

Toward a Marine Ecological Forecasting System

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Abstract- With access to growing streams of data from monitoring and observing networks, expanding computing power, and increasing model sophistication, ecological forecasting is moving from research realm to proactive management application. While many operational forecasting efforts focus on predicting the physical environment (e.g., precipitation, tides, and runoff forecasts), efforts are accelerating toward development of more routine and authoritative ecological forecasts. Operational ecological forecasting requires a new era in transdisciplinary science and collaboration among stakeholders in such areas as meteorology, hydrology, climatology, oceanography, data assimilation, marine research and technology development, resource management, spatially planning, and environmental modeling. As our scientific understanding of ecosystem structure and function have matured the ability to provide probabilistic forecasts is becoming viable for a number of critical coastal environment, health, and safety issues (e.g., harmful algal blooms, dissolved oxygen concentration, water quality/beach closure, coral bleaching, living resource distribution, and pathogen progression). An operational ecological forecasting system depends upon the assimilation of high quality data into models, including real time in situ and remote satellite observations, air-sea forcing fields, nutrient fluxes, end-to-end food webs, weather and climate reanalysis and other historical data. While many data assimilation methods have been developed and research results demonstrated over the last decade, for marine ecological data and modeling, data assimilation remains limited. Improved models and additional high quality data (in space and time) are necessary to ensure that sensors, instrumented platforms and innovative marine technology provide a full suite of capabilities. The operational concept must draw on standards for data integration and communications, and platform interoperability to ensure optimal use of core regional variables. It is envisioned that model development will be collaborative and community based, optimizing a mix of technologies from national centers and regional networks as well as academia, industry, tribal communities, and other partners. This paper will discuss steps towards a national marine ecological forecasting system that will operate a broad suite of ecological forecasts to better serve the Nation's needs.

I. INTRODUCTION

A. Society Depends on Ecological Forecasts

Ecological forecasts – the prediction of the impacts of physical, chemical, biological, and human induced change on ecosystems and their components – are at the cornerstone of the ability to protect lives and property, enhance economic security, and meet its stewardship mandates [1-3]. Each year, U.S. ecosystems provide over \$227 billion in added value to the U.S. economy through goods and services. Great Lakes, coastal and marine ecosystems, in particular, provide a vast array of seafood, tourism, and recreational benefits as well as protection from hazards and a potential source of life saving pharmaceuticals and renewable energy. These important ecosystems can also directly impact human health from

exposure to contaminated water or food. Protecting and managing ecosystems is critical to the Nation's economy and its people's quality of life. Sustaining productive ecosystems, and restoring damaged ones, depends on the ability to understand and predict with confidence the impacts of human activities and natural processes on those systems and to forecast ecological change.

The American public and coastal managers are increasingly demanding early warning of environmental variability and changes so that actions can be taken to save lives, promote coastal community resilience, and to sustain ocean and coastal ecosystems and their economic benefits. Forecasting the probability and thresholds of ecosystem threat are needed to mitigate disasters and adapt to long term change. Coastal managers are routinely faced with large-scale, complex issues requiring the integration and translation of multiple sources of information. They in turn, must apply this knowledge to predict the future impacts of management and policy decisions on people and the environment. For example, the National Environmental Policy Act (NEPA) requires the use of forecast scenarios and projections in selecting preferred alternatives for any contemplated federal action affecting the human environment [4]. Marine ecological forecasts are tools that provide a mechanism to focus research and to translate science into management applications to address our Nation's most pressing environmental issues.

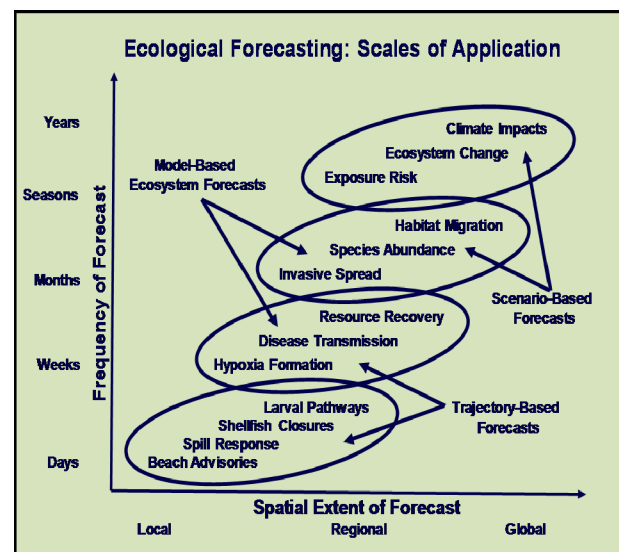


Figure 1. Management applications of ecological forecasts at representative spatial and temporal scales.

Report Documentation Page		Form Approved OMB No. 0704-0188
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.		
1. REPORT DATE JUN 2010	2. REPORT TYPE N/A	3. DATES COVERED -
4. TITLE AND SUBTITLE Toward a Marine Ecological Forecasting System		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER	
	5e. TASK NUMBER	
	5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Oceanographic and Atmospheric Administration Silver Spring, MD 20878 USA		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited		
13. SUPPLEMENTARY NOTES See also ADM202806. Proceedings of the Oceans 2009 MTS/IEEE Conference held in Biloxi, Mississippi on 26-29 October 2009. U.S. Government or Federal Purpose Rights License., The original document contains color images.		

14. ABSTRACT

With access to growing streams of data from monitoring and observing networks, expanding computing power, and increasing model sophistication, ecological forecasting is moving from research realm to proactive management application. While many operational forecasting efforts focus on predicting the physical environment (e.g., precipitation, tides, and runoff forecasts), efforts are accelerating toward development of more routine and authoritative ecological forecasts. Operational ecological forecasting requires a new era in transdisciplinary science and collaboration among stakeholders in such areas as meteorology, hydrology, climatology, oceanography, data assimilation, marine research and technology development, resource management, spatially planning, and environmental modeling. As our scientific understanding of ecosystem structure and function have matured the ability to provide probabilistic forecasts is becoming viable for a number of critical coastal environment, health, and safety issues (e.g., harmful algal blooms, dissolved oxygen concentration, water quality/beach closure, coral bleaching, living resource distribution, and pathogen progression). An operational ecological forecasting system depends upon the assimilation of high quality data into models, including real time in situ and remote satellite observations, air-sea forcing fields, nutrient fluxes, end-to-end food webs, weather and climate reanalysis and other historical data. While many data assimilation methods have been developed and research results demonstrated over the last decade, for marine ecological data and modeling, data assimilation remains limited. Improved models and additional high quality data (in space and time) are necessary to ensure that sensors, instrumented platforms and innovative marine technology provide a full suite of capabilities. The operational concept must draw on standards for data integration and communications, and platform interoperability to ensure optimal use of core regional variables. It is envisioned that model development will be collaborative and community based, optimizing a mix of technologies from national centers and regional networks as well as academia, industry, tribal communities, and other partners. This paper will discuss steps towards a national marine ecological forecasting system that will operate a broad suite of ecological forecasts to better serve the Nations needs.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT

unclassified

b. ABSTRACT

unclassified

c. THIS PAGE

unclassified17. LIMITATION OF
ABSTRACT**SAR**18. NUMBER
OF PAGES**6**19a. NAME OF
RESPONSIBLE PERSON

B. Marine Ecological Forecasting

Marine ecological forecasts cover a wide range of time and space scales and can serve a wide variety of users (Fig.1). These forecasts can improve ecosystem health and coastal management by enabling planning and policy decisions to move from a reactive to a proactive mode. In much the same way that a weather or economic forecast can help society prepare for future contingencies, an ecological forecast helps managers make informed decisions regarding alternative management scenarios or to answer “what if” questions about the ocean and coastal environments. Using these forecasts, they can select the best options and take the appropriate steps to better manage the Nation’s coastal resources and to protect human health.

NOAA is already required by mandate to forecast weather, climate, tides, fishery stocks, and recovery of protected species and, as such, has a long history of forecasting dating back to the beginning of NOAA’s ocean and weather services. While many of these efforts focus on predicting the physical environment (e.g., precipitation, tides, wind), over the past several decades, NOAA has been accelerating progress toward development of operational forecasts and forecast products to address its coastal stewardship, marine hazard reduction, and fishery mandates. As our scientific understanding of ecosystem structure and function have matured, along with advances in observational, modeling and computational power, the ability to demonstrate these ecological forecasts is now a reality for a number of critical coastal environment, health, and resource issues on several different time and space scales (e.g., harmful algal blooms, dissolved oxygen concentration (hypoxia), water quality/beach closures, coral bleaching, living resource distribution, pathogen progression, habitat protection, fisheries). Some of these require a dynamic physical model, while some do not. Examples here are not meant to be exhaustive, but illustrative of the types of issues to which ecological forecasts can apply and the benefits of collaboration toward a marine ecological forecasting system.

Forecasting Harmful Algal Blooms (HABs)

Algal blooms occur in estuarine, marine and freshwater where local, offshore and upstream forcing can promote the rapid growth and accumulation of microorganisms in the water column. Some blooms are associated with the production of natural toxins, depletion of dissolved oxygen or other harmful effects, and are generally described as harmful algal blooms (HABs). A prototype forecasting system for HAB disasters relies on monitoring and observation, early detection, data management, runs of hydrodynamic and biological-physical models, preparedness and analysis, and timely dissemination of information and warnings. Certain algae species result in discoloration of the surface water. Blooms of the toxic dinoflagellate *Karenia brevis* are commonly known as “red tides” off the coast of Florida and cause wildlife mortalities among marine species of fish, birds, mammals and other organisms. These blooms are responsible for serious public health problems and shellfish harvesting closures in the Gulf of

Mexico every year. NOAA currently provides a forecast for the development, persistence, movement, and landfall of harmful algal blooms in the eastern portion of the Gulf of Mexico to help coastal resource managers decide where to focus their sampling efforts and prepare for these blooms. The system uses satellite “ocean color” imagery (chlorophyll absorption, turbidity, reflectance, fluorescence), weather buoys (wind, temperature) and ocean current sensing, and field measurements (HAB presence and concentration) to provide forecasts accessible at a NOAA website during HAB season [5]. In addition, a Harmful Algal Bloom Bulletin is sent twice a week via e-mail to registered users in coastal resource management. Advance warning of HAB events and their potential landfall allows better management of recreational activities and natural resources to avoid deleterious effects. Authoritative and operational forecasting are important because threat levels suggesting impacts may prompt local officials or organizations to close beaches, issue health warnings, or declare commercial fishery failure. Forecast scenarios guide action plans for disaster prevention and planning. Ongoing improvements rely on enduring research and educational partnerships.

In April 2009, NOAA-supported partners at Woods Hole Oceanographic Institute and North Carolina State University released an experimental “advisory” that predicted a moderately large New England red tide, or *Alexandrium* bloom [6]. It should be noted that these types of experimental predictions are not official forecasts, and it is up to state, local or other designated official agencies and organizations to issue local warnings and forecasts. *Alexandrium* blooms are a concern because they represent recurring seasonal threats to lives and livelihoods by producing a potent toxin that accumulates in nearshore and offshore shellfish, and can cause serious illness in humans who eat contaminated shellfish. The extent to which the predicted bloom would make landfall and affect coastal resources was largely depend on the wind patterns and response of freshwater plumes. By late June, severe weather and northeast winds along the coast of Maine concentrated *Alexandrium* cells inshore, resulting in a shutdown of virtually all shellfish beds in coastal Maine in early July due to high levels of paralytic shellfish poisoning (PSP) toxins. The advisories relied on computer model solutions initiated from abundance maps of cysts (the seed-like stage of the algae’s life cycle) collected in previous years, with germination, growth, and transport of the toxic cells driven by physical circulation and biological models [7]. Going beyond climatology into the realm of forecasting, the collaboration tested data assimilation techniques. Physical circulation model included multiple nested high resolution Regional Ocean Modeling System (ROMS) of about 1 km resolution in Gulf of Maine (brining in deep ocean influences), data assimilation of satellite sea surface temperature (SST), semidiurnal and diurnal tidal forcing from sea level gauges (M2, S2, N2, K2, K1, O1, Q1, 6-hourly wind and heat fluxes from NOAA’s National Center for Environmental Prediction (NCEP) National

Operational Modal Archive Distribution System (NOMADS, at 35 km resolution), coastal river runoff data from US Geological Survey gauges, and initial conditions and open boundary conditions from large-scale parent model (basin scale Hybrid Coordinate Ocean Model, HYCOM). Related observations include fixed and mobile sampling systems such as moored and drifting buoys, platforms, autonomous underwater vehicles (AUV)/gliders, and ships. On-board Acoustic Doppler Current Profiles (ADCP) are used for underwater currents, weather buoys and piers for wind speed, and various sensors measure current, characteristic hydrography (temperature and salinity), HAB presence and concentration. The *Alexandrium* model included red-tide population dynamics (growth and mortality), cyst maps, monthly climatological nutrient fields, and temperature-parameterized mortality rates from academic contributions, and solar radiation from NCEP.

HABs are a regional problem and the maturity of the science and technology to produce forecasts and probabilistic information vary from region to region. As an example, daily nowcasts illustrating the relative abundance of *Karlodinium veneticum* (previously *K. micrum*), a HAB species, in the Chesapeake Bay are currently generated using hydrodynamic models and applying a statistical/neural network habitat model to satellite data. Estimates of ambient salinity and temperature are simulated by ROMS, by forcing it with near-real time input, such as observed freshwater inflows, winds and water levels. Fresh water inflows are provided from NOAA's Hydrologic Office and water levels by the USGS. Other key biogeochemical and bio-optical variables include dissolved oxygen, carbon, and nitrogen, suspended sediments, and light penetration. Experimental nowcasts and 3-day forecasts of relative abundance are generated daily and posted to a Web site [8]. Plans are underway to develop and implement an operational system and assimilate additional data sources that will nowcast and forecast the likelihood of blooms of this and other HAB species in Chesapeake Bay and its tidal tributaries.

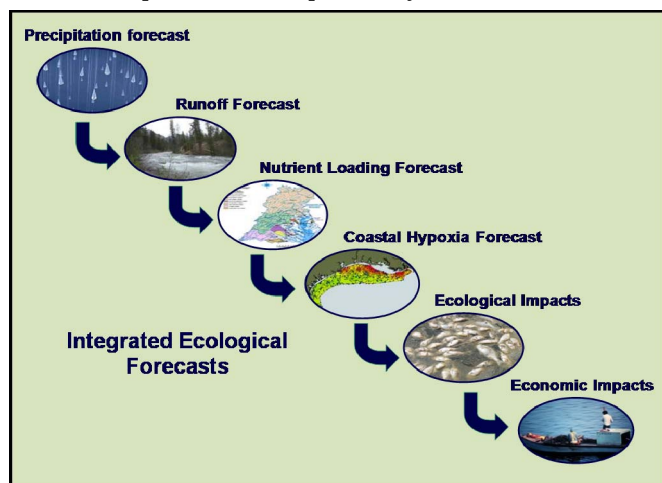


Figure 2. Ecosystem based management issues such as hypoxia can only be addressed by developing integrated ecological forecasts

Forecasting Water Quality and Beach Closures

NOAA's Great Lakes Environmental Research Laboratory (GLERL) has developed predictive hydrodynamic models based on existing NOAA models of atmospheric forcing, precipitation, runoff, wind speed and direction, waves, water currents, air and surface temperatures, and hydrodynamic circulation in the Great Lakes [9]. Weather data are acquired from the National Weather Service through the NOAAPORT satellite dissemination network and objectively analyzed in near real-time to drive the nowcasts. NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) and NCEP operate these models on a routine basis and make the output available for use in ecological forecasts. One application is a beach quality forecasting prototype to forecast hourly changes in the plume of a tributary bringing *E. coli* bacterium into Lake Michigan. The tributary forecasts will be combined with traditional statistically-based beach quality forecasting models to provide more accurate predictions of beach water quality up to 48 hours in advance. Two beaches in Lake Michigan have been selected for initial implementation.

Forecasting Coral Bleaching in relation to Ocean Temperatures

The coral reef is a unique and very rich ecosystem which supports a vast array of animal and plant species. Corals form the structural and ecological foundation of the reef system, and consist of a symbiotic relationship between the coral animal (polyp) and associated algae (zooxanthellae). When stressed, corals can expel their zooxanthellae, and appear bleached. This phenomenon has been related to elevated water temperatures. The NOAA's Center for Satellite Applications and Research (STAR) Coral Reef Watch uses satellite sea surface temperature (SST) data to alert managers and scientists around the world of the risk of seasonal coral bleaching [10]. They are also developing a bleaching prediction tool based on a SST forecast model developed by NOAA's Earth System Research Laboratory to provide an outlook ranging from one week to three months in advance. The bleaching outlook is available as an experimental product and is expected to provide coral reef managers and researchers critical information on the timing and locations of large-scale bleaching events.

Forecasting Pink Salmon Harvest in Southeast Alaska

Pink salmon support an important commercial fishery in Southeast Alaska (SEAK), with an annual ex-vessel value of around \$20 million. The National Marine Fisheries Service (NMFS) Auke Bay Laboratory has been using juvenile pink salmon catch and associated environmental data such as water temperatures in May, the state of El Niño Southern Oscillation (ENSO) during the prior year, and the depth of the surface ocean mixed layer to forecast adult pink salmon harvest in SEAK since 2004. Forecasts are posted on the Auk Bay Lab website [11], and are undergoing rigorous evaluation and testing for accuracy and utility.

C. The Need for Change

The NOAA user community spans living resource managers, coastal zone managers, emergency response managers, municipal planners, public health practitioners and a host of other stakeholders. These users are demanding timely, spatially explicit, and reliable NOAA ecological forecast products and services with a high degree of skill, availability, and usability. Much of this need comes from the fact that ecosystem-based management is not possible without ecological forecasts and probabilistic guidance. In fact, addressing holistic ecosystem management demands a suite of complex, often linked, models, tools, and technology to provide a credible scientific basis for decision making (e.g., linkage of airshed, watershed, water quality, and fisheries models). To achieve this full capability for ecosystem-based management, an operational ecological forecasting system (Fig. 2) needs to be established that will produce transdisciplinary integrated ecological forecasts. Current imperatives, such as the 2009 Chesapeake Bay Executive Order [12] and Great Lakes Restoration Initiative [13], also require ecological prediction capabilities to be fully successful.

D. The Solution

Marine ecological forecasts naturally should integrate across traditional organizational, scientific and service boundaries, and leverage existing investments in infrastructure, knowledge, and partnerships. The establishment of this capability would also be a focus for sustained operations and a driver for transitioning research results. As such, a disciplined life-cycle approach toward establishing a national marine ecological forecasting system (Fig. 3) is required. To achieve this goal, collaboration is needed to build on its existing environmental observation, modeling and prediction capabilities to build a system that will be transdisciplinary by design, provide a common prediction backbone, and address specific user needs.

Many of the individual components necessary to build the national forecasting system are already within current regional

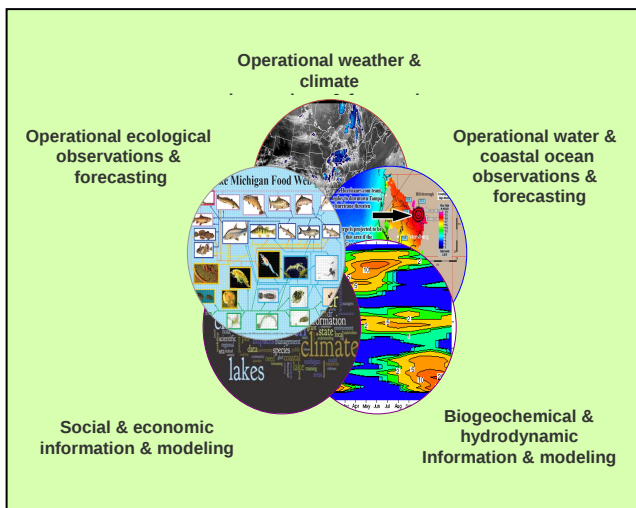


Figure 3. Components of the Marine Ecological Forecasting system.

capabilities of NOAA or can be strengthened through collaborative relationships with other agencies and institutions (Fig. 4). With a national system in place, society will have timely and trusted ecological forecasts to address pressing marine and coastal issues impacting human lives, living resources, and coastal development.

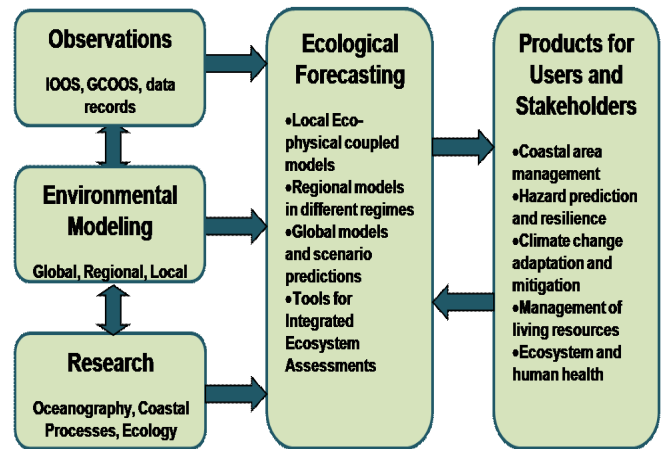


Figure 4. Notional Framework for a Great Lakes, Coastal and Marine Ecological Forecasting System.

NOAA is currently evaluating the path forward and has identified three strategic imperatives: i.) enhanced observations and more effective utilization of existing information, ii) increased model development and integration, and iii) sustained and dedicated operational and distribution capability.

II. OBSERVATION AND DATA EXPLOITATION

An operational marine ecological forecasting system depends upon the assimilation of high quality data into models, including real time observations, air-sea forcing fields, nutrient fluxes, end-to-end food webs, and historical data. Considerable observational data will be necessary and NOAA will leverage partnerships to ensure that platforms and networks provide a full suite of interoperable capabilities. The forecast system will rely on standardized data integration frameworks for optimal use of core regional variables (including currents, temperature, salinity, water level, winds, waves, and ocean color). It is anticipated that many issues will be addressed through coordination and alignment with the Integrated Ocean Observing System (IOOS) and various local, regional and global observing networks. Observation and data exploitation requires:

- Acquiring a core set of observations and measurements (physical, chemical, biological) over consistent time scales and resolutions;
- Integrating observational technology and information acquired through the global earth observing system of systems;
- Integrating transdisciplinary observational science, retrospective analysis, field experiments, and measurement methods;
- Improving understanding of key ecological and biological processes relevant to models;

- Addressing shortfalls in operation, maintenance, and modernization ageing laboratory and observation system infrastructure;
- Increasing observation and measurement in areas under sampled, and support for the continued collecting of data for existing long time series of biological variables even if the original program collecting the data has ended;
- Improving data assimilation, from both existing and planned observational systems, and Observational System Simulation Experiments (OSSEs) for model-based analysis;
- Enhancing data assembly, including quality control, processing and stewardship of real-time and delayed-mode data flow;
- Enhancing marine ecological data management infrastructure;
- Improving calibration and validation of observations;
- Improving ability to carry out research on ecological and biogeochemical process with particular relevance to lower food webs; and
- Using observations for model verification, testing, and accreditation.

Comprehensive monitoring and observation in marine and coastal ocean areas must exploit innovative marine science and technology. This will include cutting-edge advances ranging from genomic sensors and nanotechnology to improved coastal imaging with unmanned aerial vehicles and future-generation satellites. As an example, improved satellite sensors and platforms could provide data of high spatial, temporal, and spectral resolution for synoptic measures of coastal zone that, in conjunction with *in situ* monitoring and observation would be used for validation of coupled biological-physical models and to initialize them for regional ecological forecasting. An operational system based on a data-assimilative approach assumes that adequate observational capacity and coverage is available. The design and operation of the necessary monitoring and observation networks will benefit from Observational System Simulation Experiments (OSSEs). Requirements and strategies need to be refined for developing remote imaging useful for studies of features that require better than 1 km resolution and extend over large areas, but of sufficient resolution and frequency for studies of fronts, river plumes, red tides or other dynamic features. Emerging opportunities for additional data assimilation may include ensemble wind fields through expanded deployment and use of coastal HF radar (CODAR). Such radar can provide radial surface current/velocity maps to improve velocity forecasts and velocity at depth for evaluating HAB trajectories.

With respect to an ecosystem forecast system, it is clear that physical parameters constitute a significant part of the forecast process (e.g., solar radiation, temperature, salinity, mixing, surface conditions, currents, transport/fate, etc.) in that they affect the biogeochemical factors of an ecosystem. In general, the modeling physical parameters are relatively mature. It is

acknowledged that a significant challenge to using ecological forecasting for management is the integration of the biogeochemical factors with the physical parameters. Challenges include mobility (biological parameters), observation availability, and variability (e.g. biological and chemical parameters associated with nutrients and sediments). Some may consider the maturity of the biogeochemical modeling to be inversely related to its complexity, such as the number of parameters and trophic levels modeled.

In general, for improved and trusted forecast performance the initial conditions from which the model begins iterating need to be as accurate as possible. The key requirements are consistent and regular observations, especially for biogeochemical parameters, a trusted forecast model, and sensing of non-physical ecosystem parameters. Hence, data assimilation for analysis schemes will be an imperative for quantitative evaluation of sampling strategies and forecast skill in selected management applications. In addition, the model(s) must be developed to assimilate the observations provided in an optimal manner. For management applications subject to rapid change and requiring correspondingly frequent observations, data can be assimilated for subsequent iterations and updates. In operational ecological forecasting, data assimilation will provide confidence to inform management decisions such as those associated with the determination of transport and fate of nutrients, contaminants, sediments, and anoxic conditions. When dealing with an advective situation, the physical parameters play a dominant role; consequently the assimilation of physical observations will contribute to more accurate forecasts. Warning managers of ecosystem changes such as harmful algal blooms, primary productivity, and anoxic zones, resulting from quantitatively-measurable biogeochemical parameters (e.g., chlorophyll, nutrients, oxygen) are becoming tractable modeling problems that will be facilitated through data assimilation.

III. MODEL DEVELOPMENT AND INTEGRATION

NOAA is the national leader in operational environmental prediction. It has significant strengths in forecasting populations of living marine resources, and has developed forecast capabilities in weather, climate, hydrology, coastal water quality, air quality, and impacts to human health. In addition, NOAA, especially the National Marine Fisheries Service (NMFS) has viable economic and social modeling capabilities. But successful model development will need to be collaborative and community based, optimizing a mix of complementary capabilities from national centers, field offices, academics, and public-private partnerships. The use of technology such as the Earth System Modeling Framework will help enable coupling of separate models and systems. Moving toward a national marine forecast system will also necessitate a framework to exploit existing capacity and provide a physical forecasting backbone, explicitly account for uncertainty, and enable comparative studies. The conceptual approach should facilitate integrated biogeochemistry (nutrients, sediments, ocean acidification, etc.) and ecological

interactions (standing stock and rates, primary production, toxicology, population, physiology, behavior, etc.) as well as social science models. The system will advance cascading forecast models and enable fully-coupled and adaptive models. Marine model-based forecasting will require:

- Aligning temporal and spatial scales for data, models and related needs;
- Achieving consistent, verified, and acceptable levels of uncertainty;
- Identifying and validating requirements and capabilities between disciplines;
- Building capacity for adaptive modeling, visualization, and decision-tools;
- Maintaining a core set of key model parameters;
- Adopting standards and metrics for model development and skill assessment;
- Participation by scientists to ensure that the systems developed, are scientifically driven and robust;
- Promoting ensemble modeling and comparative regional studies;
- Linking meteorological, hydrological, oceanographic, biochemical, and ecosystem modeling; and
- Improving mechanics for applying results from one discipline to another.

One of the key challenges in transitioning from research toward management use is dealing with uncertainty in ecosystem models. This is an active area of development and testing using sensitivity studies, Monte Carlo and ensemble simulations. Among the elements of concern are uncertainties in multispecies and extended single species assessment models, bulk biomass (network and aggregate) and full system (ecosystem and biophysical) models. Optimizing marine ecological models to user needs requires:

- Establishing a requirements development process responsive to user needs and ecosystem risk;
- Prioritizing the product development pipeline within a common Earth System Modeling Framework (ESMF);
- Downscaling larger-scale models and output to regional and local scales;
- Establishing model metrics for regional comparisons; and
- Implementing full life-cycle product development.

IV. REGIONAL APPROACHES

Toward the national marine ecological forecasting system one path forward is adoption of a standard physical modeling backbone that would provide a consistent set of boundary conditions, including hydrology, nutrient and sediment supply from the landward side as well as open ocean fields. This approach would support regional modeling and recognize that the sensors and physical modeling backbone required may vary with the ecological problem (site) of concern. Ecological models can be either directly coupled, or can take output from the standard physical models as input for their dynamics. Interest in biologically relevant problems will provide requirements to advance physical modeling over appropriate

time and space scales dictated by ecological processes and the ecosystem of concern. In the case of complex hydrodynamics spanning large regional domains, selected applications will benefit from data assimilation to improve forecast skill. An operational system employing data-assimilative models necessitates development of marine sensor technologies, instrumentation, and observational networks with improved spatial and temporal coverage. Opportunities to incorporate genomic sensing and nanotechnology, unmanned aerial and underwater vehicles, and enhanced coastal water satellite imaging will also revolutionize ecological forecasting. By coupling validated ecological and biogeochemical models with real time weather forecast and assimilation of real-time marine and coastal-ocean data, it will be possible to provide more accurate and relevant operational forecasts of the location, time, and duration of ecosystems hazards and long term threats. There remain many challenges moving toward establishing and operating a national marine ecological forecasting system for management application; however, the marine science and technology community is in a strong position to make major advances.

ACKNOWLEDGMENT

D.G. thanks E. Bayler of NOAA NESDIS, for discussion of satellite data assimilation and modeling.

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