REPORT IN BRIEF
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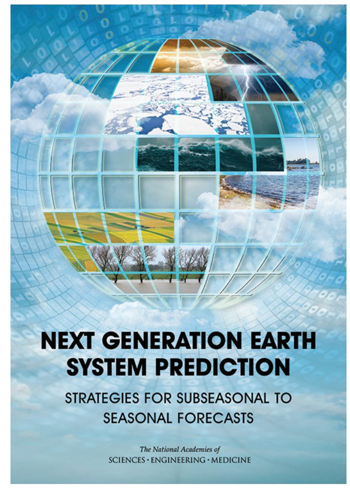
Board on Atmospheric Sciences and Climate
Ocean Studies Board

DIVISION ON EARTH AND LIFE STUDIES

Next Generation Earth System Prediction

Strategies for Subseasonal to Seasonal Forecasts



Extending weather and ocean forecasts to predict Earth system conditions weeks to months in advance will help decision makers plan ahead to save lives, protect property, and increase economic vitality—but, currently, the accuracy, skill, and scope of such extended forecasts is limited. This report presents the vision that, in the next decade, subseasonal to seasonal forecasts (those made two weeks to 12 months in advance) will be as widely used as short-term weather forecasts are today. To advance toward that vision, the report presents a research agenda that emphasizes increasing the skill of forecasts; expanding the breadth of forecast models and variables; improving the prediction of extreme and disruptive events; and bringing researchers and decision makers together to develop more actionable forecasts.

Over the past several decades, short-term forecasts—those that predict conditions in the atmosphere and ocean a few hours to a few days ahead—have become a vital part of decision making. Governments, businesses, and individuals routinely use such forecasts to plan the days ahead: Should a school system cancel classes tomorrow due to snowy conditions? Will ocean conditions this afternoon allow for Navy exercises to test wave-sensitive equipment? How much power will electric utilities need to meet air conditioning demands this week?

However, many critical planning and management decisions are made weeks to months in advance (see Figure 1). Improved subseasonal to seasonal (S2S) forecasts—defined in this report as those made two weeks to 12 months in advance—could better inform those decisions, helping to save lives, protect property, increase economic vitality, and protect the environment. For example, emergency planners could pre-stage supplies in the areas most likely to experience extreme weather in the following months. Naval and commercial shipping routes could be planned to take advantage of favorable conditions predicted for the weeks ahead. Farmers could purchase drought- or flood-resistant seed varieties as needed to increase yield for the next growing season.

Improved subseasonal to seasonal forecasts will inform critical planning and management decisions that must be made weeks to months in advance.

Given the great potential of S2S predictions to strengthen planning and decision making across many sectors, and the technical feasibility of rapidly improving S2S forecasts, the report authoring Committee's vision is that **S2S forecasts will be as widely used a decade from now as weather forecasts are today.** This report sets out a research agenda to guide progress towards that vision.

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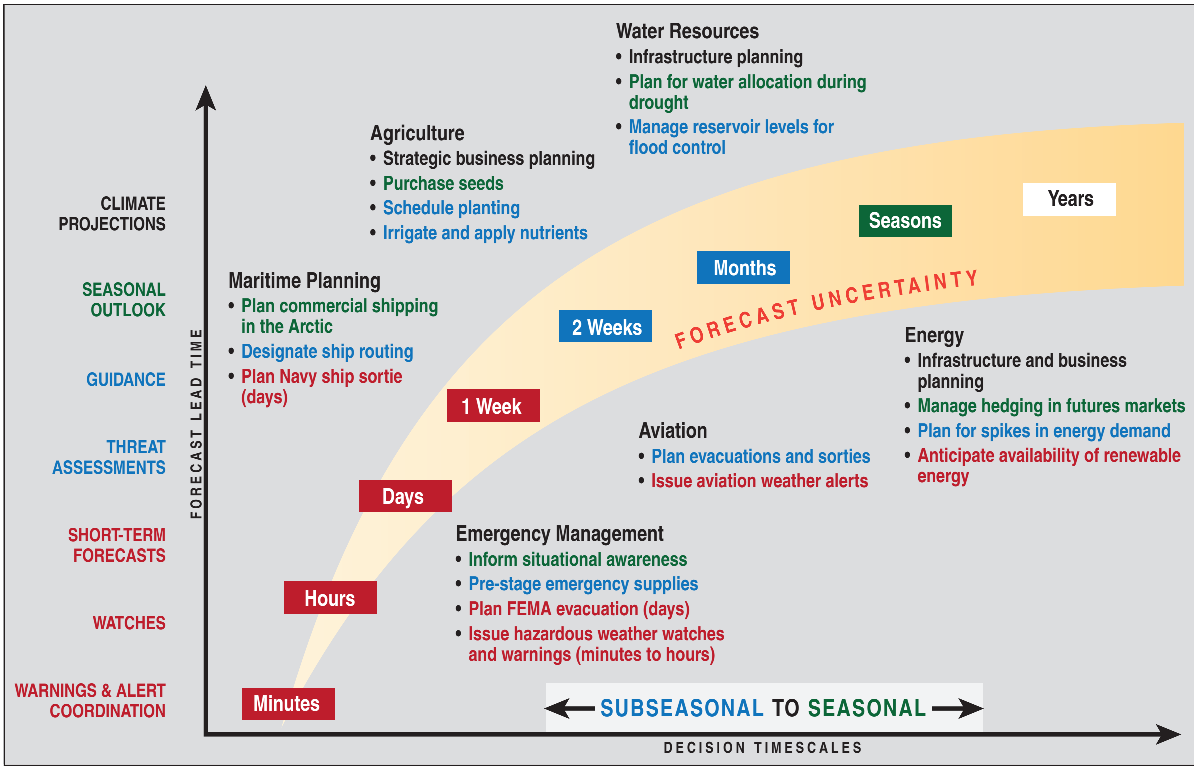

Figure 1. *S2S forecasts (shown in blue and green) fill a gap between short-term weather and ocean forecasts (shown in red) and longer-term Earth system projections (shown in black). They inform critical decisions (also shown in blue and green) across many different sectors by providing information about likely conditions between these more established prediction times.*

SOURCE: Modified from the Earth System Prediction Capability Office.

A RESEARCH AGENDA FOR S2S FORECASTING

Currently available S2S forecasts have already proven useful in the agriculture, energy, and water resource management sectors. Overcoming a number of remaining knowledge, resource, and organizational challenges will help make these forecasts much more widely beneficial to society.

S2S forecasts fall in a “gap” between today’s short-term forecasting capabilities and a growing ability to project the longer-term climate. To date, S2S forecasting efforts have not received the same focused attention as research and forecasting programs on weather or climate change timescales.

Reaching the Committee’s bold target for S2S forecasting in the next decade will require improvements in modeling, in the Earth observing network, and in understanding of sources of S2S predictability—processes in the atmosphere, ocean, or land that influence the Earth system in predictable ways. Other factors that must be addressed to improve the use and skill of S2S forecasts include lack of understanding and interaction with user communities, and a need for better supporting infrastructure such as computing power and a specialized workforce. The Committee proposes four research strategies and 16 recommendations for accelerating progress on S2S forecasting.

Research Strategy 1: Engage Users in the Process of Developing Subseasonal to Seasonal Forecast Products

It can be difficult for decision makers to translate currently-available S2S forecasts into action. For example, seasonal forecasts are often presented in terms of the probability of departure from average conditions over a three month period, which can be difficult to relate to specific decisions that depend on the timing, magnitude, and frequency of events within that forecast window.

Social and behavioral science research to better understand how current S2S forecasts are being used—and the barriers to expanding their use—is an important step towards improving S2S forecasts. Engaging S2S researchers and decision makers in an iterative, ongoing dialogue will help ensure that S2S models, forecast products, and decision making tools are created to match what is technically feasible with what is most useful to a diverse set of stakeholders.

Research Strategy 2: Increase Subseasonal to Seasonal Forecast Skill

S2S predictions rely on understanding sources of Earth system predictability (see Box 1). Basic research to expand understanding of these sources and their interactions, as well as research to determine the limits of predictability for specific Earth system phenomena, is key to improving Earth system models that are used to make S2S predictions.

Increasing forecast skill will also require improvements in all parts of the S2S forecast system, including expanding observations and improving data assimilation methods, reducing errors in Earth system models, improving methods for quantifying and addressing forecast uncertainties, and verifying forecast accuracy.

• *Observations*

Earth observations are essential for initializing models to more accurately reflect the state of the Earth system, for validating model output, and for contributing to improved understanding of Earth system predictability. However, observations of several major sources of S2S predictability—including the ocean, land, and ice—are lacking. Maintaining and in some cases bolstering routine observations of the Earth system is critical to advancing S2S prediction skill. Observing system simulation experiments (OSSEs) and other sensitivity studies should be better utilized to help prioritize observations that are the most important for improving S2S predictions.

• ***Data Assimilation***
Data assimilation is the challenging process of integrating tens of millions of observations into Earth system models. In particular, data assimilation methods that capture the interactions, or "coupling," among components of the Earth system, are important for strengthening S2S predictions. Research to develop and test the potential of new approaches ("strongly-coupled") that could spur a more dramatic leap forward should be pursued, while continuing to implement existing ("weakly-coupled") methods operational in current S2S forecast systems.

• ***Models***
Systematic errors are numerous within Earth system models and can be large compared to the signal of S2S predictability. Increasing model resolution can help reduce some of these errors, but the computational costs of such efforts are high and many errors are likely to remain. Thus, many critical Earth system processes will need to be parameterized – that is, represented using simplified equations, rather than being explicitly resolved in the model – for the foreseeable future. Improving physical parameterizations is thus fundamental to reducing model errors and increasing S2S forecast skill, and will require coordinated, coupled field campaigns, process-targeted satellite missions, and better collaboration between research and operational scientists.

• ***Calibration, Combination, Optimization and Verification***
Even with major improvements in Earth system models, some model errors will remain. Using multi-model ensembles (MMEs)—combining the output from more than one model—has demonstrated potential for improving the skill of S2S forecasts in research settings.

However, optimizing the configurations of MME forecast systems will require substantial effort to explore the benefits and costs of adding unique models to an MME, and evaluate other S2S forecast system design elements, including calibration methods, model resolution, number of ensemble members, retrospective forecasts, and options for coupled sub-models.

Verifying S2S forecasts is important for tracking and comparing model improvements, and is also essential to building user trust. Feature-based verification—which verifies forecasts based on specific features in the Earth system—is a promising method which should be pursued. Understanding the different ways users interpret forecasts will also help inform the development of improved verification metrics.

Box 1. Sources of Predictability in the Climate System

S2S predictability originates from:

- **Natural modes of variability**–e.g., atmospheric and coupled atmospheric-oceanic processes such as the El Niño-Southern Oscillation, the Madden-Julian Oscillation, and the Quasi Biennial Oscillation;
- **Slowly-varying processes**–e.g., soil moisture, snow pack and other aspects of the land surface, ocean heat content, currents and eddy positions, and sea-ice; and
- **Elements of external forcing**–e.g., aerosols, greenhouse gasses.

Box 2. Water Management in the Western United States

Winter precipitation makes up most of California's annual water budget. Water managers rely on real-time data, weather forecasts, and a sparse network of snowpack measurements to estimate spring run-off and coordinate flow between reservoirs, aqueducts, and groundwater storage facilities to meet the water needs of the drought-prone state's 38 million residents, 9 million acres of agricultural lands, and hydroelectricity industry.

S2S forecasts have the potential to be more widely used by water managers across the country: the spatial resolution of currently available forecasts is often inadequate for quantitative use, and it may not be obvious when forecast products have higher skill, such as during a strong El Niño event. Further, institutional barriers can limit the use of forecast information that comes from sources other than federal agencies.

Improved S2S forecasts could provide a better basis for many of these decisions. For example, more skillful and relevant seasonal forecasts could help water managers understand the potential for multi-year droughts. On the subseasonal scale, several weeks' notice of a potential atmospheric river event—when a narrow corridor of concentrated atmospheric moisture causes extreme precipitation—would help water managers anticipate when winter droughts might end and would also better inform management of reservoir levels to avoid flooding.

Figure 2. *Recent drought has had a severe impact on water availability in California, and water levels have been exceedingly low in many CA reservoirs. Here, water levels over a section of Lake Oroville near the Bidwell Marina are shown on July 20, 2011 (left) versus on January 16, 2014 (right). Such scarcity has heightened the need for more skillful and useful S2S forecasts.*

SOURCE: California Department of Water Resources.

• ***Moving research to operations***

Translating new ideas, tools, and technologies from the S2S research community to the operational centers that issue routine forecasts is essential to link research advances to more informed decision making. Allowing researchers access to operational systems would help in the transfer of model components and parameterizations to operational systems; at the same time, operational centers should build on knowledge gained in exploring optimum S2S forecast system configurations to accelerate the development of an operational multi-model ensemble.

Research Strategy 3: Improve Prediction of Extreme and Disruptive Events and of the Consequences of Unanticipated Forcing Events

Extreme events such as major winter storms, excessive rainfall events, and intense heat waves can often disrupt society's normal functioning. Improved predictions of such events on S2S timescales would give communities more time to plan ahead and mitigate damage.

Forecasting extreme events often involves identifying windows of time when certain interactions between Earth system processes boost the likelihood that such events will take place. Studying these interactions and ensuring they are represented in S2S forecast systems will be important for increasing the use and benefits of S2S predictions. Another important aspect of developing S2S forecast systems is to enhance capacity to predict the consequences of non-climate related disruptive events, such as volcanic eruptions, widespread fires, or large oil spills.

Research Strategy 4: Include More Components of the Earth System in Subseasonal to Seasonal Forecast Models

Major Earth system components such as the ocean, atmosphere, ice, and land are now routinely included in coupled Earth system models used for S2S forecasting. Enhancing the sophistication of model components outside the atmosphere–which has been the focus of weather forecasting – and improving their coupling is critical to advance the skill of S2S forecasting. Further benefits are likely from including additional components, such as waves, aerosols, rivers, and vegetation. Expanding S2S forecast systems to include more variables, such as sea-ice characteristics, air quality, seasonal vegetation state, can also help to make S2S forecasts more widely applicable to decision making.

SUPPORTING THE SUBSEASONAL TO SEASONAL FORECASTING ENTERPRISE

The sheer volume of observational data, data assimilation steps, and model outputs involved in S2S forecasting tests the limits of current cyber-infrastructure. Similar to climate modeling, S2S forecasting would benefit from a national plan and investment strategy to take better advantage of current hardware and software, and to meet challenges associated with the transition to new hardware systems.

The growing S2S field also needs a workforce able to cross traditional disciplinary boundaries within the Earth sciences, between computing and physical science fields, and to bridge the researcher-decision maker divide. Meeting workforce needs will involve improving training and incentives to recruit new professionals and to retain and support existing professionals in these fields.

THE PATH FORWARD

Basic and applied research, closer collaboration between federal agencies and international partners, better communication between the research, forecasting, and stakeholder communities, and engagement of the entire weather and climate enterprise will be required to reach the bold vision set forth in this report. With sustained effort and investment, the Committee believes that S2S forecasting has the potential to yield substantial benefits to a wide range of users within the next decade and beyond.

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The National Academies of Sciences, Engineering, and Medicine appointed the above committee of experts to address the specific task requested by the Office of Naval Research, the National Aeronautics and Space Administration, the Heising-Simons Foundation, and the National Academy of Sciences. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the Academies. This report brief was prepared by the Academies based on the committee's report.

For more information, contact the Board on Atmospheric Sciences and Climate at (202) 334-3512 or visit **at http://dels.nas.edu/basc**. Copies of *Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts* are available from the National Academies Press, 500 Fifth Street, NW, Washington, DC 20001; (800) 624-6242; or as free PDFs at **www.nap.edu**.