Subseasonal-to-Seasonal S2S Prediction Project

Newsletter No. 23

WCRP World Climate Research Programme

WWRP World Weather Research Programme

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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

Statistical Analysis of Science Publications Utilizing the S2S Database

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1. Introduction

Subseasonal to Seasonal Project (S2S) was launched by the World Weather Research Programme (WWRP) and World Climate Research Programme (WCRP) in November 2013, aiming to fill the gap between the weather and climate forecasting (e.g., Robertson et al., 2015). The fundamental goals of S2S are to improve forecast skill and understanding on the subseasonal to seasonal scales and to promote its uptake by operational centers and by the applications community.

To meet such goals, an extensive database was created which is called S2S database, and is one of the signature achievements of S2S (e.g., Vitart et al., 2017). The database was launched publicly in May 2015 and archived at the European Centre for Medium-Range Weather Forecasts (ECMWF) and the China Meteorological Administration (CMA), and later IRI Data library. The S2S database contains near-real-time forecasts (3-week behind real-time) and hindcasts up to 60 days which are contributed by 12 centres from all over the world (there were 11 at the beginning, and CAS-IAP joined in 2021). By the 13th August 2023, the volume of S2S database was 224.9TB (Usage statistics - S2S - ECMWF Confluence Wiki). Since its launch, the S2S database has been highly active: ECMWF has served 28 million requests and delivered 1,612.8TB data to 2049 active users from all around the world. CMA has catered to another 829 users, providing them with 95.2TB of data. During 2022, up to 3,600 visitors accessed the S2S database 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

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 collabora-

IRI Data library. In terms of geographic distribution, the largest user base is from China, approximately 700 users in total, followed by the United Kingdom with 187 users, the United States with 186 users, and South Korea with 85 users.

2. S2S Publications

All the papers in statistics are derived from the S2S website (Documents | Flat Theme (s2sprediction.net)). Since 2015, there have been 291 publications citing use of the S2S database, including a WMO bulletin, a book on S2S prediction, and 13 review articles. Figure 1 shows the time series of the annual number of papers. Two years after the S2S database was launched and open to public, the number of papers increased quickly. For most years, an average of 50 articles per year used the S2S database, with the number of papers reaching 64 in 2021.

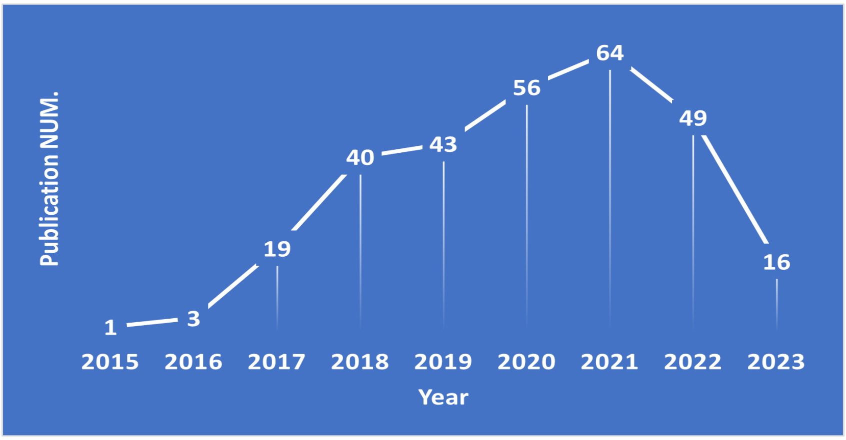

***Fig. 1** : Time Series of the annual number of the S2S database publications*

Figure 2 shows the distribution of journals that have published paper utilizing the S2S database. Only journals that have published more than 3 articles since 2015 are included in the figure. Among these journals, the Journal of Geophysical Research: Atmospheres (JGRA) has published the most literature, up to 35 articles. It is followed by Geophysical Research Letters with 27 articles and Climate Dynamics with 24 articles. Interestingly, more than half of the papers using the S2S database in JGRA are about the stratosphere's role. The S2S database also contributed to research articles in high-level Journals such as one from Nature Communications focused on using deep learning method in bias correction of MJO prediction and three from Scientific Reports focused on the prediction of High Impact Events and machine learning in improving prediction skills.

tion 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 reforecast 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 center (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

- **Annual WWRP Scientific Steering Committee(SSC) Meeting,** *29 Aug - 1 Sep 2023, Geneva, Switzerland and video/teleconference (Hybrid)*

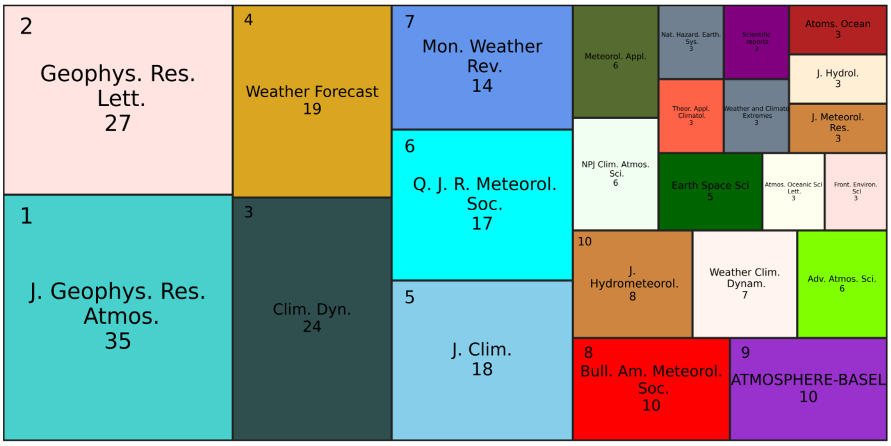

Fig. 2 *: The distribution of journals which publications utilizing the S2S database*

A chord diagram, presented in Fig. 3, highlights the research areas discussed in the publications. The majority of publications focused on the prediction skill and understanding the S2S time scale. Papers on precipitation and related topics are the most prevalent, with a total of 80 publications, covering precipitation, monsoon, and hydrology. This is followed by the temperature and its extreme events, including heat waves and cold surge. Atmospheric teleconnections, including MJO and other patterns, have also garnered significant attention. During Phase two of S2S, the number of publications focused on the stratosphere increased, especially on sudden stratospheric warming events. High impact weather and climate events (31) are also a major S2S research area, using the database for research on the predictability of the high impact events such as the longest Meiyu/Baiu/Jyangma season in 2020, the super heatwave event which occurred in Europe 2018 and 2021 in North American and the recording extreme precipitation in Henan 2022.

Fig. 3 *: chord diagram on which research area are studied using the S2S database*

In addition to the physical research, the S2S database also contribute to various applications activities, like agriculture, human health, and renewable energy.

3. Summary

Although not all publications using the S2S database have been considered, e.g., non-English publications, the S2S database has made significant contributions to scientific research in various fields. By providing access to a wealth of reforecast and real-time forecast data, the database has facilitated studies on the prediction and understanding of the S2S timescale.

Researchers have utilized the S2S database to investigate phenomena e.g., precipitation, monsoons, MJO, high impact weather and climate events. The availability of comprehensive and high-quality model data has enabled scientists to explore the complex interactions between different components of the Earth system and improve our understanding of their dynamics. In addition to this, scientists have leveraged the data to develop and refine prediction models, identify predictive indicators and patterns, and enhance forecast accuracy. This has proven valuable in areas such as agriculture, water resource management, and public health. S2S database has also facilitated collaborations and knowledge exchange among scientists worldwide. By providing a centralized platform for data sharing and analysis, it has fostered interdisciplinary research and facilitated the comparison and validation of different forecasting models and techniques.

Overall, the S2S database has been instrumental in advancing our understanding of subseasonal to seasonal climate variability, and improving prediction capabilities. Its comprehensive data resources and collaborative nature continue to drive scientific discoveries and enhance our ability to anticipate and respond to future climate challenges.

Recommended readings

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Identifying Tropical State-Dependent Bias Relevant to Midlatitude Subseasonal Predictability with Explainable Neural Networks

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Background & Motivation:

Subseasonal timescales are known for their limited predictability. However, this timescale is important for actionable decision-making in many public and private sectors. To improve subseasonal prediction skill, one area of research has explored modes of variability shown to enhance predictability when present (i.e. state-dependent predictability). Previous work has demonstrated that explainable neural networks can identify these states of enhanced subseasonal predictability in both models and observations (e.g. Mayer and Barnes 2021). However, Earth system models have biases that can affect the representation of modes of variability and their subsequent impacts, which can hinder the ability to make accurate forecasts. This research presents a possible neural network approach to identify biases in Earth system models in order to direct future research aimed at improving such biases. Here, we use "bias" to describe systematic differences in sources of enhanced predictability between models and observations. We explore how explainable neural networks together with transfer learning may be used to examine state-dependent subseasonal predictability biases in a large ensemble of Community Earth System Model version 2 (CESM2) historical simulations.

Methods:

To identify state-dependent biases, we utilize a machine learning methodology known as transfer learning (Tan et al. 2018). Transfer learning attempts to exploit information obtained from training on a problem with a large amount of data, and utilize it for a similar, data-limited application. More specifically, transfer learning takes the weights and biases learned from the larger dataset to initialize weights for the second training task, rather than using randomly initialized weights (Figure 1a). Machine learning is a data-hungry statistical approach. Therefore, transfer learning facilitates the use of machine learning for problems with smaller datasets.

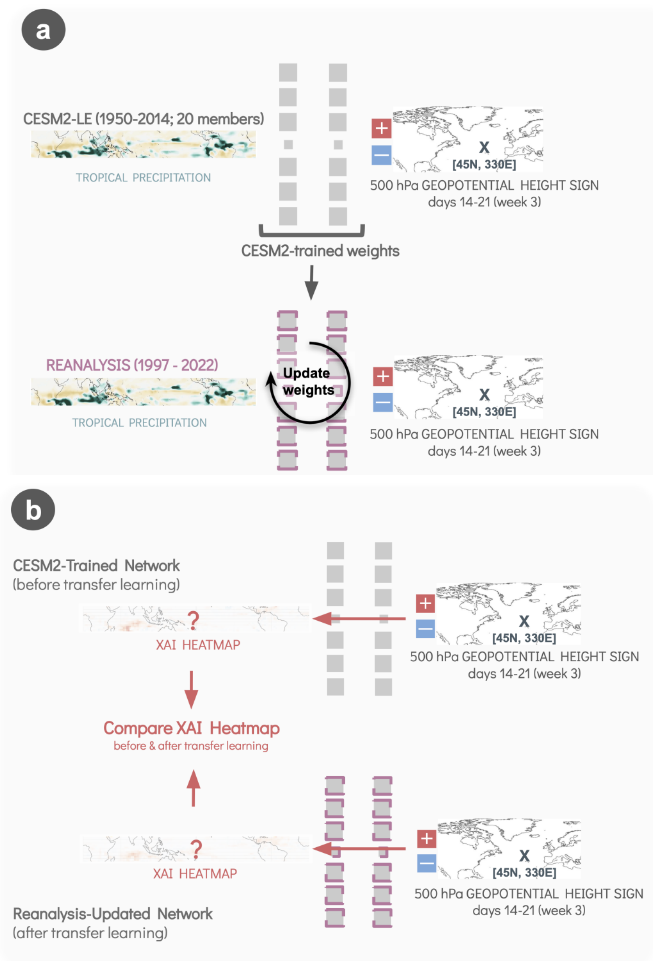

***Fig. 1** : Methodological schematic for identifying subseasonal state-dependent predictability biases through **a) transfer learning** and **b) XAI (integrated gradients)**. The top network in panels a and b represents the pre-transfer learning network – the network trained using CESM2 members. The bottom network of panels a and b represents the post-transfer learning network – the network trained using reanalysis data, initialized with the weights from the pre-transfer learning network*

In climate science, transfer learning can be particularly useful for observational applications of machine learning, where there is limited data. We can obtain information about the Earth system from the vast amount of climate model simulations, and then build upon this information using observations or reanalysis datasets. Our research utilizes this approach in combination with explainable artificial intelligence (XAI). In short, XAI methods can create heatmaps of locations in an input image relevant to a given prediction. Applying XAI to produce heatmaps before and after transfer learning can be used to identify how regions important for a prediction may (or may not) change due to the different sets of training data. For our application, heatmaps produced from the pre-transfer learning model can be compared to the post-transfer learning model (see Figure 1b) to identify possible differences in sources of predictability between models and observations. We are particularly interested in biases associated with periods or “states” that can lead to enhanced subseasonal predictability. Previous research has shown that when accuracy increases with confidence, higher network confidence can be used to identify these periods of enhanced predictability (Mayer and Barnes 2021). Therefore, XAI heatmaps for the 20% most confident neural network predictions can be used to explore *state-dependent* bias. However, this analysis can also be conducted for all confidence thresholds of interest.

Here, we are interested in tropical precipitation biases that can impact subseasonal predictability of atmospheric circulation over the North Atlantic. Therefore, we input weekly mean tropical precipitation (20°S-20°N) and train an artificial neural network to predict the sign of the following 14-21 day averaged (week 3) 500hPa geopotential height (z500) anomaly over the North Atlantic (45°N, 330°E) during extended boreal winter (November - March). At present, we use 20 ensemble members from the CESM2 historical simulations with different initial conditions. The neural network is trained with 18 members, validated with one member and tested with the remaining member. For reanalysis datasets, we use the ECMWF Reanalysis version 5 (ERA5) for z500 and NOAA Global Precipitation Climatology Project (GPCP) for precipitation during extended boreal winter from 1997-2022. The reanalysis data is split into 15 years for training, 5 years for validation and 5 years for testing.

After initial training using CESM2, the weights from this network are “transferred” and used to initialize the second network. This second network is subsequently trained further using only reanalysis data (see Figure 1a). All weights are allowed to update during retraining. Once each network is trained, we calculate the accuracy of the pre- and post-transfer learning models on the reanalysis test dataset across confidence thresholds. We can then use an XAI method, such as Integrated Gradients (Sundararajan et al. 2017), to create heatmaps of the relevant regions used by the networks to make confident, correct predictions.

Preliminary Results & Next Steps:

If transfer learning is successful, one may expect to see improved performance on the reanalysis testing data when using the updated network compared to the network trained using only CESM2 data. However, instead we find that the neural network performs *worse* after transfer learning, across all confidence thresholds (Figure 2).

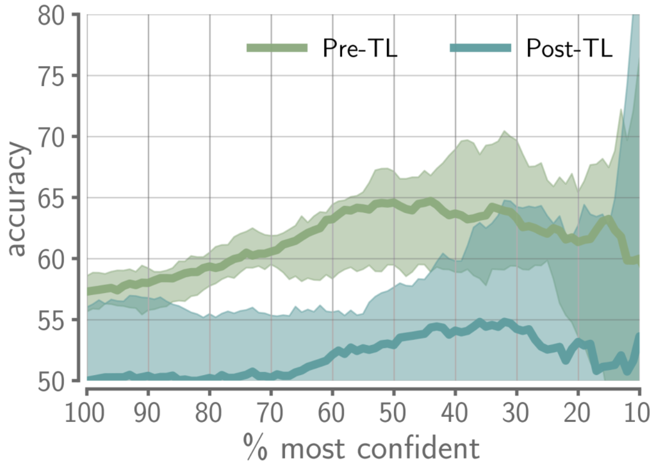

***Fig. 2** : The accuracy of the pre- (green) and post- (blue) transfer learning networks on the reanalysis testing data across confidence thresholds. The thick colored line represents the median of 10 trained networks constructed from different random seeds. The shading encompasses the values between the minimum and maximum accuracy from the networks at each confidence threshold*

We find this is the case for other testing data as well (not shown). This suggests that the neural network trained with CESM2 may sufficiently represent the relationship between tropical precipitation and North Atlantic circulation, in this simple example. As a result, additional training using reanalysis data appears to lead to overfitting and subsequently worse performance. We further examine the performance of the pre-transfer learning network on the *full* (rather than testing) reanalysis data set and compare it to the performance of the network on its associated CESM2 testing member (Figure3).

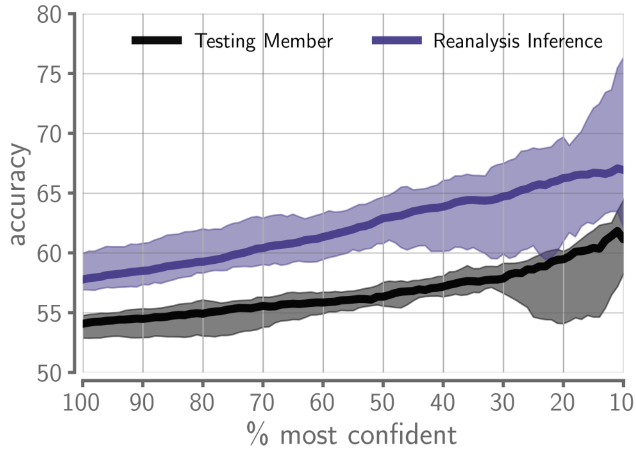

***Fig. 3** : The accuracy of all the reanalysis data (purple) and an individual CESM2 testing member (black) for the pre-transfer learning network across confidence thresholds. The thick colored line represents the median of 10 trained networks constructed from different random seeds. The shading encompasses the values between the minimum and maximum accuracy from the networks at each confidence threshold*

Unexpectedly, we find that reanalysis data performs *better* than the CESM2 testing member across all confidence thresholds.

These preliminary results suggest that transfer learning may not always improve performance. As we continue to conduct research on this topic, we plan to explore why this may be the case by addressing questions such as: can bias be identified in this particular network setup? Is the observational record long enough to correct for subseasonal biases? Could the signal-to-noise paradox play a role in the better performance of reanalysis (over the CESM2 testing member) on the pre-transfer learning neural network? Based on the results of further analysis, we plan to use the methodology outlined in this article to demonstrate how explainable neural networks may be utilized to identify state-dependent subseasonal predictability biases within climate models.

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Acknowledgement

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Constructing new metrics for identifying, real-time monitoring and predicting boreal summer extratropical intraseasonal signals over Eurasian continent

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Boreal summer extratropical intraseasonal oscillation (EISO) has drawn increasing attention owing to its importance in triggering extreme climate/ weather events and affecting regional subseasonal prediction. However, despite the urgent need of the subseasonal-to-seasonal (S2S) community, a comprehensive delineation of EISO diversity and real-time EISO monitoring remain the gap of knowledge.

A recent study published in Journal of Climate first objectively sorts out and comprehensively clarifies three dominant EISOs trapped along two extra-tropical jet streams (subtropical westerly jet and polar front jet) over Eurasia, which are summarized schematically in Figure 1. The first EISO, named EISO-SJE, features an eastward-propagating wave trapped along the subtropical westerly jet with an 8–25-day periodicity and a zonal wavelength of about 4,400 km between 25°N and 55°N. It has a quasi-barotropic structure, initiating at the exit of the North America–North Atlantic jet core and moves eastward at a phase speed of about 3.1 m s−1 with amplification over the Black Sea–Caspian Sea–arid central Asia area. The other two EISOs are trapped along polar front jet. One is EISO-PJE, describing a high-latitude 10–30-day eastward-propagating wave along the polar front jet with a quasi-barotropic structure and a zonal wavelength of about 4,200 km. It initiates nearly over Scandinavia where the bifurcation of the North America–North Atlantic jet and the polar front jet is located, migrates eastward with a speed of 3.8 m s−1, enhances over the Eastern European Plain through the Ural Mountains to the Western Siberian Plain and finally decays over the Okhotsk region. The other is EISO-PJW, depicting a westward-migrating quasi-barotropic wave along the polar front jet with a dominant periodicity of 10–40 days, wavelength of 5,600 km and speed of 4.0 m s−1 that enhances near the Ural Mountains and weakens over Scandinavia.

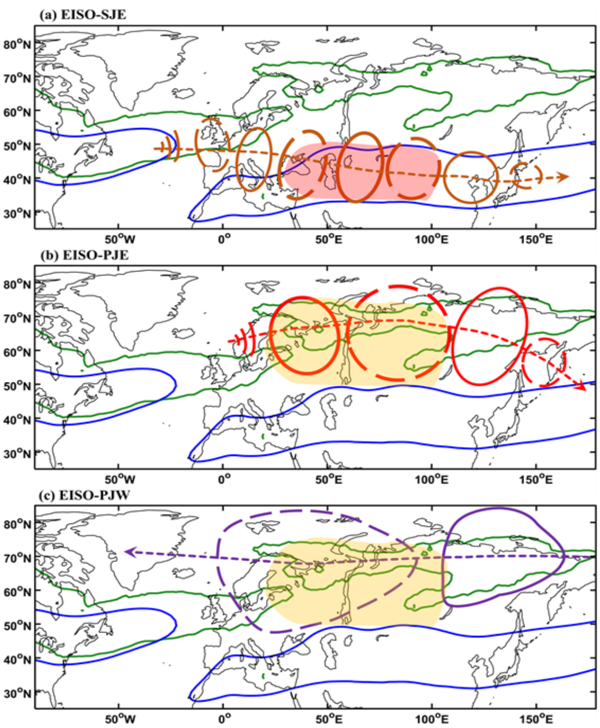

Fig. 1 *: Schematic diagram of three major propagating EISO modes in boreal summer. This figure is originally published as the Figure 13 in recommended reading [1].*

Following the three EISOs, the researchers constructed well-portrayed real-time EISO metrics, which accurately capture EISOs' spatiotemporal evolution characteristics in real-time monitoring. Using the EISO real-time monitoring metrics, the close linkages with the regional occurrence of extremes and the blocking have been clearly demonstrated (Figure 2), confirming the importance of real-time EISO metrics. Meanwhile, the subseasonal variation of Arctic sea ice are also found to be influenced by EISO-PJW (Figure 3).

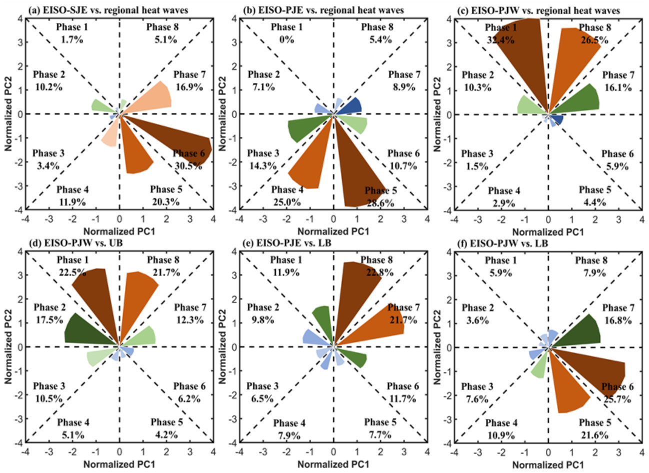

Fig. 2 : Phase relationships between three major propagating EISO modes and local heat wave events and blocking events. This figure is originally published as the Figures 10–11 in recommended reading [1].

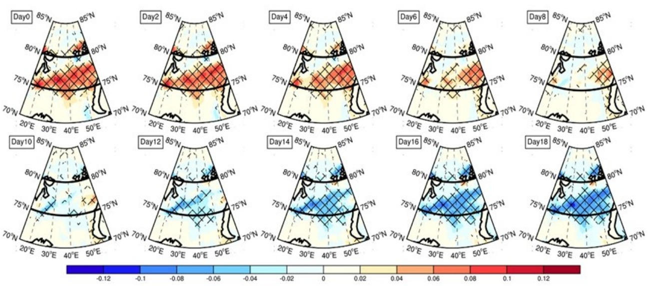

Fig. 3 : EISO's effects on the subseasonal variation of Arctic sea ice. This figure is originally published as the Figure 5 in recommended reading [2].

Based on S2S hindcast datasets, the further study found that the intensity of EISO-SJE significantly influences the skill of 2–3-week lead predictions for East Asian summer climate. Taking the surface temperature over three target areas (eastern Tibetan Plateau, Southwest Basin, and North China) as an example, the subseasonal prediction skill is evidently higher when EISO-SJE has large amplitudes in both deterministic and probabilistic evaluations (Figures 4), which indicates that EISO-SJE provides an opportunity window for subseasonal prediction over these regions.

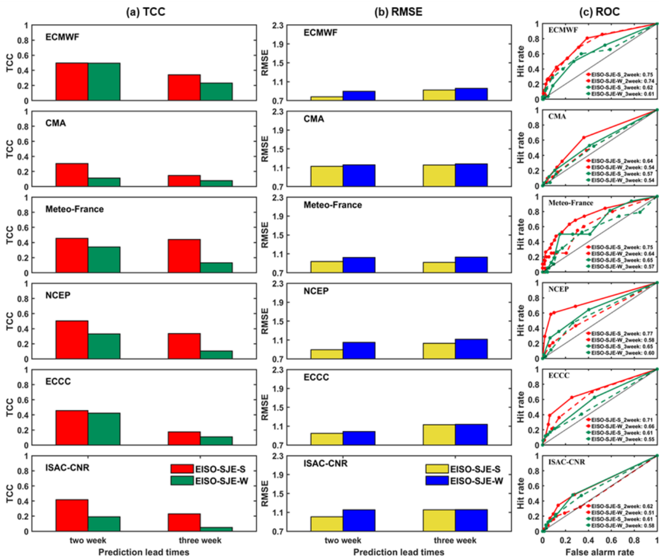

Fig. 4 : Prediction skills of surface air temperature in specific East Asian regions (eastern Tibetan Plateau, Southwest Basin, and North China) with two- and three-week lead times for different S2S dynamic models. This figure is originally published as the Figures 2–4 in recommended reading [3].

Moreover, numerical experiments exhibited that the intensity and location of EISO-SJE are modulated by the thermal and mechanical effects of Tibetan-Iranian Plateau (TIP). In detail, the TIP's mechanical effect primarily modulates the amplitude of EISO-SJE that strengthens over the TIP upstream and weakens over the TIP downstream. Comparatively, the TIP's thermal effect not only reduces/increases the intensity of EISO-SJE over the TIP upstream/downstream, but also significantly migrates the track of EISO-SJE northward (Figure 5).

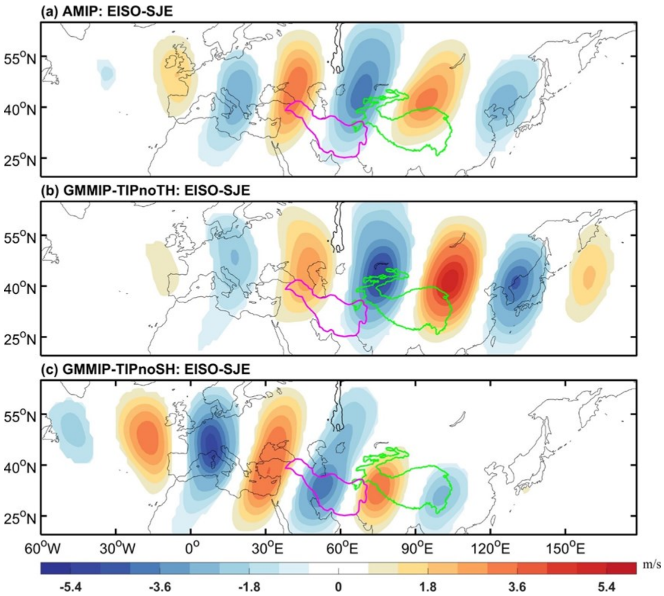

***Fig. 5** : Orographic mechanical and surface thermal effects of the Tibetan-Iranian Plateau on EISO-SJE's intensity and location. This figure is originally published as the Figure 2 in recommended reading [4].*

Together with tropical intraseasonal oscillation, these studies provide the S2S community with a well-portrayed unified picture of extratropical intraseasonal waves and the real-time metrics for operational real-time monitoring, subseasonal prediction, and model evaluation. More deepened studies about the mechanism and their applications are worthwhile to be investigated in the future.

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S2S Summit 2023, University of Reading

Steven Woolnough

National Centre for Atmospheric Science, Univ. of Reading

As the S2S Project draws to a conclusion at the end of this year the Steering Group highlighted the need for an opportunity for the community to come together to share the results of the project and to look forward to the future of S2S prediction, thus was born the S2S Summit. The meeting was held at the University of Reading from the 3rd-7th July and was organized around three broad themes, *Predictability and Processes, Modelling and Research to* Operations. 191 people attend the meeting in person from 29 different countries representing all the WMO regions, of which about half were early career researchers, a further 40 people registered to view the presentations on-line.

***Pic. 1** : S2S summit attendees at University of Reading, UK*

The opening session included introductory remarks from the S2S Project, WCRP and WWRP highlighting the importance of the sub-seasonal prediction and its potential implications, including and introduction to *SAGE* the WWRP's follow on project on S2S, and talks from on the foundations of sub-seasonal predictability from Brian Hoskins and Gilbert Brunet.

There was a mixture of oral and poster presentations across all three themes with a total of 85 oral presentations including 11 invited talks, including summaries of the S2S Projects sub-projects, and 109 poster presentations. The oral sessions were organized around sub-themes of the three broad themes, with the sessions from each theme spread through the week to ensure a broad set of topics on each day. The posters were divided into two sessions lasting two days with half the posters presented each day. One new area that has emerged since the Sub-seasonal to Seasonal and Seasonal to Decadal prediction meetings in Boulder in 2018 is the use of Machine Learning techniques for making and calibrating forecasts and for identifying and understanding drivers of predictability.

The meeting also included a breakout session to discuss the legacy of the S2S project and look forward to the future. As well as the scientific legacy of the project three particular things were identified which were also apparent from the meeting itself. The value of the S2S database; developing a broad geographical and multi-disciplinary community of scientists working on S2S; and establishing links with users of S2S forecasts. In terms of the future, recommendations included strengthening the links between the applications of S2S forecasts and the science, modelling and observations that underpin them; and an increased access to real-time forecasts and facilities to work with them to enable wider application.

In addition to the science programme there was a dedicated early career event to provide an opportunity for early career researchers from across the world to share their experiences including some short presentations from 3 recent ECRs from the UK, Indonesia and Kenya.

Data References

- https://research.reading.ac.uk/s2s-summit2023
- https://library.wmo.int/doc_num.php?explnum_id=11662

A summary of the S2S Steering group meeting

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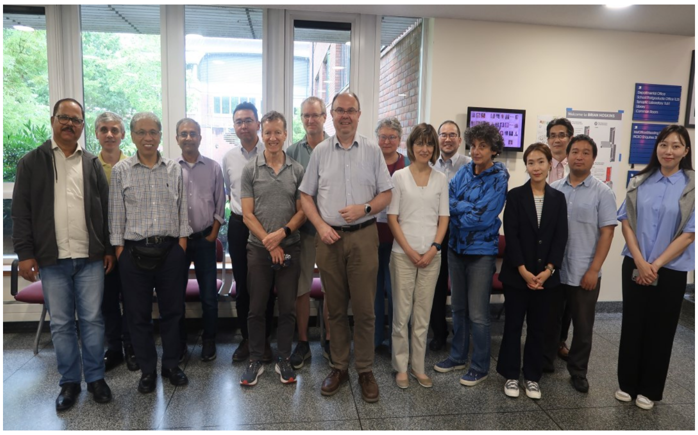
[2]International Research Institute for Climate and Society (IRI)

The Earth Institute at Columbia University



Pic. 1 *: S2S SG Meeting at University of Reading, UK*

The S2S steering group meeting took place at University of Reading on 8 July 2023, the day after the S2S Summit. 20 people (S2S steering and liaison group members, WMO representatives and members of the International Coordination office) attended this meeting, including 3 online.

This was the last in person S2S steering group meeting, since S2S will stop at the end of the year. Therefore, the main topic of this meeting was the legacy of the S2S project. Kunio Yoneyama and Munehiko Yamaguchi Munehiko presented the WWRP plans for SAGE (Sub-seasonal prediction for Agriculture and Environment), which will be one of the new WWRP projects of the WWRP Implementation Plan 2024-2027. SAGE will replace S2S as the main focus for S2S activities in WWRP. The writing of the SAGE implementation plan and the nomination of steering group members is ongoing. A first kick-off meeting will take place at the end of the year.

Regarding the S2S database, its use by the S2S community has continuously increased over the past years. Recent changes to the database included new versions of the JMA, KMA and ECMWF models. Work is ongoing to add new models (IITM, NASA, ACCESS2 from BoM and CPTEC). It is planned to continue maintaining and updating the S2S database after the end of the S2S project. A letter has been sent to all the data providers and archiving centres asking for a 5-year extension to their contribution. The move of some centres like ECMWF towards open data might open the door to a reduction of the 3-week delay in the access of S2S real-time forecasts. Another recent (but separate) development has been the designation by WMO of ECMWF as a nominated Lead Centre for Sub-seasonal Forecast Multi-model ensemble (SSFMME) which will provide near real-time access to limited number of variables (precipitation, 2m-temeperature, 500 hPa geopotential height) from the S2S data providers who accept to be S2S Global Producing Centres. After 2023, APCC will maintain the S2S website and mailing list for a period of 2 years, allowing time for SAGE or another group to take over.

The steering group discussed the content of a final report on S2S activities which should be published by the end of the year. This report will summarize the main achievements during S2S Phase 2. It is also planned to work on a second edition of the S2S book, which new content was discussed at the meeting.

Andrew Robertson announced that the WMO guidance document on operational practices for sub-seasonal prediction is in the process of being written. This effort was led by 2 WMO expert teams in SERCOM (ET for Climate Services Information System Operations) and INFCOM (ET for Operational Climate Prediction System).

Call for articles for the S2S Newsletter

S2S ICO welcomes the submission of articles to the S2S Newsletter related to research in a diverse range of S2S subprojects or on recent events for a “State of the Climate”. The S2S Newsletter is published every four months.

Please contact Ms. May La at the S2S ICO, at may.la@apcc21.org with any submissions to the S2S newsletter.

APCC
APEC CLIMATE CENTER

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.