WWRP 2018 - 2
WCRP Report No. 6/2018

WWRP/WCRP Sub-seasonal to Seasonal Prediction Project (S2S) Phase I Final Report

(November 2013–December 2017)

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

WORLD WEATHER RESEARCH PROGRAMME

World Climate Research Programme

WWRP 2018-2

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EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at:
http://www.wmo.int/pages/prog/lsp/meteoterm_wmo_en.html.
Acronyms may also be found at: http://www.wmo.int/pages/themes/acronyms/index_en.html.

Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Fax: +41 (0) 22 730 80 40
E-mail: publications@wmo.int

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EXECUTIVE SUMMARY

The World Weather Research Programme (WWRP) and World Climate Research Programme (WCRP) Sub-seasonal to Seasonal Prediction Project (S2S) was launched in November 2013, with the primary goals of improving forecast skill and understanding on the sub-seasonal to seasonal timescale (from 2 weeks to a season) with special emphasis on high-impact weather events, developing coordination among operational centres, and promoting utilization by the applications communities. S2S is one of the three post-THORPEX (The Observing System Research and Predictability Experiment) activities of WWRP - along with the Polar Prediction Project (PPP) and the High Impact Weather project (HIWeather) - and is the first joint research project between WWRP and WCRP. A major motivation of S2S was to capitalize on the expertise of the weather and climate research communities and WMO/WWRP/WCRP programmes - filling the gap between medium-range and seasonal forecasting - to address issues of importance to the Global Framework for Climate Services (GFCS), http://www.wmo.int/gfcs/overview.

The Implementation Plan for S2S (http://www.s2sprediction.net/file/documents_reports/S2S_Implem_plan_en.pdf) was written by the planning group that convened several times during 2011-2013 and it was published in 2013. The plan proposed the following set of activities toward realizing the S2S project goals, to be carried out over a 5-year period initially, with the option of extension for a further 5 years:

- The establishment of a project Steering Group representing both the research and operational weather and climate communities, and an International Project Office to coordinate the day to day activities of the project and manage the logistics of workshops and meetings.
- The establishment of a multi-model database consisting of ensembles of sub-seasonal (up to 60 days) forecasts and supplemented with an extensive set of re-forecasts following TIGGE protocols (https://www.ecmwf.int/en/research/projects/tigge).
- A major research activity on evaluating the potential predictability of sub-seasonal events, including identifying windows of opportunity for increased forecast skill with a special emphasis on events with high societal or economic impacts, and relevance to developing countries.
- A series of science workshops on sub-seasonal to seasonal prediction.
- Appropriate demonstration projects based on some recent extreme events and their impacts, in conjunction with the WWRP Societal and Economic Research Applications (SERA) Working Group.

This report describes the project's progress and main achievements to date (up to December 2017), and outlines some of the outstanding challenges. All the main activities foreseen by the Implementation Plan have been carried out to a significant degree. The signature achievement of S2S has been the creation of the S2S database of sub-seasonal forecasts (3 weeks behind real time) and re-forecasts, archived at European Centre for Medium-Range Weather Forecasts (ECMWF) and the China Meteorological Administration (CMA). The S2S database was launched publicly in May 2015 and has inspired major research activity on S2S predictability, modelling, and forecast verification and product development. Several regional S2S research activities have been established, including a major National Oceanic and Atmospheric

Administration (NOAA) initiative in the United States of America (USA), for which S2S has been a catalyst. The project has fostered S2S research by organizing/co-organizing 18 science workshops/sessions in the project's first 4 years, together with eight training courses. Six S2S sub-projects were established as a means to coordinate research and to develop the global S2S climate and weather research community; each of these is reported on below. A series of case studies has been carried out as part of the sub-project on extremes. The science findings are rapidly evolving, with the database launched only 2 years ago, and several are highlighted in this report. To date and to our knowledge, fifteen articles have been published in the peer-reviewed literature that use the S2S database. Several of the findings relate to the Madden-Julian Oscillation (MJO), a primary source of sub-seasonal predictability:

- The skill of MJO forecasts in 7 of 10 S2S models exceeds a bivariate correlation skill of 0.5 at 20-day lead, while one model reaches that level by 30 days (Figure 12).
- MJO teleconnections over the North Atlantic are of realistic sign, but too weak in all the models (Figure 13).
- MJO skill is enhanced by up to a week during the easterly phase of the stratospheric Quasi-Biennial Oscillation (QBO) in several S2S models (Figure 14).
- Evidence from the S2S database forecast ensembles suggests that the severe cold spell that afflicted western Europe in March 2013 was at least in part attributable to a strong MJO event propagating into the western Pacific.
- The skill of the S2S models to predict Euro-Atlantic weather regimes and their transitions has been assessed. Results indicate predictive skill up to about 3 weeks for the positive and negative North Atlantic Oscillations (NAO), and up to about 16 days for the other weather regimes. The S2S models display skill to predict weather regime transitions up to about 16 days.

Coordination among operational centres fostered by S2S led the WMO Lead Centre for Long-range Forecasts in 2015 to begin a pilot real-time sub-seasonal MME prediction system for its members, taking advantage of the S2S database at ECMWF. The Lead Centre is able to access the S2S database without the 3-week delay placed on public access. Further coordination across the WMO Global Producing Centres of Long-Range Forecasts (GPCLRFs) has taken place such that all of 11 operational centres now issue forecasts on Thursdays (including the four models with daily forecast starts); this compares with only 7 of 11 models at the project's outset and greatly facilitates the generation of multi-model ensemble forecasts.

The S2S project was born into a complex landscape of research and operational forecasting programmes and institutions within and external to WMO. The project was created as a nexus between WCRP and WWRP, strongly linked to WMO-Commission for Basic Systems (CBS) (http://www.wmo.int/pages/prog/www/BAS/CBS-info.html), which focuses on the development, implementation and operation of integrated systems for observing, data processing, data communication and data management, and to the provision of public weather services. The project also aspires to make a significant contribution to the WMO Global Framework for Climate Service (GFCS).

While this report can point to major achievements and project successes, there is a clear recognition that much of the research, product development and uptake by the applications communities are still at quite early stages. Much remains to be done to fully realize the S2S vision of seamless forecasting both in terms of improving the skill of the forecasts, developing the operational infrastructure, as well as creating forecast products to help inform user-decisions in the two-weeks-to-two-months range. A focus on a combination of such upstream and downstream issues is foreseen in the second 5-year phase of the S2S project.

1. THE S2S DATABASE

A primary goal of the first phase of the S2S project was to assess the current capabilities of state-of-the-art operational sub-seasonal to seasonal forecasts and identify gaps and issues in sub-seasonal to seasonal forecasts and evaluate the potential usefulness of S2S forecasts for various applications. Therefore, the first effort and major achievement of this project has been the establishment of a database containing near real-time and re-forecasts up to 60 days from 11 centres: 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). All except CNR-ISAC are officially designated GPCLRFs. Because S2S is a research project, the real-time forecasts are only available with a 3-week delay. The data is archived at ECMWF and CMA, and as of mid-2017 is also available from the International Research Institute for Climate and Society (IRI), Columbia University. Users are required to sign the S2S Terms and Conditions which stipulate non-commercial use of the S2S data.

The first 2 years of the project were dedicated to agreeing on the main characteristics of the data archive (e.g. the list of archived variables), defining the GRIB2 format for S2S data and some of the variables which were not already defined in GRIB2, producing test data from each centre, testing the archiving, and setting up the data portals. Based on the Implementation Plan, it was decided at an early stage that the S2S database would consist of a "database of opportunity" of sub-seasonal forecasts and re-forecasts produced routinely by each centre, rather than requiring a common forecasting protocol, and that the forecasts would be released through the database after a 3-week delay to avoid conflicts with the data policies of some of the GPCLRFs. It was originally proposed that the 3-week requirement be revisited after 1 year, or that it could be lifted for a limited period of time. These discussions were subsequently postponed for a potential Phase 2 of the S2S project. The S2S database has been documented in an article in the Bulletin of the American Meteorological Society (Vitart et al., 2017). The database contains most of the atmospheric and land variables proposed in the Implementation Plan (Annex 4). Work is ongoing at ECMWF to include additional ocean and ice fields.

1.1 ECMWF data portal

The ECMWF data portal was opened to the research community in May 2015 via the Data Portal and ECMWF Web API (Application Programming Interface). The number of active users per month is increasing and reaches up to 90 different active users per month in 2017 (Figure 1). By December 2017, 951 users from 92 countries (Figure 2) had registered and had executed over 5,000,000 requests to extract 230 Terabytes of data from ECMWF. ECMWF and CMA are working together closely to ensure the timely synchronization of the two databases. To assess the user satisfaction with the S2S database and the quality of the service provided by ECMWF to access the S2S data, a survey was sent in 2017 to all S2S database registered users. About 120 people replied. The overall level of satisfaction is high (45.4% are satisfied and 27.8 % are very satisfied), although the percentage of "very satisfied" is not high enough.

The survey highlighted the need to improve the speed of data retrieval and also the need for more training on use of the database (survey results can be found at http://www.s2sprediction.net). Work is ongoing to add the possibility of retrieving the data directly in Network Common Data Form (NetCDF) from the ECMWF data portal.

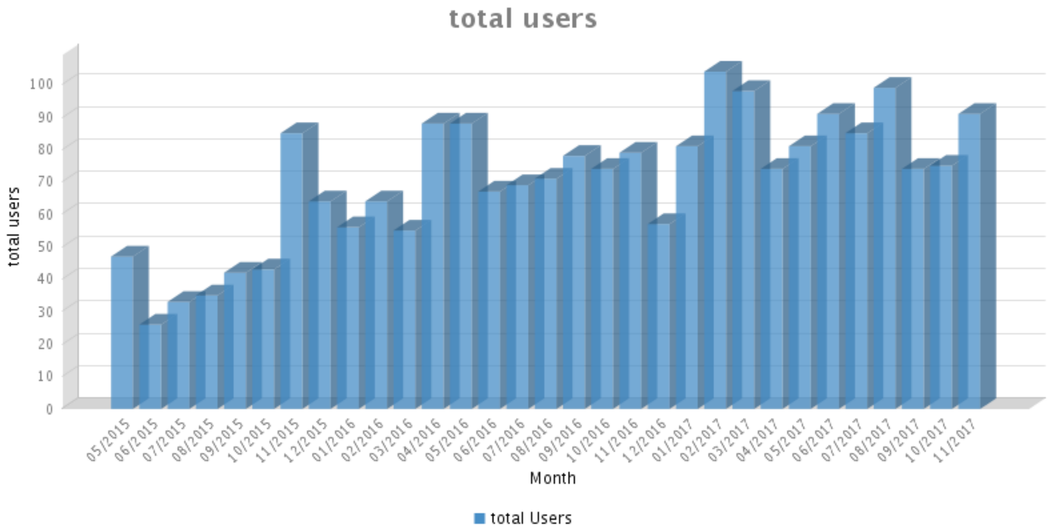

Figure 1. Number of active users of the S2S database per month since May 2015, through the ECMWF data portal. Some of the peaks of activity (e.g. November 2015 and February/March 2017) are due to training courses on the S2S database.

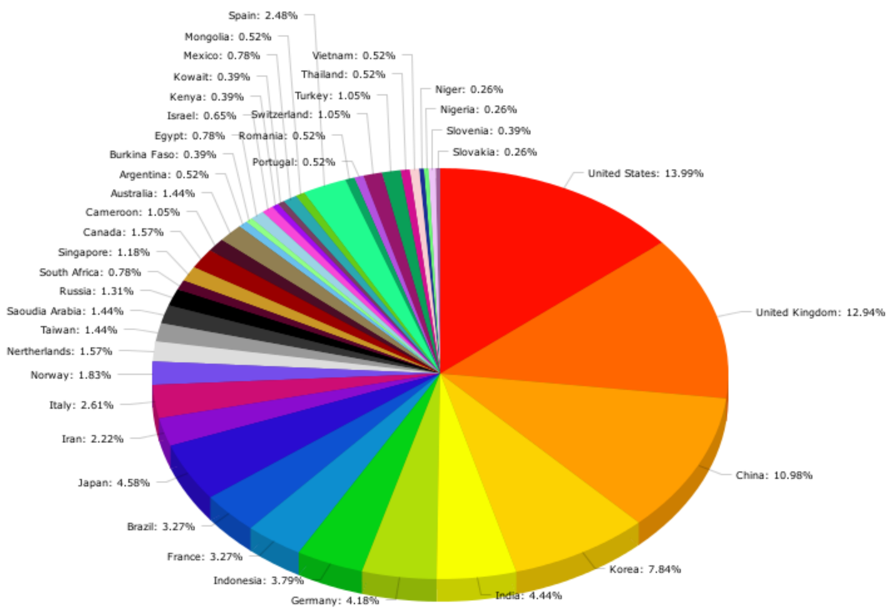

Figure 2. Proportion of ECMWF S2S database users per country with more than 3 users between May 2015 and December 2017.

1.2 CMA data portal

The China Meteorological Administration (CMA) Sub-seasonal to Seasonal Project (S2S) Archive Centre, one of the two S2S official Archive Centres, aims to collect and archive real-time ensemble forecast and re-forecast data from all S2S data-provider centres, and deliver the data to users through the web-based data download services. By December 2017, CMA S2S Archive Centre had collected and archived about 48 TB of data. The original forecast data from each S2S data provider are directly sent to ECMWF. All available S2S data in CMA are acquired from ECMWF S2S archive centre, and checked to ensure integrity and synchronization with data at ECMWF, then finally archived at CMA in an online disc storage system using the MARS system archiving as a backup. CMA is making continuous effort to keep synchronization of the S2S database with the ECMWF's data portal (http://apps.ecmwf.int/datasets/data/s2s/).

The CMA's S2S data portal was developed by CMA and officially launched on 16 November 2015. The data is published to http://s2s.cma.cn and is freely accessible. It provides the sub-seasonal to seasonal weather forecast data to the researchers worldwide for studying the predictability on time-scales up to 60 days. Based on shell scripts and ecFlow software, the CMA's S2S data portal provides users seamless services from online data storage to online acquisition. Details of the S2S models and available variables can be found at http://s2s.cma.cn/dmodels. Based on the statistics for the S2S database usage, 256 users have registered at the CMA's S2S data portal so far, and the total number of visits is more than 510,000 in 2017, increasing 400% compared to 2016. Registered users originate from more than 40 countries, with the largest number of users being from China. Up to now, about 6.1 Terabytes of data have been downloaded from the CMA's S2S data portal. The top five requested centres are ECMWF, JMA, NCEP, CMA and UKMO. The top five downloaded variables are temperature, surface air temperature, total precipitation, surface air maximum temperature, and surface air minimum temperature.

The CMA S2S data portal provides a fully online data download service. Data download services in GRIB2 and NetCDF format are available. The NetCDF format is obtained through online conversion. Currently S2S data download from CMA is provided by the Hypertext Transfer Protocol (HTTP). The CMA S2S data portal will provide the possibility to download data using the Open-source Project for a Network Data Access Protocol (OPeNDAP) in February 2018. A system of online data analysis and visualization is under development, and will become available in June 2018.

1.3 IRI Data library

A large fraction (58TB as of December 2017, about 75% of total) of the S2S Database has been downloaded at IRI, Columbia University, from the ECMWF server, and has been archived on disk (duplicated on two independent servers) in the IRI Climate Data Library (IRIDL): http://iridl.ldeo.columbia.edu/SOURCES/.ECMWF/.S2S/. This has been possible through collaboration with projects funded by NOAA's MAPP and NGGPS programmes. IRIDL provides a flexible and fully online interface to the data, which can be downloaded in a variety of formats (including NetCDF), or post-processed and visualized without the need to download. In addition to the raw S2S daily fields, derived weekly- and ensemble-averaged fields are in the process of being pre-computed for selected variables, together with an online map-room for visualization of weekly fields and anomalies. The S2S model MJO indices computed by ECMWF (see section 3.2 below) are also available via IRIDL. These developments have largely taken place in 2016-2017 and are ongoing. There were 815 (non-unique) visitors to the S2S data in IRIDL in 2016, and 6,153 in 2017.

The IRIDL S2S data has been used for teaching at Columbia University and in S2S training courses, where students have analysed the performance of the ECMWF model for particular high-impact weather events. Figure 3 shows an example for an active phase of the Indian summer monsoon in July 2015 in Bihar, northern India, visualized using the IRI Data Library. The calculations to obtain the anomaly maps in Figure 3 are encapsulated URLs, enabling the maps to be created “on the fly” and without having to download the data first.

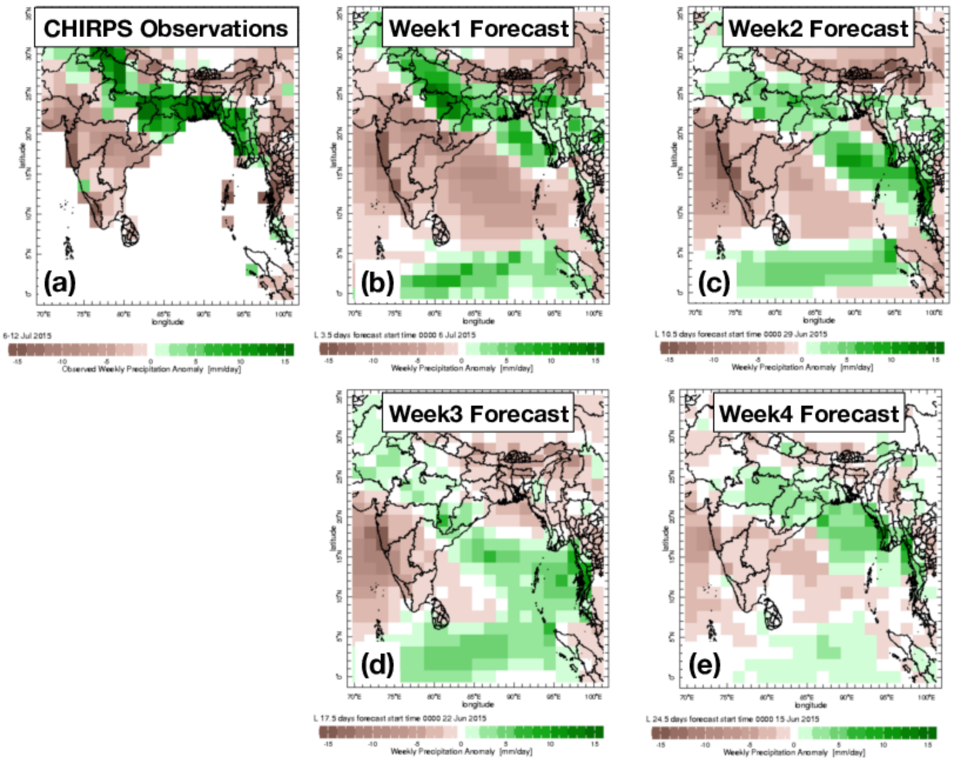

Figure 3. Weekly precipitation anomalies (mm/day) for July 6-12 2015. (a) CHIRPS data, and ECMWF forecasts ensemble mean at increasing leads from Monday starts: (b) July 6 “Week 1", (c) June 29 “Week 2", (d) June 22 “Week 3", and (e) June 15 “Week 4".

2. OPERATIONAL LINKS

2.1 Changes to operational production of sub-seasonal forecasts

Annexe 4 of the S2S Implementation Plan provides a table describing all the operational sub-seasonal forecasting systems which were planned for inclusion in the S2S database before the S2S project started in November 2013. A more recent model description table can be found in https://software.ecmwf.int/wiki/display/S2S/Models. The comparison of these two tables shows that most operational centres have upgraded their S2S systems since 2013. Some centres like UKMO and ECMWF have considerably increased the size of their re-forecasts. Other centres like KMA have increased the frequency of their sub-seasonal forecasts. In 2013, four models were producing sub-seasonal forecasts on a monthly basis, while in 2017 all models in the S2S database have a daily or weekly real-time frequency. Although the re-forecast set-up still varies greatly between operational centres, the configuration of the real-time forecasts is more consistent in 2017 that it used to be in 2013. Some of these changes can be directly attributed to the S2S project:

- CNRM produces real-time forecasts once a week instead of once a month since March 2016
- Some centres (CNR-ISAC, CNRM, HMCR) chose or moved the start date of their real-time forecasts to Thursdays.

The S2S project has improved the coordination between the production of real-time forecasts between S2S models: since May 2017, all S2S models produce real-time forecasts on Thursdays, which greatly improved the possibility to produce a multi-model combination from the 11 S2S models. There are still many differences between model re-forecasts and more time and more studies will be needed before S2S will be in position to provide recommendations to the operational centres regarding re-forecasts (recommended ensemble size, re-forecast length, frequency etc.).

S2S has also helped encourage other operational and research centres to produce sub-seasonal forecasts and participate to the S2S database, such as IITM (India) and Council for Scientific and Industrial Research (CSIR, South Africa).

2.2 Data integration with the WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble

The WMO Sixteenth World Meteorological Congress (Cg-XVI) in 2011 requested the WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble (LC-LRFMME; https://www.wmolc.org/) to explore the possibility of expanding its role to extended-range predictions. Subsequently in 2013, the Implementation Coordination Team (ICT) of the Open Programme Area Group (OPAG) for the DPFS (ICT-DPFS) set up a Task Team under the joint Commission for Basic Systems (CBS) – Commission for Climatology (CCl) Expert Team on Operational Predictions from Sub-seasonal to Longer-time Scales (ET-OPSLS) to scope the implementation of real-time sub-seasonal forecasts, and to establish the necessary links with the then-planned WWRP-THORPEX/WCRP research project on sub-seasonal to seasonal prediction. Availability of re-forecasts and real-time forecast data archive from various operational centres, developed as part of the S2S project, provided the catalyst to move forward with the development of an operational capability by the LC-LRFMME for predictions on sub-seasonal time-scales.

In December 2015, the pilot real-time sub-seasonal multi-model ensemble (MME) prediction system was developed with a subset of S2S models. The initial choice of models – ECMWF, NCEP and JMA – was guided by the day of the week when the sub-seasonal forecasts by multiple models are initiated. Currently, WMO LC-LRFMME is downloading the real-time data forecast data from a sub-set of six models in the S2S archive and producing MME products on a regular basis. A recent development where the forecast centres were encouraged by the S2S project to initiate at least one of their forecast ensembles from Thursday of the week will lead to the inclusion of larger number of models in the multi-model extended-range forecasts by the LC-LRFMME. Currently, displays at the website of WMO LC-LRFMME (Figure 4) are available about a week delay from starting date of MME prediction because of the time required for data collection. However, in future a tighter data integration between the LC-LRFMME and ECMWF will reduce the lead-time, and is highly desired given the lead-time dependence in skill of forecasts on weeks 2-4 timescale.

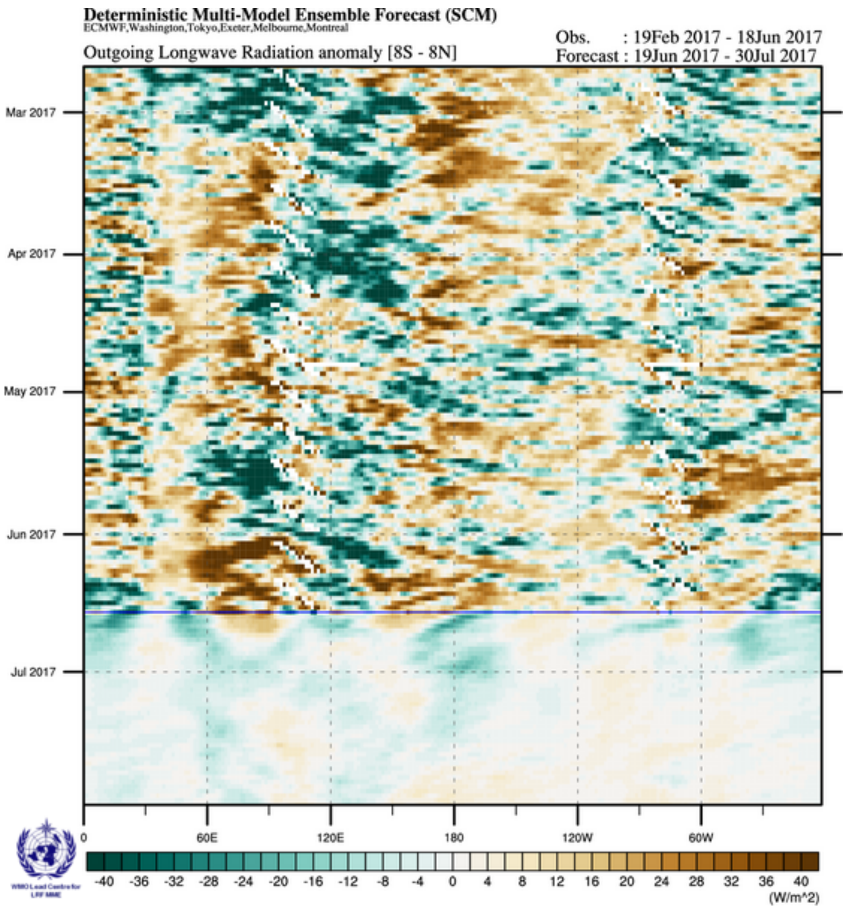

Figure 4. Deterministic forecast of Outgoing Longwave Radiation (OLR) based on six participating S2S models averaged between 8°S-8°S. Forecast OLR anomaly from 19 June-30 July 2017 is blended with the observed OLR anomaly from 19 February-18 June, 2017, and is indicative of intra-seasonal variability in the equatorial latitude. Forecast data is downloaded from the S2S data archives from the ECMWF and is processed by the WMO LC-LRFMME as part of the pilot real-time sub-seasonal forecast effort.

Figure 5 illustrates how the S2S database at ECMWF underpins both the S2S data portal (with access to the research and applications communities delayed 3 weeks behind real time), and WMO LC-LRFMME real-time access for WMO users. The operational effort led by the LC-LRFMMF would not have been possible without the initiation, S2S database infrastructure at ECMWF, and the efforts of the S2S project.

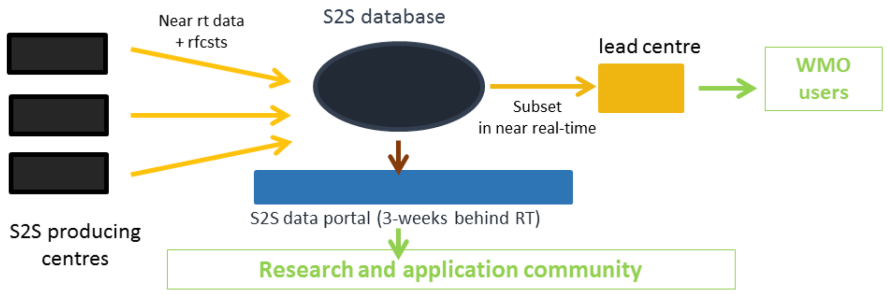

Figure 5. Schematic illustrating how the S2S database at ECMWF underpins both the S2S data portal (with access to the research and applications communities delayed 3 weeks behind real time), and WMO LC-LRFMME real-time access for WMO users.

3. SERVICE TO THE COMMUNITY

3.1 Improved communication across the S2S community through the ICO, including S2S project website, mailing list, newsletter

The primary function of S2S Project International Coordination Office (ICO), hosted and resourced by KMA, is to provide support to planning and implementation of S2S priorities, to ensure appropriate international coordination between the S2S project participating members and collaboration with related WMO programmes and other international programmes.

A principal accomplishment over the past years is setting up an improved communication environment among the S2S communities and liaison groups through S2S ICO, in order to remove barriers between S2S research, forecast, and applications. To foster enhanced communication, ICO has established the following communication environment which provides a forum for S2S communities to nurture expanded collaboration and discuss recent advances related to sub-seasonal to seasonal timescales:

(1) The S2S project website (http://s2sprediction.net): Open access to S2S information and user-friendly interaction space are important requirements for S2S Communities. The S2S project ICO developed the S2S homepage, including creating the S2S project logo, which makes possible the exchange of information and includes links to the S2S data portals at ECMWF, CMA and IRI, as well as to the NOAA SubX project data portal at IRI. The S2S website provides:
- The latest news from S2S communities including workshops and meetings, recent S2S articles, reports and books.
- Wiki pages for each of the S2S sub-projects whose role is to coordinate S2S activities with relevant bodies and to prepare reports for the regular S2S steering group meetings.

(2) The S2S project mailing list (Subseasonal_to_Seasonal_Prediction@googlegroups.com, S2S_SG_LG@ googlegroups.com): The S2S mailing list is operated under the Google Group. It offers

a virtual space to communicate among people who are interested in sub-seasonal to seasonal timescales. As of 12 June 2017, there are 342 subscribers to the mailing list.

(3) S2S newsletter: This has been published every 4 months, with six issues to date since September 2015. It contains News (introduction of sub-projects, some meeting/events outcomes, S2S database update), Upcoming Events, Publications, S2S SG/LG membership update, and Special Scientific Articles.

(4) Workshops/meetings/capacity buildings: It is of primary importance for S2S communities to interact with each other. These events are an opportunity to communicate, to exchange the outputs of the projects, and to raise community awareness of the value of S2S project to WMO Members.

3.2 FTP site for MJO indices

The S2S database is a very large database and downloading data from all the S2S models can take a significant amount of time and can be quite complex because of the different model configurations. There is also a limit in the number of people who can download S2S data simultaneously. Therefore, there is a benefit in rationalizing the use of the S2S database to avoid as much as possible duplications in its usage. For example, many research groups are interested in calculating MJO indices for model intercomparison but also to assess the impact of the MJO on various fields. By far the most popular MJO index is the Real-time Multivariate MJO (RMM) index from Wheeler and Hendon (2004). To avoid many people doing the same data retrievals and calculations, The S2S SG decided to compute the RMM indices and make them available through an ftp site. Later on, the same procedure could be applied to other popular weather indices, such as sudden stratospheric warming (SSW), weather regimes, tropical cyclone tracks, etc. This ftp site also provides an important service to the S2S research community.

The first example of weather index provided from an ftp site are the MJO RMM indices. The RMM indices from ten of the S2S models (at the time of writing KMA did not provide outgoing long wave radiation used in the computation of the index) have been computed following Wheeler and Hendon (2004) and Gottschalk et al. (2010). The calculation has been applied to the re-forecasts as well as real-time forecasts. This RMM index database is updated routinely (3 weeks behind real-time). The indices are produced in a text format which has been agreed by the S2S Steering Group. The RMM files contain the RMM principal components, amplitude and phase of the MJO for each forecast day and ensemble member. Verification from ERA Interim (also updated near real-time) have also been produced. The RMM indices are now available to the research community from the ftp site s2sidx@lanpds-dm1.ecmwf.int since March 2017. These indices have also been copied into the IRI data library http://iridl.ldeo.columbia.edu/SOURCES/.ECMWF/.S2S/ and work is ongoing to develop graphic tools to automatically plot the RMM indices.

Work is currently underway to follow the same procedure for Sudden Stratospheric Warming indices (work done at U. Reading by Andrew Charlton-Perez for SPARC/SNAP), European weather regimes (Laura Ferranti, ECMWF), American weather regimes (Angel Munoz, Columbia University) and tropical cyclone tracks (Frederic Vitart, ECMWF).

3.3 Products websites (ECMWF/S2S museum)

Another service provided by the S2S project to the research community has been the creation of two websites containing 3-week behind real time graphical products from the S2S models. These websites are an important resource for people interested in assessing how operational models predicted past events.

3.3.1 ECMWF S2S product website

A range of near-real time forecast charts based on the S2S database, with public access, is available at: www.ecmwf.int/en/research/projects/s2s/charts/s2s/.

The products can be used to monitor the S2S data and assess the quality of the forecasts, as well as providing a testbed for the development of new products, for example to identify signals for extreme events at the sub-seasonal timescale. The products include ensemble mean anomalies for some meteorological parameters, Extreme Forecast Index (EFI; Lalaurette, 2003) for 2m temperature and forecasts of the MJO. As an example of S2S products, Figure 6 shows weekly mean precipitation anomalies and forecasts from different models. This figure gives an idea of how well the predicted anomalies verified against the ECMWF analysis and also about the consistency between the different S2S forecasts.

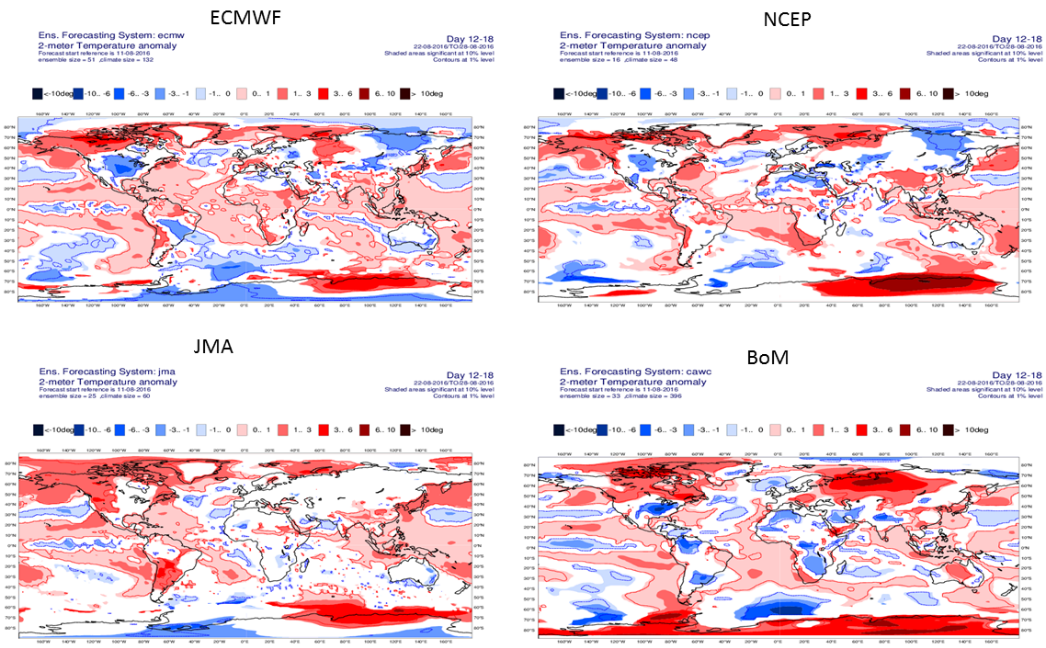

Figure 6. Weekly mean precipitation anomalies from ECMWF, NCEP, JMA and BOM forecasts starting 11 August 2016. Each model anomaly is relative to its own model climate computed from the re-forecast statistics. The areas where the ensemble forecast is not significantly different from the ensemble climatology according to Wilcoxon-Mann-Whitney test are blanked. The time range of the forecasts is day 12-18.

Currently the S2S charts are limited to seven models. Work is ongoing to include all the 11 S2S models and the range of products. To make the products comparable, the largest common period available (1999-2010) has been used to estimate the model climate. Forecast products are issued once a week (every Thursday) to keep the number of charts at minimum. Through the S2S products we can monitor the quality of the data ingested in the S2S database as well as the performance of the S2S forecasts. The ECMWF S2S Products website contains charts for all forecasts since January 2016. With this forecast-history we can: evaluate forecast performance for specific events (e.g. heat waves, wet spell etc.), analyse the consistency among different models and test the benefit of the multi-model approach. By monitoring the performance of new products (e.g. EFI based on weekly means) we will develop our understanding of the optimal way to detect a reliable signal for extreme events at the sub-seasonal time range.

3.3.2 S2S museum

The S2S museum (http://gpvjma.ccs.hpcc.jp/S2S/) is hosted at the University of Tsukuba (Japan) and has been developed by Mio Matsueda (University of Tsukuba and University of Oxford) as an extension of the "TIGGE museum" with support from the Arctic Challenge for Sustainability (ArCS) Project of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. This website is updated daily from all the new forecasts available from the S2S database. The website contains plots of: AO/AAO (Arctic/Antarctic Oscillations) index, SLP and Z500 anomalies, teleconnection indices (NAO, EA, PNA, WA, WP, and EU), Wave Activity Flux at 200 hPa, SSW (Sudden Stratospheric Warming) (only November-April), Temperature at 10 hPa, MJO, SST (60S–60N), and sea-ice cover (see example in Figure 7).

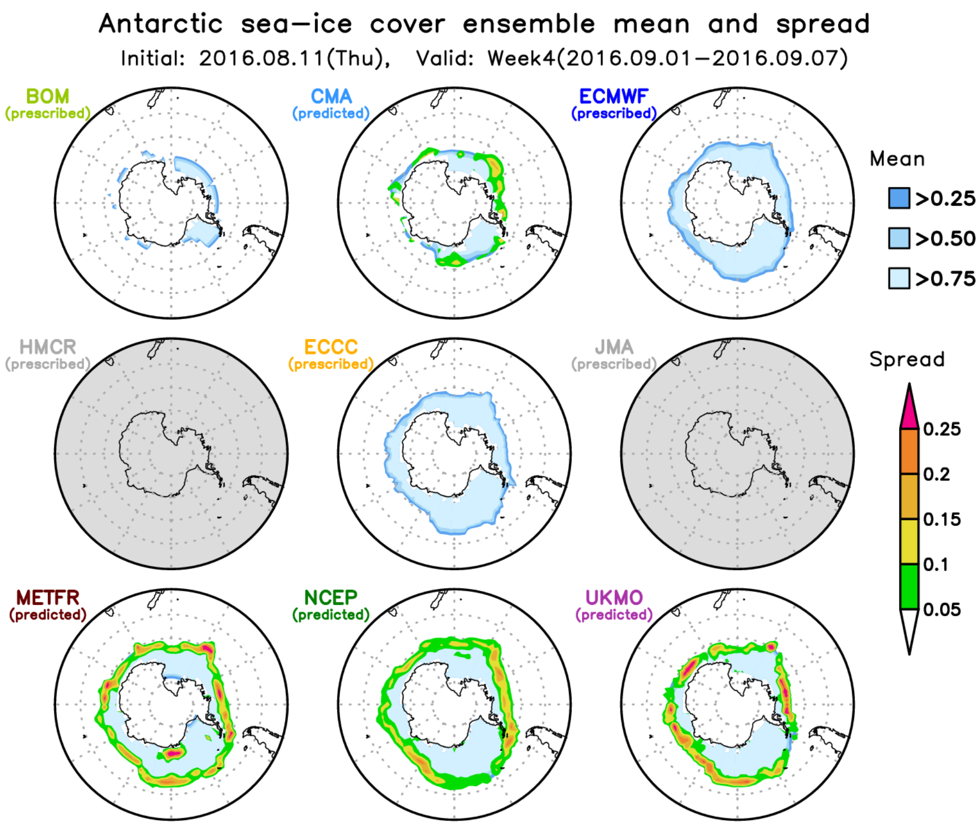

Figure 7. Antarctic sea-ice cover ensemble mean and spread from S2S models starting on 8 August 2016 and valid for the time range week 4 (day 22-28).

4. SCIENCE (RESEARCH AND MODELLING)

4.1 S2S sub-project achievements

4.1.1 Extreme weather

The S2S sub-project on extreme weather's science plan and membership are available at: http://www.s2sprediction.net/xwiki/bin/view/Main/Extremes. The main goals of the S2S sub-project on extreme weather are:

(1) Assess the predictability of extreme events such as heat, cold waves, and floods at the sub-seasonal to seasonal timescales.
(2) Assess the predictability of tropical storms.
(3) Produce case studies of extreme weather with strong societal impact.

To address (1) and (2), past and ongoing studies include:

- Predictability of tropical storms and their modulation by MJO and El Niño–Southern Oscillation (ENSO) (F. Vitart, ECMWF; Chia-Ying Lee, Columbia University).
- Predictability of weather regimes, heat waves and cold waves over Europe and their relationship to large-scale circulation patterns (L. Ferranti, ECMWF).
- Prediction of California drought index and its link to ENSO in coupled forecast system model version 2 (CFSv2) (Mingyue Chen, NCEP/CPC).
- Drought forecasting using probabilistic precipitation and predictor fields in Europe (C. Lavaysse, JRC).
- Modulation of extreme events in the USA by the MJO (C. Jones, UCSB).
- Use of Extreme Forecast Index in S2S models (L. Ferranti, ECMWF).
- Predictability of atmospheric rivers (M. DeFlorio, NASA JPL).

Most of these studies make use of the S2S database and some of them have already led to publications in the peer-reviewed literature. For instance, the EFI method has been applied to the weekly means of the S2S forecasts (see example in Figure 8). Verification of the EFI of 2-metre temperature for weeks 3 and 4 against ERA Interim showed statistically significant skill up to week 4, suggesting that the extended range forecasts could be potentially useful for the prediction of some extreme events.

Over the past years, several cases studies of extreme weather have been investigated. They include:

- The exceptionally cold March 2013 over most of Europe (second coldest March in the UK since 1910). The cold temperature anomalies also extended over large portions of North America and Asia. This cold event lasted for about a month, and was associated with a negative phase of the NAO. An article published in Meteoworld (April 2014 issue), described the results of the investigation on its sub-seasonal predictability and causality.
- Severe Tropical Cyclone Pam of 2015 which was the most intense tropical cyclone in the southern hemisphere in 2015 and one of the worst natural disasters in the history

of Vanuatu. Figure 9 suggests that this event had some extended-range predictability; the multi-model combination indicate an increased risk of tropical cyclone strike probability in the vicinity of Vanuatu (indicated by a black dot in Figure 9) 2 to 3 weeks in advance.

- Sub-seasonal variability of precipitation in the US west coast during the 2015 El-Niño event. This case study, led by C. Jones (UCSB) is still ongoing.
- Drought prediction over the Acre regions (Brazil). This case study, led by C. Castro (Centro Nacional de Monitoramento e Alertas de Desastres Natural, CEMADEN) is a collaboration between CEMADEN, CPTEC (Centro de Previsão de Tempo e Estudos Climáticos) and the Japan Radio Company (JRC) in Brazil. It is motivated by the fact that the Acre River was at the lowest level in 2016 compared to the previous 11 years, even lower than during the "famous" droughts of 2005 and 2010. This project will assess the skill and predictability of drought in the Acre region using the S2S database and involves a close collaboration with the local decision makers in the Acre's Government.

A bibliography and some of the results of this project have been included in a chapter on S2S prediction of extreme events for the S2S book which will be published by Elsevier in 2018.

Some of the case studies (e.g. Tropical Cyclone Pam) showed that increased model resolution could lead to more accurate predictions of extreme events. Experiments with super parameterization were performed on some of the case studies and also showed a positive impact on the prediction of these extreme events. These results suggest that S2S predictions should benefit from increased resolution. Other results from this sub-project (e.g. Extreme cold March 2013 case study) indicate that improving the representation of MJO teleconnection, currently too weak in the S2S models, should lead to improved S2S prediction of extreme events.

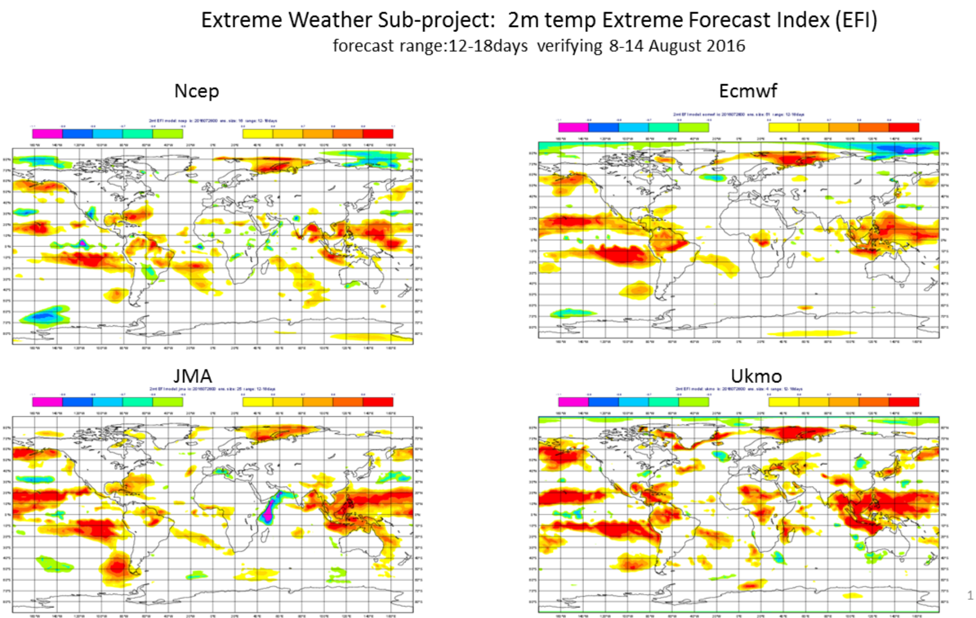

Figure 8. Extreme Forecast Index of 2-metre temperature from four S2S models: NCEP, ECMWF, JMA and UKMO. The forecasts are for the lead time 12-18 days and verifying on the week 8-14 August.

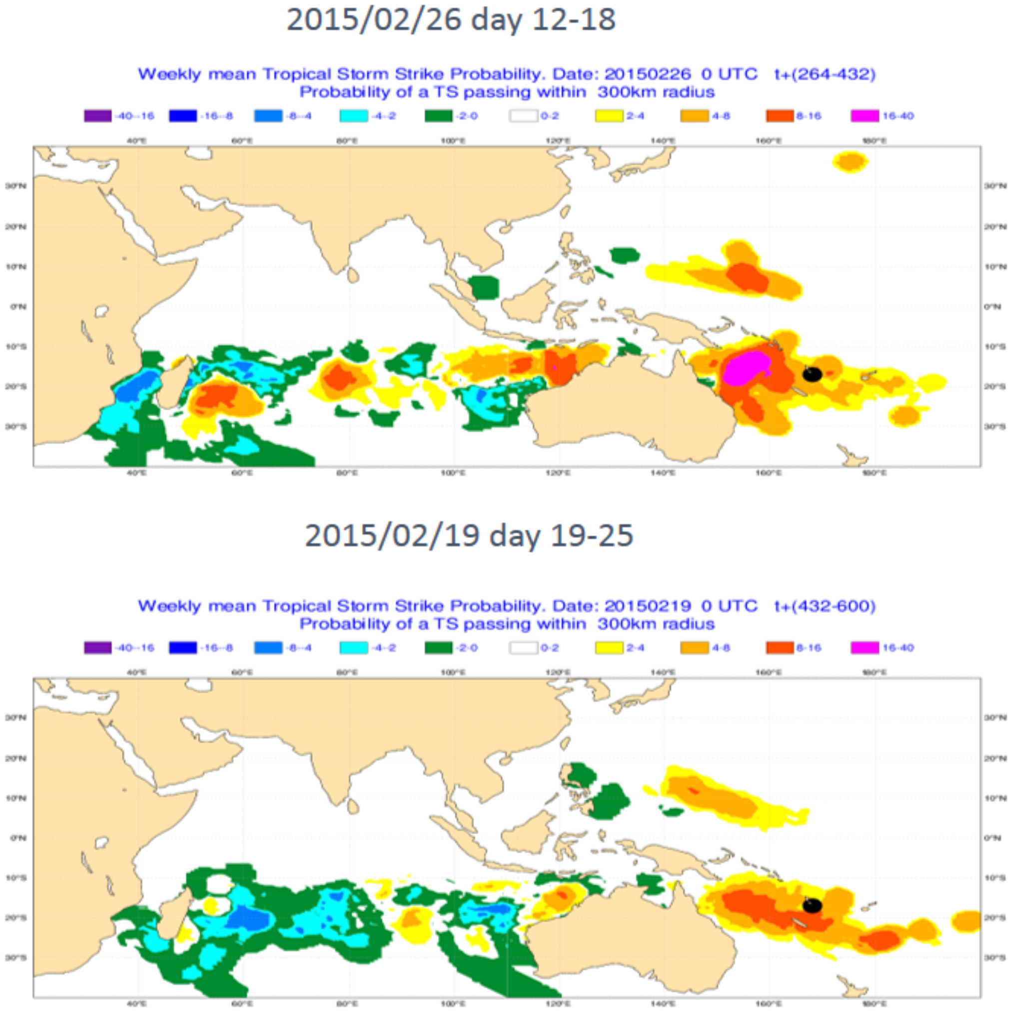

Figure 9. Probability anomalies of a tropical storm strike within 300 km radius from the multi-model ensemble (combination of ECMWF, NCEP, CMA, JMA and BoM forecasts). The forecasts were initialized on 26 February 2015 (top panel), 19 February 2015 (bottom panel) and cover the weekly period 9-15 March 2015, which corresponds to a forecast range of day 12-18 (top panel) and day 19-26 (bottom panel). The black dot in each panel represents the location of landfall of tropical cyclone Pam over Vanuatu islands.

4.1.2 Monsoons

The Monsoon sub-project aims to assess the current capability to forecast the monsoon sub-seasonal variability, including break/active episodes and onset across all of the major monsoon regions. A monsoon sub-project wiki page was developed, along with the project plan, and both are available at: http://s2sprediction.net/xwiki/bin/view/Main/Monsoon
A project team was established: Harry Hendon and Andrew Marshall (BoM), A.K. Sahai (IITM, India), Bin Wang (U Hawaii), Alice Grimm (Federal University of Parana, Brazil). The Asian-Australian Monsoon Working Group (http://www.clivar.org/asian-australian-monsoon), under the Climate and Ocean: Variability, Predictability and Change Global Energy and Water cycle Exchanges (CLIVAR-GEWEX) Monsoon Panel, agreed to promote the sub-project, especially to promote systematic evaluation of sub-seasonal monsoon predictions across all S2S models and to act as a source for analysis code and other tools.

The initial phase of the project focused on assessing predictive capability for active/brake episodes in the Australian and Indian summer monsoons. In order to provide a standard verification metric, daily indices for area-mean rainfall in the Australian summer monsoon (based on Marshall and Hendon, 2015) and for the core zone of the Indian summer monsoon (based on Rajeevan et al., 2010) have been computed for 1980-present. These indices, updated in real time, can be downloaded from http://s2sprediction.net/xwiki/bin/view/Main/Monsoon.

The index for the Australian summer monsoon was used to assess the sub-seasonal to seasonal skill with the Bureau of Meteorology (BoM) POAMA S2S model (Marshall and Hendon, 2015). The role of the MJO for modulating the monsoon and the POAMA model's capability to depict this modulation was also assessed. This study showed that the MJO produces about an 8 to 1 modulation of the occurrence of monsoon wet episodes across its life cycle, with wet periods preferentially occurring in MJO phase 6. The POAMA S2S model faithfully captured this modulation and is able to predict the MJO to at least 3 weeks lead. However, skilful prediction of monsoon-mean rainfall was limited to less than 2-week lead time (Marshall and Hendon 2015), which emphasises that although the MJO is a primary driver of monsoon variability, many other processes are involved.

Subsequent to the Marshall and Hendon (2015) study, the BoM upgraded its S2S model to be based on the UKMO GC2 coupled model (referred to as ACCESS-S1), which has markedly higher resolution than the POAMA model and uses better atmosphere initial conditions. A comparison of Australian monsoon rainfall prediction skill (Figure 10) reveals at least a 1-week lead time improvement in forecast skill, with accuracy scores (hit rates) for above median rainfall remaining above 60% for weeks 3-4 whereas for POAMA they dropped below 60% for weeks 2-3. This study indicates potential for further improvement of monsoon rainfall prediction and that the new capability with the ACCESS-S model can potentially be useful for real world applications.

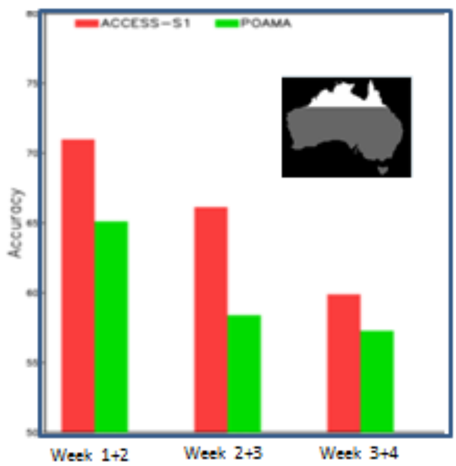

Figure 10. Accuracy score for predicting above median rainfall averaged across northern Australia during the summer monsoon. Re-forecasts from the new S2S model at BoM (ACCESS-S1 based on UKMO GLOSEA5) and the older S2S POAMA system are used for forecasts initialized on 1 Oct, 1 Nov, 1 Dec, 1 Jan, 1 Feb, and 1 Mar 1990-2012. The ACCESS-S1 system has much improved skill over POAMA due to improved atmospheric initial and model.

Similar assessment of S2S predictions for the Indian summer monsoon using the CFS S2S model implemented at IITM was provided in Sahai et al. (2016). Forecast skill for pentad mean core-zone rainfall was found to extend to ~3 pentad lead time, similar to that found by Marshall and Hendon (2015) for the Australian summer monsoon using the POAMA S2S model.

Joseph et al. (2015) developed an index to monitor monsoon onset for the Indian summer monsoon, which is suitable to be used to assess S2S predictions of onset.

The Marshall and Hendon (2015) and Sahai et al. (2016) assessments of S2S forecast skill for the Australian and Indian summer monsoons, respectively, are envisioned to be prototype studies for assessments of all other models in the S2S database and for other monsoon regions. A project to assess predictive skill for monsoon onset, which is a societally important event, has been designed and can be executed in the upcoming year. This project will be coordinated with the GEWEX/CLVAR Asian-Australian Monsoon Working Group.

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4.1.3 Teleconnections

The teleconnection sub-project was established in 2015 due to the emerging evidence of atmospheric teleconnections being an important modulator of high-impact weather events and representing an untapped source of sub-seasonal to seasonal predictability. The scientific objective of the teleconnection sub-project is to advance the understanding of the basic science underlying the two-way tropical-midlatitude interactions, and to use this understanding to advance prediction of weather in general and of high impact events in particular. The goals of the project include: (a) coordinating of scattered information on observational sources of tropical heating (satellite based observations and radiative fluxes and modern reanalysis); (b) designing and coordinating innovative numerical experiments; (c) developing metrics and process level diagnostics for evaluation of teleconnections and their associated mechanisms; and (c) identifying particular applications and improved forecast products.

The Teleconnection sub-project identified the lack of a conceptual framework allowing the potential predictability from translating into a germane skill score authored a review article "Review of Tropical-Extratropical Teleconnections on Intra-seasonal Time Scale". The article synthesizes the development over time of the progress in understanding the observed characteristics of intra-seasonal tropical – extratropical interactions and their associated mechanisms, identifies the significant gaps, and recommends new research endeavours to address the remaining challenges.

To achieve the stated goals the Teleconnection sub-project developed an international, virtual field campaign “The Year of Tropics-Midlatitudes Interactions and Teleconnections” (YTMIT) taking place between mid 2017–mid 2019. The YTMIT held its first workshop in June 2016 at George Mason University in Fairfax Virginia, USA. The purposes of this preparatory meeting were to: (1) focus on the key tropical interactions which are either not understood, not observed or missing in numerical models, with the clear goal of improving the simulation and prediction of the large scale tropical organization of diabatic heating; (2) understand those properties of the diabatic heating which are critical for the generation of remote teleconnections; and (3) further our understanding of tropical-extratropical interactions. The meeting also served as a venue for connecting with the MJO Task force and identify common interests.

The kick off meeting of the YTMIT project was held in connection with the 5th WGNE workshop on systematic errors in weather and climate models hosted by Environment and Climate Change Canada (ECCC) in Montreal, Canada, from 19 to 23 June 2017.

A number of S2S-related research projects addressing the science objectives of YTMIT are unfolding in US and Europe: Advanced diagnostics for tropical-midlatitude interactions and teleconnections on intra-seasonal timescales supported by NOAA/National Weather Service (NWS) through the Next Generation Global Prediction System (NGGPS) programme; YTMIT-CalWater2015 Atmospheric Rivers and their teleconnections sponsored by U.S. Department of Energy; Influence of Polar and Tropical latitude linkage with the mid-latitude flow within the DYNAMITE project supported by the European Union; BITMAP and InterDec supported by Belmont Forum.

The Teleconnection sub-project was the organizer of the training activity “Advanced school on Tropical-Extratropical Interactions on Intra-seasonal Time scales”, which took place in October 2017, hosted by ICTP (Trieste, Italy) and co-sponsored by WMO.

The Teleconnection sub-project organized a poster-session dedicated to YTMIT at the AGU Fall 2016 meeting.

The Teleconnection sub-project is coordinating its activities with WMO projects with synergistic activities. A suite of diagnostics for evaluating the mid-latitude large–scale weather regimes is being developed collaboratively with the WMO Working Group on Seasonal to Interannual Prediction (WGSIP) which will provide a useful tool to analyse the S2S database, and relaxation-type numerical experiments are coordinated with YOPP. With the S2S database, studies are being conducted to evaluate the impact of teleconnections on forecast skill. An example of ECMWF forecast evaluation with respect to weather regimes in the North Atlantic sector is shown in Figure 11.

The Teleconnection sub-project published a review article in the Review of Geophysics (Stan et al., 2017). The article concludes that notable progress has been made in identifying the intra-seasaonal tropical-extropical teleconnections including their centres of action and the statistical characteristics of the associated time series, and identifies a series of challenges that could lead to improvements in the ability to predict the evolution of tropical and mid-latitude circulation features for ranges beyond 2 weeks.

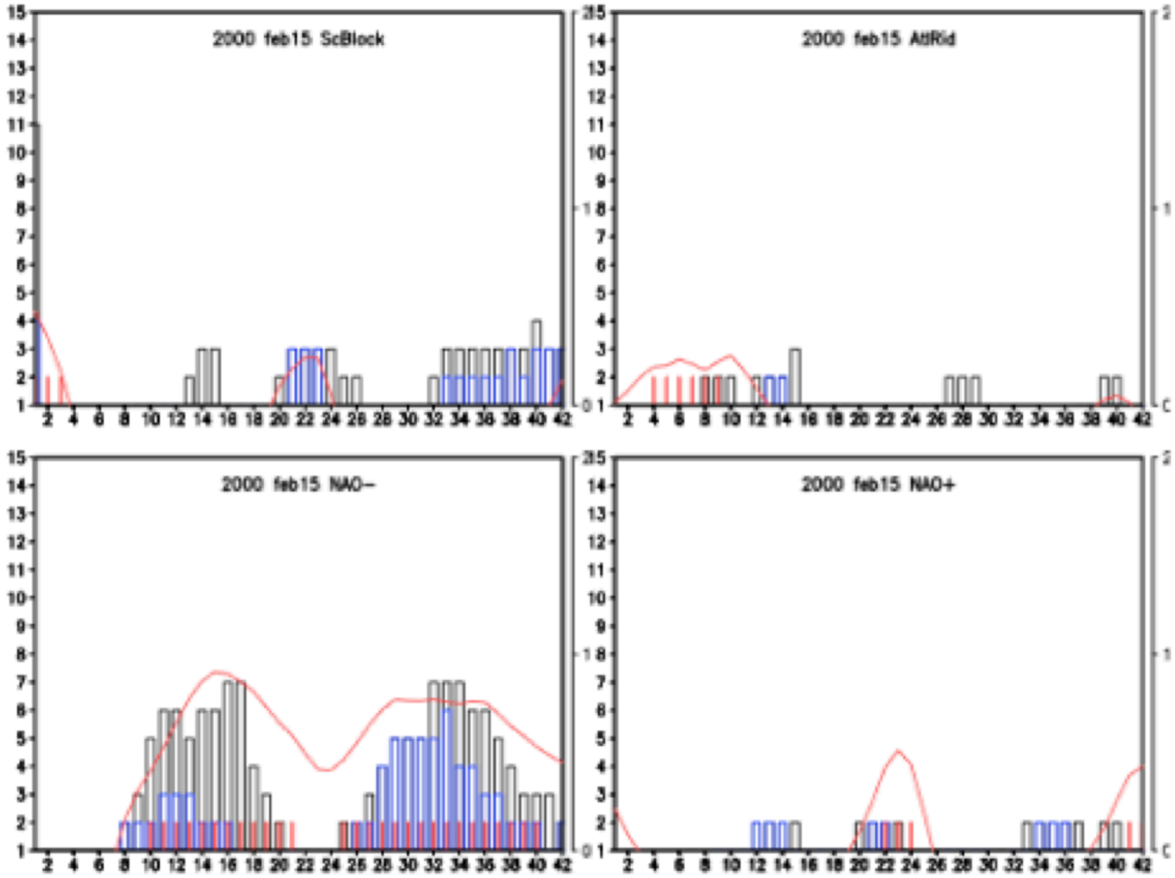

Figure 11. Euro-Atlantic cluster verification of S2S ensemble forecasts from ECMWF initialized on 15 Feb 2000. The four panels correspond to the 500 hPa geopotential height circulation regimes indicated: Scandinavian Block (upper left), Atlantic Ridge (upper right), NAO- (lower left), NAO+ (lower right). The x-axis indicates forecast day (with 1 being the initial time). The black (blue) bars indicate the number of ensemble members with anomaly pattern correlation over 0.4 (0.5) with the appropriate regime. Short red lines indicate that the verifying analysis is assigned to the particular regime by the cluster analysis. The solid red curves indicate the pattern correlation between the verifying analysis and the regime pattern indicated on the panel.

Source: David Straus and Laura Ferranti

4.1.4 Africa

The goal of the S2S Africa sub-project is to develop skilful forecasts on the S2S timescale over Africa and to encourage their uptake by national meteorological services and other stakeholder groups. This is the only continent-specific S2S sub-project, and was created to address the potentially large demand for skilful S2S forecasts in Africa, tailored to the needs of various stakeholders - to provide early warning for high-impact weather events that often have large societal impacts there. Seasonal climate forecasts are established tools for the development of climate services in Africa, promoted by the WMO through the creation of regular Regional Climate Forums (RCOFs) in Africa, and through WMO Regional Climate Centres in West, East, Southern and North Africa. This timescale gives an overall view of the season statistics but doesn’t allow approximating in time the occurrence of severe weather events. The Africa

Climate Conference in 2013 witnessed a great deal of interest from the African climate communities in the potential of S2S, for expanding seasonal forecast information to sub-seasonal scale.

The objectives of the Africa sub-project are:

(1) Assess the performance of forecasts for 5-40 days ahead using the S2S forecast archive, with focus on daily weather characteristics including rain-day frequency, heavy rainfall events, dry spells and monsoon onset/cessation dates, with relevance to agriculture, water resources and public health.
(2) Develop metrics for measuring the success of forecasts in ways that are useful to farmers and other stakeholder communities, and that allow verification and improvement of model skill through bias correction and better model diagnostics.
(3) Work with the post-Africa Climate Conference 2013 framework to connect international with African climate science communities, as well as with operational and user communities in a participatory two-way process.

Several funding proposals were written to pursue these objectives, to the Norway GFCS fund (2014), FutureEarth (2014), ClimDev/CR4D Africa (2015), and DFID-SHEAR (2015). While the GFCS fund and Department for International Development (DFID) proposals were unsuccessful, the S2S FutureEarth/ClimDev/CR4D proposals led CR4D (Climate Research for Development in Africa) to create pilot activities on S2S in Africa, directed toward the S2S Africa sub-project objectives, beginning from the end-user context. CR4D was launched to strengthen links between climate science research and climate information needs in support development planning in Africa, and grew out of the Africa Climate Conference 2013. Two regional pilots were funded, one each in Central and West Africa.

The **Central Africa** project (PI: W. Pokam, U. Yaoundé, Cameroon) activities were: (1) to present the current state of climate service for agriculture; (2) highlight climate information needed by farmers; (3) define meaningful climate index related to information need by farmers; and (4) to assess the skill of climate model predictions at S2S timescales over Central Africa. An S2S training event was organized in 2016, after which five models from the S2S database were analysed (BoM, NCEP, ECMWF, HMCR and CMA), and forecast performance assessed targeting the onset date of growing season, and maximum dry spell duration during the rainy season. Broadly, models show better skill to depict dry spell duration during the rainy season. All models show in general good skill in forecasting the maximum dry spell duration, except in some areas like the southern humid forest in Cameroon and coastal part of DRC where they tend to show very weak skill. For onset date of the growing season, models show highest skills to capture mean climatological onset date of growing season, and some of them present deficiencies in forecasting earlier and later onset date events. Broadly, considering criteria used in operations, some models present good scores up to lead time 3-4 weeks in Cameroon, while in DRC predictability is of order of 2-3 weeks. However, the predictability can be extended to 3-4 weeks for the two countries if the monsoon criteria are relaxed.

The work plan for further investigation on S2S prediction over Central Africa includes extending the study to others countries in the region, using a climate-zone analysis approach rather than local (station observation’s scale) analysis approach. Moreover, methods used to estimate onset date of growing season using an agricultural definition are only locally applicable. It is necessary to use a method suitable for region with different rainfall totals and which can ingest local specificities. A method taking into account potential biases from dataset will be considered.

Over **West Africa**, a tentative study was initiated under the coordination of the African Climate Policy Centre. The proposal aimed to assess skill of S2S models of extreme events. The series of rainfall events during September 2009 was identified as an interesting case study. Due to administrative problems, the project did not get the go ahead. It is important to note also the training workshop co-organized by ICTP and the Senegalese National weather service during 21-25 November 2016 (see http://indico.ictp.it/event/a14270/overview and http://www.wcrp-climate.org/wgsip-summary/977-wgsip18). This training used the WGSIP expert meeting to have international experts participate in the training. More than 30 fellows coming mostly from West Africa and beyond were trained with hands-on S2S analysis methods.

In **South Africa** research proposals are being developed for funding provided by local institutions such as the Water Research Commission and the National Research Foundation. The main themes to be explored and the local institutions identified to do the work include: (i) configuring models administered in South Africa to produce S2S output for contributing to the S2S archive (Council for Scientific and Industrial Research (CSIR)); (ii) predictability studies, including forecast verification (Universities of Pretoria (UP) and Cape Town (UCT), Agricultural Research Council (ARC), CSIR, South African Weather Service (SAWS)); (iii) statistical downscaling (SAWS, UP, UCT); (iv) applications models for crop, livestock and streamflows (ARC, UP, UCT, CSIR); (v) S2S dynamics of atmospheric circulation (UP, UCT, ARC, CSIR, SAWS); (vi) sources of predictability (MJO, QBO, ENSO, external forcing) (CSIR, UP, UCT, ARC, SAWS); (vii) statistical and dynamical analysis of weather systems/regimes (ARC, UP, CSIR); (viii) information content and users sectors/communities (UCT).

New UK funding opportunities have arisen for research in support outcomes that promote the long-term sustainable growth of countries on the OECD Development Assistance Committee (DAC) list. The National Centre for Atmospheric Science (Reading University) led a successful proposal, *African-SWIFT*, which will start in October 2017, to improve research capability and capacity in African Weather Forecasting from hours to months in support of Decision Making and Hazard Early Warning. The African-SWIFT partners include Universities and Research Centres in the UK, the UK Met Office; partner Universities and Met Services in each of Ghana, Kenya, Nigeria and Senegal; along with Regional Centres at IPCAC and ACMAD; and WMO. On S2S timescales the project includes research on the drivers of intra-seasonal variability for African weather; the skill of operational prediction systems on these timescales, including "windows of opportunity"; the development on operational research products exploit; and forecaster training and testbeds, and will make extensive use of the S2S database.

4.1.5 Verification and products

The S2S sub-project on verification was established with the objective of recommending verification metrics and datasets for assessing S2S forecasts quality, and also providing guidance for a potential centralized effort for comparing the quality of different S2S forecast systems, including the comparison of multi-model and individual forecast systems, and considering linkages with users and applications.

This sub-project has links with the WMO Joint Working Group on Forecast Verification Research (JWGFVR), the WMO CBS/CCI Expert Team on Operational Predictions from Sub-seasonal to Longer-time Scales (ET-OPSLS), the WMO LC-LRFMME and other S2S sub-projects. A science plan was developed and is envisaged as a guidance document to stimulate the scientific community to address S2S verification problems and questions. The science plan is available at http://www.s2sprediction.net/resources/documents/sub-projects/Verification.pdf. The science community response was overwhelming, resulting in a number of publications (Ardilouze et al., 2017; Coelho et al., 2017; DelSole et al., 2017; Drosdowsky and Wheeler, 2017; Johnson et al., 2014; Li and Robertson, 2015; Liang and Lin, 2017; Liu et al., 2017; Marshall et al., 2016; Mastrangelo and Malguzzi, 2017; Osman and Alvarez, 2017; Wheeler et al., 2016).

A dedicated Wiki page was implemented as the main channel for the sub-project activities dissemination and is accessible at http://s2sprediction.net/xwiki/bin/view/Main/Verification Originally the sub-project was focused solely on forecast verification aspects, but it was later decided to also consider forecast products aspects, and therefore the sub-project was re-labelled to verification and products. Several sub-project activities have been performed and are disseminated via the wiki including:

- A list of published literature on verification methods relevant to S2S verification, including books, technical reports and scientific papers.
- A literature survey on S2S verification, including a list of publications on S2S verification addressing the following topics: Assessment of S2S systems forecast skill, assessment of MJO and other intra-seasonal oscillations forecast skill, assessment of monsoon systems forecast skill and associated characteristics, S2S applications, and seamless verification.
- The collaboration between S2S and WMO: A questionnaire on sub-seasonal verification practices in operational centres (GPC) was developed and applied, with the purpose of sharing current practices used to verify sub-seasonal forecasts (both for operations and research) and also to help identify gaps and guide novel developments.
- The development of pilot real-time sub-seasonal multi-model ensemble (MME) predictions: The WMO LC-LRFMME developed a pilot system for real-time multi-model sub-seasonal forecasts using real-time forecasts (and re-forecasts) from a subset of models contributing to the S2S project accessible via ECMWF data archive.
- The coordination of input for the WMO ET-OPSLS on S2S application areas under development and operational needs.
- The provision of a comprehensive collection of links to available datasets for S2S verification, including links to the IRI data library and the KNMI Climate Explorer.
- The provision of links and instructions on how to access S2S project model datasets. This includes a summary table of S2S project models, links for accessing S2S models data at ECMWF and CMA data portals, links to instructions on how to extract S2S models data from ECMWF S2S portal, and links to the IRI Data Library for accessing a subset of these data (from ECMWF, NCEP and CMA models) in various file formats, including OpenDAP access.

- The provision of links to S2S forecast products webpages developed by ECMWF and the S2S Museum (University of Tsukuba/Oxford).
- The 7th International Verification Methods Workshop (7IVMW), Berlin, Germany, 8-11 May 2017, preceded by a tutorial on forecast verification methods, 3-6 May 2017. This workshop was organized by the WWRP/WGNE JWGFVR and featured a dedicated session on S2S forecast verification (http://www.7thverificationworkshop.de).
- A forecast verification chapter was produced with contributions of JWGFVR members for the S2S book which will be published by Elsevier in 2018.

Two proposals were written to support the development of S2S verification and products. The first proposal was submitted to a NOAA call in 2014 and included the development of a verification portal to serve as a centralized verification facility for the 11 ensemble prediction systems from operational centres that form the S2S data archive, but unfortunately this proposal was unsuccessful. The second proposal was submitted to a Belmont forum climate services call in 2015 and was successful having the "Climate services through knowledge co-production: A Euro-South American initiative for strengthening societal adaptation response to extreme events (CLIMAX)" project funded since 2016 for 4 years. The collaborating institutions involved in CLIMAX are: CNRS, IRD and LSCE (France), CPTEC/INPE (Brazil), Wageningen University (Netherlands), Technical University Munich (TUM) and Potsdam-Institute for Climate Impact Research (PIK), Germany. CLIMAX has a strong connection with the WMO Southern South America Regional Climate Centre (SSA-RCC).

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4.1.6 Madden-Julian Oscillation (MJO)

The science plan, membership and additional information on the MJO S2S sub-project are available at: http://s2sprediction.net/xwiki/bin/view/Main/MJO. Working in concert with the WCRP-WWRP/WGNE MJO Task Force, this sub-project includes a focus on research, model evaluation and predictability/prediction skill studies on the interactions between the Maritime Continent (MC) and the MJO, including an effort to improve local MC forecast skill, resources and collaboration.

This additional focus is motivated by the perception that the MC represents a natural predictability barrier for the MJO that is exacerbated by limited understanding of the MC as a natural predictability barrier and also to a great extent by our limitations in model representations of the MJO and MC interactions.

The main goals of the MJO sub-project include:

(1) Assess current model simulation fidelity and prediction skill, including identifying systematic model biases, over the Maritime Continent (MC) across timescales, with emphasis on the MJO.

(2) Evaluate the roles of: (a) multi-scale interactions; (b) topography and land-sea contrast; and (c) ocean/land-atmosphere coupling in MC-MJO interaction and how they influence predictability and prediction skill over the MC.
(3) Consider the effects of the MJO-MC interactions on extra-tropical forecast skill. This will be in collaboration with the Teleconnections sub-project.
(4) Develop a collaborative relationship between the S2S Project / MJO Task Force and one or more local MC meteorological agencies and their representatives in order to identify weaknesses in available sub-seasonal forecasts and better target areas for forecast improvement and product generation.

Table 1. Highlights a number of ongoing research efforts that include support for addressing the above objectives

Title	PI, Co-Is, Collaborators	Point of Contact Email	Sponsor	Period of Performance
Leveraging the MJO for Multi-Week Predictions: Improving Understanding of MJO - Maritime Continent Interactions	Waliser (JPL), Jiang (UCLA), Baronowski (UCLA) Flatau (NRL), Ridout (NRL)	duane.waliser@jpl.nassa.gov	ONR PISTON	June 2016-May 2018
Assessing Oceanic Predictability Sources for MJO Propagation	DeMott (CSU), Klingaman (U. Reading)	demott@atmos.colostate.edu	NOAA MAPP	July 2016 - June 2019
Forecasting North Pacific Blocking and Atmospheric River Probabilities: Sensitivity to Model Physics and the MJO	Barnes, Maloney (CSU)	eabarnes@atmos.colostate.edu	NOAA MAPP	July 2016 - June 2019
Madden Julian Oscillation - the Maritime Continent barrier and seamless verification	Wang, Sobel, Tippett (Columbia University)	sw2526@columbia.edu	NOAA MAPP	July 2016 - June 2019
InterDec: The potential of seasonal-to-decadal-scale inter-regional linkages to advance climate predictions	Woolnough, Chalrton-Perez, Vitart	s.j.woolnough@reading.ac.uk	NERC	Mar 2017-Mar2020
CAREER: Understanding the Source of the MJO Predictability and its Impact on the Mid-latitudes	Hyemi Kim	hyemi.kim@stonybrook.edu	NSF	June 2017-May 2022

Additional research activities related to the MJO are provided in section 4, specifically updated MJO forecast skill assessment including teleconnections to mid-latitudes in section 4.2.1 (Vitart, 2017), impacts of the QBO on MJO forecast skill in section 4.2.2 (Marshall et al., 2016) and role of mean state bias on MJO prediction skill (Lim et al., 2017).

Publications

Baranowski, D.B., D.E. Waliser, X. Jiang, M.K. Flatau and J.A. Ridout, 2017: Contemporary Model Fidelity in Representing the Diurnal Cycle of Precipitation over the Maritime Continent. *Journal of Climate*, in review.

Kim, H.M., P.J. Webster, V.E. Toma and D. Kim, 2014: Predictability and prediction skill of the MJO in two operational forecasting systems, *Journal of Climate*, 27 (14), 5364-5378.

Kim, H.M., 2017: The Impact of the Mean Moisture Bias on the Key Physics of MJO Propagation in the ECMWF Reforecast. *Journal of Geophysical Research-Atmosphere*, 122, 7772-7784, DOI:10.1002/2017JD027005.

Kim, H.M., D. Kim, F. Vitart, V. Toma, J. Kug and P.J. Webster, 2016: MJO propagation across the Maritime Continent in the ECMWF ensemble prediction system. *Journal of Climate*, DOI: 10.1175/JCLI-D-15-0862.1

Lim, Y., S.-W. Son and D. Kim, 2017: MJO prediction skill of the sub-seasonal-to-seasonal (S2S) models, *Journal of Advances in Modelling Earth Systems*, submitted.

Marshall, A.G., H.H. Hendon and D. Hudson, 2016: Visualizing and verifying probabilistic forecasts of the Madden-Julian Oscillation. *Geophysical Research Letters*, 43(23).

Mundhenk, B., E.A. Barnes, E. Maloney and C.F. Baggett, 2017: Skillful subseasonal prediction of atmospheric river activity based on the Madden-Julian Oscillation and the Quasi-biennial Oscillation. *npj Climate and Atmospheric Science*, submitted 05/2017.

Tseng, K.-C., E.A. Barnes and E. Maloney, 2017: Prediction of North Pacific height anomalies during strong Madden-Julian oscillation events. *npj Climate and Atmospheric Science*, submitted 05/2017.

Vitart, F., 2017: Madden-Julian Oscillation Prediction and Teleconnections in the S2S Database. *Quarterly Journal of the Royal Meteorological Society*, 143, 2210-2220, DOI:10.1002/qj.3079.

4.2 Examples of results using the S2S database

4.2.1 MJO prediction and teleconnections

The S2S database represents an important resource for assessing the skill of current state-of-the-art operational systems to predict the Madden-Julian Oscillation. In Vitart (2017), the MJO has been diagnosed using the index calculation described in Wheeler and Hendon (2004) and Gottschalk et al. (2010) and verified using the methodology described in Rashid et al. (2010). The index has been applied to re-forecast anomalies relative to the common re-forecast period 1999-2010 in a cross-validated way (the actual year of the re-forecast is excluded from the index calculation). Figure 12 shows the evolution of the bivariate correlation for each model ensemble mean as a function of the lead forecast time for all seasons.

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. Using re-analysis data, Cassou (2008) and Lin et al. (2009) showed that the impact of the MJO on European weather is the strongest about 10 days after the MJO is in Phase 3 or Phase 6. 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 a set of ECMWF re-forecasts using cycle 32R3 displaying realistic MJO teleconnections over the Northern extratropics, consistent with the impact Cassou (2008) and Lin et al. (2009) found in re-analysis data and Lin et al. (2010) found that the MJO has a significant impact on the intra-seasonal NAO skill scores in the ECCC model. To assess if the S2S models can simulate adequately the MJO teleconnections, 500 hPa geopotential height composites 3 pentads after an MJO in Phase 3 have been produced for each S2S model (Figure 13). Only the re-forecasts covering the period from January to April have been considered.

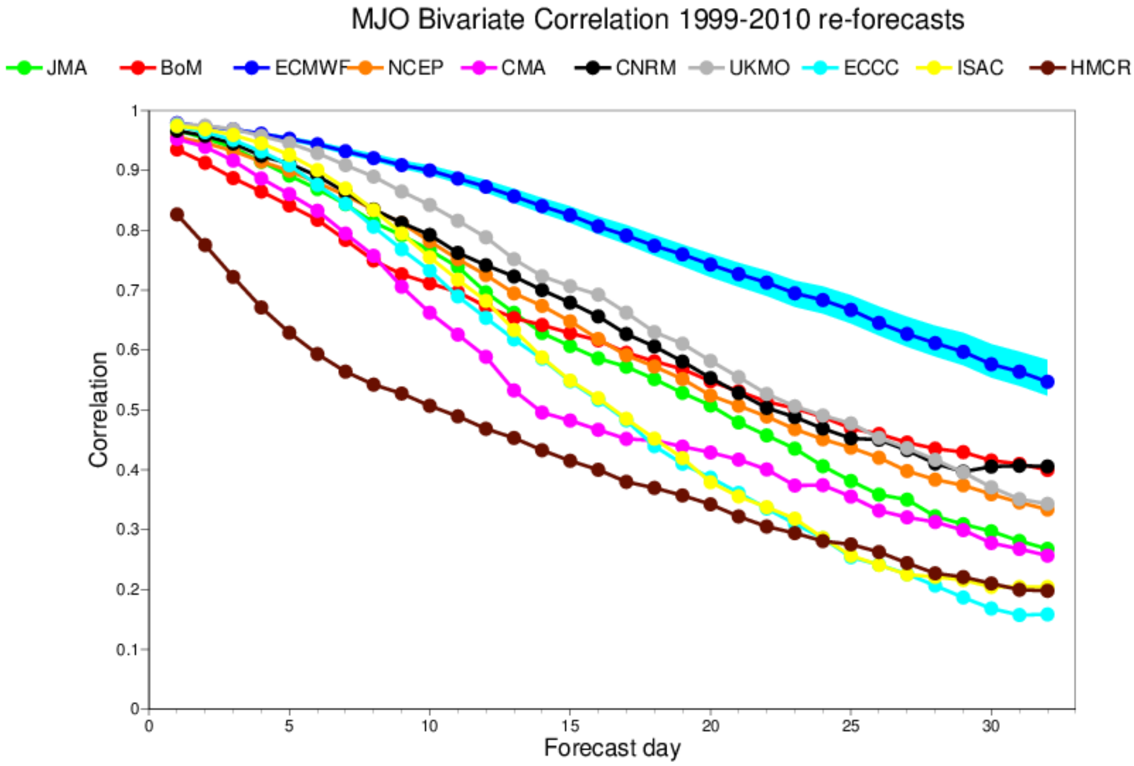

Figure 12. Evolution of the MJO bivariate correlation between the model ensemble means and ERA Interim as a function of lead time for 10 S2S models. The MJO bivariate correlations have been calculated over the period 1999-2010 for all the seasons. The cyan shaded area represents the 95% level of confidence computed from a 10,000 bootstrap re-sampling procedure.

Figure 13 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 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 Europe in the sub-seasonal time range and therefore is an important aspect to be analysed.

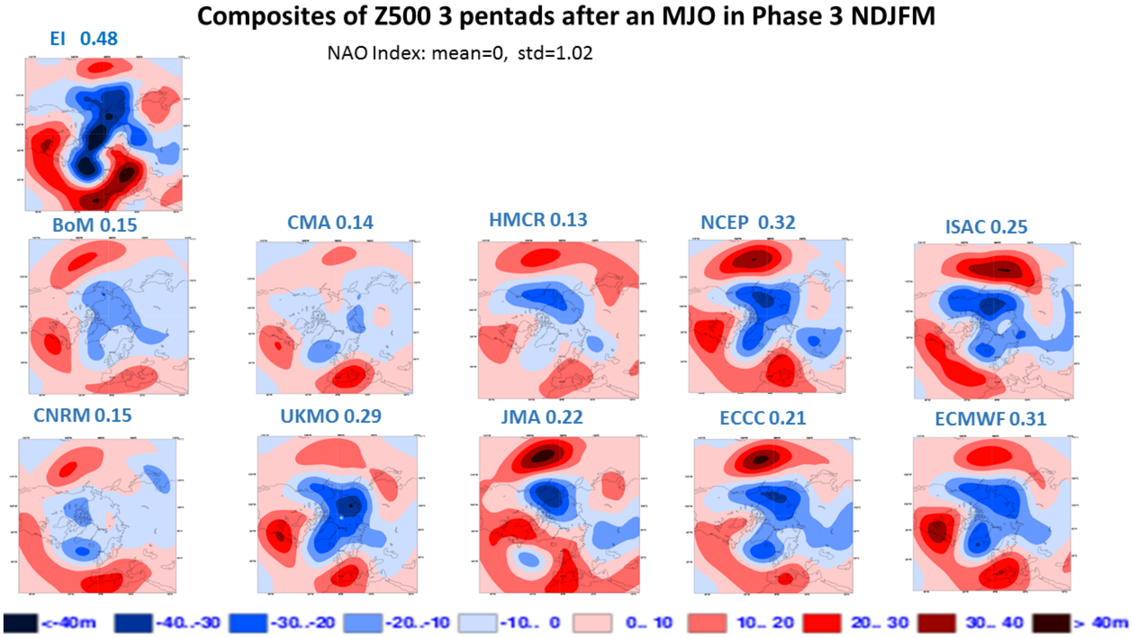

Figure 13. MJO Phase 3 3-pentad lagged composites of 500 hPa geopotential height anomaly from ECMWF, NCEP, JMA and BoM over the Northern Extratropics for the period January to April 1999 to 2010 (common re-forecast period) and ERA-Interim (left panel). Red colours indicate positive anomalies. Blue colours indicate negative anomalies. The contours are plotted every 10 meters.

4.2.2 QBO-MJO link in S2S models

MJO activity varies strongly from year-to-year (e.g. Salby and Hendon, 1994), meaning that in some years its impacts on local weather and climate (e.g. for modulating tropical cyclone formation and monsoon break episodes) will be stronger and in some years weaker. The cause of the year-to-year variability of MJO amplitude is not well understood. ENSO, which is the strongest modulator of interannual variations of tropical convection, has limited impact on the seasonal-mean amplitude of MJO, although it does strongly act to shift the MJO into the eastern Pacific during El Nino (e.g. Son et al., 2017). Recently, however, a strong connection between the amplitude of the MJO during boreal winter and the stratospheric Quasi Biennial Oscillation (QBO) has been detected (e.g. Yoo and Son 2016; Son et al., 2017), whereby during QBO east years (where the QBO is defined by the sign of the zonal mean zonal wind at 50 hPa) the MJO amplitude is increased. Since 1979, the QBO accounts for ~50% of the interannual variance of MJO amplitude. Although the mechanism for the impact of the QBO on the wintertime MJO is still being investigated, an immediate implication of this result is that the MJO should potentially be more predictable during QBO east years when the MJO is stronger. Marshall et al. (2016) indeed show this to be the case using the BoM POAMA S2S model: for re-forecasts during 1980-2015, the lead time for predictability of the MJO, assessed using the bivariate correlation of the RMM indices, is about 1 week longer during east years than during west years. Lim et al. (2016) confirmed this result using six models from the S2S database, which all had at least 15 years of re-forecasts (Figure 14). For all models, predictive skill extends to longer lead time during QBO east years. Marshall et al. (2016) and Lim et al. (2016) show that this result is not simply due to the MJO being overall stronger during QBO east years, such that there is stronger signal to noise in those years, hence improved prediction. Rather, they show that for a given similar amplitude of the MJO at the initial forecast time, the MJO is systematically better predicted during east years. That is, the MJO behaves differently in the east years, such that it more systematically propagates eastward with more coherence compared to west years.

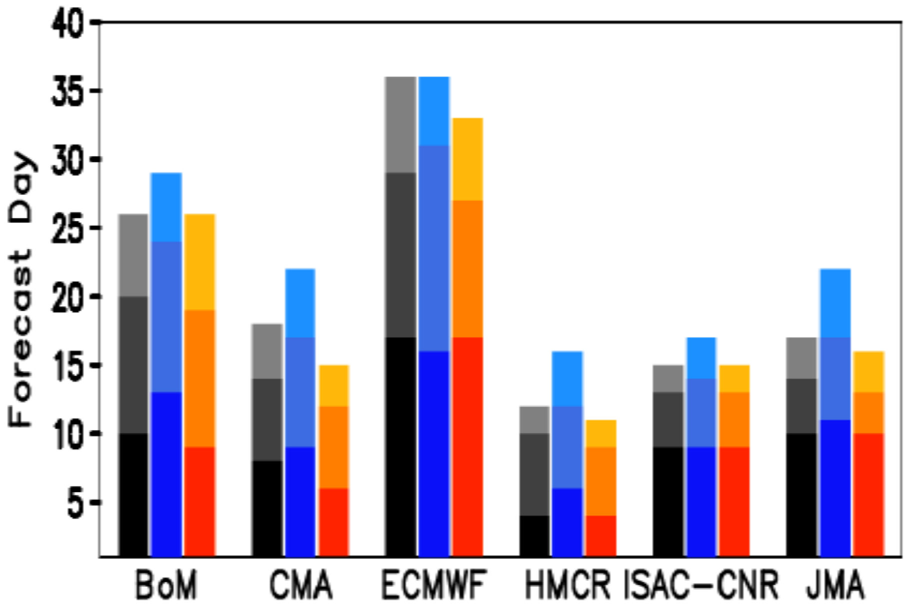

Figure 14. MJO prediction skill, based on bivariate correlation of the RMM indices, during DJFM for six S2S models. Light, medium, and dark bars indicate, respectively, lead day when the MJO bivariate correlation reaches 0.5, 0.6, and 0.8. Black bars are for all years, blue bars for QBO easterly years and red bars are QBO westerly years (QBO defined by sign of zonal mean zonal wind at 50 hPa).

Source: From Lim et al. (2016)

The S2S models include models with well-resolved stratospheres (e.g. ECMWF) and models with limited depiction of the stratosphere (e.g. BoM POAMA). So, at this point it is unclear if an impact of the QBO on the MJO is being simulated during the forecasts, or whether the improved skill derives simply from the observed MJO exhibiting more predictable behaviour during east years. This more predictable behaviour (i.e. the MJO is more cyclically persistence), presumably derives from the impact of the QBO but does not necessarily have to be explicitly modelled in order for predictive skill to benefit from the effect. Ongoing research is examining the possible mechanisms of the impact of the QBO on the MJO and the potential benefit of resolving the QBO for improved S2S prediction of the MJO.

4.2.3 Attribution of European Cold Wave, March 2013

An important area where S2S forecasts could be useful is in the attribution of the causes of extreme events to physical phenomena. S2S forecasting systems run in real-time quite frequently (at least once a week) with often large ensemble size and therefore produce a very extensive dataset which can be used to better understand the origin of some extreme events. In particular, analysing the differences between ensemble members which successfully predicted an extreme event and those which did not may help better understand the causality of the extreme event.

For example, March 2013 was exceptionally cold over part of western Europe (second coldest month since 1900 over the United Kingdom), most of Russia and part of North America (Figure 15, top right panel). This event coincided with a strong MJO event propagating into the western Pacific top left panel in Figure 15). The 16-member extended range ensemble forecasts from NCEP (CFS.v2) starting from 14 February 2013 could be classified into 2 categories: those which predicted that the MJO event which was located in Phase 3 (Indian Ocean) on 14 February 2013 would propagate into the western Pacific, and the others (about half the ensemble members) which predicted that the MJO would die over the Maritime Continent. The 2-metre temperature anomalies (produced from the ensemble members with a fairly strong MJO) produced a 2-metre temperature anomaly consistent with ERA Interim, whereas the 2-metre temperature anomalies produced from the ensemble members with no strong MJO in Phase 6 or 7 looks very different from the verification. This result suggests that this MJO event and the cold wave over part of the northern hemisphere were linked. It is planned to extend this study to the other S2S models.

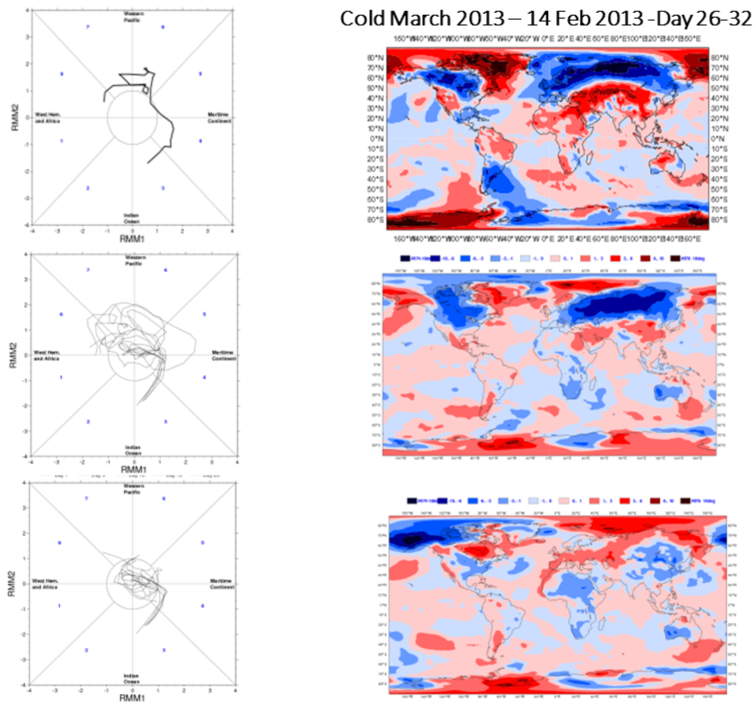

Figure 15. Weekly mean 2-metre temperature anomalies (right panels) for the verifying week of 7-13 March 2013 from ERA Interim (top panel), ensemble mean of all the NCEP forecasts starting on 14 February 2013 (lead time day 26-32) which displayed a strong MJO (middle panel) and NCEP forecasts with a weak MJO (bottom panel). The cold anomalies over North America and Asia (middle right panel) are statistically significant within the 5% level of confidence. The left panel shows the MJO forecasts using the Wheeler and Hendon index (2004) from 14 February to 14 March 2013 from ERA interim (top), the 8 ensemble members from NCEP with the strongest MJOs (middle panel) and 8 weakest MJOs (bottom panel).

4.2.4 Multi-model combinations/verification

Seasonal forecasting practice has highlighted the benefit of multi-model ensembling and the need to calibrate the output of Ensemble Prediction System (EPS) models, in order to obtain forecast probabilities that are reliable (i.e. correct on average when averaged over large numbers of past forecasts or re-forecasts). The S2S database presents challenges in applying the MME and calibration techniques developed for seasonal forecasts. Calibration requires the availability of sufficient re-forecasts. The number of ensemble members in the S2S re-forecasts is generally small, so that obtaining the forecast probabilities by simply counting the number of ensemble members that exceed a target threshold is subject to large sampling errors, while the re-forecast start dates generally differ between the models, so averaging the re-forecasts across models is difficult. To surmount these issues, Vigaud et al. (2017a,b) have used extended logistic regression to calibrate probabilistic precipitation forecasts for weekly and bi-weekly averages, and to average these across three models for which re-forecasts on Mondays are available. Figure 16 shows the Rank Probability Skill Score (RPSS) week 3–4 precipitation skill for a 3-model MME computed on the 1999–2010 period for North America in winter (a), and for boreal summer monsoon regions (c-e), based on tercile categories. Areas of positive skill tend to be preferentially over oceans in all cases, though they do extend into some land areas. The calibration and MME is successful in yielding no areas of negative skill, so that the forecasts are on average better than climatology everywhere. The reliability diagram in panel (b) shows that forecast reliability in the North American case is increased by the MME compared to the individual models. The results in Figure 16 highlight some of the challenges in developing forecasts that are sufficiently skilful to be of value. Large numbers of re-forecast years are needed to determine whether the skill is enhanced conditional on particular phases of the MJO, ENSO, and the QBO.

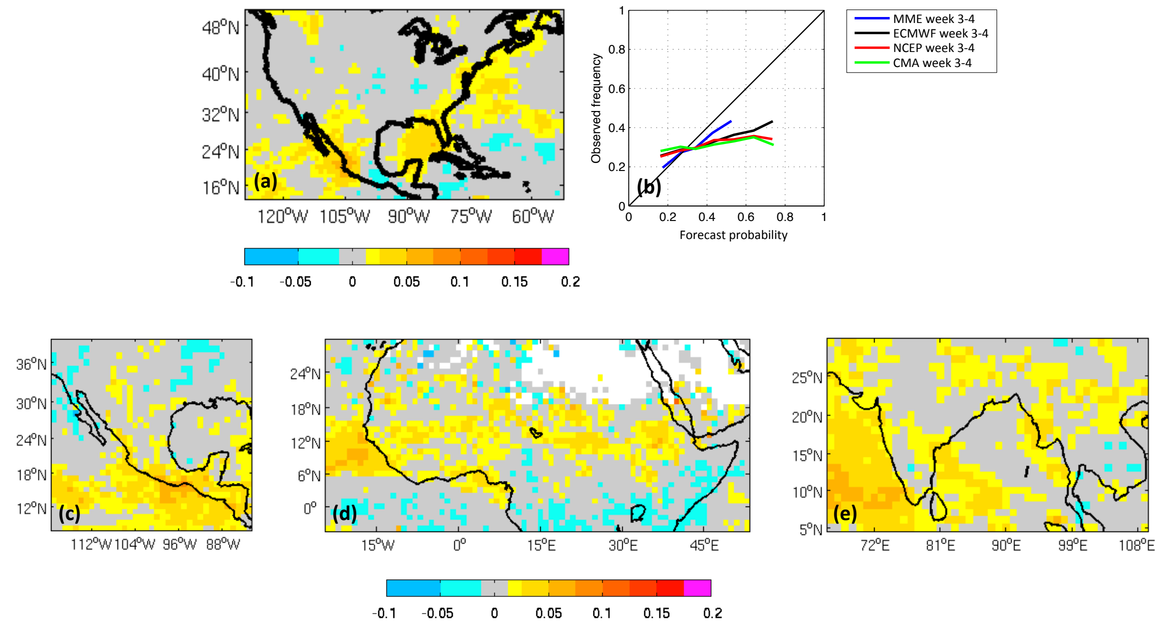

Figure 16. RPSS for week 3-4 (days 15-28) precipitation forecasts for forecasts starting during (a) January–March, and (c–e) March–August, for the geographical regions indicated. Panel (b) shows the reliability diagram for the JFM forecasts pooled geographically over the domain in (a), for the 3 individual models and the MME (blue).

Source: adapted from Vigaud et al. (2017a,b)

4.2.5 Role of mean state bias on MJO prediction skill

Lim et al. (2017) highlighted the critical role of the mean state bias on MJO prediction. Figure 17 from Lim et al. (2017) shows that models with smaller bias in the horizontal moisture gradient tend to have higher MJO prediction skill (left) and smaller errors in MJO amplitude (middle) and phase (right). The meridional gradient shows tighter relationships than the zonal gradient, suggesting a bigger role that the meridional moisture gradient might play in determining MJO performance. This result is consistent with the collective evidence from theory, observations, and modelling that has emphasized the role of the basic state moisture distribution on the propagation of the MJO. The bias in the horizontal moisture gradient is associated with the dry bias near the Maritime Continent and the eastern Indian Ocean, which is common to many S2S models (Lim et al., 2017). The results of Lim et al. (2017) warrant efforts to identify process-level causes of the common dry bias.

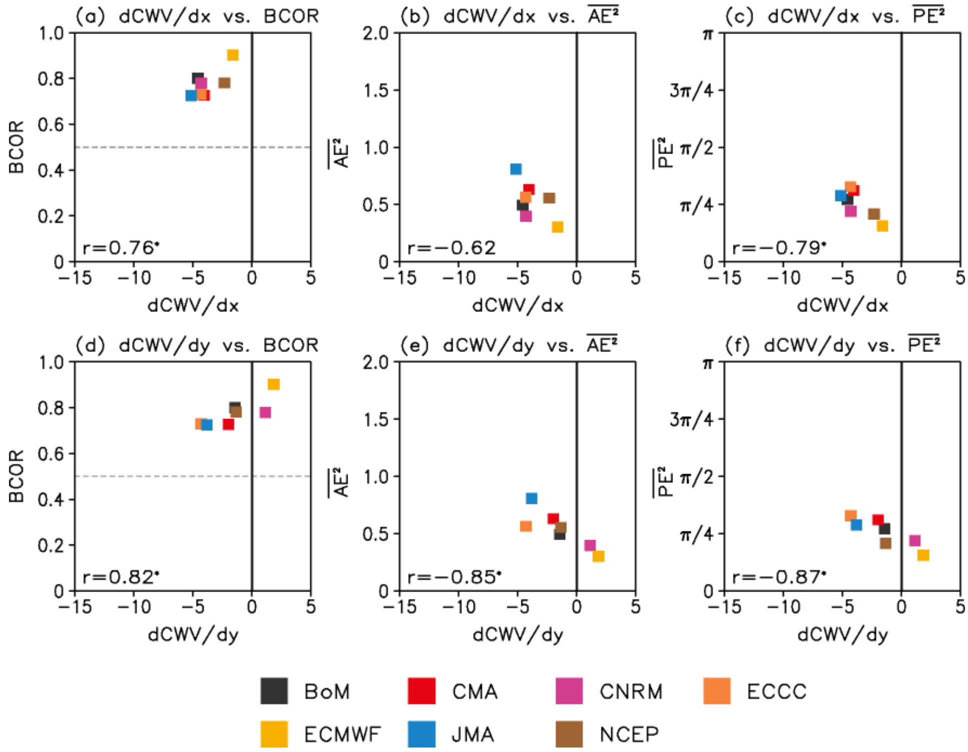

Figure 17. Relationship between the model mean biases in horizontal moisture gradient and the MJO prediction skill, initialized in MJO phases 2-3, at the forecast lead time of 2 weeks: (upper) scatter plot between zonal-moisture-gradient bias versus (a) bivariate correlation skill of the real-time multivariate MJO index (BCOR), (b) mean-squared MJO amplitude error ($\overline{AE^2}$), and (c) mean-squared MJO phase error ($\overline{PE^2}$). (d-f) same as (a)-(c) except with meridional-moisture-gradient bias. The zonal moisture gradient is obtained by taking the difference between area-averaged mean moisture over the Eastern (100°W- 80°W 10°S-10°N) and Western (60°W-80°W, 10°S-10°N) Indian Ocean, while the meridional moisture gradient is obtained as the difference between area-averaged mean moisture over equatorial (60°W-20°E, 5°S-5°N) and subtropical (60°W-20°E, 25°S-20°S and 60°W-20°E, 15°N-20°N) regions. The number in the left-bottom corner indicates correlation coefficient between the two quantities. Correlation coefficient that is statistically significant at the 95% confidence level is denoted with asterisk.

5. SPAWNING OF S2S REGIONAL RESEARCH ACTIVITIES

A number of programmatic efforts targeting S2S have emerged around the world since 2013:

Activities over **Africa** are summarized under the Africa sub-project in section 4.1.

In the **USA**, NOAA's Climate Program Office (Modeling, Analysis, Prediction and Projections program - MAPP) and National Weather Service have both initiated multi-year research priorities on S2S predictability and forecasting since 2014. NOAA MAPP has built a large S2S Task Force of PIs (http://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/MAPP/MAPP-Task-Forces/S2S-Prediction-Task-Force), and launched a multi-model sub-seasonal Climate Test Bed project (SubX) that will issue sub-seasonal forecasts in real time in 2017–18; these initiatives have explicitly reached out to collaborate with S2S and the MAPP Task Force PIs are making extensive use of the S2S database. The White House issued an executive order to NOAA to develop extended range forecasts in 2014, after which the Climate Prediction Center (CPC) began issuing week 3–4 experimental probabilistic outlooks for the U.S. in late 2015. A National Research Council study on Developing a U.S. Research Agenda to Advance Sub-seasonal to Seasonal Forecasting (National Academies of Sciences, Engineering, and Medicine 2016) made extensive reference to the S2S project, and extended the S2S range of timescales from two weeks to 12 months. That study put forward an ambitious vision that "S2S forecasts will be as widely used a decade from now as weather forecasts are today."

In **South-East Asia**, the ASEAN Specialized Meteorological Centre (ASMC) initiated a multi-year S2S programme in 2017, targeting the meteorological services in ASEAN countries. The programme makes explicit reference to S2S and using the S2S database as a resource. The programme will be spread over 4 years, split into two phases and with two workshops in each phase. Activities in Phase 1 will focus on familiarization of the S2S concept and database, as well as extensive skill assessment of the models available on the database. Activities in Phase 2 will focus on training in developing products for risk- and impact-based predictions on the S2S timescale. The programme is motivated by the anticipated availability of real-time S2S forecasts through the WMO Lead Centre in 2-3 years.

In **South America**, the CLIMAX project (funded over the 2016-2020 period - see section 4.1.5) is investigating the skill of sub-seasonal predictions available through the S2S project database, with particular attention to South America. As part of CLIMAX, CIMA at the University of Buenos Aires started producing experimental S2S monitoring and prediction tools/products (http://climar.cima.fcen.uba.ar/) with focus on southern South America in support of the WMO SSA-RCC. CPTEC/INPE developed a website for monitoring daily rainfall over Brazil, with particular attention devoted to characterizing the climatological distribution of rainy season onset and demise dates (http://clima1.cptec.inpe.br/estacaochuvosa/pt) and also investigated the feasibility of producing empirical, dynamical and combined probabilistic rainy season onset forecasts (Coelho et al., 2017). The Latin American Extraordinary Events Observatory started producing experimental sub-seasonal monitoring and prediction products that are publicly available in their Datoteca (http://datoteca.ole2.org/maproom/Sala_de_Mapas/index.html.es#tabs-4), a local version of IRI's Data Library. The First South American School on Sub-seasonal predictability and prediction was held from 10-14 Jul 2017 in

Asuncion, Paraguay, bringing together experts from 10 South American countries to discuss S2S predictability sources and physical mechanisms, data handling and verification methods. The participants used IRI's Climate Predictability Tool to assess the skill of South American sub-seasonal deterministic and probabilistic predictions of surface temperature and rainfall, made available through the S2S project database. More information (in Spanish) is available in the School website: http://www.cmc.org.ve/mediawiki/index.php?title=I_Escuela_Sudamericana_de_Predicibilidad_y_Pronóstico_Sub-Estacional.

In **India,** the Indian Institute of Tropical Meteorology (IITM) has developed a multi-model sub-seasonal forecasting system based on the NCEP CFSv2 model, and this was transitioned in 2016 to operations at the Indian Meteorological Department (IMD). It is planned to include the IMD forecasts in the S2S database. The forecasts are made year-round in real-time every week on Thursday (Wed ICs) for next 4 weeks, using initial conditions from NCMRWF/INCOIS, with on the fly re-forecasts for the same day from 2003 to 2016. NCMRWF (National Center for Medium Range Weather Forecasts) has submitted a large flood forecasting proposal to the Ministry of Earth Sciences, which will have an S2S component. Phase 2 of the Monsoon Mission will include a component focused on applications, with an interest to develop S2S applications over India.

6. TRAINING ACTIVITIES

Eight training courses on S2S have taken place/planned since inception of the S2S project, many co-sponsored by the S2S project. These capacity building events have targeted young scientists in developing countries working in national meteorological services and universities. Curricula have included lectures on underlying S2S science, models, forecasting and verification methods, and tailoring of forecasts for applications. Practical sessions have included accessing and downloading data from the S2S database and analysing skill and case studies of the sub-seasonal predictability of high-impact weather events in the participants' countries. Instructors have been drawn from the S2S steering group and beyond, often with S2S members co-developing the curricula. To date, over 100 scientists have been trained in five events in Italy, South Korea, Senegal, Cameroon, and Singapore, with another two planned in 2017 in Rwanda and Paraguay.

2014

- APEC Climate Center Training Program on Subseasonal to Seasonal Prediction, 16–23 October, 2014, Busan, South Korea. Participants: 18 young scientists from National Meteorological and Hydrological Services (NMHSs) in 16 developing countries.

2015

- Advanced School and Workshop on S2S Prediction and Application to Drought Prediction, 23 November to 4 December 2015, ICTP, Trieste, Italy. Participants: about 40 young scientist trainees.

2016

- School on Climate System Prediction and Regional Climate Information, 21-25 November 2016, ANACIM, Dakar, Senegal. Organized by ICTP, ANACIM, WCRP and S2S. Participants: about 25 young scientist trainees, and 10 lecturers and tutors.

- Workshop on Sub-seasonal to Seasonal Prediction - Central Africa, CIFOR-Central Africa, Yaounde, Cameroon, 25-29 July 2016. Participants: nine Central African scientists.

2017

- First Workshop on Subseasonal-to-Seasonal Prediction for Southeast Asia (S2S-SEA I), Singapore, 27 February-3 March 2017. Participants: About 14 trainees from ASEAN country national meteorological services.
- The First South American School on Sub-Seasonal Predictability and Prediction was held in Asunción (Paraguay), 10-14 July 2017 (in Spanish).
- ICTP Advanced School on Tropical-Extratropical Interactions on Intra-Seasonal Time Scales, 16-27 October 2017 http://indico.ictp.it/event/7998/. Participants: About 38 trainees from five regions of the world with the following distribution: 34% from Asia, 26% from Africa, 16% from Latin America, 16% from Europe, and 8% from North America.

7. WORKSHOPS/CONFERENCES

A number of workshops and conferences have been organized (or co-organized with other groups) by S2S:

- February 2014: 1st International Conference on Sub-seasonal to Seasonal Prediction (College Park Maryland, USA)

- December 2014: AGU Session on Sub-seasonal to Seasonal Prediction of Weather and Climate (AGU Fall Meeting, San Francisco, USA)

- June 2015: Workshop on Sub-seasonal to Seasonal Predictability of Monsoons (Jeju Island, Republic of Korea)

- November 2015: ECMWF Workshop on Sub-seasonal Predictability (ECMWF, UK)

- December 2015: AGU Session on Sub-seasonal to Seasonal Prediction of Weather and Climate (AGU Fall Meeting, San Francisco, USA)

- December 2015: AGU Session on The Year of Tropics-Midlatitude Interactions and Teleconnections (AGU Fall Meeting, San Francisco, USA)

- April 2016: Workshop on Intraseasonal Processes and Prediction (S2S/MJO-TF) in the Maritime Continent (Singapore)

- April 2016: EGU session on Sub-seasonal to Seasonal forecasting in hydrology and outlooks for water services (Vienna, Austria)

- June 2016: S2S Side Event at the WMO EC-68 (Geneva, WMO Headquarters)

- July 2016: S2S workshop at Royal Meteorological Society Conference (Manchester, UK)
- September 2016: 16th Annual Meeting of the European Meteorological Society (EMS) and the 11th European Conference on Applied Climatology (ECAC) (Trieste, Italy)
- October 2016: Coupled data assimilation workshop (co-organized with DAOS, Toulouse, France).
- December 2016: Workshop on Sub-Seasonal to Seasonal Predictability of Extreme Weather and Climate (Monell Building Columbia University at Lamont-Doherty Earth)
- December 2016: AGU 2016 Fall Session on Sub-seasonal to Seasonal Forecasting of High-Impact Weather and Climate Events (San Francisco, USA)
- Fifth International Conference on Climate Services (ICCS5), Cape Town, South Africa, 28 Feb–2 March 2017. http://www.climate-services.org/iccs/iccs5/
- May 2017: S2S verification session at the 7th International Verification Methods Workshop (IVMW) (7IVMW) (Berlin, Germany)
- June 2017: S2S session on teleconnections at the 5th WGNE workshop on systematic errors in weather and climate models (Montreal, Canada).
- August/September 2017: The IAPSO-IAMAS-IAGA assembly (Cape Town, South Africa)
- October 2017: Advanced School on Tropical-Extratropical Interactions on Intraseasonal Time Scales (ICTP, Italy)
- November 2017: 6th WMO International Workshop on Monsoons (IWM-VI) (Singapore)
- December 2017: AGU 2017 Fall Session on Sub-seasonal to Seasonal Forecasting of High-Impact Weather and Climate Events (New Orleans, USA)
- September 2018: 2nd Conference on Sub-seasonal to Seasonal Prediction (NCAR, Boulder, USA).

8. LINKAGES WITH OTHER GROUPS

CBS: An important link has been established between S2S and the Lead Centre for Long-Range Forecast Multi-Model Ensemble (LC-LRFMME) at KMA (see section 2.2. for more details). A prototype of real-time sub-seasonal multi-model ensemble forecasts has been established at KMA who accesses real-time forecasts and re-forecasts from NCEP, ECMWF, JMA and KMA using the S2S database at ECMWF. The contribution of S2S to this project is the establishment of the S2S database which can also be used for real-time data exchange and research and verification of new S2S products.

WGNE: A strong link has been established between the WGNE MJO task force and the S2S MJO sub-project. A common workshop was organized in April 2016 on the representation of convection over the Maritime Continent. The S2S project is also supporting the Year of Maritime Continent initiative, which takes place in 2017 and 2018. Representation of teleconnections in dynamical models (tropics-extratropics, high-latitudes-mid-latitudes) has been identified as joint project between WGNE and S2S. A session on S2S teleconnections has been organized at the WGNE workshop on systematic errors in Montreal in June 2017.

PPP/YOPP: The S2S project plans to make available additional variables in the S2S database (e.g. sea-ice thickness) during the YOPP field campaign. The S2S sub-project on teleconnections is coordinating relaxation-type experiments with YOPP to better understand the teleconnections between tropics and high latitudes.

HIW: There are strong synergies between HIW and the S2S sub-project on extremes. A member of HIW (Brian Golding) is member of the S2S Extremes sub-project.

SPARC/SNAP: SNAP is using the S2S database to evaluate the skill of operational S2S models to predict the stratospheric variability and its impact on the lower troposphere. An article on S2S has been published in the January 2016 SPARC newsletter to encourage the SPARC community to perform more studies with the S2S database. So far 10 projects have been launched by members of the SPARC community to analyse the S2S database for stratospheric studies (http://www.met.reading.ac.uk/~stratclim/snap/projects.php), including the study mentioned in 4.2.2.

SERA: A member of SERA is acting as liaison member in S2S. A collaboration study between SERA and S2S has been established in 2017 to assess the need of end users regarding sub-seasonal prediction. Phone interviews of several S2S end users from different sectors have been performed. The results will be published in 2018 and will be used during S2S Phase 2 (2018-2023).

Joint WWRP/WGNE Working Group on Forecast Verification Research: Links have been established with this working group through the verification and products sub-project. A session on S2S was organized at the Verification workshop (Berlin, May 2017).

DAOS: A member of DAOS is acting as liaison member in S2S. The S2S project was involved in the organization of the DAOS workshop on coupled data assimilation (Toulouse, October 2016) through one of his members being part of the conference scientific committee.

PDEF: A member of PDEF is acting as liaison member in S2S. A collaboration study between S2S and PDF has also been launched**.** This study investigates the modulation by the Madden Julian Oscillation of recurving tropical storms in the western North Pacific and the Rossby wave caused by these tropical storms in the Northern extratropics.

WGSIP: A strong relationship has been established with WGSIP. The teleconnection sub-projects of S2S and WGSIP are collaborating and the WGSIP sub-project on systematic errors is using the S2S database. S2S and WGSIP are also coordinating their next steering group meetings in Exeter (2017) with common sessions and their next workshops in Boulder in 2018 (S2D conference).

GEWEX/GLASS is keenly interested in the role of land-atmosphere feedbacks at S2S timescales, and the potential for improved forecast skill by: (1) improving land surface state initialization in forecast models; and (2) improving the representation of coupled land-atmosphere processes in those models. The GLASS Local Coupled (LoCo) effort is particularly congruent with S2S, and its working group is pursuing research with output from the S2S dataset to better understand how current models represent coupled land-atmosphere processes, which includes validation against observational data: from the US Department of Energy Southern Great Plains (SGP) facility, FLUXNET sites around the world, various field campaigns including LAFE (US Great Plains) and LIAISE (Spain), reanalysis products and ultimately satellite-derived observations of land-atmosphere coupling metrics.

9. PUBLICATIONS/REPORTS

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11. ACKNOWLEDGEMENTS

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ANNEX

Steering group membership

Current members

Andrew Robertson (IRI, USA) Co-chairperson
Frederic Vitart (ECMWF, UK) Co-chairperson
Arun Kumar (NCEP/CPC, USA)
Hai Lin (ECCC, Canada)
Harry Hendon (BoM, Australia)
Yuhei Takaya (JMA, Japan)
Duane Waliser (JPL NASA, USA)
Tongwen Wu (CMA, China)
Willem Landman (U Pretoria, S. Africa) (2016-now)
Cristiana Stan (GMU, USA) 2015-now
Anca Brookshaw (ECMWF/UKMO, UK) 2015-now

Past members

Alberto Arribas (UKMO, UK) 2013-2015
June-Yi Lee (U Busan, Republic of Korea) 2013-2016
Ben Kirtman (UM RSMAS, USA) 2013-2016
Hyun-Kyung Kim (KMA, Republic of Korea) 2013-2014

Liaison members

Richard Graham (UKMO, UK) - CBS
Oscar Alves (BoM, Australia) - PDEF
Daryl Kleist (U Maryland, USA) –DAOS
Caio Coelho (CPREC, Brazil) – JWGFVR
J-P Ceron (retired, France) – CCL
Joanne Robbins (UKMO, UK) – SERA
Paul Dirmeyer (GMU, USA) GEWEX/GLASS
Steve Woolnough (U. Reading, UK) – GEWEX/GASS
In-Sik Kang (SNU, Republic of Korea) – WCRP JSC
Nicholas Klingaman (U. Reading, UK) – S2S-TF

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For more information, please contact:

World Meteorological Organization

Research Department

World Weather Research Programme

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Tel.: +41 (0) 22 730 81 11 – Fax: +41 (0) 22 730 81 81

Email: cpa@wmo.int

Website: http://www.wmo.int/pages/prog/arep/wwrp/new/wwrp_new_en.html

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