REPORT TO CONGRESS

SUBSEASONAL AND SEASONAL FORECASTING INNOVATION: PLANS FOR THE TWENTY-FIRST CENTURY

Developed pursuant to:
Section 201 of the Weather Research and Forecasting Innovation Act of 2017,
(Public Law 115-25)

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SECTION 201 OF THE WEATHER RESEARCH AND FORECASTING INNOVATION ACT OF 2017, PUBLIC LAW 115-25, INCLUDED THE FOLLOWING LANGUAGE

‘‘(c) FUNCTIONS.—The Under Secretary, acting through the Director of the National Weather Service and the heads of such other programs of the National Oceanic and Atmospheric Administration as the Under Secretary considers appropriate, shall—

> *(1) Collect and utilize information in order to make usable, reliable, and timely foundational forecasts of subseasonal and seasonal temperature and precipitation;*
> *(2) Leverage existing research and models from the weather enterprise to improve the forecasts under paragraph (1);*
> *(3) Determine and provide information on how the forecasted conditions under paragraph (1) may impact—*
>> *(A) The number and severity of droughts, fires, tornadoes, hurricanes, floods, heat waves, coastal inundation, winter storms, high impact weather, or other relevant natural disasters;*
>> *(B) Snowpack; and*
>> *(C) Sea ice conditions; and*
>
> *(4) develop an Internet clearinghouse to provide the forecasts under paragraph (1) and the information under paragraphs (1) and (3) on both national and regional levels.”*

Further, under Title II, Section 201(h) Congress requests a report to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science, Space, and Technology of the House of Representatives. This report shall include:

> *“A. an analysis of how information from the National Oceanic and Atmospheric Administration on subseasonal and seasonal forecasts, as provided under sub-section (c)* [quoted above]*, is utilized in public planning and preparedness;*
> *B. Specific plans and goals for the continued development of the subseasonal and seasonal forecasts and related products described in subsection (c)* [quoted above]*; and*
> *C. An identification of research, monitoring, observing, and forecasting requirements to meet the goals described in subparagraph (B).”*

THIS REPORT RESPONDS TO THE CONGRESSIONAL REQUEST

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EXECUTIVE SUMMARY

Over the past 20 years, the demand for subseasonal-to-seasonal (S2S) information has been steadily increasing as Federal, state, local, and tribal authorities seek to prepare for and reduce risk from meteorological events well in advance. *Subseasonal* is defined in PL 115-25, as the period from 2 weeks to 3 months, and *seasonal* ranges from 3 months to 2 years.

This report outlines the current use of National Oceanic and Atmospheric Administration (NOAA) S2S products and services, and how NOAA plans to improve the usability and transference of data, information, and forecasts. It will serve as a guidepost for NOAA planning and execution, as well as to inform the public and NOAA's stakeholders on its efforts on subseasonal and seasonal forecasting. It was developed with input from Federal, regional, state, tribal, and local government agencies, research institutions, and the private sector. The report starts by identifying current S2S products and services, and then outlines innovations needed to enable and improve them. Two main goals for improving products and services are: (i) improving the skill of foundational tools in order to improve the skill of the official S2S forecasts, and (ii) enhancing the value of S2S products for stakeholders.

As described in the report, NOAA's S2S forecasts and information are used by core partners, and it is the interaction with these partners that guides NOAA to improve the usability and transference of data, information, and forecasts. The coordination and communication of S2S related information is quite active and remains critically important to continue to build the NOAA S2S forecasting enterprise. NOAA also partners with other agencies through agreements, such as the National Earth System Prediction Capability (National ESPC), and derives research and development (R&D) benefits from such collaborations.

R&D for advances in scientific knowledge and mission capabilities are necessary to ensure NOAA can provide the information needed on subseasonal and seasonal timescales to support decision making for public planning, preparedness, and early warning; and meet rapidly expanding applications for subseasonal and seasonal forecasts and related products. R&D will need to focus on identifying opportunities to better exploit regional influences impacting S2S predictability and forecast skill. Advances in our understanding of physical processes operating within the Earth System will be needed to identify sources of predictability in models and take advantage of known sources of S2S predictive skill. Opportunities for improvement include more carefully estimating the initial state of the ocean, the land surface, and polar ice conditions. Advances are needed for forecast systems, including multi-model ensemble forecast systems, to be able to predict the evolution of the coupled land-atmosphere-ocean-sea ice system, to correctly provide an estimate of the most likely state of the system, and to determine the uncertainty in the forecast. S2S forecast verification and evaluation research will be important to better understand forecast limitations and identify forecast opportunities where we can expect enhanced skill and reliability. In order to function most effectively, there will need to be changes in how the components of the S2S enterprise (research, transition to operations, operations, public sector, academia, and private sector) work together.

The Weather Research and Forecasting Innovation Act of 2017 (WRFIA or the "Weather Act") instructs NOAA to prioritize improving weather data, modeling, computing, forecasting, and warnings for the protection of life and property and for the enhancement of the national economy. The reauthorization of the WRFIA in January 2019 instructs NOAA to establish the Earth Prediction Innovation Center (EPIC) to accelerate community-developed scientific and technological enhancements into the operational applications for numerical weather prediction. EPIC will be used as NOAA moves forward with S2S model enhancements.

In accordance with WRFIA and other public laws and directives (see Section VII, References), in November 2019, NOAA released and is implementing cloud data, artificial intelligence (AI) and unmanned systems (UxS) strategies that will advance our S2S forecasting efforts. Using these tools, NOAA will improve its weather observations and their processing, and augment data collection, often at lower cost, increased safety, and reduced risk. Greater computational power will reduce both processing time and agency costs. Using "commercial" cloud computing offers many potential benefits to NOAA, from cataloging, quality controlling, and processing of observations, to research and development of new S2S models leveraging both private sector and academic sector R&D efforts and ingenuity.

AI also offers advances to streamline NOAA's mission delivery. For example, potential AI advances include: aerial and underwater surveys from ships and autonomous platforms; quality control of weather observations; improving physical parameterization for weather, ocean, ice modeling, and improving the computational performance of numerical models; automating weather warning generation; operation of unmanned systems for surveys; using machine learning to analyze satellite imagery for severe weather detection, oil spills, hazardous material trajectory, wildfire detection and movement, and more; and more efficient processing, interpretation and use of observations. Each of these tools promotes greater internal and external collaboration, which can expand communities of practice, improve consistency, and provide templates to partners. As we implement our cloud, AI and UxS strategies, we will further our lifesaving and economically impactful missions, and strengthen our role as scientific and technological leaders.

End users of S2S information are critical partners in this endeavor to move forward with our S2S predictions. They have varying missions and will use the information in different ways. From region to region across the country, and for decision makers within each region, S2S forecasts are only beneficial if they are presented in a way that can and will be used to meet their respective needs. Social and behavioral science research is critical to provide a better understanding of how to effectively communicate information to various audiences on the uncertainties inherent in S2S forecasts. As forecasts have improved, so has our understanding of some of the needs of decision makers, as well as how to deliver this information in ways to inform decisions. In order to continue to increase impact and use of these data, and further address the needs of decision makers, NOAA understands that they must incorporate methods obtained through the social and behavioral sciences to best communicate risk and uncertainty. NOAA social scientists are working on more advanced ways to understand communities' needs, such as conducting studies on changing risk perception and the value of scientific information. Future activities that embrace these societal aspects will enhance the use and applicability of weather data, forecasts, and information.

Our society continues to change and become more vulnerable to the impacts from extreme S2S influenced weather events, including tornadoes, hurricanes, snow, blizzards, heat, cold, drought, fire, sea ice, inundation, and floods. Improved S2S prediction is a critical component to enable informed decision-making, and to adequately address extreme events ranging from drought to flooding and heat to cold. As our S2S predictive capability improves, stakeholders and decision makers at all levels will have better information to make informed decisions to save lives and property and enhance the national economy. This report provides the guidelines to achieve these goals.

SUBSEASONAL AND SEASONAL FORECASTING INNOVATION: PLANS FOR THE TWENTY-FIRST CENTURY

I. Introduction

This report is provided in response to the requirement under Title II, Section 201(h)(1) of the United States Congress enacted P.L.115-25, with the short title, "Weather Research and Forecasting Innovation Act of 2017," enacted on April 18, 2017, and referred to herein as the "Weather Act." The S2S portion of the bill was reauthorized under the 2019 National Integrated Drought Information System (NIDIS) Reauthorization Act. The stated purpose of the Act is, "To improve the National Oceanic and Atmospheric Administration's weather research through a focused program of investment on affordable and attainable advances in observational, computing, and modeling capabilities to support substantial improvement in weather forecasting and prediction of high impact weather events, to expand commercial opportunities for the provision of weather data, and for other purposes."

Title II, Subseasonal and Seasonal Forecasting Innovation, includes the following language:

''(c) FUNCTIONS.—The Under Secretary, acting through the Director of the National Weather Service and the heads of such other programs of the National Oceanic and Atmospheric Administration as the Under Secretary considers appropriate, shall—

> (1) Collect and utilize information in order to make usable, reliable, and timely foundational forecasts of subseasonal and seasonal temperature and precipitation;
> (2) Leverage existing research and models from the weather enterprise to improve the forecasts under paragraph (1);
> (3) Determine and provide information on how the forecasted conditions under paragraph (1) may impact—
>> (A) The number and severity of droughts, fires, tornadoes, hurricanes, floods, heat waves, coastal inundation, winter storms, high impact weather, or other relevant natural disasters;
>> (B) Snowpack; and
>> (C) Sea ice conditions; and
>
> (4) Develop an Internet clearinghouse to provide the forecasts under paragraph (1) and the information under paragraphs (1) and (3) on both national and regional levels."

The Weather Act defines subseasonal as the period from 2 weeks to 3 months, and seasonal as the period from 3 months to 2 years. Note that herein "Subseasonal to Seasonal," or alternately

"Subseasonal and Seasonal," will be referred to as "S2S" as is the common practice in the scientific community.

Title II, Section 201(e)(2) calls for the Under Secretary to build upon existing forecasting and assessment programs and partnerships, including "by contributing to the interagency Earth System Prediction Capability." The National ESPC draws together prediction and research efforts from days to 30 years from multiple agencies. The S2S effort within NOAA represents part of the agency's contribution to that partnership, and benefits from innovations derived through it.

Further, under Title II, Section 201(h)(1), Congress requests a report to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science, Space, and Technology of the House of Representatives, no later than 18 months after the enactment of the Weather Act (18 October 2018). This report shall include:

A. An analysis of how the information from the National Oceanic and Atmospheric Administration on subseasonal and seasonal forecasts, as provided under sub-section (c) [quoted above], is utilized in public planning and preparedness;
B. Specific plans and goals for the continued development of the subseasonal and seasonal forecasts and related products described in subsection (c) [quoted above]; and
C. An identification of research, monitoring, observing, and forecasting requirements to meet the goals described in subparagraph (B).

This Report to Congress is the summary of a comprehensive analysis, which is available for more detailed information and reference. In addition to meeting the reporting requirement requested by Congress, these documents will also serve as a guidepost for NOAA planning and execution, as well as to inform the public and NOAA's stakeholders, on its efforts on S2S forecasting.

I A. Background

The Organic Act of 1870 established the Weather Bureau of the United States with authority and responsibility for forecasts and warnings. Responsibilities also included collection of meteorological observations that ultimately formed the basis for the historical climate record of the United States. Weather forecasts are produced out to 7 days daily, and longer range probabilistic S2S predictions produced by the National Weather Service (NWS) are currently available out to 13 months.

Improvements in numerical weather prediction and our understanding of the major modes of variability over the past 20 years has steadily increased the demand for S2S information. Federal, state, local, and tribal authorities seek to prepare for and reduce risk from meteorological events ranging from weeks to seasons in advance. Industries, such as tourism, insurance, commerce, water management, agriculture, financial markets, and transportation, will all benefit from improved extended weather (i.e., S2S) information for decision-making, planning, and efficient conduct of commerce. Critical user needs include improved precipitation forecasts for water-supply management, actionable information on anticipated droughts to prepare for impacts such as crop loss and famine early warning, accurate forecasts of sea-ice changes that will affect Arctic transportation and environmentally safe mineral extraction, and fire-weather forecasts.

The S2S forecast endeavor is inherently challenging. Much of the skill that is possible with shorter-lead numerical weather predictions reflects the information content of the current state of the atmosphere, such as a careful definition of the position of the jet stream. Unfortunately, the mathematically unavoidable geometric growth of even the smallest initial errors (the so-called "chaos effect") in the atmospheric state makes pinpointing the details of weather predictions increasingly difficult for longer-lead forecasts. Most of the achievable skill of atmospheric forecast variables (temperature, winds, and precipitation) at the longer S2S time scales can be traced back to information from the other components of the environment, such as the ocean and soil states (see Figures 1, 2). These other components provide enormous sources or sinks of energy that change more slowly over time and modulate atmospheric weather patterns, whereas the surface components have more or less energy than average and that varies in time. For example, with El Niño, the anomalously warm ocean-surface temperatures are in the eastern Pacific; with La Niña, the anomalously warm ocean-surface temperatures are in the western Pacific. These affect the location and frequency of tropical thunderstorms and cyclones which, in turn, affect the positioning of the jet stream that affects U.S. weather. Similarly, unusually moist initial soil conditions in the central United States may result in a positive feedback loop causing more summer rainfall and less hot temperatures as more of the solar energy evaporates water rather than heating the surface. Early-winter Siberian snow cover is hypothesized to modulate the wintertime climate over North America via changes to the storm track.

To realize the full predictive potential across S2S lead times, models must leverage the information content in the land, ocean, and sea ice (Figure 2). It is essential to develop these highly precise coupled prediction systems that accurately estimate the initial state of the ocean, sea ice, and land state (including snow cover), and the evolution of their complex interactions with the atmosphere during the forecast. This, in turn, requires a comprehensive understanding of how these physical interactions work, a codification of this understanding into computer algorithms, the generation of these very computationally intensive calculations on high-performance computers, and their statistical adjustment before use by weather forecasters and customers.

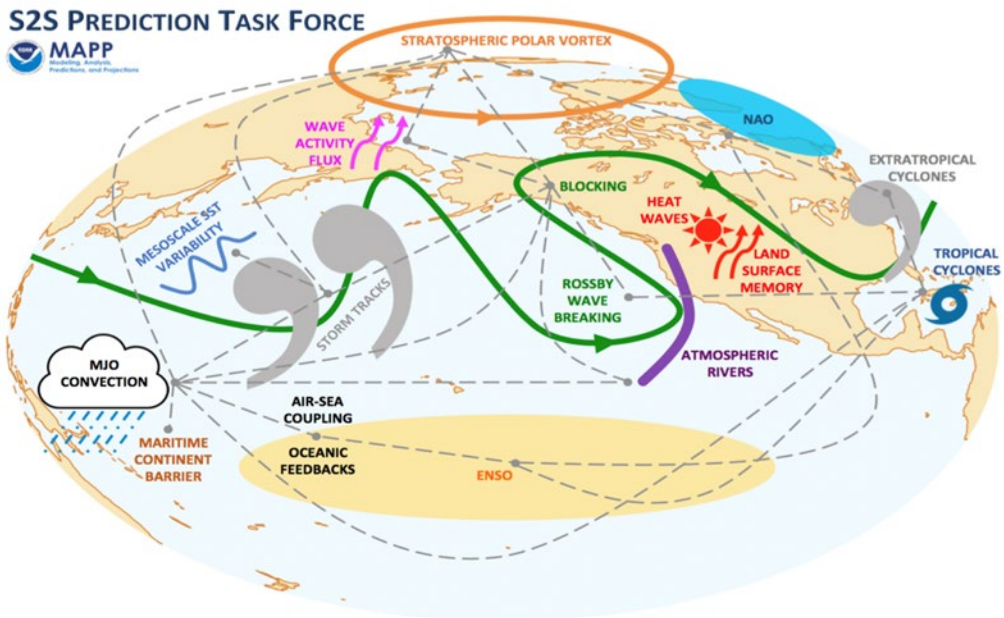

Figure 1: A conceptual illustration of the complex interconnections between weather phenomena and various low-frequency sources of variability. Figure prepared by Cory Baggett, Colorado State University, with input from the NOAA/CPO/MAPP S2S Prediction Task Force.

Section II of this report describes NOAA's current set of organizations and products that contribute to S2S development, and how they are used in public planning. Section III follows with plans and goals for the continued development of S2S forecasts and related products. Section IV provides a brief overview of the research, monitoring, observing, and forecasting requirements needed to meet the goals. Section V describes the procedure for obtaining input for this report from government, academic, and private stakeholders. Section VI gives a brief summary; Section VII lists references; and Section VIII documents the acronyms used in the report and provides a list of potential future products that could be developed within the next 5- to 10-years, given sufficient investment and demonstration of skill.

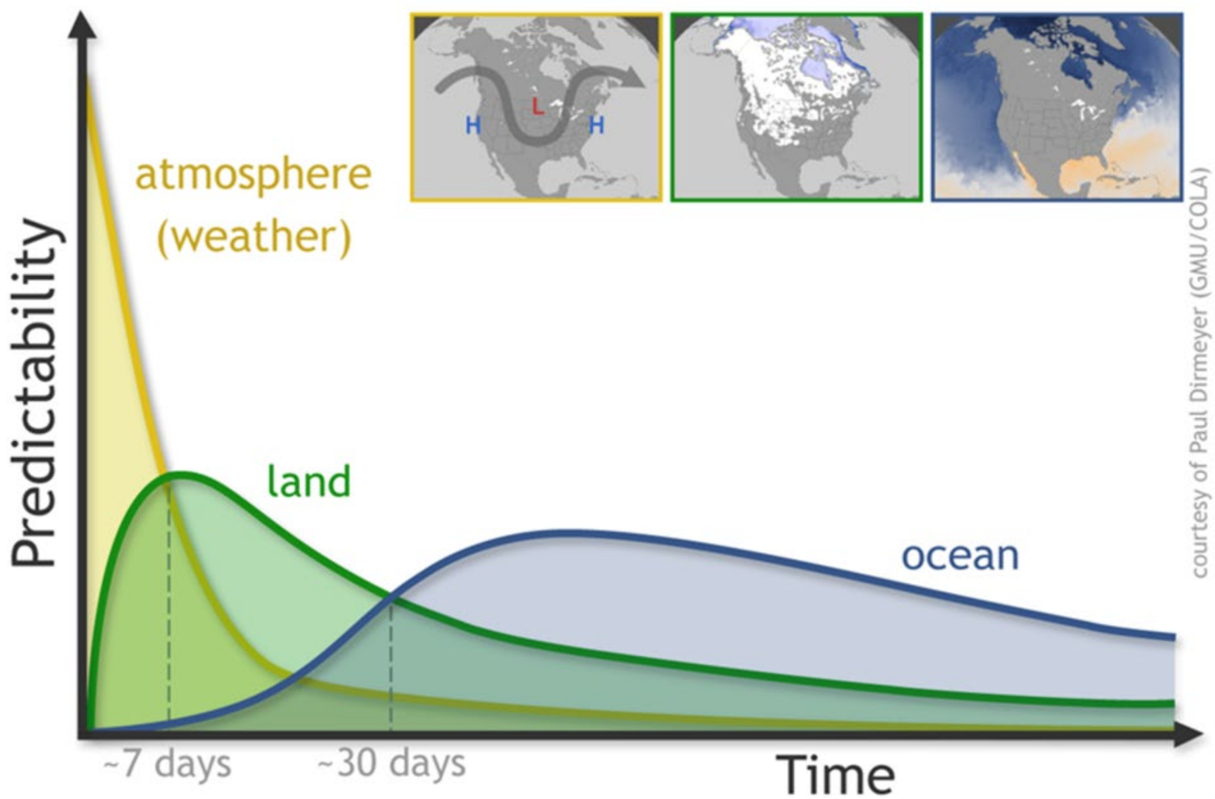

Figure 2: Illustration of how much variability can be explained from the atmospheric state (yellow), the land-surface state (green), and the ocean state (blue) over various forecast lead times (horizontal axis). At shorter lead times, the initial state of the atmosphere has the greatest impact on the prediction. At lead times of weeks to 1-2 months, the land-surface state provides a modest source of predictive skill. At lead times of 30 days and beyond, knowledge of the state of the ocean, in particular variations in the sea surface temperature, are the dominant source of skill.

II. CURRENT S2S PRODUCTS AND SERVICES

The NWS has undertaken product development and issuance of S2S outlooks and monitoring products since the early 1990s. Much of the NWS S2S product operations in these two key areas has been undertaken by the Climate Prediction Center (CPC) housed within the National Centers for Environmental Prediction (NCEP) in College Park, MD. Section 2 summarizes key components of the NOAA S2S product suite in the prediction and monitoring areas. A standardized approach was utilized for the summary information in Section 2.1, which briefly lists key aspects of each product.

Table 1: A list of the major S2S forecast products produced by NOAA.

Product Name	Forecast Variable(s)	Forecast Period	Release Frequency	Additional Information
Extended Range Outlook	Probabilities of different tercile classes of weekly mean temperature and total precipitation	Days 8-14	Daily	A 5-day mean forecast for Days 6-10 is also operationally produced at the current time
Week 3-4 Outlook	Probabilities of 2 classes (above-/below-normal) of two-week mean temperature and total precipitation	Days 15-30	Once per week	Released on Fridays
Monthly Outlook	Probabilities of different tercile classes of monthly mean temperature and total precipitation	~30 day period of upcoming month	Near mid-month, last day of month	An updated forecast for the upcoming month is released on the last day of each month
Seasonal Outlook	Probabilities of different tercile classes of 3-month mean temperature and total precipitation	~90 day period of upcoming 13 overlapping 3-month seasons	Near mid-month	The 13 overlapping seasons (3-months) result in a series of forecasts that extend out to ~1 year
U.S. Hazards Outlook	Potentially hazardous extremes related to temperature, precipitation, wind, flooding, severe weather and fire weather	Days 8-14	Daily	
Global Tropics Hazards and Benefits Outlook	Potentially hazardous / beneficial weekly tropical rainfall and temperature, elevated odds for tropical cyclogenesis	Week 1 and Week 2	Once per week	Released on Tuesday; Product updated on Fridays for northern Pacific and Atlantic areas during hurricane season

Monthly Drought Outlook	Net change in drought category as defined by the U.S. Drought Monitor	By the end of the upcoming month	Once per month	Released on last day of the month
Seasonal Drought Outlook	Net change in drought category as defined by the U.S. Drought Monitor	By the end of the upcoming 3 month season	Once per month	Released near mid-month
MJO Outlook	Briefing package (PDF file format of images and text) summarizing MJO current strength and forecast	Next 2 weeks	Once per week	Released on Monday
ENSO Diagnostic Discussion	Briefing package (PDF file format of images and text) summarizing current ENSO status and forecast	Next 8 overlapping 3-month seasons	Once per month	Released 2nd Thursday of each month
Seasonal Hurricane Outlook	Number of named storms, hurricanes and major hurricanes; Probability of seasonal activity overall (above-, below-, or near-normal) as defined by ACE	June through November	Late May, updated in early August	Outlook is produced for the northern Central and Eastern Pacific and the Atlantic Ocean
Monthly Sea Ice Forecast	Arctic monthly mean sea ice extent, sea ice concentration, sea ice melt and freeze dates. Both deterministic and probabilistic formats	Next 9 months	Once per month	
Seasonal Sea Ice Forecast	Arctic seasonal mean sea ice extent, sea ice concentration, sea ice melt and freeze dates. Both deterministic and probabilistic formats	Next 9 months	Once per month	

Famine Early Warning System (FEWS) Products	Outlooks for regions outside the U.S.: Regional hazards outlooks, seasonal temperature and precipitation outlooks, and Inter-Tropical Convergence Zone forecast	Week 1 and 2; Upcoming season; Weekly, respectively	Once per week; Once per month; Once per week, respectively	Additional critical information provided to FEWS includes satellite rainfall estimates, and dynamical model data and derived products
Office of Foreign Disaster Assistance (OFDA) Products	Similar to FEWS products but products primarily are post-processed dynamical model data that specifically focus on potential extreme events	Week 1 and 2; Upcoming season; Weekly, respectively	Once per week; Once per month; Once per week, respectively	
National Water Model (NWM) Long-Range Forecast	Streamflow, soil moisture, snow pack and related hydrologic states	30 days	4 x day	4 ensemble members produced 4 times per day, forming a 16-member daily ensemble
Advanced Hydrologic Prediction Service (AHPS) Ensemble Streamflow Forecasts	Probabilistic and exceedance graphics depicting chances of exceeding various river stage levels and categorical flood thresholds	90 days	Monthly, with daily updates as needed	Graphics available at ~3000 specific river locations and on the Long Range River Flood Risk Outlook national map

Table 2: S2S-relevant climate monitoring products.

Product Name	Parameters Monitored	Update Frequency	Additional Information
U.S. Drought Monitor (Note that the Drought Monitor is produced through a partnership between USDA, NWS (CPC), NIDIS, NDMC, and NCEI)	Drought intensity categories	Weekly	Drought categories are: D0 abnormally dry, D1 moderate drought, D2 severe drought, D3 extreme drought, D4 exceptional drought
CMORPH Global Precipitation	Precipitation estimation globally	30 minutes	Horizontal resolution is 8 km. Incorporates both Geostationary and low earth orbit satellite information in the product preparation
Unified Gauge Analysis	Precipitation; Global land areas only; Rain gauge data only	Daily	CONUS horizontal resolution is 1⁄8 degree while for other regions it is 1⁄2 degree
Outgoing Longwave Radiation (OLR)	Outgoing Longwave Radiation; Global coverage	5-day and monthly mean data produced in real-time	Horizontal resolution is 2.5 x 2.5 degrees
Extratropical Teleconnection Patterns (recurring and persistent air pressure and wind patterns that span vast geographical areas, such as entire ocean basins and continents)	Arctic Oscillation; North Atlantic Oscillation; Pacific-North America Pattern; Antarctic Oscillation (Note that not all patterns that are monitored are listed here)	Daily and monthly	Teleconnection patterns have a strong seasonality to their structure, duration, and impacts

Climate Reanalysis (R1, R2, NARR and CFSR)	Many atmospheric, land, and oceanic variables are analyzed as part of these systems	6-hourly	Daily, monthly and seasonal averages are prepared and disseminated to various stakeholders
Global Ocean Data Assimilation System (GODAS) for Ocean Monitoring	Three dimensional state of the ocean for informing CPC operational products, especially the ENSO Diagnostic Discussion	5-day and monthly mean data produced in real-time	
Climate at a Glance	Temperature, precipitation and drought trends since 1895	Monthly	Updated roughly the 6th of each month
Drought Termination and Amelioration	Estimates of how much precipitation is needed in a given time period to end or reduce the severity of drought, and the historical likelihood of that occurring	Weekly	A version incorporating forecast probabilities from the Climate Prediction Center is under development
Monthly State of the Climate	A set of reports and associated data that diagnose recent weather and climate trends and variability, and put recent events into historical context	Monthly	Released on or about the 8th of each month
Billion Dollar Weather and Climate Disasters	An analysis of weather and climate events that cause at least one billion $USD in direct losses	Quarterly	Does not account for indirect losses

The spectrum of S2S products listed in the tables demonstrates a variety of skill characteristics. There has been significant improvement in some aspects of S2S forecasts, as shown in Figure 3, which is the Government Performance and Results Act metric for seasonal temperature. Higher forecast skill should result in improved decision support for users. The technological improvements denoted in the figure were accomplished through research to operations (R2O) transitions in collaboration with the research community. The Climate Forecast System (CFS) models strongly leveraged the modular ocean model (MOM) and data assimilation efforts at the Geophysical Fluid Dynamics Laboratory (GFDL). The North American Multi-Model Ensemble (NMME) consists of three operational models from the United States and Canada (CFSV2, CanCM3, and CanCM4) and four research models from the United States (GFDL FLOR, GFDL CM2.1, NCAR CCSM4, and NASA GEOS5). The recent degradation in forecast skill results from the inability of our best tools such as the NMME to accurately forecast cold anomalies. NOAA is establishing the next version of its S2S global model (known as the Unified Forecast System, or UFS) as a community model. In order to accelerate improvements in the UFS, NOAA is establishing EPIC, which will enable the research community to develop new and emerging model technologies that can be quickly transitioned into operations. EPIC is a key example of our efforts to collaborate in new ways with new partners, assimilate increased quantities of data, and ultimately transition R2O.

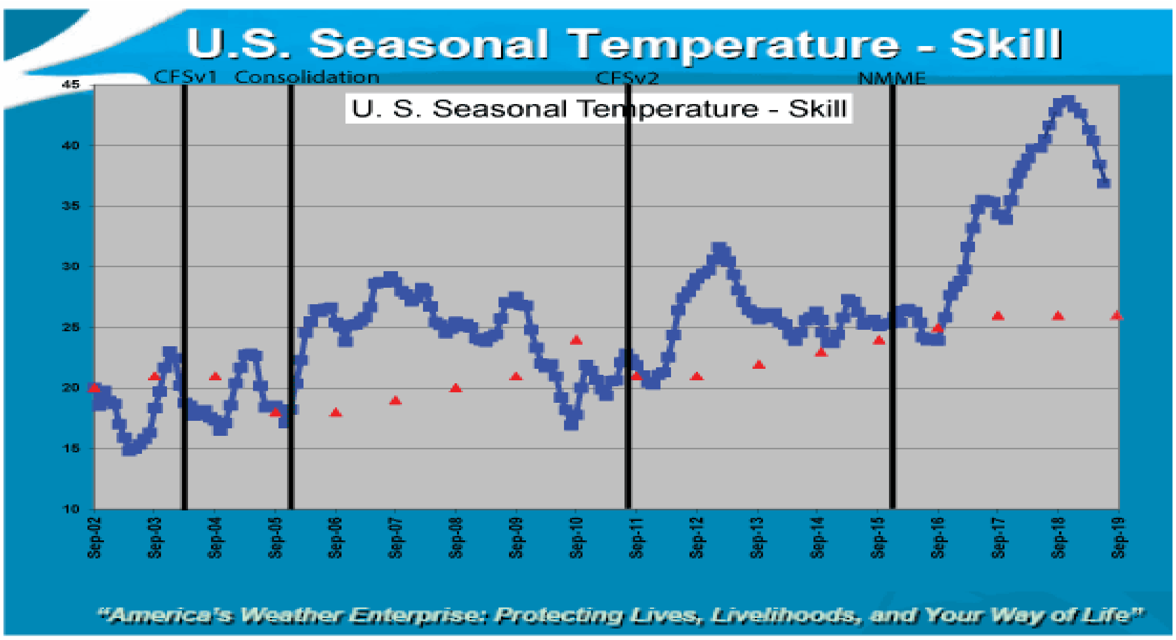

Figure 3: Heidke Skill Score (HSS) for U.S. seasonal temperature outlooks over the period from Fiscal Year (FY) 2002 through the first portion of FY 2019. The specific calculation of the metric is a 48-month running mean of the HSS (blue line). The HSS ranges from -50 to 100, with values of 0 or less (negative) indicating no forecast skill, while positive values depict forecast value over a climatological benchmark. The greater the positive values shown, the higher the forecast skill. The red triangles are the goal for each fiscal year over the period. For example, a score of 30 means the prediction is correct 50 percent more times than a climatology forecast, which is a significant improvement. The black lines denote the introduction of major tool improvements used for the CPC seasonal forecast process. These are the Climate Forecast

System version 1 (CFSv1), CPC objective tool consolidation, the Climate Forecast System version 2 (CFSv2), and the NMME.

However, similar improvements in other S2S forecasts, such as those for precipitation, are still needed. Close coordination and end-to-end planning of activities ranging from the research needed to identify sources of predictability, to the transition of research advances to operations, to support that sustains operational products and services, is required to ensure success.

Current NWS operational S2S products and services are reliably disseminated in several ways. CPC S2S operational services are securely provided to the NWS regional and local field structure through the Advanced Weather Interactive Processing System (AWIPS). In addition to this governmental internal secure network, NWS operational S2S products and services are available via other platforms, including the Internet and NOAA Weather Radio. Considerable communication and coordination of NWS operational S2S products and services are undertaken by a critical set of local and regional experienced S2S related experts as described in the next paragraph.

Within NOAA, S2S information and data are provided by the National Centers for Environmental Information (NCEI), the River Forecast Centers (RFCs), and NOAA Research Laboratories. Other S2S information and data are provided by NIDIS, which has an interagency mandate to coordinate and integrate drought research. Several NOAA-funded Regional Integrated Sciences and Assessment (RISA) centers and the six Regional Climate Centers (RCCs) also provide S2S data tailored to the needs of their regional stakeholders. Although not an official part of NOAA, state climatologists are important partners in the dissemination and interpretation of NOAA products for their respective stakeholder communities. Collectively, these organizations support CPC operational S2S responsibilities by generating experimental, next-generation guidance. They also commonly work with the public, academia, and private user communities to advance understanding of context and risk; support knowledge to action networks; and to innovate services, products, and tools to enhance the use of science in decision making.

In the analysis, a number of examples are provided that illustrate the use of the NOAA S2S prediction products for public planning and preparedness by major federal and state stakeholders. For example, the U.S. Department of Agriculture (USDA) Climate Hubs use CPC S2S predictions to inform their stakeholders about potential impacts to agricultural production. CPC temperature and precipitation outlooks are used by NWS Incident Meteorologists who serve firefighters and multiple other government organizations, including the U.S. Forest Service. CPC Arctic sea-ice forecasts are used by the NWS Alaska Region for environmental protection and the mineral extraction sector to better plan their work in the Arctic. The U.S. Agency for International Development (USAID) Office of Foreign Disaster Assistance (OFDA) and Famine Early Warning System Network (FEWSNET) use CPC products for famine preparation and response and risk reduction associated with drought. The Federal Emergency Management Agency (FEMA) uses CPC prediction products to evaluate the seasonal potential for large-scale events, such as southeastern U.S. tornado outbreaks. The Bureau of Land Management (BLM) uses NWS Office of Water Prediction (OWP) products to inform water availability for livestock. Seasonal hydrologic forecasts are used by many partners, including the New York City

Department of Environmental Prediction (NYCDEP), and the U.S. Bureau of Reclamation (USBR). S2S precipitation forecasts are used by state and local water resource managers to manage seasonal water usage in regions of the nation where skill level is sufficiently high, including Florida and Texas. The U.S. Drought Monitor (USDM) captures the current state of drought, which occurs on S2S timescales, by using a synthesis of objective tools and feedback from stakeholders on the ground regarding current conditions, and is used by many agencies serving agricultural interests.

III. CURRENT PLANS FOR IMPROVING S2S PRODUCTS AND SERVICES

The two main goals of NOAA's current S2S plans are: (a) improving the skill of the S2S predictive guidance (as much as possible, given the inherent limits of predictability), and (b) enhancing the value of S2S products for stakeholders. This section documents plans and goals for the continued development of S2S forecasts and related products and services.

III A. Improving the Skill of Forecast Products

A coupled numerical weather-climate prediction system is the primary tool used to produce S2S forecasts and outlooks for the NWS. Many of the basic components of this system are being enhanced through the Next Generation Global Prediction System (NGGPS) program. However, the NGGPS system is intended primarily to develop the prediction system for improved weather applications while providing a prediction infrastructure suitable for extension to S2S. NOAA efforts in EPIC support continued advances in S2S modeling and accelerate R2O transitions. EPIC provides the platform to leverage the weather and climate enterprise expertise, enable scientists and engineers to effectively collaborate in areas important for improving operational global modeling skill, using and leveraging existing resources across NOAA, and creating a community of global climate modeling system.

Additional R&D will be needed to build upon the NGGPS infrastructure to optimize the system for S2S prediction. A schematic of the prediction system is provided in Figure 4, below. The beginning of the S2S forecast process starts with the collection and quality control of observations. While there is a comparatively rich network of atmospheric observations, dominated by satellite data, there is a much sparser network of ocean, soil, and snow observations, especially below the surface. Data assimilation (DA) algorithms statistically combine a previous short-range forecast and newly available observations. Current-generation DA algorithms provide separate estimates of the ocean state, the land state, and the atmospheric state; that is, they are "uncoupled" and information from the rich atmospheric observation network is not used directly to adjust the ocean, ice, or land state. The comparative lack of land-surface and ocean sub-surface observations and the sub-optimal uncoupled algorithms are shortcomings that contribute to less accurate estimates of the current state for S2S applications. Addressing this will be a key area of R&D in NOAA, described more fully in the subsequent section.

With initial state estimates for S2S applications NOAA will generate multiple coupled predictions, i.e., an "ensemble" of possible future forecast states. The ensemble provides an estimate of the range of possible future forecast scenarios, and the average of the ensemble provides an estimate of the most likely state. In practice, due to model deficiencies, the useful signal and the estimate of forecast uncertainty from the ensemble are degraded by systematic errors, and the ensemble from the current-generation system produces a biased mean forecast (say, too cold, or too much light rain) and under-estimation of the range of possible conditions.

This challenge with ensembles will be addressed by improving the prediction system, again described in the next section, as well as through improved statistical correction procedures. The statistical correction procedure requires the archival of many past forecasts and observations (or gridded state estimates). Systematic differences between forecasts and observations are used to adjust the real-time numerical guidance, and this "post-processed" guidance is typically what is used by forecasters to make their products.

There are a number of examples where statistical methods have been productively applied to harvest information in observational data and from MME output to develop S2S predictions, either directly through the development of stand-alone statistical forecast guidance or in combination with dynamical model output post-processed in varying ways and complexity to create forecast tools that utilize statistical methods and dynamical model guidance: so-called hybrid systems. These statistical and hybrid guidance products have proven to be valuable, if not essential, tools that provide complementary skill to dynamical models for making operational NWS S2S predictions.

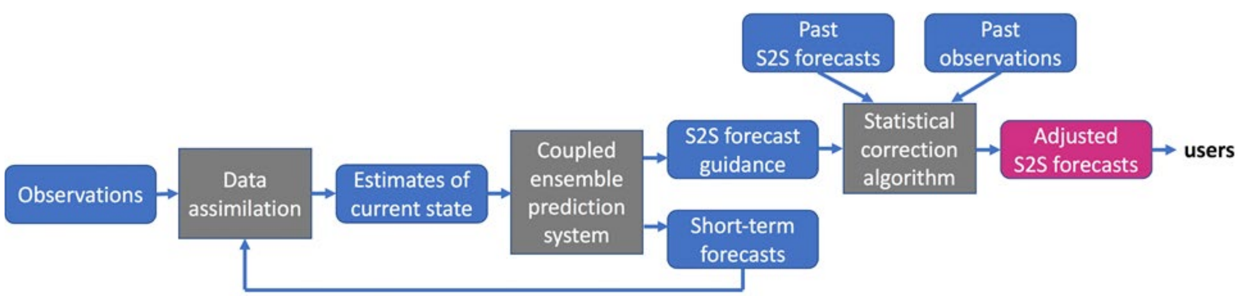

Figure 4: System architecture schematic of the UFS for operational Earth system prediction at S2S time scales. The data assimilation algorithm statistically blends together the information from a prior short-range coupled forecast together with recently available observations. The coupled prediction system makes forecasts out to seasonal time scales. The statistical correction algorithm (post-processing) uses the discrepancies between past forecasts and observations to modify the current S2S forecast guidance so that it is unbiased, maximally skillful, and reliable.

III B. Enhancing the Value of S2S Products for Stakeholders

In the past few decades, through interactions between scientists and decision makers, we have learned that various populations/sectors/decision makers absorb, understand and use information differently. Social sciences are able to provide tools and methodologies that help provide a better understanding of how to communicate this information effectively. In order to continue to improve impact and use of these data, NOAA understands that they must incorporate methods uniquely available through the social and behavioral sciences to best understand the communities with which they are working, and to communicate risk and uncertainty. The National Academies of Sciences (2016) encouraged usage of "social science research that leads to more comprehensive and systematic understanding of the use - and barriers to use - of seasonal and subseasonal Earth system predictions." The Academies (2016) also encouraged the weather enterprise to support research on "risk assessments and responses, and factors influencing these processes." The report calls for research on how to better reach and inform special-interest populations with unique needs while additional studies point to the need to address changing risk preference of users of information in any prediction range.

S2S forecast products are inherently probabilistic. In order to develop an effective communications strategy that works in partnership with affected communities and users, NOAA will incorporate insights and lessons from social science approaches to ensure that the format and transmission of information is sensitive to the context of use and users, especially as it relates to their decision process in the face of extreme water and climate events within the S2S range. This broader approach is critical to the success of any large and complex effort. Recognizing the importance of ensuring its products, information, and services produces the best probabilistic S2S forecasts to inform decision makers and the public, NOAA intends to more fully incorporate methods used within the social and behavioral sciences, with the development and/or assessment of its current suite of forecasting products, information, and services.

By using social and behavioral scientific methods to guide product modernization, NOAA will not only collect a baseline understanding of the applicability and use of the S2S forecast product suite, but also assess broader information needs and technologies that will help guide the necessary upgrades, enhancements, and new products that the product suite needs to produce usable, reliable, and timely foundational forecasts. Additionally, with user communities articulating a need for forecaster uncertainty and confidence information, NOAA will need to invest in a spectrum of products and services that directly and indirectly convey probabilistic information. Fundamentally, the effective conveyance of uncertainty and risk as it relates to S2S forecasts encourages more resilient behavior to achieve reduced loss to life and property.

IV. IMPROVING S2S PRODUCTS AND SERVICES

This section of the report focuses on the identification of longer-term forecasting, research, monitoring, and observing requirements to fill knowledge, understanding, and capability gaps identified in the analysis of the portfolio of current S2S products and services utilized in public planning and preparedness. The scope of R&D includes not only needed foundational scientific advancements, but also R&D efforts that are in progress however not yet mature enough to be implemented for operational delivery of S2S information products and services within the next 5 years.

IV A. Forecasting Requirements

The elements that could help produce state-of-the-science S2S forecasts include: (a) directed research that accelerates the process understanding and discovery of sources of predictability; (b) a robust R2O process that translates the process understanding and sources of predictability into improved prediction algorithms; (c) sufficient high-performance computing to perform the research, to generate operational forecasts, to generate the supporting data sets (e.g., reanalyses and reforecasts), and to store data and transmit products (i.e., bandwidth); (d) sustained recruitment and retention of the specialized staff to perform the research, development, and operations; and (e) a robust verification and monitoring system to indicate whether intended changes to the prediction system produce statistically significant improvements. In the foreseeable future, the volume and velocity of our data is expected to increase exponentially with the advent of new observing system and data acquisition capabilities, placing a premium on our capacity and wherewithal to scale the IT infrastructure and services to support this growth. Modernizing our infrastructure requires leveraging cloud services as a solution to meet future demand. Appendix B gives a table of potential future forecast products, which may be developed in the next 5 to 10 years.

IV B. Research Requirements

The S2S comprehensive analysis discusses the research requirements in greater detail. A healthy research process will provide an understanding of the physical processes that are then incorporated into improved algorithms for the S2S prediction system. Significant R&D is needed in the development of advanced coupled data assimilation methods to improve the definition of the ocean and land state using the robust atmospheric observational data. Since these coupled DA procedures statistically combine newly available observations with a prior model forecast, the accuracy of these methods also depend on providing accurate forecasts of the local relationships between ocean, atmosphere, land, snow, and ice, as well as the predictive uncertainty of these relationships. In this way, development of improved coupled S2S ensemble prediction systems is a primary concern. This will involve improving the underlying prediction system; the development of physically based representation of uncertainty in the coupled state; improvement in the representation of key processes, such as clusters of tropical thunderstorms; the interaction of the stratosphere with the troposphere below it; the effects of aerosols on the transmission of energy from the sun and the earth; and improvements in the processes that govern changes in the state of the land surface, snow cover, sea ice, and ocean. Also needed are optimal ways to generate the computationally expensive supporting reanalysis and reforecast data sets and to use them in a statistically sophisticated manner. Reanalysis is a systematic approach to produce data sets for climate monitoring and initializing reforecasts. Reanalyses are created via an unchanging ("frozen") DA scheme and model(s) which ingest all available observations (atmosphere, oceans, ice, and land) every 6-12 hours over the period being analyzed. This unchanging framework provides a dynamically consistent estimate of the climate state at each time step. Reforecasts are a set of forecasts made for the historical period using the same DA and forecast system used for the real-time forecasts. Reforecasts over an extended period (~30-35 years) are an essential part of this model system, as they are used to evaluate the skill of the forecast system and for calibration of the real-time forecasts in order to improve the forecast skill.

Additionally, R&D is needed for regional and local climate forecasting tools to aid in the delivery of decision support services at the scales where climate-sensitive decisions are made.

IV C. Observational Requirements

Observations and monitoring networks provide the foundation for an enhanced S2S prediction system and the operational delivery of S2S information products and services. Observations are needed to improve understanding of the critical processes on S2S timescales, evaluate S2S model forecast system performance and guide model development, enable the accurate initialization of S2S forecast systems, and quantify S2S prediction skill and reliability. Particularly key observations include observations of the state of the ocean below the surface, including temperature, salinity, and currents. Observations of the state of the land (including soil moisture) as well as the atmosphere and fluxes just above it are sparse, and an improved network of such observations would help improve the fidelity of land-surface models. Data from satellites, such as the NOAA polar orbiting satellites, the Joint Polar Satellite System (JPSS), will provide information that will need to be included into the data assimilation scheme for climate modeling. These data are available globally and will complement other satellite data from the international community obtained and used in the analysis. NOAA has been using unmanned systems or UxS, and has put forth for comment a strategy to expand and coordinate the use of these force multipliers for many programs including data needed to improve S2S predictions. While observations are important, they often can be expensive, especially when maintained in perpetuity, and the comparative costs and benefits of new observations will need to be weighed against the costs and benefits of improving other aspects of the prediction system. Better exploitation of existing observations and utilization of partner observations must also be explored.

IV D. Monitoring Requirements

Subseasonal to seasonal prediction leads to a unique set of monitoring requirements. These are: (1) diagnostics of recent events, especially extreme and high impact events, such as tornadoes, hurricanes, snow, blizzards, heat, and floods, to understand why they occur and evaluate how well or poorly the forecasts for these events verified; (2) construction of gridded fields of key observed quantities for the hydrologic cycle, such as precipitation, surface temperature, and soil moisture; and (3) overarching requirements for development of foundational datasets for S2S monitoring. The thorough evaluation of the forcing of extreme S2S events and verification of associated forecasts requires a long-term dynamically and physically consistent reanalysis dataset. The basic idea behind reanalysis has been described elsewhere in this report in the context of reforecasts. The reanalysis needed in the diagnostic and evaluation context has some unique needs compared to that used for initializing reforecasts. In particular, the diagnostic/evaluation reanalysis needs to be many decades long in order to adequately describe the mean state as well as capture a sufficient sample of previous extreme events so that the current event can be understood in the historical context. Reanalysis for diagnostics/evaluation requires use of a frozen modeling and data assimilation system for both the historical period and in real-time to ensure that unphysical inhomogeneities, are not introduced due to changes to the model or data assimilation system. It also requires special techniques to minimize unphysical inhomogeneities or jumps that occur due to changes in the observing system over time.

IV E. Advancing S2S Forecast Capabilities and Products

One area of R&D will need to focus on identifying opportunities to better exploit regional influences (Arctic, tropical North Atlantic, tropical Pacific, Indian Ocean) impacting S2S predictability and forecast skill. S2S forecast verification and evaluation research will be important to better understand forecast limitations and understand the potential for forecasts of opportunity, which have the potential for enhanced forecast skill and reliability. Likewise, R&D efforts are needed to determine dynamical aspects of forecast improvements (e.g. spatial scales) that can reduce long-standing systematic errors in dynamical models (e.g. stationary wave amplitude, storm tracks, and tropical cyclone paths). In addition to scientific advances resulting from the R&D needed to fully exploit potential sources of S2S predictive skill, there will need to be significant changes in how the S2S research community works and partners both internally with the operational community and with the private sector.

While much of the research priorities described in the previous section are intended to advance the dynamical forecast system modeling capabilities to improve S2S predictions, a number of additional R&D efforts will contribute to improved S2S products and services. Research should continue to explore the appropriate use of statistical models and hybrid statistical-dynamical systems in advancing S2S predictability and forecasting, rather than focusing only on dynamical models, especially on the longer timescales of S2S (13 to 24 months). It is important for the S2S research community to have access to a research S2S forecast system that closely resembles the NOAA operational system and that can be used throughout NOAA, as well as by partners in the weather and S2S communities. A coordinated research effort will need to develop and make readily accessible to the research community a comprehensive multi-model ensemble archive of extended historical predictions produced using S2S forecast systems. AI solutions to ensemble-based forecasting are beginning to show promising results. Researchers are currently exploring an AI-based ensemble model that bore significantly more accurate results than other models and closely resembled the forecast produced by NWS. Another important research area is the assessment of the predictability of extreme events, such as heat and cold waves, and floods. For these case studies to diagnose the retrospective skill of a variety of high-impact, extreme S2S events will require the development of research methods to explore the predictability of not only average conditions and average events, but also very extreme individual events.

A paradigm shift will be needed in how the S2S research community engages and interacts with operations in the transition of R2O. The deconstructed portrayal of R2O, as depicted in Figure 5, illustrates various pathways to accelerate scientific findings into forecast system improvements with NOAA's community Unified Forecast System (via NGGPS). As research advances at an ever-increasing pace, NOAA has plans in place to ensure that we are poised to coordinate AI research, development, acquisition, and application in a way that allows all NOAA components, and our partners, to further our mission. As several NOAA applicable AI innovations already exist in the private sector or academia, EPIC can play a crucial role in helping to effectively tailor existing AI. Already, NOAA's National Ocean Service and NWS are using AI in a partnership with UC Santa Cruz to detect rip currents from coastal imagery, and these observations are improving NOAA's rip current forecast model.

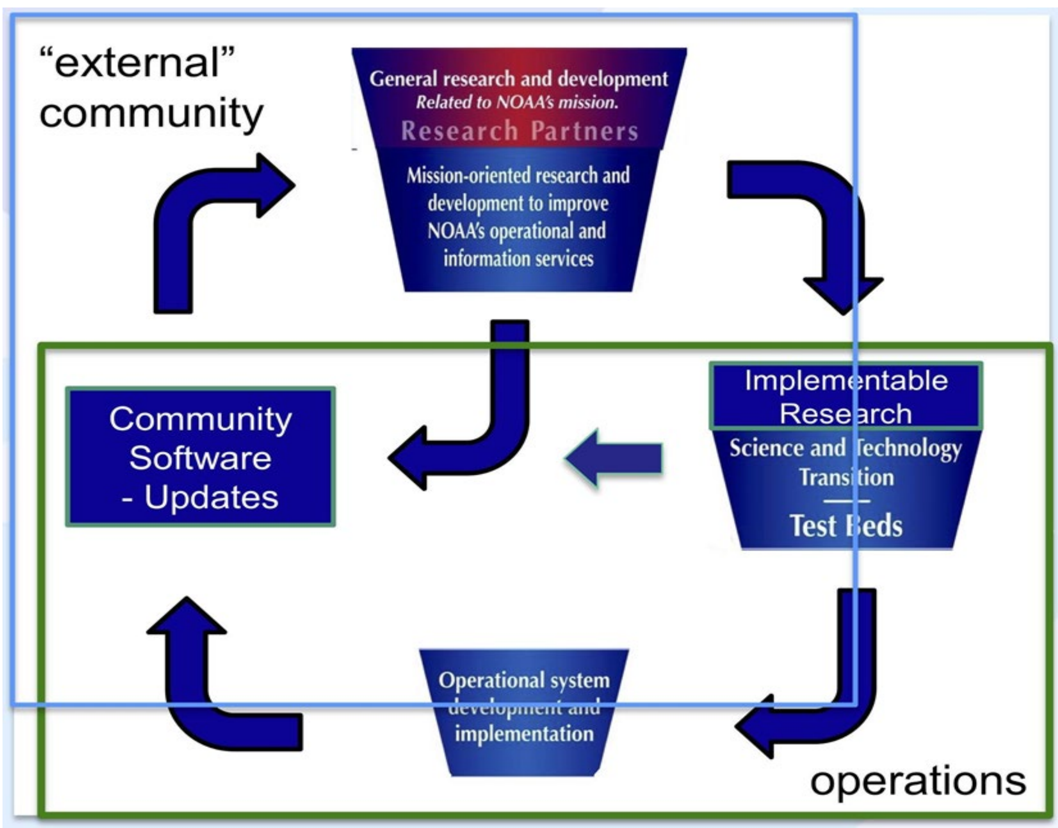

Figure 5: This is a version of the NOAA R2O funnel, which outlines an accelerated community approach to the implementation of R&D. It is derived from the NGGPS effort to develop a NOAA community UFS.

Likewise, the mission-oriented S2S R&D conducted at NOAA's Office of Oceanic and Atmospheric Research (OAR) laboratories, or funded as extramural grants to individual Principal Investigators, will have to be transitioned expeditiously to operations in order to meet rapidly-expanding demands for subseasonal and seasonal forecasts and related products. For example, in this new S2S research paradigm, rather than waiting for results to be published, a federally funded S2S research scientist working in a NOAA research laboratory would be required to share experimental results with operational colleagues as scientific findings emerge, share access to the experimental forecast or prediction system, and work in partnership to rapidly transition experimental prediction system capabilities into operations.

In addition, NOAA is exploring new ways to incentivize and reward progress in AI developments. NOAA is planning to establish an annual R&D prize competition series for AI applications in environmental science in order to further collaboration and enhance agency capabilities.

IV F. S2S Information Dissemination and Delivery

In the last decade or so, the precision and use of S2S forecasts has improved and expanded. During that same time, there has been an increased realization of the importance of understanding the consumers of that science. Organizations such as NOAA understand the importance of working with decision makers, social scientists, and critical partners, such as state climatologists and RCCs, to ensure that the forecasts/data are relevant and actionable. Because the volume of data we generate, use, and store is vast and expected to increase exponentially, we have an opportunity and responsibility to use the cloud to provide ubiquitous access to, and cost-effective use of, NOAA data and services. A strategic, unified use of cloud computing capabilities will help us take advantage of emerging technologies, collaborate with partners using industry best practices, and maximize portability.

We know that NOAA scientists no longer create new forecasts solely for their scientific value, provide them to their partners, and leave them to interpret the key information on their own. A few key lessons have been learned that will help frame the approach for deliberate adoption of new forecasts, data, and methods into decision makers' toolboxes. Examples include understanding the communities that will be using the forecast data and information, continuing the co-design of science, and developing information useful to the users and decision makers.

NOAA scientists know it is important to be cognizant of the communities within which the forecasts/data will be used. Until recently, there was a common belief that improving the quality of the forecasts would result in their increased use. However, other factors are equally important, including the societal and scientific relevance of the forecast variables and their specificity, and the manner in which the forecast and information are communicated (NAS, 2016). The use of social science techniques helps decision makers better understand potential impacts and provides substantive information for improved decision support in order to save lives and property. These interactions also help to point to new weather and S2S forecast and data needs for these decision makers.

Researchers have found that decision makers that use probabilistic forecasts are interested in knowing more about what is behind the forecasts and how the forecast can be linked to their decision process. Accordingly they are interested in such things as the reliability of the probabilities beyond performance of the prediction inputs, and the overall forecast system. Decision makers will determine the level of forecast uncertainty they are comfortable with incorporating into their planning efforts. NOAA social scientists are working on more advanced ways to understand communities' needs, such as conducting studies on community risk perception and the value of scientific information. Future activities tying these societal aspects will enhance the use and applicability of weather data, forecasts, and information.

In addition to ensuring that users obtain the most value from NOAA data, in the future we at NOAA must ensure that all data is easily accessible. Because the volume of data we generate, use and store is vast and expected to increase exponentially, we have an opportunity and responsibility to use the cloud to provide ubiquitous access to, and cost-effective use of, NOAA data and services. We believe a strategic, unified use of cloud computing capabilities will help us take advantage of emerging technologies, collaborate with partners using industry best practices, and maximize portability. Transitioning to cloud services also provides an impetus and new opportuniites for NOAA to modernize data storage and dissemination systems.

IV G. Regional Pilot Projects to Accelerate S2S Predictive Skill Improvement

Other parts of this report describe current S2S prediction capabilities and research for improving and expanding those capabilities. This section takes a different approach and briefly maps out a path forward for accelerating S2S prediction skill by focusing on four regional projects. These projects were chosen based on the existence of major climate phenomena that have huge economic impacts and for which current S2S predictive skill is too low to be effectively used by many stakeholders. They were also chosen because the limited predictive skill of the climate phenomena highlighted for these regions is due to fundamental limitations in our current understanding and models. Therefore, improving predictive skill for these projects would improve skill for other regions as well. These projects complement the baseline research activities documented elsewhere in this report and would accelerate improvements in our S2S prediction skill that would be achieved by that research. NOAA has shown through the Hurricane Forecast Improvement Program (HFIP) that it is possible to develop and execute a comprehensive, focused program to accelerate predictive skill improvements for the operational prediction of a major meteorological phenomena, such as hurricanes (including track and intensity). The HFIP program serves as a useful paradigm for the required elements to ensure success of the projects. It is important to note that each of the four project areas would separately require a level of investment and time commitment (on the order of a decade) for completion, similar to that for the HFIP program.

Key elements of the successful HFIP program include:

- Recognition of the difficulty of the problem and the fact that there is no single activity that will solve the problem. Rather, compounding incremental improvement will lead to long-term measurable gains in forecast skill.
- Well-defined metrics and timelines for evaluating success that are co-developed with the relevant stakeholder communities.
- Recognition of the need to focus on operational outcomes, i.e. not research for research's sake.

- Sufficient sustained investment in all required aspects of the problem, including human resources, high-performance computing, observing systems, and transition of research innovations to operations.
- Leveraging the talents of all parts of the weather enterprise, including NOAA labs, other federal agencies, the research community, and relevant NWS operational centers.
- Focusing on gaps in the end-to-end chain from increased understanding of sources of predictability through operational implementation of new and improved tools.
- Rigorous and documented testing and verification protocols.
- Targeted social science to improve the utility of forecast products to stakeholders and provide objective measures of the impact of those products.
- Strong project management including regular updates on progress and course correction as determined by evidence-based decision making.

The four project areas are:

- Winter S2S precipitation forecasts for water management in the western U.S.
- Spring and summer S2S precipitation forecasts in the central U.S.
- S2S forecasts of Arctic sea ice
- S2S forecasts of tropical cyclone activity

One unifying modeling deficiency for S2S forecasts in general, and the pilot projects in particular, is the current low level of skill in forecasting tropical convection beyond a few days. The current consensus of the scientific community based on several decades of research is that a significant fraction of the predictable part of mid-latitude variability is driven by tropical convection, which causes slowly evolving changes in the upper level steering flow, i.e. the jet stream. Therefore, a key aspect to improving S2S predictive skill for each of the pilot projects is improving the forecast skill for tropical convection and its associated teleconnections to other regions in the NOAA unified global model. There are other important physical processes for each of the pilot projects and they are covered in more detail in the respective project descriptions.

Key Science Challenge for the Pilot Projects:

Winter S2S Precipitation Forecasts for Water Management in the Western U.S.

The dominant fraction of the annual mean precipitation along the west coast of the United States and in the mountain regions west of the Mississippi River occurs from October through April. In many regions, this precipitation falls as snow, and the mountains act as a natural reservoir. Key science challenges to improving these forecasts include: inadequate model resolution (horizontal and vertical) to resolve the mountainous terrain, which influences the intensity of precipitation and the relative fraction of precipitation that falls as rain versus snow; improved fidelity in modeling of the atmospheric boundary layer in mountainous regions; and an inability to predict periods of blocked versus unblocked flow over the eastern North Pacific Ocean and western U.S.

Spring and Summer S2S Precipitation Forecasts for Agriculture for the Central U.S.
The dominant share of precipitation in the central U.S. falls during the spring and summer. This rainfall is critical for farmers and ranchers. When drought occurs, it can have devastating consequences as seen with the 2017 flash drought that occurred in South Dakota, Montana, and North Dakota. Key science challenges for improving these forecasts include: lack of observations and inaccurate modelling of the land surface and hydrologic cycle, especially soil moisture and the processes leading to flash drought; improved fidelity in modeling of warm season precipitation processes; and understanding and prediction of large-scale upper-level dynamical flow anomalies that occur in this region at this time of year.

S2S Forecasts of Arctic Sea Ice
The Arctic region has some of the most extreme and challenging environmental conditions on Earth. Accurate forecasts for Arctic sea ice are critical for stakeholders from the national defense, mineral extraction, environmental stewardship, and tourism communities. Key science challenges for improving these forecasts include: enhanced observations of sea ice properties including thickness; improved modeling of the processes controlling melting and formation of sea ice; and improved modeling of the atmospheric and oceanic boundary layers in the Arctic region.

S2S Forecasts of Tropical Cyclone Activity
Tropical cyclones are devastating due to their associated high winds, storm surge, and excessive rain. Key science challenges for improving these forecasts include: improved understanding and modeling of large-scale wind shear in the tropics and subtropics; and improved forecast skill of sea-surface temperature (SST) in the main development regions. (Please note that these are large-scale indicators of enhanced versus suppressed activity, rather than predictions of individual events).

V. PROCESS AND CONSULTATION FOR DEVELOPING THIS REPORT

When developing this report, NOAA consulted with relevant Federal, regional, state, tribal, and local government agencies, national and international research institutions, and various organizations within the private sector. NOAA established a team comprised of senior leaders and scientists representing relevant NOAA line offices. The team functioned as a panel to identify key issues to be addressed, developed an outline for a plan, collected and reviewed existing plans and documents, solicited briefings from various subject matter experts, held a workshop, and queried deep relationship core partners via a questionnaire. Public "town hall meetings" were also held at national meetings of the American Meteorological Society, American Geophysical Union, and American Association of State Climatologists. Outreach and information gathering was extensive and comprehensive.

The initial analysis that led to this report was made available to the Interdepartmental Committee for Meteorological Services and Supporting Research (ICMSSR) for review and comment. ICMSSR comprises representatives of the 15 Federal agencies that engage in meteorological activities or supporting research, have a major need for meteorological services, or set policy and direction for such services and research. These 15 agencies are: the U.S. Departments of Agriculture, Commerce, Defense, Energy, Homeland Security, Interior, State, and Transportation; the Environmental Protection Agency, National Aeronautics and Space Administration, National Science Foundation, National Transportation Safety Board, and Nuclear Regulatory Commission; the Office of Management and Budget, and the Office of Science and Technology Policy. An annotated outline of the report was made available to the public for review and comments. The annotated outline was a 15-page document that gave a brief summary of each section of the report. The public was encouraged to provide feedback on the scope of the outline and potential utility of subseasonal and seasonal information. Nearly 100 respondents from academia, state government, water resource agencies, and the Federal Government provided comments that were addressed in the report.

VI. SUMMARY

Our society continues to change and become more vulnerable to impacts from extreme S2S influenced weather events, including tornadoes, hurricanes, snow, blizzards, heat, cold, drought, fire, and floods. Improved subseasonal to seasonal prediction is a critical component to enable decision makers to make informed decisions to address extreme events ranging from drought to flooding and heat to cold. As our S2S predictive capability improves, decision makers at all levels will have better information to make informed decisions to save lives and property.

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VIII. APPENDIX

Appendix A: Acronyms

AHPS:	Advanced Hydrologic Predictive Service
AWIPS:	Advanced Weather Interactive Processing System
BLM:	Bureau of Land Management
CANCM3:	Canadian Climate Model Version 3
CANCM4:	Canadian Climate Model Version 4
CCSM4:	Community Climate System Model Version 4
CFSR:	Climate Forecast System Reanalysis
CFSv1:	Climate Forecast System version 1
CFSv2:	Climate Forecast System version 2
CM2.1:	Coupled Model Version 2.1
CMORPH:	CPC Morphing Technique
CPC:	Climate Prediction Center
CPO:	Climate Program Office
CTB:	Climate Testbed
DA:	Data Assimilation
ECMWF:	European Centre for Medium Range Weather Forecasts
ENSO:	El-Niño Southern Oscillation
EPIC:	Earth Prediction Innovation Center
ESMF:	Earth System Modeling Framework
ESP:	Ensemble Streamflow Prediction
ESPC:	Earth System Prediction Capability
FEMA:	Federal Emergency Management Agency
FEWS:	Famine Early Warning System
FEWSNET:	Famine Early Warning System Network
FLOR:	Forecast-Oriented Low Ocean Resolution
GEOS:	Goddard Earth Observing System
GFDL:	GFDL: Geophysical Fluid Dynamics Laboratory
GODAS:	Global Ocean Data Assimilation System
HFIP:	Hurricane Forecast Improvement Program
HSS:	Heidke Skill Score
ICMSSR:	Interdepartmental Committee for Meteorological Services and Supporting Research
JPSS:	Joint Polar Satellite System
MAPP:	Modeling, Analysis, Predictions, and Projections program
MJO:	Madden-Julian Oscillation
MOM:	Modular Ocean Model
NARR:	North American Regional Reanalysis
NAS:	National Academy of Sciences
NASA:	National Aeronautics and Space Administration
NCAR:	National Center for Atmospheric Research
NCEI:	National Centers for Environmental Information
NCEP:	National Center for Environmental Prediction

NDMC: National Drought Mitigation Center
NGGPS: Next Generation Global Prediction System
NIDIS: National Integrated Drought Information System
NMME: North American Multi-Model Ensemble
NOAA: National Oceanic and Atmospheric Administration
NWM: National Water Model
NWS: National Weather Service
NYCDEP: New York City Department of Environmental Prediction
OAR: Office of Oceanic and Atmospheric Research
OFDA: Office of Foreign Disaster Assistance
OLR: Outgoing Longwave Radiation
OSTP: Office of Science and Technology Policy
OWAQ: Office of Weather and Air Quality
OWP: Office of Water Prediction
R2O: Research to Operations
RCC: Regional Climate Centers
RFC: River Forecast Centers
RISA: Regional Integrated Sciences and Assessment
RMA: Risk Management Agency
S2S: Subseasonal to Seasonal
SIP: Strategic Implementation Plan
SST: Sea surface temperature
UFS: Unified Forecast System
USAID: United States Agency for International Development
USBR: United States Bureau of Reclamation
USDA: United States Department of Agriculture
USDM: United States Drought Monitor

Appendix B: Potential Future Products

Pending scientific evaluation of skill and utility to stakeholders, and determination of resource requirements, the following are potential products that could be delivered in the mid- to long-term future (5 to 10 years).

Product Name	Forecast Variable(s)	Forecast Period	Release Frequency	Additional Information
Extended Range Forecasts	Probabilities of different tercile classes of weekly mean wind, waves, blocking (global), snowfall, severe weather, aviation weather (global), and fire weather.	Days 8-14	Daily	Probability of exceedance tools would also be made available so that stakeholders would have access to the full PDF.
Week 3-4 Forecasts	Probabilities of 2 classes (above-/below-normal) of two-week mean temperature extremes (hot and cold).	Days 15-30	Once per week	Probability of exceedance tools would also be made available so that stakeholders would have access to the full PDF. Temperature extremes forecasts may be global pending sufficient investment and skill.
Monthly Forecasts	Probabilities of different tercile classes of monthly mean tropical cyclone activity, temperature extremes (hot and cold), drought onset and amelioration. Precipitation forecasts tailored for water supply forecasts.	~30 day period	Weekly updated	Probability of exceedance tools would also be made available so that stakeholders would have access to the full PDF. Temperature extremes and drought forecasts may be global pending

				sufficient investment and skill.
Seasonal Forecasts	Probabilities of different tercile classes of 3-month mean of global tropical cyclone activity, temperature extremes (hot and cold), drought onset, and amelioration. Precipitation forecasts tailored for water supply forecasts.	~90 day period 3-month seasons	Near mid-month	Probability of exceedance tools would also be made available so that stakeholders would have access to the full PDF. Temperature extremes and drought forecasts may be global pending sufficient investment and skill.

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