Science directions in a post-COP21-world of transient climate change: enabling regional to local predictions in support of reliable climate information

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

COMMENTARY
10.1029/2018EF000979

Key Points:
- The challenge of improving seamless regional climate forecast requires enhanced scientific understanding of regional to local climate processes
- Establishing actionable climate information calls for the technical development of multiscale approaches to climate predictions
- Reaching these goals relies on international coordination and on a close interaction between the science and stakeholder communities

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Citation:
Stammer, D., Bracco, A., Braconnot, P., Brasseur, G. P., Griffies, S. M., & Hawkins, E. (2018). Science directions in a post COP21 world of transient climate change: Enabling regional to local predictions in support of reliable climate information. *Earth's Future*, *6*. https://doi.org/10.1029/2018EF000979

Received 2 JUL 2018
Accepted 19 OCT 2018
Accepted article online 31 OCT 2018

Science Directions in a Post COP21 World of Transient Climate Change: Enabling Regional to Local Predictions in Support of Reliable Climate Information

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Abstract During recent decades, through theoretical considerations and analyses of observations and model simulations, the scientific community has fundamentally advanced our understanding of the coupled climate system, thereby establishing that humans affect the Earth's climate. Resulting from this remarkable accomplishment, the COP21 agreement marks a historic turning point for climate research by calling for actionable regional climate change information on time scales from seasonal to centuries for the benefit of humanity, as well as living and nonliving elements of the Earth environment. Out of the underlying United National Framework Convention on climate Change process, improving seamless regional climate forecast capabilities emerges as a key challenge for the international research community. Addressing it requires a multiscale approach to climate predictions. Here we offer a vision that emphasizes enhanced scientific understanding of regional to local climate processes as the foundation for progress. The scientific challenge is extreme due to the rich complexity of interactions and feedbacks between regional and global processes, each of which affects the global climate trajectory. To gain the necessary scientific insight and to turn it into actionable climate information require technical development, international coordination, and a close interaction between the science and stakeholder communities.

Plain Language Summary During recent decades, through theoretical considerations and analyses of observations and model simulations, the scientific community has fundamentally advanced our understanding of the coupled climate system, thereby establishing that humans affect the Earth's climate. Building on this remarkable accomplishment, the COP21 agreement marks a historic turning point for climate research by calling for actionable regional climate change information on time scales from seasonal to centuries for the benefit of humanity and the full biosphere. Out of the underlying United National Framework Convention on climate Change process, improving seamless regional climate forecast capabilities emerges as a closely linked challenge for the international research community. Addressing this challenge requires a multiscale approach to climate predictions. Here we offer a vision for realizing an approach that emphasizes enhanced scientific understanding of regional to local climate processes as the foundation for progress. The scientific challenge is extreme due to the rich complexity of interactions and feedbacks between regional and global processes, each of which affects the global climate trajectory. Technical development, international coordination, and a close interaction between the science and stakeholder communities are also required. In their absence scientific insight cannot be gained or turned into actionable climate information.

1. Introduction

During recent decades, the scientific community has fundamentally advanced climate science to the point that quantitative projections of the future evolution of global climate are routinely provided. These projections are largely based on the output of climate models driven by scenarios of anthropogenic greenhouse gas emissions. Through theoretical considerations, in depth analysis of climate observations, and model simulations, a detailed mechanistic understanding has emerged of the global coupled climate system that forms the basis for the Intergovernmental Panel for Climate Change (IPCC) assessment process. Conclusions drawn therein about the unambiguous influence of humans on the Earth climate were key incentives for international climate negotiations, which ultimately led to the historic United National Framework Convention on climate Change (UNFCCC) COP21 conference agreement signed in Paris in 2015. Through this process, the statements made by the scientific community (IPCC, 2013) that "Warming of the climate system is unequivocal" and that "human influence on the climate system is clear" were endorsed by virtually every nation of the world.

Placing human activity as the primary climate change forcing was made possible through long-term investments into the development and implementation of a sustained in situ and space-based climate observing system, as well as an integrated conceptual view of the climate system. These advances materialized through international coordination in which the evolution of scientific insight and the development of science-driven infrastructure work hand in hand. Specifically, the establishment through this international coordination of a hierarchy of complex Earth system models as tools to achieve quantitative climate projections has been instrumental for the routine generation of climate change information now available.

Current understanding of the interplay between climate and the carbon cycle reveals that the Earth will continue to warm as long as atmospheric greenhouse gas concentrations continue to rise (IPCC, 2013). It was also suggested (e.g., Mauritsen & Pincus, 2017) that surface temperatures will continue to rise even after anthropogenic carbon emissions cease. This will be due to prolonged changes of the Earth's global heat content and available fresh water, and it will severely impact the cryosphere (further mass loss) and sea level (further increases) for decades to centuries. The long-term commitment to climate change results from the long residence time for anthropogenic CO_2 in the atmosphere and from the enormous storing capacity of heat, fresh water, and carbon in the ocean and cryosphere, serving as the long-term memory and *flywheel* for the climate system. There is also concern that the ongoing warming would affect the characteristics of internal modes of variability (e.g., Cai et al., 2015) or the frequency and intensity of extreme events (Diffenbaugh et al., 2017). Climate change has already increased the likelihood of some types of extreme event (e.g., Stott et al., 2004), but their prediction, especially in the case of extreme tropical or extratropical cyclones, is still limited by our lack of fundamental understanding of the mechanisms and processes driving them (Bhatia et al., 2018).

A pivotal consequence of the COP21 agreement is the need for a profound transformation of society to bring the climate's evolution onto a managed trajectory via substantially reduced emissions of greenhouse gases (Steffen et al., 2018). Through this call, the COP21 agreement brings to the forefront the fundamental science challenges to approach society's needs for information in support of climate change mitigation and adaptation strategies. Central to any future climate science strategy is the development of reliable regional to local climate information provided on time scales from seasonal to centuries and beyond for the benefit of life on Earth.

Many of the climate processes leading to severe societal consequences act on regional to local spatial scales; hence, those are the scales at which climate information needs to be provided. Unfortunately, current projections are very uncertain at these scales. Furthermore, understanding and predicting regional to local climate changes require maintaining a global perspective, since regional climate change is influenced by the large-scale climate and, at the same time, feeds back to the global system. This two-way interaction requires an integrated and seamless approach to climate prediction suitable to bridge the present gap between various scales and processes.

This paper articulates an integrated approach toward improved regional climate information from the standpoint of physical climate science and the required underlying science and infrastructure development. Building on discussions held during the WCRP/CLIVAR 2016 conference held in Qingdao, our thesis is that significant progress in regional climate prediction can be realized only by developing a quantitative understanding of the role of fine scale phenomena in the climate system. This understanding is fundamental to reducing the gap between weather predictions and skillful long-term climate predictions. Closing this gap is necessary for developing climate adaptation and mitigation strategies. In addition to individual research, optimally advancing the needed climate science requires internationally coordinated efforts on climate monitoring, model and theory development, and analysis strategies. Quantitative understanding of fine-scale phenomena is also needed to properly represent details of the local and regional forced response in, for example, the intensity of extreme convective precipitation or extreme wind pressures experienced during violent convective weather.

2. Improved Predictions for Society

The UNFCCC call for the development of reliable regional climate information, introduced above, requires skillful regional to local climate predictions ranging from seasonal to centennial time scales. On this broad range of time scales it is currently extremely challenging to provide climate information that is both relevant and accessible to the variety of decision makers and stakeholders. To make further progress, the forecast skill of the physical variables needs to improve through a basic understanding of the cross-scale functioning of the physical climate system, although there are (uncertain) limits to skill due to the chaotic nature of the system. At the same time, improvements in forecast skill above present-day situations will be obtained only through the careful exploitation of improved understanding of slow, coupled climate processes. Finally, the generation of local societally relevant information relies on a better understanding of the climate-human interaction.

To address all these challenges in support of humanity and life on Earth requires the climate science community to tackle the following two linked actions: (1) understanding transient climate change at regional scales and (2) developing robust multiscale predictions.

2.1. Understanding Transient Climate Change at Regional Scales

A core question for 21st century climate science concerns how natural processes and dynamical mechanisms of the coupled climate system respond and adjust to historically unprecedented anthropogenic forcing. To address it requires deepening our basic understanding of how the climate system works. How will the climate system transition from its preindustrial state into a new equilibrium, if any, through the presence of human-induced climate forcing from CO_2, other trace gases, aerosol emissions, and land use changes? What will that new equilibrium look like and what are the consequences for life on Earth?

Investigations seeking answers to such existential issues aim to quantify the Earth's equilibrium sensitivity to anthropogenic climate forcing. Research unambiguously points to clouds as the central agent affecting equilibrium climate sensitivity, thus prompting efforts to robustly understand and quantify their role (e.g., Schneider et al., 2017). Notably, it takes many centuries for the climate system to reach a new equilibrium. However, humans experience climate as a transient adjustment to both natural and anthropogenic forces. This transient stage involves natural climate variations with a footprint at the regional scale that can be very energetic and hence mask anthropogenic climate influences on time scales spanning decades to centuries (Deser et al., 2014). Consequently, the key climate question for humanity involves understanding processes and mechanisms that affect the transient trajectory of the climate system as it adjusts to anthropogenic forcing. Addressing questions about transient climate change requires understanding fundamental physical processes and characterizing their role and feedbacks in oceanic and atmospheric circulation patterns. Implicit in this statement is the assumption that any forced response of the climate system impacts the large-scale circulation. However, such a forced response may also result in detailed regional to local structures that are of importance to stakeholders.

Figure 1 illustrates underlying multiscale dynamical processes and interaction mechanisms in the climate system, taking the atmosphere and the ocean as examples, that need to be properly represented in climate projections to improve regional to local climate information. In the ocean, the turbulent processes that directly impact the regional transfer of momentum, energy, heat, and tracer properties span lateral scales from hundreds of kilometers (the mesoscale) to just a few meters (the submesoscale and finer scales), whereas in the atmosphere they span scales from thousands to hundreds of kilometers (its synoptic and mesoscale) to few kilometers and tens of meters (the convective scales). These processes are at the root of how air-sea, land-sea, and ice-sea interactions occur and thus act as the regulator for heat and carbon transport across the ocean interface thereby modulating the atmospheric warming relative to what it would otherwise. A portion of this energy then penetrates to the ocean interior (e.g., Griffies et al., 2015; Zhong et al., 2017) thus affecting long-term trends and changes.

Continuing with the ocean as an example for all other elements of the climate system, fundamental aspects of how the ocean circulation works as part of the climate system are concerned with questions like: What are the force balances leading to the motion of seawater, interactions between seawater elements, and exchanges with other components of the climate system? How does the ocean reversibly stir and irreversibly mix properties across its boundaries and within the interior? How will stirring and mixing be modified as the

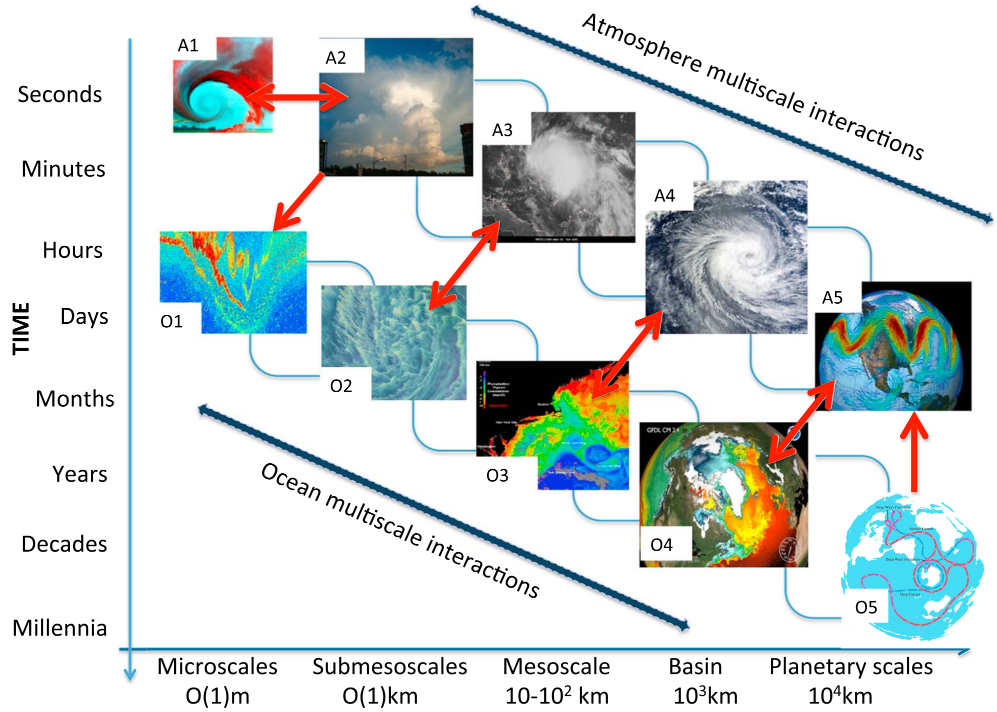

Figure 1. Multiscale processes and scale interaction mechanisms in the atmosphere and ocean that need to be properly represented or parameterized in climate projections to improve regional to local climate information. The figure shows the processes acting separately in the atmosphere and ocean as well as their coupling mechanisms leading to coupled dynamical modes of variability. Panels labeled A1 to A5 represent atmospheric microscale turbulence, cumulus convection, cloud clusters, cyclones, and planetary waves, respectively. Panels labeled O1 to O5 represent ocean internal waves and mixing, submesoscale turbulence, mesoscale circulation, basin scale circulation, and the global overturning ocean circulation, respectively. The atmosphere and ocean are taken as examples, recognizing similar cross-scale interactions operating in the cryosphere and land. Moreover, in the figure only dynamical phenomena are considered, and not chemical and biological interactions, and they are structured in a traditional manner, according to their spatial scales. Phenomena listed are examples for *response units*. These units have different spatial scales (in length) when atmosphere or ocean or land or inner-Earth processes and systems are considered since they have different inertia/damping/memory/carrying characteristics.

ocean warms and generally becomes more stratified? Beyond enhancing our conceptual understanding of how the ocean works, this research informs the representation and parameterization of the attendant physical processes in numerical Earth systems models. There are many associated implications for the simulation of physical, biogeochemical, and ecosystem portions of the climate system, and their interactions and feedbacks. Similar considerations hold for the atmosphere.

Theoretical and observational studies of fluid instabilities and associated turbulent processes at the scales shown in Figure 1 suggest a relatively new phenomenological paradigm for the ocean (McWilliams, 2016). Mechanical energy is transferred from the large scales of boundary forcing and mesoscale stirring to the small scales of molecular dissipation. The cascade is mediated by nonlinear interactions between balanced mesoscale features (e.g., baroclinic mesoscale eddies and boundary currents/jets), weakly balanced submesoscale filaments and secondary instabilities (McWilliams, 2016), and unbalanced gravity waves (MacKinnon et al., 2017). Developing and refining various theoretical, modeling, and observational support for this phenomenology forms a key focus for physical oceanography (Nikurashin & Ferrari, 2013) and ocean biogeochemistry (McGillicuddy, 2016).

2.2. Multiscale Approach to Predictions

We do not know precisely the future trajectory of climate—be it on a global or a local scale (Deser et al., 2014). However, we anticipate that different trajectories will lead to different thresholds and risks and, at the same time, will affect the characteristics of interannual to multidecadal variability as well as extremes, thereby influencing our ability to mitigate changes and impacts. Understanding the web of physical processes involved and their response to anthropogenic forcing is an essential challenge that needs to be solved in support of climate science's quest to produce reliable regional and local climate predictions and climate information.

The multitude of benefits that can emerge in the future from skillful climate predictions can be anticipated by examining the impact of ongoing seasonal predictions for the tropical Pacific. There, El Niño–Southern Oscillation (ENSO) fluctuations dominate interannual variations, leading to large swings of tropical surface temperatures and precipitation patterns over the ocean and land. Many severe consequences for populations surrounding the Pacific emerge from those climate fluctuations, including those associated with water availability, wildfires, or food supply from the ocean and land. After the development of seasonal ENSO predictions by Cane and Zebiak (1985), the field rapidly evolved to the point that today seasonal climate information (e.g., temperature and precipitation forecasts, and drought and flood warnings) is readily available to the international stakeholder community. Similar progress has been made for the onset of monsoons (Pradhan et al., 2017), which are critical for the water and food supply of many nations in Asia, the Americas, and Africa. For both ENSO and monsoons, however, there remain fundamental questions regarding their underlying mechanisms, flavors, and present and future predictability (Kumar et al., 2017; Polson et al., 2014). More recent research has expanded to other parts of the world and to longer (decadal) time scales (Cassou et al., 2017; Smith et al., 2013).

Climate information available on the decadal time scales remains rather uncertain and thus requires extensive research before the sources of predictability are fully identified and for its full potential to be accessible by stakeholders. A reliable climate prediction system would represent the pinnacle of actionable climate science, with potentially huge societal implications. No such system exists yet, but many national and international efforts are targeted at its development and the associated science, engineering, and climate services.

What climate variations and extremes can be expected in the future? How will future sea level change impact coastal zones? Will we get more droughts or heat waves and how often? How will atmospheric storm tracks or precipitation patterns change? Can we better characterize tipping points specific to environmental factors or sector of activities? Questions like these motivate the quest for new strategies to climate modeling and predictions that span across all relevant scales from the global to the local and from the past to the future. This multiscale approach to climate predictions that consider interactions on this huge space and time scale range can only be accomplished after closing the gap between short-term weather forecast and climate projections. Doing so requires covering the range transitioning from an initial state to a forced problem, all the while accounting for the chaotic nature of variability and changes in predictability under climate change forcing.

We envision that within a decade, examples of multi-spatiotemporal-scale seamless prediction systems will be in place, serving many purposes that are presently well beyond our capabilities. For example, improving the resilience to climate change and extreme weather events, particularly for megacities located in coastal tropical and subtropical regions, requires reliable predictions of available water resources. Skill can only be achieved through improved basic representation of the hydrological cycle in climate models, including air-sea exchanges of heat, fresh water, and momentum and by testing these models on a wide range of climate conditions, including paleoclimate (Braconnot et al., 2012; Kageyama et al., 2018).

Further improvements are needed for representing how climate variability modes project onto regional and local precipitation patterns. With the growing concern of damages caused by extremes (Handmer et al., 2012), society will increasingly require predictions of shorter-term climate risks, specifically subseasonal to seasonal as well as interannual fluctuations. An important focus of research will be the provision of reliable interannual to decadal time scale climate change information, which resonates with typical planning horizons of a few decades (depending on the adaptation time scale of the sector that is involved). It will include regional information about changes in precipitation patterns, sea level rise and the associated changes in coastal protection measures, extreme summer temperatures, and more. Planners are also interested in long-term climate change aspects that often go as far as the 100-year time scale (Carson et al., 2015).

For these aims to be realized, substantial barriers must be overcome in the existing prediction approaches to subseasonal to seasonal as well as interannual fluctuations (Hov et al., 2017). This situation holds even for seasonal predictions, as demonstrated by the lack of forecast skill for the 2015–2016 El Niño event that highlighted the limitations of the current prediction systems (McPhaden, 2015) and the need for understanding ENSO diversity (Capotondi et al., 2015). For a deeper understanding of the multiscale climate system and its predictability, considerations need to be given to the variety of ocean, atmosphere, land, and cryosphere processes covering a broad range of space and time scales as illustrated in Figure 1. To make climate information more reliable, it is also important to better understand what parts of the climate system are predictable and why, and what parts are less predictable due to a stronger chaotic nature.

Climate predictability is specifically dominated by modes of variability intrinsic to the climate system that involve ocean-atmosphere-land-cryosphere interactions. These modes need to be properly initialized for useful predictions. Fundamental to reliable prediction is the determination of the memory-carrying state of the ocean and its representation in coupled forecast models. However, the ocean is sparsely sampled and possesses intrinsic variability rendering a chaotic nature to its regional and local scales. Further uncertainty arises from the chaotic nature of the coupled climate system. Each of these facets affects the observability of the ocean state, exacerbating deficits in the observing system as well as our understanding of climate processes.

Because broadband natural variability is strong, the need to quantify its role, its interaction with anthropogenic forcing, and how they both affect climate extremes is of major concern. Society experiences climate change through the superposition of natural climate modes and anthropogenic-induced changes. Anthropogenic change can be enhanced or reduced depending on the phase of natural variability modes. A recent example concerns the slowdown in surface temperature warming resulting from a temporary sequestration of heat within the ocean (Marotzke & Forster, 2015). The way societies experience this net climate change on regional to local scale can have significant impacts on future carbon emissions. The implicit assumption here is that internal variability and the forced response are additive. However, there may be cases where changes in the mean state do affect internal variability and extremes.

At the present time the ability to verify progress in climate modeling is fundamentally hampered by the limited length of most observational climate records of roughly half a century. This problem calls for a sustained long-term observing system, prompt and open sharing of observations, and extending this record further back through rescuing undigitized historical data. These issues become even more difficult as one extends prediction from seasonal to decadal or centennial time scales. Moreover, we are forced to use the same data for forecast calibration, model tuning, process exploration, and a myriad of other applications. The end result is that the likelihood of overfitting and overinterpreting the available record increases with lengthening forecasting time scales. New information only becomes available at the rate of one season per year and one tenth of a decade per year, that is, slowly compared to decision time scales. As further complication, a multiscale approach to climate predictions requires representing processes in climate models and observing in nature over a broad range of space and time scales. Can we develop faithful physical parameterizations rather than awaiting sufficient computer power to explicitly represent all processes across huge space-time scales?

It will remain impractical for the foreseeable future to fully resolve all processes in climate models or to observe them on a routine basis. Furthermore, for periods several decades or longer into the future we can only provide projections rather than predictions. In contrast to a prediction, any projection conditionally relies on an assumed emissions scenario. Currently, we can only provide a range of plausible future emission pathways, which depend on international policy choices. Hence, the fundamental challenge for progress toward actionable climate science in the 21st century is represented by the need for reliable climate prediction systems without yet being able to precisely represent key fundamental physical processes (Roberts et al., 2018). Progress can be made by better understanding multiscale interactions that affect the spectrum of budgets for heat, water, and carbon that then can serve to improve our ability to predict those aspects and thereby understand the different pathways by which human activity influence the different spatiotemporal scales, weather patterns, and extreme events.

3. A Strategy for Future Physical Climate Research

Performing fundamental climate research—both individual and coordinated—is important for achieving progress toward generating reliable regional to local climate information in support of decision making. Climate change, however, represents a globally interconnected challenge to humanity that no single institution, agency, or even nation can deal with on its own. Instead, international coordination is required to install, operate, and maintain an advanced climate research infrastructure, to foster and set up research partnerships between nations, to coordinate the transfer of actionable knowledge to government bodies around the world, and to build up capacity and education. The latter holds especially in developing countries where the need for climate information is pressing due to limited resources available for the development of mitigation and adaptation strategies. Only international coordination, in partnerships with government bodies, can ensure the creation and implementation of an internationally agreed and supported climate research strategy. Such strategy needs to include the open and unrestricted dissemination of climate science knowledge and data to policy and decision makers around the world to the benefit of humanity.

During recent decades the World Climate Research Programme (WCRP) has successfully developed such an internationally coordinated approach. WCRP was established in 1980 under the sponsorship of the World Meteorological Organization, the International Science Council (formerly International Council for Science), and the Intergovernmental Oceanographic Commission of The United Nations Educational, Scientific and Cultural Organization to answer fundamental questions related to the physical climate system. One major objective of WCRP has been to determine to what extent climate can be predicted and the extent by which humans influence climate. Today, WCRP has broadened its mission: It coordinates and guides international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being. Therefore, WCRP research provides the climate science that underpins the UNFCCC and as such provides much of the knowledge needed by the IPCC to prepare its periodic assessments. The research conducted under WCRP guidance and coordination must serve the demand for actionable and readily accessible information of the entire climate system and of its regimes. Hence, it requires a strong engagement with civil society, government, and the private sector. Programmatic partnerships with other key entities such as Future Earth and its different core projects, the World Weather Research Programme, the Global Atmospheric Watch, the Integrated Research on Disaster Risks, and the Global Framework for Climate Services are of highest importance.

International coordination requires that three components be carefully considered: (1) international coordination of national efforts in support of established strategic directions; (2) coordination of a sustained international infrastructure; and (3) development of an information transfer and stakeholder dialog process.

3.1. International Coordination of Climate Research

Now that almost all nations recognize that humans affect the Earth climate and will continue to do so in the future, it is imperative to develop new approaches that contribute to the solution of this major challenge for humanity. In this regard, it is important to recognize the global nature of the climate system and, at the same time, consider the regional and even local manifestations of climate variations across all relevant time scales. In other words, the scientific focus must gradually shift from purely global considerations toward the understanding of the physical and dynamical processes that drive regional-to-local climate variability. Predictions of climate anomalies or disturbances from the well-established large-scale climatology must now address the needs of decision makers at the regional to local spatial scales. An important aspect of the international coordination of climate research involves the establishment of an international consensus on what needs to be done locally and regionally to achieve international climate system science goals and, perhaps most importantly, how we will know when the research objectives have been achieved.

Figure 2 highlights different elements that are supported by international coordination of climate science: (1) understanding multiscale climate processes and dynamics (e.g., multiscale climate processes, changes in oceanic and atmospheric circulation, energy, water, and carbon cycles) and (2) fostering seamless climate predictions (e.g., multiscale predictions and long-term projections, data assimilation, detection, and attribution) while providing actionable climate information.

3.2. Coordination of Sustained International Infrastructure

Pivotal to future successful climate research is the existence of a sustained infrastructure entailing a global climate observing system (Weatherhead et al., 2017) and an ever improving/increasing computation infrastructure that also takes care of the huge data storage requirements for climate research. As mentioned above, observations are central and continuous investments are required to advance observing systems and to evolve sensor technologies. Of importance in this context is our ability to observe the state of the ocean and the cryosphere, which determines the near-term (seasonal to decadal time scale) evolution of the climate system. However, the climate observing system needs to cover all climate components, as

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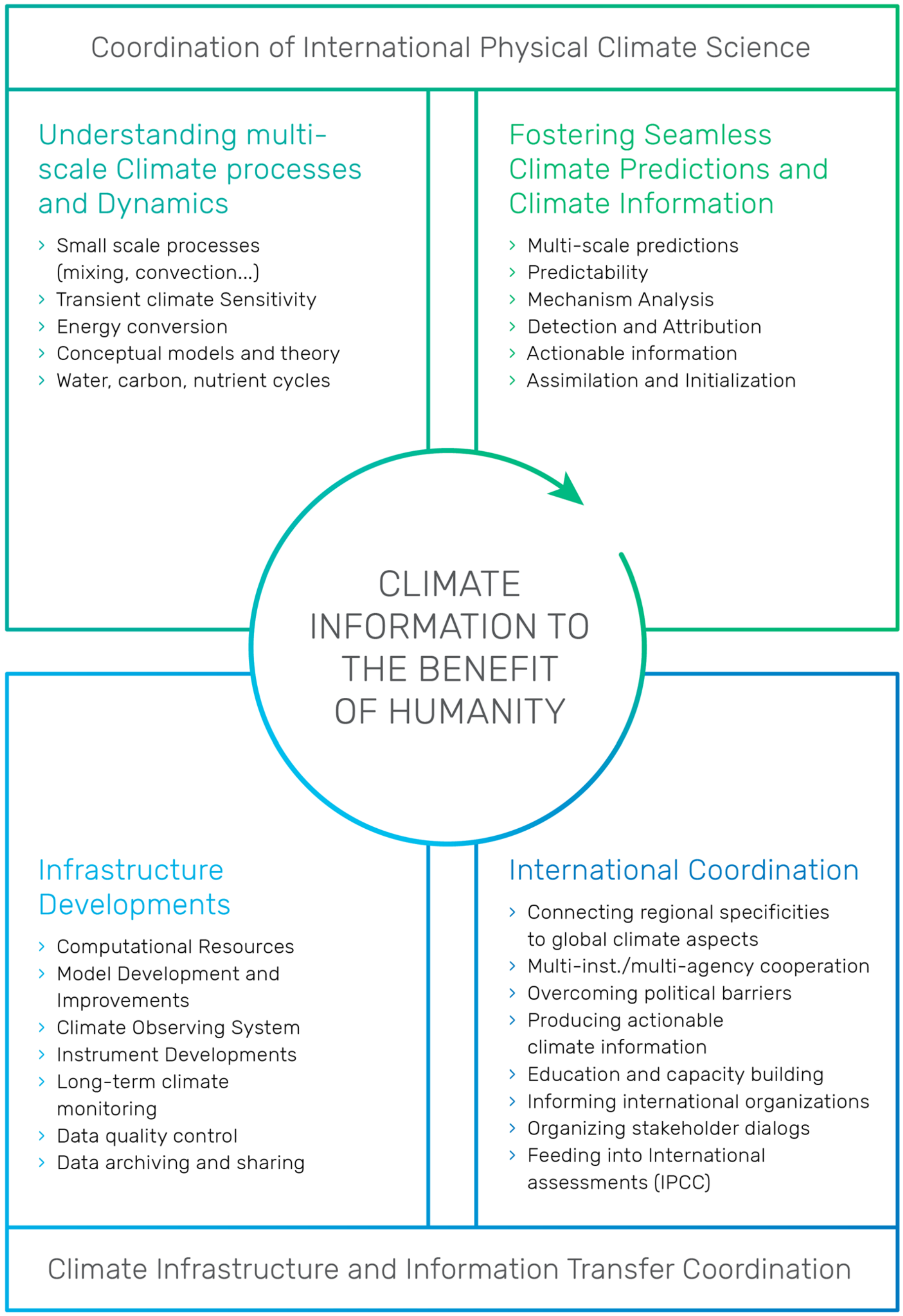

Figure 2. Schematic illustration of the path toward actionable climate information. Shown are the two major aspects that form the basis for future physical climate research such as organized under World Climate Research Programme. Under the heading Coordination of international physical climate science, the two branches *multi-scale process understanding* and *seamless climate predictions* reside. Under the heading Climate infrastructure and information transfer coordination, the two branches *international coordination* and *infrastructure development* need to be advanced and sustained.

detailed by the Global Climate Observing System implementation plan. In addition, investments are needed for focused studies targeted to enhance process understanding and thereby improve models. Resources are also required to provide prompt and open access to all climate observations, and to *rescue* historic but not yet digitized climate data from the past two centuries, which are critical for a detailed understanding of long-term changes.

At the same time, we need to further improve Earth system models, develop climate-consistent data assimilation capabilities (coupled ocean-atmosphere-land-cryosphere assimilation) and include in such models downscaling capacities to resolve regional features. In this context, under WCRP coordination, a consensus should be found regarding the expected spatial resolution of such models, the processes that should be resolved, and those that could be parameterized. WCRP should lead the international effort toward the development of the next generation of multiscale Earth system models and support endeavors to access enhanced computing capability for the execution of cloud resolving and ocean mesoscale eddy-resolving Earth system models.

Over recent decades, climate research has evolved to one of the most data intensive sciences existing today, requiring resources that reside at the upper end of the current high-performance computing implementations or beyond. A considerable amount of resources is not only devoted to executing complex models but also to processing and storing large amounts of data. New approaches should be developed to handle such large data sets, to extract the information about climate change processes, and to display/visualize data so as to maximize the degree of understanding. Perhaps the time has come to establish an international CERN-type organization (i.e., the European Organization for Nuclear Research, known as CERN) focusing on high-end climate simulations and data interpretation (see suggestion in the summary of the 2008 *World Climate Modeling Summit* at the European Centre for Medium-Range Weather Forecasts (ECMWF) at https://www.ecmwf.int/en/about/mediacentre/news/2008/world-modeling-summit-climate-prediction).

Figure 2 highlights the major components associated with the development of an international climate infrastructure (e.g., computational resources, model development and improvements, climate observing system, instrument development, long-term climate monitoring, and data quality control and archiving) and with the coordination of the related efforts (e.g., connecting regional specificities to global climate aspects, multiinstitutional/multiagency cooperation, overcoming political barriers, producing actionable climate information, education and capacity building, informing international organizations, organizing stakeholder dialogs, and feeding into international assessments [IPCC]).

3.3. Need for International Leadership

Providing climate information to society requires the development of an effective communication infrastructure, including platforms for a sustained dialog with societal actors. International programs should work closely with climate services to establish this dialog. Science-based climate information requires the integration of the two different components of international coordination mentioned above: science and infrastructure (see Figure 2).

Besides scientific insight and foresight, the development of a sustained and strategic climate research program and a related prediction capability demands political leadership and financial support. Substantial investments with the use of smart engineering and effective coordination approaches between different national and international agencies and a variety of stakeholders including the private sector must be made. Such an ambitious plan also requires the systematic and sustained training of a new generation of scientists who will use new technologies to observe and simulate climate variability and change and translate their findings into actionable information.

Acknowledgments
Helpful comments from two anonymous referees are gratefully acknowledged. This paper results from the OSC conference. We acknowledge the role of the Qingdao National Laboratory for Marine Science and Technology (QNLM) as local host and sponsor as well as the organizational leadership of the CLIVAR ICPO hosted by the First Oceanographic Institute (FIO) of SOA in Qingdao. NCAR is sponsored by the National Science Foundation. D. S. was supported in part through the DFG-funded Excellence Center *CliSAP* at Universiät Hamburg. There are no additional data to disclose.

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