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The Sub-seasonal to Seasonal Prediction (S2S) Project Database

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Summary: A database containing sub-seasonal to seasonal forecasts from 11 operational centres is available to the research community and will help advance our understanding of the sub-seasonal to seasonal time range.

Abstract

Demands are growing rapidly in the operational prediction and applications communities for forecasts that fill the gap between medium-range weather and long-range or seasonal forecasts. Based on the potential for improved forecast skill at the sub-seasonal to seasonal time range, a sub-seasonal prediction (S2S) research project has been established by the World Weather Research Program/World Climate Research Program. A main deliverable of this project is the establishment of an extensive database, containing sub-seasonal (up to 60 days) forecasts, 3-weeks behind real-time, and reforecasts from 11 operational centers, modelled in part on the THORPEX Interactive Grand Global Ensemble (TIGGE) database for medium range forecasts (up to 15 days).

The S2S database, available to the research community since May 2015, represents an important tool to advance our understanding of the sub-seasonal to seasonal time range that has been considered for a long time as a “desert of predictability”. In particular, this database will help identify common successes and shortcomings in the model simulation and prediction of sources of sub-seasonal to seasonal predictability. For instance, a preliminary study suggests that the S2S models underestimate significantly the amplitude of the Madden Julian Oscillation (MJO) teleconnections over the Euro-Atlantic sector. The S2S database represents also an important tool for case studies of extreme events. For instance, a multi-model combination of S2S models displays higher probability of a landfall over Vanuatu islands 2 to 3 weeks before tropical cyclone Pam devastated the islands in March 2015.

1) Sub-seasonal to seasonal prediction

Demands are growing rapidly in the operational prediction and applications communities for forecasts that fill the gap between medium-range weather (up to 15 days) and long-range or seasonal (3–6 months) forecasts. Skillful sub-seasonal to seasonal prediction (forecast range more than 2 weeks but less than a season) provides an important opportunity to inform decision makers of, for example, changes in risks of extreme events or opportunities for optimizing resource management decisions. Although many challenges remain to make sub-seasonal forecasts sufficiently reliable, skillful and tailored for users, a great return on investment in weather and climate science and model development is to be expected if the science and forecast products of sub-seasonal to seasonal prediction can be successfully connected to societal applications.

Weather-related hazards, including slow onset of long-lasting events such as drought and extended periods of extreme cold or heat, trigger and account for a large proportion of disaster losses, even during years with other very large geophysical events (e.g., Haitian and Chilean earthquakes) (source Munich Re: http://www.iii.org/sites/default/files/docs/pdf/munichre-010715.pdf). 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 at the sub-seasonal time scale and in part by the complexity of processes and the numerous facets involved in decision making. Developing countries are most affected by major gaps in access to forecasts and knowledge. The goal of the Sub-seasonal to Seasonal Prediction (S2S) Project and its associated database is to help fill these gaps.

2) The S2S Project

Sub-seasonal forecasting, bridging a gap between the more mature weather and climate prediction communities, is at a relatively early stage of development. Forecasting the day-to-day weather is often considered as an atmospheric initial condition problem. Most of the current operational medium-range forecasting systems (forecasts up to day 15) are not coupled to an ocean model, although there can be an influence from ocean (e.g. Bender and Ginnis 2000) and land conditions (e.g. Koster et al, 2010). Forecasting at the multi-season to multi-annual range depends strongly on the slowly-evolving components of the earth system such as the sea surface temperature. In between these two time scales is sub-seasonal to seasonal variability (defined here as the time range between 2 weeks and 2 months). Forecasting for this time range has so far received much less attention than medium-range and multi-season prediction despite the considerable socio-economic value that could be derived from such forecasts. This timescale is critical for proactive disaster mitigation efforts. It is considered a difficult time range since the lead time is sufficiently long that much of the memory of the atmospheric initial conditions is lost and it is too short for the variability of the ocean to have a strong influence. However, recent research has indicated important potential sources of predictability for this time range such as the MJO, the state of ENSO, soil moisture, snow cover and sea ice, stratosphere-troposphere interactions, ocean conditions and tropical-extratropical teleconnections (see for example review in Vitart et al., 2015).

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 centers and by the applications community (Vitart et al, 2012). An extensive database containing sub-seasonal (up to 60 days) forecasts and reforecasts (sometimes known as hindcasts) has been created to enable research to operational pathways to accomplish these goals. It is modelled in part on the THORPEX Interactive Grand Global Ensemble (TIGGE) database for medium range forecasts (up to 15 days) (Bougeault et al, 2010) and the Climate-System Historical Forecast project (CHFP) (http://wcrp-climate.org/index.php/wgsip-chfp/chfp-overview) for seasonal forecasts. The research is organized around a set of six topics (Madden-Julian Oscillation, Monsoons, Africa, Extremes, Teleconnections and Verification), each intersected by the cross-cutting research and modeling issues, and applications and user needs. The latest science plans of each sub-project are available online (http://www.s2sprediction.net/documents/reports). Some of the main research questions include:

- 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 initialization strategy for a forecasting system that includes ocean, land and cryosphere? What is the optimal way to generate an ensemble 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 are the origins 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 should they 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?
- How well do we understand the fundamentals of predictability and dynamical processes of the sub-seasonal variability?

3) Description of the S2S database

The S2S database builds on the experience of creating the TIGGE database and can be seen as its extension to the longer forecasts ranges. The S2S database includes near real-time ensemble forecasts and reforecasts up to 60 days from 11 centers: Australian Bureau of Meteorology (BoM), China Meteorological Administration (CMA), European Centre for Medium-Range Weather Forecasts (ECMWF), Environment and Climate Change Canada (ECCC), the Institute of Atmospheric Sciences and Climate (CNR-ISAC), Hydrometeorological Centre of Russia (HMCR), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), Météo-France/Centre National de Recherche Meteorologiques

(CNRM), National Centers for Environmental Prediction (NCEP) and the United Kingdom's Met Office (UKMO). A key difference with the TIGGE database, is that the S2S database includes reforecasts, whereas none are included in the TIGGE database. For short-range weather forecasts, model error is not usually so dominant that a reforecast set is needed, but for the sub-seasonal to seasonal range model error is too large to be ignored. Therefore an extensive reforecast set spanning several years is needed to calculate model bias. Such reforecasts in some cases can also be used to evaluate skill. The models are also generally different from the TIGGE models. For instance, S2S models can have the atmospheric component coupled to an ocean model and an active sea ice model (Table 1).

Because S2S is a research project, the real-time forecasts are only available with a 3-week delay. Table 1 displays the main characteristics of the S2S models. Tables 2, 3, 4, 5 and 6 show the list of variables which have been requested for the S2S archive, which include standard variables at many pressure levels, together with a large number of single-level variables including thermodynamic, hydrological, and surface flux fields. However, some models are providing just a subset of the requested variables. The list of variables provided by each model can be found here: https://software.ecmwf.int/wiki/display/S2S/Provided+parameters. Pressure level fields are available in the stratosphere at 50 and 10 hPa to facilitate the diagnostic of sudden stratospheric warming events and their downward propagation. The frequency of archiving is once a day except for maximum and minimum near surface temperature and total precipitation which are available 4 times a day (computed over 6-hour periods). The data is archived in GRIB2 format, and a conversion to NetCDF will be made available. There are plans to add some oceanic variables in the near future, from the coupled ocean-atmosphere models: sea surface salinity, depth of the 20 degree isotherm, heat content in the top 300 m, salinity in top 30 meters, U and V surface current and sea surface height. It is also planned to include sea-ice thickness for the models which have a dynamical sea-ice model.

The S2S database is a database of "opportunity", which means that the forecasts have not been produced specifically for the S2S project following an agreed protocol. Table 1 highlights differences in model setup between the operational centers. The main differences between real-time forecasts from different centers include:

- The forecast time range varies from 32 to 60 days
- The horizontal resolution of the atmospheric model varies from a few hundreds kilometers resolution to about 30 kilometers.
- The ensemble size varies from 4 to 51 members. This reflects a different of strategy between operational centers. The centers producing a low number of ensemble members typically produce forecasts in lag mode (combining ensemble members from different start dates to produce an ensemble forecast).
- The frequency of initializing forecasts varies. Some models are run in burst mode on a sub-weekly basis with a large ensemble size (e.g. ECMWF, BoM, ECCC..), whereas other models are run in continuous mode on a daily basis with a smaller ensemble size (e.g. NCEP, UKMO, CMA, KMA..). Other models (e.g. CNRM) are run on a monthly basis.
- Some models have an atmosphere component coupled to an ocean and a sea ice model (e.g. UKMO, NCEP, CNRM, CMA) while other use a combination of persistence

of initial conditions and climatology to define the oceanic and sea ice boundary conditions (e.g. JMA, ECCC).

The configuration of the reforecasts also varies greatly between the models:

- Some models have a re-forecast set covering a period exceeding 30 years (e.g. JMA, BoM), while other re-forecast sets span a much shorter number of years (e.g. NCEP, UKMO)
- Some reforecasts are produced progressively “on the fly” (as at ECMWF), while others are computed all at once prior to operational implementation (e.g., BoM, NCEP).
- The ensemble size can vary from just 1 member (e.g. CNR-ISAC) to 33 members (BoM).
- Some models have reforecasts produced on a daily basis (e.g. NCEP) while others have reforecasts on a sub-weekly basis (e.g., BoM, ECMWF) and others have reforecasts on a monthly basis (e.g CNRM).

There is much greater diversity between the various S2S forecast systems than in other databases for medium and seasonal time ranges (e.g. TIGGE, EUROSIP, CHFP). Very different strategies are currently in use. For example, some centers take advantage of their seasonal and climate systems, while other centers employ systems used for weather forecasting. This highlights the current lack of consensus on the best practice for sub-seasonal prediction unlike for medium-range and seasonal forecasting and diversity of priorities of operational centers. One of the goals of the S2S project is to make recommendations on the optimal configuration of sub-seasonal systems. The S2S database will enable these issues to be addressed by clustering the models sharing similar characteristics (e.g. coupled ocean-atmosphere models vs atmosphere-only models; lag vs burst initialization…) and comparing their forecast skill scores.

Despite the differences in system set-up, there are enough commonalities between them to make inter-comparisons or multi-model combinations possible, as will be shown in Section 3. For instance, almost all of the S2S systems produce real-time ensemble forecasts every Thursday, and have reforecasts covering the period 1999-2010. Therefore, it is possible to create a multi-model combination of the S2S models every Thursday, calibrated using the common period 1999-2010.

The database is currently updated routinely with near real-time forecasts and reforecasts from nine data providers, namely, JMA, NCEP, BoM, ECMWF, UKMO, CMA, CNRM, CNR-ISAC and HMCR. Data from ECCC and KMA will be available soon. The S2S database is hosted by two archiving centers, ECMWF and CMA, and was opened to the public on 6 May 2015 at ECMWF via the Data Portal and ECMWF Web API (Application Programming Interface) and in November 2015 at CMA. Users can register, visit the data portal and browse the contents of the database, and are encouraged to use the ECMWF Web API to download data in batch.

By the end of 2015, about 300 users from 42 countries had registered and had already executed over 200,000 requests to extract about 30 Terabytes of data from ECMWF. ECMWF and CMA are working together closely to ensure the timely synchronization of the two databases. The S2S database at ECMWF can be accessed at http://apps.ecmwf.int/datasets/data/s2s and http://apps.ecmwf.int/datasets/data/s2s-reforecasts for the reforecasts. The S2S database at CMA can be accessed at http://s2s.cma.cn/ .

At CMA, about 22 Terabytes of forecast and re-forecast data have been collected from ECMWF. S2S data is archived on tapes into the MARS system (same archiving system as at ECMWF) and also stored into a large online storage system with a preprocessed unified form. The CMA data portal, as the ECMWF data portal, provides descriptions of the models from the different centers and S2S data parameters, in addition to the data download service. Two ways of searching and accessing the data are supported: free text search and faceted search. The method of downloading data is similar to the e-commerce "shopping-cart" through a "Data cart". All the S2S data can be accessed by HTTP currently and OPeNDAP in the near future. The S2S data in GRIB2 format can be directly downloaded at CMA, and data in NetCDF format obtained through online conversion.

4) Examples of use of the S2S database

4.1 Multi-model prediction

In order to monitor the S2S forecasts, a basic set of products has been developed, including ensemble mean anomalies for few meteorological parameters and some atmospheric indices. These products are generated routinely at ECMWF from each individual forecast system and for a multi-model combination. Figure 1 shows an example of multi-model prediction of 2-meter temperature anomalies from three S2S models, along with the verification. This figure shows that a cold event in the northeast of US and Canada in February 2015 was well predicted for the day 12-18 time range. These S2S products will be made available on the ECMWF public website to support the S2S community with a 3-week delay by the end of 2016.

4.1 The strong March 2015 MJO event

The S2S dataset can be used to assess the performance of current state-of-the-art sub-seasonal to seasonal forecasting systems to predict recent extreme events. For instance 2015 witnessed an exceptional MJO event in March; it exhibited record amplification resulting in the largest amplitude ever recorded (above 4 standard deviation; Marshall et al. 2016) and triggered the formation of twin tropical cyclones, one on each side of the Equator. The amplification was promoted by the unusually warm waters near the dateline (Marshall et al. 2016), which preceded development of strong El Nino conditions in the eastern Pacific later in the year. The surface westerly winds that developed in the western Pacific as a result of this March MJO event with twin cyclones likely enhanced the development of the strong El

Niño later in the year. It is encouraging to see that all the models and the multi-model combination (black line in Fig. 2a) forecasted a strong MJO event more than 2 weeks in advance (Figure 2a). Most models also predicted the occurrence of an MJO event 3 weeks in advance (black line in Fig. 2b), although the amplitude is generally underestimated, and no ensemble member predicted such a strong amplitude event.

This record-strength MJO event also contributed to the formation of Tropical Cyclone Pam, which intensified to Category 5 strength and hit the islands of Vanuatu in the south Pacific on 13 March with devastating effects. Around 15 people were killed and many buildings were destroyed. The cyclone was the second strongest on record in the southern Pacific, second only to Zoe (2002). It is regarded as the worst natural disaster in Vanuatu’s history. The cyclone formed on 6 March east of the Solomon Islands and was classified as a tropical storm on 9 March.

Previous studies (e.g. Vitart, 2009) have demonstrated that state-of-the-art extended-range forecasting systems can simulate the modulation of tropical cyclone activity by the MJO, with an increase risk of tropical cyclone activity over the South-West Pacific when the MJO is in Phase 6 and 7. In order to assess the skill of the S2S models to predict the probability of a tropical cyclone hitting Vanuatu, tropical cyclones have been tracked in each ensemble forecast member from CMA, JMA, NCEP, ECMWF and BoM using the algorithm described in Vitart et al. (1997). Figure 3 shows the probability of a tropical cyclone strike within a 300 km radius for the multi-model combination of the 5 real-time forecasts starting on 19 and 26 February 2015 and verifying on the weekly period 9-15 March 2015 when Pam hit the islands of Vanuatu. Figure 3 suggests that this event had some extended-range predictability, the multi-model combination indicating an increased risk of tropical cyclone strike probability in the vicinity of Vanuatu (indicated by a black dot in Figure 3) 2 to 3 weeks in advance. The multi-model also predicted the possibility of a tropical cyclone strike in the western Pacific, which is consistent with the twin tropical cyclone genesis associated to the strong MJO event of March 2015. The multi-model forecast from 26 February also predicted an increased risk of tropical cyclone strike east of Madagascar and over the northwest coast of Australia which could correspond respectively to tropical Storm Haliba (7-10 March 2015) and tropical cyclone Olwyn (8-14 March 2015).

4.3 MJO Teleconnections in the Northern Extratropics

Accurate predictions of MJO events are not sufficient for successful sub-seasonal forecasts. The ability to predict the impact of MJO events on the global circulation is crucial. By acting to excite the NAO, the MJO affects European weather (Cassou 2008; Lin et al. 2009) and North Atlantic significant ocean wave heights (Marshall et al. 2015). Cassou (2008) and Lin et al. (2009) showed that the probability of a positive phase of the NAO is significantly increased about 10 days after the MJO is in Phase 3 (Phase 3 + 10 days), and significantly decreased about 10 days after the MJO is in Phase 6 (Phase 6 + 10 days). The probability of a negative phase of the NAO is decreased (increased) about 10 days after the MJO is in Phase 3 (Phase 6). The impact of the MJO on two other Euro-Atlantic weather regimes, the Atlantic Ridge and Scandinavian blocking, is much weaker.

Vitart and Molteni (2010) showed that a set of ECMWF reforecasts using cycle 32R3 displayed realistic MJO teleconnections over the Northern Extratropics, consistent with the observed impacts (Cassou 2008; Lin et al. 2009). Lin et al. (2010) further found that the MJO has a significant impact on the intra-seasonal NAO skill scores using the ECCC model. This section evaluates whether the MJO teleconnections in the Northern Extratropics are adequately simulated in the reforecasts from the S2S database. We do this by forming 500 hPa geopotential height composites 10 days after an MJO is in Phase 3 for all cases when the predicted MJO has amplitude larger than one standard deviation. Only the reforecasts covering the period from January to April have been considered.

Figure 4 shows that the models generally capture the spatial pattern of the teleconnection but tend to overestimate the intensity of the MJO teleconnections in the North Pacific and underestimate its projection onto the positive phase of the NAO over the North Atlantic basin. This underestimation could be explained by the analysis being based on a single observed realization whereas the model composites are averaged over several ensemble members. Since not a single ensemble member reproduced the intensity of the teleconnection in the North Atlantic sector as strongly as in the analysis, it follows that underestimation of the MJO impact over the Atlantic (Vitart and Molteni (2010) is a real deficiency, common to several models. The under-representation of the MJO impact over the Euro-Atlantic sector is likely to limit the predictability and predictive skill over the North Atlantic and Europe in the sub-seasonal time range and therefore is an important aspect to be analyzed.

5) Other activities

The above examples give a flavour of the potential scope for research that the database offers. This database will also help to assess the potential of current operational S2S systems to forecast the extreme events around the globe, which are discussed in the BAMS special annual supplement on extremes, and other events which have led to major humanitarian aid responses. Three important aspects of the S2S database---namely that it contains (a) an archive of real-time forecasts (3 weeks delayed), (b) accompanying re-forecast sets, and (c) that these outputs are from WMO-recognized systems used currently for operational forecasts---make it a uniquely powerful tool for improving operational forecasts and exploring and prototyping decision support elements based on S2S forecast information. The WMO Lead-Centre for Long-Range Forecast Multi Model Ensembles (LC-LRFMME) will have access to the S2S database and will obtain the real-time forecasts *without* the 3-week embargo, enabling National Meterorological and Hydrological Services (NMHSs) to utilize real-time forecast information in a few years time once the necessary research has been done to estimate and document skill and approval has been obtained by WMO. The S2S database will augment the resources available to developing countries to enable the research in early warning system products. The S2S project is using the database to train young developing-country scientists to access the data, perform the necessary research, and collaborate with international experts.

6) Conclusions

The S2S database**,** a key component of the WWRP-WCRP Sub-seasonal to Seasonal Prediction Project science plan, is currently open to the public. It contains reforecasts and also near real-time sub-seasonal to seasonal forecasts from all the major operational centers. This database represents an important tool to advance our understanding of the sub-seasonal to seasonal time range that has been considered for a long time as a “desert of predictability”. Use of this database by the research community can include:

- Assess the average forecast skill of sub-seasonal to seasonal predictions in a statistical way through the large number of reforecasts and near-real time forecasts;
- Assess the potential predictability of the S2S models and identify forecast windows of opportunity;
- Perform case studies to assess the skill of the model during a specific period or event;
- Identify sources of predictability, dynamical processes and their impact on the forecast skill scores (e.g. sudden stratospheric warmings, MJO and its teleconnections, sea-ice, soil initial conditions...);
- Assess the models capability to represent these key dynamical processes that are sources of sub-seasonal predictability so as to guide ongoing model development
- Assess the benefit of a multi-model approach on sub-seasonal time scale and estimate the effective ensemble size of the multi-model ensemble as in Pennell and Reichler (2011) for climate models.
- Assess the representation of model uncertainty in the current operational systems;
- Assess the potential benefit of sub-seasonal to seasonal forecasts in applications;
- Compare the strategies for model initialization (e.g. burst vs lag ensemble initialization).

Work is ongoing to extend the list of oceanic and sea-ice variables and improve the conversion of the data into NetCDF. There are also plans to automatically compute some products from the database (e.g MJO, North Atlantic Oscillation, El-Niño Southern Oscillation, Sudden Stratrospheric Warming indices, weather regimes, tropical cyclone tracks...) and make them available to the community to avoid multiple computations of the same indices. For example the International research Institute for Climate and Society (IRI) at Columbia University also plans to make available a user-oriented subset of products from the S2S database hosted at ECMWF and CMA.

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References:

Bender, Morris A., Isaac Ginis, 2000: Real-Case Simulations of Hurricane-Ocean Interaction Using A High-Resolution Coupled Model: Effects on Hurricane Intensity. Monthly Weather Review: Vol. 128, No. 4, pp. 917-946.

Bougeault, P., Z. Toth, C. Bishop, B. Brown, D. Burridge, D. Chen, E. Ebert, M. Fuentes, T. Hamill, K. Mylne, J. Nicolau, T. Paccagnella, Y.-Y. Park, D. Parsons, B. Raoult, D. Schuster, P. Silva Dias, R. Swinbank, Y. Takeuchi, W. Tennant, L. Wilson and S. Worley, 2010: The THORPEX Interactive Grand Global Ensemble (TIGGE). Bull. Amer. Met. Soc., 91, 1059–1072. http://journals.ametsoc.org/doi/abs/10.1175/2010BAMS2853.1

Brunet, G., M. Shapiro, D. Hoskins, M. Moncrieff, R. Dole, G.N. Kiladis, B. Kirtman, A. Lorenc, B. Mills, R. Morss, S. Polavarapu, D. Rogers, J. Schaake and J. Shukla, 2010: Collaboration of the weather and climate communities to advance sub-seasonal to seasonal prediction. Bulletin of the American Meteorological Society, 1397-1406.

Cassou C. 2008. Intraseasonal interaction between the Madden–Julian Oscillation and the North Atlantic Oscillation. Nature 455: 523–527, doi: 10.1038/nature07286.

Dee, D. and co-authors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quart. J. Roy. Meteor. Soc, 137, 553-597.

Hansen, J. W., 2002: Realizing the potential benefits of climate prediction to agriculture: Issues, approaches, challenges. Agric. Sys., 74, 309–330.

Hurrell, J., G. Meehl, D. Bader, T. Delworth, B. Kirtman, and B. Wielicki 2009: A unified modelling approach to climate prediction. Bull Am Met Soc., 90,1819-1832.

Koster, R.D., S.P.P. Mahanama, T.J. Yamada, G. Balsamo, A.A. Berg, M. Boisserie, P.A. Dirmeyer, F.J. Doblas-Reyes, G. Drewitt, C.T. Gordon, Z. Guo, J.-H. Jeong, D.M. Lawrence, W.-S. Lee, Z. Li, L. Luo, S. Malyshev, W.J. Merryfield, S. Seneviratne, T. Stanelle, B.J.J.M. van den Hurk, F. Vitart and E.F. Wood, 2010: The contribution of land surface initialization to *subseasonal forecast skill: First results from a multi-model experiment. Geophys. Res. Lett., 37, L02402,doi:10.1029/2009GL041677.*

Lin, H., G. Brunet, and J. Derome, 2009: An observed connection between the North Atlantic Oscillation and the Madden-Julian Oscillation. J. Climate, 22, 364-380.

Lin, H., G. brunet and J.S. Fontecilla, 2010: Impact of the Madden Julian Oscillation on the intra-seasonal forecast skill of the North Atlantic Oscillation. Geophys. Res. Lett., 37, L19803.

Marshall, A. G., H. H. Hendon, and G. Wang (2016), On the role of anomalous ocean surface temperatures for promoting the record Madden-Julian Oscillation in March 2015, Geophys. Res. Lett., 43, 472-481.

Andrew G. Marshall, Harry H. Hendon, Tom H. Durrant, Mark A. Hemer, 2015: Madden Julian Oscillation impacts on global ocean surface waves. Ocean Modelling, 96, 136-147.

Morss, R., J. Lazo, H. Brooks, B. Brown, P. Ganderton and B. Mills. 2008. Societal and economic research and application priorities for the North American THORPEX programme, Bull. Amer. Meteor. Soc., 89, 3, 335-346

O'Connor, R. E., B. Yarnal, K. Dow, C. L. Jocoy, and G. L. Carbone, 2005: Feeling at risk matters: Water managers and decision to use forecasts. Risk Anal., 25, 5, 1265–1275.

Pennell C. and T. Reichler (2011): On the Effective Number of Climate Models, J. Climate, 24 (9), 2358-2367.

Pielke, R., Jr., and R. E. Carbone, 2002: Weather, impacts, forecasts, and policy: An integrated perspective. Bull. Amer. Meteor. Soc., 83, 3, 393–403.

Rayner, S., D. Lach, and H. Ingram, 2005: Weather forecasts are for wimps: Why water resource managers do not use climate forecasts. Climatic Change, 69, 197–227.

Shapiro and others, 2010 An Earth-system Prediction Initiative for the 21st Century. BAMS doi: 10.1175/2010BAMS2944.1

Shukla J. et al 2010 Towards a new generation of world climate research and computing facilities BAMs, 91, 1407-1412.

Vitart, F., J.L. Anderson and W.F. Stern, 1997; Simulation of interannual variability of tropical storm frequency in an ensemble of GCM integrations. J. Climate, 10, 745-760.

Vitart, F., 2009: Impact of the Madden Julian Oscillation on tropical storms and risk of landfall in the ECMWF forecast system. Geophys. Res. Lett., 36, L15802, doi:10.1029/2009GL039089

Vitart F, Molteni F. 2010. Simulation of the MJO and its teleconnections in the ECMWF forecast system. Q. J. R. Meteorol. Soc. 136: 842–855.

Vitart, F., A.W. Roberston and S2S steering group, 2015: Sub-seasonal to seasonal prediction: linking weather and climate. World Meteorological Organization, 2015: Seamless Prediction of the Earth System: from Minutes to Months, (G Brunet, S Jones, PM Ruti Eds.), (WMO-No. 1156), (ISBN 978-92-63-11156-2), Geneva

Wheeler, M. and H. Hendon, 2004: An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction. Mon. Wea. Rev., 132, 1917-1932.

Wonacott, T.H. and R.J. Wonacott, 1977: Introductory statistics. John Wiley, 650 pp.

Figure captions:

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Model	Time-range	Resolution	Ens size	Freq	Rfc	Rfc period	Rfc freq	Rfc size	Ocean Coupling	Sea-ice coupling
BoM	d 0-62	~2x2 L17	33	twice weekly	fixed	1981-2013	6/month	33	YES	NO
CMA	d 0-60	~1x1 L40	4	daily	fixed	1994-2014	daily	4	YES	YES
ECCC	d 0-32	0.45x0.45 L40	21	weekly	on the fly	1995-2012	weekly	4	NO	NO
ECMWF	d 0-46	0.25/0.25 day 0-10 0.5x0.5 after day 10 L91	51	twice weekly	on the fly	past 20y	2/week	11	YES	NO
HMCR	d 0-61	1.1x1.4 L28	20	weekly	On the fly	1985-2010	weekly	10	NO	NO
CNR-ISAC	d 0-31	0.8x0.56 L54	41	weekly	fixed	1981-2010	Every 5 days	1	NO	NO
JMA	d 0-33	~0.5x0.5 L60	25	twice weekly	fixed	1981-2010	3/month	5	NO	NO
KMA	d 0-60	~0.5x0.5 L85	4	daily	on the fly	1996-2009	4/month	3	YES	YES
CNRM	d 0-61	~0.7x0.7 L91	51	monthly	fix	1993-2014	2/month	15	YES	YES
NCEP	d 0-44	~1x1 L64	16	daily	fixed	1999-2010	day	4	YES	YES
UKMO	d 0-60	~0.5x0.8 L85	4	daily	on the fly	1996-2009	4/month	3	YES	YES

Table 1: Main characteristics of the 11 contributions to the S2S databas**e** where:

Time range: Forecast lead time in day

Resolution: Longitude and latitude resolution in degrees. The number after the letter L represents the number of vertical levels.

Ens size: Number of members in the real-time forecast ensemble.

Freq: How often (Frequency) the forecasts are run.

Rfc: Re-forecast (hindcast) are run using the actual forecast model but for past several years on the same (or nearby) calendar day as the forecast. The re-forecast is used to calibrate the actual forecast. There are two types of reforecasts:

> **fixed:** Some operational centers (e.g. NCEP) use the same version of their model ("frozen" version) to produce real-time S2S forecasts over a period of several years (typically 4-5 years). Therefore, the reforecasts are produced once, often before the first real-time forecast is produced, and used for several years to calibrate the real-time forecasts.
>
> **on-the-fly:** Other operational centers (e.g. ECWMF) update their model version several times per year. In order to ensure model consistency between real-time forecasts and re-forecasts, the re-forecasts are produced continuously just before the real-time forecast they will be used to calibrate. For example, at ECMWF, every week, a set of reforecast is produced starting the same day and same month as the next real-time forecast (e.g. 1st January 2015) but for the past 20 years (1st January 1995 to 2014).

Rfc period: The number of years the reforecasts are run. In some centers, the number of re-forecast years is fixed, but the list of years varies from year to year. For instance the re-forecast years at ECMWF cover the past 20 years.

Rfc freq: How often the reforecasts are run.

Rfc size: The number of ensemble members for reforecasts.

Ocean coupling: Indicates if the atmospheric component is coupled to a dynamics ocean model

Sea-ice coupling: Indicates if an active dynamical sea ice model is included or not.

Name	Abbreviation	Unit	Frequency
Geopotential height	gh	gpm	Instantaneous once a day (00Z)
Temperature	t	K	Instantaneous once a day (00Z)
U-velocity	u	m s-1	Instantaneous once a day (00Z)
V-velocity	v	m s-1	Instantaneous once a day (00Z)

Table 2: 3-D parameters available on 10 pressure levels (1000, 925, 850, 700, 500, 300, 200, 100, 50 and 10 hPa) from all models.

Name	Abbreviation	Unit	Frequency
Specific humidity	q	kg kg-1	Instantaneous

Table 3: 3-D parameter available on 7 pressure levels (1000, 925, 850, 700, 500, 300, 200) from all models.

Name	Abbreviation	Unit	Frequency
Vertical pressure velocity	w	pa s-1	once a day

Table 4: The following parameter is available at 500 hPa

Name	Abbreviation	Unit	Frequency
Potential vorticity	pv	K m2 kg-1 s-1	once a day

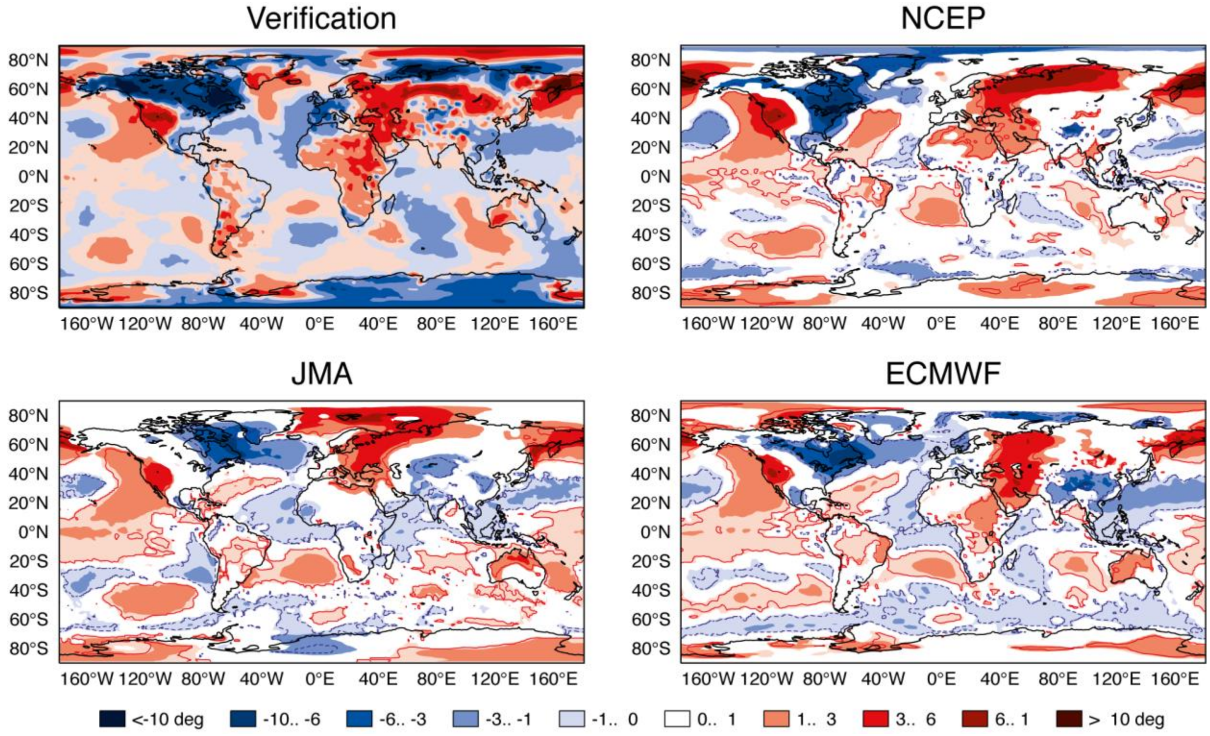
Table 5: The following parameter is available only at 320K.

Name	Abbreviation	Unit	Frequency
10 meter u	10u	m s-1	Instantaneous once a day (00Z)
10 meter v	10v	m s-1	Instantaneous once a day (00Z)
CAPE	cape	kg-1	Daily average
Skin temperature	skt	K	Daily average
Snow depth water equivalent	sd	kg m-2	Daily average
Snow density	rsn	kg m-3	Daily average
Snow fall water equivalent	sf	Kg m-2	Accumulated once a day
Snow albedo	asn	%	Daily average
Soil moisture top 20cm	sm20	kg m-3	Daily average
Soil moisture top 100cm	sm100	kg m-3	Daily average
Soil temperature to 20cm	st20	K	Daily average
Soil temperature top 100cm	st100	K	Daily average
Surface air max temperature	mx2t6	K	Instantaneous 4 time a day
Surface air min temperature	mn2t6	K	Instantaneous 4 times a day

Surface air temperature	2t	K	Daily average
Surface air dewpoint temperature	2d	K	Daily average
Sea surface temperature	wtmp	K	Daily average
Sea ice cover	ci	proportion	Daily average
Surface pressure	sp	Pa	Instantaneous once a day (00Z)
Mean sea level pressure	msl	Pa	Instantaneous once a day (00Z)
Total cloud cover	tcc	%	Daily average
Total column water	tcw	Kg m-2	Daily average
Total precipitation	tp	Kg m-2	Accumulated 4 times a day
Convective precipitation	cp	Kg m-2	Accumulated once a day
Northward turbulent surface stress	nsss	N m-2 s	Accumulated once a day
Eastward turbulent surface stress	ewss	N m-2 s	Accumulated once a day
Water runoff and drainage	ro	kg m-2	Accumulated once a day
Surface water runoff	sro	kg m-2	Accumulated once a day
Land sea mask	lsm	Proportion	Instantaneous once a day (00Z)

		of land	
Orography	orog	gpm	Instantaneous once a day (00Z)
Soil type	slt	Categorical	Instantaneous once a day (00Z)
Top net thermal radiation	ttr	W m-2 s	Accumulated once a day
Surface latent heat flux	slhf	W m-2 s	Accumulated once a day
Surface net solar radiation	ssr	W m-2 s	Accumulated once a day
Surface net thermal radiation	str	W m-2 s	Accumulated once a day
Surface sensible heat flux	sshf	W m-2 s	Accumulated once a day
Solar radiation downwards	ssrd	W m-2 s	Accumulated once a day
Surface thermal radiation downwards	strd	W m-2 s	Accumulated once a day

Table 6: *List of single level parameters*



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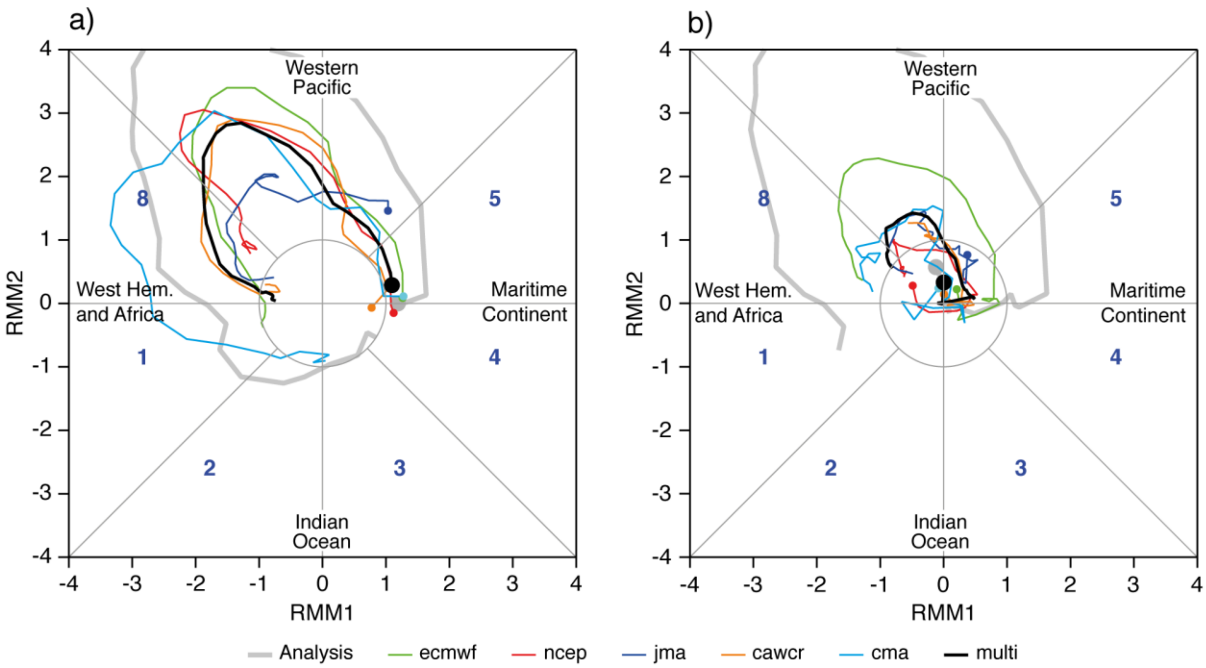

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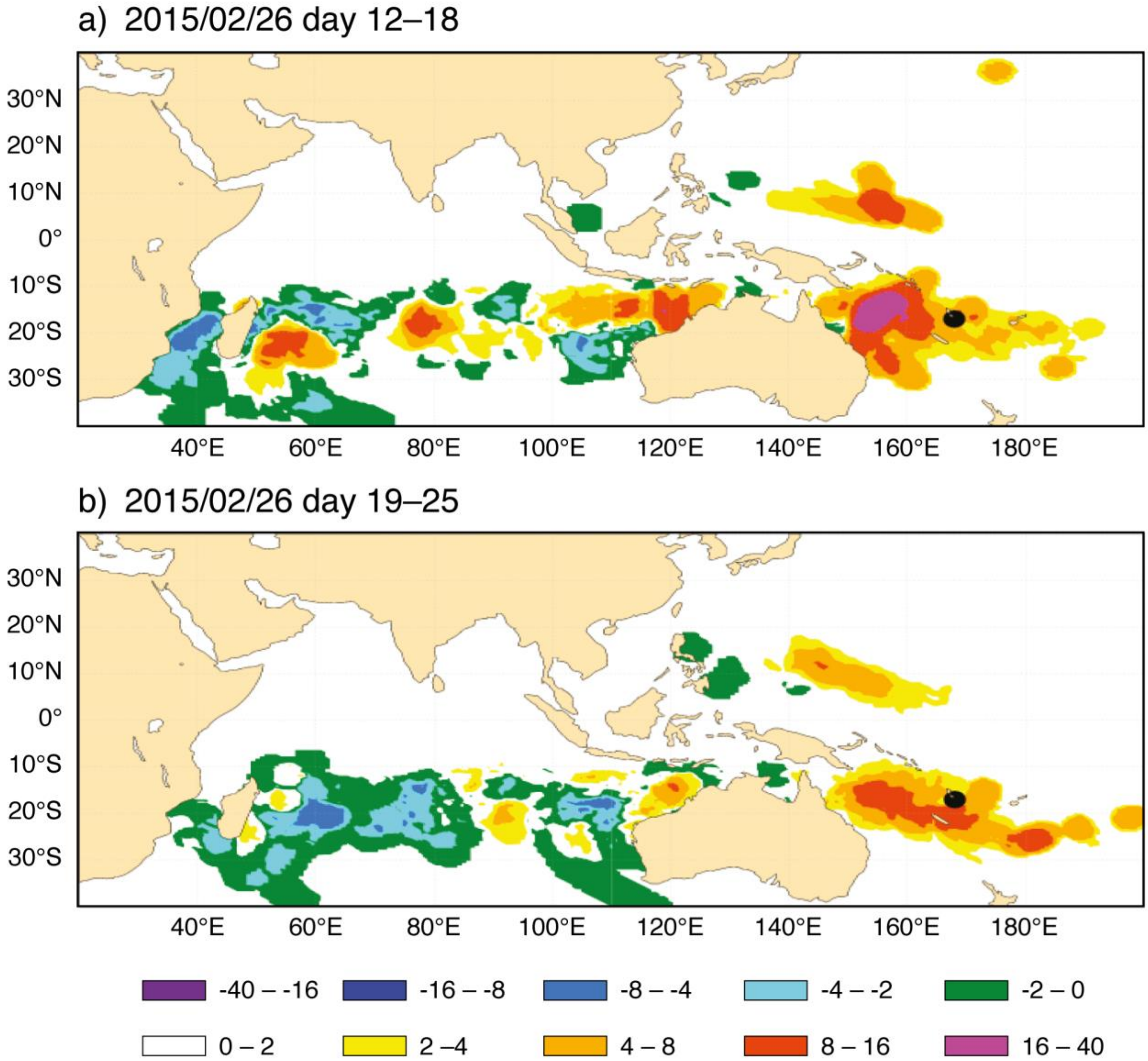

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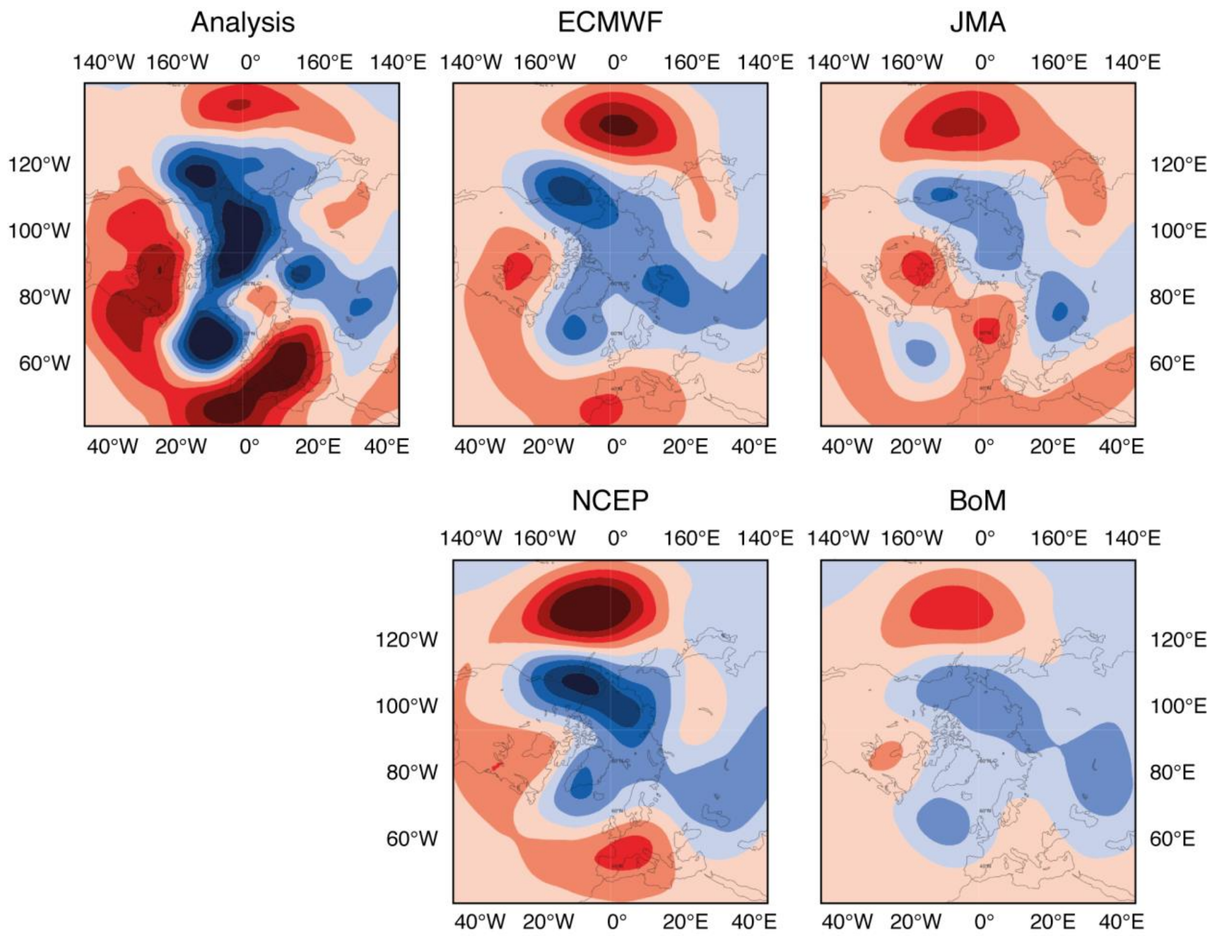

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