Science Advisory Board

ADVANCING EARTH SYSTEM PREDICTION

WITH THE ASSISTANCE OF THE SAB CLIMATE WORKING GROUP

MARCH 31, 2021

Advancing Earth System Prediction

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1.0 Executive Summary

The National Oceanic and Atmospheric Administration's (NOAA) is the only federal agency in the U.S. government with "prediction" in its mandate. The convergence of climate, Earth system, and weather modeling, occasioned by the implementation of the Finite-Volume Cubed-Sphere dynamical core-Global Forecasting System (FV3-GFS) model, presents an opportunity for NOAA to advance Earth system prediction in order to save lives and property and support the Blue Economy. This white paper provides guidance on ways to enhance the quality and value of NOAA's Earth system prediction by including more sources of predictability and, thus, predictive skill for the development of a seamless forecast system to meet decision making needs across timescales. Recommendations begin from observations and modeling and extend to operational oceanography and forecasting. These efforts will inform forecasting for known decision making needs. Further guidance is offered on strengthening the exchange of information about decision maker needs and scientific capabilities, increasing accessibility of data and improving coordination with partners. Technological advances to support these advances are also addressed. The full list of recommendations is summarized in Appendix A.

The guidance and recommendations are organized into the following topic areas:

- Observations
- Ice and Inundation
- Operational Oceanography and Forecasting
- Decision Maker Needs
- Enhancing Coordination
- Model Technology

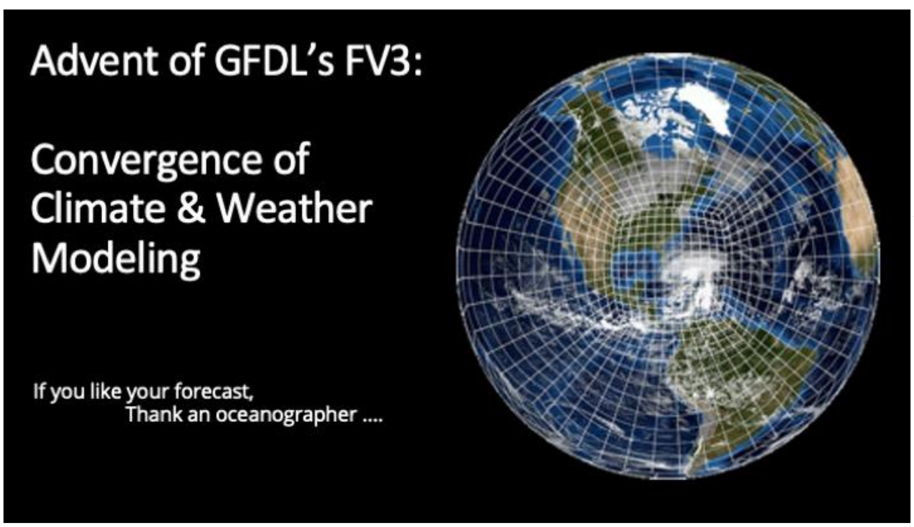

Figure 1. FV3 has been implemented to upgrade the current operational Global Forecast System (GFS) to run as a unified, fully-coupled system in NOAA's Environmental Modeling System infrastructure[1]. It is the convergence of Climate and Weather modeling. Quote from Craig McLean, the Assistant Administrator for NOAA Research.

2.0 Introduction

In alignment with NOAA's operational and legislative mandates[2] to expand the breadth of Earth system modeling and extend the infrastructure and user support for Unified Forecast Systems (UFS) to full Earth system coupling, this white paper offers guidance to advance

NOAA's Earth system predictive skill. As part of the development of a seamless forecast system, these efforts can address the needs of decision makers across timescales needed to inform long term investments in land use development, energy, transportation, water, communications, and marine infrastructure.

The implementation of the Finite-Volume Cubed-Sphere dynamical core-Global Forecasting System (FV3-GFS) model (June 2019) demonstrates the convergence of weather, climate, and Earth system modeling and predictions[3]. This upgrade will allow NOAA to dramatically improve forecasting abilities, observation quality control, data assimilation, and model physics, among other areas. What does this new model make possible for our nation and citizens?

There are several active areas in which Earth system prediction can play a significant role and are imperative to further NOAA's environmental/ocean intelligence including: 1) the Precipitation Prediction Grand Challenge; 2) the NOAA Climate and Fisheries Initiative; 3) the study of Coastal Inundation on Climate Timescales; and 4) the Hurricane Forecast Improvement Project, as well as general support for Blue Economy.

Now is the time for improving process understanding and sources of predictability and, thus, predictive skill for the development of a seamless forecast system across timescales. In doing so, we can leverage the nation's sense of urgency typified by: 1) the National Science and Technology Council's Fast Track Action Committee for Earth System Predictability (with the National Academies); 2) the FV3-GFS model release; 3) the Ocean-Based Climate Solutions Act introduced in the House in October 2020; 4) the UN Decade of Ocean Science for Sustainable Development (2021-2030); and 5) the National Academies of Sciences, Engineering, and Medicine (NASEM) Ocean-Shot for Transformative Research.

3.0 Observations

This section addresses critical needs in three areas of observations - land, atmospheric chemistry, and ocean and coastal shelf

3.1 Land Observations

Motivation

While attention is often focused on the physical aspects of Earth's atmosphere, NOAA's land and "chemistry" related measurements are just as critical. NOAA's measurements of physical and chemical properties of the Earth-system take center stage in efforts to understand climate change, weather patterns, ozone layer depletion, and air quality. It is critical to address how best to use these observations to get the most out of the investment: prioritizing the assessment of the continuity of ongoing observations and observation systems, preventing degradation of observational networks, expanding and improving observational networks where Earth system prediction requires additional, not just new measurements. We note that once a measurement opportunity is lost, it can never be replaced since geophysical conditions in space and time cannot be revisited.

NOAA, being a predominantly oceans and atmosphere centric agency, does not necessarily lead in land observations. However, it relies on land information, in addition to the atmospheric and oceanic information, for delivering its Earth system prediction products and services.

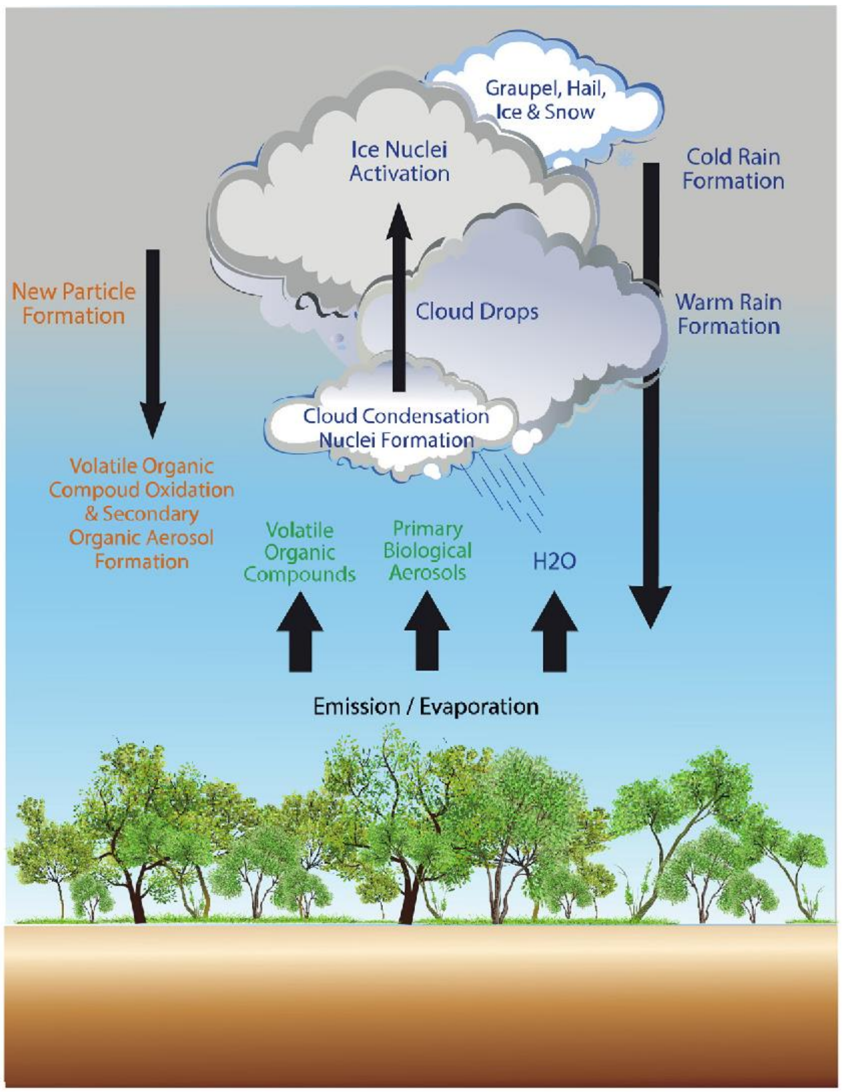

Figure 2: Schematic illustration of the land surface and vegetation influences on rainfall and air quality predictability through water and aerosol cycles[4].

Rainfall and drought predictions are major goals of NOAA. Land surface feedback is a promising source of predictability, especially for warm season rainfall over regions in the interior continents such as the U.S. Great Plains. Land vegetation feedback is especially important for improving prediction of heatwave driven flash droughts, more so over the agriculture areas such as Midwest and U.S. Great Plains[5]. However, climate models, including the NOAA Climate Forecast System (CFS), that are initialized by realistic soil moisture cannot sustain land surface memory beyond one month, whereas observation suggests that land surface memory can persist on seasonal or longer time scales[6],[7] and potentially improve seasonal prediction of rainfall[8]. In part because of models' inability to tap into land surface memory beyond one month, we have failed to predict major droughts in the U.S. such as the

2011 Texas Drought and 2012 Great Plain drought. Thus, clarifying what limits current climate models from realistically representing land-surface memory will provide a key for improving models and their prediction of rainfall and drought, especially on Subseasonal to Seasonal (S2S) scales.

Similarly, snowpack plays an important role in land-atmosphere interactions over snow-covered regions (such as western mountainous regions and northern states) in winter, spring, and early summer. Snowpack provides a memory for S2S prediction of the atmosphere and land states, including water resources. Furthermore, NOAA's National Weather Service has the most successful and longest record from citizen science: the Cooperative Observer Program (COOP) that consists of tens of thousands of volunteer observers of temperature, humidity, precipitation, and snow depth across the U.S. These snow depth measurements contribute to the development of gridded snow depth and snow mass data development for model initialization and evaluations.

Recommendation 1: Lead the coordination, through multi-agency collaborations, of the observation of surface, deep soil and groundwater, as well as the atmospheric boundary layer and free troposphere, clouds and precipitation profiles, which are mostly available, but not coordinated in space and time.

Recommendation 2: Develop and improve gridded snow mass datasets, including investment in quality check of the citizen science measurements, over U.S. and globally for improving model initialization in weather and S2S prediction, especially for stream and river flows and floods over snow-covered regions.

3.2 Atmospheric Chemistry Observations

Motivation

While the coupling of land processes and atmospheric physics (e.g., the energy and water cycle) has always been included in weather and Earth system models, the land coupling with atmospheric chemistry has been recognized more recently. In fact, this two-way coupling between atmospheric chemistry and land is minimal in the current operational models by NOAA's National Center for Environmental Prediction. One pathway for this coupling is the biogenic emission of Volatile Organic Compounds (VOCs), where in situ measurements over different land cover types are needed to quantify the detailed physical, chemical, and biogeochemical processes. For instance, how does drought affect this emission? How does this depend upon land cover type? Another pathway is the emission of aerosols (e.g., via dust storms) and measurements are needed to quantify the impact of soil moisture, bare soil fraction, and vegetation type on dust generation.

The atmospheric boundary layer acts as the bridge linking the land surface to the free atmosphere, and most of the human activities are within the boundary layer. Integrated measurements of land processes, atmospheric chemistry, and other boundary layer measurements over different land cover types (at least from forests to grassland, from crops to shrubland) can provide insight into boundary layer dynamics. Better understanding of the land-boundary layer coupling through both chemical and physical processes will inform improved weather and S2S predictions and their applications (e.g., public health through the prediction of wet bulb temperature). Using chemical (of lifetimes that vary from seconds to days) measurements to understand the dynamics would also enable better quantification of human emissions and better assessment of impacts on humans, agriculture, and the ecosystem.

Aerosols data is essential for climate and weather forecasting as well as air quality predictions. The radiative forcing by aerosols can be very large and can change patterns in weather, including forecasting. With its observational networks of radar, sounding, aerosols and trace gases, NOAA is in an unique position to advance our understanding and modeling capability of the aerosol influences on extreme rainfall and droughts in partnership with the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE).

Maintaining and continuing high quality observations of ozone, surface ultraviolet (UV) radiation, ozone depleting gases, and tropospheric constituents is scientifically essential, policy relevant, and legislatively mandated. Over the past four decades, NOAA has developed unique expertise in understanding air quality, especially in elucidating the chemical processes that are essential for predictions; this is complementary to the U.S. Environmental Protection Agency's (EPA) regulatory and surface monitoring role, and climate change monitoring and modeling. This expertise critically depends on the use of intensive field campaigns, maintaining observational sites, instrumentation development, heavy-lift aircraft, and computation capabilities, considering especially:

- **Infrastructure, including personnel.** Currently, NOAA is losing or at risk of losing capacity and expertise because of the loss of personnel and important infrastructure. Examples include retirement of people with expertise, loss of surface observation sites (e.g., Summit, Greenland, and Trinidad Head, California), old/aging instruments, and NOAA's essential UV monitoring network. Instrument modernization programs would greatly benefit NOAA's observational capabilities: maintenance, upgrading, and bringing them to 21st century standards will reduce costs, enhance reliability, and expand geographical reach. Aircraft is another crucial component; heavy lift P-3 aircraft essential for summer studies of highest air quality degradation, are reassigned during summer months for hurricane reconnaissance flights. Discovery and continued research in air quality depends on measuring up to hundreds of compounds in real time with sophisticated analytical detectors in urban and rural locations currently only accessible by aircraft.
- **Private Sector.** Another issue is the role of the private sector, which was minimal a decade ago but has increased in recent years. Both NOAA and NASA have programs now to purchase data from ground measurement networks or satellites owned by the private sector. A careful tradeoff analysis and observing system design is needed for the synergistic land surface and atmospheric chemistry measurements among NOAA, the private sector, states, and other federal agencies, with the goal of better weather, S2S, and air quality prediction.

Recommendation 3: Enhance land observations with focus on land impacts on atmospheric boundary layer structure, and biogenetic, dust and biomass burning aerosols, and their interaction with clouds and precipitation, either by initiating NOAA's own or contributing to joint efforts; and realign some of the "chemistry" measurements capabilities to address the issue of boundary layer meteorology that will enhance weather prediction, deposition process understanding, and climate change science.

Recommendation 4: Enhance and refocus the NOAA infrastructure (people; heavy-lift aircraft; chemical, aerosol, and radiation measurements, etc.) to improve weather forecast, emission quantification to inform societal action, climate change quantification to inform mitigation and adaptation, and reducing impacts of wildland fires.

3.3 Ocean and Coastal Shelf Observations

Motivation

As we continue to see increased severity of extreme events linked to changing earth systems, state-estimates and predictions are critical for coastal communities and industries, marine resource managers, and planning for extreme events from storms through to algal blooms[9]. Improved climate and ocean forecasts will rely on an operational data stream to support prediction initialization. Phenomena-based observations are also vital to help validate and improve system parameterizations and development. As the timescale for prediction extends to the interannual and decadal, it becomes vital to measure deeper in the ocean[10]. Additionally, assessments of global change rates, and what is controlling the concentration of greenhouse gases in the atmosphere, requires quantifying the ocean heat and carbon budgets directly.

There are a number of opportunities for big gains in ocean and coastal shelf observations. Present day prediction systems heavily rely on key observational networks, many of which are critical to sustain. However, even these key observational networks could be improved due to major gaps both spatially (e.g. polar, deep and shelf/slope oceans) and in key parameters (such as sea ice thickness, ocean biogeochemistry and biological data). The value of these observations will continue to increase as NOAA's forecasting systems evolve to fully coupled data-assimilation Earth systems across a range of timescales. Fortunately, new technological advances present opportunities to target some of these major gaps.

Recent improvements in satellite communication systems, sensor technology, and profiling float capabilities present an opportunity for revolutionary gains in tracking and understanding ocean cycling of nutrients and carbon on a global scale. Equipping 1000 of the 4000 operating Argo profiling floats with a suite of biogeochemical sensors will enable a step change in our ability to quantify, model, and predict ocean chemical cycles and how they drive ocean productivity and carbon uptake. In addition, the broad-scale and real-time data stream is ideally suited for ingestion into biogeochemical-capable ocean and Earth System forecasting systems, ultimately to enable improved prediction of new aspects of ocean and climate variability and change. Key synergistic data streams for a biogeochemical (BGC) Argo mission are the very high quality and full depth Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) repeat global multidisciplinary surveys, and satellite missions of both physical parameters (sea surface salinity, sea surface temperature, sea level height, wind, etc) and ocean color. The opportunity for NOAA is to both directly support the development of the biogeochemical Argo infrastructure and to accelerate development of model and data assimilation systems to exploit this new data stream.

The deep oceans comprise a vast reservoir of both carbon and heat, and potentially a source of predictability at decadal and longer timescales. They are critical to understanding Earth's response to anthropogenic forcing at the decadal and centennial timescales. In addition, both marine biological resources and deep sea mining activities are extending into the deep ocean in the face of scant information on the nature of this environment and its rate of change. Deep ocean observations (below 2000m) remain very scarce and have heavy dependence on access to global class research vessel time. Deep reaching profiling floats can help fill in the vast spatial gaps currently in our global deep ocean observing system, with around 1250 required globally to track deep ocean change on annual timescales.

An opportunity exists to drive forward a step-change in the shelf and coastal observing system, particularly for water profiles that are vital for initializing forecasts. Coastal radars combined with a fleet of shelf gliders monitoring the shelf hydrography, nutrient and bio-optical properties is one path forward. A rigorous design study of the needs of shelf forecasting systems could greatly benefit the needed development of the shelf observing system.

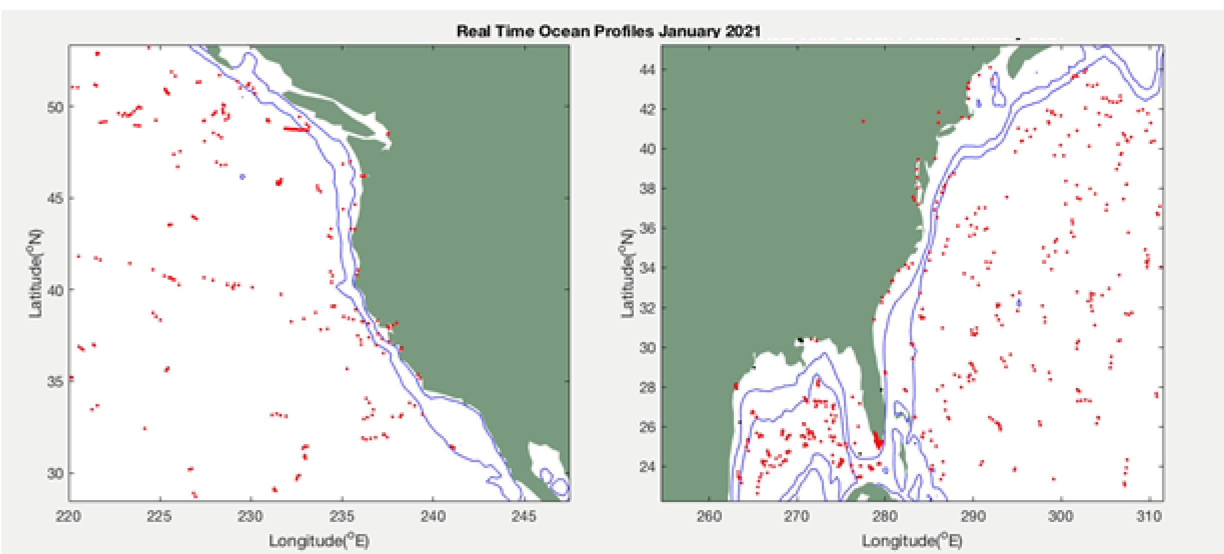

Figure 3: Locations (red) of profiles proximate to the mainland U.S reported in real-time to operational centers in January 2021 based on reports via the Global Temperature and Salinity Profile Program project. Two isobaths are shown: 200m and 2000m.

The offshore 'bluewater' upper-ocean climate observing system has rapidly evolved over the past decades, exploiting autonomous platforms and satellite sensors. Progress on the shelf and at the coasts, however, has been less rapid. In the past, shelf data streams relied on vessel-based surveys, but these are now being reduced due to budget stresses. Present day real-time ocean profile coverage of the shelf and slope are often found to be spatially less dense than found offshore (Figure 3), although we infer that faster shelf time scales and smaller space scales likely demand a higher density.

Recommendation 5: Target major gaps in the ocean observing system (shelf seas, deep and polar oceans, and living ocean). Expand the use of new and improved drifters, buoys, and autonomous instruments to facilitate a cost-effective expansion of the observing network below the ocean surface.

Recommendation 6: Ensure capability through robust observing system design projects and implement experiments to design networks of integrated observations and platforms including satellites, ships, floats, gliders and moorings for both physical and biogeochemical parameters.

Recommendation 7: Assess the utility of a nationwide shallow-water network of autonomous platforms (like gliders and floats) for physical and biogeochemical measurements for the shelf and coastal oceans and under-ice.

Recommendation 8: Build out the Argo network, including deep Argo and floats with biogeochemical sensors. Plan to enhance the fleet of global ocean observing ships.

4.0 Ice and Inundation

Motivation

The Arctic is experiencing coastal erosion, wildfires, threatened species, and permafrost degradation. Residents have grave concern for food security when animal habitat is damaged and transportation on the sea and land is more variable and dangerous. The Arctic has warmed faster than the global mean and Arctic sea ice has declined rapidly. Similarly, the Antarctic has experienced sea ice and ice sheet changes that are unprecedented in the satellite record.

Ice and snow across Earth's surface have a major impact on the amount of solar heating on Earth. Extreme weather and ocean turbulence are often connected to strong temperature gradients, which occur in proximity to ice and snow. Meltwater from land and sea ice and river runoff are known to alter ocean stability, and therefore sea surface temperature, through ocean mixing and circulation. Meltwater and runoff are also concerns for coastal inundation through sea level rise. Coastal inundation depends on other factors as well, like storm surge, which are considered here because they may compound the threat of inundation from meltwater and runoff and the modeling issues are related.

Currently, dynamical ice sheet components are seldom coupled synchronously to Earth system models (ESMs) used for prediction. More often ice sheet melt is coupled heuristically to snow accumulation or prescribed with a period annual cycle derived from an earlier estimate; therefore, the Earth system model does not take into account interannual variability in meltwater from coupled ice sheet-weather/climate interactions. Such sequential (uncoupled) ice sheet modeling hampers accurate forecasts of coastal inundation, maritime safety, icebreakers, and more.

Predictability on S2S and longer timescales exists due to the persistence of ice and ocean conditions and coupled interactions. There are only a handful of mechanisms in the Earth system that impart predictability beyond the short weather timescales and interactions. Not only does predictability associated with ice and ocean imply that there is greater potential for accurate local prediction, but also has remote influences that can benefit prediction elsewhere.

Recommendation 9: Create a strategic plan to implement global predictions, projections, and scenarios coupling dynamical sea ice and ice-derived runoff components with the atmosphere, ocean, and land in global models. Sea ice and ice sheet components must have high quality initializations for ice sheet and sea ice mass and coverage through advanced data assimilation means.

Recommendation 10: Work towards using an ensemble of predictions from a global model for stakeholder products. Regional modeling for calculating inundation should be nested within boundary conditions from global model simulations with coupled sea ice and ice sheets for consistency in treating variability and meltwater and its influences on ocean stability and circulations.

5.0 Operational Oceanography and Forecasting

Motivation

The U.S. needs a NOAA-led ocean forecasting system that produces regional and global products to support ocean and weather prediction, the Blue Economy (including shipping, ports, and commerce), and fisheries and ecosystem prediction applications. Given NOAA's mandate for environmental forecasts and the growing evidence of the dynamic ocean's impacts on weather, climate and fisheries resources, NOAA is clearly positioned to take the lead in developing a national, open access, high resolution forecasting system. Other agencies' missions are limited to coastal regions and only NOAA's includes the blue water ocean.

The opportunity exists now to apply Earth system prediction tools and approaches to operational oceanography to improve ocean, sea level, weather, and especially hurricane forecasts. Assimilating ocean data, including biogeochemistry, will support fisheries applications. Ocean reanalyses, especially those including carbon, will support NOAA's predictive capability with respect to ever-evolving initial conditions, as well as support the verification of international carbon treaties and other pollution emissions.

NOAA Geophysical Fluid Dynamics Laboratory's Modular Ocean Model (MOM6) is state-of-the-art and will advance all of NOAA's objectives involving prediction. The present plans to utilize MOM6 at high resolution for coupled data assimilation (for storms) and regional high resolution for ocean forecasts are not clear, or appear to be slated for several years away. How the present patchwork of myriad model/assimilation systems used for ocean services and hurricane prediction will be benchmarked and compared with a future unified system is not at all clear to the Climate Working Group or NOAA staff. Indeed, it is not clear who has the ultimate leadership for the development of ocean forecasting at NOAA.

A more unified, whole-of-NOAA strategy on high resolution ocean data assimilation and forecasting is needed, to: 1) make up lost ground compared to other nations; 2) simplify the modelling infrastructure used in service provision; and 3) build a linked NOAA-wide team of ocean data assimilation experts all supporting the development and improvement of a single system. Ocean forecasts are particularly relevant for ecosystem forecasting and there is a potential to make more specific recommendations here in addition to the recommendations on the review of the NOAA Climate and Fisheries Initiative Implementation Approach.

Recommendation 11: Implement an open-source operational ocean forecast system using MOM6 as soon as possible (on an accelerated timeline, i.e. not waiting until 2025). Include Earth system prediction benchmarks that quantify ocean pH, carbon, nutrients, with the intent of enabling consistent regional downscaling of ocean transport and ecosystems.

Recommendation 12: The NOAA ocean forecast system (based on MOM6) should include development and implementation of ocean data assimilation, ocean reanalysis and the framework for coupled ocean-atmosphere assimilation & reanalysis.

Recommendation 13: Current NOAA capability in regional ocean forecasting benchmarks and skills test should be applied to evaluate MOM6 global and regional simulations to accelerate transition to robust climate-relevant timescale boundary conditions.

6.0 Decision Maker Needs

Motivation

Climate change is raising new questions for design and protection of long-term investments including infrastructure and complex, interdependent systems. Rates of change, deep uncertainty, and abrupt changes are key elements of this decision space. There are sector-specific and cross sector needs to understand what changes to adapt to and when. Recent experiences with climate and air quality hazards such as wildfires in the West have exposed the shortcomings of independent sectoral approaches to building climate resilience. This also illustrates the need to understand the limits of current hazard mitigation strategies. Improved Earth system prediction can inform these decision spaces.

The new challenges and new information sources require modifying decision making practices. Decision makers consider information provided to evaluate potential hazards and determine value in opportunities. Those decisions take in information from multiple sources at different spatial and temporal scales. Decision makers are seeking information provided to clarify the decision space, not make the decision. This clarification involves evaluating uncertainty in predicted outcomes of hazards or opportunity. Other efforts for the integration of major scientific innovations into sectors such as agricultural and coastal management receive ongoing support from teams of specialists within each state (e.g., Natural Resource Conservation Service) working with individuals and communities to introduce and assist users in developing their understanding and use of new information. With the rapid evolution of Earth system prediction, the level of specialist services needed to build capacity and confidence in using climate predictive skills for sector and intersectoral applications requires further assessment. Maximizing the societal benefits of advancing Earth system prediction will require progress in systems for identifying and responding to user needs and expanding the accessibility of models and data to wider professional communities supporting decision making.

- **User-Informed Product Development**. NOAA-funded climate and society interaction initiatives, such as the Regional Integrated Sciences and Assessments (RISA) programs, are engaging user communities and defining requirements for new climate products to inform decision making. NOAA has an opportunity to complete the product development cycle by defining processes for prioritizing and transitioning user-informed climate data product requirements into new operational data products.
- **Changepoint Detection**. Alterations to the frequency, intensity, range of areas impacted by changes in climate patterns and extremes are raising awareness of the limitations of historical observations to guide planning to protect health, property, livelihoods and resources. Climate data thresholds used in decision making may become invalid due to gradual or abrupt changes in climate patterns. Rates of change in climate decision indicators need to be monitored and used to continually update the timing of decision points and thresholds in climate products and decision-making processes. Improved insight into potential future conditions is important to advance long term planning to minimize harm and losses as well as to capture opportunities.
- **Decision Scales**. Improved predictions offer opportunities to inform decisions at monthly, seasonal, and annual decision cycles to the decadal processes of planning and developing infrastructure (Figure 4). There is continued focus on predicting weather variables, such as precipitation and temperature, at climate time scales but only limited focus on enhancing predictability of derived variables and indices which are more closely aligned to longer range decision processes. For example, decisions of how to manage the risks of more frequent recurring flooding would be more cost effective with better understanding of how long a proposed solution (such as tide valves) might be effective against system changes. Planning and implementing increased capacity to address rising tides or wildfires or replacing/upgrading major elements of transportation and water/wastewater systems can take years of pre-study, fund raising, and approval processes before construction begins.
- **Open Innovation**. In a changing climate, the predictive power of the current generation of climate indices (such as El Niño-Southern Oscillation) is rapidly diminishing under the influence of new Earth system processes. Rapid development and updating of postprocessing algorithms are required to continue interpreting Earth system prediction model outputs and communicating predictions of future conditions to users. Developing open innovation platforms to engage a broader community of data scientists and Artificial Intelligence/Machine Learning (AI/LM) experts in detecting new patterns of predictability, developing new algorithms and creating new derived products is necessary.

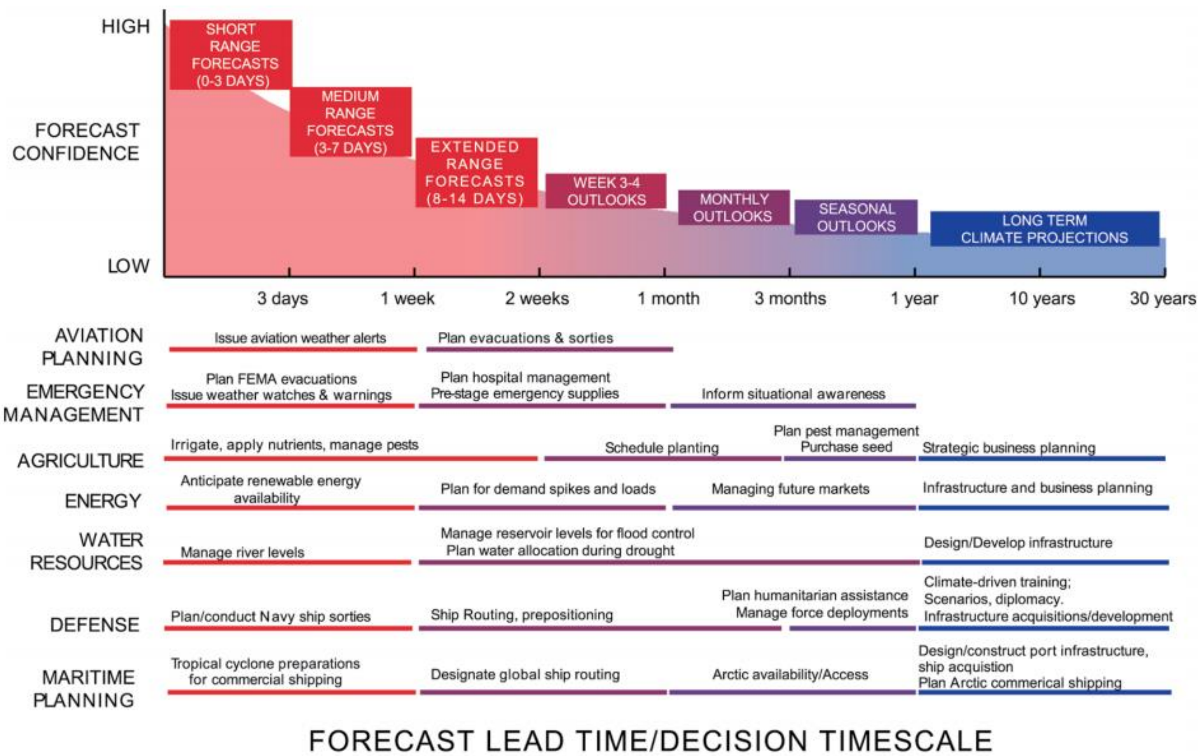

Figure 4: Sampling of federal decision needs across time scales. Decisions span weather to climate prediction/ projection capabilities, with responsibilities for actions falling throughout the federal and commercial sectors[11].

Recommendation 14: Enhance product specifications to include the distinctive dimensions of decision requirements for infrastructure and investment decision making that are influenced by progressive and abrupt change in climate processes and timescales and how advances in Earth system prediction can meet those needs across sectors.

Recommendation 15: Develop plans to foster the continued refinement of model information and derived products, at multiple time scales and spatial scales. In order to better characterize decision spaces, the Earth system prediction model output should be made available in combination with other decision-relevant information.

Recommendation 16: Develop a framework for incorporating research and development needs as informed by the end user decision spaces. This should include systematic, regularized opportunities for collaborative exploration based on decision-centric benchmarks of data and product performance of new components of Earth system prediction.

Recommendation 17: In conjunction with planning for the implementation of the Service Delivery Network, evaluate the appropriate level of specialist support needed to maximize benefits of advanced Earth system predictions. Coordinate these activities within NOAA so they can integrate feedback from decision makers and users' applications into continuing Earth system prediction improvements.

7.0 Enhancing Coordination

Motivation

Earth system prediction requires interdisciplinary and cross-workforce collaboration and coordination to be successful. Historically, the substructures within NOAA have made change difficult to implement (Figure 5). NOAA is on an improvement trajectory, but enhancing Earth system prediction requires wading into areas relatively uncharted for NOAA.

Recommendation 18: Every NOAA Strategic Implementation Plan related to Earth system prediction should include a line that addresses the goals, objectives, responsible parties and metrics of assessment relevant to the collaboration and coordination between:

1) Responsible line offices within NOAA
2) NOAA and other Federal agencies
3) NOAA and State agencies
4) NOAA and other partners – academic and industry
5) NOAA and stakeholders

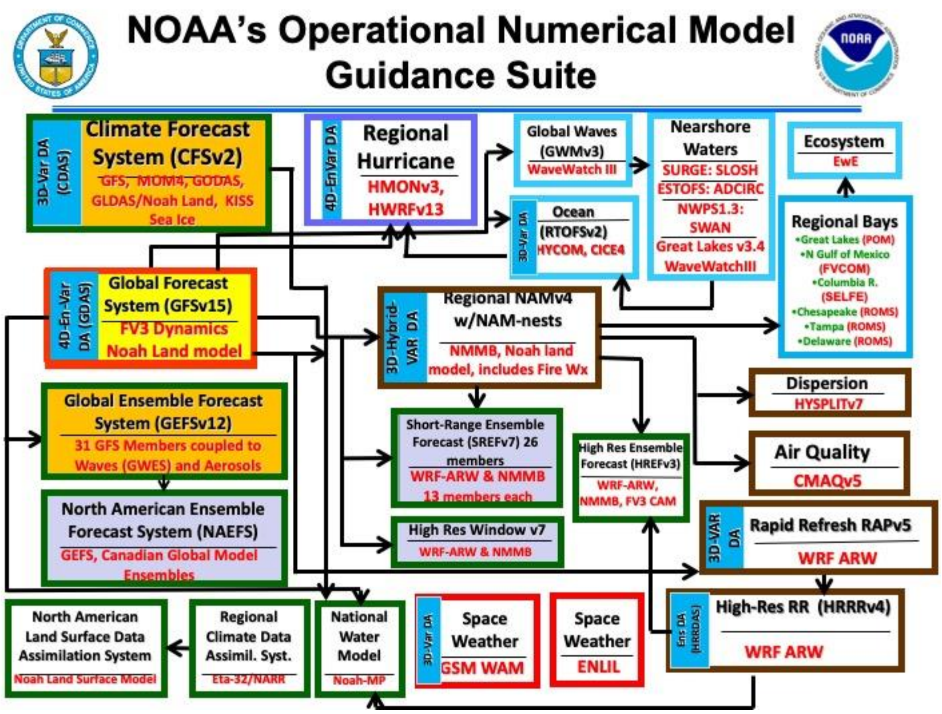

Figure 5: Courtesy of Brian Gross, Director, Environmental Modelling Center.

8.0 Model Technology

The opportunity is for NOAA to accelerate adoption/adaptation of technologies for optimizing model forecast performance, while informing a "do no harm" approach. The transition from research to operations can benefit from benchmarking improvements prior to operational use by allowing competition for model performance demonstration from academia and industry teams within a pseudo-operational environment using cloud environments and advanced observations. A big gain is that NOAA organizations, including the National Centers for Environmental Prediction (NCEP), Earth Prediction Innovation Center (EPIC), Joint Effort for Data assimilation Integration (JEDI), and Joint Center for Satellite Data Assimilation (JCSDA), can quantitatively assess future state operational performance benchmarking improvements from cloud computing, artificial intelligence, and advanced observing systems.

8.1 Cloud Computing

Motivation

Cloud computing is capable of addressing gaps in security, ingest capacity, data assimilation, processing, storage, and delivery of forecasts[13]. Cloud Service Providers (CSPs) provide scalable ingest, computing capacity, storage, community access, product distribution and delivery which enables elastic processing of large data items. CSPs provide enterprise-level mechanisms for managing data authenticity and provenance. These features enable governance models for authoritative decision-support tools and products. The ability to conduct post-processing in the cloud supports benchmarking new model capabilities prior to operational release. The movement of large environmental data holdings to CSPs expands capacity and flexibility for data flow, workflow, and business models thus improving interoperability, open data sharing, and public access. Data accessibility could be enhanced by redesigning data delivery services to include publicly accessible application programming interfaces with spatial and temporal sub-setting capabilities.

Recommendation 19: Establish agreements with Cloud Service Providers and members of the Earth system value chain to realize benefits of cloud technology for advancing predictions.

8.2 Artificial Intelligence

Motivation

The NOAA Artificial Intelligence Strategy[14] goal is to reduce data processing costs, and provide higher quality and more timely scientific products and services for societal benefits. AI/ML focus areas range from thinning data to automated pattern recognition. A key issue in applying AI/ML algorithms in the workflow for modeling and decision support is trust. Accurate high-quality historical training datasets are key for quality AI-based applications. Applying AI can introduce bias into the model system resulting in unintended impacts on prediction accuracy. AI/ML system performance is a function "experience" that can improve over time. Finding approaches to assess trustworthiness of results given expertise of analysis with varying environmental conditions will be important for operationalizing AI/ML use in predictions.

Recommendation 20: Establish accurate, high-quality, historical training datasets and indicators for trust in applying Artificial Intelligence/Machine Learning technologies to advance Earth system predictions.

8.3 Advanced Remote Sensing Technologies

Motivation

Consistent with the 2018 National Research Council Earth Science and Applications from Space Decadal Survey[15], advanced remote sensing technologies, including ability to measure parameters to derive 3-D winds, is seen by the community as a "holy grail." While the Aeolus instrument has not delivered as planned, a NASA mission advancing 3-D winds will benefit NOAA.

Spatial and temporal coverage can be improved, leveraging a large number of inexpensive sensors[17]. Multiple organizations are deploying constellations, including CubeSats, with instruments providing expanded coverage. Suppliers are claiming high confidence in 24-49 hour forecasts, albeit with few credible observations in the upper atmosphere. CubeSats have potential to fill this gap, with implications for longer term climate scale prediction. In addition, the new commercial data downlink and delivery systems are capable of providing data with low latency and minimal delay. Such closer to real time data can support more refined forecast products and greater science and societal benefits.

Recommendation 21: Accelerate acquisition and assimilation of commercial sources of data and delivery systems along with development of Earth Science Decadal recommended observing systems.

Recommendation 22: Benchmark performance quality, productivity, and cost using proven methodologies to quantify improvements to close gaps, identify root causes for deficiencies, and inform actionable improvement opportunities.

9.0 Sources

1. Adapted from the National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory. FV3: Finite-Volume Cubed-Sphere Dynamical Core. https://www.gfdl.noaa.gov/fv3/
2. The CWG recognizes that predictability depends on lower readiness level work, especially in the observations, field campaigns, process understanding, process models, that are needed to improve global models (e.g., address systematic errors) and hence improve predictions.
3. For example, the National Integrated Drought Information System Reauthorization Act of 2018 (Public Law 115-423) directed NOAA to establish the Earth Prediction Innovation Center (EPIC) to accelerate community-developed scientific and technological enhancements into operational applications for numerical weather prediction (NWP) and, in particular, to support the Unified Forecast System (UFS) community model.
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Appendix A: Recommendations

3.0 Observations

3.1 Land Observations

Recommendation 1: Lead the coordination, through multi-agency collaborations, of the observation of surface, deep soil and groundwater, as well as the atmospheric boundary layer and free troposphere, clouds and precipitation profiles, which are mostly available, but not coordinated in space and time.

Recommendation 2: Develop and improve gridded snow mass datasets, including investment in quality check of the citizen science measurements, over U.S. and globally for improving model initialization in weather and S2S prediction, especially for stream and river flows and floods over snow-covered regions.

3.2 Atmospheric Chemistry Observations

Recommendation 3: Enhance land observations with focus on land impacts on atmospheric boundary layer structure, and biogenetic, dust and biomass burning aerosols, and their interaction with clouds and precipitation, either by initiating NOAA's own or contributing to joint efforts; and realign some of the "chemistry" measurements capabilities to address the issue of boundary layer meteorology that will enhance weather prediction, deposition process understanding, and climate change science.

Recommendation 4: Enhance and refocus the NOAA infrastructure (people; heavy-lift aircraft; chemical, aerosol, and radiation measurements, etc.) to improve weather forecast, emission quantification to inform societal action, climate change quantification to inform mitigation and adaptation, and reducing impacts of wildland fires.

3.3 Ocean and Coastal Shelf Observations

Recommendation 5: Target major gaps in the ocean observing system (shelf seas, deep and polar oceans, and living ocean). Expand the use of new and improved drifters, buoys, and autonomous instruments to facilitate a cost-effective expansion of the observing network below the ocean surface.

Recommendation 6: Ensure capability through robust observing system design projects and implement experiments to design networks of integrated observations and platforms including satellites, ships, floats, gliders and moorings for both physical and biogeochemical parameters.

Recommendation 7: Assess the utility of a nationwide shallow-water network of autonomous platforms (like gliders and floats) for physical and biogeochemical measurements for the shelf and coastal oceans and under-ice.

Recommendation 8: Build out the Argo network, including deep Argo and floats with biogeochemical sensors. Plan to enhance the fleet of global ocean observing ships.

4.0 Ice and Inundation

Recommendation 9: Create a strategic plan to implement global predictions, projections and scenarios coupling dynamical sea ice and ice-derived runoff components with the atmosphere, ocean, and land in global models. Sea ice and ice sheet components must have high quality initializations for ice sheet and sea ice mass and coverage through advanced data assimilation means.

Recommendation 10: Work towards using an ensemble of predictions from a global model for stakeholder products. Regional modeling for calculating inundation should be nested within boundary conditions from global model simulations with coupled sea ice and ice sheets for consistency in treating variability and meltwater and its influences on ocean stability and circulations.

5.0 Operational Oceanography and Forecasting

Recommendation 11: Implement an open-source operational ocean forecast system using MOM6 as soon as possible (on an accelerated timeline, i.e. not waiting until 2025). Include Earth system prediction benchmarks that quantify ocean pH, carbon, nutrients, with the intent of enabling consistent regional downscaling of ocean transport and ecosystems.

Recommendation 12: The NOAA ocean forecast system (based on MOM6) should include development and implementation of ocean data assimilation, ocean reanalysis and the framework for coupled ocean-atmosphere assimilation & reanalysis.

Recommendation 13: Current NOAA capability in regional ocean forecasting benchmarks and skills test should be applied to evaluate MOM6 global and regional simulations to accelerate transition to robust climate-relevant timescale boundary conditions.

6.0 Decision Maker Needs

Recommendation 14: Enhance product specifications to include the distinctive dimensions of decision requirements for infrastructure and investment decision making that are influenced by progressive and abrupt change in climate processes and timescales and how advances in Earth system prediction can meet those needs across sectors.

Recommendation 15: Develop plans to foster the continued refinement of model information and derived products, at multiple time scales and spatial scales. In order to better characterize decision spaces, the Earth system prediction model output should be made available in combination with other decision-relevant information.

Recommendation 16: Develop a framework for incorporating research and development needs as informed by the end user decision spaces. This should include systematic, regularized opportunities for collaborative exploration based on decision-centric benchmarks of data and product performance of new components of Earth system prediction.

Recommendation 17: In conjunction with planning for the implementation of the Service Delivery Network, evaluate the appropriate level of specialist support needed to maximize benefits of advanced

Earth system predictions. Coordinate these activities within NOAA so they can integrate feedback from decision makers and users' applications into continuing Earth system prediction improvements.

7.0 Enhancing Coordination

Recommendation 18: Every NOAA Strategic Implementation Plan related to Earth system prediction should include a line that addresses the goals, objectives, responsible parties and metrics of assessment relevant to the collaboration and coordination between: 1) responsible line offices within NOAA, 2) NOAA and other Federal agencies, 3) NOAA and State agencies, 4) NOAA and other partners – academic and industry, and 5) NOAA and stakeholder.

8.0 Model Technology

8.1 Cloud Computing

Recommendation 19: Establish agreements with Cloud Service Providers and members of the Earth system value chain to realize benefits of cloud technology for advancing predictions.

8.2 Artificial Intelligence / Machine Learning

Recommendation 20: Establish accurate, high-quality, historical training datasets and indicators for trust in applying Artificial Intelligence/Machine Learning technologies to advance Earth system predictions.

8.3 Advanced Remote Sensing Technology

Recommendation 21: Accelerate acquisition and assimilation of commercial sources of data and delivery systems along with development of Earth Science Decadal recommended observing systems.

Recommendation 22: Benchmark performance quality, productivity, and cost using proven methodologies to quantify improvements to close gaps, identify root causes for deficiencies, and inform actionable improvement opportunities.

Appendix B: CWG Membership

Climate Working Group Members			
	**Joellen Russell, PhD** University of Arizona **Co-Chair**		**Kirstin Dow, PhD** University of South Carolina **Co-Chair**
	**Michael Anderson, PhD** California Department of Water Resources		**Kwabena Asante, PhD, PE** GEI Consultants
	**Cecilia Bitz, PhD** University of Washington		**Paul Fleming** Microsoft
	**Rong Fu, PhD** University of California, Los Angeles		**Le Jiang, PhD** I.M. Systems Group, Inc.
	**Ali Omar, PhD** National Aeronautics and Space Administration		**A.R. Ravishankara, PhD** Colorado State University
	**Susan Wijffels, PhD** Woods Hole Oceanographic Institution		

Science Advisory Board Liaisons		Environmental Information Services Working Group Collaborators	
	**Eugenia Kalnay, PhD** University of Maryland **SAB Co-Liaison**		**Ron Birk** The Aerospace Corporation **EISWG Member**
	**Everette Joseph, PhD** National Center for Atmospheric Research **SAB Co-Liaison**		**Xubin Zeng** University of Arizona **EISWG Member**