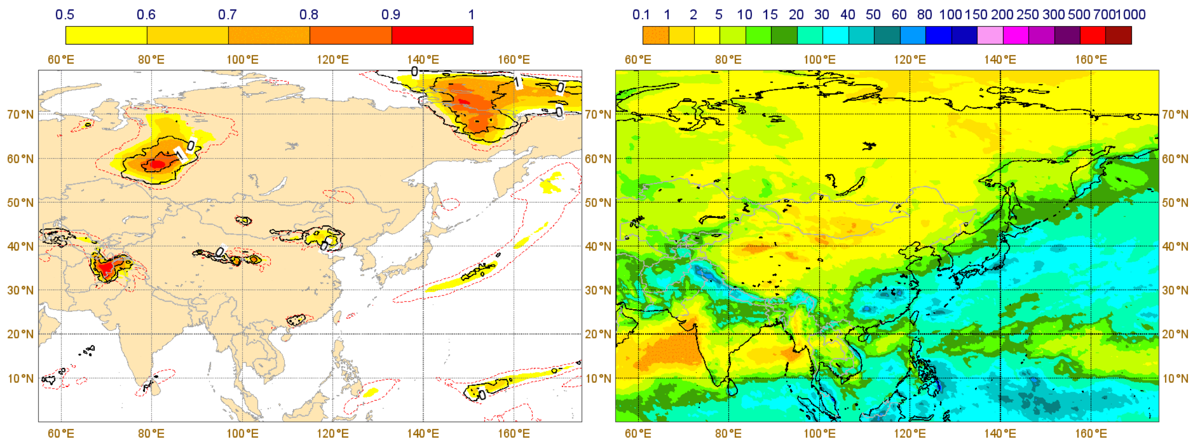

Figure 4. Left panel: ECMWF Extreme forecast index (EFI), shaded (see legend) and red contours (=0.3), and Shift of tails (SOT, black contours) for 24h precipitation, for a 72-96h lead, for a period ending 00UTC 25 February 2015. Right panel: 99th percentile of 24h precipitation for late February, computed from 20 years of re-forecasts. Note the large EFI and SOT values near the Pakistan-Afghanistan border warning of extreme weather in advance; the associated avalanches and flooding killed over 200 people. The right panel helps one to quantify 'extreme' in terms of actual precipitation; high EFI values near 60N/80E would very probably be associated with much smaller amounts than the high EFI values over Pakistan/Afghanistan.

22.3.4 Impact forecasting

As NWP does not represent important extraneous factors forecasting the net impact of hazardous weather events is and will remain a challenge for the National Hydrological and Meteorological Services (NHMSs). To address this challenge forecast applications are increasingly being developed, to combine focused impact models with forecast models. This trend is expected to continue. Such activity is relatively common in hydrological applications (e.g. to predict flooding); other examples include applications to improve the air traffic management (Ping-wah and Pak-wai, 2014), the prediction of aircraft icing (Kalinka et al. 2015), the prediction of ice accretion on pylons/bridges (Cherneski et al. 2014), and assessing vehicle overturning risk, in which the road-normal wind component is key (Hemingway et al. 2014). In these various applications, success comes from incorporating, within the impact model, the 'infrastructure factors' that affect impact. Failures can still arise however when the output of the driving meteorological model is incorrect, because of weaknesses in NWP or intrinsic uncertainties - this is where incorporating the skills unique to forecasters are important.

Even with current and future advances in numerical modelling and forecasting applications, the community must not lose sight of the fact that a reliable ensemble prediction system (from a weather parameter perspective) is not necessarily a reliable ensemble from an impact perspective. There is a non-linear mapping from weather to impact. An example would be storm surges, where the impact can depend crucially on timing relative to tides, yet ensemble perturbation techniques do not take this into account. Thus application development and human input remain valuable in this process.

In the above context one should recognise that, compared to weather forecasting, impact-based forecasting poses additional challenges, when weather scenarios occur that have not been envisaged by the models and therefore not mapped to an impact scenario. Not only does the forecaster have to anticipate such weather scenarios, but they have also to map them onto likely impacts, without assistance from the (then irrelevant) impact model output. This will require careful management, and may conceivably even necessitate the use of synthetic weather scenarios. This could be similar to the "cat modelling" or analogue approach utilised offline by re-insurance companies for example, wherein a synthetic cyclonic windstorm, of catastrophic proportions, is notionally tracked across a large population centre, to estimate the economic losses that would arise. Looking much further ahead, as weather models encompass more earth system complexity, they will increasingly incorporate impacts (e.g. flooded land), so the need for separate systems may eventually reduce.

Although in the past many severe events have been well-forecast from the weather perspective, with accurate weather warning information disseminated in a timely fashion by the responsible NMHS each year the impacts of severe hydro-meteorological events around the world still give rise to multiple casualties and significant damage to property and infrastructure, with adverse economic consequences that can persist for many years. Whilst some impacts cannot be prevented, in many instances there are undoubtedly more mitigating actions that can and should be taken. One important reason for the disconnect relates to the gap between understanding the forecasts and warning of hydro-meteorological events, and understanding the potential impacts, on the parts of both the authorities responsible for civil protection and emergency management and the population at large. Put simply, while there is a realisation of what the weather is likely to be there is frequently a lack of understanding of what this weather will do.

If the above gap is to be closed, then we need to develop an all-encompassing approach to observing, nowcasting, modelling and predicting severe hydro-meteorological events, and the consequent cascade of hazards through to impacts. Tackling this problem requires a multi-disciplinary approach to access the best possible science, develop optimal forecast applications as well as services, to manage multi-hazard events, and to provide the best possible evidence base on which to make the costly decisions needed to help business processes and to protect the population in the future.

All countries need to provide their citizens and economic sectors with actionable information that wherever possible identifies the timing and anticipated impacts of specific hazards. An informed population that fully understands what a hazard will do is more likely to take the necessary protective actions. A challenge can occur in regions where knowledge of, for example infrastructure factors, is not so readily available and communication networks are limited. Cell phone technology is, however, very widely available and can be utilized for the warning process. An excellent example is the WMO Mobile Alert project in East Africa (WMO Bulletin, 2012).

Impact-based forecasting, at its simplest, is the translation of hazard jargon into clear information about the likely impact. Supplementing the forecast of “60 knot winds” with the likely impact on homes, for example, would increase awareness of the actual threat to life and property. More quantitative impact-based forecasts would explicitly take into consideration vulnerability at specific locations - construction of aircraft and risk of icing; elevation and risk of flooding; capacity of buildings and bridges to withstand wind, mudslides, flood water; the resilience of critical infrastructure, such as electrical power, water and sanitation; the resilience of hospitals, schools and other public services, as well as the capacity of government to respond. The timing and location of livelihood activities, such as farming and fishing, which expose people directly to hazards, such as winds, lightning, and waves, need to be quantified so that impact-based forecasts are tailored to those at risk. A typhoon with the centre located 300 km away has a different impact than if it was overhead and requires different “action”.

In many countries, these data are being more and more routinely acquired as a part of extensive risk mapping projects. This paradigm shift in thinking is supported by WMO in which the WMO Guidelines on multi-hazard impact-based forecast and warning services (WMO, 2015) provides additional supportive information. Figure 5 describes the key components of a multi hazard, impact-based forecasting system and represents the relationships between the key elements. There are three possible pathways towards estimating impact for a given hydro-meteorological hazard:

(i) The solid arrows represent the modelling approach where each element is explicitly calculated. To do this requires detailed data on vulnerability and exposure, which may need to be acquired from other agencies.
(ii) The dotted orange arrow relates a more subjective approach where qualitative information is collected from expert partners. This information represents the sum of their experience and allows the estimation of impact directly from the magnitude of the hazard.

(iii) The dotted red arrow represents a more traditional approach whereby the magnitude of the likely impact is related directly to the magnitude of the meteorological hazard. This approach can help in identifying and reducing risk, but takes no explicit account of exposure or vulnerability; just the magnitude of the meteorological hazard itself.

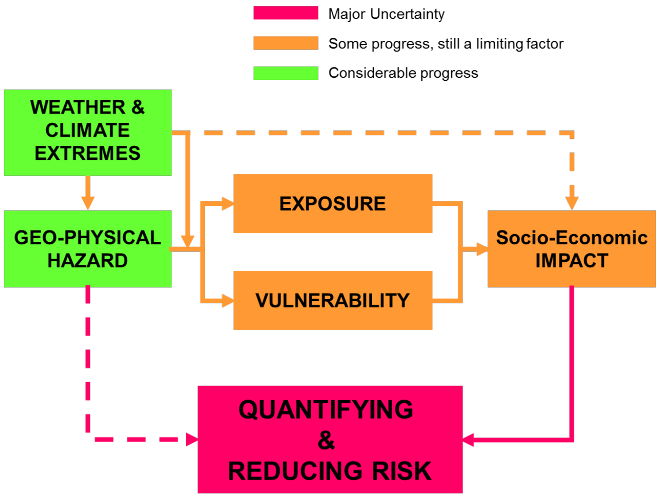

Figure 5. Key components of a multi hazard, impact based forecasting system

Source: WMO (2015)

22.3.5 Verification

Underpinning the envisioned forecast process is the need for appropriate verification methods, and the commitment to carry out verification of all products including nowcasting and direct NWP output, as well as post-processed and forecasters' products. Verification methods must be tuned to user needs. Forecasters should also benefit from the verification of model output using the newer spatially-oriented methods; such verification can help to assess the quality of model forecasts in synoptic terms. Spatially-oriented verification methods also make good use of high spatial density observation datasets such as radar and satellite data. Quality control of observations should not involve models when the data is to be used in verification.

Most users of forecasts are interested in forecasts for point locations. Thus point-wise verification using observations is of utmost importance. Although point observations poorly sample many parts of the globe there is a general tendency for higher observation density where the users are concentrated, which increases the relevance of the verification to users.

The common practice of verification against one's own analysis is of use to the modelling and nowcasting community for diagnostic purposes, to aid in modelling research, but is of much less value for other users of NWP forecasts. Such verification against model-dependent analyses overstates the accuracy of the model by removing the difference between the model climatology and the true climatology from the error, and by removing sub-grid scale components contained in the observations.

There is a general lack of verification activity for model products which are delivered to users in countries that cannot run their own NWP due to lack of resources. The NWP centre which creates the products usually limits its verification to its own region of responsibility. For example, the three global centres which create and deliver deterministic and ensemble products to the WMO SWFDPs (Severe Weather Forecast Demonstration Projects) in Africa and other areas have not done much user-relevant verification of those products. It is recommended that all research projects related to the use of NWP output include verification activity in the project development budget, so that new products can be delivered along with an estimate of their accuracy.

The needs for verification research to support the future forecast system are described in Ebert et al. “Numerical prediction of the Earth System: Cross-cutting research on verification techniques” in this book.

22.3.6 The innovation process

To implement the envisioned high-impact weather forecast process the results of the appropriate research and development needs to be transferred into weather forecasting and warning processes and procedures. Engagement, innovation or technology transfer processes are quite complex, particularly across scientific and social cultures. There are cognitive and behavioural social processes that also need to be considered alongside the scientific. It is natural to make generalizations and treat an end user community in broad brush terms but this is not an effective perspective. The change process for the adoption of new technology or innovation, in general, is described in Figure 6. Where it is possible to “impose” the change, change is introduced through “early adopters” (Rogers, 2003). Early adopters will then influence the “early majority pragmatists” to adopt the innovation. This is true for both internal users (forecasters) and external users (customers) of scientific forecast applications or those with advanced or basic technologies. There will always be a group that cannot or will not change. Therefore a basic and fundamental requirement is to create processes and mechanisms to engage, understand and influence the “user”. The current process is generally ad hoc and perhaps passive in most situations as “silos” are formed that can be impenetrable. Pro-active technology transfer development, demonstration projects or test beds (“end to end to end”), where early adopters from both sides participate, are needed to accelerate the engagement and to bridge the gaps (Keenan et al. 2003; May et al. 2004; Lakshmanan et al. 2007; Stumpf et al. 2008; Joe et al. 2010; Goodman et al. 2012; Ralph et al. 2013; Isaac et al. 2013; Groenemeijer et al. 2013). The most important aspect of these research-to-operations-to-end user initiatives is scientific cross-fertilization but also engagement at the behavioural and cognitive decision-making levels. The applications must meld with service provision and the decision processes so that they can adapt and mutually evolve in order for the “early majority” to be able to follow the “early adopters”.

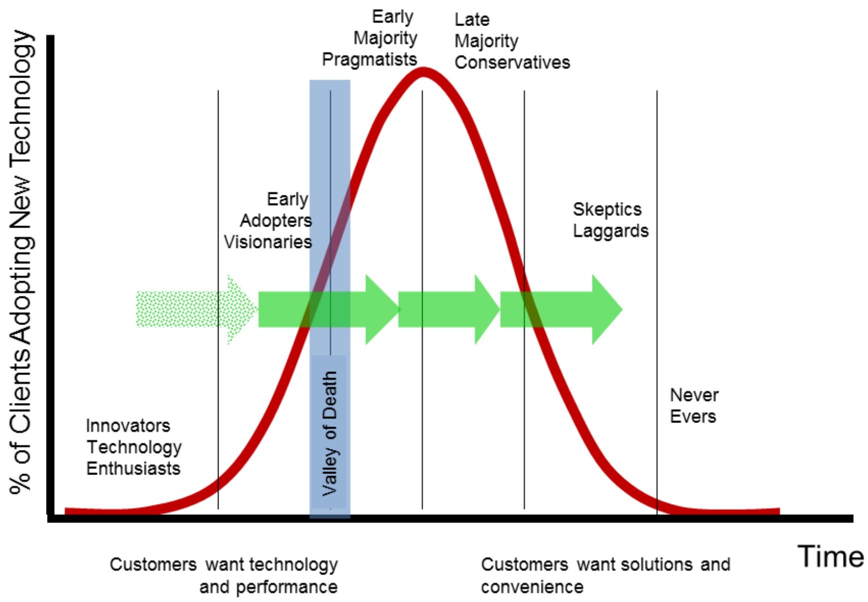

Figure 6. Technology adoption is a social process. The majority of the population (early pragmatists and late conservatives) follow the early adopters when adopting new technology. The innovators are less influential as they are viewed as those who will take anything new and not necessarily for the right reasons. Early adopters are respected for their judgment and opinions. Too often, implementation plans for new technology aim at the majority and not early adopters. The green arrows indicate the technology transfer path. The blue rectangle indicates the critical “valley of death” that must be crossed to successfully adopt change (Rogers, 2003).

The deliverable of the above described “test beds” for the envisioned future forecast process (Figure 1) would be the development of “impact models” and “decision-support-systems”. Decision-making is an active area of research. It is not a broad, mature social science and it evolves and adapts, requiring a combination of products and human interaction (see Chapter 23 of this book). Even the simplest decisions are complex and automation can only address simple situations. Most decisions will therefore require a high degree of personal interaction to develop the trust and confidence required. However, if the decision-making can be quantified and objectified, then weather products and services can generate risk based products as guidance for the end user and it could be envisaged that they propagate up the production process into the “model post processing” in the fullness of time.

22.4 CONCLUSIONS

The future weather forecasting and warning process of National Meteorological and Hydrological Services (NMHSs) will focus on high impact, multi-hazard, seamless weather prediction that includes uncertainty information throughout. It will consist of several complex components including observations, ensemble-based NWP systems, forecast applications and last but not least the human forecaster (Figure 1). In this context forecast applications have been defined here to be scientific and technological tools, of wide-ranging types, that supplement or build upon NWP to help deliver valuable, tailored products to customers. The emphasis on high-impact weather products requires a multi-faceted approach. The overall goal for the development of those applications is to reduce the impacts of weather-related hazards.

As rapid nonlinear developments in the atmosphere frequently result in gaps between actual weather conditions (seen in observations) and the latest available rapid update model forecasts, nowcasting applications will still be needed. They will analyse, extrapolate and forecast high-impact weather events with very frequent updates, at high temporal and spatial resolutions, and will cover lead times ranging from minutes to about one hour. NWP will extend more and more to convective scales, and so its use in nowcasting will grow, but will not replace observation-based nowcasting completely. Future research and application development in the nowcasting sphere will focus on both improving the traditional nowcasting technologies and on increasing use of NWP and data assimilation therein. Observations and their interpretation have been key especially for short lead times. Improvements in observations - including density and expansion into non-meteorological data such as surface characteristics, or even the weather impacts themselves - will be needed for two reasons. Firstly they will need to successfully blend with the upcoming generation of high resolution numerical environmental prediction models. Secondly they will need to feed the associated forecast applications, both of which form key parts the envisioned multi-hazard prediction system. Further research is needed to improve the optimal combination of nowcasting and NWP systems for lead times from minutes to hours. As weather forecasts should, from a strictly scientific perspective, all have a probabilistic format there is also a need to quantify uncertainty in nowcasting information. In countries with less access to various sophisticated data sources and lack of resources to run their own NWP, options to use lower resolution NWP and satellite data should be exploited.

Statistical post-processing applications will further improve the quality of weather forecasts and bridge the gap between the pure NWP forecasts and end-user products. Such products include weather-related warnings for the public or impact forecasts for specific customers. These applications use statistical relationships between the forecast output of an NWP models and the observations. Given the dramatic increase in the range of deterministic and ensemble NWP model output data available it will be ever more important for efficient, yet increasingly sophisticated applications to extract the relevant meteorological information and provide this in a timely manner directly to automated systems and forecasters alike. This will be invaluable in helping those forecasters (and to an extent the automated systems) to assess, forecast and communicate weather-related hazards and their impact. In this context a paradigm change in the use of statistical post-processing is needed. Rather than emphasizing only the correction of deterministic or ensemble NWP output, statistical processing applications of the future should also emphasize the intelligent combination of information from all available sources. This will lead to an optimized, calibrated probability distribution (PDF) covering all possible scenarios, including extremes. The human forecaster will still have responsibilities for interpreting available data, for making decisions and for creating and communicating final products to the customer, though automation will play an increasingly important role here. As human resources in the forecast process will remain limited, sophisticated decision support systems are needed to help the forecaster utilise the growing volumes of complex meteorological data, and free up time so that their valuable cognitive skills can be brought to the fore. Those forecast and warning decision support tools must follow a "human-centred design" rather than a "designer-centred design" approach. Further research is required to explore the potential and limitations of automation in the forecast and warning process, and thereby also define the optimal roles for and the expertise levels of the forecaster of the future. As NWP does not represent important extraneous factors forecast applications are increasingly being developed to combine forecast models with focused impact models. This trend is expected to continue. Although each year many severe hydro-meteorological events have historically been well-forecast from the weather perspective, with accurate weather warning information disseminated in a timely fashion by the responsible NMHS, around the world these still give rise to multiple casualties and significant damage to property and infrastructure. One important reason for this apparent disconnect relates to the gap between understanding the forecasts and warnings of hydro-meteorological events and an understanding of their potential impact. This is true for, both the authorities responsible for civil protection and emergency management, and for the population at large. Put simply, while there is a realisation of what the weather might be there is frequently a lack of understanding of what that weather might do. We can be optimistic that by achieving better interconnectivity between numerical ensembles, forecast applications, situational awareness, impact understanding and human cognitive skills this shortcoming can be successfully overcome, for the benefit of societies right across the world.

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CHAPTER 23. IMPROVED UNDERSTANDING OF AND TECHNIQUES FOR DECISION-MAKING

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Abstract

The growing population, its spatial distribution, and its reliance on increasingly complex, integrated infrastructures and networks are just a few of the many factors that play a role in the multifaceted problem of addressing and mitigating the impacts of weather-related hazards. While there has been considerable improvement over the last few decades in the ability to predict and assess high-impact weather events, the effective application of weather-related data and information in critical decision-making often remains below acceptable levels. There are a number of challenges surrounding the use and application of weather data including, but not limited to, disparate stakeholder requirements, forecast uncertainty, the need for actionable information, a better understanding of weather impacts, and the effective use and incorporation of weather data and information into the decision-making process. The weather community has recognized these and other deficiencies, and work is steadily progressing to close key gaps associated with weather-based decision-making. Central to these efforts is research and development that is focused on enabling and enhancing new technologies, capabilities, and services that will foster decision-level information for mitigating weather-related hazards and impacts.

23.1 INTRODUCTION

Weather forecasts and warnings are useless unless people base decisions on them, but effective decision-making requires stakeholders to understand the potential impacts of predicted weather - what the weather will DO rather than what it will BE. Impact depends not just on how severe the hazard (weather) may be, but also on the vulnerability and exposure of society and stakeholder assets. Furthermore, forecasts of weather are fundamentally uncertain, and forecasts of weather impact generally even more so. Improving decision-making from forecasts therefore requires improved understanding of both the potential impacts of the weather and of the uncertainties and probabilities of those impacts occurring. This puts the decision into a full risk-management framework where risk is defined as the product of likelihood and impact, and depends on vulnerability and exposure as well on hazard.

Societal impact in decision-making became a key theme of the World Weather Open Science Conference (WWOSC-2014), discussed in many plenary sessions as well as the specific session on decision-making. Two examples highlighted concerned major tropical cyclones occurring in the previous two years, Typhoon Haiyan (also known as Yolanda) in the Philippines in November 2013 and Hurricane Sandy which struck the United States in October 2012. Emma Porio from the Philippines described in plenary how the excellent forecasts of the track and severity of Haiyan failed to prevent over 6000 fatalities because the warnings did not convey to people what the impacts would be. People in the city of Tacloban did not understand what a storm surge was, or would do, so were not prepared for the massive surge and inundation, and in some cases took exactly the wrong protection, burying their possessions to protect them from wind. Louis Uccellini (US National Weather Service), opening the decision-making session, described the importance of effective and consistent communications in protecting the people of New York from Sandy (Uccellini, 2014). He noted the importance of effective use of multi-model ensemble forecasts to provide the best guidance on probabilities and talked of “shifting risk preferences” and the “spectrum of decision makers” in considering how different people responded appropriately to warning messages. To maintain consistency of message and response, the NWS avoided using the word Hurricane, knowing that if it was technically downgraded to a Tropical Cyclone before landfall, then people would drop their guard even though the likely impacts would be little changed.

Maximizing safety, mobility and efficiency, while minimizing associated costs, is a common goal of many weather forecast users across a number of industries and market sectors, as well as national and local civil protection agencies and the general public. Statistics reveal that significant improvements in weather research and, consequently, weather forecast quality have been achieved over the last several decades. A widely quoted statistic is that the atmospheric predictability has improved by approximately 1 day per decade during the past 20 years (e.g. Nurmi et al. 2013a). Nevertheless, the global population remains quite vulnerable to weather-related hazards. In a study conducted by Lazo et al. (2011), it was determined that the economic impact due to variability in weather (precipitation and temperature) was as much as 3.4% of the 2008 U.S. gross domestic product or $ 485 billion. Since 1980, European economic losses associated with extreme weather have been in excess of € 400 billion (based on 2010 values), with the majority of this loss related to storms and flooding (Hov et al. 2013). Such figures can be attributed to the weather-related impacts that occur throughout several sectors including transportation, agriculture, energy, construction, retail, finance, and insurance. In some sectors such as transportation, these losses are associated with the loss of life and injury. For example, data released by the Federal Highway Administration in the United States suggest that weather is responsible for over 1 million vehicle accidents each year, resulting in more than 6000 fatalities and over 400,000 injuries. In Europe, it was found out in the recent EU funded research project EWENT (Extreme Weather impacts on European Networks of Transport) that the annual road accident costs amount to over € 20 billion and the estimated savings based on current weather services are c. € 3.4 billion (Nokkala et al. 2012). All these figures point to the fact that more needs to be done to mitigate the impacts of weather hazards, particularly in the face of climate change. The question is how much of the c. € 17 billion difference could be gained with improved understanding of and techniques for the weather information delivery chain and decision-making process. One key success factor is the ability to bridge the gap between the science and end users (professionals and laypeople). This means delivering data and information in a manner that better supports weather-critical decision-making.

To aid better decision-making, many forecast providers are attempting to issue risk-based forecasts and warnings - based on the combination of Probability and Impact. The probability aspect of risk may be addressed by modern forecasting systems involving ensemble prediction, but the estimation of impact, which depends on the vulnerabilities of stakeholders and may be measured in terms of human safety, economic costs or other factors, remains a huge challenge involving the crossover between physical and social science. Stakeholders' attitude to risk will depend on the metrics they use to assess impacts which may be based on threats to life or economic costs, for example, so that different users may make very different decisions when threatened by the same probability of a hazard. Many research projects (e.g. EU FP7 projects EWENT and MOWE-IT) have addressed societal impacts of weather-related hazards, but while huge progress has been made in probabilistic hazard prediction, progress with impacts has been relatively modest. Impact modelling requires a deep understanding of the user's business, and simple cost/loss decision rules rarely reflect real world complexity – users make multiple decisions at different lead times and levels of risk.

For forecast providers to maximise the effectiveness of decision-making from their forecasts or warnings they (1) need to engage closely with stakeholders to understand their vulnerabilities and attitudes to risk, and then (2) develop communication strategies which enable the users to take effective and timely decisions and actions. Forecasts are always subject to uncertainty, whether assessed objectively or subjectively, and an important part of the discussion with stakeholders is the level of confidence required for them to take protective action. Such discussions should be taken in advance so that categorical decisions can still be taken in real-time despite the uncertainty.

23.2 FORECAST UNCERTAINTY

To allow society as a whole to make best use of forecasts for effective decision-making requires communication of uncertainty information to the public. A common perception among meteorologists and communicators is that people ("the public") do not understand probabilities, and simply want to be given the best estimate of the forecast outcome which effectively makes their decision for them. However, since every forecast user has their own personal vulnerabilities to the weather, and also a personal view on risk averseness, no single best-estimate forecast can serve the decision-making requirements of all users. The only way to serve all needs is to communicate the full information known on forecast uncertainty. There are many ways to summarise such information, but for many purposes an effective summary might be a most-likely value (often from an ensemble mean or median) plus the probabilities of one or more extreme (high impact) thresholds. Any such summary inevitably reduces the extent to which the forecasts can be applied to the decision-making needs of every user, and therefore the choice of thresholds in a generalised public forecast is a balance between simplicity for ease of understanding and complexity to allow tailoring to individual user needs. It should be noted that in some cases a high-impact event may be generated by the minimum value of a hazard, not necessarily the maximum, for example low river flow may cause problems for navigation (Demeritt et al. 2013).

While there is some evidence that many people are confused or concerned by the term probability, there is growing research evidence that most people (at least in advanced developed countries) can make better decisions when provided with uncertainty information (Joslyn and LeClerc, 2012). Joslyn and Savelli (2010) found that the public in the U.S. understood that forecasts were uncertain, and when forecasts were presented without uncertainty information would make their own judgements of uncertainty, often wrongly, especially in relation to extreme weather events. Decision-making could therefore be improved by providing explicit uncertainty information with the forecast.

Both Roulston and Kaplan (2009) in laboratory controlled experiments, and Stephens et al. (2011) using an on-line game, found that people from a range of backgrounds and academic disciplines were able to make better decisions when forecasts were presented with uncertainty than when a simple deterministic forecast was presented. Stephens et al. (2011) used a range of presentations of varying complexity and found that people made the best decisions with the most complex (and information-full) presentations. A recent survey conducted on behalf of the Met Office Public Weather Service, which ran a number of focus groups with members of the UK public, found that people were broadly accepting of the need and reasons for communicating uncertainty, and receptive to simple presentations. People did find some of the more complex presentations confusing and too scientific, but the use of a percentage figure was considered to be “the most succinct and easily grasped way of conveying probability” and were able to relate information on uncertainty to the sort of day-to-day decisions that they might take. LeClerc and Joslyn (2015) also found evidence showing that uncertainty information reduces the impact of false alarms.

While there is experimental evidence that probabilistic information can help users make better decisions, there is also evidence that institutional difficulties are created by probabilistically qualifying warnings. Some users prefer not to assume responsibility for taking decisions in the face of uncertainty. In the UK, Demeritt (2012) found that emergency responders were reluctant to act on probabilistic forecasts at long lead times, when the probabilities are <50-60%. In many countries emergency response protocols are organized solely around a high level state of emergency requiring the mobilization of civil protection, hence requiring quite high confidence thresholds for issuing warnings. Thus flood warnings focus on short term (0-24 hour) warnings to support public evacuations, rather than on medium-term forecasting in support of flood damage mitigation, and responders have no legal response protocol for a lower probability several days in advance (Demeritt and Norbert, 2011; Demeritt et al. 2015). Effective use of probabilistic warnings to take full advantage of the best science may thus require significant changes to the framework in which responders operate.

Much like the potential confusion and lack of understanding of uncertainties or probabilities by the public, the same can be said about understanding forecast verification information. However, information on forecast quality, whether it be probabilistic, deterministic, categorical or the combination of these different forecast types, should always be communicated to forecast end users, not forgetting the general public. This will improve their general confidence in the forecasts, allow them to identify situations in which forecasts can be considered reliable, and help them identify the extent to which forecasts are useful as basis for decision-making in weather sensitive activities (Ebert et al. 2013; See also chapter on Cross-cutting Research on Verification Techniques in this book). There is some early evidence (Joslyn et al. 2013) that non-experts in meteorology already understand basic verification metrics and graphics. However, greater efforts are needed to develop better and more intuitive forecast verification measures and products for end users to improve their background understanding for decision-making.

23.3 DECISION SUPPORT STRATEGIES

Weather data and forecast providers such as national meteorological services and private sector companies have begun to focus more on addressing the gaps that exist between their offerings and end users' operations. These efforts are manifesting themselves in two primary areas, decision support services and decision support systems. Decision support services involve a consultancy structure in which the forecast provider develops a deep understanding of the end user's operations in order to facilitate real-time, two-way communication and interaction that targets the weather-dependent operational aspects that are most important to the end user before, during and after an event. A decision support system is a tool that, in its most mature form, uses decision models to couple weather forecasts with data and information concerning an end user's operations to deliver objective, repeatable guidance that will support decision-making (Petty et al. 2010). Attempting to build into a system the complexity of customer vulnerabilities is hugely challenging, especially as vulnerabilities often evolve according to antecedent events and through the course of an event. The services and systems being developed and employed attempt to address the aforementioned need to cultivate a more comprehensive understanding of end user operations through stakeholder engagement and advance effective communication strategies. Although considerably more work is required, there are a growing number of emerging examples where collaborative efforts between end users and forecast providers have resulted in very novel methods and techniques that deliver considerable value in terms of weather-based decision-making.

Early work on decision-making using probability forecasts was mostly based on a simple cost-loss model for a binary decision. Consider the probability p of something happening (e.g. road temperature falling below freezing) and a related decision (treat roads against ice formation). Consider the cost C of protection against the event (road treatment) and the potential financial losses if there is no protection and the event occurs, L. Then the mathematically rational decision would be to take action when the probability exceeds the cost-loss ratio: $p>C/L$. (Murphy 1977; Mylne, 2002; Richardson 2000). While this model provides the basis of a rational framework for decision-making, it has rarely been used in practice for a number of reasons. Few decisions are as simple as a binary yes-no based on a fixed threshold at a fixed time. The example given of road treatment against ice is as near as such a decision comes, but will still be affected by, for example, how risk-averse the road manager or her political masters are – is their prime concern to save tax payers' money or to minimise risk of life? - which may depend on when the next election is!

A few examples have been developed of decision tools which extend the concept of a C/L model to more realistic decision-making problems. Dale et al. (2014) describe a tool using ensemble forecasts of flooding which estimates a cost to each ensemble member depending on the depth and extent of flooding predicted by that ensemble member. Thus rather than using the probability of exceeding a single flood/no-flood threshold, the ensemble members are weighted according to the severity of flooding impacts predicted. The mean cost may then be balanced against the cost of protection, so that protection may be justified by either a high probability of a low to moderate impact flood or by a low probability of a very severe flood.

A number of countries now issue their Public Weather Service (PWS) warnings in a risk-based framework, often employing a "traffic-light" colours scheme to communicate levels of risk and therefore levels of response action in a simple pre-arranged language. The UK National Severe Weather Warning Service (Neal et al. 2013) uses such a matrix taking account of both likelihood and impact (Figure 1). This framework was agreed in collaboration with key stakeholders responsible for civil protection such as fire and rescue services; while those stakeholders are likely to have specific planned responses to levels of warnings such as having extra staff on stand-by or deploying extra flood defences, the public are given very simple messages to "Be aware" (Yellow), "Be prepared" (Amber) and "Take Action" (Red). The tick in the box on the matrix is added by the forecaster to indicate the combination considered of greatest relevance to civil responders, based on a subjective assessment of the highest level of impact considered realistic, but the matrix also reflects that any probability of a higher impact event is invariably connected with a higher probability of a lower impact. Assessment of the likely level of impact in the UK is still largely subjective and based on the accumulated experience over many years of the types of impact associated with different strengths of wind, rainfall accumulations etc. Neal et al. (2013) describe how an ensemble-based first-guess warnings system uses probabilities of exceeding a number of thresholds to estimate warning colours objectively. Impact thresholds vary across different regions of the UK according to the climatology and resulting vulnerability to levels of hazard.

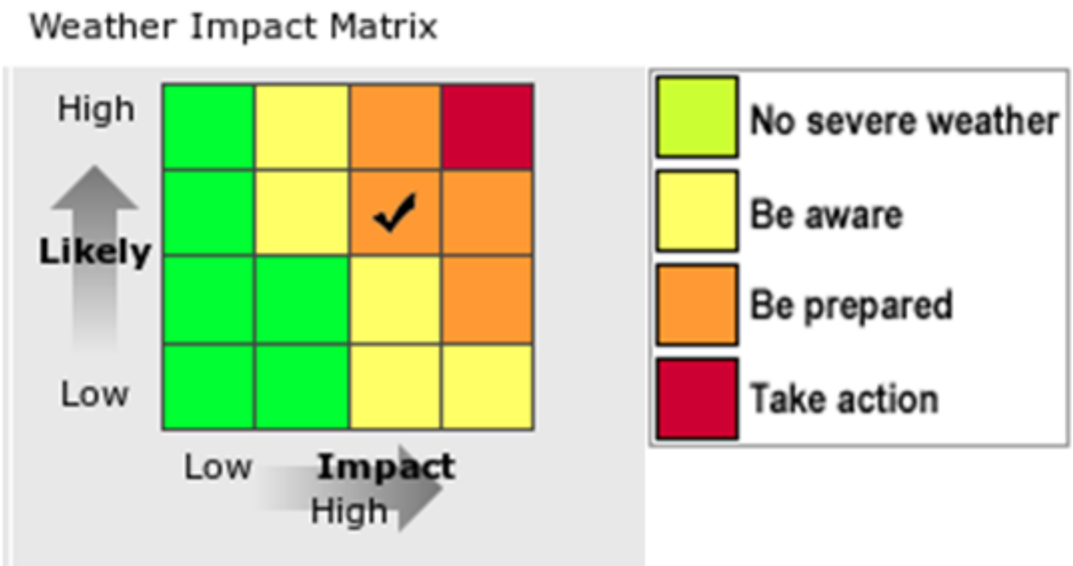

Figure 1. The risk matrix used in the UK National Severe Weather Warnings Service to determine a warning colour based on a combination of severity of impact of anticipated weather and the likelihood of occurrence of that impact.

In practise civil protection will involve many stages of decision as information and confidence evolves closer to a predicted event. Helen Titley (Met Office) described at the conference the forecasts for the worst storm surge to affect the east coast of England since 1953, in December 2013, which demonstrated the power of such a risk-based warning system (Titley, 2014). The Met Office operates a storm surge ensemble prediction system, and this first flagged a low probability (one or two ensemble members) of an extreme surge event over six days in advance. Due to the potential severity, the Environment Agency (responsible for flood warnings) issued a Yellow (low probability, high impact) alert to civil responders some five days ahead - enough to alert responders to start low-level preparedness actions. By three days ahead the probability had increased enough to upgrade to Amber which triggered greater actions and at two days ahead a Red (high probability - high impact) leading to evacuations of vulnerable populations.

One of the challenges of risk-based prediction is to reduce the subjectivity in estimation of the impact axis of the matrix in Figure 1. The same hazard may generate a range of different impacts, each of which must be modelled or estimated independently. For example a strong wind may cause impacts on roads due to bridge closures or vehicles being blown over, on railways due to fallen trees or power line damage, and to lives through flying debris, plus many more. Each of these could potentially be modelled independently, taking account of local vulnerabilities and exposure data. Figure 2 illustrates one example of a Hazard Impact Model (HIM) which estimates risk of disruption on the UK road network due to strong winds. The model projects ensemble forecasts of high winds onto the road network and uses speed and direction thresholds for different vehicle types, based on previous research, to estimate the likelihood of vehicle over-turning. Different road sections are weighted according to their vulnerability, depending on whether the road is exposed or sheltered from the wind, on a bridge or tunnel for example, and then further weighted according to the exposure given by the number of vehicles using the road and therefore likely to be affected by an over-turned vehicle, to estimate an overall level of risk shown by the colour code on the map. This model provides UK forecasters with an objective estimate of risk due to winds, but covers only one aspect of potential wind impact. The complete picture is highly complex and may still be best estimated by an experienced human forecaster.

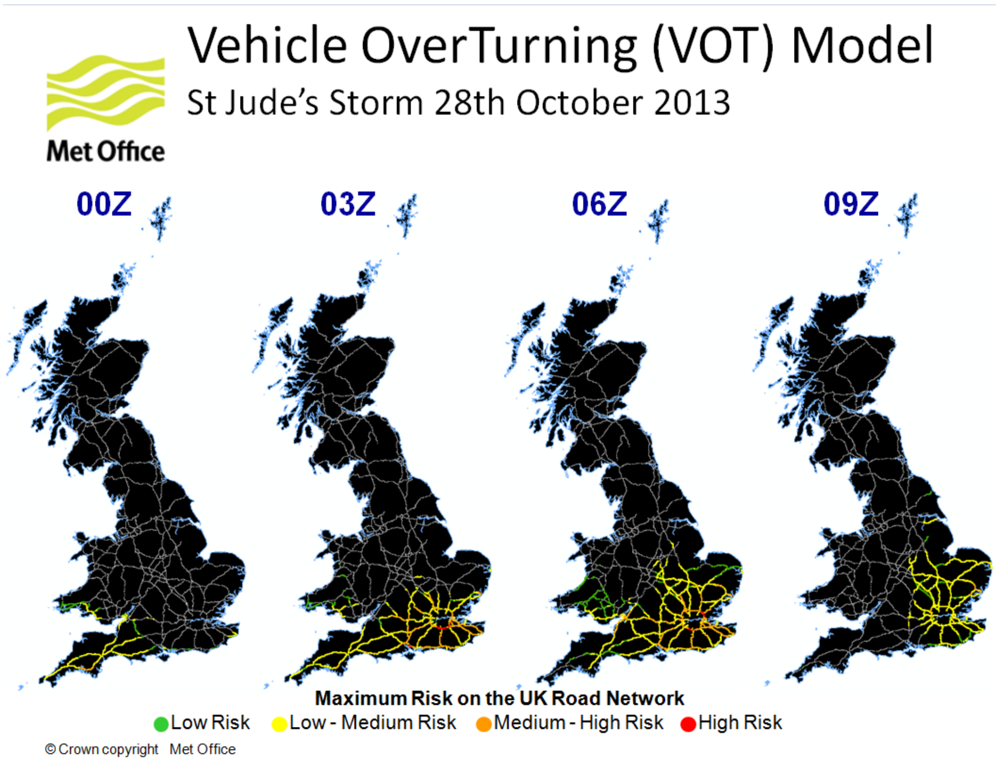

Figure 2. Example of the vehicle overturning module of the Hazard Impact Model (HIM) developed by the Met office to estimate risk of transport disruption due to strong winds over-turning vehicles, showing how the risk evolves through time as the storm tracks across the UK.

All transport sectors (i.e. aviation, maritime, road, and rail) are known to be highly weather dependent. The European MOWE-IT project (www.mowe-it.eu) (Management Of Weather Events In The Transport System; under the EU 7th Framework Programme, FP7) has among its goals the development of methodologies that will assist transport authorities and transport system end users in mitigating the impacts of natural hazards and extreme weather phenomena on transport system performance. MOWE-IT has just recently published a set of five mode-specific guidebooks for Aviation, Rail, Road, Inland Waterway and Maritime transport[a] which are directed at decision-makers and other stakeholders having the objective to reduce the extreme weather impacts on transport (e.g. for roads[b]). It is envisioned that information contained in all of the guidebooks will enable forecast providers and forecast end users to understand the types and magnitudes of impacts expected from disparate weather hazards across different transportation sectors. Leveraging this information in collaborative ways will support the creation of plans, services and tools that can aid in mitigating weather-related impacts through enhanced decision-making.

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[a] *See www.mowe-it.eu/wordpress/deliverables*
[b] *See www.mowe-it.eu/wordpress/wp-content/uploads/2013/02/MOVE-IT_road_guidebook_final.pdf*

Another EU FP7 project, FOTsis (Field Operational Test on safe, intelligent and sustainable road operation) is a large-scale field testing of road infrastructure management and end user systems piloted along nine selected European highways. Weather-driven solutions and services have a fundamental role in FOTsis, because adverse weather accounts for some of the most notorious disruptions in road transportation addressing thus huge economic impacts (Nurmi et al. 2013b). In a similar manner to the UK National Severe Weather Warning Service described above, the FOTsis end-to-end weather applications do not deliver customary weather forecasts like rainfall or weather symbols but, rather, employ weather-related information as explicit “traffic-light” kind warning alerts against potentially adverse weather events jeopardizing traffic conditions and safety. Hence, the end users will not receive direct meteorological information at all, but explicit impact messages providing guidance for their actions. To produce such alerts shown in Figure 3 (aka “minimize/control your speed”, “stop driving”), the critical threshold values for all required meteorological variables were assigned taking carefully into account the specific local climatology at each of the pilot highways (the example in Figure 3 is for the A2 Highway in central Spain).

Parameter/Event	Thresholds	Action message
Snow / Sleet	" Any snowfall, incl. hail "	" Minimize your speed "
	≥ 2 cm/h or ≥ 10 cm/6h or ≥ 1 cm/h + T ≤ -10C	" Stop driving "
Rain	1 - 5 mm/h	" Control your speed "
	5 - 10 mm/h	" Minimize your speed "
	≥ 10 mm/h	" Stop driving "
Freezing rain	Rain ≥ 1 mm/h + Tair < 0C	" Stop driving "
	Rain + Tsurface < 0C	" Stop driving "
Visibility	Visibility ≤ 400 m	" Control your speed "
	Visibility ≤ 250 m	" Minimize your speed "
	Visibility ≤ 80 m	" Stop driving "
Blizzard	Max wind gust ≥ 17 m/s & Tmean ≤ 0C (24 hrs) & Precip ≥ 10 mm (24 hrs)	" Stop driving "
Wind, mean	≥ 12 m/s	" Control your speed "
	≥ 17 m/s	" Minimize your speed "
	≥ 21 m/s	" Stop driving "
Wind, gust	≥ 17 m/s	"Control your speed"
	≥ 25 m/s	" Minimize your speed "
	≥ 32 m/s	" Stop driving "
Surface Friction	≤ 0.4	"Control your speed"
	≤ 0.3	" Minimize your speed "
	≤ 0.2	" Stop driving "
Surface condition	Damp	" Control your speed "
	Wet	" Control/Minimize your speed "
	Snow on the road	" Stop driving "
	Ice on the road / Black ice	" Stop driving "
Road maintenance		
Road surf temperature	< -7C	" Salting does not help "
Snow accumulation	> 3cm	" Time to plow "

Figure 3. Meteorological variables and their thresholds leading to explicit action messages as guidance for road end users in the Spanish pilot highway within the FOTsis project.

Source: Nurmi et al. 2013b

In the United States, the National Weather Service (NWS) has embarked on a multiyear strategic initiative designed to build a “weather ready nation” in which the country is more resilient to weather-hazards as a result of improved preparedness and more effective response in the face of high-impact weather. As part of this plan, the NWS is instituting a services framework that includes Impact-based Decision Support Services (IDSS) wherein enhanced interpretation and consultation, along with more focus on societal impacts, will be leveraged in an attempt to improve the decision-making process of key stakeholders (NWS, 2013). It should be noted that these steps will be carried out in concert with other fundamental activities such as improvements in the science and technology used to produce forecasts and warnings, including information on forecast uncertainty derived from ensemble-driven modelling and post-processing. These NWS activities are consistent with some other national meteorological institutes and forecast providers and demonstrate the organization’s commitment to high-quality decision support through effective stakeholder engagement and enhanced communication strategies.

23.4 CONCLUSION

Successfully reducing the impacts of weather-related hazards is dependent on several factors; however, the weather-critical decisions made by end users are a fundamental element in impact mitigation. Improvements in weather-based decision-making will ultimately result in advances in areas such as operational safety and efficiency. Research and development aimed at improving the decision-making process will benefit from collaborative input from a broad range of professionals (e.g. physical and social scientists, usability practitioners, etc.). Particular focus should be given to societal impacts, which entails working closely with forecast end users to better understand and quantify weather-related impacts, as well as developing strategies for communicating information that will enable end users to more effectively manage risk. Research and development activities should also include examining ways to produce and communicate forecast uncertainty. The delivery of uncertainty using probabilities is one method to support forecast end users, with recent research suggesting that end users, including the general public, are capable of using such information. Nonetheless, there are also ancillary techniques that should be explored. The combination of forecast uncertainty and impact information can lead to powerful decision-level services and tools for addressing weather-related hazards and impacts.

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CHAPTER 24. THE HIGH-IMPACT WEATHER PROJECT

Brian Golding and Sarah Jones

Abstract

Despite substantial advances in both forecasting capability and emergency preparedness, recent years have seen a large number of natural disasters that have cost many lives, displaced large numbers of people, and caused widespread damage to property and infrastructure. Many of these disasters result from severe weather interacting with society. At the same time, less severe weather events place a continuing strain on society through more frequent impacts of smaller magnitude. This is especially evident in less developed countries with more fragile economies and infrastructure. In addition, weather forecasts are becoming increasingly important for economic applications (e.g. forecasting energy supply and demand) and for protecting the environment. In all these areas users of weather information expect more sophisticated guidance than was the case ten years ago. THe Observing System Research and Predictability EXperiment (THORPEX) programme delivered major advances in the science of weather forecasting thus providing the knowledge basis for improving early warnings for many High-Impact Weather (HIWeather) events for one day to two weeks ahead. At the same time, new capabilities in short range forecasting arising from the use of new observations and convective-scale numerical weather prediction models and ensemble prediction systems have made it possible to provide warnings of weather-related hazards, directly, up to one or two days ahead. Together with advances in coupling prediction models and better understanding by social scientists of the challenges to achieving effective use of forecasts and warnings, these advances offer the basis for a dramatic increase in the resilience of communities and countries to the threat of hazardous weather and its impacts. The time is ripe to capitalize on these advances. HIWeather is a ten year activity within the World Weather Research Programme (WWRP) to: "Promote cooperative international research to achieve a dramatic increase in resilience to high-impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications".

24.1 WEATHER-RELATED HAZARDS

The scope of the project is defined by the needs of users for better forecast and warning information to enhance the resilience of communities and countries in responding to a carefully selected set of hazards. While not comprehensive, they cover a wide range of impacts so that advances in building resilience to them may be expected to have more general relevance. The selection has been guided by their importance as a cause of disasters, by relevance to developing countries, by vulnerability of those living in megacities, and to span the complete range of climate regimes.
The key weather-related hazards are:

- **Urban flood:** including flooding from the sea, rivers and directly from rainfall that exceeds drainage capacity, and including rain-induced landslides; with particular emphasis on flood impacts in the growing megacities of the developing world, especially those situated in the tropics and subtropics. Flooding is the most common cause of disasters in the world today. Since most of the world's major cities lie either on the coast or on a major river, the problem is set to increase as cities grow, sea level rises, and the hydrological cycle becomes more intense in a warming atmosphere. Management of floods varies according to their scale and source. For large river floods with large forecast lead times, river controls can be used to either make space for the water or to retain it upstream of vulnerable populations. For coastal floods with large lead times, evacuation may be most appropriate. For flash floods and surface water flooding, local protection and movement of people requires more precise forecasts at much shorter lead times.
- **Wildfire:** emphasising requirements associated with fire fighting and fire management as well as prediction of fire risk. Increasing use of wilderness areas for recreation and the spread of human settlement into forested areas are both increasing the risk from this hazard. Fire is associated with drought and high temperatures, so there will be opportunities for linking with

the Sub-seasonal to Seasonal (S2S) (see Chapter 20) project in extended range prediction of these conditions. However, management of live fires also requires a detailed knowledge of both the vegetation state and wind, which can only be predicted for very short periods ahead.

- **Localised extreme wind:** including localised wind maxima within tropical and extratropical cyclones (e.g. sting jets), downslope windstorms, and tornadoes. Great advances have been made in the prediction of both tropical and extratropical cyclones over the past decade, but wind damage and disruption mostly occur in small areas, e.g. within embedded mesoscale and convective scale weather systems. Decisions on appropriate protective action depend on knowing the location, timing and intensity of these localised wind maxima.
- **Disruptive winter weather:** including snow, ice, fog and avalanche, and focussing on transport, energy and communications impacts. While not usually the cause of disasters, this collection of hazards, with related meteorological causes and overlapping impacts, is a major source of social and economic disruption in mid-and high-latitude regions. There will be opportunities to work with the Polar Prediction Project (PPP) (see Chapter 19) on this hazard.
- **Urban heat waves and air pollution:** while extreme heat and poor air quality may occur separately, both are associated with long-lived weather patterns, both give rise to similar health responses, and major heat-related disasters tend to involve both ingredients. There will be opportunities to work with the S2S project on the extended range predictability of blocking events, but the main focus will be on the spatial and temporal variability of the hazard and the influence of the urban fabric through emissions and heat fluxes from the built environment.

24.2 RESEARCH THEMES

The research required to deliver enhanced resilience to these hazards will be carried out in five themes that cover areas traditionally separated into the physical and social sciences. Achieving the outcomes of the HIWeather project depends on these two scientific communities working together. Research objectives have been identified within each theme that, together, will enable specific advances in the management of impacts from the five hazards. Many of the initial activities in the themes will be focused on gathering and sharing evidence of current best practice, to bring the communities together, for use as a springboard for new work and to support capacity building through knowledge exchange activities.

24.2.1 Predictability and processes

Research will be focused on the meteorological processes that influence the predictability of HIWeather: control of convective-scale predictability by large scale processes in tropical and extra-tropical latitudes; differences in predictability of hazardous weather relative to “normal” weather; association with forecasts that are very sensitive to initial state; mechanisms that produce quasi-stationary hazardous weather systems; role of diabatic heating; role of boundary layer and land surface; pre-conditioning of the land surface for hazards. These research challenges will be addressed through the use of datasets from recent and planned field experiments, through coordinated case studies and model intercomparisons, and in review papers and targeted workshops.

24.2.2 Multi-scale forecasting of weather-related hazards

Research covers the observations, nowcasting, data assimilation, modelling and post-processing required to forecast weather-related hazards using coupled numerical weather, land surface, ocean and chemistry models, including modelling of floods, landslides, bushfires, air pollution etc. Research will focus on advances in the whole prediction chain needed to forecast the hazards, on prediction at convective-scale (<3 km), on coupled modelling and on the use of ensembles to quantify probability and uncertainty. Specific activities will be carried out reviewing the use of existing and new observation sources; comparing new approaches to multi-scale coupled modelling and data assimilation systems, drawing on parallel activities in the S2S project; developing ensemble perturbations for small scales and hazards; and meeting the product specifications identified by the Communications theme. The research will make use of a catalogue of hazardous weather case studies developed with the Predictability and Processes theme, together with datasets from recent and planned field experiments, reanalyses and reforecasts, and will demonstrate and evaluate new techniques in Forecast Demonstration Projects (FDP).

24.2.3 Human impacts, vulnerability and risk

Research will be led by social scientists, with a focus on the interface between the physical hazard and the human impact. It will cover modelling of the role of the built environment in hazards, and of the exposure and vulnerability of individuals, businesses and communities. Workshops are planned to draw the physical and social science communities together through agreed definitions of key words and concepts, which will be documented in a white paper. Research will initially focus on building a community of interested scientists across NMHSs, academia and the private sector to review recent experience and current capabilities, to document the requirement and state-of-the-art in meeting it, and to identify and prioritise gaps in hazard prediction inputs, impact models and evaluation capability. This will inform subsequent activities in impact monitoring and in the construction, evaluation and deployment of impact models. Identifying and sharing best practice will be a recurrent activity for this theme, while Demonstration Projects will provide opportunities for evaluating new capability.

24.2.4 Communication

Research will focus on the choices of information content, language, format and media channels used, spatial and temporal precision, timeliness and context that together determine whether forecasts & warnings will be received, trusted, understood and acted on. A catalogue of post-event reviews will be developed, together with regular surveys and workshops involving weather services, private sector meteorologists and key user groups. This will be used to assess high-impact weather communication methods and their transferability, leading to a published review paper. This initial work will inform subsequent activities in developing communication methodologies and monitoring responses. Identifying and sharing best practice will be a recurrent activity for this theme. New capability will be evaluated in FDPs and success stories shared. Workshops and special sessions at conferences will be convened and a journal special issue is planned to attract social scientists to contribute in this field.

24.2.5 User-oriented evaluation

Research will focus on the profile of accuracy and value through the forecasting, warning and communication chain with an emphasis on the information required by decision makers to build their trust in the information they receive. An intercomparison project will assess whether recent advances in meteorological verification can usefully be extended to more variables, including the hazards themselves for which allowing for observation quality will be important. A white paper will be published and new techniques will be evaluated in FDPs. Together with the Communication theme, a catalogue of post-event reviews of the effectiveness of forecasts and warnings will be compiled. Targeted workshops and conference sessions will be held to involve users and social scientists in exploring metrics of the value of forecasts and warnings in user decision-making. Evaluation requires observations so this theme will work with the Human Impacts, Vulnerability and Risk theme to investigate how to use new sources of data in verification. Research on economic benefit of forecasts and warnings, will also be carried out through workshops involving economists and private sector meteorologists, leading to the publication of a white paper.

24.3 CROSS-CUTTING ACTIVITIES

Eight cross-cutting activities have been identified across the themes to draw them together.

- **Benefits in operational forecasting:** The challenges and requirements of the operational forecasting process will be elicited to help define the priorities of the individual research themes. The resulting research and knowledge will be used to inform and recommend changes to the operational forecasting process. The constraints and needs of implementation will be an underlying concern of several of the themes, particularly the communication theme.

- **Design of observing strategies:** while conventional observing systems are well supported through the World Meteorological Organization (WMO) Commission for Basic Systems (CBS) activities, there is a need for research into the opportunities and limitations of observing strategies for the future global observing system. The research should consider the potentially conflicting demands of deploying local technologically advanced observing systems relative to maintaining more traditional observational capability globally. A new priority for this activity will be to look at the needs and opportunities for updating the social and economic data, such as traffic flows and chronic illness distributions, required by impact models and for real-time observations of impacts and responses, potentially including the use of crowd-sourcing, social networks, and ubiquitous sensors.
- **Uncertainty:** is an underpinning characteristic of all the physical and socio-economic systems represented in the research themes. Forecasts are expected to be probabilistic requiring improved knowledge of processes that lead to uncertainty and improved methods of quantifying and evaluating uncertainty; key issues in communication revolve around expressing and perceiving uncertainty.
- **Field campaigns and demonstrations:** will provide observations and model outputs to support new understanding, to verify modelling advances, to understand user needs, and to test the value of new products and communication methods. Datasets from previous campaigns will be exploited further and new programmes (including Research Development Projects (RDPs) and FDPs initiated). This activity should enhance academic and operational collaboration.
- **Knowledge transfer:** while stakeholder engagement is treated separately as indicated by the arrows in the concept diagram, knowledge transfer between disciplines, between advanced to less advanced centres and between academic experts and operational centres is a key cross-cutting activity.
- **Verification:** while the research theme on evaluation is focussed on new research that supports process understanding, model development, communication, use and value of forecasts, the application of verification principles has a role in all research activities that will be coordinated by the Evaluation theme. It also has a key role in identifying and measuring the benefits achieved by the High-Impact Weather project itself.
- **Impact forecasting:** the emphasis across all of the research themes is on predicting impact-related parameters that, alongside the weather forecast variables, will support effective decision-making. This requires input from the vulnerability and risk theme into the other themes.
- **Data management and archiving:** both model and observation data needs to be made readily available to support HIWeather research activities. To complement the routine THORPEX Interactive Grand Global Ensemble (TIGGE) and TIGGE-Limited Area Model (LAM) datasets, demonstration projects will be encouraged to set up high-resolution convective-scale ensemble forecast datasets consistent with TIGGE-LAM standards. This activity should enhance collaboration between researchers and operational Numerical Weather Prediction (NWP) centres.

Some of these serve to ensure that key common areas of expertise are applied throughout the project, while others will enable the pooling of skills and resources so as to take forward and demonstrate the results of multiple research themes.

24.4 IMPLEMENTATION

The activities necessary for the success of the HIWeather Project are described in the Implementation Plan (available from www.wmo.int/wwrp, see also Figure 1). Many of the research and cross-cutting activities will converge on field campaigns, RDP/FDPs which will be focussed on particular hazard forecasting problems in specific climates so as to establish an evidence base of best practice that may be applied globally. New RDP/FDPs will be promoted, probably in conjunction with field experiments aimed at broader objectives, in the areas of urban flooding, winter weather, fire weather and extreme local winds. It is also planned to use available forecasting test-beds to evaluate advances in use of observations, modelling and product generation.

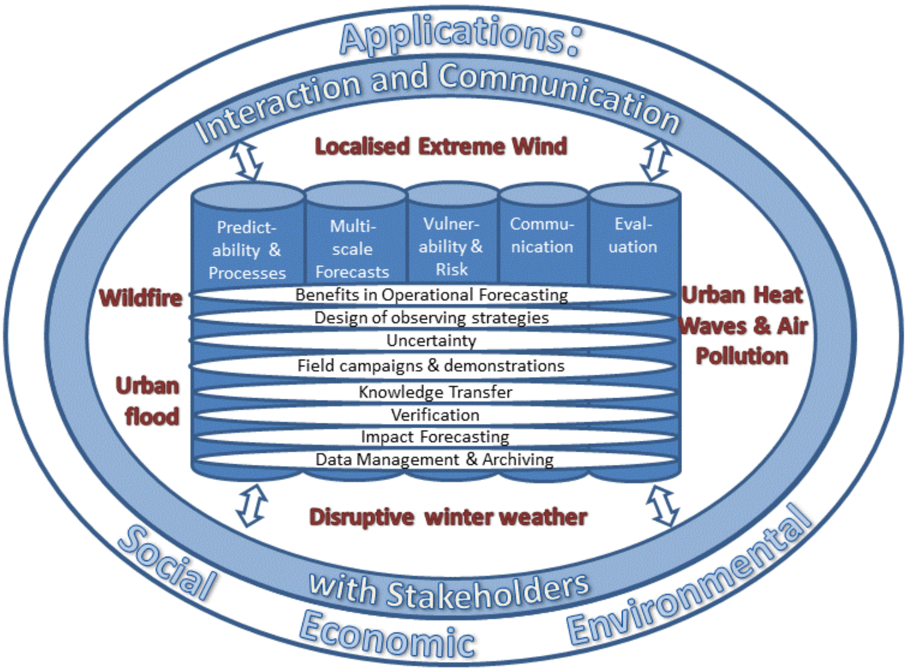

Figure 1. Conceptual diagram of the HIWeather project. Research Themes (pillars) are areas of core research in which academia, research institutions and operational forecasting centres will work together to address the gaps in capability needed to deliver the mission statement. Cross-cutting activities and issues (ellipses) will be addressed by multi-disciplinary teams drawn from multiple research themes.

The proposed research will revolutionize the knowledge available to be used in support of weather-related hazard management, both through development of new capabilities and through sharing of existing good practice, providing better accuracy and more relevance, from systems designed with proactive risk reduction and effective emergency-response as their aim. At the same time, the research benefits will cascade to “normal” weather, enabling National Meteorological and Hydrological Services (NMHS) to make more effective contributions to their national economies, especially in less developed countries. These outcomes will contribute significantly to delivering the aims of the follow-on to the Hyogo Framework for Action, which will be agreed at Sendai in 2015.

The research will build on advances made in THORPEX and dovetail closely with the other two projects arising from THORPEX: the PPP and S2S projects. The WWRP working groups, along with the Working Group on Numerical Experimentation (WGNE) will be important contributors to the research. Links with the Climate Impacts community in the World Climate Research Programme (WCRP) will be developed to enable research results gained in HIWeather to be applied to assist communities and countries in their adaptation to a changing climate. The cooperation between the academic and operational communities developed in THORPEX will be maintained and strengthened. The programme will work closely with other international and national programmes in disaster reduction and hazard forecasting, and will establish links with major business-led programmes that address weather sensitivities. A primary goal will be to build capacity in less developed countries, particularly through RDP/FDPs, engaging widely with the academic and emergency response communities in the host countries.

It is essential that the project is user-driven and outcomes oriented. The science themes must work together to deliver new capabilities that will benefit users of forecast and warning information. Key international programmes, especially in disaster risk reduction, are already in place. It is important not to overlap with them, but to ensure that weather-related aspects are adequately dealt with. This will be particularly key with respect to business-led initiatives such as the development of next generation air traffic management and large scale energy management systems. Interaction and communication between researchers and stakeholders will be an essential part of the project. Relevant stakeholders range from global and national scale funding agencies to individuals. A range of activities will be needed from individual engagement at the local level during FDPs, through regional scale workshops for emergency response and business groups, to major conferences and briefing sessions for international bodies. Finally, aspects of human impacts of weather and of the communication, interpretation and use components of forecast delivery are not widely understood in the meteorological community. This project provides an opportunity to facilitate wider understanding, especially amongst young scientists who will be the scientific and policy leaders of tomorrow

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Further references are available in the HIWeather Implementation Plan.

CHAPTER 25. CONCLUSIONS

Gilbert Brunet, Sarah Jones and Paolo M. Ruti

Whether on an urban or planetary scale, covering timescales of a few minutes or a few months, the research programmes covered in the chapters of this book are dedicated to improving the prediction of high-impact weather and environmental events. This challenge, at the intersection of scientific research and society's need, is amongst the most important scientific and technological challenges of our time. The ground-breaking advances in data assimilation, observations, predictability, dynamical-physical-chemical processes, global-regional-urban numerical weather and Earth system prediction described in this book show how much progress has been achieved since the first numerical prediction by Charney, Fjørtoft and von Neumann in 1950.

The successful utilization of the global observing and communication network and efficient use of weather remote sensing technologies (e.g. radar, satellites, etc.) is due to an unprecedented thrust of recent decades in scientific research on data assimilation and observations. The major advances made in our knowledge and understanding of the dynamical, physical and chemical processes pertaining to the earth system and of the factors that determine its predictability serve to guide the goals of numerical weather prediction (NWP). Investigations in turbulence, cloud physics, radiation, atmospheric chemistry, numerical methods, the organization of convective systems, non-linear system dynamics, wave theory, ensemble prediction systems, verification and many other topics allow weaknesses in the forecast system and priorities for future development to be identified.

Thus increases in the predictive skill of the weather and environmental forecasting systems operated in National Meteorological and Hydrological Services (NMHSs) rely on theoretical advances, major international measurement field campaigns and on the sophisticated interplay of research and development innovations in observing technologies (radars, profilers, satellites, etc.), numerical methods (spectral methods, finite element, etc.), sub-grid scale physics parameterizations (deep convection, cloud, mountain, etc.), atmosphere-ocean-sea-ice and land-surface-hydrology coupling, atmospheric dispersion and air quality, and data assimilation of surface, upper air and satellite observation systems and high performance computing systems.

A unique aspect of weather and environmental prediction that drives these advances in skill is the necessity to provide forecasts daily and seamlessly at all relevant lead times. The operational weather and environmental prediction products have proven to be a rich source of information for those wishing to develop new scientific concepts and theories. Indeed forecast systems provide the opportunity to develop and test hypotheses and improve theories and techniques through experimentation, assessment, and through verification and quantification of the forecast improvements every day against observations.

Increases in predictive skill must be translated into improved applications tailored to the needs of the end users. Significant advances have been made in improving the synergetic use of observations and model output in nowcasting techniques and combining these with NWP output to improve forecast products and warnings. More emphasis will be placed in future on the further automation of the forecast process, allowing for more effective manual intervention in critical weather situations and in improved techniques to forecast the impacts of weather-related hazards and to integrate the information from these forecasts in the decision making process.

The forecast enterprise includes constant pressure from users and operational centres to improve their prediction products and their dissemination in order to save lives and reduce fatalities, improve public safety and the quality of life, protect the environment, insulate economic sectors from danger and increase socio-economic benefits. These pressures and the competition and co-operation among operational centres have ensured that the best relevant ideas of research will be incorporated into forecast systems when practical. Thus, weather and environmental forecasting has become increasingly complex and international over all time and space scales with more and more credible environmental applications (e.g. forecasting sea-ice, water quantity and quality, air quality). Hence the need to coordinate weather and environmental research and development internationally and between academic and operational research is increasingly an important goal of the World Meteorological Organization (WMO).

This book describes the important weather and environmental prediction research challenges that need to be tackled in the foreseeable future through coordinated international research programmes. The WMO is well positioned to tackle this international challenge. WMO, sponsor of the World Weather Research Programme (WWRP), the Working Group on Numerical Experimentation (WGNE), the Global Atmosphere Watch (GAW) atmospheric composition research programme and co-sponsor of the World Climate Research Programme (WCRP), has promoted a unified approach to multi-disciplinary research. WMO also calls for a step-up in high-performance computing investments for coordinating and accelerating weather, climate, coupled chemical and hydrology model development, validation and use.

WWRP has defined three major new projects: the Sub-seasonal to Seasonal Prediction Project (S2S), the Polar Prediction Project (PPP), and the High-Impact Weather Project (HIWeather) and supports working groups on data assimilation and observing systems, predictability, dynamics and ensemble forecasting, tropical meteorology, nowcasting and mesoscale research, verification, and societal and economic research applications (Figure. 1). WWRP supports the development of centralized facilities for data sharing in support of academic research and NWP model intercomparisons. WWRP and WCRP are jointly coordinating research programmes, such as S2S and PPP, which link global weather and climate research and prediction.

Figure 1. Schematic representation of WWRP structure. On the left are the societal challenges defined by the Commission for Atmospheric Sciences related to high-impact weather and its socio-economic effects in the context of global change; to modelling and predicting the water cycle for improved disaster risk reduction and resource management; to urbanization and the need for research and services for megacities and large urban complexes; and to evolving technologies, their impact on science and its utilization. The World Weather Research Programme will address these challenges through promoting coordinated research activity at international level in an interdisciplinary framework, involving academic and operational research communities, and supporting the education and training of early career scientists. The WWRP will achieve these aims through the focus areas of the working groups (right side), and the research carried out in the Polar Prediction Project, the Sub-seasonal to Seasonal Prediction Initiative, and the High-Impact Weather Project.

Some of these activities also engage the International Council of Scientific Unions (ICSU), through its co-sponsorship of Global Climate Observing System (GCOS) and WCRP and its academic constituency. In particular with the latter, there are strong links to the International Association for Meteorology and Atmospheric science (IAMAS) and the International Association for Hydrological Science (IAHS). For instance, the new ICSU programme IRDR (Integrated Research on Disaster Risk) and WWRP co-host a joint working group on Societal and Economic Research and Applications (SERA) of weather forecast products and services.

An active physics community is thriving through WCRP's Global Energy and Water Exchanges project (GEWEX), which runs numerous projects typically bringing together observations and large-eddy to global model hierarchies for process understanding and parameterization development, eventually serving both weather and climate communities.

WGNE is also very active in bringing together modelling centres, sharing progress and running projects to tackle problems of common interest. It also provides a vehicle to link expertise in weather and climate science that is becoming increasingly valuable to both communities. For example, as NWP models move towards coupled oceans there is clearly much to be learned from experiences with coupled seasonal and climate models.

Success in following this future roadmap of weather and environmental prediction challenges will depend on the collaboration, strength, commitment and excellence of the above-mentioned organizations, working groups and research programmes. The past track record provides a solid base for confidence.

The WWRP exists to develop, share and apply knowledge that contributes to societal well being, principally by helping to manage weather-related risks to safety and property but also by enabling individuals, businesses, and institutions to take advantage of opportunities afforded by weather conditions. Fundamental aspects of this knowledge include an improved understanding of atmospheric processes that give rise to weather phenomena and enhanced ability to predict weather events and their consequences with sufficient spatio-temporal precision, accuracy and advanced warning to support decisions.

We are entering a new era in technological innovation and in use and integration of different sources of information for improving well being and the ability to cope with multi-hazards. New predictive tools able to detail weather conditions to neighbourhood level, to provide early warnings a month ahead, and to forecast weather-related impacts such as flooding and energy consumption will be the main outcomes of the next ten years research activities in weather science. A better understanding of small-scale processes and their inherent predictability should go together with a better comprehension of how weather related information influences decisional processes and with better strategies for communicating this information. Within this perspective, this book is intended to be a valuable resource for anyone dealing with environmental prediction matters, providing new perspectives for planning and guiding future research programmes.

AFTERWORD

The material presented in this book is based on the results presented at the World Weather Open Science Conference (WWOSC-2014) held in Montreal from 16 to 21 August 2014. As co-chairpersons of the International Programme Committee, the Science Programme Committee and the User, Applications and Social Science Programme Committee we would like to take this opportunity to express our sincere appreciation for the support we received from many people in the realization of this ground-breaking international conference.

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This book is a tangible measure of the success of the WWOSC-2014 and ensures that the work put into organizing the conference and into the scientific presentations and discussions will be of benefit to a broad community. Thus, we express our particular gratitude to those who have made it possible to produce this book: to Paolo M. Ruti for his excellent work as co-editor, to the international experts listed below who provided advice during the editorial process, to Pauline Mooney-Corelli at WMO for completing the major task of producing the book on a very tight timescale, and to all of the authors who devoted their valuable time to writing and revising their specific chapters.

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