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PERSPECTIVE OPEN

Progress in subseasonal to seasonal prediction through a joint weather and climate community effort

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Public expectations have been set for the development of skillful meteorological forecasts of unprecedented leads out to a month or two, filling the so-called subseasonal to seasonal prediction gap. While both the weather and climate communities, coordinated internationally by the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP), respectively, can contribute to address this challenge, neither of them can effectively meet the challenge alone. The WWRP/WCRP Subseasonal to Seasonal (S2S) Prediction Project and related initiatives such as the Modeling, Analysis, Predictions and Projections (MAPP) Program S2S Prediction Task Force are providing a framework for needed weather–climate community interactions. Such joint weather–climate efforts need to be sustained in the future for continued progress in subseasonal to seasonal prediction.

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THE WEATHER–CLIMATE PREDICTION GAP

Traditionally weather forecasts cover the time range out to 2 weeks, while climate forecasts start at the seasonal timescale and extend out. There is effectively a weather–climate prediction gap at the subseasonal to seasonal (S2S) range (from two weeks to a season; Fig. 1). This is despite the fact that S2S forecasts are highly sought after by the energy, water management, agriculture and emergency sectors, just to name a few. The chaotic processes underpinning atmospheric dynamics seem to set the limit of skillful numerical weather prediction to two weeks, as information contained in the initial state of the atmosphere is gradually lost.[1] An approach that goes beyond the simple extension of traditional numerical weather prediction (NWP) at ever increasing lead times is necessary as we enter this underserved forecasting territory.[2] Based on the basic recognition that S2S forecasts are neither weather nor climate forecasts, understanding, tools and experience developed over the years by both the weather and climate communities are needed to best address this challenge.[3]

Weather forecast skill has steadily increased over the past decades, owing to significant coordinated research, development and investment. The World Weather Research Programme's (WWRP) focus on research to improve the accuracy, lead time and utilization of weather prediction has significantly contributed to this achievement by serving as a coordinating platform for a large number of actors (international organizations, national meteorological services, universities, research centers, donors, and civil society). Better models, better initial conditions and advances in high performance computing, the latter of which have enabled forecasts at progressively higher resolutions and with larger ensembles, have all contributed to such progress. The longest lead time at which a weather forecast typically contains useful skill has increased by ~1 day per decade—i.e., a day 6 forecast is now as skillful, on average, as a day 5 forecast was a decade ago.[4] This steady improvement has saved lives and mitigated the economic impact of adverse weather conditions. These trends have raised users' expectations that weather forecasts out to several weeks are achievable.

Predictions of meteorological conditions at longer lead times, one to two seasons ahead, have been developed for several decades now as part of climate community research efforts under the auspices of the World Climate Research Programme (WCRP) and transitioned into operational production under the auspices of the World Meteorological Organization. Since the 1980s, the WCRP has fostered the understanding and modeling of foundational Earth system processes that underpin its climate variability and predictability. For instance, model based forecast systems can predict global climate fluctuations associated with the El Nino Southern Oscillation (ENSO) at least 6 months in advance. These systems have been applied to the seasonal prediction of the North Atlantic Oscillation and also the prediction out to a few weeks of the Madden–Julian Oscillation (MJO), a primary source of predictability at the subseasonal scale (e.g., ref. [5]). As for weather forecasts, these climate forecasts have resulted in increased preparedness, with significant economic savings and societal benefits. For example, they have enabled preparedness to extreme events such droughts and enhanced tropical cyclone and flood seasons. Despite progress, there are still challenges to seasonal climate prediction that include, for example, translating skillful ENSO forecasts into skillful mid-latitude precipitation forecasts (e.g., ref. [6]).

TRADITIONAL WEATHER AND CLIMATE PREDICTION APPROACHES

Traditional weather and climate prediction systems are quite different from each other and neither is perfectly suited for S2S prediction. Moreover, our knowledge of the processes that support the existence of predictability at the weather (up to 2 weeks) or the climate (seasonal and beyond) timescales is not readily applicable to timescales in between. There is the need to

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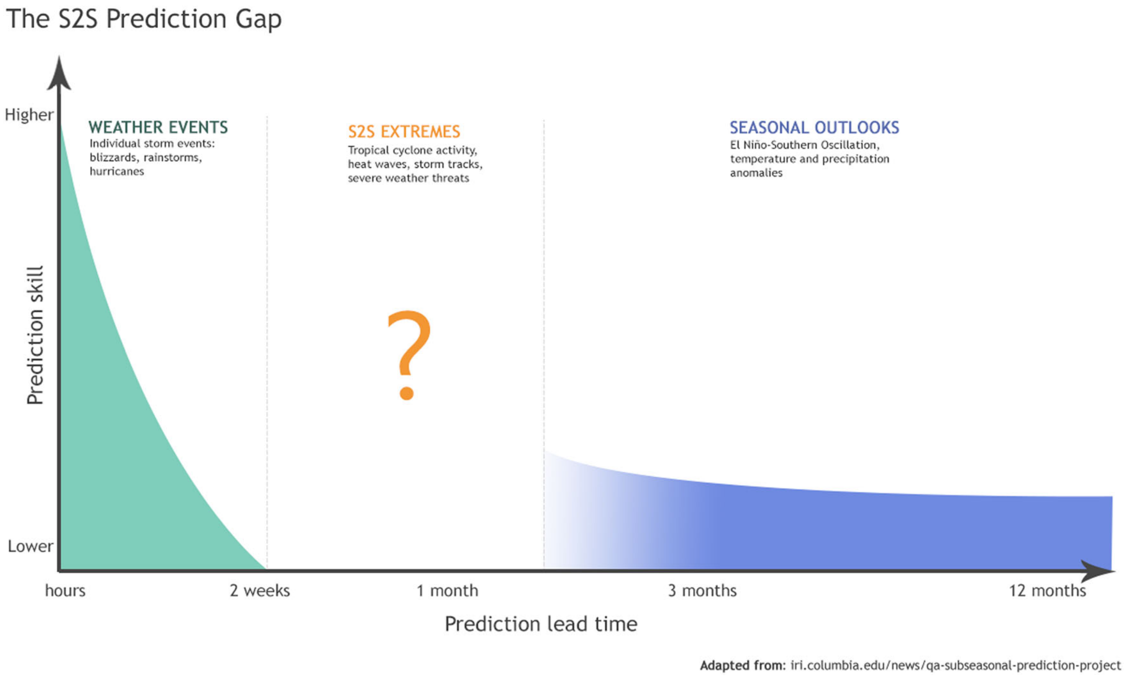

Fig. 1 A schematic illustrating the S2S or weather–climate prediction gap. The diagram shows estimated forecast skill based on the lead time of the forecast's issuing; the types of phenomena being predicted for the various time ranges are also indicated. Going from weather to seasonal forecasts, prediction skill decreases and also the nature of the predictability sources underpinning the predictions changes considerably. Comparatively less is known regarding forecast skill and predictability sources in the S2S range, 2 week up to a season. NOAA CPO graphic adapted from original by Elisabeth Gawthrop and Tony Barnston, IRI

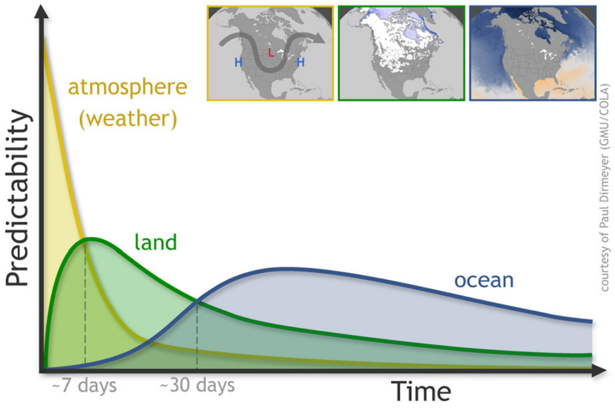

Fig. 2 A schematic illustrating the role of different parts of the Earth's climate system (atmosphere, purple; land surface, green; ocean, blue) as sources of S2S predictability (vertical axis). For short lead times, knowing the initial state of the atmosphere counts the most. At 2-week to 4-week lead times, knowledge of the land surface is also needed. Forecasting more than 30 days ahead typically requires knowledge of the ocean, such as the sea surface temperature variations linked to El Niño. NOAA CPO graphic adapted from original by Paul Dirmeyer, GMU/COLA

continue to develop prediction systems that best exploit sources of predictability at these timescales. The primary basis for longer lead forecasts, beyond 2 weeks, is the interaction of the atmosphere with other, more slowly varying Earth system components, such as the ocean or the land, that evolve over timescales of weeks, months or years, rather than days as in the atmosphere (Fig. 2). Via interactions with the atmosphere, these other Earth system components provide boundary conditions to guide the evolution of the atmosphere with some increased degree of predictability resulting from lower frequency phenomena. Traditional NWP systems include complex high resolution and advanced representations of atmospheric processes and a detailed description of its state at the beginning of the forecast, but typically do not simulate the evolution of other Earth system components. In contrast, climate models are typically "coupled" models and include two-way interactions between the atmosphere and ocean, and possibly other Earth system components such as the land and the cryosphere. However, because traditional climate models incorporate coupled processes and are hence computationally more expensive than weather models, they are generally characterized by lower grid resolution and less detailed atmospheric process representation. As a result, phenomena such as tropical cyclones and well-defined mid-latitude fronts are typically not as realistically depicted in climate models as in weather models. Both the typical legacy atmosphere-only weather models and relatively lower-resolution coupled climate models have inherent limitations that inhibit their direct application to the subseasonal-to-seasonal time window forecasting problem, however both also provide the foundations for this effort.

A UNIFIED APPROACH TO SUBSEASONAL TO SEASONAL PREDICTION

A practical example, to help illustrate the S2S prediction challenge, but also the opportunity of increased prediction skill, is that of the above-mentioned MJO, a large-scale, 30–90 days period and eastward propagating coupled phenomena between atmospheric circulation and tropical deep convection which provides conditional skill in the subseasonal time range (e.g., ref. [7]). The representation of processes like the MJO in numerical models requires preserving at the same time, and as much as possible, the benefit of initial conditions and exploiting the control provided by the slowly varying components of the Earth system while accurately representing the evolution of complex atmospheric processes and coupled air-sea-land interactions. In a coupled model, initial conditions create numerical shocks from the imperfect balance and inconsistencies between those components due to the lack of observations to represent the whole system at a given time. Those shocks increase the loss of memory from the initial conditions and may also be partially responsible for the model drifting away from the true state due to the accumulation of various errors inherent to any numerical model over time.

To address the limitations of traditional weather and climate models, in recent years there has been a convergence in approaches in weather and climate modeling and forecasting, and the development of systems that incorporate the best of both. Current climate model development projects include efforts to simulate the Earth system with increasingly higher resolution, flexible and more sophisticated physical representations, and improved initial conditions, following the example of the NWP community. At the other end of the spectrum, weather models have been increasingly incorporating coupled interactions between the atmosphere and the ocean, as well as other Earth system components, similar to what has been previously done for climate modeling and forecasting. For example, this is the case for the WWRP Polar Prediction Project where the weather community is using an Earth system approach for long-range forecasting (out to months). At the institutional level, this convergence of approaches is reflected by the evolution toward a more unified or seamless suite of models used for weather to climate modeling and forecasting. This unified approach has been embraced by several leading operational and research centers, such as the UK Met Office and NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), among several others where a common model dynamical core and flexible physical representations are used across all timescales. This approach has the appeal of streamlining model development and providing a seamless forecast suite to address the temporal continuum of societal applications.

The modeling and forecasting system evolution described above has been accompanied by an increasing recognition of the weather–climate linkage underpinning observed variability. For instance climate conditions, whether those associated with ENSO anomalies, a given state of the MJO, or a warming climate, modulate the statistics of day-to-day weather and the likelihood of extremes. For example, the recent European heat waves of summer 2003 and 2010[8] have received considerable attention because of both their potential link to larger scale warming patterns and to blocking phenomena, which strongly characterize the subseasonal timescale in mid-latitudes. An analysis of the main characteristics of summer Euro-Russian blocking events in global reanalysis as well as in the 20th century CLIVAR atmospheric simulations revealed that summer blocking episodes become significantly longer in the second half of the century.[9] Similarly, the "atmospheric rivers"[10] that bring sudden pulses of moisture, and occasional flooding that can alleviate drought in the American West, are modulated by seasonally evolving ENSO conditions. Elucidating these weather–climate linkages requires knowledge of processes and prediction tools that engage both the climate and weather scientific communities. Moreover a better understanding of the mechanisms responsible for systematic errors across long-range weather to seasonal timescales has immediate benefits for climate predictions and projections.

FOSTERING FUTURE PROGRESS IN SUBSEASONAL TO SEASONAL PREDICTION

The experience and scientific knowledge matured by both the weather and climate scientific and prediction communities as part of WWRP and WCRP over recent decades are highly relevant to filling the weather–climate prediction gap. Optimal collaboration is crucial to making progress in the development of subseasonal to seasonal forecasts, which are inherently neither weather nor climate forecasts. The international S2S Prediction Project[11] was jointly created by WWRP and WCRP in recognition of the need to bring those communities together and to fill the gap between long-range (weather) forecast and seasonal (climate) prediction. The Project has indeed attracted the attention of both communities, and motivated some key research efforts. For example, NOAA now has a new Task Force (the MAPP S2S Prediction Task Force, see ref. [12]) that brings together both weather and climate scientists, and is organized by the Office of Oceanic and Atmospheric Research/Climate Program Office but co-supported by a partnership involving the National Weather Service and other US agencies programs that have interests spanning the weather–climate timescales. The WWRP/WCRP S2S Prediction Project is catalyzing international research and facilitating communication and coordination across the weather–climate communities. The international S2S Prediction Project and underpinning national research initiatives will provide an ideal approach to achieving the best possible forecasts at these timescales, with significant socio-economic benefits. Such joint weather–climate efforts need to be sustained in the future for continued progress in subseasonal to seasonal prediction, and it could be seen as an effective process in place for co-design of WWRP and WCRP activities that are important for both weather and climate.

At the practical level, work focused on S2S timescales is providing an opportunity to benchmark research-to-operation transfer processes, with an interactive dialog between researchers and stakeholders. The North American Multi-Model Ensemble System for seasonal prediction[13] and the Subseasonal Experiment (SubX; see ref. [14]), involving the research community and operational centers to test prediction systems and apply predictability knowledge for real-time S2S prediction, are examples of how this can work. The S2S framework can help address key scientific-technical issues such as testing new assimilation methods for coupled-systems and better understanding of the mechanisms that create Earth system model biases, linking the growing fast-mode atmospheric error with the comparatively slow evolution of error in other Earth system components.

Continuing the evolution toward seamless approach to the weather–climate continuum to develop subseasonal to seasonal predictions requires sustaining current successful efforts by international and national institutions, both research and operational centers, and their stakeholders and sponsors. This is based on the explicit recognition that neither weather or climate communities are in a unique position to make progress in closing the S2S prediction gap and that prediction systems to be applied are not simply "weather" or "climate" prediction systems. Rather the approach is an evolution toward an integrated weather–climate prediction framework including increasingly unified modeling and prediction systems, with physical representations applicable at varying spatial and temporal scales; data assimilation system; traceable verification; and frameworks flexible enough to address the needs of a range of applications; and a network of experts with knowledge spanning the weather to climate timescale which can be further stimulated by a closer alignment of academic programs. To enable such overall evolution, both weather and climate research programs need to continue to be involved (e.g., such as in the MAPP S2S Prediction Task Force), rather than one or the other exclusively, so as to optimally build from relevant state-of-art community knowledge and models rather than "reinvent the wheel". Research by these programs with joint initiatives specifically targeted to foster joint S2S science and development is key to ensure that both weather and climate scientific communities continue to be effectively engaged. Internationally, what has been set into motion by the joint S2S Prediction Project can help evolve the WWRP and WCRP programs toward an increasingly seamless approach to Earth System science coordination. These programs have importantly demonstrated that improvements in science and operational predictions are driven by international cooperation in synergy with national approaches, and can play an important role in promoting and supporting cross weather–climate community interactions within relevant institutions and networks.

Data Availability

Data is available as specified in the cited references. In particular:

The S2S Prediction Project data are available from the European Center for Medium Range Forecasts (ECMWF): http://apps.ecmwf.int/datasets/data/s2s/levtype = sfc/type = cf/.
The North American Multi-Model Ensemble data are available from the IRI (http://iridl.ldeo.columbia.edu/SOURCES/.Models/.NMME/) and the Earth System Grid at NCAR (https://www.earthsystemgrid.org/search.html?Project = NMME).
The SubX data set are accessible through a public archive at Columbia University's International Research Institute for Climate and Society (IRI) Data Library: http://iridl.ldeo.columbia.edu/SOURCES/.Models/.SubX/.

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All authors researched, collated, and wrote this paper. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration.

ADDITIONAL INFORMATION

Competing interests: The authors declare no competing financial interests.

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