Subseasonal *to* Decadal Prediction

Filling the Weather–Climate Gap

Adapted from "Current and Emerging Developments in Subseasonal to Decadal Prediction," by **William J. Merryfield** (Environment and Climate Change Canada), **Johanna Baehr, Lauriane Batté, Emily J. Becker, Amy H. Butler, Caio A. S. Coelho, Gokhan Danabasoglu, Paul A. Dirmeyer, Francisco J. Doblas-Reyes, Daniela I. V. Domeisen, Laura Ferranti, Tatiana Ilynia, Arun Kumar, Wolfgang A. Müller, Michel Rixen, Andrew W. Robertson, Doug M. Smith, Yuhei Takaya, Matthias Tuma, Frederic Vitart, Christopher J. White, Mariano S. Alvarez, Constantin Ardilouze, Hannah Attard, Cory Baggett, Magdalena A. Balmaseda, Asmerom F. Beraki, Partha S. Bhattacharjee, Roberto Bilbao, Felipe M. de Andrade, Michael J. DeFlorio, Leandro B. Díaz, Muhammad Azhar Ehsan, Georgios Fragkoulidis, Sam Grainger, Benjamin W. Green, Momme C. Hell, Johnna M. Infanti, Katharina Isensee, Takahito Kataoka, Ben P. Kirtman, Nicholas P. Klingaman, June-Yi Lee, Kirsten Mayer, Roseanna McKay, Jennifer V. Mecking, Douglas E. Miller, Nele Neddermann, Ching Ho Justin Ng, Albert Ossó, Klaus Pankatz, Simon Peatman, Kathy Pegion, Judith Perlwitz, G. Cristina Recalde-Coronel, Annika Reintges, Christoph Renkl, Balakrishnan Solaraju-Murali, Aaron Spring, Cristiana Stan, Y. Qiang Sun, Carly R. Tozer, Nicolas Vigaud, Steven Woolnough, and Stephen Yeager**. Published Online in *BAMS*, June 2020. For the full, citable article, see DOI:10.1175/BAMS-D-19-0037.1.

Tremendous recent progress in climate prediction on subseasonal to decadal time scales has been enabled by better observations, data assimilation, and models originating from the weather prediction and climate simulation communities together with ever-increasing computational power.

World Climate Research Program (WCRP) efforts led initially to predictions one to two seasons ahead becoming part of the WMO operational infrastructure. More recently, a joint World Weather Research Program (WWRP) and WCRP Subseasonal to Seasonal Prediction Project has started tackling the weather–climate gap (from two weeks to a season). The NOAA-led Subseasonal Experiment project has similar aims. New frontiers have been enabled by Earth system models that represent the carbon and other biogeochemical cycles in addition to the physical climate system. As a result, skillful multiyear prediction is likely achievable for biogeochemical and ecological Earth system components.

The ultimate collective subseasonal to seasonal (S2S; 2 weeks to season) and seasonal to decadal (S2D) endeavor is to improve the prediction of the spatial–temporal continuum connecting weather to climate through a coordinated, seamless, and integrated Earth system approach. The S2S and S2D communities share common scientific and technical challenges. This essay* synthesizes those commonalities across time scales and Earth system components, and from basic research to operational delivery.

Mechanisms of predictability

A major source of S2S predictability is the organization of tropical convection by the Madden–Julian oscillation (MJO), predicted skillfully by S2S project models up to 3–4 weeks ahead. The associated

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*** This essay stems from international conferences on subseasonal to seasonal and seasonal to decadal prediction jointly convened by WWRP and WCRP in September 2018 in Boulder, Colorado: (www.wcrp-climate.org/s2s-s2d-2018-home).**

tropical–extratropical teleconnections impart S2S forecast skill for many extratropical phenomena, including Euro-Atlantic weather regimes, the jet stream, atmospheric rivers, and hail/tornado activity. However, good representations of the basic state as well as tropical air–sea interactions and atmospheric convection are necessary for these teleconnections to be correctly simulated. S2S predictability also derives from the stratosphere through its relatively long time scales of variability and lagged influences on the troposphere. Atmosphere–ocean interactions, fundamental for S2D predictability, can be influential on S2S time scales.

S2S forecasts for sea ice, which strongly influences surface fluxes and lower-atmospheric temperatures, provides a source of S2S predictability for polar and possibly midlatitude regions.

A primary source of S2D atmospheric predictability is the variety of teleconnections arising from changes to the Walker circulation and Hadley circulation. These influences impact tropical cyclones and rainfall, whereas anomalous upper-level divergence due to tropical rainfall anomalies leads to Rossby waves that impact the extratropics.

Prediction based on these teleconnections requires predictable sea-surface temperature (SST) anomalies. On seasonal time scales, tropical SST anomalies are dominated by ENSO. ENSO SST anomalies are largely predictable out to a year, particularly in winter and early spring, and sometimes out to two years.

S2D atmospheric predictability also arises from longer time-scale processes over land, mainly involving soil moisture and vegetation. These highlight the need for land surface initialization and realistic vegetation models.

An additional source of S2D predictability is variations in radiative forcing, which provide significant skill on multiyear time scales. Much of this skill arises from changes in greenhouse gases.

Modeling issues

More S2S models are incorporating ocean and sea ice components, improving representation of coupled processes and enhancing forecast skill. Ocean coupling can improve MJO propagation and enhance subseasonal prediction. Improvements in cloud parameterizations and in representing the diurnal cycle of the atmospheric boundary layers also are crucial for advancing S2S modeling, as are improved observations of the stratosphere, including aerosols and chemistry.

Poor vertical resolution, low model lid height, inadequate gravity wave parameterizations, and biases in the tropospheric mean state (e.g., the location of stationary Rossby waves) could limit the predictive skill from stratosphere–troposphere coupling, but prediction systems have rapidly improved in many of these areas.

Modeling issues for S2D prediction naturally overlap with those for S2S prediction. However, S2D prediction emphasizes representing slower climate variations such as ENSO, and reducing model biases in the ocean that may take months to years to develop becomes crucial. Model biases are common across prediction time scales and systems. Increased model resolution can reduce model biases, though computational cost is a constraint. Innovative bias correction methods include multiple models exchanging information during a simulation. Tackling these diverse and persistent modeling issues should involve coordination between the S2S/S2D prediction, climate modeling, and data assimilation communities.

Initialization issues

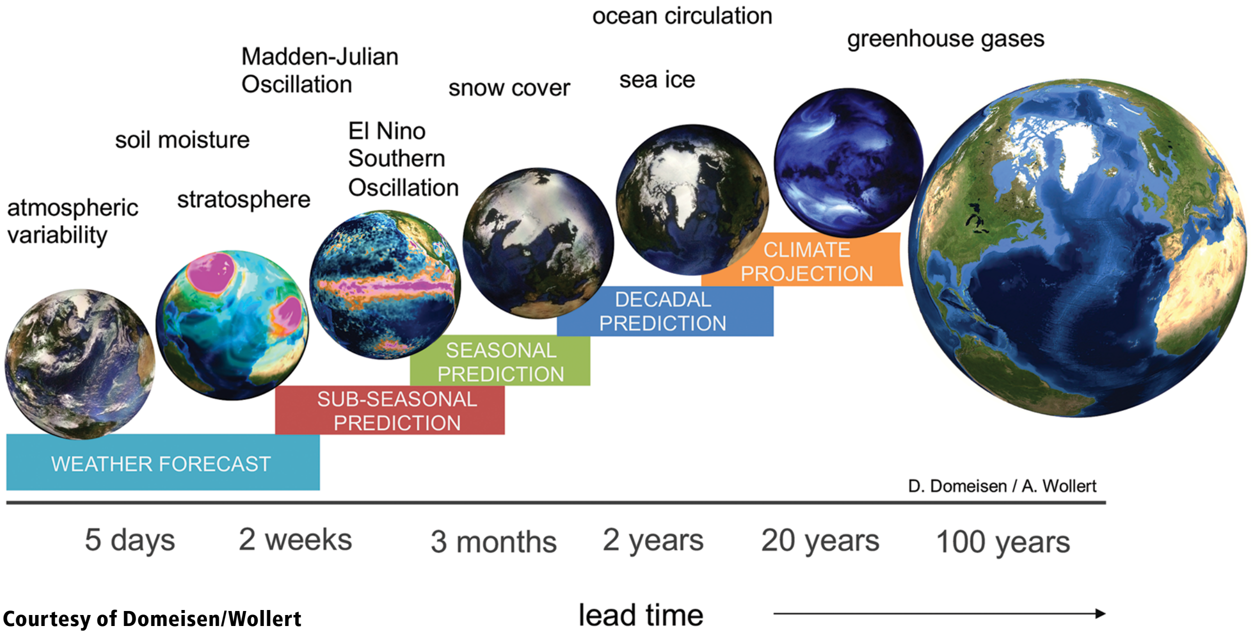
Subseasonal and seasonal prediction systems generally initialize their atmospheric components with observations, similarly to numerical weather prediction. Because atmospheric initial conditions contribute less to predictability on multiannual time scales, some decadal prediction systems do not initialize the atmosphere.

Climatically important land variables can be initialized by assimilation of observations, principally from satellites, although long-term continuity is needed; realistic snow initialization can positively impact subseasonal predictions of surface temperatures. Historically, land surface and atmospheric models are developed separately so that coupled processes are often not represented accurately.

The importance of initializing the oceans stems from their relatively long thermal and dynamical time scales, through which they are essential to S2D climate predictability. Recent advancements in observing enable improvements in ocean and sea ice state estimates, potentially leading to better forecasts.

The components of climate prediction models have often been initialized individually, without coupling. However, this does not make optimal use of observations. Efforts are thus underway to develop coupled data assimilation methods that simultaneously use observations from multiple components, such as the atmosphere and ocean.

Finally, initialization shocks that arise from imbalances in initial states are a major issue, particularly in decadal predictions.



Courtesy of Domeisen/Wollert

Ensemble predictions and forecast information

In contrast to ensemble weather forecasts, a consolidated verification strategy for S2S predictions is not yet established, and developing such a framework is a priority. One purpose of S2S hindcasts is to provide a larger sample for more confident verification statistics. However, because S2S hindcasts are initialized using reanalysis and most often have a smaller ensemble size, their verification generally underestimates real-time forecast quality.

S2S ensemble forecasts have shown promise in providing useful predictions for high-impact events including severe heat waves and cold spells, as well as regional probabilities of the occurrence of tropical storms. Furthermore, S2S multimodel ensembles generally outperform individual models.

Limited forecast quality in current S2D ensemble prediction systems motivates research on extracting skillful and reliable information from large amounts of forecast and hindcast data. One emerging theme of such research is that S2D prediction systems sometimes underestimate the predictable signal. As a result, very large ensembles that effectively filter out unpredictable noise demonstrate higher skill in predicting phenomena such as the winter North Atlantic Oscillation and seasonal to multiannual regional precipitation variations than was previously thought possible. While very large ensemble sizes can isolate weak predictable signals, much smaller ensemble sizes are sufficient for skillful prediction of tropical SST variations, which have larger signal-to-noise ratios.

Climate forecasts for decision-making

Continued development of S2S forecasts has the potential to benefit the many societal decisions made at that time scale. Improved dialogue between S2S forecasters, developers, and end users will accelerate the awareness and application of S2S forecasts.

While research efforts are assessing the value of S2D forecast information for many applications, such as fisheries management, consultation with decision-makers is essential in order to tailor forecast information to the needs and expectations of users.

Application-oriented research is also focused on water management. Global climate prediction models have shown skill in predicting the next winter's snowpack in much of the western United States. Because temperature influences snowmelt and runoff, skillful seasonal temperature forecasts can improve this region's water supply forecasts.

Additional sectors for which S2D forecasts are being assessed for decision-making include agriculture, energy demand and generation, tropical cyclone and coastal flooding preparedness, Arctic marine transportation, wildfire risk, and food security. For all such applications it is vital that uncertainties be adequately quantified and conveyed.

Finally, postprocessing is an important area of research. Postprocessing is necessary because biases in forecasts can be as large as the predicted signal, and therefore real-time predictions must be adjusted before delivery to users. These requirements are shared across subseasonal to decadal prediction time scales.

Conclusions and the future of subseasonal to decadal prediction

Earth's weather and climate are inherently chaotic. Realizing untapped prediction skill will require improvements on numerous fronts. These include fundamental understanding of fine-scale processes, leading toward their robust parameterization; accurately representing property exchanges across Earth system components through realistic coupling limiting systematic errors; sustained Earth observing systems and advanced data assimilation methods enabling balanced initial conditions that avoid shocks and mitigate model drifts; and innovative numerical and ensemble generation techniques to address model scalability issues. Additional important avenues toward improved services include development of probabilistic information for high-impact weather and climate events, and optimal postprocessing and data fusion to add value to multimodel ensembles, among many others.

These challenges are broad, but so are opportunities for steady progress across time scales, ranging from curiosity-driven science to the systematic model evaluation and improvement in a collaborative and open research/operational environment. ⁂

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BAMS: What would you like readers to learn from this article?

William Merryfield (Environment and Climate Change Canada): *The science of subseasonal to decadal climate prediction, although much younger than weather prediction, is developing rapidly and approaching a mature state in which research is enabling services across this range of time scales.*

Daniela Domeisen (Institute for Atmospheric and Climate Science, ETH Zurich): *Traditionally, forecasts have been made a few days in advance, followed by long-term climate predictions out to centuries. There is, however, significant potential for all time scales in between, from weeks to decades (S2D). While we're just starting to understand how to make predictions for these time scales, we already have some success stories. In turn, both short-term weather and long-term climate prediction can learn from S2D prediction.*

BAMS: How did you become interested in multiple scales of forecasting?

WM: *It's been something of a journey. My graduate work was in astrophysics, and at one point I had the opportunity to migrate to physical oceanography, which was easy because my hydrodynamics codes could be applied with only minor changes. Few areas in the physical sciences have such direct paths to benefitting society, and that appealed to me. Physical oceanography in turn led to research in ocean modeling, coupled climate modeling, and finally application of these models to climate prediction.*

DD: *There is enormous potential and there are countless applications for forecasts beyond two weeks, and any information that is put out there will be used—so in the weather and climate community we'd better make sure we understand the biases and the uncertainty of these predictions, and we communicate them accordingly.*

BAMS: What surprised you the most in preparing this synthesis article?

WM: *These conferences brought into perspective how much this field has expanded, both in breadth and numbers, since I became involved a little over a decade ago. The many early-career scientists who were represented is a strong indicator that the field will remain vigorous for many years to come.*

BAMS: What was the biggest challenge of writing the article?

WM: *In the synthesis for this paper, the biggest challenge was distilling the state of the science from the hundreds of presentations at two coordinated international conferences. This was enabled by session notes and summaries provided by 64 coauthors. While enormously helpful, it was still quite challenging to blend these many excellent contributions into a cohesive article.*

BAMS: What's next?

DD: *We are now working to investigate in more detail the potential to predict extreme events on time scales beyond two weeks, which is crucial for emergency preparedness. Furthermore, we continue to explore potential applications for S2D forecasts.*