Subseasonal-to-Seasonal S2S Prediction Project

Newsletter No. 16

In This Issue…

1. What is S2S ?

To bridge the gap between medium-range weather forecasts and seasonal forecasts, the World Weather Research Programme (WWRP) and World Climate Research Programme (WCRP) launched a joint research initiative in 2013, the Subseasonal to Seasonal Prediction Project (S2S). The main goal of this project is to improve forecast skill and understanding of the subseasonal to seasonal timescale, and to promote its uptake by operational centres and exploitation by the applications communities.

Phase II of the S2S project began in January 2019 and will continue until 2023. A new set of scientific sub-projects has been developed, as outlined in the sidebar in next pages. Enhancements to the database will be made including access to the S2S ocean and additional models. The second phase will also include new research-to-operations activities and a real-time supplications initiative introduced in this edition of the newsletter.

S2S Phase II Proposal is available at http://s2sprediction.net/file/documents_reports/P2_Pro.pdf

CW3E-JPL S2S Research and Experimental Forecast Products To Benefit Western U.S. Water Resource Management

Mike DeFlorio (CW3E/Scripps)

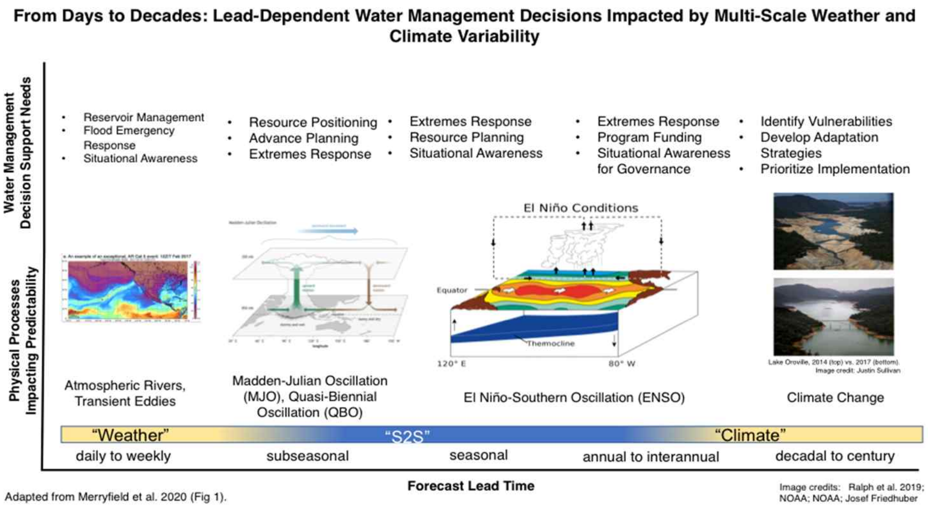

Fig. 1 Lead-time dependent water management decision support needs (from daily to decadal/century lead times) and selected physical processes that affect predictability of precipitation over the western U.S. region. From DeFlorio et al. 2021 (EOS, in revision)

The western U.S. region experiences the largest year-to-year variation in annual precipitation relative to normal conditions in the country (Dettinger et al. 2011). This high level of internal variability, combined with projected increases in the frequency of precipitation extremes into the mid and late 21st century (Polade et al. 2017), creates unique challenges for western U.S. water resource managers. These challenges, along with many other stakeholder needs around the globe, have recently led to an increased investment by local, state, and federal agencies to improve S2S prediction of rainfall, snowpack, atmospheric rivers (ARs), and ridging events. Figure 1 summarizes the lead time-dependent water management decision support needs in the western U.S.. along with several relevant physical processes that impact predictability from weather to climate lead times (figure from DeFlorio et al. 2021). These western U.S. stakeholder needs are the underlying motivation for increased investment into S2S research and experimental forecast product development.

To address the emerging need for better S2S forecasts, the California Department of Water Resources (CA DWR) has funded a partnership between the Center for Western Weather and Water Extremes (CW3E; PI: Dr. F. Martin Ralph) and the NASA Jet Propulsion Laboratory (NASA JPL; PI: Dr. Duane E. Waliser), along with key collaborators from the International Research Institute for Climate and Society (IRI) and the University of Arizona. The primary goal of this partnership and collaboration is to produce experimental S2S forecast products, supported by research focused on assessing the historical skill of dynamical, statistical, and hybrid dynamical-statistical models in predicting western U.S. precipitation, AR activity, and ridging events at S2S lead times. A key aspect of this endeavour is that our CA DWR stakeholders have direct input on the design and display of the experimental S2S forecast products, as well as on the methodology, target predictands, and datasets used in the research efforts that support these forecast products.

In particular, the CW3E-JPL team is one of sixteen groups participating in the WMO S2S Real-time Pilot Initiative. Our group uses near real-time output from several models in the S2S Database to compute integrated vapor transport (IVT), which is then used to detect ARs over the North Pacific/western U.S. region. The AR detection data is then used to make forecasts of week-1, week-2, and week-3 lead time AR activity. In addition, our group uses 500hPa geopotential height output from several S2S models to make forecasts of North Pacific/western U.S. ridging events at weeks 1-6 lead time. Both the experimental S2S AR activity and ridging forecasts are supported by hindcast skill assessments using hindcast data from the S2S Database (DeFlorio et al. 2019a,b; Gibson et al. 2020a,b). Figure 2 summarizes the interaction between ARs and ridging events over the western U.S. region, and provides an example of both the subseasonal AR activity and ridging outlooks.

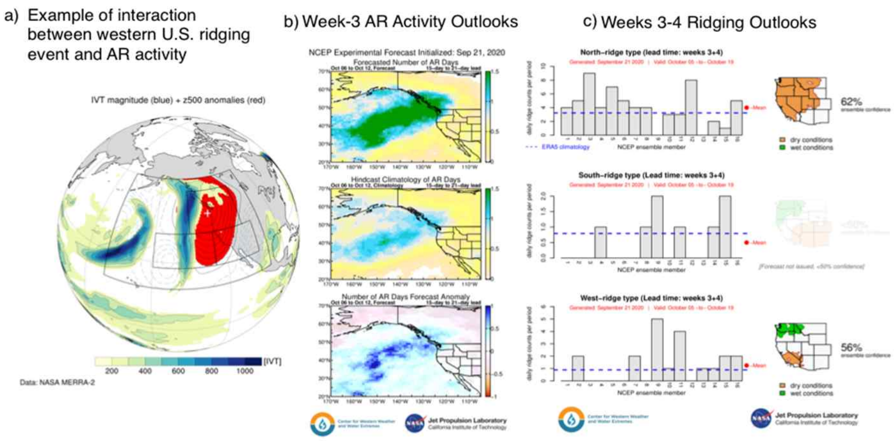

Fig. 2 a) Example of interaction between western U.S. ridging event and AR activity. Integrated Vapor Transport (IVT) magnitude (blue) and 500hPa geopotential height (Z500) anomalies (red) are shown for 16 January 1985. The three small black rectangles denote the locations of three prominent ridge types that covary with western U.S. precipitation deficits (see Figure 1, Gibson et al. 2020). White cursor denotes the centroid of the positive height anomalies shown on this day; b) CW3E/JPL week-3 AR activity outlook. Forecast initialized on September 21, 2020 and verifies October 6-12, 2020. Top panel shows the forecasted number of AR days to occur during the week-3 verification period; middle panel shows the NCEP hindcast climatology of AR days during the October 6-12 week in the hindcast record; bott om panel shows the anomaly forecast field (top minus middle panels). Hindcast skill assessment provided in DeFlorio et al. 2019a,b; c) CW3E/JPL weeks 3-4 experimental ridging outlook. Forecast initialized on September 21, 2020 and verifies October 5-19, 2020. The left panel shows the occurrence frequency of each ridge type (bars) compared to climatology (horizontal line) for each of the model ensemble members. If over 50% of the ensemble members predict more ridging than expected (for this time of year), then the right panel maps are displayed indicating the likelihood of wett er or drier conditions based on how these ridge types typically influence precipitation. Methodology for calculating ridge types provided in Gibson et al. 2020a; hindcast skill assessment provid-

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2. Six sub-projects in S2S Phase II

The new research Phase II sub-projects will address issues related to sources of predictability, forecast system configuration, and model development. These sub-projects are more oriented towards model experimentation than the Phase I sub-projects which were more about model assessment. Some of the new sub-project research plans will include coordinated experiments and also process studies in coordination with the Working Group on Numerical Experimentation (WGNE).

1. **MJO and teleconnections**: This sub-project focuses on the representation of teleconnections and their modulation in S2S models. Metrics for assessing model teleconnections and diagnosing sources of errors in teleconnections will be applied.

2. **Land**: This sub-project investigates the impact of the observing system on land initialization and S2S forecasts, the representation of the coupled land/ atmosphere processes in S2S models, and contribution of anomalies in land surface states to extremes. It will work in concert with other relevant programs to pool resources and coordinate scientific studies (e.g. GEWEX/GLASS).

3. **Ocean**: This sub-project aims to evaluate the ocean feedbacks which directly influence sub-seasonal variability and prediction skill, the predictability influenced by pre-existing ocean state, the effect of low-frequency variability on S2S predictability, the impact of ocean mean state drift on S2S predictability, mechanisms which affect extreme ocean weather (heat waves) and their predictability.

4. **Aerosol**: This sub-project is a collaboration between S2S, WGNE and GAW. It aims to evaluate the benefit of interactive instead of climatological aerosols on sub-seasonal forecasts through a series of coordinated re-forecast experiment with and without interactive aerosols. The sub-seasonal predictability of aerosols will be assessed as well as their impact on sub-seasonal forecast skill scores.

5. **Ensembles**: This sub-project will study the influence of burst vs lagged ensemble initialization on the forecast spread using S2S database. It will also investigate the impacts of stochastic parameterizations and coupled initial perturbations on the sub-seasonal prediction, review the techniques for coupled initial perturbations which are under development in a few centers (ECMWF, NCEP, BoM, and JMA).
6. **Stratosphere**: This is a joint sub-project between S2S and WCRP/SPARC/SNAP. Its main goals include: developing additional stratospheric diagnostics and investigating the use of DynVarMIP additional diagnostics to S2S models; Coordinating damping experiments to examine the dynamics of downward coupling; Studying the link to tropospheric dynamics.

3. Upcoming events

- **Virtual International Conference on the "Future Directors of Subseasonal to Seasonal Prediction over South Asia"**, *29-31 March 2021, online. https://www.tropmet.res.in/erpas/s2s/index.php*
- **European Geosciences Union (EGU) 2021,** *19-30 April 2021, online. https://www.egu21.eu/*
- **2nd WMO International Verification Challenge***, 30 April 2021, online. https://www.emetsoc.org/second-international-verification-challenge/*
- **ASP Summer Colloquium and Workshop***, 12-23 July 2021, online. https://www.cgd.ucar.edu/events/2021/asp-colloquia/*
- **S2S Session at IUGG 2021***, 18-23 July 2021, Busan, Republic of Korea. http://baco-21.org/2021/english/01_introduce/02_introduce.asp*
- **S2S Session at AOGS 2021***, 1-6 August 2021, online. https://www.asiaoceania.org/aogs2021/public.asp?page=home.html*

From research to operations: Covering the last mile of a climate service for energy

Andrea Manrique-Suñén, Ilaria Vigo, Andria Nicodemou, Isadora Christel and Albert Soret (Barcelona Supercomputing Center)

Large-scale deployment of renewable energy sources is key for the clean energy transition, which is needed to comply with the greenhouse gas (GHG) emissions reduction agreed upon in the Paris Agreement and to achieve the European Green Deal ambition of reaching carbon neutrality by 2050. However, renewable energy generation and electricity demand are largely dependent on atmospheric conditions. The energy industry typically uses past climatology data to determine future conditions, which cannot help anticipate extreme events. The EU-funded S2S4E project conducted research on S2S forecasts for the energy sector and developed an operational forecasting tool, the S2S4E Decision Support Tool (DST; www.s2s4e.eu/dst). This tool was co-designed with the energy industry to provide climate information to energy producers and providers for the next weeks and months on variables such as temperature, precipitation and solar radiation, helping them make better-informed decisions (read more in S2S Newsletter No.11, and Soret et al., 2019).

With the completion of the project in December 2020, we want to highlight some core aspects of the development of a climate service for energy within the project.

Co-development of a climate service for energy

Co-development has been a pillar of the project. A fruitful collaboration among research institutes, energy companies, small and medium-sized enterprises, and a consulting company allowed for creating an interdisciplinary team with a common goal. Since the very beginning of the project, and building on previous experience, each partner has been actively involved in the creation process. Three energy companies represented the needs of the sector. Transforming sector needs into research lines and translating the outcomes into usable information for energy users is a complex but fundamental process. It entails not only the scientific development of forecasts for essential climate variables and indicators, but also everything that is related to the delivery and understanding of the information (operational workflow, forecast release timings, visualisations, products, etc.).

Implementation of a real-time operational forecast workflow

The operationalisation of the forecasts entailed both scientific and technical challenges. The DST has been providing subseasonal and seasonal forecasts in real-time until the project ended in December 2020. The subseasonal forecasts were updated every Thursday and provided information for the following four weeks. An operational workflow was designed to download, post-process and deliver these forecasts, adapted to the schedule of the ECMWF-Ext-ENS prediction system (Vitart et al., 2008) provided by the S2S Real-Time Pilot Initiative. Hindcasts were also downloaded from the system, and served for forecast calibration and quality assessment using as a reference system ERA5 reanalysis (Hersbach et al. 2020). The details of the operational implementation are being included in an upcoming publication (Manrique-Suñén et al., 2021). A fundamental step for the usability of climate predictions is to remove the drift. The methodology employed was the variance inflation (Doblas-Reyes et al., 2005), which also modifies the predictions to have the same interannual variance as the reference. The calibration was applied to each lead time and the climatological distribution of both prediction system and reference were calculated using a running window, to avoid misrepresentation of the climatology (Manrique-Suñén et al., 2020).

Probabilities of each tercile category (above normal, normal or below normal) and the probability of extremes (above p90 and below p10) were presented in the

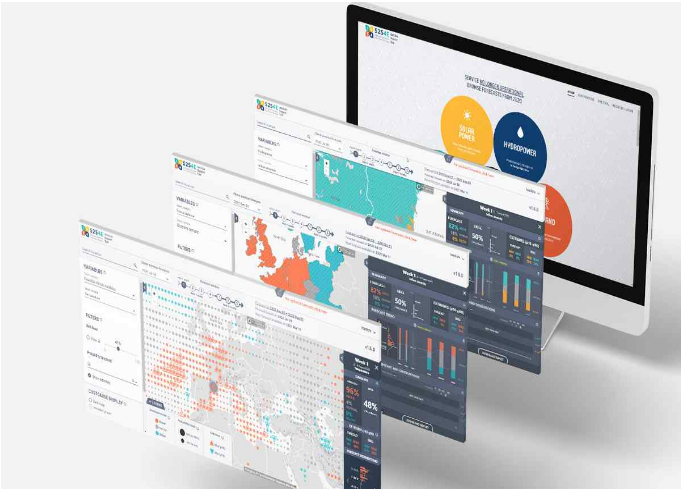

Fig. 1 The S2S4E Decision Support Tool (www.s2s4e.eu/dst)

DST. Each forecast was provided with an associated skill score (per variable, grid point, initialisation and lead time) to guide the user in the interpretation of the forecast. Fair Ranked Probability Skill Scores were employed for the tercile categories and Fair Brier Skill Scores were shown for extremes (above p90 and below p10). The workflow to process this information involved downloading and calibrating the available hindcast each Monday, and performing the skill calculation, which needed to be ready by Thursday. On Thursday, the real-time forecast was downloaded and calibrated, and the probabilities were computed from the 51 ensemble members and transferred to the DST for visualisation along with the skill information.

Improving user's interaction with S2S forecasts

The development of the DST visual interface involved S2S4E experts from different disciplines (climate science, design, user-centered design, user interaction and cognitive psychology). Building on the user feedback obtained for a previous prototype (Project Ukko; Christel et al., 2018) and S2S4E research on user needs (e.g. Orlov et al., 2020), we developed a new tool with changes in the visual encoding of uncertainty and the use of interactive elements. In general, changes in the shape and size (i.e. the visual encoding of the information) as well as the reduction of categories, enhanced the clarity and ease of use of the DST, reducing the feeling of effort when processing and dealing with climate information (Calvo et al., 2021). The DST design also offered multiple interactive elements that allowed users to filter non-relevant information or highlight relevant information for the decision at hand. The application of user-centered design to these interactive elements reduced the cognitive load of users and thus improved user experience.

Beyond the DST, the project also co-developed with energy users other formats for the provision of S2S forecasts, such as PDF outlooks, temperature extremes outlooks published on social media, webinars or analyses of forecast performance through case studies of past events.

Testing operational forecasts with users

When the first operational version of the service was launched, the co-creation had still a long way to go. In fact, the operational testing phase provided constant information exchange, allowing for improving the service and supporting the integration of the forecasts in decision-making processes. From one to one structured meetings with users to hands-on sessions and free access to the prototype, users within the project consortium and beyond actively interacted with the DST and the S2S4E team. The service has been substantially improved based on the lessons learned, however further tailoring to user needs will be implemented in the commercialisation phase. The key findings about the development of climate services for energy are collected in an upcoming paper (Vigo et al., 2021), which also discusses the strengths and weaknesses of the co-development methodology adopted.

The process in these four core aspects of the project has not always been smooth. Different challenges arose that highlighted the importance of the demand side and the need to improve the co-creation dynamics from research to operations.

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Subseasonal to Seasonal Forecast Skill from the Stratosphere: A New Set of Coordinated Experiments

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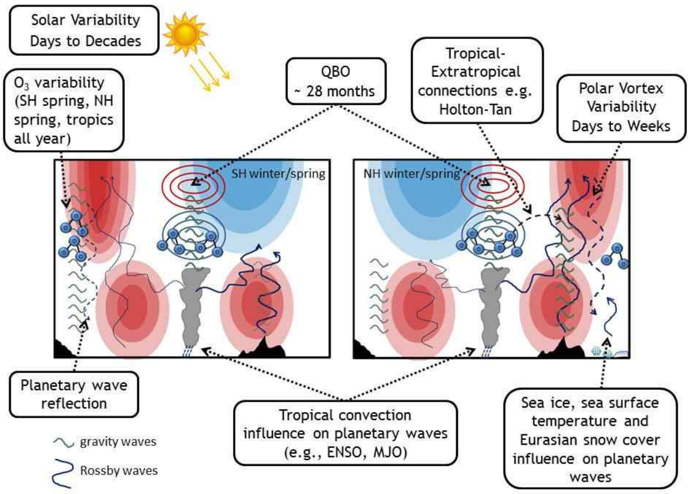

Figure 1: Schematic of stratospheric processes and their impacts on weather and surface climate processes. (Reprinted from Butler et al. 2019 with permission from Elsevier)

The stratosphere is home to a number of important low-frequency modes of climate variability. In the tropics, the quasi-biennial oscillation consists of alternating easterly and westerly jets that descend with a remarkably regular period near 28 months. At high latitudes, the circumpolar westerlies that form in the winter hemisphere are intermittently disturbed by planetary-scale Rossby waves propagating up from below. Over the Arctic, in roughly two out of three winters, this can lead to a complete reversal of the climatological winds in events known as sudden stratospheric warmings. Similar events over Antarctica are much more unusual, but have also been observed, most recently in 2019.

Remote as these events may be from the surface, they can have robust and at times potent impacts on weather (see Fig. 1). Sudden stratospheric warmings have been shown to produce a persistent equatorward shift of the eddy driven jets: this corresponds to the negative phase of the annular modes in each hemisphere. They have also been tied to more frequent cold air outbreaks in the Northern Hemisphere. These impacts make the stratosphere an important potential source of forecast skill on subseasonal to seasonal time-scales. A recent review (Domeisen and Butler, 2020) showed how these events are often implicated in extreme weather conditions and their impacts on, for example, public health. Assessing this potential is one of the primary goals of the SNAP (Stratosphere Network for the Assessment of Predictability) project, a working group of both the S2S Prediction project and of SPARC (Stratosphere-troposphere Processes And their Role in Climate), one of the core projects of the World Climate Research Program.

The SNAP community has recently published a pair of papers (Domeisen et al. 2020ab) focusing in part on forecast skill related to Northern Hemisphere sudden stratospheric warmings in forecasts contributed to the S2S database (Vitart et al. 2017). This work confirms that operational forecast models can to some extent capture the surface impacts of sudden stratospheric warmings, and has demonstrated robust, enhanced subseasonal forecast skill in some regions in the weeks following the stratospheric events. However, this ensemble of opportunity approach only allows for correlative conclusions to be drawn. In particular, because of the diversity of forecast initialisation dates and ensemble generation strategies, and because models are able to forecast these sudden stratospheric warmings with differing degrees of success (Rao et al 2020), some of the differences in surface impacts observed between modelling systems are likely to have been obscured.

To address this limitation, SNAP is coordinating a new set of controlled numerical experiments, designed to isolate and quantify the contribution of the stratosphere to forecast skill on subseasonal time scales. These experiments target three recent stratospheric events: two major Northern Hemisphere sudden stratospheric warmings in February 2018 and January 2019, and the unusual near-major sudden warming in the Southern Hemisphere that occurred in September 2019. Each of these events was followed by a surface extreme thought to be connected to the stratospheric anomalies: a European cold snap in mid February of 2018, a North American cold snap in late January 2019, and persistently warm and dry conditions in late October and November of 2019 over much of Australia that were linked to record-

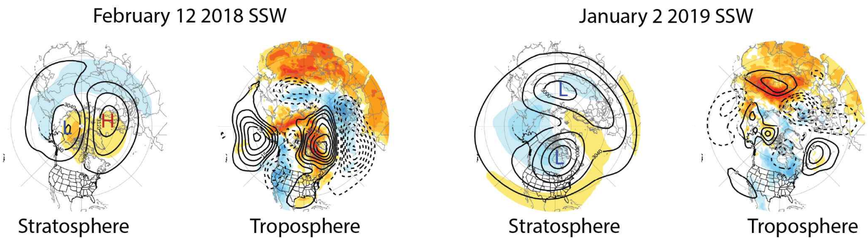

Figure 2: Stratospheric and tropospheric anomalies following the 2018 (left) and 2019 (right) stratospheric sudden warmings. Stratosphere panels show 10 hPa heights (contours) and temperatures (shading), while troposphere panels show 500 hPa heights (contours) and 2m temperatures (shading) (Reprinted from the supplementary information of Butler et al. 2020 with permission from John Wiley and Sons)

breaking bushfires. Nonetheless, the 2018 and 2019 Northern Hemisphere sudden stratospheric warmings were followed by very different behaviors of the North Atlantic jet: in 2018 the NAM was highly negative, consistent with the 'canonical' equatorward shift seen in composite events, while after the 2019 event, the NAM remained neutral or even positive (see Fig. 2). Comparing these two events will thus shed light on a major unresolved question in stratosphere troposphere coupling regarding why the equatorward shift materializes after some, but not all stratospheric events (Knight et al. 2020, Rao et al. 2020).

The basic experimental protocol consists of a set of three forecast ensembles: (1) a standard, free running forecast ensemble, (2) a 'perfect stratosphere' forecast in which the stratosphere is relaxed towards the observed evolution, and (3) a 'control' forecast in which the stratosphere is relaxed towards climatology. Crucially, the relaxation (or 'nudging') in the second and third ensembles will be applied only to the zonally-symmetric component of the stratospheric flow. This approach has been used successfully to isolate stratospheric impacts in free-running global models (Hitchcock and Simpson 2014), and reduces undesirable artifacts associated with imposing regional nudging. It will also allow us to study how well forecast models can capture the upward-propagating planetary waves responsible for disrupting the stratosphere in the first place, a crucial first step in exploiting the extended-range predictability of the stratospheric anomalies. An additional 'perfect stratosphere' ensemble is also included in which the full stratospheric circulation is relaxed towards observations, not just the zonally-symmetric component. Further details of the experimental protocol will be described in an article soon to be submitt ed to a peer-reviewed journal.

To date, twelve modeling groups at eleven centers are planning to contribute integrations following this protocol. In designing the experiments we have emphasized ensemble size and high-resolution data output. This will allow for an unprecedented, multi-model comparison of the dynamics underlying the surface responses to sudden stratospheric warmings. Moreover, by including 'counterfactual' forecasts in which the stratospheric circulation remains in a climatological state, the experimental protocol will allow for formal att ribution statements to be made regarding the surface extremes that followed the stratospheric anomalies.

The goal is to have the experiments completed by summer of 2021. The initial analysis will be carried out by a set of community working groups. We expect initial results to be reported towards the end of 2021 through the first half of 2022. Although the experiments have been designed with the extratropical response to high-latitude stratospheric variability in mind, they will also shed new light on interactions between the stratosphere and the troposphere in the tropics. Additional working groups will be coordinated to investigate the impact of the stratosphere on organized convection in the tropics (including the Madden Julian Oscillation), and the representation of the wave spectrum responsible for forcing the quasi-biennial oscillation. After an initial embargo period, the dataset will be made available to the broader community in the summer of 2022.

Anyone interested in participating in the community analysis of these experiments is encouraged to contact the authors for further information.

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Subseasonal Prediction of Wintertime Northern Hemisphere Extratropical Cyclone Activity by SubX and S2S Models

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1. Purpose

Extratropical cyclones can bring heavy precipitation, strong winds, storm surge, and heavy snowfall, especially in winter, which have significant societal impact. In this study, the prediction skill of December to February (DJF) week 3-4 extratropical cyclone activity (ECA) in the Subseasonal Experiment (SubX) and the Seasonal to Subseasonal Prediction (S2S) project is assessed. The skill of multi-model ensemble (MME) mean is also analyzed since the skill of MME is usually better than a single model.

2. Data and methods

Seven S2S models (CMA, CNR-ISAC, CNRM, ECCC-GEM, ECMWF, HMCR and NCEP-CFSv2) and six SubX models (EMC-GEFS, NCEP-CFSv2, ECCC-GEPS5, GMAO-GEOS, ESRL-FIM and RSMAS-CCSM4) are selected to construct the MME of S2S or SubX by using a lagged ensemble method during winters from 1999/2000 to 2009/2010. Similar lagged ensemble method is also used to construct a 4-day lagged ensemble of NCEP-CFSv2 with 16 members. ECA is defined by applying a 24-hour difference filter on mean sea level pressure data. Seasonal cycle is removed at different lead times at each grid point. The ERA-Interim Reanalysis is used as the verification data. Prediction skill is estimated by calculating the anomaly correlation coefficient (ACC) between the models and the Reanalysis.

3. Results

Fig.1 shows the spatial pattern of ACC for ECMWF and NCEP-CFSv2, as well as the MME of SubX and S2S in week 3-4. ECMWF and NCEP-CFSv2 are selected here as they are the two models with highest skill in the SubX and S2S. High ACC is found over east Asia, the central and eastern North Pacific, the Bering Sea and Alaska, central North America, the Gulf of Mexico and western Caribbean Sea, and the North Atlantic along 30°–45°N and 60°–75°N. The MME of SubX and S2S have better prediction skill than that of any single model.

The source of predictability can be attributed to ENSO and stratospheric polar vortex. Fig. 2a shows the absolute value of ACC between Reanalysis ECA and DJF averaged Nino 3.4 index, while Fig. 2b shows the absolute value of ACC between Reanalysis ECA and week 2-3 polar vortex index (PVI), which is defined as the averaged 100-hPa zonal wind anomaly to the north of 60°N. The two panels in Fig. 2 can be considered as using ENSO and stratospheric polar vortex to hindcast the week 3-4 ECA, and can be directly compared with Fig. 1. The spatial pattern in Fig. 2a is very similar to Fig. 1 over the Pacific, North America and the western North Atlantic. The regions where models have high prediction skill (central Pacific, Alaska, central US, and the Atlantic) corre-

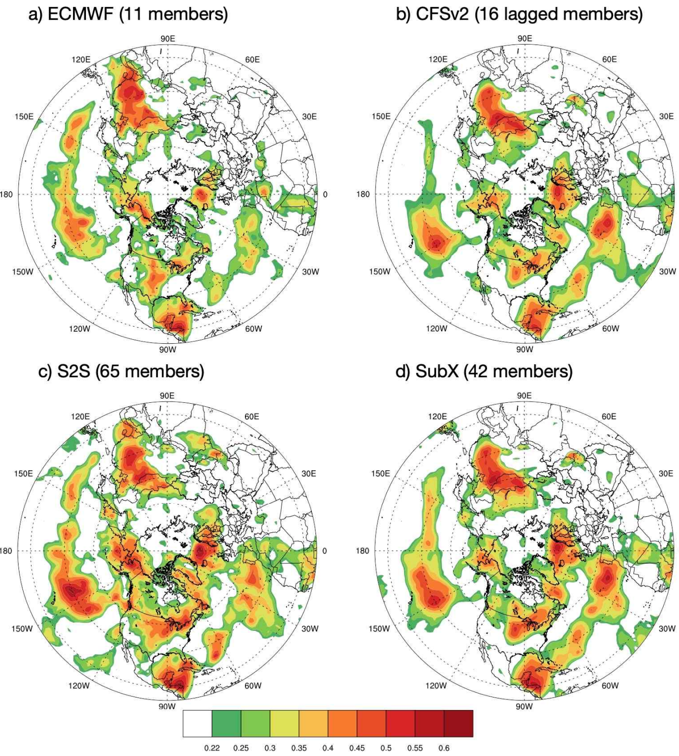

Fig.1 Prediction skill (ACC) of week 3–4 extratropical cyclone activity for ECMWF (11 members), NCEP-CFSv2 (16 lagged members), S2S MME (65 members) and SubX (42 members). ACC above 95% significance level is shown.

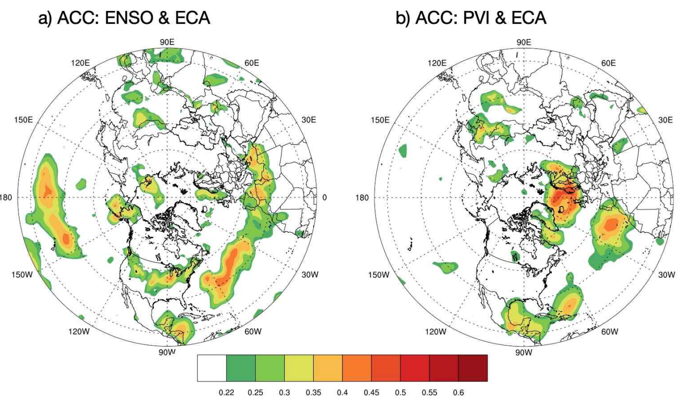

Fig.2 a) Absolute value of ACC between week 3–4 extratropical cyclone activity and DJF averaged Nino 3.4 index. b) Absolute value of ACC between week 3–4 extratropical cyclone activity and week 2-3 polar vortex index.

spond to regions where the ACC is high by using ENSO index to hindcast. Thus at least part of the prediction skill in these regions likely originates from ENSO. In Fig. 2b, the correlation is relatively high over the eastern North Atlantic, Scandinavia and Norwegian Sea, as well as over East Asia. The spatial pattern is also similar to Fig. 1 from the Atlantic to the entire Eurasia, with similar amplitude over the North Atlantic. This suggests that the prediction skill in these regions likely originates from the anomalies in the stratosphere. Note that PVI is well predicted by models during week 2-3, and similar patterns of ACC between ECA and ENSO, or between ECA and PVI, can be found in the model hindcasts.

4. Conclusions

The prediction skill of winter week 3-4 extratropical cyclone activity in both SubX and S2S models is evaluated. High prediction skill is found over east Asia, the central and eastern North Pacific, the Bering Sea and Alaska, central North America, the Gulf of Mexico and western Caribbean Sea, and the North Atlantic. The predictability comes from ENSO over the North Pacific, North America and the western North Atlantic, while the predictability over the northern North Atlantic originates from the stratospheric polar vortex. Multi-model ensembles generally outperform any single model, with ECMWF and NCEP-CFSv2 having the best skills among the models evaluated in this study.

Acknowledgment

This article is extracted from Zheng et al. (2021) published in Weather and Forecasting, 36(1), 75-89. https://doi.org/10.1175/WAF-D-20-0157.1. © American Meteorological Society. Used with permission. Fig. 1 and 2 are plotted by using the same method in the publication above but during a different time period.

Sub-seasonal to Seasonal Prediction System for the Indian Summer monsoon

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The quasi-periodic intraseasonal signals drive the highly potent subseasonal to seasonal (S2S) prediction. Despite enigmatic predictability, the S2S forecasting techniques have hugely improved over recent times. The next phase of the ensemble prediction system for the S2S scale is being developed to comprehend the moderate-to-adverse impacts of monsoon rainfall over India. Targeted advancement towards this system is briefly summarized in the subsequent sections.

Development Chronology of S2S prediction system version 1

In 2011, the Ministry of Earth Sciences (MoES), Government of India launched the "National Monsoon Mission" (NMM) with a vision to develop a state-of-the-art dynamical prediction system for monsoon rainfall on subseasonal to seasonal scale (Mohapatra et al. 2020; Rao et al. 2020). National Centre for Environment Prediction (NCEP) 's coupled Climate Forecast System (CFS) was acquired as a part of MoU between MoES, Govt. of India and NOAA, US. Under NMM, an ensemble prediction system (EPS) of the complex-but-same model environment category was developed by (Abhilash et al. 2014c) using CFS. Their Sensitivity experiments with varying perturbations revealed that the full tendency perturbation in all primary met-fields exhibit better dispersion. Thus designed EPS has good skill in predicting dynamical variables (~25 days) than precipitation (~15 days). The predictability limit of active/break spells of monsoon rainfall of this 11-member EPS of perturbed initial conditions (Abhilash et al. 2013)was studied. It was found that the initial-error (predictability) is higher for forecast initialized in the active phase than in the break.

Although this EPS has shown promising results for extended range prediction of monsoon active/break spells, this system's under-dispersive tendency was a major concern. To improve the spread, a multi-model strategy seemed beneficial as proposed by contemporary studies (Harrison et al. 1999; Krishnamurti et al. 2000). Therefore, the atmospheric component of CFS, i.e., Global Forecast System (GFS), was considered to achieve inter-model spread while preserving the agreement between the forecasts. But GFS lacked the atmospheric column moistening driven by the interactive ocean in a coupled system, hence had poor northward propagation associated with monsoon intraseasonal oscillations (MISO) (Sahai et al. 2013; Sharmila et al. 2013). Later, it was found that the GFS forced with bias-corrected real-time SST from CFS has significant skill in extended range prediction (Abhilash et al. 2014a)

Simultaneously, the EPS in CFS with finer horizontal resolution (T126 instead of T62) showed a reasonable skill for deterministic rainfall forecast and MISO prediction (Abhilash et al. 2014b). Further, (Sahai et al. 2015a) studied the impact of still finer horizontal resolution (T382) on the extended range forecast. They have seen a reduction in climatological bias over the monsoon domain and improved basic MISO state in higher-resolution. However, they also concluded that the improvement is not significant as per the computational cost and error reduction is not reflected as improvement in real-time prediction. Nevertheless, a subsequent study by (Joseph et al. 2015b) advocated higher resolution for predicting rainfall extremes.

(Abhilash et al. 2015) established that a multi-model ensemble, including resolution variants of CFSv2 and bias-corrected GFS running with perturbed initial conditions, has better ensemble spread and statistical skill than a single-model single-resolution ensemble. This multi-model ensemble (MME) performed reasonably well up to 4 pentad lead for the 2013 and 2014 monsoon season (Sahai et al. 2015b; Borah et al. 2015). (Joseph et al. 2015a) developed and tested the monsoon onset criteria for this grand multi-model ensemble using 14 years of hindcast and highlighted that MME predicted monsoon onset matches with declared onset by India Meteorological Department (IMD). Later, this Multi-model ensemble prediction system was handed over to IMD for operational S2S forecast (Pattanaik et al. 2019).

A significant amount of work had been done to design various forecast products for heatwaves (Mandal et al. 2019), cyclogenesis and track prediction (Saranya Ganesh et al. 2019, 2020, 2021), MISOs, and Madden-Julian Oscillations (Sahai et al. 2016; Dey et al. 2019, 2020). MME showed a remarkable skill for meteorological subdivisions (Joseph et al. 2019) and hence paves the way for sector-specific applications like health (Sahai et al. 2020), agriculture (Pattanaik et al. 2019; Amat et al. 2021), hydrology (Shah et al. 2017; Shrivastava et al. 2018), and disaster management, which further broadened the utility of MME forecasts. A few post-processing techniques were also developed, including signal amplification (Saranya Ganesh et al. 2018) and downscaling (Borah et al. 2013; Sahai et al. 2017; Kaur et al. 2020) for extreme events.

Steps towards S2S prediction system version 2:

Subsequently, the initiatives for the next version of the above mentioned S2S prediction system are progressing forward. The new strategy's primary aim is to accomplish skill by developing a physics-based ensemble in which the spread in the ensembles emerges from the model physics. The earlier studies have suggested that the physics ensemble has a larger spread than the initial condition ensemble. Hence, it provides a better probabilistic forecast for the extreme weather anomalies conditioned that the forcing to upward motions is weak (Stensrud and Fritsch 1994; Stensrud et al. 2000). The multi-physics S2S strategy uses a combination of convection and microphysics parameterization schemes in CFS. It runs at seamless resolution mode for 36 days, where a higher resolution of T574 (~23km) transitions into T382 (~38km) after 15 days. The multi-physics system exhibits a gain of 2-4 days predictability over its predecessor at a subdivision level. Fig. 1 compares the anomaly correlation coefficients of version 1 (LHS column) with multi-physics version 2 (RHS column) at week 1, week 2, and week 3+4 lead. It is evident from the figure that version 2 has significant improvement over version 1. Further Assessment of the new system will improve the understanding of this physics-based ensemble's strengths and limitations and help refine the prediction strategy.

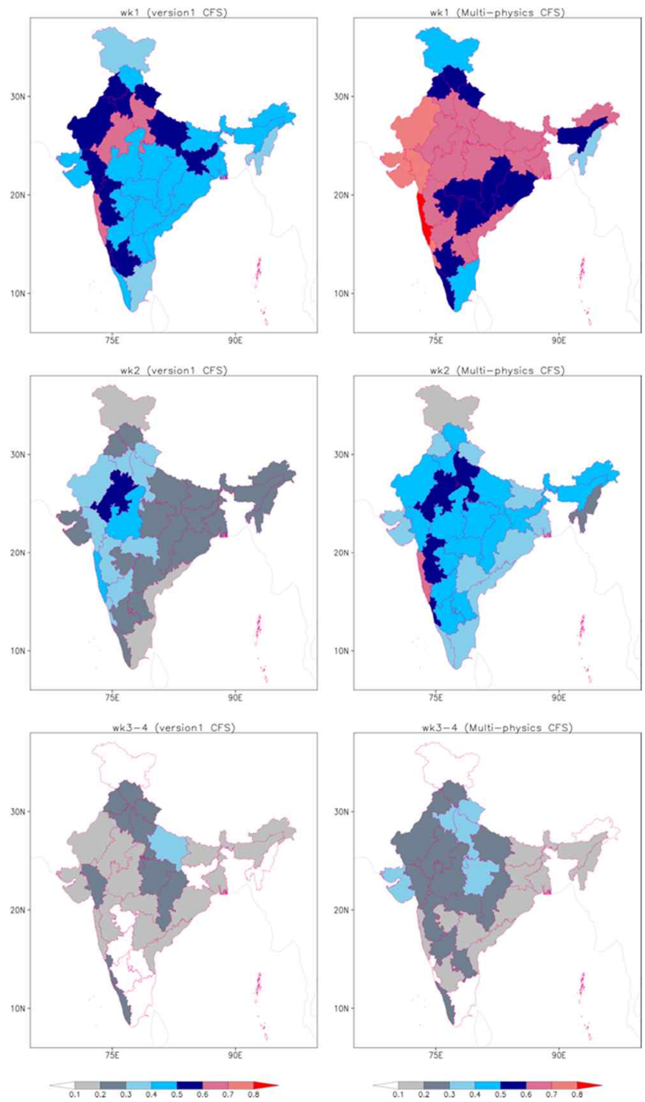

Fig 1. The anomaly correlation Coefficients for meteorological subdivisions of India from S2S prediction system version 1 (LHS column) and multi-physics prediction system (RHS column) at week 1 (top row), week 2 (middle row), and week 3+4 (bottom row).

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S2S Webinar Series

Sharing knowledge with our peers helps get feedback and is essential for the S2S sub-projects to achieve success. With the uncertainties associated with COVID-19, we have started a new tradition of sharing research and knowledge online through the WMO S2S Prediction Project monthly S2S webinar series. This series highlights various aspects of the project and promotes engagement from the broader community, cycling through the various S2S sub-projects/activities. The first S2S webinar was launched in May 2020. The webinars are generally one-hour, with a few short presentations. The S2S webinar recording and presentation files are available on the S2S homepage (s2sprediction.net).

AI/ML methods for S2S Prediction (Frederic Vitart, ECMWF)

A webinar on Artificial intelligence/Machine learning (AI/ML) methods for S2S prediction was held online on 27 January 2021. Five talks related to AI/ML were given by Peter Dueben (ECMWF), Marlene Kretshmer (U. Reading), Zheng Wu (ETH Zurich), Michael Scheuerer (Norwegian Computing Center) and Andrew Robertson (IRI). This webinar was particularly well attended by about 200 people worldwide. The recording of the webinar is available at: https://youtu.be/8Lvo0TCArB4

Pete Dueben provided an overview on how machine learning may help to improve weather and climate prediction. It is unlikely that ML/AI will completely replace weather forecasting in the coming years, but AI/ML is likely to become more frequently used in many parts of the forecasting chain, including observation processing, data assimilation, parameterization in forecast models, as well as post-processing. Marlene Kretshmer argued for the use of causal inference theory and causal networks to establish causal relationships between climate features in physically separated regions. These causal relationships cannot be established by correlations. Two examples of the use of the causal network were presented to establish what is the link between precipitation in Denmark and the Mediterranean and what is effect of ENSO on California precipitation. Zheng Wu presented a dynamical mode decomposition which has been applied to the prediction of sudden stratospheric warmings. Using this method, the weakening of the vortex can be predicted as early as 25 days in advance. which is beyond the current predictability limit. Michael Scheuerer presented two new post-processing approaches based on artificial neural networks, one of them using large scale predictors forecasts. These methods have been applied to the weekly mean prediction of precipitation over California. They outperformed state-of-the-art parametric approaches for statistical post-processing. The last talk by Andrew Robertson presented a new AI/ML competition by the WWRP/WCRP S2S project that will be take place in 2021. The objective is to provide the best week 3 and 4 forecasts of 2-metre temperature and precipitation over several regions (northern, southern Hemisphere, Tropics).

S2S Ensemble Sub-Project (Yuhei Takaya, MRI-JMA)

An S2S Webinar on the S2S Ensemble sub-project was held online on 17th February 2021. Four talks related to ensemble techniques were given by Drs. Anna Borovikov (SSAI, GMAO GSFC NASA), Frederic Vitart (ECMWF), Judith Berner (NCAR) and Matt Janiga (NRL). The webinar was well attended (more than 100 worldwide participants) and the recording of the seminar is also available at https://youtu.be/xpXUJIFKGtM.

Dr. Borovikov introduced GMAO's S2S forecast system, its new version (version 3) features a Synchronized Multiple Time-lagged (SMT) approach to generating perturbations. This new approach improves prediction on the S2S timescale. Dr. Vitart discussed the comparison of so-called lagged ensemble vs burst ensemble strategies for initializing S2S forecasts. Hindcast results suggest that a lagged-ensemble can be a viable alternative to the current burst ensemble extended-range forecasting system if the daily ensemble size exceeds 20. The introduction of the lagged ensemble in the ECMWF system is planned for 2021/22. Dr. Berner focused on the stochastic physics parameterization for S2S forecasts. The stochastic physics schemes perturb model tendencies to represent model uncertainty. This scheme results in mitigating ensemble overconfidence and potentially reducing systematic errors. Based on the NCAR CESM model simulation, the MJO lifecycle (propagation over the Indian Ocean) was also improved. She also introduced a python-based community S2S-verification package (climpred, https://climpred.readthedocs.io/en/stable/), which is freely available from GitHub repository. Dr. Janiga presented the Navy Earth System Predictability Capability atmosphere-ocean sea-ice coupled model (Navy-ESPC). He described version 1 (ESPC V1) that is currently operational, and the next version (ESPCv2), which is scheduled for operational implementation in 2023. ESPC v2 will include upgrades to the component models and candidate improvements to the ensemble deigns, including Stochastic Kinetic Energy Backscatter (SKEB) and Analysis Correlation based Additive Inflation (ACAI).

Upcoming Webinars

There will be a webinar on **'Atmospheric Composition'** on March 31 at 14:00 UTC with the following tentative speakers:

- "The S2S Aerosol Subgroup Intercomparison Project Protocol" by Ariane Frassoni
- "Aerosol impacts at the S2S scale in the ECMWF model" by Angela Benedetti
- "Impact of interactive aerosol and aerosol-cloud interaction on seasonal prediction at NASA/GMAO" by Donifan Barahona
- "Impact of aerosol on the MPAS model" by Georg Grell

The webinar schedule is delivered via emails to people who are enrolled in the S2S mailing list. The webinar schedule varies from month to month based on the speakers' locations. We look forward to seeing you online!

Welcome to our New S2S SG/LG Members!

Andrea Molod

Andrea Molod is the lead of the Seasonal Prediction model and data assimilation system development group at NASA's Global Modeling and Assimilation Office, the developers of the GEOS Subseasonal to Seasonal (GEOS-S2S) system. Her background and experience is largely in atmospheric and coupled model development, including development of atmospheric physical parameterizations, the interaction of the atmospheric processes with gaseous and aerosol constituents, and the interaction of the model and data assimilation systems.

Call for articles for the S2S Newsletter

S2S ICO welcomes the submission of articles to the S2S Newsletter related to the research in a diverse range of S2S subprojects (http://s2sprediction.net). The S2S Newsletter is published every four months.

Please contact Ms. Bo Ra Kim, S2S ICO, at bkim@apcc21.org with any submissions to the S2S newsletter.

S2S ICO based in APCC in Busan, Republic of Korea

The S2S International Coordination Office (ICO) is located at the **APEC Climate Center (APCC)** in Busan, Republic of Korea.