FINAL // NOAA'S RESPONSE TO THE SCIENCE ADVISORY BOARD'S PAPER ENTITLED "SUBSEASONAL-TO-SEASONAL-TO-DECADAL: A PATHWAY TO IMPROVED PREDICTION" (LINKED HERE)

1.0 Executive Summary

In December 2019, and with the assistance of the Climate Working Group (CWG), the NOAA Science Advisory Board (SAB) published, "Subseasonal-to-Seasonal-to-Decadal (S2S2D): A Pathway to Improved Prediction" (linked here). The SAB members made nine recommendations, with detailed approaches, to inform NOAA's strategy for improving predictions at Subseasonal-to-Seasonal-to-Decadal (S2S2D) time scales.

NOAA acknowledges the Science Advisory Board and the Climate Working Group for their dedication and contributions to NOAA. NOAA also acknowledges that fully addressing and implementing each of these recommendations requires significant time and resources.

2.0 Introduction and Context

While SAB members' recommendations in this paper will inform NOAA's organizational-level strategies and office-level implementations, and while NOAA's response addresses each recommendation individually, NOAA acknowledges the SAB's implicit intention that the recommendations be considered continuously and holistically. That ongoing and integrated process is led by NOAA's Weather, Water, and Climate Board, which is currently chaired by the Assistant Administrator for the National Weather Service and consists of the Assistant Administrators from each of the NOAA Line Offices.

NOAA takes a broad view of S2S2D prediction that accepts the SAB's recommendations in this paper and invites additional earth system prediction and predictability recommendations in future papers. For example: Why are boundary layer processes explicitly called out as opposed to other processes, such as stratosphere-troposphere interactions or regional aerosol impacts? As NOAA researchers try to understand and predict the coupled system, planetary boundary layer and surface interactions are important, but so also are other processes—especially microphysics, shallow and deep convection, clouds, and radiation. More importantly, it is the coupling of these processes that leads to the observed phenomena, their variations, trends, and extremes. NOAA thus takes an approach to S2S2D prediction that continuously and holistically integrates the SAB's nine recommendations (detailed in sections 3-7) and the following seven items:

1. **Improving theoretical understanding.** Improving theoretical foundations leads to better understanding of the sources of predictability in the climate system: Which processes are key to improved predictions? How do we know that?
2. **Augmenting the observing system with intention.** Augmenting the global observing system in ways that have been shown, via theoretical considerations or model-based

studies, to increase predictive skill is important. Increasing observations, in the absence of such guidance, may not translate to increased predictive skill.

3. **Improving models.** Improving models in ways that seek to exploit that increase in our fundamental understanding and that could lead to improved predictive skill. There is a need to assess which model weaknesses can be most effectively addressed to yield increased skill.
4. **Addressing model systematic errors.** Identifying and addressing model systematic errors through the reformulation of moisture-related parameterizations, improved resolution, and improved component couplings (see also the Precipitation Prediction Grand Challenge Strategic Plan, Objective 3).
5. **Focusing on strongly-coupled ensemble-based data assimilation.** Focusing on a strongly-coupled ensemble-based data assimilation system that can update all the components simultaneously—using the observations of all components together. A strongly-coupled data assimilation approach is expected to result in more balanced initial states with less unphysical transient behavior in subsequent forecasts as the updates to each model component adjust to each other. Another benefit of this strongly-coupled data assimilation approach is that more information is extracted from the observations, especially when some components are more sparsely observed. Improvements in initialization systems that translate observations into initial conditions for model-based predictions may be the most important issue to address in the near term.
6. **Expanding the current S2S2D prediction system.** Continuously expanding and improving the current seamless subseasonal-to-decadal prediction system, Seamless System for Prediction and EArth System Research (see also SPEAR), which has already incorporated the FV3 dynamical core, MOM6 ocean code, and other recent earth system component developments.
7. **Post-processing.** Statistically post-processing of forecasts and projections will remain a critical process in providing early warning and informing preparedness at S2S2D timescales from skillful and reliable predictions at the temporal and spatial scales required for policy, planning, and decision making.

Finally, NOAA acknowledges that legislative authorizations, appropriations, and mandates, of course, may supersede the recommendations and approaches outlined herein.

3.0 Hybrid Statistical-Dynamical Models

Recommendation 1. Fund hybrid statistical-dynamic models (including contributions from machine learning, artificial intelligence, deep learning, etc.) to bridge the gap between the needs of stakeholders and limitations of the dynamic models at regional scales, especially for S2S2D predictions.

Accepted. There is much that may be gained from increased investment in hybrid dynamical-statistical approaches, including machine learning, artificial intelligence, and deep learning. NOAA's support for these approaches includes not only "stand-alone" prediction systems, but also support for techniques that could be implemented in close association with dynamical models. Increasing competitive funding for hybrid statistical-dynamical research will accelerate the recommended outcomes and leverages previous research in this area that is now transitioning into operations for operational monitoring. For example, research on tropical variability and seamless prediction of daily extremes and S2S climate variability is transitioning to NOAA's Climate Prediction Center via NOAA's Climate Testbed.

NOAA also intends to increase funding for research to understand the underlying physical processes: When developing hybrid models, the stochastic representation of a physical process is not a "work-around" for not understanding the physical system; stochastic parameterization must be consistent with the physical system it represents, as underscored by Boltzmann's equivalence of statistical and thermodynamic entropy.

4.0 Boundary Layer Processes

Recommendation 2. Fund boundary layer chemical dynamics research to help weather forecasting and calculations, as well as quantification of surface fluxes for air quality and climate needs.

Accepted. NOAA funds, and has identified additional opportunities to fund, research to advance understanding of chemistry and aerosols in the land-atmosphere and ocean-atmosphere interfaces. NOAA also funds, or has identified additional opportunities to fund, research on the related implications for microphysics, radiation, and air quality. For example, current and anticipated projects are focused on understanding atmospheric boundary-layer processes, evaluating weather and climate models and improving model parameterizations, satellite retrievals and routine components of the atmospheric and oceanic observing systems (see also Boundary Layer Observations and Processes).

5.0 Global Ocean Observations

Recommendation 3. Work towards realizing an expansion of observation networks into the tropics, deep, and polar oceans; obtain global oceanic biogeochemical [BGC] observations through the implementation of deep Argo, BGC Argo and enhancements in Argo beyond the 2020 design.
Recommendation 4. Restore funding for ship time in support of sustained ocean observations and deployments.

Accepted, noting:

- Increased observations could yield increased skill if they are the **right** observations, as determined by theoretical considerations.
- While the Global Ocean Observing System has a significant gap in the systematic collection of biological observations to understand impacts on living resources from climate and other human-induced change, NOAA has opportunities and relevant mandates to support the active international effort to address these gaps in systematic collection.

- An important consideration in improving forecasting to decadal scales is also integrating the diverse, platform-agnostic, comprehensive ocean data into a useful, quality-controlled, and stewarded, comprehensive set of ocean observations.

The Argo program is celebrating twenty years of providing data, now in near-real time. The Deep Argo program continues to develop, in part because of the public-private partnership between Paul Allen and NOAA's Pacific Marine Environmental Laboratory that is enabling an array of Deep Argo floats in the western South Atlantic Ocean. NOAA began funding the BGC Argo Program, an international effort to develop a global network of BGC sensors on Argo profiling floats, for BGC Argo deployments in FY2020 and increased that funding in FY2021; the National Science Foundation funds BGC Argo through a mid-level technology grant for "GO-BGC" at the $50M level (see also GO-BGC). NOAA, in concert with other partners, anticipates future infrastructure support for deployments, data archiving, and quality control.

For each of the Argo initiatives, NOAA acknowledges the challenges of securing funding that assures the long-term consistency, continuity, and integrity of those observations. However, the Marine and In-situ Meteorological Observing System Architecture (MIMOSA) effort, a NOAA Satellite Observing System Architecture (NSOSA)-like study of non-satellite systems, and the associated long-range strategic plans for the acquisition and management of the data in each observation system, will make a difference.

This recommendation also could inform NOAA's redesign of the observing system in the tropical Pacific through the Tropical Pacific Observing System (TPOS) 2020 process and the NOAA strategy to expand and implement Argo capabilities to include BGC and Deep Argo. The newly designed TPOS will expand observation networks to a broader range of latitudes and oceanic and atmospheric regimes, contributing to improved coupled weather and subseasonal forecasting capabilities. To move beyond the new 2020 design, as is recommended, TPOS leaders are considering updates to the current scientific objectives that support improved observations of the El Niño-Southern Oscillation; maximize the efficiency of observations for ocean, weather, and climate prediction systems; and advance scientific understanding of physical, biogeochemical, and ecosystem variability and predictability in the tropical Pacific. For example, research projects to improve profiling float technology in equatorial Pacific BGC studies and developing autonomous biogeochemical profiling floats also will be helpful.

NOAA is balancing funding for ship time with enhanced use of emerging technologies that leverage public funds for public benefit. For example, through a new memorandum of understanding, NOAA scientists will advise and join OceanXoffsite on missions aboard specially designed high-tech OceanX vessels to advance shared goals to explore and characterize the deep ocean. At the same time, NOAA is also leveraging the following emerging technologies:

- **Uncrewed Systems**. NOAA has built a framework for requirements-driven and cost-effective unmanned systems across the agency.

- **Artificial Intelligence.** NOAA is leveraging Artificial Intelligence (primarily Machine Learning) to reduce the cost of data processing and provide tailored scientific products and services.
- **'Omics Strategy.** NOAA is improving analysis of DNA, RNA, and proteins, especially, to improve understanding of changes in the environment and ecosystems and how they will affect humans and the ecosystems on which humans rely.

While these types of technologies and approaches have their advantages, so also does actual ship time in support of sustained ocean observations and deployments. The key is to maintain consistent measures over time for the relevant phenomena. For example, NOAA recently acquired two new ocean research ships to replace aging ships in the fifteen-ship fleet and is now responding to a congressional request for a full assessment of the fleet.

6.0 Biogeochemical Processes

Recommendation 5. Fund a global biogeochemically-sensored autonomous profiling float array and train the personnel to deploy and calibrate them.
Recommendation 6. Invest in terrestrial biogeochemical research and modeling, especially collaborations with the United States Department of Agriculture (USDA); collaboration between Geophysical Fluid Dynamics Laboratory (GFDL) and Climate Prediction Center (CPC) would accelerate improvement of terrestrial biogeochemical processes in S2S2D predictions.

Accepted, and incorporating as outlined in Section 5.0, "Global Ocean Observations." Moreover, NOAA is leading a whole-of-government response with domestic and international partners and coordinating via structures such as the National Science and Technology Council and the Executive Office of the President's Office of Science and Technology Policy's Earth System Predictability Initiative to leverage resources and prioritize investments. NOAA also is investigating additional opportunities to engage with the U.S. Department of Agriculture, especially to increase understanding of the role of vegetation.

Specific to Recommendation 6, NOAA, in general, and NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), in particular, require resources to augment fire-prediction modeling through improved representation of air-to-ground lightning, assimilation of soil moisture and snow cover, and better analytical tools for causal attribution. In synergy with the land-atmosphere boundary layer effort, improvement in the representation of chemistry and aerosol emissions also is necessary. Related, NOAA's National Weather Service (NWS) mission demands predictive capability in terrestrial and oceanic ecosystems at lead times out to two years. NOAA's Environmental Modeling Center can continue to drive to fully-coupled systems while depending upon NOAA's Climate Prediction Center for validation of the results and relying upon GFDL's experts to transition their innovations into NWS operational systems.

7.0 Improved Engagement and Communications on S2S2D Timescales

Recommendation 7. Train NOAA's workforce, academics, and commercial enterprises in the use of FV3-GFS and invest in educational outreach and resources.
Recommendation 8. Invest in the social sciences and human infrastructure for engaging sectors and communities in supporting decision-making and communicating earth system predictions.
Recommendation 9. Expand capacity to assess the return on science investment using multiple metrics such as economic impacts, diversity, and the number of people and locations served.

Accepted. NOAA is increasing engagement and communications throughout the research-to-operations pipeline, whether for weather forecast modeling training tailored to developers or user-support services tailored to community resilience managers. The Climate and Global Change Postdoctoral Program, for example, is considering engagement and communications on S2S2D timescales.

NOAA continues to enhance social science research investments across the agency and, simultaneously, to incorporate research- and practice-based social science into the agency's work and workforce development. NOAA's Social Science Committee strengthens, coordinates, and integrates this capability, as does the Office of the Chief Economist. NOAA also acknowledges that this is a continual process that must be matched with continual service delivery and self-evaluation, which is represented with multiple service delivery outlets and communities of practice. In short, NOAA is committed to long-term studies of the returns on investment and to collecting consistent measures.

8.0 Conclusion and Acknowledgements

NOAA acknowledges the Science Advisory Board and the Climate Working Group for their dedication and contributions to NOAA.