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Advancing coastal ocean modeling, analysis, and prediction for the U.S. Integrated Ocean Observing System

John Wilkin[a], Leslie Rosenfeld[b], Arthur Allen[c], Rebecca Baltes[d], Antonio Baptista[e], Ruoying He[f], Patrick Hogan[g], Alexander Kurapov[h], Avichal Mehra[i], Josie Quintrell[j], David Schwab[k], Richard Signell[l] and Jane Smith[m]

[a] Marine and Coastal Sciences, Rutgers, The State University of New Jersey, USA

[b] CeNCOOS, MBARI, Moss Landing, California, USA

[c] Office of Search and Rescue, U.S. Coast Guard, New London, Connecticut, USA

[d] U.S. IOOS Program Office, Silver Spring, Maryland, USA

[e] Center for Coastal Margin Observation & Prediction, Oregon Health & Science University, Portland, Oregon, USA

[f] Marine, Earth and Atmospheric Sciences, North Carolina State University, USA

[g] U.S. Naval Research Laboratory Stennis Space Center, Mississippi, USA

[h] College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA

[i] Environmental Modeling Center, National Centers for Environmental Prediction, NOAA/National Weather Service, College Park, Maryland, USA

[j] IOOS Association, Harpswell, Maine, USA

[k] University of Michigan Water Center, Ann Arbor, Michigan, USA

[l] U.S. Geological Survey, Woods Hole, Massachusetts, USA

[m] Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, Mississippi, USA

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Abstract

This paper outlines strategies that would advance coastal ocean modeling, analysis and prediction as a complement to the observing and data management activities of the coastal components of the U.S. Integrated Ocean Observing System (IOOS®) and the Global Ocean Observing System (GOOS). The views presented are the consensus of a group of U.S. based researchers with a cross-section of coastal oceanography and ocean modeling expertise and community representation drawn from Regional and U.S. Federal partners in IOOS. Priorities for research and development are suggested that would enhance the value of IOOS observations through model-based synthesis, deliver better model-based information products, and assist the design, evaluation and operation of the observing system itself. The proposed priorities are: model coupling, data assimilation, nearshore processes, cyberinfrastructure and model skill assessment, modeling for observing system design, evaluation and operation, ensemble prediction, and fast predictors. Approaches are suggested to accomplish substantial progress in a 3-8 year timeframe. In addition, the group proposes steps to promote collaboration between research and operations groups in Regional Associations, U.S. Federal Agencies, and the international ocean research community in general that would foster coordination on scientific and technical issues, and strengthen federal-academic partnerships benefiting IOOS stakeholders and end users.

Keywords: coastal ocean; modeling; forecasting; real-time; operational; data assimilation; cyberinfrastructure; skill assessment; model coupling; observing system design; GOOS

1. Introduction

The United States Integrated Ocean Observing System (IOOS®) is a federal, regional, and private-sector partnership working to enhance the collection, delivery, use and prediction of ocean information. The coastal component of IOOS (Coastal IOOS) involves 17 federal agencies and 11 Regional Associations (RA) with the RAs having primary responsibility for non-federal observations within their respective regions, for integrating those assets with the federal system, and for delivering timely and effective products to meet regional user needs in the Great Lakes, coastal ocean and adjacent deep sea of the U.S. EEZ (Price and Rosenfeld 2012).

Real-time observations by Coastal IOOS capture the state of the ocean at particular locations and times, and long-term monitoring enables the detection of climate variability and trends. But measurements alone are not enough. Numerical modeling allows for interpolation, interpretation, and prediction of the environment, and combining data with models aids the conversion of observations into meaningful information products. Sustained development of modeling capabilities, the application of models to enhancing the design and operation of observing systems, and effective data management and communication, are vital components of a truly integrated system.

On basin and global scales, modeling research and development for IOOS is coordinated through collaborative agreements between federal agencies (notably NOAA and U.S. Navy) and partnerships between federal, academic and international groups through initiatives such as the Global Ocean Data Assimilation Experiment (GODAE) OceanView Science Team (GOVST 2014; Bell et al. 2015) and its specialist Task Teams. While RAs already have regional modeling capabilities and are active in coastal model development, overall coordination of the Coastal IOOS modeling subsystem is less mature. The call made by the IOOS Modeling and Analysis Steering Team (MAST) (Ocean.US 2008) for a high level of sustained coordination remains largely unmet. For example, while there has been progress on aspects of coastal modeling through the IOOS Coastal and Ocean Modeling Testbed, there have been no pan-regional efforts in which groups using differing methodologies have analyzed common data sets and inter-compared model-based coastal ocean state estimates using standardized metrics in the way that GOVST has promoted such efforts for global systems.

The National Ocean Policy Implementation Plan (National Ocean Council 2013) echoed this call for coordination, and in response the U.S. Interagency Ocean Observation Committee (IOOC) convened a Modeling Task Team (MTT) and workshop in 2014 to propose strategies and priorities for advancing coastal modeling capabilities for IOOS. The workshop brought together expertise and community representation from the RAs and federal partners in IOOS, including agencies for which applied coastal ocean modeling is vital to advancing their capacity to meet mandated responsibilities.

This paper presents the consensus of the MTT on priority areas for coastal modeling research and development in the next 3-8 years, approaches to accelerating the integration of models with the observing and data management subsystems of IOOS, and promoting research and operational collaboration.

2. Background

2.1 Integration of IOOS subsystems and partner coordination

IOOS is composed of three major subsystems: observations, modeling, and data management and communications (DMAC). Integration of these components is required to achieve an accurate representation of the ocean state because models without observations give at best a virtual representation of the ocean state, while without models the observations provide an incomplete picture due to their inevitable scarcity. Modeling provides the predictive capability that is vital to many user requirements. DMAC infrastructure facilitates this integration and dissemination of the output to the user community.

In Coastal IOOS, the subsystems are integrated to varying degree within each Region, but at the national level they operate largely separately. Growing coordination between DMAC and the observing subsystem at the national level is principally *within* individual observing technologies, and not yet *across* technologies in ways that centralize data access by ocean variable. This complicates discovery of data for model assimilation, forcing, and validation, and the implementation of re-locatable and interoperable modeling systems. Additionally, it divorces discussions on strategies for observational data acquisition, management, archiving and reporting from those for modeling, which impedes the use of models for improving the observing system.

Traditionally, federal agencies were the primary organizations implementing U.S. operational models (Federal Backbone (FB) systems), while academic institutions concentrated on process studies and model development and experimentation. Now, many non-federal agencies routinely run real-time modeling systems. Though these systems might not meet federal requirements for operational robustness and reliability, nevertheless many user communities find the immediate environmental information served by RA models to be valuable. This may be because the systems are superior in local skill, or because they offer regional products, higher resolution, or local expertise that are not matched by FB systems. A need has grown to clarify the roles of federal and non-federal modeling groups, enhance the communication among them, and further explore ways to incorporate RA efforts into FB systems.

To better coordinate coastal modeling across the FB and RAs to make modeling research and development more responsive to user requirements, the MTT deliberated on procedures that could address common needs, encourage efficiencies, and make two-way connections to end users and stakeholders. It was concluded that the U.S. coastal modeling community should consider empaneling two consultative and advisory groups to these ends, possible formats for which are presented in Section 5.

2.2 IOOS coastal modeling objectives

In a synthesis of RA build-out plans for the coming decade, Price and Rosenfeld (2012) noted 27 products or services desired to meet stakeholder needs in the areas of marine operations; coastal, beach and nearshore hazards; water quality; ecosystems and fisheries; and long-term change and decadal variability. Two-thirds of these products and services required results from models. The synthesis identified, therefore, that it was a core requirement across all regions that modeling capabilities be developed to deliver analyses and forecasts, on appropriate time and space scales, for ocean circulation, waves, inundation, weather, water quality and ecosystems.

The principal goal of IOOS coastal modeling can therefore be summarized as enhancing the value of observations through model-based synthesis and data assimilation to provide robust and reliable past, present, and forecasted ocean conditions to underpin user products. A second, important goal is to apply models to observing system design and operation to help optimize the observational suite and thereby further enhance model-based outputs.

With these goals and requirements in mind, the MTT members and workshop participants applied their technical expertise and regional experience to consider how to advance modeling capabilities for coastal IOOS. The group was steered by a charge to the MTT to consider the full spectrum of model uses, emerging modeling technologies, anticipated technical and scientific challenges, and how to sustain continuous improvement in model skill and development of new and enhanced model-based products.

Guided by this charge, the MTT identified seven topic areas as priorities for concerted community effort in research and development over the next 3-8 years.

1. **Model coupling,** emphasizing improvements to ocean state realism through coupling technique developments applicable to ocean circulation, ice, air, ecosystem, wave and other components

2. **Data assimilation (DA),** including research and development on DA methods, and DA-system inter-comparison frameworks emphasizing use of the full suite of IOOS observations, including ecological data

3. **Nearshore processes,** linking ocean analyses with models of surface and groundwater flow, wetlands, estuaries, surf zone dynamics, coastal geomorphology and sediment transport, discharge and plume dispersion, pathogens, toxins, harmful algae, and biogeochemistry

4. **Cyberinfrastructure and model skill assessment**, including development of a pan-regional IOOS data portal built on standardized web services, and comprehensive tools and benchmarks for interoperability, modeling metrics, and skill assessment

5. **Modeling for observing system design, evaluation and operation**, using observing system simulations, network gap analyses, sensitivity analysis, and prototyping the cycle of designing, operating, and evaluating a coastal observing system

6. **Ensemble prediction**, developing probabilistic prediction methods for weather, inundation, navigation, and extreme events, and delivering quantitative uncertainty estimates for models and products

7. **Fast predictors**, using dynamical models and observations to train specialized models for targeted applications

All of these topics have emerging communities of practice within the field of coastal ocean modeling. The first three will accelerate progress on data assimilative and coupled physical-ecological models for estimating ocean state conditions relevant to a variety of ocean users. Areas 4 and 5 enhance the integration of modeling with IOOS Observing and DMAC subsystems, while the last two topics address how modeling systems can be used to analyze uncertainty and explore scenarios. These topics are expanded upon in Section 3.

2.3 Workforce development

It is difficult to find knowledgeable, experienced personnel to fill all the positions available in the U.S. for ocean modelers, especially in the realms of model coupling and advanced applied data assimilation. In their 10-year build-out plans developed in 2011, the RAs estimated that in total they would need the equivalent of about 100 personnel to operate the modeling part of the regional IOOS enterprise (Price and Rosenfeld 2012). This includes operators, forecasters, product developers, and research and development personnel. There is an unmet need to develop intellectual capacity in this area.

Beyond coordinated, targeted research and development, it is therefore also important that students and early career scientists be entrained into these efforts to ensure the evolution of a skilled workforce that can sustain applied coastal modeling in the long term.

3. Scientific developments in coastal modeling capabilities

The priorities for coastal modeling research and development introduced above are not specific to a given model, but have relevance across a variety of models and applications and should facilitate integration of models, observations, and data management. They were chosen by the MTT not to address needs of specific user communities, but to deliver fundamental capabilities that will underpin expanded, comprehensive use of the full suite of IOOS observations to realize the objective of an integrated coastal modeling and observation system.

Under each topic we present the MTT consensus as a set of recommended actionable tasks that are tractable and, if pursued by the community, would lead to substantive progress on expanding capabilities in the short-to-medium term.

3.1 Model coupling

Greater dynamical complexity in the coastal ocean’s response to forcing can be achieved by directly coupling component models for ocean, atmosphere, and waves, and several RA groups have demonstrated the emergence of important feedbacks when 2-way interactions are included (e.g. Olbarietta et al. 2012). Resolving fast time scales and short length scales can impact processes in coastal weather prediction (Chambers et al. 2014), and accurate coupling requires attention to consistency and frequency of exchange of fluxes of heat, momentum and mass (e.g. Warner et al. 2010). Beyond ocean-atmosphere dynamics, there are important interactions with the geosphere (sediment transport, shoreline migration), biosphere (optically active ecosystem constituents; cloud condensation nuclei), and cryosphere (sea-ice and ice shelves).

In the federal agencies there is some movement toward standardization of model coupling architecture, such as the National Unified Operational Prediction Capability (NUOPC) and Earth System Modeling Framework (ESMF), whereas in academia approaches are more diverse to accommodate active experimentation in coupling complexity.

Recommendations

3.1.1. Experimentation is needed in coupling earth system component models of groundwater, wetlands, surface water hydrology, geomorphology, air-sheds, ecosystems, and biogeochemistry. Efforts should include human systems that impact water, energy and ecosystem services.

3.1.2. Limitations of existing toolkits for coupling coastal land-ocean-atmosphere processes should be identified, and capabilities expanded accordingly. Where it does not compromise innovation, RA activities should anticipate transition to operations by working with toolkits supported by federal partners. Operational centers should make complementary efforts to transfer expertise to academic units, and provide a simulated operational environment for research community experimentation. Such activities would be suited to the "Center without Walls" concept (Section 4), but could commence with workshops and personnel exchanges.

3.1.3. Observational and experimental research programs should be developed that address scientific gaps in model dynamical fidelity highlighted by coupled models.

3.1.4. Enhanced cyberinfrastructure systems and tools, and added high performance computing power are required to allow experimentation with ways in which coupled systems can add to the IOOS coastal modeling enterprise.

3.2 Data Assimilation: Improving ocean state estimation through model/data synthesis

Well-configured contemporary coastal ocean models now routinely achieve a useful degree of realism. However, when run for extended time periods they may capture mesoscale variability that is accurate only in a statistical sense, with events and features at the submesoscale being significantly distorted due to the limits of predictability inherent in nonlinear dynamics. Other errors stem from approximation and parameterization of the governing equations, numerical discretization, and insufficient numerical resolution.

While every effort might be taken to increase skill, models will never be error-free. Guided by recognized successes in Numerical Weather Prediction (NWP), improvements in forecast quality can be achieved utilizing data assimilation (DA) to optimally combine observations and model estimates to derive a "best estimate" of the ocean state from which to launch a forecast. From the standpoint of mathematical and practical implementation, coastal ocean DA is challenged by the large problem size (the number of model variables to adjust), difficulties projecting surface observations to the 3-D ocean state, strong nonlinearities in the dynamics, the error of representation associated with observed dynamics absent from the model, and limited understanding of how model errors evolve.

The theoretical underpinnings of DA and the many approaches taken in practice from simple nudging through optimal interpolation to the Ensemble Kalman Filter (EnKF) and 4-dimensinal variational (4DVAR) methods need not be reviewed here. RAs have experimented with and contributed to research on many approaches, and have implemented pilot real-time DA systems that have shown skill and found users. They have also highlighted research challenges in several important areas, such as joint assimilation in coupled ocean-atmosphere-wave-ice or physical-biogeochemical models, how to better use sampling platforms like autonomous underwater vehicles, and how to retain the resolution of coastal fronts and jets amid detailed bathymetric and coastline constraints.

Recommendations

3.2.1. Facilitate adoption of all available observations into prototype DA systems by establishing a unified IOOS pan-regional data portal offering timely delivery and geospatial search and sub-setting of quality-controlled observations from all platforms in U.S. coastal waters. Beyond near real-time operation, the service should include a deep archive of past observations for multi-year retrospective re-analyses.

3.2.2. Initiate projects that compare differing DA frameworks when presented with a common analysis and prediction challenge or region, a comprehensive unified data stream, and an agreed set of performance metrics.

3.2.3. Experts from the research community should be placed into FB development environments to transition progress on new methods and best practices, while also acquainting RA researchers with the constraints of practical operational environments.

3.2.4. Emphasizing coastal ocean environments, collaborative research should be encouraged to build new capacity in ensemble and variational algorithms, observation operators, computational efficiency and scalability, the incorporation of new data types (e.g. bio-optics), and coupled systems (e.g. ocean-atmosphere-wave-ice).

3.2.5. DA methods should be introduced to water quality and ecosystem models and models of littoral and nearshore waters, including the assimilation of biogeochemical observations.

3.2.6. It should be recognized that a substantial user community exists for long retrospective re-analyses of the ocean state in support of marine living resource management and the diagnosis of coastal climate trends.

3.3 Nearshore processes

Circulation and water elevation in the nearshore zone impacts natural and built environments through coastal water quality, dispersal of pathogens and pollutants, coastline erosion, wetland and estuary ecosystems, and fisheries. Understanding and predicting these processes are important for establishing resilient, sustainable coastal communities.

Nearshore processes act on a range of time scales, from very short (wave run-up, dune over-topping) through weather time scales (storm surge, river plumes, littoral zone currents), to longer time scales that drive geomorphological change (coastal erosion, sediment deposition), and global sea level rise and human induced changes in the watershed. Biogeochemical and water quality models depend upon skillful hydrodynamic models to determine physical transport and mixing across all these scales in order to simulate eutrophication, hypoxia, algal blooms, pathogens, toxins, and sediments. But water quality models themselves also need development. Eutrophication models that simulate nutrients, biomass and oxygen in the water column and benthos may have dozens of empirical coefficients. Models of phytoplankton community dynamics, microbial pathogens, or community level responses to toxins may entail an even higher level of parameterization; rigorous calibration or even identification of dominant processes and sources of error is difficult. Aquatic ecosystem models must also consider stresses that arise from the adjacent land and air, and should not stop at some chemical endpoint but extend through flora and fauna to ecosystem services; thus coupled model developments are key to progress in this area.

Models for predicting coastal hazards have typically evolved from hydrodynamic models with features and capabilities added as required to capture key processes. Adding further sophistication will further expand computational demands and possibly render high fidelity models prohibitive for many applications. "Fast predictor" models that are trained using data and/or complex models may be more amenable to computing probabilistic products for extreme events and exploring environmental scenarios.

Recommendations

3.3.1. Nearshore water quality model development should consider multiple stressors, interaction with coastal flora and fauna, and ecosystem services. Testing and evaluation in multiple regional settings should be aimed at progress toward robust and portable models.

3.3.2. A pan-regional or national effort is required to coordinate the production of consistent physical and biogeochemical ocean boundary conditions for regional coastal models.

3.3.3. Circulation model enhancements are required for wave transformations and overland wave and water propagation (e.g. wave nonlinearities, growth and decay, swash, rip currents, and representation of reefs).

3.3.4. Improvements are required in modeling the transport of non-cohesive and mixed grain sediments from offshore bars to dunes, bluffs and cliffs, including erosion and recovery; and in modeling long-term morphological change of beaches, barrier islands, marshes and estuary shorelines as land cover changes and sea level rises.

3.3.5. Observing system simulation experiments should be pursued to determine which biogeochemical and sediment observations, and observation strategies, are more effective for constraining model skill in nearshore processes.

3.4 Cyberinfrastructure and model skill assessment

Coastal IOOS requires cyberinfrastructure standards, services and tools that enhance discovery and utilization of observations and modeling system outputs. Evolving community metadata conventions and web services for data access are complementing the development of standardized tools that enhance the efficiency of scientific analysis and the development of model-based products. But there is still significant work to be done in improving the scope and robustness of these tools, and training and documentation is needed to encourage and facilitate their widespread adoption.

To support their local stakeholders, RAs have developed portals that serve their own models, observations, and regional satellite data subsets, but the portals differ among the 11 RAs, making it difficult to aggregate collections of unique data for larger regions. A centralized catalog and catalog services providing access to *all* observations acquired by RAs and other IOOS and global observing systems on the continental shelf and in adjacent deep waters would enable greater community engagement in coastal model skill assessment and would provide a foundation for inter-comparison studies of DA models and observing system experiments.

Metrics that characterize model performance provide information on model strengths and weaknesses to spur research and development to improve model skill and robustness. Such metrics are routine in the NWP community, and GODAE has formulated metrics for mesoscale forecast systems (Hernandez et al. 2009) that offer a useful starting framework for appraising coastal models.

The short time frame for which some model outputs are retained on data servers, their partial coverage in space and time (e.g. serving only surface or daily average conditions), and the provision of analyses but not the full set of forecasts, all limit community efforts at model inter-comparison and skill assessment.

Research to Operations transitions could be accelerated if non-federal researchers had access to an experimental operational environment – a “computational sandbox” – that mimicked data streams within FB centers. Researchers could then evaluate how a prototype system performs in a setting that simulates the actual constraints on data availability (latency and quality control) in an operational center, and experiment with the impact of changes in dynamical parameterizations, algorithms, or configuration for open-source codes used in operation.

Recommendations

3.4.1. Create documentation describing best practices for managing model data using dynamic documents that are updated regularly and invite community input. Communicate these capabilities through workshops and training materials.

3.4.2. Expand the development of standardized tools and lower level utilities for popular scientific analysis software and communicate these capabilities through workshops and training materials.

3.4.3. Establish a pan-regional data portal that aggregates coastal ocean data from all RAs and national IOOS systems, deposits metadata in a geospatial database, allows standardized queries of temporal and spatial extents, keywords, and variable names, and delivers data seamlessly for both interactive scientific analysis and automated computing environments.

3.4.4. Create a parallel testing environment (computational sandbox) that enables researcher access to data streams and model configurations that simulate those within FB operational centers.

3.4.5. Engage the coastal modeling community in developing a set of model skill metrics. Initiate the routine generation and reporting of these metrics across all Coastal IOOS modeling systems.

3.5 Modeling for observing system design, evaluation and operation

Though principally a user of IOOS observations, coastal modeling also has complementary roles to play in strengthening the observing system itself. These include demonstrating how observations add skill to model-based analyses and forecasts, and contributing to the design and efficient operation of observing systems.

Sampling density and accuracy directly impact data assimilative analyses, so DA systems can be used to quantitatively appraise the information content of observation networks. Observing System Experiments (OSE) that selectively with-hold observations can examine the sensitivity of forecast skill to observation types or platforms and the density or frequency of observations. Observing System Simulation Experiments (OSSE) that sample model output to construct sets of hypothetical observations can be used to identify gaps in a network, reveal vulnerabilities to operational failures of observing elements, evaluate the potential of instruments that do not yet exist (e.g. new satellites), and to examine how analysis skill changes with quality control standards. Array mode analyses (e.g. Bennett 1990; Le Hénaff 2009) are examples of model-based approaches to identifying patterns of ocean variability that are not constrained by an observational network and whose predictability might improve with acquisition of new observations.

An extension of these methods is adaptive control of observing platforms such as autonomous underwater gliders. Model-based systems can suggest where relocatable assets might most profitably be sent to acquire independent data about under-observed regions. Moreover, predictions of the ocean current regime in which autonomous vehicles operate offer insight on a vehicle's "reachability area" (Garau et al. 2014; Wang et al. 2013) given vehicle speed and power characteristics.

Recommendation

3.5.1. DA modeling groups within the RAs should undertake OSE and observation impact analyses of their regional observing systems to build a pan-regional, multi-model view of observing system strengths and vulnerabilities.

3.5.2. IOOS gap analyses of the adequacy of observing network density (e.g. the number and location of HF-radar sites; the frequency and location of repeat glider transects) should include model-based OSE, OSSE and sensitivity analyses.

3.5.3. A regional demonstration project using many more observing assets than is presently typical should test whether quantitatively justified array designs can in practice perform better than ad hoc "expert" observing strategies with respect to agreed skill metrics relevant to specific user requirements; and with a very dense data set test how well DA systems quantified their actual forecast skill, uncertainty, and observation impact.

3.5.4. A pilot project should test algorithms for glider path planning that integrate environmental awareness from modeling systems. The NSF Ocean Observatories Initiative (OOI) Coastal Arrays are well positioned to capitalize on these capabilities of IOOS coastal modeling.

3.5.5. The coastal modeling community should assess future observing systems (e.g. swath altimetry, high-resolution geostationary satellite SST and color) to gauge the value they could add to existing networks and their capacity to supplant existing technologies with superior capabilities.

3.6 Ensemble prediction

Small perturbations in the initial state, forcing or model parameters lead to divergence of forecast end states, which limits the duration over which a single forecast has useful predictive skill. Within an individual model framework, ensembles are widely used to quantify this spread in forecast trajectories. Multi-model ensemble methods offer the added possibility to reduce forecast errors that stem from errors within individual models due to algorithmic and parameterization choices, misrepresentation of dynamics, and other systematic factors.

IOOS partners and international colleagues operate numerous regional models and basin or global models that cover U.S. coastal waters. Multiple models using differing approaches operating in common geographical areas provide the fundamental capacity for combining model outputs as ensembles. The promise of ensemble methods is that they provide ocean state estimates with lower expected error than any single dynamical forecast, while a challenge is selecting ensemble sets that efficiently and effectively capture forecast error statistics.

Recommendations

3.6.1. Coastal modelers should develop and test systems that perturb their model forecasts in order to characterize and quantify forecast spread, and establish a quantitative basis for subsequent multi-model mergers.

3.6.2. The coastal ocean modeling community should prototype a consensus forecast system based on a multi-model ensemble approach for a pilot region covered by several models and for which a dense data set exists.

3.6.3. A working group or workshop should be convened to foster community multi-model ensemble efforts by setting conventions for participation, addressing appropriate metrics for coastal model weighting, verification and validation, and developing the presentation of probabilistic forecast information to stakeholders.

3.7 Fast predictors

The computational expense of high fidelity, high-resolution simulations of circulation and other coastal processes (sediments, biogeochemistry, ecosystems) are often prohibitive for probabilistic “Monte Carlo” methods in which a large number of long simulations are used to sample the model error probability space. This may demand that lower resolution and lower fidelity models be employed. Alternatively, fast and robust surrogate modeling systems (e.g., van der Merwe et al. 2007; Taflanidis et al. 2013) offering adequate accuracy and enhanced computational efficiency can be developed based on a database of high fidelity simulations or observations. Surrogate models allow both deterministic and probabilistic simulations with short turnaround times, and can be used in support of data assimilation and network optimization (e.g. Frolov et al. 2009).

Recommendations

3.7.1. Coastal modeling groups should create and skill-assess decade-scale, high-resolution simulation databases of circulation, sediment transport, biogeochemistry and other key processes for training fast predictor modeling systems.

3.7.2. Encourage development of coastal "fast predictor" systems with a view to deploying these for physical and environmental stakeholder needs, and for observing system design and operation, network optimization, analysis of return periods for hazards, and integration into DA systems.

3.7.3. Initiate a test-bed to coordinate surrogate model development and application, and to undertake retrospective analyses of well-observed events to evaluate surrogate versus traditional forecasting methods.

4. Coordinating and sustaining a coastal modeling strategy

Building a nationally coordinated coastal ocean analysis and prediction system that is responsive to user requirements, exploits the best numerical codes and algorithms, and utilizes the full spectrum of in situ and remotely sensed data, requires a level of regional-federal partnership that has hitherto been absent in the U.S. coastal modeling community. Accordingly, we recommend that the community consider empaneling consultative and advisory groups to help shape a more coordinated national collaboration.

The members of these groups would be knowledgeable of existing and emerging capabilities and user requirements, and would be charged with advising on the division and sharing of effort between the FB and the RAs that would enable mutually beneficial partnerships. Other key activities would be ensuring that DMAC yields the necessary data access and interoperability of cyberinfrastructure elements to aid the partnership, and communicating to FB and RA modeling groups the needs or model-based investigations on gaps, vulnerabilities, and efficiencies in observing asset deployment. The MTT identified requirements for fostering interchange on scientific and technical experience, and strengthening federal-academic partnerships to encourage efficiencies and connections to end users and stakeholders.

Recommendations

4.1. Form a caucus comprised principally of modelers and model users from the RAs, with added involvement from federal counterparts in much the same way that the GODAE OceanView community melds federal and academic participation in research for global and basin-scale modeling. The caucus could foster interchange of research and development experience and needs within the U.S. coastal ocean research community through events such as, for example, focused workshops, training events, test-beds and themed publication collections. Galvanized by these efforts to promote coordination of coastal modeling capacity growth in the short term, it will be collaborative programs and teams that evolve in the longer term that ultimately enable IOOS to deliver coastal ocean model-based products and information that meet user needs on a sustained basis.

4.2. Form a Task Team to further prioritize and guide initial action on the recommendations in this paper, and take steps to establish collaborative environments for Coastal IOOS modeling. This would include facilitating RA exposure to FB operational environments, establishing channels by which federal research and development needs, and user requirements, are communicated to the research community. In the longer term a mechanism such as a community Steering Team that sustains coordination of FB and RA modeling activities may be in order to keep pace with evolving research priorities, an expanding observing system, and increasingly sophisticated downstream applications that use data-informed modeling infrastructure.

Greater coordination and communication will ensure that federal agencies reap the benefits that IOOS observing and modeling can bring to their respective responsibilities for scientifically informed stewardship of the nation's marine environment; and also that the full suite of expertise resident in the RAs and academic partners is brought to bear on delivering the technical and scientific solutions that agencies require. It should be noted that enhanced academic and operational coordination, and accelerated research and development, will not be accomplished by regional and coastal U.S. IOOS alone, but will include relationships to international partners engaged in global and basin scales modeling and analysis.

5. Implementation: Accomplishing progress on research priorities

The actions suggested in Section 3 are varied and would require quite different approaches to implement. Here we present an overview of existing U.S. programs and organizational structures that have supported coastal modeling in the past and comprise instruments that could help enact many of the recommendations.

A subset of the recommendations call for establishing closely collaborating communities of practice formed of non-traditional groupings of ocean science professionals, and these do not match well to existing supporting frameworks for research and development in the U.S. Accordingly, we advocate a novel "Center Without Walls" concept to provide a home for these collaborative endeavors.

The remarks below are not intended to be exhaustive, but merely illustrative of the capacity of existing funding avenues to support innovation and experimentation in coastal ocean modeling.

5.1 Coastal and Ocean Modeling Testbed

The mission of the IOOS Coastal and Ocean Modeling Testbed (COMT) is to accelerate the transition of advances from the research community to operational ocean products and services. COMT teams (of federal, academic, and private industry members) have addressed projects related to coastal inundation, estuarine and shelf hypoxia, and contributed to creating crosscutting cyberinfrastructure of benefit to the IOOS data infrastructure in general.

COMT tasks have a defined beginning and end, and deliverables. As such, it is a useful mechanism for assembling teams to tackle recommendations above on establishing a data assimilation inter-comparison test-bed, and supporting enhanced software tools and a pan-regional data portal. The call for pilot projects to explore model-based analysis of observing systems falls squarely in the COMT bailiwick. The coordinating groups advocated in Section 4 could provide valuable input suggesting COMT priorities.

5.2 Federal funding opportunities

National Ocean Partnership Program

The National Ocean Partnership Program (NOPP) is a collaboration of federal agencies that support oceanographic research and technology, resource management, education, and outreach. A relevant example of previous NOPP sponsorship is the substantial effort (more than 50 investigators) that demonstrated performance and application of the HYCOM model for eddy-resolving, real-time ocean prediction (Chassignet et al. 2009). That project, which received the 2007 NOPP Excellence in Partnering Award, has since transitioned to operations and is widely used as boundary conditions to RA real-time coastal models.

Recommendations in Section 3 on model coupling, ensemble prediction, and littoral and nearshore environments outline activities where NOPP partnerships that cross multiple federal agencies and bring together existing and emerging capabilities could drive significant progress.

National Science Foundation

There are topics in Section 3 that would meet NSF's criteria for innovation and relevance, and progress could be achieved by individuals or by teams submitting NSF "Collaborative Research" proposals.

It is also within NSF's mandate to encourage research targeted at specific national needs and community interests. NSF formed Climate Process and Modeling Teams (CPT) to "speed development of global coupled climate models … by bringing together theoreticians, field observers, process modelers and the large modeling centers to concentrate on the scientific problems facing climate models today." To foster collaboration exploring, for example, connections at the interface of wetlands, estuaries, the nearshore zone and coastal ocean, NSF could establish "Coastal and Nearshore Process and Modeling Teams".

NSF's investment in the OOI Coastal Endurance and Coastal Pioneer arrays provides opportunities to put into practice efforts at inter-comparison of data assimilation methods and observing system assessment, gap analysis, and experiments with optimization of operations.

NSF Science and Technology Centers (STCs) use team science to address "grand challenges," and to catalyze technology transfer, workforce development and broaden participation. NSF might call for an STC to focus on one or more of the research categories we have highlighted, while also contributing to needed workforce training.

NASA

Satellites are a growing component of IOOS coastal observing with the specter of significant enhancements in the advent of swath altimetry (SWOT), geostationary coastal imaging (GEO-CAPE), and new SAR and hyper-spectral imaging technologies from other international agencies. At the ocean mesoscale, NASA project scientists have amply demonstrated the synergy between remote sensing, in situ ocean observation by Argo profiling floats, and advanced data assimilative modeling. With NASA encouragement, the coastal oceanography community could make comparable advances in the synthesis of coastally focused satellite observations in conjunction with IOOS in situ observations, and in so doing make a sizeable reciprocal contribution to NASA's missions.

Prior to launch, satellite mission design has long utilized rigorous methods for quantifying requirements for instrument precision, orbital sampling patterns, error budgets, and resolution. During mission operations simulation and modeling play a key role in adapting to operational contingencies and instrument performance. Bringing NASA expertise to bear on evaluating, enhancing, and operating IOOS coastal observatories through collaborative projects (e.g. Wang et al. 2013) would further the synergistic use of satellite and in situ data.

5.3 Core IOOS funding

RAs have differing levels of involvement in numerical modeling. Some create products using results from models run by other organizations, while others configure and run models for their region and produce model-derived products (Price and Rosenfeld 2012). RAs might use IOOS funding to develop new, or expand existing, model capabilities, but in few instances is it sufficient to sustain robust real-time operations or to bring a modeling system to full maturity for transition from research to another entity that will operate it.

The RAs coordinate various elements of regional observing systems and play a key role in delivering observations to the models. They also play a part in directing coastal ocean model development by helping identify user needs that would benefit from products and services that incorporate model output, and may help to design and distribute such products. Supporting ongoing improvements in modeling systems for stakeholder information products needs to be an IOOS funding priority in concert with sustaining the observatories themselves.

RAs act largely independently in constructing and operating portals and web services to deliver data and model-derived products. However, as we have noted already, there is an increasing need for pan-regional inter-operable services to access data and models. RAs could also be making greater use of models for observing system design. One of the community entities suggested in Section 4 could spur IOOS to encourage greater coordination and collaboration in these respects.

5.4 NOAA Cooperative Institutes

Through its Cooperative Institute framework NOAA can support non-federal organizations with outstanding research programs in areas relevant to NOAA long-term goals. A Cooperative Institute for applied coastal ocean modeling collocated with a NOAA research or operational laboratory could create a strong, long-term collaboration between academic researchers and NOAA groups at the forefront of operational implementation of coastal products. Experts from the RA research community could contribute directly to the transition of developments and practices to operations, and the environment would also enable RA researchers to become more aware of practical operational constraints and emerging user requirements. Many cooperative agreements between NOAA and academic partners provide for formal sponsorship of students through fellowships, and thus Cooperative Institutes would also help educate and train the next generation the nation's scientific workforce.

5.5 "Center Without Walls"

Some of the research priorities in Section 3 require collaborative activity on the part of non-traditional groupings of ocean and information science professionals. For example, creating a new generation of flexible and computationally more efficient models, and advanced earth system model coupling, are topics where experts with different skills need to work in close collaboration and in conjunction with significant supporting cyberinfrastructure.

The MTT expressed concern that some such groupings may not align well with existing mechanisms for supporting U.S. research and development, and suggested a new construct – a "Center Without Walls" (Cw/oW) – as a framework to foster close collaboration across a breadth of skills. The envisioned center would bring together diverse expertise to make rapid and significant progress on targeted projects, yet also provide a home for a professional core to sustain on-going development of tools and best practices for working with ocean models and observational data. The center would facilitate synergies with RA modeling where appropriate, but would not be focused on particular coastal geographic regimes.

The center could be virtual – hence the "without walls" moniker – with modest anchoring facilities at a university or federal laboratory, though a physical home proximate to an oceanographic operational center also has merit. Either way, the Cw/oW would provide infrastructure and protocols that enable experimentation within a virtual operational environment – what might be called a "computational sandbox" – to accelerate Research to Operations transitions. This would echo the successful European Centre for Medium-range Weather Forecasting (ECMWF) Fellowship Program by encouraging coastal modeling researchers from universities and other agencies to spend extended periods of time working on problems directly related to improving operational modeling within federal agencies.

By formalizing such a center, infrastructure could be made available to conduct training workshops and develop comprehensive cyberinfrastructure tools with a dedicated technical workforce. Such an effort might represent a maturing of software development efforts pioneered under COMT. The center would need to be funded primarily by new resources.

6. Summary and Actions

The strategies and recommendations presented here seek to advance the coastal modeling subsystem of IOOS, and coastal GOOS, through targeted research innovation and by establishing better links between federal and non-federal modelers to communicate needs and developments.

The priority areas (model coupling, data assimilation, nearshore processes, cyberinfrastructure and model skill assessment, modeling in support of observing systems, ensemble prediction, and fast predictors) are aimed at developing the capabilities necessary to make full use of the observational assets of IOOS through advanced data assimilation, to use models to inform and improve the observatory, and to enhance the fidelity, scope and utility of models to underpin the creation of model-derived products that meet the needs of IOOS stakeholders.

To improve coordination between federal and non-federal modeling groups, and among the respective modeling, observing and data management subsystems of IOOS, it is suggested that two groups be empaneled: (i) a caucus comprised of model developers would be a forum for interchange of research and development experience that is responsive to needs of the U.S. coastal oceanography and ocean modeling community, and that would sustain the development cycle in the longer term; and (ii) a Task Team that would guide initial implementation of the actions this article describes and take steps to facilitate collaborative environments conducive to coordinating federal efforts with activities in the IOOS regions, and globally.

Benefits that would flow from these initiatives are efficiencies through the coordination of efforts that address common needs, demonstration of the value and skill of integrated coastal ocean modeling through robust validation and assessment processes, and contributions to the development of a workforce that can capitalize on the nation's investment in coastal observing.

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