Organizing US Civilian Operational Oceanography Forecasting Services

A Climate Working Group Report, in support of the NOAA Science Advisory Board

Authors: Joellen Russell and Susan Wijffels

Executive Summary:

NOAA is the only US government organization mandated to steward our oceans and provide predictions. At present, however, other nations have outstripped US civilian capabilities with respect to global oceanographic forecasting and the required supporting observations. Building on the recognition of the value of earth system modeling (ESM), there is a need to **organize ocean forecasting services to better serve commerce, fisheries, and climate** including S2S forecasting and precipitation prediction. These services will build upon existing products available through NOS and enable NOAA to better fulfill its obligations in these areas. To meet these aspirations, accelerated development in global ocean modeling with forecasting capability is needed. Thus, the US needs a NOAA-led **operational ocean forecasting system** that produces regional and global products to support ocean, weather and hazard prediction throughout the country, the blue economy (including offshore energy, shipping, ports, and commerce) and fisheries and ecosystem prediction applications and our national and economic security interests. Near real time operational physical and biogeochemical oceanography is now critical to saving lives and property, assessing and quantifying carbon dioxide removal strategies, and predicting the zeroth order anthropogenic trend. NOAA can capitalize on the proven merits of targeted ocean observations, process studies and sustained observation systems in order to incorporate additional sources of predictability and increased predictive skill to fulfill its critical and unique governmental mission.

Applying **Earth System Prediction** capabilities to this operational oceanography framework by assimilating ocean data, including biogeochemistry, will further improve forecasts to protect lives and property, promote the safety, security and growth of the blue economy (including marine carbon dioxide removal-mCDR), and support fisheries and ecosystem management. Only NOAA is charged with ocean monitoring and prediction - this white paper lays out how committing to operational oceanography (data collection, modeling, dissemination, etc.), combined with Earth system prediction, takes NOAA most of the way to providing a **global environmental intelligence network.** This term frames the overall problem of NOAAs mission and goals with respect to ocean services that would be used by NOAA, Commerce, Defense, and other government branches, and succinctly describes what the US needs during this time of global climate change to ensure its safety, grow its economy, and protect and provide for its citizens. Additionally, a unified (across line offices) NOAA approach (shared and nested models, grids, variables, etc.) to high resolution (<10km) ocean reanalysis and forecasting is necessary to increase forecasting capability, make up lost ground compared to other nations, and simplify NOAA's modeling infrastructure.

Given NOAA's mandate for environmental forecasting, and because NOAA is the only agency with a mission including the blue water ocean, it is clearly positioned to take the lead in developing a national, open access, high resolution forecasting system. A unified NOAA approach on high resolution ocean data assimilation and forecasting is necessary to increase forecasting capability, develop national capacity and reduce reliance on external information sources, and simplify modeling infrastructure.

The Climate Working Group has 4 main recommendations that will be described in detail below. NOAA should:

1. Clarify the objectives and goals of a civilian operational oceanographic and prediction service, by organizing a multi-office work team to develop goals, objectives, and actions for preparing and providing global ocean forecast product services to support commerce, fisheries and climate needs. This should be framed in the context of a **global environmental intelligence network in a changing climate**, and organized as a cross-NOAA team tasked with its delivery.
2. Develop a cost-effective **targeted list** of **ocean** products and **services**, both at global and regional scales, that are **needed to maximize the reduction of uncertainty** for the multiple applications within NOAA and for the larger community. Observing System Simulation Experiments (OSSE's) should guide this development.
3. **Reconfigure** the model and prediction **development plans** to ensure the needed suite of ocean products and services are developed, tested and operationalized as soon as possible. Identify opportunities for early implementation to achieve early successes in product delivery. Delaying implementation until 'full coupling' is in our view a mistake, though this should remain the long-term goal.
4. Gather links to products into a **single 'ocean portal'** where products are easily locatable and/or discoverable (from the NOAA home page), accessible and downloadable (with machine to machine services), and including the input observations. Having an ocean product portal facilitates accessibility and value of both observations and model related products which better serves US interests.

Background:

Ocean state estimates and predictions are being developed in many nations, and exist in various forms (both operational and experimental) within NOAA. The US, as a nation with a large coastline, extensive offshore territories and that is exposed to many climate risks, can benefit greatly from global and tailored regional ocean intelligence. In particular the use cases and impact areas include:

1. Coupled weather forecasting: advancing tropical and extra tropical storms preparedness including weather and storm-related sea level and inundations. Tropical storm intensity has been shown to be sensitive to upper ocean heat distributions, and extratropical systems are sensitive to strong sea surface temperature fronts typically found in eastern and western boundary systems.
2. Offshore energy industry efficiency and safety (including the emerging offshore wind energy sector): uses include routine operations (wave and current forecasts), real-time response to emergencies such as oil spills and other pollution events (e.g. Fukushima, Deep Water Horizon), and use of long re-analyses to inform safe and efficient infrastructure design.
3. Safety at sea: requires wave/current and sea ice forecasting for vessel warning systems and to guide search and rescue campaigns.
4. Shipping industry efficiency and safety: Ship safety and routing to save fuel and avoid ecosystem impacts.
5. Marine resource management: understanding and quantifying the links between fishery resources, ecosystem and climate/ocean changes is a key requirement for ecosystem-based fisheries management, as called for in the NOAA Climate and Fisheries Initiative
6. Coastal hazards and impacts: prediction of water quality such as harmful algal blooms, marine heat-waves, acidification and their impacts. The offshore/shelf/coastal links are mediated by mesoscale and smaller scale variability, which requires 10km or smaller model spatial resolution.
7. Managing climate extremes: improving subseasonal to seasonal climate prediction through the integration of skillful and well-initialized (with observations) oceans is a key element of this system essential to advancing predictions of extremes that would benefit many sectors including energy, water, agriculture, and fisheries.
8. Climate projections and assessments: as the major sink for heat (and thus controlling the climate system thermal inertia), tracking and simulating correctly ocean warming and heat uptake is critical to future climate projections. Heat and freshwater distribution are also a major controller of regional sea level rise, and the patterns/frequency of marine heat waves.
9. Global carbon inventories and assessments: required to reduce uncertainties in carbon inventories and projections, as called for at international carbon management such as the Conference of the Parties. The efficacy, impacts and project-level quantification of marine Carbon Dioxide Removal projects also requires accurate ocean state estimates with full biogeochemistry.

We need a Google Map equivalent of new shipping lanes that are more precisely calculated to reduce risk, save time, fuel and money, and protect marine mammals and fisheries and sensitive ecosystems to promote the new Blue Economy[1].

The increasing use of offshore structures to provide ocean-sourced energy for communities and industries requires better forecasts of wave heights, severe wind and weather, and sea ice with more lead time to reduce risks and damages.

Ocean acidification, changes in oxygen, marine heat waves, and shifting optimal habitats in space, depth, and time of year are not local phenomena. They require global environmental intelligence because Ecosystem Prediction isn't just about human impact on ocean waters – it's about other things that could and will drift into these waters. The sudden disappearance of the Alaskan snow crab fishery during the winter of 2022/2023 is an excellent example of an ecosystem change that might have been predicted. Szuwalski et al. (2023) concluded that a marine heat wave observed in 2018, led to higher caloric requirements which, when combined with a restricted range, resulted in the mass starvation event last winter. Other examples are the potential long-term ecosystem impacts of the vast foreign fishing fleets now efficiently targeting prime stocks at the edges of international waters.

The opening of ice-covered seas to surface travel will have profound economic and security implications and the US needs **global environmental intelligence** about what (and/or who) is in, on and around our national and coastal waters. Dynamic sea ice prediction will be essential to identify and monitor available sea lanes for our own use as well as state-based (e.g. Chinese fishing fleets, and Russian Arctic icebreakers) and non-state-based (i.e. pirate) activity. Chemical oceanographic observations will identify potential pollutants (like Fukushima debris) as well as allow us to assess our carbon dioxide removal strategies and monitor our international carbon agreements.

At present, China, Europe, Australia, and other nations have surpassed US civilian capabilities, and they indicate a path forward. The European Centre for Medium term Weather Forecasting (ECMWF) is currently on its 5th version of their global ocean forecasting model, Ocean5; China runs operational prediction and reanalysis services at global resolution of 1/12° with a 1/24° Indian Ocean.

It is clear based on both recent research and real operational forecasting experience (largely in Europe), that the future pathway is a system with coupled atmosphere, ice, surface wave and ocean elements at high-resolution and with data assimilation and forecasting capabilities, including biogeochemical aspects of the Earth system. In addition, higher resolution coupling will likely improve seasonal to subseasonal climate prediction. Many of these advances require supercomputing and observational resources that are still not widely available in most countries.

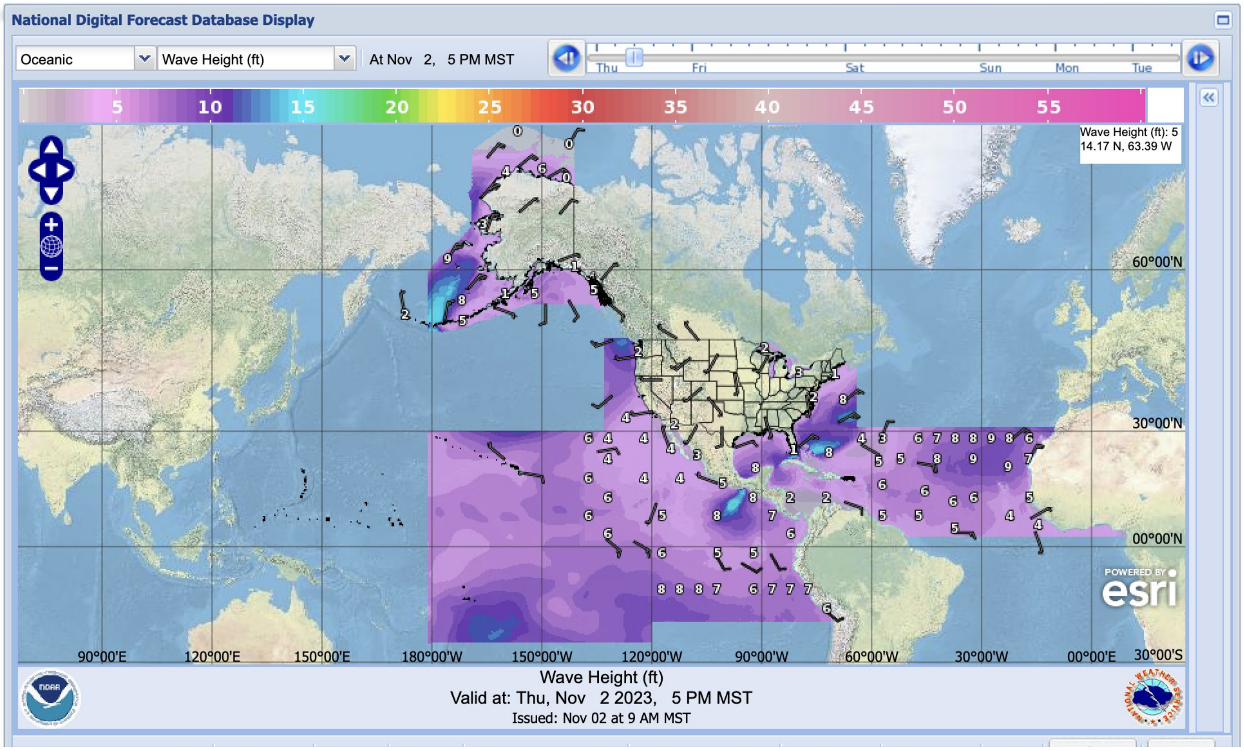
[1] The U.S. Bureau of Economic Analysis (BEA) estimates that the marine economy accounted for 1.9 percent, or $432.4 billion, of current-dollar U.S. gross domestic product (GDP) in 2021.

However, they will be available in the medium term, and a key piece of this longer-term goal is achieving skillful and global high-resolution ocean state estimation (full data assimilation) and forecasting. Thus, besides improving services for key application areas as noted above, solving this challenge is part of building the scaffold for future improved and seamless Earth System prediction across many timescales [see the CWG Earth System Prediction White Paper].

Present status: Due to real operational and development needs, various Line Offices in NOAA have already developed ocean analysis and forecasting capacities in several independent or minimally connected efforts. Some efforts appear to be lacking critical mass and development and upgrades among these are slow, while other efforts are duplicated in other parts of NOAA. Each system requires maintaining dynamical models, observational pipelines, data assimilation systems, validation and skill assessments etc. As model complexity and resolution demands continue to increase, maintaining several marginally connected and parallel efforts appears unsustainable and suboptimal. This is already recognized across NOAA and plans are underway to address this (see below).

Availability: NOAA ocean products and services are hard to find and access. They comprise a complex mix of global, regional and very local products and predictions. Some have poorly quantified skills and the options are very confusing. Given that NOAA funds around 50% of global *in situ* ocean observations, NOAA should exploit its investment as efficiently as other nations do, and offer a clear menu of ocean products and services derived from this investment.

Currently, neither the National Weather Service (NWS) landing page's 'forecast menu' nor the NOAA.gov 'Oceans and Coasts' landing page lists any global open ocean products or forecasts. The 'NowCoast' portal does visualize recent ocean surface temperatures and currents, but with no clear links to data files or downloadable information. The global Real Time Ocean Forecast Systems (RTOFS) serving site is not easily findable at NOAA's Environmental Modelling Centre's (https://polar.ncep.noaa.gov/global/) site and still bears the disclaimer that 'These are not official NWS products and should not be relied upon for operational purposes. This web site is not subject to 24/7 support, and thus may be unavailable during system outages.' While RTOFS is a high-resolution ocean-sea ice product, it only provides forecasts at 8-day lead times and lacks ocean surface waves. It is difficult for users to find an 'official' NOAA global ocean current and conditions forecast. The time has come for NOAA to prioritize and address these needs.



Caption: NOAA's Global Marine Forecast: Coverage and total area of forecasted ocean locations are less than optimal. Forecast of surface wave height is shown. (from: https://ocean.weather.gov/ and https://digital.weather.gov/)

Immediate Plans: As the CWG understands them, the EMC-led Unified Forecasting System (UFS) plans appear to address some of the model diversity challenges with the goal to base predictions on a single coupled high-resolution ocean/atmosphere/ice and wave modeling and data assimilation system. This step would entail having FV3-MOM6 dynamical cores. However, it is unclear if this longer-term evolution of this effort will produce a set of ocean predictions and reanalysis products and services, that covers physics, surface waves, sea-ice, sea level and ocean biogeochemistry. Work on moving RTOFS from HYCOM to MOM6 is underway, but how this effort fits into the larger UFS plans, and how it will produce a definitive set of ocean prediction services and reanalysis products is unclear. The more difficult and challenging work of going towards full high-resolution coupling should not preclude making progress on improving and delivering ocean-only products and services on the way. Indeed, progress on these related issues will strengthen future efforts by ensuring the ocean system is fit for purpose and skillful.

Characteristics of Success: Based on discussions with both NOAA and international community leaders, the global state-of-the-art systems share several characteristics to which NOAA can aspire. They are:

1. Global high resolution (0.1 degree or better), with regional higher resolutions systems forced by the global system.
2. Provide predictions for out to two weeks up to 2 years.

3. Easy to find and access with a clear menu of products and services accessed through an ‘ocean service’, such as Copernicus Marine Services or BlueLink.
4. Well documented system descriptions (e.g. skill levels, modeling and assimilation methods and observations data inputs).
5. Upgraded on a regular cycle. That is, they have parallel research and development and improvement activities (usually in collaboration with academia) to drive regular R2O upgrades.
6. Often include sea-ice and surface wave analyses and forecasts, and are extending into biogeochemical parameters.
7. Routinely carry out observing system impact and design studies to help guide future investments in satellite and in situ observing networks to improve system skill.

NOAA already has many of these elements in place, but there appears to be a lack of a NOAA-wide set of goals for ocean services, or a unified strategy to deliver and distribute them to users. To address these challenges and possibly focus efforts, we recommend the following actions.

Recommendation #1: Recognize that operational oceanography is essential to the development and maintenance of a global environmental intelligence network in a changing climate.

To rectify the current weakness of global operational oceanography in the US generally and at NOAA specifically, this need should be adopted as core business for NOAA with clear lines of oversight on goals and progress, and clarity on which part of the organization has responsibility for which elements of the products and services, and the strategy to deliver a more streamlined and efficient system. NOAA can clarify the objectives and goals of a civilian operational oceanographic and prediction service, by organizing a multi-office work team to develop goals, objectives, and actions for preparing and providing global ocean forecast product services to support commerce, fisheries and climate needs. This effort should be framed in the context of a global environmental intelligence network in a changing climate, and organized as a cross-NOAA team tasked with its delivery.

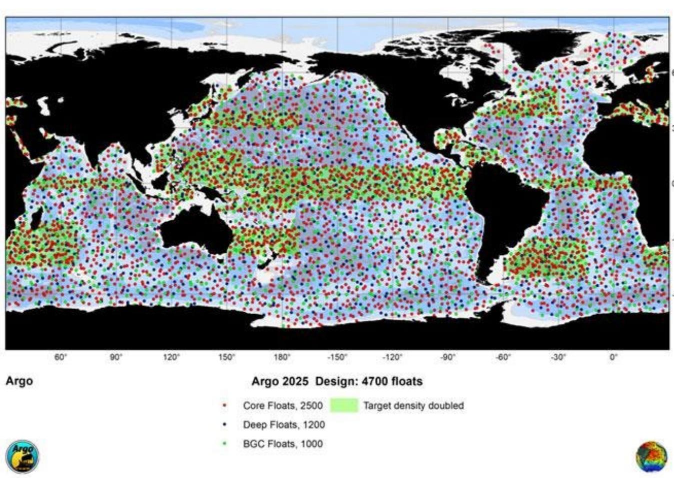
Recommendation #2: Develop a cost-effective targeted list of ocean products and services, both at global and regional scales, that are needed to maximize the reduction of uncertainty for the multiple applications within NOAA and for the larger community.

This list should include: global ocean reanalyzes and predictions at 10 km or better of temperature, salinity, velocity, surface waves, sea level, sea ice, biogeochemical parameters and carbon; predictions out to 10 days or more; high resolution global reanalyzes to cover the altimetric period (1993 - present). The global system should be capable of driving higher resolution regional and coastal models and services, building on and extending those already operated by the NOS.

Recommendation #3: Reconfigure the model and prediction development plans to ensure the needed suite of ocean products and services are developed, tested and operationalized as soon as possible. Identify opportunities for early implementation to achieve early successes in product delivery. Delaying implementation until ‘full coupling’ is in our view a mistake, though this should remain the long-term goal.

Research-to-Operations is not integrated across NOAA well enough – more of this model development should rest at EMC. EMC is the connective tissue between the global ocean research modeling and weather service prediction. The National Ocean Service will want to parallel these efforts so that NOAA gets all the wealth and benefit from the National Ocean Services past experience in regional wave, inundation and current forecasting. Tracking parallel skill metrics, side-by-side for the developing global system and the present regional systems is required to guide implementation and transition strategies.

As part of the planned activities, it will be critical to build a single and efficient data pipeline and model-ready archive of observations gathered from various platforms and networks (ships, floats, satellites, gliders, etc.). For best use in ocean assimilations, state estimates and simulations, the data should be harmonized, standardized, integrated and assimilated into a single and well documented archive, which is updated regularly as delayed-mode data can replace real-time versions. This archive would then be the basis of producing multidecadal gridded observational reanalyzes (like those produced for the atmosphere e.g., ECMWF Re-analysis, ERA). This product would then allow ocean model and Earth system model simulations to be initialized (similar to weather) to make short-term and seasonal predictions. Reanalyzes and/or state estimates provide improved initial conditions for less uncertain short-term and seasonal predictions. They are also a valuable service used across academia for research, as well as industry for many applications such as offshore structure design, pollution control planning, etc.



Caption: The plan for the OneArgo Network includes 2500 Core Floats, 1000 BGC Floats, and 1200 Deep Floats (from: https://argo.ucsd.edu/oneargo/)

With the data assimilation capability required for the reanalysis and prediction services, plans should include carrying out regular observing system simulation experiments (OSSEs) to probe the efficacy and value of various observing system networks and elements. OSSEs will ultimately ensure a robust and efficient observing system. For example, such OSSEs will assess the utility of nationwide shallow-water autonomous platforms (like gliders) for physical and biogeochemical measurements for coastal oceans and under-ice, ship surveys, unmanned surface vehicles, moored systems, satellite data streams and will ensure the efficient design of the OneArgo network, which includes deep and biogeochemical floats.

Recommendation #4: Gather links to products into a single 'ocean portal' where products are easily locatable and/or discoverable (from the NOAA home page), documented, accessible and downloadable (with machine to machine services), and including the input observations. Having an ocean product portal facilitates accessibility and value of both observations and model related products which better serves US interests.

To make the existing and new ocean services findable, we suggest a new easily found landing page where ocean products and services are all described and download sites are linked (as a catalog - a good example is the Copernicus Marine and Environmental Monitoring Service (CMEMS): https://marine.copernicus.eu/).

Ideally there should be a uniformity of output formats, good documentation of skill assessments, upgrades and improvements. In addition, publishing the data archives that underpin the services is also highly valuable to the community, particularly academic partners that might be collaborating on system enhancements.

Conclusions:

The US community needs ocean forecasting services that are embedded in a global system that captures major ongoing climate changes. Such ocean intelligence is essential for better weather and climate readiness including Ecosystem Prediction, the Blue Economy, Weather and Climate Prediction, Coastal Hazard prediction and National Security.

Despite their distance from the oceans, better weather, seasonal and interannual predictions are also critical for inland places like the Southwest US where the trajectories of warming and hydroclimate change are largely determined by the mixing of the ocean and are critical to the health, safety, and prosperity of millions.

NOAA already has many of the elements needed to deliver a world-class global ocean reanalysis and prediction service. The generation and dissemination of a public, usable, timely, and accessible climate forecasts will give all communities the critical information they need on equal footing, without requiring additional (i.e. commercial) resources. By explicitly delineating delivery goals, responsible teams and focusing existing efforts, highly valuable services could be delivered in the near term, while the aspiration for fully coupled high resolution Earth System Prediction is pursued.