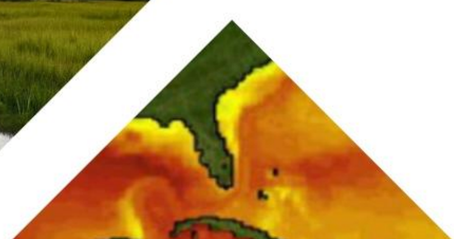


NOAA Modeling Strategy

Strategic Plan 2024–2033







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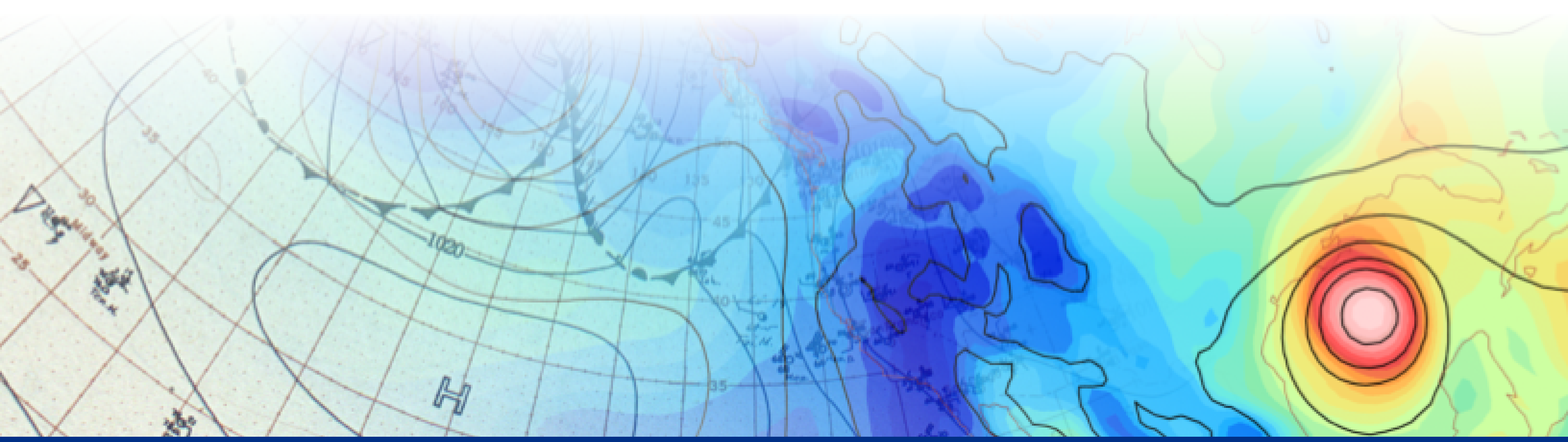
SECTION 1

Introduction

The National Oceanic and Atmospheric Administration (NOAA) Modeling Strategy aligns, unifies, simplifies, focuses and leverages NOAA's full Earth System Modeling (ESM) portfolio of research, operations, and applications to support every NOAA mission area. NOAA's mission areas require a highly complex and integrated modeling infrastructure, where environmental (physical), biogeochemical, ecosystem, space, and human modeling components are foundational. The term "Modeling" is used here for the foundational end-to-end modeling process starting from model initialization to simulations performed with numerical computer models to model testing, evaluation and improvements, as well as product generation and dissemination. Social science is also needed to appropriately refine requirements from stakeholders and to increasingly connect human decisions and activities into Earth System models. The motivation for developing this strategy is to leverage emerging technologies and unify modeling capabilities to increase collaboration, both within and beyond NOAA, to achieve the NOAA mission.

The development of this Strategy is commissioned by the NOAA Modeling Team (NMT) under NOAA's Earth Systems Integration Board (ESIB). The Strategy provides a 10-year framework to advance cutting-edge research, development, and operational implementation activities for all modeling that is foundational to NOAA's science and service missions. Modeling and prediction capabilities are foundational in the overall NOAA value chain to achieve the Societal Challenge outcomes and outputs in the Weather, Water and Climate Strategy[9], as developed by the ESIB. The NOAA Modeling Strategy is also aligned with legislative policies and administration priorities, including the NOAA Administrative Order (NAO) 201-218 "Software Governance and Public Release Policy" and the Weather Research and Forecasting Innovation Act of 2017. This overarching Strategy leverages and integrates existing NOAA strategies, guiding principles and initiatives, as posited by the NOAA Climate Ready Nation Strategic Plan[8], The Priorities for Weather Research Report[4], the Precipitation Prediction Grand Challenge[5], the Climate, Ecosystems and Fisheries Initiative[6] and the NOAA Science Council Strategies for Data[11], Artificial Intelligence[12], and the Cloud[13]. Lastly, the NOAA Modeling Strategy supports the U.S. Department of Commerce Strategic Plan[15] for 2022-2026, and positions NOAA to be the global leader in Earth System Modeling as set forth under the principles of the Earth Prediction Innovation Center (EPIC) and Unified Forecast System.



SECTION 2

VISION, PRINCIPLES, AND PURPOSE

Vision

Through the NOAA Modeling Strategy, research, operations and applications efforts are unified, aligned, and leveraged to deliver a world-class, widely-accessible, fully-coupled Earth Modeling System for NOAA capable of exploiting emerging computational architectures and technologies.

Principles

Modeling is an essential component of NOAA's services and capabilities value chain. NOAA's models are a critical link between its observation network and the decision making information that NOAA delivers to the public and its stakeholders. NOAA must provide an integrated suite of Earth System Model predictions and projections across a wide range of temporal and spatial scales. NOAA's Service Delivery Framework enables effective engagement with the community and promotes an agile bridge between NOAA model improvements, research, operational modeling activities, and the provision of critical decision support. Rather than describing a specific list of modeling capabilities, this Strategy is developed around some key defining principles described below:

- Unification
- Diversity
- Open Science
- Community
- End-to-End Modeling
- Workforce and
- HPC Resources

NOAA has adopted a **unified approach** to modeling[2] and therefore focuses on a prioritized set of shared modeling solutions where possible. The NOAA modeling portfolio must support a wide-range of decision-support applications across temporal and spatial scales. Timescales range from (re)analyses of the state of the Earth System to hourly, daily, weekly, subseasonal, seasonal and decadal predictions, and centennial projections; spatial scales range from local to global domains. NOAA has many "component" Earth System models. In the next decade, NOAA will continue to employ evidence-based, coupled Earth System development with a unified system of models.

Unification and alignment across research, operations and applications are essential to implement an effective modeling system. By employing a **diverse** suite of modeling approaches, we can encourage innovation essential to address emerging needs and capabilities in both research and operations (including operational products). Emerging fields like Artificial Intelligence, Social and Behavioral Sciences and Open, Community-based Science are an integral part of this Modeling Strategy. A central tenet is fostering collaboration to deliver a comprehensive modeling system.

NOAA has been directed by Congress to move towards an **open science** and transparent community approach to (operational) model development, most recently with the passing of the LEGEND Act[3], and as reviewed in the NAO 201-118[1]. Exemptions for such an approach may occur in cases of, for instance, national security, use of proprietary data, and ethical conflicts of interest when modeling explicitly supports regulatory activities. Effective open-science approaches focusing on the NOAA mission require a well defined process and governance of the iterative Research to Operations/Applications to Research (R2X2R) process.

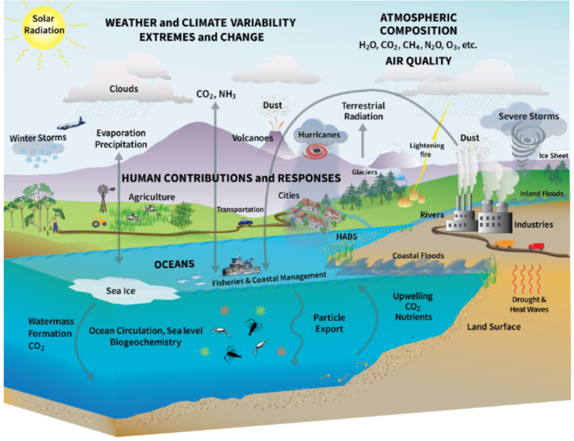
With NOAA's vast mission space, it is essential to partner with other federal agencies as well as the external **community** to make contributions to our modeling systems. Through sustained, transparent engagement with our partners and stakeholders, NOAA will be optimally positioned to align our modeling capabilities with their evolving needs. Together with our partners, we also must apply social, behavioral and economic sciences, and work closely with state and local stakeholders to ensure the modeling systems meet the needs of the nation.

Modeling focused on the NOAA mission needs to cover the **end-to-end effort** in the NOAA value chain, starting from the observational infrastructure providing essential observations used to improve modeling skill and ending with service delivery and decision support information[9]. A robust observation portfolio is critical for model initialization, development, evaluation, and ancillary efforts such as reanalyses and reforecasts (R&R), assessments of particular observations via observing system experiments and nature runs. Similarly, a robust research portfolio is critical to improve the understanding and representation of key processes and phenomena. Understanding, observations, and modeling together underpin harnessing predictability to improve Earth system predictions. Finally, an operational infrastructure is required to deliver information reliably to stakeholders through a variety of service channels.

Efficacy of modeling is driven by the availability of people and **resources**. Sustained funding is essential for workforce management and development, and compute resources for both core modeling efforts and user-driven processing of model output, data storage and data access. NOAA fosters a culture of diversity, equity, and inclusivity[18] and learning to recruit, retain, and maintain a well-trained and motivated workforce that is necessary to develop and sustain NOAA's model portfolio.

Purpose

The NOAA Modeling Strategy is intended to improve the coordination and alignment of modeling across NOAA and with the external community. By unifying modeling approaches across NOAA, leveraging a comprehensive earth system observation portfolio, revitalizing workforce development to better meet modeling needs at NOAA, and by applying innovative technologies, the guidance below will result in transformational advances in modeling across NOAA, and inform future budget, workforce, and future IT infrastructure and HPC planning. The principles and goals of this Strategy are illustrated through a select set of mission-focused NOAA modeling activities.



Earth Systems Model

NOAA's earth system models combine atmosphere, ocean, land, and sea ice components for comprehensive understanding of the interactions between physical, chemical, and ecological drivers and feedbacks on the earth system on time scales of minutes to millenia.

(Figure from Dunne et al., 2020; JAMES)

SECTION 3
NOAA MODELING STRATEGIC GOALS

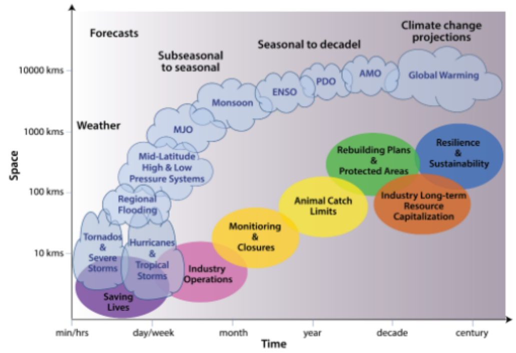
Goal 1: Unify Modeling Approaches Across NOAA.

Defining a prioritized set of models supporting the breadth of modeling needed for NOAA's mission will foster collaboration, transparency and efficiency, and build trust with NOAA's community of partners, while optimizing NOAA's resources.

Objective 1.1: Maintain a NOAA Modeling Inventory to understand and manage the breadth of Earth System modeling (ESM) at NOAA. This will improve coordination of related modeling efforts, and allow for identification of opportunities to integrate efforts across the Earth System while simultaneously identifying novel approaches for operational or scientific use.

Objective 1.2: Implement open source and community modeling approaches, as described in NAO 201-118[1] across Line Offices, to increase collaboration with the broader community where possible. NOAA's existing community modeling efforts provide a framework for NOAA to incorporate external community advances and outwardly share its own advances.

Objective 1.3: Retire obsolete models and products to free up resources to support



Time and Spatial Scales (CEFI)

NOAA develops models tailored to represent a continuum of weather and climate processes and applies them to a continuum of applications from fisheries to industry operations to long term ecosystem resilience as part of the Climate Ecosystems and Fisheries Initiative (Figure from Tommasi et la., 2017; Prog. Oceanogr)

current and future unified modeling systems. NOAA Line Offices will maintain standardized processes for identification and retirement of models that have been superseded.

Objective 1.4: Define coding processes and standards and develop code management repositories with supporting documentation and contribution guides to support community modeling as well as facilitate trust between all members of the modeling teams and potential model users. NOAA will embrace open science paradigms where possible to facilitate transparent collaboration and to maximize leveraging of contributions of a broad community to NOAA's mission.

Objective 1.5: Standardize metrics and diagnostics to create trust between all members of the modeling teams. NOAA's standardization efforts create equitable testing and evaluation of new innovations.

Goal 2: Integrate Modeling And Observations[11] Of The Environment.

Many of the component models of a holistic coupled environmental modeling system represent initial value problems (e.g., atmosphere and ocean models), where model initialization, also generally known as Data Assimilation (DA), is critical for reliable prediction. Some specific modeling efforts, such as ecosystems, protected species and fish population assessments, are likewise critically dependent on observing systems. All modeling systems require observations for development, validation, and general monitoring. Therefore, observations, DA, and modeling need to be addressed holistically.

Objective 2.1: Ensure that observation strategies adequately serve modeling needs. The NOAA Modeling Team will actively work with the NOAA Observing Systems Council (NOSC) to ensure that observations portfolios adequately support numerical modeling in NOAA. Unified use of data in modeling greatly benefits from the development and adoption of community-based standards.

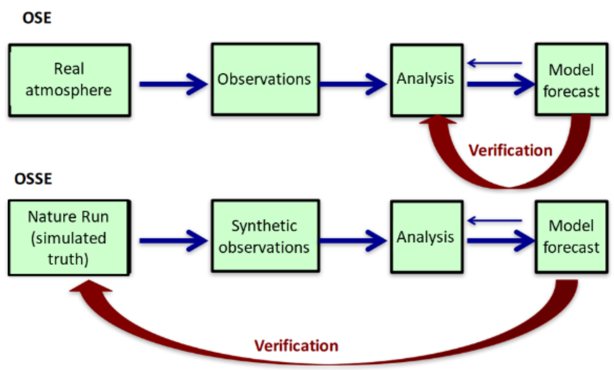
Objective 2.2: Use modeling to support decisions on prioritized needs for observing systems in support of the NOSC. Modeling, including DA, will be used to quantify observation impacts related to model performance (e.g., Observing System

Experiments (OSEs), Observing System Simulation Experiments (OSSEs)).

Objective 2.3: Develop a Data Assimilation (DA) Strategy with DA as an integral part of modeling. DA software needs to be integrated with modeling software, and is similarly subject to all other Goals presented in this strategy.

Objective 2.4: Provide equitable, continuous, standardized and timely access to accurate, quality-controlled real-time and historical data sets to advance the understanding and modeling of processes and systems for research, operations, and other applications.

Objective 2.5: Establish protocols and methodologies for model evaluation using observational data. Standardization of evaluation techniques across components of the ESM should be integrated into community tools like the [Model Evaluation Tools (MET)](), will increase access to evaluation tools for modelers and model users, and are essential for creating trust inside the modeling community.



OSEs and OSSEs

For assessing the impact of current, future, and hypothetical observations and observing system configurations on numerical modeling predictions, observing system experiments (OSEs) and observing system simulation experiments (OSSEs) can be employed. OSEs assess the impact of current observations and observing system configurations by conducting data denial assessments, which remove a set of observations from the numerical modeling and prediction calculation and compare the difference with the results achieved when that data is included. OSSEs provide similar assessments for future/hypothetical observations and observing system configurations. However, because the observations are synthetic, the comparison employs a simulated baseline/truth known as the Nature Run. The impact of the different future/hypothetical (synthetic) observations and observing system configurations are compared via their impact on the modeled output versus the baseline, the Nature Run.

Goal 3: Implement An Evidence-Based Governance Model, Including Broad Community Involvement Where Possible.

Collaborative development of model systems requires trust. Trust is built if the acceptance of innovation is reproducible and predictable. This requires a formal evidence-based governance process. A governance process also needs to be able to identify needs and prioritize development and operational implementations within a secure environment. The latter implies a requirements-based process with input from all relevant stakeholders.

Objective 3.1: Create and support modeling initiatives where models can be developed and used for both research and operations, with a governance that supports both of these objectives. Promote the value of adopting operational models as a community basis for research in order to capture advancements, while also investing in potential long-term alternative or innovative approaches.

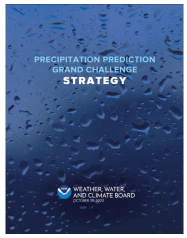
Objective 3.2: Ensure NOAA's modeling activities are responsive to internal and external user requirements, driving the scope of NOAA's modeling systems. Strengthen mechanisms to communicate operational needs and priorities to the research community.

Objective 3.3: Develop and implement a formal procedure to accelerate modeling innovations and advancements through the R2X2R (Research to Operations/Applications to Research) pathway. This enables both rapid incorporation of innovations into operations, and leveraging high-fidelity operations for research.

Objective 3.4: Maintain forward looking modeling-related Strategies, Roadmaps and Plans. Documented strategies and timelines should be reviewed at least annually, progress towards implementation of objectives communicated broadly, and accommodate agility to modify strategies and plans.

Modeling Priorities Across NOAA-Wide Strategies

[WWCB]



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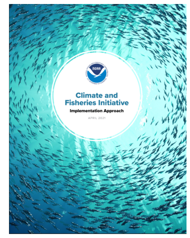
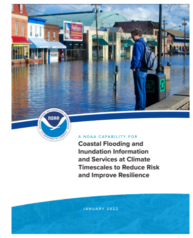


[CEFI]



[Coastal Inundation]

COASTAL MODELS

1. Build a comprehensive, operational near-shore coastal forecast system, ranging from weather to subseasonal/seasonal timescales, including total water level, surge, ice, currents, waves, erosion, biogeochemistry and ecosystems

PRECIPITATION & DROUGHT

2. Improve UFS 7-day precipitation forecasts; Improve forecasts of precipitation from landfalling coastal storms
3. Predict how climate change will affect drought and related cascading hazards of heat-drought-fire
4. Improve prediction models for precipitation: UFS initialization, model biases, co-development of all model components, integration of observations; Probabilistic forecasts of precipitation extremes and cascading hazards

OCEAN MODELS

5. Develop predictions for oceans biogeochemistry and ecosystems, from daily to decadal time scales
6. Improve ocean physics and assimilate ocean data

HYDROLOGY

7. Evolve the Next Generation of NOAA's NWM to improve skill, including land variability, software standards, interoperability
8. Deliver initial water quality prediction capabilities for water temperature, salinity and turbidity in rivers, lakes, estuaries

SEVERE WEATHER

9. Forecast wildfires and related Air Quality
10. Improve tornado prediction (WoFS), including using more in-situ data

SPACE WEATHER

11. Build coupled modeling continuum of sun-earth system and integrate data

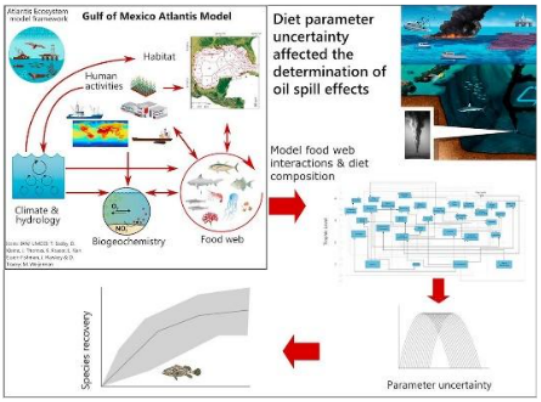
Goal 4: Advance Software Modernization Across NOAA And Effectively Procure High Performance Computing (HPC) Assets.

Efficient and effective use of HPC is needed to sufficiently resource both operations and research to support NOAA's mission. Communities tend to work on diverse hardware (i.e., different compute platforms). This will require portable software, which in turn requires modern software practices.

Objective 4.1: Identify, provide and support essential HPC infrastructure as NOAA moves forward to new, advanced applications and architectures, and newer HPC uses such as Artificial Intelligence (AI)/Machine Learning (ML) with differing computational and support requirements. A balance between traditional on-premises IT systems and cloud infrastructure[13] should be adopted. Additionally, leveraging resources across agencies should be exploited.

Objective 4.2: Develop and unify modern software standards that improve the performance, portability, security, and scientific accuracy of models running on next-generation exascale computers. Defining and adhering to software standards is a critical element needed to build trust across the community.

Objective 4.3: Enable innovation through effective adoption of cloud-based services



AI/ML (Fisheries)

In furtherance of the mission to support productive and sustainable fisheries for the nation using sound science and an ecosystem-based approach to management, NOAA Fisheries scientists use end-to-end ecosystem models, such as Atlantis and Ecopath with Ecosim, to understand the effects of stressors (such as oil spills and climate change) on fisheries, living marine resources, and habitats. These models can be quite complex with many parameters used for climate and hydrologic forcings, and biochemistry, ecological (food web), and human dimension components of the modeling system. Because of this complexity, parameter uncertainty can lead to unclear assessment of the effects of ecosystem stressors. NOAA Fisheries scientists are using artificial intelligence/machine-learning-based statistical emulators on HPC/Cloud resources to more efficiently explore model parameter space and to better understand impacts of stressors on ecosystems and key species. [17]

for secure, stable model development environments and broad data access. Develop effective governance, new funding strategies, and agile open-development approaches, which are applicable across the agencies. Performance portability needs to be an integral part of all stages of model development to ensure successful transitions to operations and economical use of models in research.

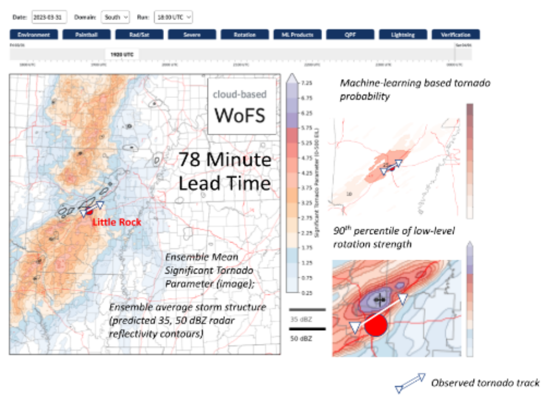
Objective 4.4: Modernize NOAA's software to improve model efficiency across all hardware platforms, as well as software architecture, and advance the next generation of close coupling strategies between model components. Utilize a multidisciplinary team of scientific and HPC technology Subject Matter Experts (SMEs) to ensure software engineering meets current best practices while co-developing an exascale capable infrastructure.

Goal 5: Bolster Service Delivery Approaches and Innovative Technologies.

When achieved, this goal will increase NOAA engagement across the Federal, academic and private sectors to drive innovation that supports NOAA’s mission areas based on user needs, which is critical in evolving and sustaining NOAA’s R&D and operational capabilities, including products and services. Combined with the use of transformational technologies, NOAA will realize a world-class Earth Modeling System that will accelerate the transition of innovations into operations, be optimized for performance, and fully-accessible to our community of partners.

Objective 5.1: Utilize the NOAA Service Delivery Framework and incorporate social, behavioral, and economic sciences to continuously document user needs and requirements to prioritize future improvements to the NOAA Earth Modeling System through R&D, and to evaluate and build the modeling community. Documented requirements targeting improvements will also define the long-term R&D work plan for the modeling enterprise.

Objective 5.2: Strengthen interdisciplinary physical, biological, ecological, environmental and social science research, promote the use of social science to facilitate the development of effective model-based products, and communicate complex impacts to the total Earth system across timescales. Gaining insight into how decision makers and users interpret, interact with, and apply model-based information will help define NOAA’s network of service delivery applications. Iterative and interactive development with users and stakeholders will help ensure that products fulfill user needs.



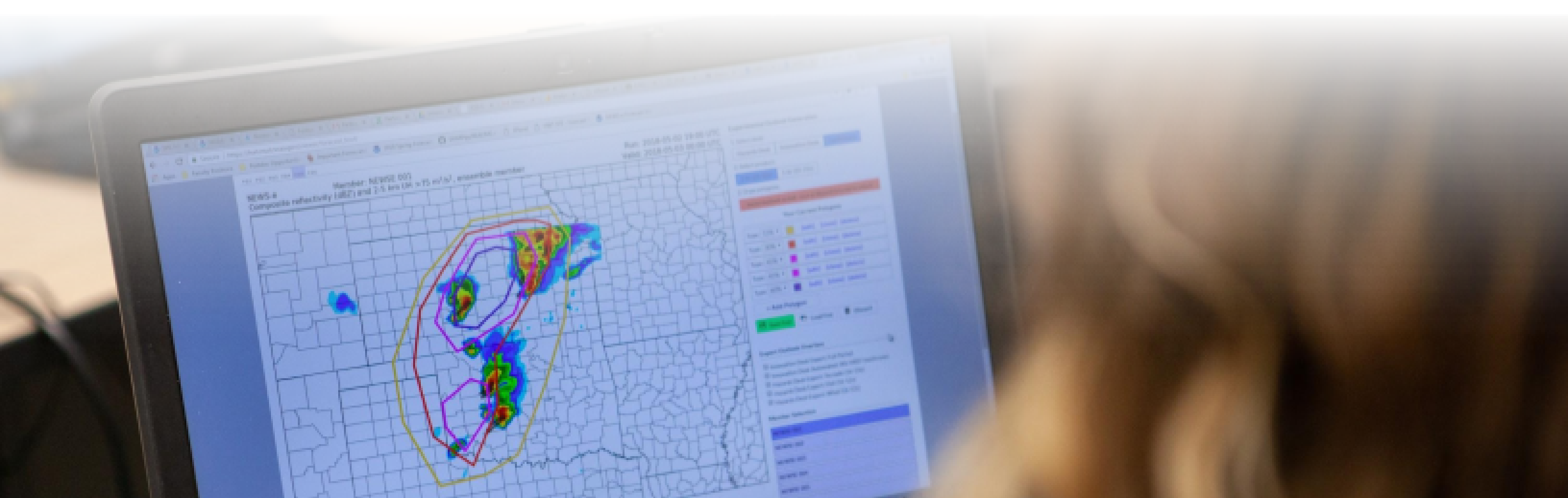
Warn-on-Forecast System (WoFS)

The Warn-on-Forecast System (WoFS) is a first-of-its-kind storm-scale ensemble modeling system that uses rapid data assimilation (15 min) and rapid forecast relaunch (30 min) to target high-impact severe weather and flash flood events. WoFS provides probabilistic and machine-learning based products, some of which are seen here for an EF-3 tornado that struck Little Rock, AR, on March 31, 2023. WoFS predicted the storm location within 10 miles and a ramp up of rotation intensity and tornado likelihood at 78-minute lead time. Signals like these could be used to gain lead time for severe weather and rainfall hazards.

Objective 5.3: Exploit artificial intelligence (AI)[12] and machine learning (ML) techniques to enhance or replace predictive modeling and DA capabilities, improve model skill, performance, and computational and cost efficiencies; implement successful AI/ML approaches and outputs into practice; and develop and optimize modeling, post-processing, and product development solutions.

Objective 5.4: Leverage innovative cloud technologies, and develop and apply big data approaches for analysis and extraction of value from large ensemble datasets, to manage large volumes of model information, enable community collaborations supporting model development, facilitate and accelerate transitions into NOAA, and ensure broad public access to model reanalyses, forecasts, long-term projections, and other modeling products.

Objective 5.5: Effectively utilize and deliver data from novel and emerging observing platforms. Develop flexible methodologies for ingest and dissemination from sources such as UxS (uncrewed systems)[14] and commercial platforms.



Goal 6: Support Workforce Development.

Supporting the broader Earth system science community along with NOAA researchers to build a well-prepared diverse pipeline of scientists and engineers (e.g., NOAA's Cooperative Science Centers and Cooperative Institutes) ready to address societal challenges is vital to our modeling future. NOAA will support our workforce[8] through engagement, professional development, and student opportunities that enable scientific innovation and a multitude of perspectives.

Objective 6.1: Support Earth system modeling community across NOAA's investments to share knowledge, lessons learned, and best practices NOAA-wide. Engaging the community through webinars, open forums, and regular meetings is key for a strong community of practice.

Objective 6.2: Foster a diverse and inclusive ESM community by expanding the talent pool creating partnerships with other governmental organizations, academic institutions, and the private sector. Ensuring that our practices are equity-centered enables a broader section of the community to participate fully.

Objective 6.3: Identify and resource ESM graduate degrees, professional development, and technical training courses (e.g., HPC), including development of new training courses, ensuring availability to the current and future NOAA workforce.

Objective 6.4: Support and lead collaborative events such as conferences, workshops, coding events (e.g., hackathons), and external rotational assignments targeted to stay current in Earth system modeling. Education and outreach are key components to proper succession planning for NOAA's growing modeling portfolio.

Objective 6.5: Actively encourage graduate programs, internships and cooperative student training programs in ESM and supporting HPC technologies relevant to the NOAA mission to improve recruitment, retention, and the hiring pool for ESM proficient NOAA workforce.

Conclusions

To ensure the NOAA Modeling Strategy realizes transformational advances in performance, skill, and efficiency, NOAA will review and update regularly a list of essential Strategies and Implementation Plans (see Appendices). NOAA is already improving the performance of its ESM suite to effectively support the protection of life and property across the world. We will continue to grow and strengthen our leadership in environmental science and technology. Together with our advances in NOAA's other science and technology focus areas—AI and Machine Learning, DA, Cloud Computing, and HPC—NOAA's ESM activities will help the U.S. to regain global leadership in environmental prediction, attain NOAA's Climate Ready Nation vision, and sustainably expand the U.S. Economy.

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Appendices

Strategies and Implementation Plans

Because modeling at NOAA covers a large set of mission-directed topics, it is not feasible to provide a concise set of actionable modeling plans in the overarching strategy. Nevertheless, stated targets like model resolutions and ensemble sizes can be powerful elements of a modeling strategy. Such actionable plans and strategies at NOAA are developed and executed for parts of the modeling suite, where the present strategy is used to assure that such individual plans are consistent with each other where possible. The Table below presents a selection of some of the major strategies and implementation plans associated with this Strategy, including the NOAA modeling inventory mentioned in Objective 1.1. This Table is intended to provide insight in the level of planning performed at NOAA, and is not intended to be complete.

Plan	Status
Historical documents	
A Strategic Vision for the NOAA's Physical Environmental Modeling Enterprise	These manuscripts represent the initial push toward the Unified Forecast System (UFS) and were developed in 2016-2018. The documents were finalized after NOAA had established the basic approaches to be used for EPIC and signed by four NOAA Line Office Assistant Administrators in 2020.

2017-2018 Roadmap for the Production Suite at NCEP	
A Vision Paper for the Earth Prediction Innovation Center (EPIC) (2019)	These manuscripts represent the foundation of the development of the Earth System Innovation Center (EPIC) development at NOAA.
The Earth Prediction Innovation Center (EPIC) Community Workshop Report (2019)	
EPIC Strategic Plan (2021)	
Active efforts	
Weather Water and Climate Strategy (2023-2027)	In execution. Note that the strategy was developed by the Weather Water & Climate Board (WWCB), which since the publication of the strategy has been reorganized as the Earth Systems Integration Board (ESIB).
Precipitation Prediction Grand Challenge 2020-2030	This active challenge in NOAA includes modeling as an integrated effort.
NOAA Climate, Ecosystems and Fisheries Initiative (2023)	In execution. This initiative links ecological modeling to physical (ocean) modeling.
NOS Modeling Vision (2021)	The first two documents are foundational to the National Ocean Services (NOS) modeling efforts, the third document is under development and expected to be published late 2023 or early 2024.
NOS Modeling Strategy 2023-2028	
The NOS Implementation Plan (*in development*)	
NOAA Data Assimilation Strategy (*in development*)	In development by the NOAA Modeling Team in parallel to this modeling Strategy. Expected to be published early 2024.
Joint Center for Satellite Data Assimilation Annual Operating Plans	This site presents the annual operating plans for the Joint Effort of Data Assimilation Integration (JECI), which represents the core Data Assimilation efforts in this Strategy
NCEP Environmental Modeling Center (EMC) 5-Year Implementation Plan (FY23-FY27). Transitioning NCEP Production Suite to UFS Applications	This is a living document with links to the development plans of individual applications in the NCEP production suite.
NOAA's Seasonal Forecast System (SFS) Development Plan (*in development*)	The plan is presently being drafted and is expected to be published early 2024.

Data	
NOAA Model Inventory	A first inventory has been completed as a NOAA Modeling Team activity, and is expected to be published in 2024.

Definitions

Open Source vs. Open Science: "Open-source" implies that the (end-to-end) software is available to the general public effectively without restrictions. Presently, "open source" code is generally distributed using version control tools like GitHub. Open source code is generally copyrighted, licensed and sometimes trademarked[1]. Open-science in the context of modeling refers to the capability of a broad community to contribute to open-source codes. Note that a commitment to open-source code management does not imply open-science, and that a commitment to a full open-science community is less common than a commitment to an open-source code distribution.

Community Modeling: Community modeling implies a two-way exchange of information, where a group of users contributes back to the model and provides active and relevant evaluation. This requires dynamic code management with many groups contributing to the same code. It also requires a well-defined and implemented governance strategy to prioritize improvements and assure that diversity does not become a cancerous growth of competing options and features. A final critical aspect of community modeling is agreed-upon standardized metrics and test procedures. With this, community modeling becomes a powerful tool to accelerate model development while reducing costs.

Unified (Unification of) Modeling[2]: Unified modeling implies that a (group of) organization(s) uses the most effective (i.e. typically smallest) number of actual models for a set of similar tasks, as is consistent with the necessary model diversity to support scientific advancement, while providing an efficient application of the models for both science and operations. This approach results in a lean business model, with the capability to build critical mass for model development across organizations. It does not imply unitary modeling where only a single model for each application type is allowed. It is also not limited to NOAA alone, but by definition includes research and operations throughout the government and academia, both domestically and internationally.

Unified modeling also implies that models are increasingly coupled, as appropriate, to ensure that the information flowing from one thematic area appraises modeling in other related thematic areas. NOAA models need to be coordinated such that the information is exchanged across the suite of models to provide more accurate feedback between model components and to support an increasing array of applications. Unified modeling also implies that a framework exists for flexible and interoperable development, so that for a given thematic area new process models can be readily tested to replace existing ones with minimal impact to downstream applications.

Finally, unified modeling implies that across model applications and across thematic areas of emphasis, best practices in model application are identified, shared, and utilized. The disciplinary focus of modeling should never preclude methodological advances of model practice from being shared across disciplines. Establishing means, mechanisms, and venues for such modeling practice exchanges is critical to a unified modeling approach.

Earth System Modeling (as a foundation): As defined in the NOAA Modeling Team's Terms of Reference[10]: Earth System Models, or ESMs, integrate climate, weather, biosphere and water prediction, data assimilation, ecosystem modeling, and other Earth system science (ESS) applications. ESS considers interactions and feedbacks, through material and energy fluxes, between the Earth's subsystems' cycles, processes and "spheres", e.g., atmosphere, hydrosphere, cryosphere, biosphere (terrestrial and marine), and human systems as appropriate for the science or forecast requirements. At its broadest scale, ESS brings together researchers across both the natural and social sciences, from fields including biology (ecology), chemistry (biogeochemistry), economics, geography, geology, meteorology, hydrology, glaciology, oceanography, climatology, sociology, anthropology, limnology, and space science. ESS assumes a holistic view of the dynamic interaction between the Earth's spheres and their many constituent subsystems, fluxes and processes, the resulting spatial organization and time evolution of these systems, and their variability, stability and instability.

NOAA's Service Delivery Framework[16]: This framework describes a consistent approach that will enhance NOAA's delivery of mission-related services, and could also be applied to other NOAA initiatives that cite the need to continuously understand and apply user needs to guide product and service development. Institutionalizing and integrating these processes to align with other weather-, ocean-, coast-, climate-, and fisheries-related initiatives and activities will better equip NOAA to fulfill its vision of developing and sustaining resilient ecosystems, communities and economies.

Photo Credits

Front Cover

- A GOES-16 (GOES East) visible satellite image of Hurricane Don at 6:20 PM EDT on July 22, 2023 in the Atlantic. Don was the first hurricane of the 2023 Atlantic hurricane season. Image credit: NOAA.
- Slices of Earth observational and modeling data. Image credit: NASA Scientific Visualization Studio.
- Fog cloaks Cape Perpetua in the Siuslaw National Forest. Image Credit: NOAA Photo Library (Tom Hamilton).
- Schooling jack mackerel. Image credit: NOAA (Adam Obaza, NOAA Fisheries).
- AOML Begins Tenth Year of Hurricane Glider Operations. Image credit: NOAA Atlantic Oceanographic and Meteorological Laboratory.

- High tide flooding on Smith Island, Maryland in August 2022. Image credit: NOAA.
- The Hurricane Analysis and Forecast System (HAFS) “moving nest" Model. Image credit: NOAA.

Page 2 - A GeoColor image of the U.S. from NOAA's GOES-16 satellite on July 18, 2023. Image credit: NOAA.

Page 3 - Old weather map overlaid with a 20CR reconstruction of sea level pressure and precipitable water. Image credit: NOAA Physical Sciences Laboratory.

Page 6 - A collage of typical climate and weather-related events: heatwaves, drought, hurricanes, wildfires and changes in sea ice coverage. Image credit: NOAA

Page 7 - The collage shows examples of weather, ocean, fisheries habitat and climate priorities for interdisciplinary research. Image credit: NOAA.

Page 8 - A NOAA ozonesonde ascends over the South Pole in this time-lapse photo taken October 21, 2020. Image credit: NOAA (Yuya Makino/IceCube).

Page 9 - Buoy deployment. Image credit: NOAA.

Page 10 - A collage of typical climate and weather-related events: floods, heatwaves, drought, hurricanes, wildfires and loss of glacial ice. Image credit: NOAA.

Page 12 - Twin supercomputers Dogwood and Cactus are new additions to NOAA's weather and climate operational supercomputing system. Image credit: NOAA (GDIT).

Page 13 - Vehicle assembly and service technician Josh Keller unties Saildrone 1084 to deploy it for a 2023 U.S. Coast Guard Great Lakes Fisheries survey. Image credit: NOAA (Saildrone).

Page 14 - Cloud-based Warn-on-Forecast. Image Credit: NOAA Cloud Based WoFS.

Page 15 - We are scientists, engineers, researchers, technicians, and more who remain united in our common mission: science, service, stewardship. Image credit: NOAA.