

Subseasonal-to-Seasonal- to-Decadal (S2S2D)

A Pathway to Improved Prediction

NOAA Science Advisory Board

With the assistance of the Climate Working Group

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Subseasonal-to-Seasonal-to-Decadal (S2S2D): A Pathway to Improved Prediction

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1.0 Executive Summary

The implementation of the Finite-Volume Cubed-Sphere dynamical core-Global Forecasting System (FV3-GFS) model combines the superior dynamics of global climate modeling with the day-to-day reliability and speed of operational numerical weather prediction. This convergence of climate and weather modeling also demonstrates the need for improved predictions on all timescales ranging from multiple decades, interannual, seasonal, and subseasonal, to days. The FV3-GFS upgrade can be the foundation for NOAA to dramatically improve forecasting abilities and for improved observation quality control, data assimilation, and model physics.

The Climate Working Group therefore asserts that an orderly prioritization and resourcing of efforts in the following five focus areas will support the development of a seamless subseasonal-to-seasonal-to-decadal (S2S2D) prediction system for decisions that save lives and livelihoods:

- Hybrid statistical-dynamical models;
- Boundary layer processes;
- Global ocean observations;
- Biogeochemical processes: oceanic and terrestrial; and
- Improved engagement and communications on S2S2D timescales.

This white paper lays out recommendations for expanding prediction science to include the entire earth system, particularly key elements affected by our changing climate. While the nine recommendations are numbered for convenience, the numerals indicate neither prioritization nor preference.

1.1 Hybrid Statistical-Dynamical Models

Dynamic climate models generally have better skill in predicting large-scale atmospheric and oceanic circulation and thermodynamic structures, but have large uncertainty in representing and predicting subgrid scale processes. The development of hybrid statistical-dynamic models offers a cost-effective approach that can improve skill over dynamic ensemble forecasts and produce bias-corrected and value-added products for dynamic predictions, especially at the local, regional, and subseasonal-to-seasonal (S2S) scale, and may also lead to the discovery of sources of predictability. However, hybrid statistical-dynamic modeling is poorly supported by NOAA, especially with respect to competitive research. Relatively small amounts of support would enable NOAA to apply the latest research results and bring actionable climate information to stakeholders relatively inexpensively.

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.

1.2 Boundary Layer Processes

The boundary layer is the lowest part of the atmosphere—where the atmosphere and terrestrial/oceanic surfaces interface. The structure and dynamics of the boundary layer are critically important to the understanding of weather and climate, the dispersion of pollutants, and the exchange of heat, water vapor, and momentum with the underlying surface. However, while advances in earth system prediction are predicated upon increased skill in boundary layer simulations, most boundary layer simulations use parameterizations from decades-old experiments that were carried out in very specific regions. Moreover, new technology allows the use of chemicals with multiple lifetimes to

diagnose boundary layer processes. Incorporating the near surface chemical processes to understand and quantify the boundary processes would have an enormous impact in helping weather forecasting, calculation and quantification of emissions for air quality, and climate needs.

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.

1.3 Global Ocean Observations

The United Nations declared 2021–2030 the Decade for Ocean Science and Sustainable Development to reverse the cycle of decline in ocean health and develop a worldwide common ocean science framework to improve conditions for sustainable ocean development. Opportunities for major enhancements of the Global Ocean Observing System (GOOS) have emerged in recent years, and include: 1) a redesign of the Tropical Pacific Observing System (TPOS) to produce a more resilient and integrated system; 2) the development of new sensors for autonomous observation of biogeochemical (BGC) properties on moorings, gliders, and profiling floats; 3) observations of the complete ocean, including Deep Argo, BGC Argo, and Polar-deployed Argo; and 4) implementation of the Deep Ocean Observing Strategy (DOOS). While the groundwork has been laid for the above expansions of NOAA’s ocean portfolio, few of these initiatives have secured committed funding. Additionally, NOAA’s research fleet of vessels used for sustained ocean observations has had declining support. Without committed funding, these ocean observation enhancements will not be realized.

Recommendation #3. Work towards realizing an expansion of observation networks into the tropics, deep, and polar oceans; obtain global oceanic biogeochemical 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.

1.4 Biogeochemical Processes

1.4.1 Biogeochemical Observations: Oceanic

Scientists are in a race to understand the ocean’s role in our climate and marine life just as it undergoes a rapid physical and biological change as a result of anthropogenically induced climate change. The principal drivers of life in the ocean are temperature; salinity; ocean circulation; the supply of nutrients and light; and carbon dioxide (and associated pH) and oxygen concentrations. Increasing atmospheric CO₂ is driving increased oceanic uptake of CO₂ and leading to oceanic warming and acidification. The ability to detect changes in biogeochemical processes that occur due to oceanic warming and acidification is greatly hindered by undersampling as vast swaths of the ocean have never been studied or have been sampled only once per decade. The advent of FV3-GFS and the assimilation of oceanic biogeochemical information will allow NOAA to move from a reactive to a proactive approach to expand predictive capabilities into ecosystems and carbon cycle domains and support the expanding Blue Economy.

Recommendation #5. Fund a global biogeochemically-sensored autonomous profiling float array and train the personnel to deploy and calibrate them.

1.4.2 Biogeochemical Observations: Terrestrial

Climate and the carbon cycle are tightly coupled on many timescales. On interannual to multi-decadal scales, terrestrial biogeochemical processes dominate carbon-climate feedbacks and atmospheric CO₂ variations. Over land, vegetation controls the water exchange between subsurface soil layer and atmosphere and surface energy balance and runoff. By connecting to deeper pools of soil moisture, vegetation feedbacks can mitigate/delay or amplify/accelerate climate anomalies driven by the ocean. Terrestrial biogeochemical processes represent an important source of predictability and prediction skills across S2S2D timescales. While the importance of vegetation in determining S2S2D predictability has been increasingly appreciated in recent years, it is still understudied. An increased understanding of the importance of vegetation for decadal predictions will reveal new opportunities for advancing the predictive capabilities of earth science prediction beyond the limit currently set by oceanic predictability.

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.

1.5 Improved Engagement and Communications on S2S2D Timescales

Recommendations and mandates in the Weather Research and Forecasting Innovation Act of 2017 (“The Weather Act”) and a recent National Academy of Sciences report for engaging with stakeholders on S2S2D timescales—coupled with the implementation of FV3-GFS—make this an opportune time for NOAA to review the agency’s capacities and processes for iterative communication with stakeholders. Opportunities for improving engagement and communications with stakeholders on S2S2D timescales include filling in the gaps in the existing organizational structure that is supporting climate services; enhancing capacity to produce tailored forecast communication products through software development; developing forecasts and decision-making tools to address S2S2D information needs; and expanding capacity to assess the return on science investment. NOAA needs to enhance the infrastructure for engaging sectors and communities, communicating forecasts, and supporting decision-making needs to secure the full value of the FV3-GFS investment and meet the mandates of the Weather Act.

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.

2.0 Introduction

The convergence of climate and weather modeling, occasioned by the implementation of the FV3-GFS model, presents an opportune time for NOAA to rapidly leverage the improvement of observational capability across the entire earth system to save lives and property and support the Blue Economy.

In short. This white paper lays out recommendations for expanding prediction science to include the entire earth system, particularly the key elements affected by our changing climate.

The National Oceanic and Atmospheric Administration's (NOAA) mission is critical to our Nation's economy and welfare: collecting and processing data to protect lives and property; monitoring Earth's weather, climate, and natural resources; and charting our waters for safe navigation and maritime commerce.¹ In a world dominated by unrelenting anthropogenic climate change, earth system prediction on subseasonal-to-seasonal-to-decadal timescales (S2S2D) is essential to saving lives and property and supporting industry.

Climate is woven into the fabric of NOAA's mission.² The challenges of serving the Nation's interests amid an increasingly changing climate is a daunting task. The goal of a seamless service to address users' decision-making needs—ranging from the locations of algal blooms closing Gulf Coast beaches to expected snowfall in the southern Sierra Nevada to the prospects of heat and drought in the upper Mississippi Valley—are lofty yet attainable aspirations.

The pathway to improved predictions is multi-pronged and founded on advances in unlocking crucial mysteries of the atmosphere-ocean circulation, often amplified by land/vegetation feedbacks. NOAA can leverage the capabilities of the FV3-GFS model with existing and emerging observational arrays. However, these existing efforts across NOAA must be enhanced with specific attention given to hybrid-statistical dynamic modeling, boundary layer processes, and expanded ocean observations. This information is essential to the weather and climate model predictions at all timescales that inform a safe Nation in the face of environmental challenges.

The Climate Working Group asserts that an orderly prioritization and resourcing of pertinent projects focused on observations, modeling, and communication will leverage the opportunity to create a successful and seamless S2S2D prediction system. We propose five areas for which concerted focus and effort would greatly improve NOAA's earth system prediction framework: hybrid statistical-dynamical models; boundary layer processes; global ocean observations; oceanic and terrestrial biogeochemical processes; and the communication of research for the protection of life, property, and the enhancement of the national economy.

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.

3.1 Context

Global and regional dynamic climate models generally have better skill in predicting large-scale atmospheric and oceanic circulation and thermodynamic structures, but have large uncertainty in representing and predicting subgrid scale processes with direct societal impacts, such as those that control precipitation, clouds, ice, eddies of the ocean, soil moisture, and vegetation. At climate scales, the errors in these subgrid processes also interact with large-scale circulation, amplifying the biases in the responses of large-scale circulation to climate forcing and natural variability in the dynamic climate models. Hybrid statistical-dynamic models represent an effective approach (i.e., a low-hanging fruit) to bridging the gap between the needs of society and the limitations of dynamic climate

models, especially at regional-local and S2S scales. Hybrid statistical-dynamic ensemble predictions have been shown to improve skill over dynamic ensemble forecasts and to produce bias-corrected and value-added products for dynamic predictions.

3.2 Opportunities

As the U.S. experiences more frequent and stronger extreme climate events, the demand for more skillful predictions from state and regional stakeholders is also increasing. In particular, stakeholders are demonstrating an emerging interest in hybrid statistical-dynamic models as those have shown prediction skill over many regions where dynamic models have shown no prediction skill, especially at the subseasonal-to-seasonal (S2S), regional, and local scales for droughts, floods, fires, and effects on ecosystems.

The development of hybrid statistical-dynamic models is also relatively inexpensive and effective for incorporating the insight gained from climate process studies and for providing predictions tailored to the needs of the stakeholders. For example, since 2015 the Texas Water Development Board has adopted a hybrid statistical-dynamical seasonal prediction for summer rainfall to support the state's drought preparedness,³ a prediction system built on insight gained from the latest drought process studies supported by NOAA's Climate Program Office (CPO) Modeling, Analysis, Predictions, and Projections (MAPP) program. After the severe 2012-2016 California drought, the Department of California Water Resources has also begun supporting the development of hybrid statistical-dynamic S2S predictions.

This emerging interest from stakeholders provides a great opportunity for NOAA to deliver value-added and actionable climate information and fast track the research-to-operations (R2O) for regional applications through hybrid statistical-dynamic modeling. Success of this approach should raise stakeholders' appreciation of the value of NOAA's climate research, including the usefulness of the NOAA dynamic models and earth system prediction systems, and create opportunities for collaboration between states and NOAA. The improved prediction skills shown by hybrid statistical-dynamic predictions can also challenge researchers' understanding of predictability and lead to the discovery of sources of predictability.

3.3 Gaps

At present, hybrid statistical-dynamic modeling is poorly supported by NOAA, especially with respect to competitive research. Since hybrid statistical-dynamic modeling involves research (in identifying predictors and training the models), operations (providing predictions), and applications (identifying predictors tailored to stakeholders' needs), it can easily fall through the cracks of the existing climate programs within NOAA. Thus, its potential benefits to NOAA are far from being fully realized.

3.4 Conclusions

Hybrid statistical-dynamic models represent a cost-effective and low-hanging fruit for bridging the gap between the needs of stakeholders and limitations of the dynamic models at regional scales and especially for S2S predictions. Relatively small amounts of support from NOAA, leveraged by states or private sectors whenever possible, would go a long way in enabling NOAA to apply its latest research results and bring actionable climate information to its stakeholders inexpensively. Joint support from the Office of Weather and Air Quality's (OWAQ) S2S program and CPO's Earth System Science and Modeling (ESSM) and Climate and Societal Interactions (CSI) programs will enable S2S and ESSM to fast-track the application of research to address the needs of stakeholders.

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.

4.1 Context

The boundary layer is the lowest part of the atmosphere wherein the atmosphere and terrestrial/oceanic surfaces interface (see Figure 1), and where humans live, emit, and feel the impacts of various environmental issues such as weather, climate, climate change, and air quality. These atmospheric/terrestrial/oceanic interactions control exchanges of kinetic and thermal energies and materials such as aerosols and pollutants at the surface, which in turn drive the global weather and climate system as a whole. Conditions in the boundary layer can greatly influence earth system dynamics, including how much rain will fall during a storm, where and how far pollutants will spread, or the strength and path of hurricanes and tornadoes. Increased societal demands for extended forecasts highlight the need to advance earth system modeling, and a better understanding of the boundary layer is key to improving these models.

Improved observations of the boundary layer and its interactions with the ocean, land, and ice surfaces have great potential to advance science on a number of fronts, from improving forecasts of severe storms and air quality to constraining estimates of trace gas emissions and transport. However, the boundary layer is a difficult region to quantify as it has substantial variability due to the nature of the underlying surface, diurnal cycling, thermal stratification, vertical entrainment (mixing vertically), advective processes (carrying substances), and other processes.

While advances in environmental prediction are predicated upon an increased skill in simulations of the boundary layer, boundary layer processes have mostly been parameterized based on a few experiments performed decades ago and carried out in specific geographical regions. New observing technologies and approaches have the potential to radically increase the density of observations and allow new types of variables to be measured within the boundary layer, which will have broad scientific and societal benefits that include an increase in skill, especially in climate, air-quality, and short-term forecasts of hazardous weather. Improved atmospheric measurements could also enhance understanding of the exchanges between the biosphere and the atmosphere and the air-sea exchanges; better understanding of these exchange processes is important for scientific knowledge of biogeochemical cycles, impacts of climate change on ecological systems, and estimates of carbon storage in natural systems.

4.2 Opportunities

There are crucial components of the planetary boundary layer circulation, including complex boundary layer flow and air-sea interactions, that determine the energy balance in the lowest layer of the atmosphere. Research in the last decade has increased the physical understanding of processes such as the influence of soil moisture, gas-particle exchanges between air and water (deposition and emissions); mixed ice-sea surfaces and resultant fluxes of heat and moisture; and the air flow within urban canopies and land-surface characteristics. Boundary layer research must answer: (1) What is the boundary layer's volume (by time of day, location, etc.)? (2) What are the gradients (vertical and horizontal)? (3) How and how well is it mixed? (4) How might we use chemicals with different

lifetimes for diagnoses? New observing technologies and approaches have the potential to radically increase the density and variety of observations to be measured and answer these key questions.

One such approach is the enhanced capability to measure free radicals (e.g., nitrates/ NO_3^-) and atmospheric chemical components, particularly components with variable lifetimes from seconds to years to centuries. Assimilating chemical data could help improve the understanding of boundary layer characteristics. As NOAA already measures very small concentrations of species with variable lifetimes for other studies, there is a unique opportunity to refocus the current chemical process studies to address the needs of boundary layer dynamics, particularly if coupled with NOAA's modeling capabilities—over a wide range of scales from Large Scale Eddy Simulations to weather to air quality to climate—in NOAA's laboratories and associated cooperative institutes.

Understanding of the boundary layer is also constrained by the lack of observations at sufficient spatial coverage and temporal resolution. Unique nighttime and daytime chemicals and their variations must be measured day and night and in the transition times. Various types of Light Detection and Ranging (LiDAR) enable measurements of mixing and turbulence. The ability to field these measurements in varying terrains (including complex terrains, such as built environments) and surfaces (ships for the ocean and mobile labs for land and the cryosphere) will enable wider and more complete coverage. Furthermore, there is a treasure trove of data from previous field studies that can be mined to determine how best to optimize measurement paradigms.

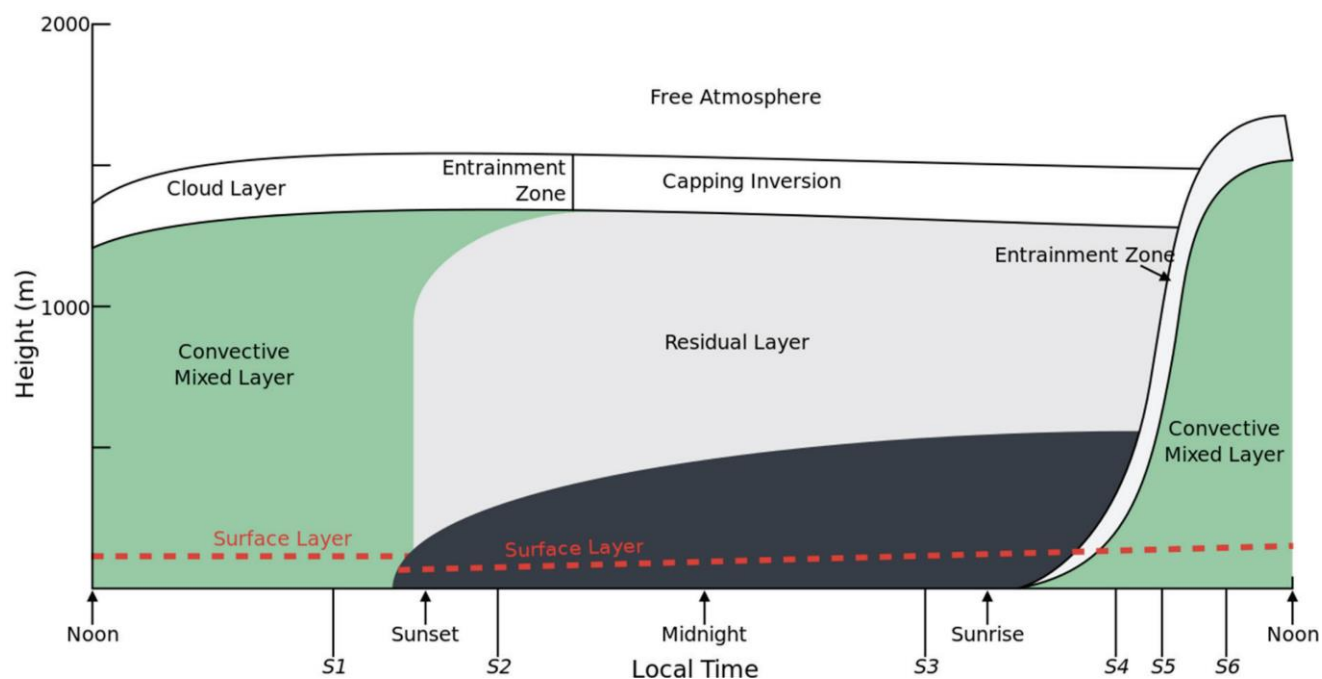


Figure 1. Schematic of the structure of the atmospheric boundary layer in high pressure regions over land, showing daily variations. Image Credit: National Academy of Sciences, 2018.⁴

In addition, the temporal and spatial observations from advanced space sensing systems, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), offer opportunities to fine-tune the BL dynamics with better parameterization routines. This will be particularly important with the air-quality modeling component of the FV3-GFS and down-scaled air chemistry models that are initialized with

the FV3-GFS boundary conditions. The importance of incorporating the near-surface chemical processes may have significant value in the future of earth system predictions.

The new FV3-GFS (GFS v15.1) model does incorporate several new boundary layer schemes (see Figure 2) and its hybrid planetary boundary layer parameterization is flexible enough to show improvements in mountain range lee-side cyclogenesis, cold air damming, and low-level barrier jets.⁵ Even so, there are still limitations and known errors within the model forecast of the planetary boundary layer. Ultimately, the skill of the FV3-GFS will depend on the accuracy of its cloud cover forecast because clouds have the greatest impact on the radiative transfer through the atmosphere. Since the FV3-GFS predicts cloud water content including which parts are ice, rain, snow, and graupel, these have a direct feedback into the radiative processes in the cloud, which plays a role on the optical depth of the model grid columns and its energy balance. Success in modeling the clouds will improve the skill of the model on all time and space scales.

NOAA has a large cadre of scientists, instruments, aircraft, and expertise in surface processes and chemistry that can be brought to bear. However, NOAA has not succeeded in owning boundary layer studies or promoting a program on boundary layer chemical studies and atmospheric dynamics/meteorology. Much of the research into the measurements and processes within the boundary layer has been spread across various NOAA labs and partner agencies with limited coordination. Among the ten NOAA labs and affiliates that focus on boundary layer dynamics, only two have remote sensing systems for atmospheric water vapor measurements. NOAA has an opportunity to significantly improve boundary layer process understanding through a concerted, focused effort.

4.3 Gaps

The need for improved boundary layer process understanding that has not been met over the past few decades is ripe for action. NOAA can greatly help since the agency has the capabilities that could be brought to bear on the issue. This could be done using some of the currently available programs and expertise (e.g., Air Resources Laboratory, Chemical Sciences Division, Physical Sciences Division, Geophysical Fluid Dynamics Laboratory, etc). It is important to find some key champions for this effort within NOAA and in the academic community. A few sporadic attempts do not constitute a program; this requires concerted efforts and plans. It is also important to impress upon NOAA scientists and associated academic colleagues that a large-scale effort could be supported if the appropriate plans are made and coordinated execution capabilities are highlighted. The following areas highlight areas for which a concerted effort could greatly improve boundary layer process understanding:

1. There is a lack of realistic boundary layer representation in current models.
 - a. Issue. Deposition of chemicals is parameterized based on few, decades-old observations carried out in very specific regions.
 - b. Opportunity. Improve the understanding of how quickly and efficiently chemicals are transferred (fluxes) from the atmosphere to the ocean.
 - c. Outcome. Improvement in air-quality prediction.
2. Boundary layer processes are poorly understood because previous and current approaches rely upon parameterizations.
 - a. Issue. Parameterizations of the boundary layer are not geographically representative over complex terrains.

- b. Opportunity. Measure and represent the time of evolution of the boundary layer at the diurnal/seasonal timescales. Measure various chemical species with variable lifetimes.
 - c. Outcome. Develop geographically representative parameterizations.
3. New technologies and computational capabilities exist that have not been brought to bear upon boundary layer issues, among them:
 - a. Representing the time of evolution of the boundary layer at the diurnal/seasonal timescales;
 - b. Measuring species lifetimes; and
 - a. Artificial Intelligence (AI).

4.4 Conclusions

The payoff from a boundary layer chemical and atmospheric dynamics research effort through a concerted program would be enormous. Improved boundary layer process understanding will help weather forecasting and calculations as well as quantification of emissions for air quality and climate needs. It will also provide valuable information to air-quality managers and planners, climate impact assessment efforts, health experts, wildfire forecasters, and marine life managers.^{6,7,8,9,10,11}

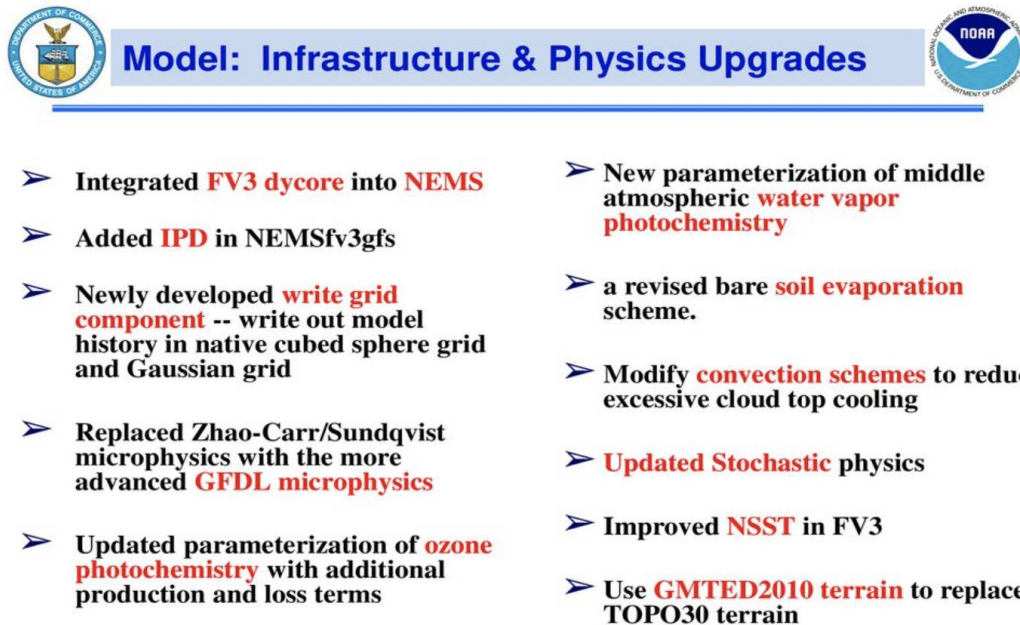


Figure 2. An overview of FV3-GFS infrastructure and its associated physics updates. Image credit: National Oceanic and Atmospheric Administration, 2019.¹²

5.0 Global Ocean Observations

Recommendation #3. Work towards realizing an expansion of observations networks into the tropics, deep, and polar oceans; obtain global biogeochemical observations through the implementation of deep Argo, BGC Argo and the enhancements in the Argo beyond 2020 design.

Recommendation #4. Restore funding for ship time in support of sustained observations and deployments.

5.1 Context

A once-per-decade review of sustained global ocean observations is being carried out in 2019 and, at OceanObs'19, participants shared “the decadal progress of ocean observing networks and chart innovative solutions to society’s growing needs for ocean information in the coming decade.”¹³ Concurrently, the United Nations has declared 2021–2030 the Decade for Ocean Science and Sustainable Development “to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework that will ensure ocean science can fully support countries in creating improved conditions for sustainable development of the Ocean.”¹⁴ The OceanObs'19 process and the UN Decade will identify gaps in the current observing system and opportunities to leverage and grow the observing system for increased societal value and to ensure the ocean’s sustainable development. These and other activities are tracked by the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM),^{15,16} an organization that also tracks the status of the Global Ocean Observing System (GOOS) and issues an annual report card and monthly maps of the global implementation (see Figure 3).¹⁷

5.2 Opportunities

Opportunities for major enhancement of the GOOS have emerged in recent years, largely through autonomous technology advances (platforms and sensors). These opportunities are articulated in OceanObs'19 Community White Papers.¹³ The following topics, in particular, are under discussion in the OceanObs community forum, and will be weighed for implementation:

1. A comprehensive redesign of the Tropical Pacific Observing System (TPOS) as a more resilient and integrated system has been carried out and documented.¹⁸ TPOS 2020 will, among other objectives, “refine and adjust the TPOS to monitor, observe and predict the state of El Niño Southern Oscillation (ENSO) and advance the scientific understanding of its causes.”¹⁸
2. New sensors have been developed for autonomous observation of biogeochemical (BGC) properties on moorings, gliders, and profiling floats. These create the opportunity to extend global observations beyond the physical variables (temperature, salinity, pressure, velocity), to include oxygen, pH, nitrate, bio-optical parameters to study ocean acidification, deoxygenation, and other fundamental biogeochemical cycles and climate-related variability. This aligns with the initiative by NOAA’s Climate Program Office to further address the effects of ocean acidification and also parallels the development of modelling and forecast systems for ocean health.
3. The present observing system, for most of its elements, spans only the upper ocean from 0–2000 meters and under-serves the polar oceans (particularly the Arctic), thus measuring only half of the ocean’s volume. Currently, NOAA does not have sustained support for Deep Argo, BGC Argo, and Polar-deployed Argo. Observation of the complete ocean will reduce the uncertainty in Global Ocean Heat Content, the global freshwater budget, carbon budget, ocean health, and other key climate and Blue Economy indices.
4. More generally, observing the deep ocean has progressed as a “GOOS” project like TPOS named the Deep Ocean Observing Strategy (DOOS).¹⁹ A DOOS Science and Implementation Guide²⁰ was written and made available for general feedback and a white paper was contributed to OceanObs'19.¹⁹

5.3 Gaps

While the groundwork has been laid for the above expansions of NOAA’s ocean portfolio, few of these initiatives have secured committed funding. Both Deep and BGC Argo remain at the pilot stage,

as do the polar expansions (Arctic and Southern Oceans) and tropical density enhancements as called for by TPOS2020 and other assessments. Adding biogeochemical profiles to the new ocean observing systems and self-organizing maps of surface and subsurface ocean temperature anomalies should improve understanding of the deeper ocean and its role in multi-annual and decadal climate trends. Without committed funding, these enhancements will not be realized.

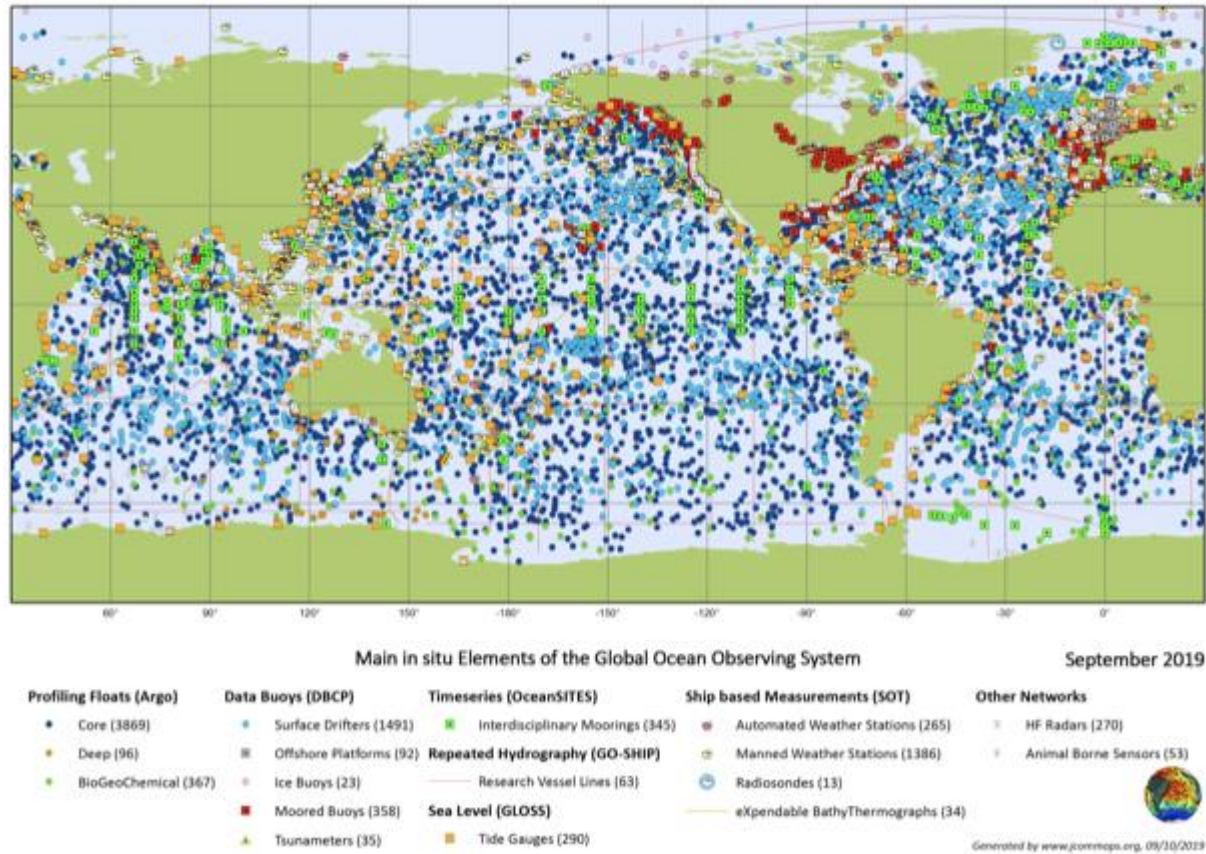


Figure 3. The status of *in situ* elements of the Global Ocean Observing System is shown in JCOMM’s monthly maps, here for September 2019, and Annual Report Card. Among the international contributors to the *in situ* observing system, NOAA plays the largest role. Image credit: Joint Technical Commission for Oceanography and Marine Meteorology, 2019.¹⁷

Another serious gap in U.S./NOAA sustained ocean observations is the declining support for the research fleet of regional-to-global-capable vessels. Research vessel operations are critical for all *in situ* elements of the observing system. In FY2019 and FY2020, NOAA’s Ocean Observing and Monitoring Division (OOMD) is facing a substantial decrease in ship time funding through the Office of Marine and Aviation Operations (OMAO). This will impact many programs that depend on ship time, including the Distributed Biological Observatory (DBO) in the Arctic, the Woods Hole Oceanographic Institution (WHOI) Hawaii Ocean Time-series Station (WHOTS), the Pacific Marine Environmental Laboratory (PMEL) Kuroshio Extension Observatory (KEO), the Northwest Tropical Atlantic Station (NTAS), the Stratus mooring, the Atlantic Meridional Overturning Variability Experiment (MOVE), and others. A critical and immediate need is the restoration of funding for ship time in support of sustained observations and deployments. A longer-term plan is needed to provide, support, and maintain the capable vessels needed to support the evolving ocean-observing efforts.

5.4 Conclusions

Technology development in autonomous platforms and sensors has provided an unprecedented opportunity for comprehensive and cost-effective ocean observing to:

- Support the Blue Economy;
- Measure the ocean's physical state and ecosystem health; and
- Enable the sustainable development of the oceans.

6.0 Biogeochemical Processes

6.1 Biogeochemical Observations: Oceanic

Recommendation #5. Fund a global biogeochemically-sensored autonomous profiling float array and train the personnel to deploy and calibrate them.

6.1.1 Context

Biogeochemical (BGC) processes play a central role in the carbon cycle, marine ecosystems, and climatic land-atmosphere-ocean feedbacks. Scientists are in a race to understand the ocean's role in our climate and marine life just as it undergoes rapid physical and biological change as a result of human activities. The principal drivers of life in the ocean are temperature, salinity, and ocean circulation; the supply of nutrients and light; and the carbon dioxide (and associated pH) and oxygen concentrations.²¹ NOAA needs a global observing network for oceanic biogeochemical (BGC) tracers in order to move from a reactive to a proactive approach. An oceanic BGC observing array would support the maintenance and management of ocean health, the management of marine resources, the improvement of prediction resources, carbon monitoring and treaty verification, and the overall development of prediction science.

6.1.2 Opportunities

Assessments by the National Research Council,²² National Academy of Sciences,²³ and the Executive Office of the President's Office of Science and Technology Policy²⁴ place a BGC-Argo array within a broader U.S. ocean science framework. Significant international planning has also occurred.^{25,26,27} In 2016, the G7 Science and Technology Ministerial meeting²⁸ adopted Action O38 of the 2016 Global Climate Observing System Implementation Plan, which details "Development of a Biogeochemical Argo array."²⁹ The plan specifically calls for "the deployment of a global array of ~1000 profiling floats equipped with pH, oxygen, nitrate, chlorophyll fluorescence, backscatter and downwelling irradiance sensors," with a particular recommendation for "increasing the capability of the global Argo network to include more biological and biogeochemical observation."²⁹ One outcome of this planning was unanimous approval by the Intergovernmental Oceanographic Commission Executive Council for the operation of BGC sensors on Argo floats.³⁰ Floats equipped with these sensors have been shown to be able to remotely determine the air/sea exchange of carbon dioxide^{31,32,33,34}—the first non-ship-based measurements to do so.

Opportunities for advancing the oceanic biogeochemical observing network will continue to follow in the path pioneered by the Argo array. The success of the United States Special Operations Command (SOCCOM) mission in the development and underway deployment of 200 biogeochemically-sensored floats (157 deployed, 136 operational as of July 10, 2019) has demonstrated the feasibility of instrumenting the entire ocean to measure the significant components of the carbon system (pH) along with other relevant tracers (e.g., nitrogen, oxygen, etc.).

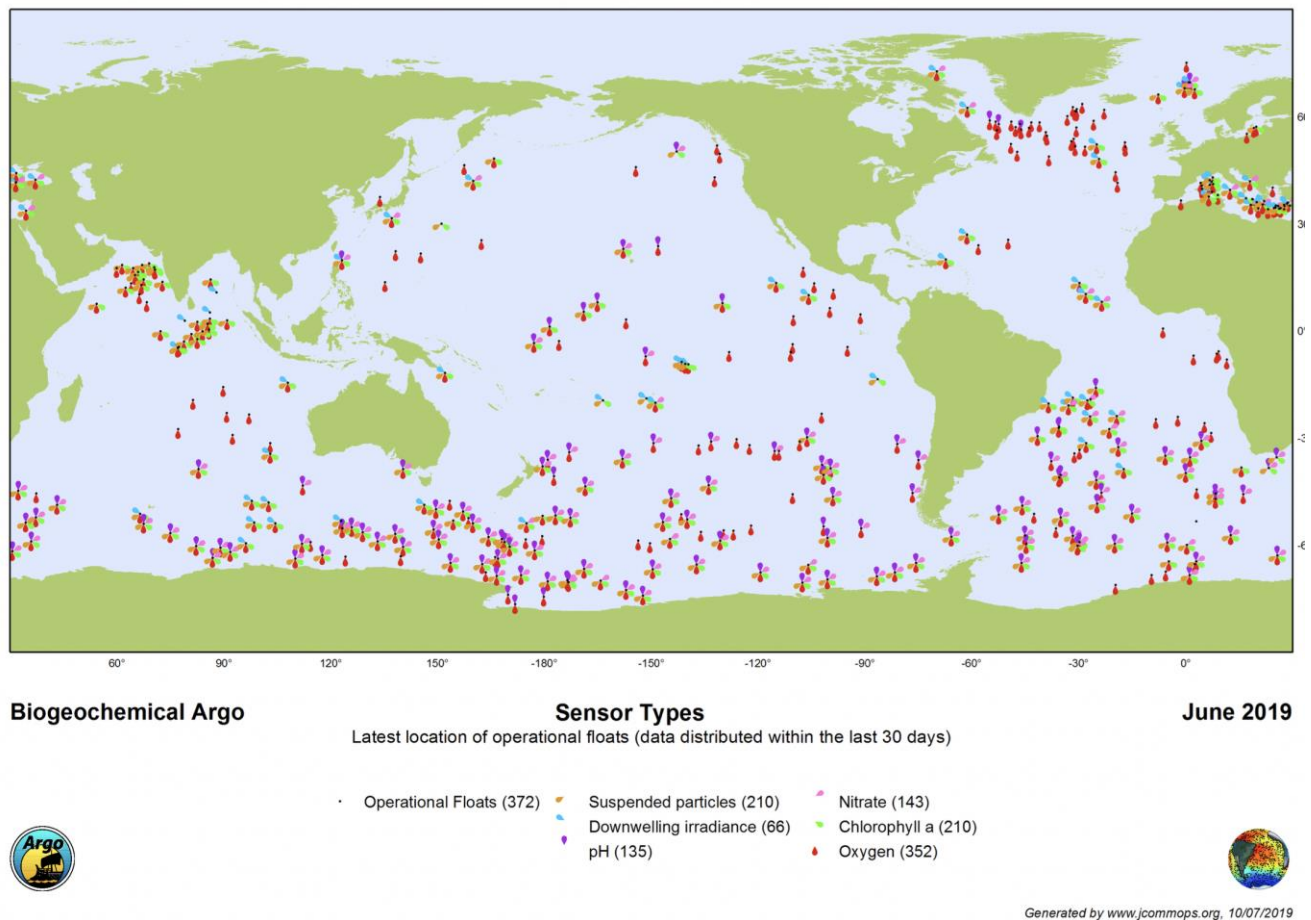


Figure 4. Biogeochemical float array indicating the position of the 372 operational floats recording biogeochemical parameters in June 2019. Image credit: ARGO and JCOMM, 2019.³⁴

Assimilation of biogeochemical observations of the Southern Ocean has led to the first oceanic biogeochemical state estimate (BSOSE).³⁵ A significant feature of NOAA's new high-resolution coupled weather-climate model, FV3-GFS, is the ability to increase the resolution over regions of interest. Assimilation of global atmospheric and oceanic data will open two new critical avenues of research. The first is forecasts and predictions from the latest earth system models (that include FV3 and its powerful nesting features for higher resolution locally) of ocean health and productivity for fisheries management and human health and economics. The second is a global carbon state estimate that will be able to separate terrestrial emissions and uptake from oceanic emissions and uptake, allowing the quantification of terrestrial carbon budgets on a regional or national level.

Presently, large areas of the ocean are only sampled once per decade, if at all, with sampling occurring mainly in summer. The ability to detect changes in biogeochemical processes that occur due to the warming and acidification driven by increasing atmospheric CO₂ is greatly hindered by this undersampling. Satellite systems are effective at detecting global patterns for a few biogeochemical parameters at the sea surface (in the absence of clouds), but a global array of biogeochemical sensors would revolutionize our understanding of ocean carbon uptake, productivity, and deoxygenation. The array is revealing the biological, chemical, and physical events that control these processes, and a full array would enable a new generation of global ocean prediction systems in support of carbon cycling,

acidification, hypoxia and harmful algal blooms studies, as well as the management of living marine resources.

6.1.3 Gaps

Researchers' best efforts to predict climate change and its impacts on marine life are blunted by limited understanding. Traditional ship-based and mooring technologies make possible only the most coarse-grained decadal timescale observations of most of these drivers of life. Vast swaths of the ocean have never been studied (see Figure 4), especially in the winter. Satellite observations have much higher resolution, but only for a few ecosystem variables, and only for the top few meters of the water column where light can penetrate. Researchers are flying nearly blind while the principal drivers of life in the ocean are undergoing significant changes.

Biogeochemically-sensored autonomous profiling floats require ship-based deployment as well as a detailed calibration at the time of deployment. Deployment of these floats, therefore, cannot be done successfully without ships and trained personnel on them. In addition, production of biogeochemical floats must be transformed from the current laboratory scale to an industrial scale.

The effects of warming, acidification, and deoxygenation on biogeochemical processes are difficult to predict with numerical models or remote sensing observations only—NOAA should emphasize both. FV3-based earth system models are ideally suited to this task, but FV3-GFS is brand new. Training NOAA's workforce and academics, as well as commercial enterprises in its use is going to require time as well as a committed investment in educational outreach and resources.

Because the U.S. contribution to the Argo program does not directly fund data analysis, a linked data assimilation and analysis effort is essential. NOAA's efforts should include biogeochemical data assimilation; this effort will contribute to the observational effort by revealing potential problems in data quality in near-real-time. This real-time synthesis and analysis effort will also serve as the foundation for an early warning system for ocean changes that cannot be easily recognized. It will produce annual products for ocean carbon, oxygen, and nitrogen cycling that include the identification of anomalies in these cycles.

6.1.4 Conclusions

NOAA has a long, distinguished history of providing accurate predictions to the Nation and the world. Prediction science on a larger scale in both time (days to seasons to decades) and space (regions and nations) is becoming more critical for more aspects of human endeavors (food, health, economy, trade, infrastructure, impacts, etc.). The advent of FV3-GFS and the addition of oceanic biogeochemical information will expand our prediction capabilities into ecosystems and carbon cycle domains, and support our Blue Economy.

6.2 Biogeochemical Observations: Terrestrial

Recommendation #6. Invest in terrestrial biogeochemical research and modeling, especially collaborations with the United States Department of Agriculture (USDA); collaboration between NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) and NOAA's Climate Prediction Center (CPC) would accelerate improvement of terrestrial biogeochemical processes in S2S2D predictions.

6.2.1 Context

On S2S2D timescales, terrestrial biogeochemical processes dominate carbon-climate feedbacks and atmospheric CO₂ variations.³⁶ Over land, vegetation controls the water exchange between subsurface soil layer and atmosphere and surface energy balance and runoff. By connecting to deeper pools of soil moisture, vegetation feedbacks can mitigate/delay or amplify/accelerate climate anomalies driven by ocean. Recent studies have shown that vegetation responses to climate anomalies, especially warmer spring temperature, are responsible for initiating a third of the flash droughts, especially over the midwest and Pacific Northwest U.S.,³⁷ and also contributed to the 2012 Great Plains extreme droughts.³⁸ Biogeochemical processes represent an important source of predictability at S2S scales in addition to that provided by oceanic variability.

6.2.2 Opportunities

Biogeochemical research is one of the most rapidly advancing fields in climate research. The improved understanding of vegetation responses to climate variability, extremes, and biogeochemical models used in climate projections have laid the foundation for improving the predictive understanding and modeling capability for climate variability, extremes, and marine ecosystems. Thus, the time is ripe for NOAA to harness these advances in science and modeling capability for improving predictability and prediction skills from S2S to interannual and multi-decadal timescales.

6.2.3 Gaps

While the importance of vegetation in determining S2S predictability has been increasingly appreciated in recent years, it is still understudied, especially its role in drought onset, development, and recovery. For example, researchers do not understand why a one-year meteorological drought in Texas in 2011 led to a four-year hydrological drought. It is still unclear how inadequate representation of the vegetation processes contributes to biases in evapotranspiration and runoff, which ultimately influence rainfall predictions. In addition, the ways in which managed vegetation, such as crops, influences surface water and energy and carbon budgets at least at regional scale, has received little attention from NOAA's weather and climate programs.

6.2.4 Conclusions

Since the Department of Energy (DOE) and National Aeronautics and Space Administration (NASA) have invested in biogeochemical research and modeling, collaborations with biogeochemistry programs and with the United States Department of Agriculture (USDA) are opportunities for NOAA to leverage investments in this area. In addition, collaboration between the Geophysical Fluid Dynamics Laboratory (GFDL) and the Climate Prediction Center (CPC) should accelerate improvement of biogeochemical processes in S2S2D predictions.

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.

7.1 Context

Improved engagement and communications with stakeholders on S2S2D timescales will require that NOAA continues to invest in its traditional three prongs: education, communication, and adaptation. Several recent activities and advances make this an opportune time for NOAA to review and revise the agency's engagement capacities and processes:

- The Weather Act requires NOAA to “prioritize weather research to improve weather data, modeling, computing, forecasts, and warnings for the protection of life and property and the enhancement of the national economy.”³⁹
- The National Academy of Sciences (NAS) report, *Next Generation Earth System Science: Strategies for Subseasonal to Seasonal Forecasts*,⁴⁰ Research Strategy 1 recommends two strategies for engaging users in the process of developing S2S forecast products.
 - Recommendation A: Develop a body of social science research that leads to a more comprehensive understanding of the use of and barriers to the use of seasonal, subseasonal, and decadal Earth system predictions.
 - Recommendation B: Establish an ongoing and iterative process in which stakeholders, social and behavioral scientists, and physical scientists co-design S2S2D forecast products, verification metrics, and decision-making tools.
- A quadrennial National Climate Assessment⁴¹ for the US has been mandated by Congress, therefore sustaining and advancing the science to support decision-making is necessary.

Additionally, improving engagement and communication on S2S2D timescales may depend on NOAA's Science Advisory Board conducting a review of the agency's capacities and processes for: a) iteratively identifying; b) communicating the information needs of community, sectoral, and regional decision-makers to NOAA leadership; and c) conveying information about NOAA's enhanced science capabilities back to these groups. The Climate Working Group suggests that NOAA may need to enhance efforts in traditional areas of social science infrastructure, cooperative institutes, and engagement to identify decision maker needs through the CPO Climate and Society Interactions programs, including the Regional Integrated Sciences and Assessments Program (RISAs).

7.2 Opportunities

NOAA's high-resolution coupled climate model, the FV3-GFS, model will increase NOAA's capacity to produce more accurate and longer lead time forecasts. Engagement with stakeholders on the needs and capabilities of new forecasts products is consistent with the mandates in the Weather Act and the NAS recommendations on S2S2D forecasts. The combination of FV3-GFS simulations with machine learning and pattern recognition, augmented by satellite observations, ocean biogeochemical measurements, and the Argo array will support these advances.

There are four major areas for improving improving engagement and communications with stakeholders on S2S2D timescales:

- Filling in the gaps in geographic coverage for the existing organizational structure supporting climate services (see Figures 5 and 6).
- Enhancing capacity to produce tailored forecast communication products through software development.
- Furthering the development of forecasts and decision-making tools to address S2S2D information needs.
- Expanding capacity to assess the return on science investment using multiple metrics such as economic impacts, diversity, and the number of people and locations served.

7.3 Gaps

The implementation of the FV3-GFS model highlights a major milestone for NOAA's science investments as well as stakeholder's increasing need for accurate forecasts with long lead times. The prioritization and resourcing of efforts in the preceding four areas will enhance NOAA's infrastructure for engaging stakeholders and supporting decision-making in order for NOAA to secure the full value of the FV3-GFS investment, meet the mandates of the Weather Act, and create a successful and seamless S2S2D prediction system to better save lives and property and support our Nation's economy.

The first opportunity for NOAA to improve engagement and communication is to fill in the gaps in geographic coverage for the existing organizational structures that support climate services. The current lines supporting engagement with decision-makers have numerous unfilled positions (Figures 5 and 6), thus limiting the capacity for NOAA to leverage existing organizational structures for communication and supporting climate services. Furthermore, to meet users' pressing S2S2D needs, enhanced iterative communication is needed to continually connect users decision-making needs with NOAA's enhanced science capabilities.

Second, NOAA needs to invest in the return on science investment in order to inform the agency's priority-setting for weather research. While the Weather Act requires prioritizing weather research for the protection of life and property and the enhancement of the national economy, NOAA's capacity to inform this priority-setting by evaluating needs and assessing improvements to national economy is limited. NOAA may evaluate the return on science investment by the level of improvement, numbers of people, and diversity of locations served as well as in economic metrics.



Figure 5. Currently funded Regional Integrated Sciences and Assessments positions. Image credit: National Oceanic and Atmospheric Administration, 2019.⁴²

NOAA's Regional Climate Services Directors



Figure 6. NOAA's Regional Climate Services Directors. Image credit: National Oceanic and Atmospheric Administration, 2019.⁴³

Third, enhancing NOAA's capacity to produce tailored forecast communication products will require software development. For example, improved communication includes providing more timely communication of salient information by using improvements in artificial intelligence, machine learning, and automated pattern recognition to identify impact patterns and climate anomalies and push info out. It also includes sharing information about the value of forecasts. Training NOAA's workforce and academics, as well as commercial enterprises, in FV3-GFS use is going to require a serious investment in educational outreach and resources, as well as engagement with communities and sectors to understand the value of the new capabilities for decision-making.⁴²

Finally, further development of forecasts and decision-making tools to address S2S2D information needs are needed in addition to warning systems. As climate changes force decision-makers away from assumptions of stationarity, it will be important to learn which timeframes decisions makers believe are most critical to their evolving needs. For example, Charleston, South Carolina's resilience officer requested the following of the climate community at the 2019 Climate Prediction Applications Science Workshop (CPASW): Right now, he can work with near-term and long-term forecasts. However he would like more information at the two-to-fifteen-year timeframe. When he buys new vehicles for the emergency management service fleet, he needs to know if he needs to purchase F350 trucks with higher flood clearance or can he get by with cheaper, lower clearance sedans?

7.4 Conclusions

NOAA's science investments have reached an important milestone as the new FV3-GFS becomes operational. NOAA needs to enhance its infrastructure for engaging sectors and communities, communicating forecasts, and supporting decision-making needs to secure the full value of the FV3-GFS investment, meet the mandates of the Weather Act, and create a successful and seamless S2S2D prediction system to better save lives and property, and support our Nation's economy.

8.0 Conclusion

As the U.S. experiences more frequent and stronger extreme climate events, the demand for more skillful predictions from state and regional stakeholders will increase, both to develop early warning

systems to improve societal preparedness and to gain a better understanding of the impacts of climate change.

The implementation of the FV3-GFS model demonstrates the need for improved predictions on all time frames ranging from multiple decades, interannual, seasonal and subseasonal, to days. At the same time, though, the FV3-GFS upgrade provides a foundation for NOAA to dramatically improve forecasting abilities and for improved observation quality control, data assimilation, and model physics.

An orderly prioritization and resourcing of efforts in hybrid statistical-dynamical models; boundary layer processes; global ocean observations; oceanic and terrestrial biogeochemical processes; and enhanced engagement and communication will support the development of an S2S2D prediction system that informs the decisions that save lives and property and support our Nations' economy.

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