National Oceanic and Atmospheric Administration
Strategic Research Guidance Memorandum
FY2025

There are several key research and development themes emerging across NOAA, requiring budget consideration for their success. These high level themes are summarized below in random order. Details of FY25 research priorities mapped onto the NOAA 2022-2026 Strategic Plan are provided in this document in full.

Data acquisition, open data, big data	● Continued support of new aircraft and instrumentation, especially in light of upcoming aircraft retirement schedules ● Continued data acquisition to monitor and predict the Earth system including space weather ● Ensure data stewardship including record continuity, accuracy, consistency, and accessibility ● Expand research to make use of big data, especially artificial intelligence and machine learning ● Continued expansion of open science capabilities and data delivery to support commerce ● Expand deep ocean instrumentation capabilities ● Continued investment and support for high performance computing
Data assimilation and reanalysis	● Build sustained operational reanalysis capabilities ● Continued support of data assimilation advancements ● Leverage to forecasts, seasonal-to-decadal predictions, and product delivery ● Support sustained, long-term satellite records and their incorporation into data assimilation, reanalysis, and models
Earth system modeling across timescales	● Advance skill and resolution ● Expand outlooks and information across timescales for decision makers ● Support transitions from research to operational outlooks and products
Social, Behavioral, Economic Sciences (SBES)	● Increase use of SBES along with product and service design and development ● Measure societal impacts of NOAA's products and services ● Conduct authoritative science to support new fields of nature capital and prediction applications ● Support economic forecasting and cross-timescale economic impact assessment reliant on NOAA data
Workforce and partnerships	● Advance workforce development at NOAA and with our partners ● Leverage strategic partnerships to deliver research and development goals ● Support co-design and co-development of applications to fully exploit datasets (satellite and other)
Accessibility and equity	● Build a workforce that reflects the diversity of our Nation ● Review and expand accessibility and equity of our data, products, and services

Table of Contents

1. Background

The National Oceanic and Atmospheric Administration (NOAA) maintains a robust research and development (R&D) portfolio that enables the Agency to:

- Observe, understand and predict changes in climate, weather, water, oceans, coasts, and space.
- Conserve and manage coastal and marine ecosystems and resources.
- Share and disseminate knowledge and information with the public.

To accomplish these goals, NOAA brings together the best R&D from internal and external organizations and transforms that R&D to create value for the public. This is achieved by transitioning NOAA R&D to operations, applications, information services, policies, and commercial products. NOAA's R&D activities also advance the agency's commitment to engage the public in a two-way dialogue that involves mutual learning and value derived from the sharing and exchange of scientific knowledge, cultural knowledge, and experience. Incorporating the best available science and equally valuable non-scientific knowledge support a Nation ready to adapt to a changing environment and enable the preparation, recruitment, and training of the future NOAA workforce. NOAA's mission is a marvelous attraction and inspiration for students in STEM (science, technology, engineering, and mathematics) disciplines, and the many additional areas of talent needed to support the science mission. Using a cross-disciplinary approach that includes social, behavioral, and economic sciences helps determine how people receive and use NOAA's R&D, informs the value of our products, and allows for a better understanding of the needs of different communities, guiding a path forward to better serve the public. Strategic partnerships expand our capabilities to meet our goals. They include: other federal agencies, educational organizations such as our cooperative science centers, cooperative institutes, and Sea Grant institutions, as well as commercial and private entities.

NOAA's Administrative Order on Research and Development (NAO 216-115B)[1] defines the process and principles that guide the planning, execution, and evaluation of NOAA's R&D portfolio. Section 5.03 of that NAO requires the Chief Scientist, through consultation with the NOAA Science Council, to publish and update NOAA's corporate strategic plan. This Strategic Research Guidance Memorandum serves as a one-year update for the NOAA 2022-2026 Strategic Plan. Herein, areas of R&D that merit special budget consideration are highlighted.

The research portfolio of NOAA can be defined by the long-term missions, documented in NOAA's origination and subsequent laws. These missions define the purpose of the agency, but do not limit our methods of pursuing them. The vision and innovation of our scientists and extramural colleagues, the state of technology, plus new and emerging opportunities and priorities are open doors to enrich the R&D portfolio. Pursuing and implementing an Earth systems approach throughout our work is a clear priority and needs to be a foundation of our R&D portfolio, ensuring a fully integrated and comprehensive approach to our mission.

Leveraging the NOAA 2022-2026 Strategic plan, the three main priorities include:

- Establish NOAA as the United States (U.S.) federal government authoritative source for climate products and services; build a Climate Ready Nation.

[1] *NAO 216 115A http://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/216-115.pdf*

- Advance economic development without sacrificing environmental stewardship, with a particular focus on advancing the New Blue Economy.
- Integrate equity into everything we do, including our science, and how we build and provide services.

The innovation of our scientists and extramural colleagues has generated opportunities and paths for us to pursue, defined in the products of our Councils and Boards, including the Climate Council, Science Council, Earth System Integration Board, Observing Systems Council, Fleet Council, and Oceans and Coasts Council. The NOAA Science Advisory Board and other Federal Advisory Committees have given focused recommendations to NOAA and should be heeded and considered in budget planning. Such recommendations include attending to the current science and technology (S&T) focus areas[2].

No profound advancement will succeed in isolation, and NOAA's most successful innovations involve multiple Line Office Organizations. The interdependencies of these initiatives must be considered and coordinated.

2. Research Priorities

To determine R&D priorities, researchers, technology developers, and managers at all levels of the Agency should review their current portfolios in light of the principles articulated in NAO 216-115B[3] and the NOAA R&D Vision Areas: 2020-2026[4].

> This Strategic Research Guidance Memorandum does not intend to mention every element of the NOAA R&D portfolio, nor discourage sustained investment in the existing portfolio. The Memorandum provides guidance in areas that warrant additional focus, advancement, and/or investment in the view of the Chief Scientist, after consideration of the constructive input from the NOAA Science Council, with senior representatives from every Line Office Organization. This memorandum is intended to be guidance, and will not replace the many tools NOAA has to define and support budget justifications.

2.1 Authoritative Source of Climate Products and Services

Through upgraded climate information, improved weather forecasts and enhanced infrastructure, NOAA will build a Climate Ready Nation, resilient and prepared for future climate change. NOAA will address climate change mitigation efforts and ensure safety and preparedness for all Americans.[5]

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[2] *NOAA Science and Technology Focus Areas. Available here: https://sciencecouncil.noaa.gov/NOAA-Science-Technology-Focus-Areas*
[3] *NAO 216-115B: https://www.noaa.gov/organization/administration/nao-216-115a-research-and-development-in-noaa*
[4] *NOAA R&D Vision Areas: 2020-2026. Available here: https://repository.library.noaa.gov/view/noaa/24933.*
[5] *Reproduced from the NOAA 2022-2026 Strategic Plan, Strategic Goals Summary. Available at: https://www.noaa.gov/sites/default/files/2022-06/NOAA_FY2226_Strategic_Plan.pdf.*

Climate Change

Climate change is stressing the traditional balance of the Earth system. The consequences can be complex and non-intuitive, chronic or abrupt, reversible or irreversible, creating an urgent need for scientific understanding and communication. For example, the Arctic has been warming faster than any other place on the planet, resulting in both physical changes such as sea ice cover changes and permafrost melting, and biological changes including fisheries abundance and health. Societal impacts related to these changes involve natural hazards, reduced stability of Arctic communities, polar maritime transportation, coastal resilience, food security, and national security. Other examples include extreme rainfall, driven by changes in the atmosphere from a warmer ocean, impacting inland and coastal areas; heatwaves happening on land and in the ocean, disrupting ecosystems, food supply stability, human activities, infrastructure, and commerce; and changes in the water cycle affecting water quality and availability.

Changes have been observed in distribution, intensity, and/or frequency of many weather and climate extremes, such as droughts, wildfires, hurricanes, flooding, coastal inundation, cold outbreaks, and extreme heat.[6] Research investments in these areas have brought marked improvement in forecasting, prediction, and projection. Further investment will advance skill, understanding, and our ability to forecast, predict, and project the Earth system as a whole. Advancing R&D in this area requires investment internally and in the extramural community in the following areas:

- Collecting in-situ and remotely-sensed observations, including observations of the various components and interactions of the Earth system and space, operating tightly coupled Earth system prediction systems, and integrating decision support systems to inform decision makers and the public about planetary changes.
- Research and identify Earth system extremes and phenomena that have emerged from climate change and have not been previously experienced in historical record. These efforts will contribute to a new understanding of the Earth system based on the most current information available.
- Review and develop metrics and research for their applicability in a changing climate. Historic algorithms may have reduced utility in a changing climate. For example, drought metrics in regions experiencing aridification lose meaning if the region shifts to permanent (in a historical context) drought condition. The emergence of climate surprises—events and phenomena absent in the historical record—bring forth challenges requiring new techniques for R&D.
- Enhance service delivery and decision support tools to help build a climate-ready nation.
- Infuse social, behavioral, and economic science (SBES) advances in climate services delivery and recommend best practices in climate information communication to improve utilization of climate services.
- Improve understanding, prediction, and management for the high latitudes – Arctic and Antarctic, and their potential impact on the lower latitudes.
- Document changes in climate through a comprehensive program to generate authoritative long-term climate data records from in situ and satellite observations.

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[6] Changes and projections have been summarized in the National Climate Assessment. The next assessment will be released in 2023. The most recent is available at: https://nca2018.globalchange.gov/.

- Supports other key applications including correcting systematic biases in forecasts on a variety timescales (i.e. subseasonal to seasonal), providing quality controlled input/validation for reanalysis/reforecasts, and supporting retrospective studies of past extreme events to help mitigate future events.

Extreme Events

Extreme events can cause major human, property, and financial costs.[7] Extreme events include hurricanes, tornadoes, severe thunderstorm outbreaks, tsunamis, droughts, wildfires, air quality degradation, floods, hail, extreme temperatures, marine heatwaves, coastal inundation, and space weather (variations in the environment between Earth and the Sun). Research to improve forecasting, prediction, and projection of these perils is necessary for decision makers to reduce extreme event impact before, during, and after occurrence. Supplemental funding is an unreliable basis for extreme weather impacts; sustained funding would provide continuous work on key areas.

- NOAA should operationalize the science of attribution–investigating whether and by how much climate change may be responsible for extreme events– as a climate service to provide the American public access to authoritative climate assessments of extreme events experienced on the regional scale. The increased number and severity of record wildfires, drought, heatwaves, winter storms and flooding events in recent years has resulted in frequent requests to quantify how the risks of these perils are changing in time. This effort would include making plain-language characterization of the drivers behind extreme events publicly available, based on documented NOAA Research methods. This work should build on cloud and artificial intelligence infrastructure to operationalize a multimillion-dollar research-to-operations effort. It will provide complementary information to the Billion Dollar Disaster product, contextualizing changing risks and their causes.

Hurricanes are typically the most costly weather disaster in the U.S. Forecasts and process understanding of these storms and how they vary in time can be improved by better data products (new algorithms incorporating artificial intelligence and blended data sources), observations, data assimilation, forecast techniques, and modeling.

- Funding should support our pipeline of observing capacity, including aircraft instrumentation (i.e.remote sensing), and foundational moored buoy systems, to ensure there is no loss of critical observations for storm forecasting in 2030.
- Continued testing of uncrewed systems should take place with research of their value to data assimilation to support hurricane forecasts.
- We recommend funding to continue supporting the original Hurricane Forecast Improvement Project path of success, including supporting SBES.

Extreme climate and ocean related events impact the marine life that live in these ecosystems, which then affects associated economies that depend on the marine resources. Fisheries economic losses can run in the billions of dollars, forcing some to shut down, having significant equity, social, and cultural impacts. Recent works demonstrate that regional economies take at

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[7] *For example, annual costs and frequencies of extreme weather and climate events costing at least $1bn are monitored by NOAA with data available since 1980: https://www.ncei.noaa.gov/access/billions/*

least three to five years to recover from these events[8,9,10]. Coupled modeling and observations will help to better forecast these impacts.

- Funding should support our pipeline of predictive capacity for major ocean-related phenomena, to ensure events like marine heatwaves or sea ice retreat do not cause significant regional and national economic duress.
- Models to predict and forecast these events, and their socio-economic consequences are needed.
- Models should be developed to explore options for mitigation or adaptation, so that regional marine resource economies have advanced warning to plan for these events.

Wildfires and associated air quality degradation damage property and can lead to loss of life. Improving wildfire forecasts, from the daily incident scale to the seasonal scale and beyond a year, is necessary for community planning and preparation. Fire behavior models and tools for Incident Meteorologists save the lives of local citizens and firefighters. Air quality impacts from fires degrade public health; consequently, they need to be better understood and included in air quality forecasting.

- Support funding the Fire Weather Testbed and Operations Proving Ground, associated research activities, and the transition from NOAA Research to operations (at National Weather Service [NWS] and National Environmental Satellite, Data, and Information Service [NESDIS]) of resulting products to better prepare the nation for increases in fire weather extremes. Integrate fire weather predictions into global and regional scale Earth system predictions to incorporate and advance fire: prediction, behavior, and impacts.

Space commerce has rapidly expanded and infrastructure investments in the power grid are being made for energy security, expansion of renewables, and adaptation to weather and climate extremes. Space weather (space weather storms from the Sun and changes in space that can affect technology on Earth and in orbit) is a growing concern for assets in space as well as on the ground (e.g. transformers, grid reliability).

- NOAA should lead a multi-agency approach to collaborative research into modeling the impacts of space weather events on the economy and environment.
- Expand research capabilities at NOAA and with partners, particularly National Science Foundation, to transition space weather research into space weather forecast operations in the NWS.
- The space weather forecast model should be integrated into the operational weather forecast system as a fully unified forecast system.

The tsunami threat to the U.S. is significant. This threat is exacerbated by sea-level rise which makes formerly safe zones increasingly vulnerable. The Cascadia Subduction Zone, off the west coast of the U.S., and the Aleutian Arc pose possibly the most catastrophic tsunami threat to U.S. life and property, but non-seismic source tsunamis are becoming increasingly likely and

[8] *Bellquist, L., V. Saccomanno, B. X. Semmens, M. Gleason, J. Wilson. 2021. The rise in climate change-induced federal fishery disasters in the United States. PeerJ 9, e11186. https://doi.org/10.7717/peerj.11186*
[9] *Moore, C., J.W. Morley, B. Morrison, M. Kolian, E. Horsch, T. FrÖlicher, M.L. Pinsky, R. Griffis. 2020. Estimating the Economic Impacts of Climate Change on 16 Major US Fisheries. Climate Change Economics 12 (1), 2150002. https://doi.org/10.1142/S2010007821500020*
[10] *Weatherdon, L.V., A.K. Magnan, A.D. Rogers, U.R. Sumaila, W.W.L. Cheung. 2016. Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. Frontiers in Marine Science 3, 48. https://doi.org/10.3389/fmars.2016.00048*

can be locally devastating. Glacier loss in areas of Alaska can lead to landslide source tsunamis that have historically shown tens-of-meters of run-up. The good news is that a robust observational network can forecast the energy, movement, and impact of tsunamis.

Precipitation, prediction, and coordinated hydrologic modeling are critical to understanding the availability of water, its impact on the land surface, and hydrology. From sub-hourly to seasonal time scales, the Precipitation Prediction Grand Challenge (PPGC) initiative aims to improve the rate of precipitation forecast skill from 15% to 30% per decade. Improvements of this magnitude will result in an additional two days of lead time for decision makers for impending extreme rainfall events. Further, the initiative endeavors to extend subseasonal (two weeks to three months) precipitation forecast skill. This effort is well planned and will involve working across multiple organizational levels, including the need to be resourced with a sustained budget.

- Support funding for the PPGC to increase prediction skill necessary to protect public and property from unanticipated impacts caused by increasing precipitation and hydrological extremes.
- Improve data assimilation through improved quality control, artificial intelligence, and other methods. Increase observations of air-sea interaction in the Pacific and assimilate such observations into NOAA models.
- Support improvements in data fusion of quantified precipitation estimates from rain gauge, radar and satellites to improve short range forecasts through artificial intelligence and machine learning, and to focus on high terrain areas where radar-derived precipitation rates are limited.
- Support the NOAA Hydrometeorological Testbed to evaluate new modeling tools and techniques for precipitation, and transition promising results into tangible services for communities.
- The NOAA Research and Development Database contains over 200 hydrology research projects; consequently, the relationship to advances in the National Water Model from these activities needs to be defined and best utilized.

While the specific needs of hurricane, wildfire, space, and precipitation extremes have mainly been highlighted, sustained funding for other extreme types is also needed.

- Improvements to weather forecasts, seasonal prediction, and long term variability and change should also be supported for hazards including but not limited to: severe weather, tornadoes, atmospheric rivers (flowing columns of water vapor in the atmosphere that can bring heavy rain or snowfall), floods, droughts, heatwaves, and clear air turbulence.
- Marine heatwaves and harmful algal blooms in the Great Lakes, coastal, and ocean areas require multi-timescale research support.
- Investments in severe weather forecast improvement, including defining metrics that improve service delivery to NOAA stakeholders.
- Heat is the number one weather-related killer, with the Center for Disease Control and Prevention noting over 700 heat related deaths, over 9,200 hospitalizations, and over 67,000 emergency department visits due to heat annually. Improvements to understanding heat risk, perception, and barriers through SBES research must be coupled with accurate and timely forecasts, and actionable communication and messaging.

Satellite Data

The satellite derived information that NOAA collects or acquires from partnerships in current and forthcoming satellite systems is necessary for seamless Earth system and climate analyses and forecasts. The wealth of data from these systems needs to be further exploited and better applied in our science.

- We recommend funding to improve the assimilation of satellite observations and derived information in environmental prediction, Earth system models,[11] ecosystem models, smoke forecast models, and space weather models. Satellite and in situ observations should be blended for process studies and assessments, and to learn new methods of application for the data collected (e.g., artificial intelligence techniques) for early detection of extreme events and hazards.
- Expand NOAA's Interdisciplinary Earth system science applications and research to ensure that satellite-derived data is provided to users as relevant, accessible, and actionable information. We can better utilize data NOAA already has and expand our capacity for innovative science that brings together a vast variety of information sources (i.e., satellite, in situ data, census, cadastral, surveys) and sectors for integrated, whole Earth system science. To take this further, we can leverage the NESDIS Common Cloud Framework, on-going Data Agnostic Common Services (DACS), and data access and dissemination initiatives. These are focused on completing the infrastructure needed to securely ingest, generate science products, and distribute and archive data. Initial focus for enhanced applications should be on Polar regions, coastal resilience, water quality, extreme events including disaster mitigation, preparedness response, and recovery.
- We recommend accelerating the development of higher level, multi-source (blended) satellite products to better support high level decision-making on the part of NOAA and its customers.
- We recommend additional funding for joint and dedicated satellite and living marine resource applications research, a cross–NOAA effort. NOAA science has shown that regional, marine resource-dependent economies are ultimately driven by primary production of the ocean. These are hard constraints on the fisheries and seafood production of any given marine ecosystem, and being able to track, in real time, ocean productivity will help to better inform fishery portfolio planning.
- We recommend sustained support for joint and dedicated satellite and harmful algal bloom (HABs) applications research, a cross-NOAA effort. HABs are mandated for monitoring, reporting and predicting. The impacts of HABs cost tens to hundreds of millions of dollars, shut down multiple beaches, impact multiple aspects of the blue economy and ocean-use sectors, have non-trivial health impacts, and pose an equity challenge as research on them is only focused in a few select areas. Being able to track HABs in real time will help provide better planning in the tourism, shellfish closure, and public health sectors.
- Pursue joint venture activities with the commercial sector, other federal agencies, and academic and international partners, to enhance the exploitation of existing satellite data, increase readiness in the use of expected future satellite data, and increase innovation and agility in the space and ground architecture.

[11] Numerical models of the full physical climate system (atmosphere, ocean, land, cryosphere) along with biogeochemistry and ecosystems.

- Better support for the incorporation of non-NOAA, partner, satellite data in our products (e.g, National Aeronautics and Space Administration–NASA). These are an extraordinarily valuable resource that remains underutilized due to budgetary constraints.

Total Water and Flood Inundation Mapping and Modeling[12]

NOAA will deliver version 3.0 of the National Water Model in FY23, including an integrated water prediction capability to provide total water-level forecasts out to 10 days along the coastal and inland waterways where storm surge, tides, wave run-up, and riverine flooding cause inundation. This integrated modeling capability will improve forecasts of compound flooding and enhance associated impact-based decision support services. Less commonly-included impacts of weather-driven shallow-water resonances (e.g. meteotsunami) will also be possible.

- Recommend additional research funding for the linked probabilistic total water level forecast, including post-processing to quantify and mitigate the uncertainties that arise from meteorological inputs and from coupled coastal and inland process models.

For more than two decades, the emergency management community has articulated a growing need for real-time, detailed, actionable, street-level flood inundation maps depicting areal extent, depth, and infrastructure impacted by flood waters. In response to these challenges and growing needs, NOAA will implement both analysis and forecast inundation mapping services for all communities nationwide, promoting service equity and addressing the needs of previously underserved communities inland and along the coast. By FY26, NOAA will revolutionize U.S. water prediction capabilities by disseminating, for the first time in history, real-time high spatial resolution forecast flood inundation maps for 3.4M river/stream miles (as defined by the U.S. Geological Survey National Hydrography Dataset). These Flood Inundation Maps, which graphically depict the areal extent of water on a map, will inform critical decisions that save lives and property before, during, and after a flood event. Quantification of inundation forecast uncertainties produces more accurate warnings to prompt evacuations that save lives and stage response personnel and materials in safe locations in the vicinity of forecast impacts and reduce emergency post-event response time. In support of this effort, NOAA recently concluded two consecutive, successful demonstrations of real-time Flood Inundation Mapping led by the National Water Center as part of FY18-19 and FY20-21 Department of Commerce Agency Priority Goals.

Near real-time national flood inundation maps derived from integrating satellite and aerial observations are valuable to river forecasters and decision makers for disaster monitoring and relief efforts, as well as validation of near real time flood inundation mapping services. Insurers, infrastructure related industries, and governments need to quantify the future expected range of flood and water levels in order to prepare and inform proper infrastructure investments. Knowing the current state of water levels during, or just before a flood event is equally as important as knowing the flood potential and likelihood decades in advance. Science is necessary to produce both real-time water prediction and to characterize long-term flood potential at a scale useful to the community of users.

[12] *Some of this work is funded in the Bipartisan Infrastructure Law passed in 2022; any additional need should be clarified against amounts already appropriated.*

- Continued investment in research, development and demonstration are needed to deliver and evolve flood inundation mapping services at the street level for all communities nationwide to depict location, time, duration, and depth of flood waters.
- Invest in the use of commercial satellite imagery, both optical and synthetic aperture radar, to provide on demand flood information.
- Produce an annual state of the flood report to document flood events - extent, duration, and impacts.

Subseasonal to Seasonal Prediction

Across the NOAA mission portfolio, the subseasonal to seasonal timescale[13] has emerged as a compelling period for forecast services required by multiple users and constituencies. These include water managers, emergency managers, fisheries and protected species managers, public health professionals, the fishing industry, transportation, agriculture, energy, financial futures, and many other markets. While captured in the authorizations for the National Integrated Drought Information System, the Weather Research and Forecasting Innovation Act, and within both the the Climate, Ecosystems, and Fisheries Initiative (CEFI) and Coastal Inundation at Climate Timescales Initiative, the seasonal to subseasonal timescale is important to many additional mission applications.

- Understanding the dynamics and forecasting the future marine ecosystem can realize solutions for ocean sustainability, as well as inform coastal communities of their economic future.
- Advance our ability to connect models of climate change to models of ecosystem and fishery changes.

NOAA is planning on developing the Seasonal Forecast System (SFS) to “fill the gap” between shorter range weather forecasts and longer term climate change simulations/projections. This SFS capability will make significant progress towards seamless prediction within NOAA’s Unified Forecast System (UFS) framework.

- In collaboration with NWS, NOAA Research should prioritize the development and operational transition of SFS in the next few years, with emphasis on developing a fully coupled Earth system model. This includes the development of coupled data assimilation (implementing observations from multiple Earth system components such as the atmosphere and ocean together to create the basis for a better model and forecast) and advancing UFS components (the atmosphere, oceans, land and cryosphere).
- Accurate SFS requires better modeled physics descriptions of slowly changing processes on the land, in the oceans, for ice, and for atmospheric chemistry. Investment in the significant development of land vegetation and groundwater, sea-ice growth and melt, ocean mixing, and atmospheric ozone model components is critical.
- Models must adequately capture the initial states of the atmosphere, ocean, land surface and cryosphere, as well as the interactions, or coupling, of these different components. Data assimilation improvements for the land, ocean and sea ice states are needed in order to more accurately represent the initial states of those model components that provide the long-term memory of the Earth system.

[13] *Subseasonal forecasting is between two weeks and three months and seasonal forecasting is between three months and two years per the Weather Act 2017*

- A historical reanalysis and reforecast for multi-decades is needed for model calibration and to further improve seasonal forecast outlooks.
- Post-processing methods, including machine learning, should also be supported to improve the accuracy of predictions.

Reanalysis and Reforecasts

Earth system reanalyses and reforecasts are essential digital infrastructure that support NOAA's operational and research mission as well as the rapidly growing climate and weather enterprise. They are fundamental to producing useful forecasts and for understanding the physical processes controlling the predictability of high-impact weather events. State-of-the-art global reanalyses and reforecasts are critical to understand, assess, and improve prediction of trends in extreme events, changes in water security, human health impacts, coastal inundation risk, climate impacts on marine ecosystems and fisheries, vulnerability for catastrophic infrastructure failure, and environmental change in under-observed polar regions.

U.S.-focused regional reanalysis is an emerging need for products supporting resilient infrastructure planning (e.g., informing precipitation estimates for designing high hazard dams to withstand flooding, establishing renewable energy sites, and for forecast informed reservoir operations), transportation safety (e.g., calibration of aviation turbulence, icing), and other environmental information (e.g., changes to near-shore environment, historical fire emissions). Archived observations are reprocessed and used as input to the reanalysis to ensure consistent, quality controlled observations, with uncertainty estimates. Examples include the reprocessing of NOAA's 50+ year archive of satellite polar orbiting and geostationary satellite records.

- Sustained support is required to build and maintain an operational reforecast and reanalysis product, including reprocessed datasets.

Accelerated developments of the high-resolution Hurricane Analysis and Forecast System (HAFS) is necessary to address impacts of landfalling hurricanes (e.g., heavy rains, high winds, tornadoes, storm surge, inundation). This effort would include coupled data assimilation focused on the inner core of hurricanes, to produce a HAFS reanalysis from the last 25 years, coinciding with global reanalysis. This would allow for improved probabilistic hazard guidance and warnings, enabled by improved track, intensity, and storm size predictions before formation and throughout a storm's life cycle.

- Sustained research is required to develop optimal reanalysis and reforecast strategies for hurricanes.

Seasonal to Decadal Prediction[14]

Information is needed from seasons to decades for decision making and risk quantification. Seasonal outlooks[15] have become operational in the last decade and can be expanded with improved accessibility. Decadal predictions and large ensembles can be developed for new outlooks and actionable guidance to support infrastructure, policy, investment, and operations.

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[14] *Some of this work is funded in the Inflation Reduction Act passed in 2022; any additional need should be clarified against amounts already appropriated.*
[15] *Seasonal refers to timeframes between three months and two years per the [Weather Act 2017]*

- Further investment is needed in Earth system numerical prediction capabilities including the atmosphere, ocean, cryosphere, space, land, hydrologic cycles, and biogeochemistry. This will improve understanding and prediction skills.
- Development and interpretation of sector-specific climate futures can improve accessibility to support economic growth.
- Improve seasonal forecast products by post-processing methods such as machine learning and promote the development of high-quality labeled datasets.
- Expand outlooks and Earth system capabilities to represent ecosystems and living marine resources under a changing climate.
- Targeted SBES research is required to not only improve communication of data, products, and services, but also inform priority areas for development.

Proper coordination of investments and programmatic direction should be aligned between models built for different timescales (subseasonal to seasonal to decadal) so they can be leveraged across model systems. Enhanced coordination is needed between line offices, programs, and laboratories..

- Determining how to transition the advances of an energy conserving model that covers both weather and climate timescales to operations is both timely and necessary.
- Further coordinate work on data assimilation to improve initial conditions for both weather forecasts and climate predictions. Improve data assimilation for unique seasonal-to-decadal systems coordinating with efforts at weather timescales.
- Improved software linkages between various efforts (Flexible Modeling System, Unified Forecast System, Earth system models at longer timescales like the Seamless system for Prediction and Earth system Research [SPEAR]) should also be made so fundamental software infrastructure supports seamless use and integration across models.

Polar Considerations

Polar regions require special consideration, primarily due to changes in the cryosphere, regionally specific ecosystems, and potential for impacts on global climate.

- Include land-ice sheet modeling and prediction in Earth system models. This is critical for quantifying future sea level rise, predicting tsunami events from major calving events (icebergs splitting off into the sea), and identifying the risk of abrupt climate change in polar regions.
- Develop new and enhanced authoritative products for Essential Ocean Variables (e.g. sea ice thickness, concentration, motion, type) from existing and next-generation observations from NOAA and non-NOAA partner missions, including commercial missions.
- Create user-ready, fit-for-purpose satellite products with equitable access to enable greater data discovery and direct use in modeling, operational analysis and forecasting, maritime transportation, fisheries, and climate monitoring.
- Develop advanced coupled distribution and production of living marine resource modeling in polar regions, to precede, anticipate, and mitigate expected extra-territorial disputes beyond exclusive economic zones (an area of the sea in which a coastal nation has jurisdiction over the resources) for these resources.

The Arctic is rapidly warming at a faster pace than the rest of the globe, affecting global conditions, warranting further study in modeling and forecasting. New observing systems and further exploitation of existing capabilities should be used to assess global greenhouse gas effects and feedbacks, decreased snow cover, changing sea ice, and the many changes noted in the 2022 Arctic Report Card. For years, the Arctic has eluded appropriate agency prioritization. NOAA's Arctic research priorities align with the 2022-2026 Interagency Arctic Research Plan and the goals of the U.S. Arctic Research Commission.

- NOAA has an important role to respond to Arctic challenges through innovative research and monitoring, including establishing an Arctic Global Ocean Observing System. NOAA should expand Arctic science in collaboration with other participating agencies and nations, and determine the necessary funding, tools and methods.
- NOAA conducts critical ecosystem monitoring and analysis to respond to climate driven changes such as, poleward movement of marine species vital to commercial and subsistence fisheries, changes in migratory behavior for bowhead and beluga whales, disruptions in Alaska Native communities subsistence harvest and any shifts in the pelagic-benthic relationship that could disrupt ecosystem productivity.

The Antarctic and Southern Ocean have a large impact on the global climate system and, despite ongoing efforts, remain under-observed. Carbon flux of the region remains unquantified. Understanding the land and sea-ice cover, ocean, and atmospheric variations, and their impacts on the Earth's climate system, as well as on key Antarctic marine species, require strategic research in multiple areas.

- We recommend expanding support of the rebuilt NOAA field station on the Antarctic peninsula. This is a critical location to better measure and understand the variations in Antarctic krill and krill-dependent populations that support large components of its marine ecosystem, consistent with the demands of Earth system science and international treaty obligations.
- Augment NOAA's enterprise research and monitoring capabilities for southern high latitude marine and ice environmental information by creating or enhancing multi-satellite, fit-for-purpose products of sea surface temperature, height, and salinity, and sea ice production, thickness, and drift.
- Improve our understanding of the Southern Ocean climate and extreme events, and their trends and interactions with the global system by augmenting NOAA's multi-decadal, polar-specific, satellite-based, and in-situ climate data records.
- Improve monitoring of the Southern Ocean carbon cycle.

2.2 Economic Development, Environmental Stewardship, New Blue Economy

Utilizing its deep understanding of ocean and coastal environments, NOAA will provide data, information, and services to catalyze American competitiveness, accelerate growth of sustainable ocean industries, and facilitate the technology advancements for coastal and marine solutions to climate challenges. To develop a robust blue economy, NOAA will continue to support a thriving ocean enterprise that adds sustainable economic opportunities while providing valuable climate, weather, fisheries, and ocean services and solutions.[16]

[16] *Reproduced from the NOAA 2022-2026 Strategic Plan, Strategic Goals Summary. Available at: https://www.noaa.gov/sites/default/files/2022-06/NOAA_FY2226_Strategic_Plan.pdf.*

Sustainable Offshore Wind Energy Development

Support for sustainable offshore wind energy development invites research questions about its impacts on marine and coastal areas. NOAA science can inform planners and regulators about impacts, citing constraints and benefits, hub height, wind productivity, and wind forecasts. The regulatory consultation process will require the best available science within the areas of NOAA's jurisdiction. Every Line Office has a role in contributing to the success of national offshore wind strategy objectives. NOAA will also need to maintain and adapt its fishery and protected species survey and observing capabilities as offshore wind development progresses. The impact is particularly strong on the spatial footprint of NOAA Fisheries surveys to monitor fish and protected species populations and their ecosystem.

- Advance spatial modeling and suitability analyses to reduce impacts to NOAA trusted resources, surveys, and observation platforms; support federal, state, and industry requirements for most economic installations of renewable energy; and boost the New Blue Economy with reliable data and decision support.
- Couple the advancements in autonomous technology and uncrewed systems with the rapid growth and availability of Omics and environmental DNA (eDNA) to explore new fisheries monitoring capabilities in regions developed for offshore wind.
- Develop an efficient plan to monitor and manage marine ecosystems in a changing Earth system due to both a changing climate and built environment.

Ocean Data Acquisition, Accessibility, and Application

Advances in observation, processing, and visualization technology have increased the demand for NOAA's data stewardship and archiving services to manage increasingly large, complex, and variable oceanic data as well as provide trusted, curated, interoperable, and timely data.

- Increase acquisition of data in key regions for fisheries management and to support the New Blue Economy.
- Develop new data infrastructure and access platforms to increase data and model accessibility and application by decision makers.
- Find better integrations between oceanic data and other sources (e.g., satellite, airplane) to improve understanding and operational forecasts and predictions. For example, recent work paired hurricane gliders with hurricane flights to improve understanding of air-sea interactions and conditions fueling hurricane intensification and forecast skill.

International Efforts with U.S. and NOAA Interests: Ocean Research and the UN Decade of Ocean Science for Sustainable Development

The UN Decade of Ocean Science for Sustainable Development highlights the criticality of ocean science and technology in the achievement of sustainable pathways for society. Given this, all NOAA line offices are engaged in formulating and implementing actions[17] for the Decade. These actions will only be successful if resourced appropriately, and NOAA should seek to support activities involving our people and interests. Principal among Decade actions are:

- The National Ocean Mapping Exploration and Characterization strategy that defines mapping the U.S. exclusive economic zone by the end of the Decade, and Seabed

[17] *Actions are programs, projects, contributions and activities, as defined by the Decade implementation plan*

2030, which defines the global community working to finally map the world ocean by 2030.
- Physical and chemical oceanography bring compelling research needs including the carbon cycle and Marine Carbon Dioxide Removal.[18]
- Biological observations, including through uncrewed systems, will be advanced by activities endorsed within the Marine Life 2030 and Ocean Biomolecular Observing Network programs, and
- Facilitating transmission of new types of ocean observations in any data format seamlessly to and from the World Meteorological Organization Global Telecommunication System .
- The UN Ocean Decade Tsunami Programme has been established to consider, develop and deploy an instrumentation grid that will greatly reduce the uncertainties related to tsunami formation, detection, monitoring and forecasting. This would ensure positive confirmation and measurement of all tsunamis within 10 minutes of origin for the most at-risk coastlines.
- Partner with international NOAA analogs to develop marine biodiversity portals for data sharing, as part of the recent Biological Diversity Beyond areas of National Jurisdiction considerations.

NOAA maintains an inventory of Ocean Decade actions of interest, all of which seek to leverage partnership, including other federal and state agencies, academia, non-governmental organizations, and international organizations. NOAA should seek to contribute its part to the success of these actions, in partnership with the U.S. National Committee and Decade Collaborative Centers. In addition to the UN Ocean Decade, there are other International Ocean commitments that NOAA needs to continue to monitor.

2.3 Cross-Cutting Climate and New Blue Economy Science & Technology Focus Areas:

Artificial Intelligence, Uncrewed Systems,'Omics, Citizen Science, Data and Cloud

The NOAA Science & Technology (S&T) Focus Areas are sectors of rapid innovation that drive scientific discovery and economic growth. The benefits of artificial intelligence and machine learning, Uncrewed Systems (UxS), and advances in bioscience (‘Omics) are maturing across NOAA’s mission areas. Advancements in each of these technologies can reduce costs and accelerate delivery of new discoveries and methods to provide higher quality and more timely scientific products and services for societal benefits. Examples range from increased community preparation by improving accuracy and notice of severe event warnings; through sustainable production of safe food from our coasts, oceans, and Great Lakes; to conserving biodiversity despite increasing pressure on the environment. Working across the Focus Areas will further accelerate solutions, including synergy within the focus areas of Data, Cloud, and Citizen Science.

There is a need and opportunity to leverage NOAA’s current organizational structure to more effectively implement these technologies through improvements in computational and analytical capacities, targeted research, technology transition, workforce proficiency, and partnerships across NOAA’s lines, federal agencies, and extramural research and commercial communities.

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[18] *A draft NOAA marine carbon dioxide removal strategy was released in 2022. It is available at: https://sciencecouncil.noaa.gov/Draft-CDR-Strategy.*

- Build capacity through continued championship, strategic oversight, and utilization of the S&T strategies and plans[19] to guide action and investment.
- NOAA will have to automate many data stewardship tasks using artificial intelligence and machine learning, among other technologies, in order to maximize the utility of data under our stewardship.
- Catalyze the research, engineering, and partnerships needed to:
    - Develop artificial intelligence, machine learning, edge computing, and cloud solutions through NOAA's Data and Cloud enterprises and the virtual NOAA Center for Artificial Intelligence. These efforts will ensure NOAA's ability to efficiently store, process, evaluate, and interpret the growing outpouring of information that is the hallmark of the Big Data era.
    - Accelerate transition of NOAA missions to UxS through expanded projects, public-private interactions[20],[21], and synergy across the agency and S&T Focus Areas.
    - Advance high-performance biocomputation and harmonized approaches to bioscience (e.g., eDNA/microbiome) to authoritatively document biological impacts and reveal mechanisms of resilience to large-scale stressors, including climate change.
    - Enable citizen science (research conducted with the participation from the general public) to support equitable access to scientific opportunities and information.

Scientific data stewardship targets making data and information more Findable, Accessible, Interoperable, and Reusable (the FAIR principles). To enable and facilitate Open Science and FAIR principles, NOAA must revolutionize its scientific data stewardship tools and services. This requires adoption of cutting edge data collection, preserving and sharing technologies and policies to best utilize them, especially those afforded by networked systems and services, including the cloud and related technologies.

- Expand NOAA's data stewardship and archiving capability to address current and growing demands for services and provide the foundation to handle additional data. Build on NESDIS' DACS and Dissemination and Access initiatives to leverage the cloud for data stewardship and operational sustainment of data sets that are key to informing strategic long-term investments in the public and private sectors.

3. Enabling Equity and Environmental Justice, Connecting NOAA's Missions

NOAA will strive to ensure the needs of America's underserved and vulnerable populations are met through delivery of services, education, and training to prepare all communities for increasing extreme weather and climate hazards. Not only will NOAA focus on partnerships that increase its reach to underserved and vulnerable communities, it will also implement practices within the agency to ensure equal opportunities and treatment of employees.[22]

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[19] *https://sciencecouncil.noaa.gov/NOAA-Science-Technology-Focus-Areas*
[20] *Additional information here: https://www.whitehouse.gov/ostp/news-updates/2022/10/28/biden-harris-administration-advances-ocean-science-and-technology-through-partnerships/*
[21] *https://oceanexplorer.noaa.gov/news/oer-updates/2022/uncrewed-saildrone-alaskan-waters.html*
[22] *Reproduced from the NOAA 2022-2026 Strategic Plan, Strategic Goals Summary. Available at: https://www.noaa.gov/sites/default/files/2022-06/NOAA_FY2226_Strategic_Plan.pdf.*

The concept of equity and environmental justice will be included in the science priorities that NOAA pursues, in the assessment of users in need of the information, and in recruiting diverse talent into the agency. Listening sessions and community engagement allow Line Offices to determine service needs and gaps, and define new research directions in social and physical science. Examples of this include:

- Creating and/or effectively utilizing existing social vulnerability indices
- Targeted studies of urban heat and air quality mapping
- Targeted studies of sea level rise
- Assessing community based climate risk
- Addressing the disparities in services provided to underserved populations

Research necessary to perfect our approach to true equity and environmental justice will likely center on investments in the SBES. NOAA's science and technical workforce does not represent the cultural diversity of America. We are among the lowest of science agencies in minority recruitment, yet we sponsor academic preparation in multiple cooperative science centers (CSCs) matched to our scientific disciplines. Increasing the CSC participation in the S&T portfolio and within the cooperative institutes will reveal a diverse breadth of talent for hiring.

- NOAA shall deliver mission products and services on an equitable basis across all communities and economies.
- Expand environmental justice research
- Improve accessibility and delivery of climate resilience science and technology equitably
- Build a workforce that reflects the diversity of our Nation

4. How to Achieve our Research Priorities: Methods and Tools

4.1 High Performance Computing[23]

High Performance Computing (HPC) has been invaluable to meeting NOAA's mission. However, it must grow to meet evolving R&D and operational system needs to ensure innovations can be transitioned. The NOAA Office of the Chief Information Officer has established a measure of NOAA HPC needs today. Even with the additional Inflation Reduction Act (IRA) funds for HPC, NOAA will still hold less HPC capacity than is necessary to fulfill our mission, as the need for these resources continues to grow within the agency. HPC capacity has been a risk for NOAA and will continue to be in the coming years. For example, while NOAA has developed high resolution seasonal-to-decadal prediction capabilities and the highest resolution large ensemble of climate projections, these capabilities have been built in a restrictive HPC environment. Increased capacity can expand Earth system prediction, resolution, ensemble size, and skill.

- Continue the informed acquisition of next-generation systems and services that span the traditional and cloud markets, securing the proper architectures for the various research and operational missions.
- Include integrated software engineering efforts focusing on new and emerging computing architectures and modern software development methodologies.
- Expand HPC capability to reach the required level and ensure partnerships between the research laboratories and operational components.

[23] *Some of this work is funded in the Inflation Reduction Act passed in 2022; any additional need should be clarified against amounts already appropriated.*

4.2 Environmental Observations Design, Evolution, Integration, and Exploitation

Accurate, reliable and efficient observations and measurements of the complex Earth systems of space, atmosphere, land, ocean, cryosphere, and biosphere are essential for the NOAA mission. Much of the world relies on the observing systems that NOAA has invented, developed, organized, and deployed. They provide the inputs to the different models used in NOAA to provide products and services to the public.

From satellites, to ground-based instruments, use of uncrewed systems, ships, submersible and surface platforms – whatever the mechanism - reliable sensors and measurements need to be proven for NOAA use. New investments are required to move beyond the current state of observational concepts and fill the gaps. Rapid commercial and other government agency development of sensors and methods, that formerly had been NOAA's responsibility to develop, are increasingly available and may serve mission requirements.

- Find or develop a modern, efficient, and effective set of high-quality observing systems meeting NOAA standards to enhance mission economy and performance.
- Upgrade and complete modernization of NOAA's observing systems, which should be led by research and operational requirements and proven tools and methods. Calibration and testing phases are required to support these efforts.
- Integrate the measurements of multiple systems, allowing more-effective monitoring of the different environmental domains (land/hydrology, ocean, weather, cryosphere, biosphere, space weather) spanning time scales from nowcasting to climate scales.
- Connect observing communities to modelers, to user communities of those models, through research-proven systems.
- Collaboration with industry, such as SMART, will be crucial for deep-ocean measurements. The vast network of commercial fiber-optic cables provides an ideal support structure for scientific instruments to measure bottom pressure, seismic acceleration and water temperature variance.

Observation systems alone will not be complete without funds to analyze the resulting data streams across timescales and research topics across the agency. The NOAA programs and activities that are the stewards of the observing system need to be resourced to do more than develop and maintain an observing system.

- Resource the scientific analysis of these data sets to provide internal and extramural support for renewed understanding.
- Quantify the impact of observing systems on the quality of NOAA's modeling systems, forecasts, warnings and hazard information.
- Develop key partnerships to leverage external experts to accelerate innovation.

4.3 Partnerships

Partnerships have proven beneficial though they take both time and relationship management. The benefits of aligning with other federal agencies bilaterally as with the National Science Foundation, the U.S. Geological Survey, the U.S. Navy, the U.S. Environmental Protection Agency and through the National Ocean Partnership Program, Interagency Council for Advancing Meteorological Services implementation, and U.S. Global Change Research Program can be even more fruitful if NOAA programs lead with initiatives.

- NOAA shall continue to follow an Earth system approach in our R&D portfolio and continue to improve integration across Lines.
- Partnerships should be expanded to other agencies on the impact and use of NOAA data, products, and services to achieve their non-scientific missions.

Philanthropic and non-governmental organization partnerships are increasing and beneficial. NOAA should continue to engage private sector or non-governmental entities through cooperative research and development agreements, memorandum of understanding, and other agreements and programs such as the Small Business Innovation Research program. Consider new entrants and collaborators into the research fields of NOAA, including the climate forecast industry, materials science, medical, environmental engineering, non-traditional sensor designs, citizen science, and use of prize incentives.

- Be expansive and innovative in structuring and securing partnerships.
- Partnerships should also be developed with private industry users and manufacturers to leverage the best of technology and practices.

4.4 Integration of Social, Behavioral, and Economic Sciences Research Across NOAA Mission Areas

The NOAA Science Advisory Board has long recommended the agency demonstrate more progress in the use of social, behavioral, and economic sciences (SBES) to more effectively achieve our mission and equitably inform the public. The protection of life and property from the negative impact of environmental hazards, extreme events, and emergencies requires the integration of social and physical science disciplines and expertise at all levels and time scales. This multidisciplinary approach must extend over the life cycle of a project and not be an afterthought.

All aspects of NOAA's mission warrant SBES investment. Understanding how people receive and use Earth system information and understanding changes in communities is a proven but underfunded benefit. Moreover, addressing the needs of traditionally underserved communities in urban areas and in communities of Indigenous Peoples warrant the application of SBES to determine the gaps in service, provision, and to help engage with a community to better understand and equitably serve those needs.

- Incorporate SBES within the fabric of our work and demonstrate the resolve to produce outcomes and products that are readily usable, understandable, and beneficial to the public.
- Identify service gaps and methods to reach all communities equitably.