11-22-2013

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JOURNAL OF GEOPHYSICAL RESEARCH: OCEANS, VOL. 118, 6319–6328, doi:10.1002/2013JC008939, 2013

Introduction to special section on The U.S. IOOS Coastal and Ocean Modeling Testbed

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Received 15 March 2013; revised 30 October 2013; accepted 18 November 2013; published 11 December 2013.

[1] Strong and strategic collaborations among experts from academia, federal operational centers, and industry have been forged to create a U.S. IOOS Coastal and Ocean Modeling Testbed (COMT). The COMT mission is to accelerate the transition of scientific and technical advances from the coastal and ocean modeling research community to improved operational ocean products and services. This is achieved via the evaluation of existing technology or the development of new technology depending on the status of technology within the research community. The initial phase of the COMT has addressed three coastal and ocean prediction challenges of great societal importance: *estuarine hypoxia*, *shelf hypoxia*, and *coastal inundation*. A fourth effort concentrated on providing and refining the *cyberinfrastructure* and cyber tools to support the modeling work and to advance interoperability and community access to the COMT archive. This paper presents an overview of the initiation of the COMT, the findings of each team and a discussion of the role of the COMT in research to operations and its interface with the coastal and ocean modeling community in general. Detailed technical results are presented in the accompanying series of 16 technical papers in this special issue.

Citation: Luettich, R. A., et al. (2013), Introduction to special section on The U.S. IOOS Coastal and Ocean Modeling Testbed, *J. Geophys. Res. Oceans*, *118*, 6319–6328, doi:10.1002/2013JC008939.

1. Introduction

[2] Marine environments and their adjacent shorelines, wetlands, and communities are threatened by climate change, sea-level rise, storm-induced flooding, nutrient enrichment, oxygen depleted "dead zones," oil spills, and other unforeseen stressors. The coastal and ocean modeling and information technology research communities have, collectively, developed advanced capabilities for predicting marine responses to existing and emerging threats and serving the resulting information to both scientific and lay users. Concurrently, models have been put into "operational use" (operational use is broadly defined to cover a wide range of society-critical applications including forecasts, forensic studies, risk assessment, design, and system management) at an accelerating rate by organizations (e.g., NOAA, US Navy, US Army Corps of Engineers, EPA, FEMA, regional and state authorities) that are tasked with reversing, mitigating, or responding to these important societal problems. However, to date, there has been limited success integrating the research and user communities into a coherent, multiinstitutional program that targets research and development activities such as systematic model intercomparisons; model skill assessment; algorithmic/parameterization improvements; model implementation guidance; cyberinfrastructure analytical and visualization tools; data standards; and data archives to aid the development and operational use of these models. With funding from NOAA's U.S. Integrated Ocean Observing System (U.S. IOOS) Office and coordination from the Southeastern Universities Research Association (SURA), strong and strategic collaborations among experts from academia, federal operational centers, and industry were forged to create the U.S. IOOS Coastal and Ocean Modeling Testbed (COMT).

[3] The U.S. IOOS program identified modeling and analysis as one of three functional subsystems of a fully coordinated enterprise in the U.S. IOOS Blueprint [*U.S. IOOS*, 2010]. The other two subsystems are

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2169-9275/13/10.1002/2013JC008939

(1) observations and data transmission and (2) data management and communication. As a result of this determination, in June 2008, the U.S. IOOS program office sponsored a Modeling and Analysis Steering Team (MAST) Workshop to identify specific steps to advance this subsystem [*Ocean.US*, 2008]. One of the leading recommendations of the Workshop report was to develop a coastal and ocean modeling testbed to advance joint activities and develop the modeling and analysis strategy of the U.S. IOOS enterprise [*Ocean.US*, 2008] including standards-based cyberinfrastructure. A general need was recognized for U.S. IOOS to embrace and implement a synergistic (and bidirectional) path connecting research and operations. This U.S. IOOS Coastal and Ocean Modeling Testbed is the first attempt to implement recommendations from the MAST report.

[4] As an initial step, this program focused on modeling phenomena associated with the coastal environmental conditions that prevail along the U.S. Atlantic and Gulf of Mexico coasts. In contrast to the Pacific coast, these realms are distinguished by wide, low gradient continental shelves; high input of buoyancy, nutrients and sediment from rivers; and the frequent occurrence of tropical and extratropical storms. Although the initial phase did not include models of U.S. West coast, Hawaiian Island or Alaskan waters, the COMT was intended from the outset to be extensible to those and other model applications in the future.

[5] The initial phase has yielded a flexible and extensible community research framework (including a testbed archive, a supporting cyberinfrastructure and an interdisciplinary network of scientists and users) to advance the testing and evaluation of predictive coastal and ocean models. This framework supports integration, comparison, scientific analyses, and archiving of data and model output. The cyberinfrastructure includes the archive of model and observational data as well as tools for comparing and assessing the models and observations. Since its inception in June 2010, the COMT has made significant advances, many of which are reported in detail in the papers in this special issue.

2. Testbed Mission and Structure

[6] The *mission* of the Coastal and Ocean Modeling Testbed is targeted research and development to accelerate the transition of scientific and technical advances from the coastal ocean modeling research community to improved operational ocean products and services.

[7] The *vision* of the program is to increase the accuracy, reliability, and scope of the federal suite of operational coastal and ocean modeling products to meet the needs of a diverse user community. Operational use covers a wide range of society-critical applications including forecasts, forensic studies, risk assessment, design, and system management.

[8] The initial phase of the COMT addressed three coastal and ocean prediction challenges of great societal significance: *estuarine hypoxia*, *shelf hypoxia*, and *coastal inundation*. To facilitate focused and effective execution of modeling activities, coordinated teams were assembled to address each of these challenges. The estuarine hypoxia team was focused on the Chesapeake Bay region; the shelf hypoxia team was focused on the northern Gulf of Mexico. Both of those environments experience hypoxia related to nutrient and buoyancy input, although the northern Gulf of Mexico is an open shelf environment with weak tidal mixing and strong river-induced stratification, whereas the Chesapeake Bay is semienclosed, moderately tidally mixed and moderately stratified. The inundation team addressed the effects of hurricanes in the Gulf of Mexico and extratropical storms in the Gulf of Maine. A fourth team concentrated on providing and refining *cyberinfrastructure* and cyber tools to support the three modeling teams and to advance interoperability and community access to the modeling activities within the COMT.

[9] Luettich (UNC) and Wright (SURA) served as Principle Investigators for the program as a whole; Luettich also led the coastal inundation team; C. Friedrichs (VIMS) and M. Friedrichs (VIMS) led the estuarine hypoxia team; Harding (NGI) and Fennel (Dalhousie) led the shelf hypoxia team and Howlett (ASA) and Graves (UAH) led the cyberinfrastructure team. The Southeastern Universities Research Association (SURA) provided the overall management of the 54 investigator project, which involved 18 academic institutions and 10 federal agencies/programs. SURA also facilitated access to high performance computing resources and provided a dedicated server and software for hosting the COMT collaboration website (testbed.sura.org and www.ioos.noaa.gov/modeling/testbed.html) and the COMT archive. To ensure independent and nonconflicted oversight, a Testbed Advisory and Evaluation Group (TAEG) comprised of scientific and computer experts from academia and the federal government was established. The TAEG, chaired by R. Signell (USGS), made objective recommendations regarding team selection, resource allocations, and progress assessments and helped to provide a long-range vision and direction for the COMT.

[10] Below we provide an overview of the goals and accomplishments of each component of the COMT with further technical details provided in the 16 subsequent articles included in this special issue. References to specific models are contained in Appendix A to this paper. The paper concludes with a discussion of the role of the COMT in research to operations and its interface with the coastal and ocean modeling community in general.

3. Estuarine Hypoxia

[11] The goal of the COMT's estuarine hypoxia component was to evaluate existing hydrodynamic and water quality models used or likely to be used for operations and/or for regulation (e.g., establishing nutrient Total Maximum Daily Loads) in the Chesapeake Bay region. By engaging experts from NOAA, EPA, and the US Army Corps of Engineers, and leveraging the ongoing efforts of the Chesapeake Community Modeling Program and the Community Surface Dynamics Modeling Program Chesapeake Focus Research Group, existing community resources were coordinated to evaluate a diverse suite of models for Chesapeake Bay hydrodynamics and oxygen dynamics. The hydrodynamic models included multiple implementations of ROMS, EFDC, and CH3D. Comparisons were made to observed temperature, salinity, and dissolved oxygen over multiple spatial and temporal scales. A range of standardized hindcast boundary conditions, including those

downscaled from other agency models, were used to force and test the Chesapeake Bay models, during both wet and dry years, and under diverse wind conditions. A wealth of long-term observational data from the EPA Chesapeake Bay Program was utilized for model-data comparison. Model skill assessment was performed based on traditional metrics such as bias and root mean squared differences and Target diagrams [*Jolliff et al*., 2009, *Hofmann et al*., 2008, *Friedrichs et al*., 2009]. Results are summarized below.

[12] *Scully* [2013] and *Hong and Shen* [2013] explored the sensitivity of Chesapeake Bay hypoxia models to wind forcing and river discharge. For the hydrodynamic component of their modeling effort, Hong and Shen utilized EFDC, while Scully applied ChesROMS. Both of these 3-D hydrodynamic models, along with the other 3-D models compared by the estuarine hypoxia team, successfully reproduced the observed seasonal cycle and spatial distribution of temperature and salinity in the Chesapeake Bay. The oxygen submodels used by Scully and by Hong and Shen were different, although they both aimed to isolate physical controls on the dissolved oxygen concentrations. Scully assumed that biological utilization of dissolved oxygen was constant in both time and space and occurred only in the water column. Hong and Shen added sediment oxygen demand and temperature-dependence to their formulation for respiration. Both approaches demonstrated skill in reproducing observed hypoxia, and their conclusions regarding the dominant controls on seasonal fluctuations in hypoxia were consistent.

[13] A clear finding from both of these studies was the strong role played by wind in determining the extent and duration of hypoxia in the Chesapeake Bay. Scully found that variations in wind speed and direction had a far greater impact on the seasonal cycle of hypoxia than seasonal variability in river discharge. However, integrated hypoxic volumes were sensitive to the overall magnitude of river discharge at interannual time scales. Hong and Shen highlighted physical control of hypoxia by tracking the vertical transport time for water since its exposure to the aeration at the surface. Bottom dissolved oxygen was found to have a strong negative correlation with vertical transport time. Vertical transport time, in turn, was reduced dramatically by strong wind forcing, but was insensitive to seasonal river discharge pulses.

[14] *Bever et al*. [2013] utilized the high spatial and temporal resolution provided by 3-D models (ChesROMS, CBOFS, and CH3D) to improve the interpolation needed to transform monitoring cruise data into estimates of Chesapeake Bay hypoxic volume (HV). For calculations of dissolved oxygen, CH3D was paired with the Chesapeake Bay Program's multiconstituent eutrophication model, whereas a much simpler, constant respiration model [*Scully*, 2013] was utilized with both ChesROMS and CBOFS. Multiple methods of calculating HV from dissolved oxygen distributions were used (1) to examine the uncertainties associated with computing HV estimates from point measurements, (2) to obtain a more accurate time series of HV within Chesapeake Bay, and (3) to design alternative sampling strategies with reduced HV uncertainties. Results showed that uncertainty in the HV estimates resulting from the monitoring cruises lasting 2 weeks generally exceeded the uncertainty associated with sampling a finite number of points. This suggests that time series data from a limited number of stations are superior to data from bay-wide cruises for purposes of HV evaluation.

[15] Another focus of the estuarine hypoxia team was the exploration and evaluation of skill metric formulations. *Bever et al*. [2013] utilized both the Wilmott skill metric [*Wilmott*,1981] and Target diagrams [*Jolliff et al*., 2009, *Hofmann et al*., 2008, *Friedrichs et al*., 2009] to compare HV estimates computed using information from a finite number of stations versus computed using fully-resolved 3-D model integrations. Both of these skill metrics led to consistent conclusions, although the graphical nature of the Target Diagram approach was helpful when trying to illustrate the relative skill of multiple model formulations. Current work is considering a new skill metric for model-data comparison of vertical profiles based on the Discrete Frechet Distance (DFD) [*Mascret et al*., 2006]. The DFD approach retains shape information of modeled and measured curves in contrast to traditional second-moment-based measures (such as Wilmott skill or the Target Diagram).

[16] Because of the role of the neighboring continental shelf in influencing the Chesapeake Bay, studies by the estuarine hypoxia team also included skill assessment of Middle Atlantic Bight (MAB) circulation models. *Wilkin and Hunter* [2013] evaluated whether real-time models presently in operation for the MAB can deliver useful predictions of subtidal frequency currents and subsurface temperature and salinity for downscaling purposes, such as for forcing the seaward boundary of the Chesapeake Bay. *Wilkin and Hunter* [2013] examined seven real-time models and regional climatology of the MAB versus observations from underwater gliders and hydrographic vessels. Several of the real-time models were determined to provide useful predictions of open boundary conditions for real-time inner shelf and estuary models.

[17] Additional highlighted outcomes of the estuarine team's work include:

[18] 1. Improvements were achieved in the skill of several models for predicting the timing and location of hypoxic conditions in the Chesapeake Bay. Such "dead zones" have a significant impact on living marine resources; predicting their occurrence is critical for ecosystem management within the Bay.

[19] 2. The size and seasonal variability of the Chesapeake Bay's "dead zone" was more accurately estimated using the mean of multiple models, rather than any single model evaluated in the COMT. The use of multiple models has been recommended to the Chesapeake Bay Program for the analysis of water quality conditions in the Bay [*Friedrichs et al*., 2012].

[20] 3. A simple dissolved oxygen formulation [*Scully*, 2013] for forecasting the location and timing of seasonal hypoxia was transitioned to NOAA/CSDL's research version of the Chesapeake Bay Operational Forecast System for evaluation.

4. Shelf Hypoxia

[21] The goals of the COMT's shelf hypoxia component were to evaluate a coupled, physical-biogeochemical model of the northern Gulf of Mexico shelf for transition to operations, aid in this transition by building a collaboration

between academic hypoxia researchers and model developers at NOAA CSDL, and evaluate the U.S. Navy's regional circulation prediction system for the Gulf of Mexico and Caribbean as a baseline operational capability. The biogeochemical shelf model, capable of forecasting the evolution of real-time shelf ecosystem processes and hypoxia, was nested within three operational Gulf of Mexico nowcast/forecast models in order to evaluate the significance of realistic shelf boundary conditions for the initiation and evolution of hypoxia on the shelf. A compilation of available hydrographic, nutrient and oxygen observations for the period 2004–2008 was generated for model assessment.

[22] Nested shelf simulations (i.e., with realistic boundary conditions from operational Gulf of Mexico models) show improved model skill in representing observed horizontal salinity distributions compared to unnested simulations (i.e., with climatological boundary conditions) [*Marta-Almeida et al*., 2013] indicating that hypoxia forecasts should benefit from model nesting. However, analysis of an ensemble of simulations showed large variability in comparison to the mean simulated salinity distributions, presumably due to small-scale eddy activity on the edge of the front of the Mississippi/Atchafalaya river plume [*Marta-Almeida et al*., 2013]. This variability was greatest in the summer, which is also the period of greatest oxygen consumption, and therefore has significant implications for the predictability of hypoxia throughout the region.

[23] Simulations with the coupled physical-biogeochemical shelf model show that hypoxia predictions are very sensitive to the definition of the sediment oxygen consumption term and to stratification strength [*Fennel et al*., 2013]. Hypoxia was found to occur within a relatively thin layer above the bottom, well below the main pycnocline. Outside of this near bottom layer, significant photosynthetic production of oxygen in the water column helps to maintain dissolved oxygen concentrations above hypoxic levels [*Lehrter et al*., 2009]. (This is in contrast to Chesapeake Bay, where hypoxia can be simulated realistically without consideration of sediment oxygen consumption and the oxycline typically coincides with the main pycnocline.) A comparative assessment of hypoxia predictions in nested and unnested simulations showed that one operational parent model roughly doubles the simulated hypoxic area (due to increased stratification strength in the western part of the model domain), while hypoxia predictions remained within the range of uncertainty for other parent models [*Fennel et al*., 2013]. Interestingly, the outlier parent model did not produce markedly different skill scores than the others when assessed against observations primarily from the Mississippi/Atchafalaya river plume [*Marta-Almeida et al*., 2013; *Fennel et al*., 2013].

[24] Uncertainty in hypoxia predictions resulting from uncertainty in physical and biological model inputs such as atmospheric forcing, initial and boundary conditions and selected model parameters was analyzed with the help of an emulator technique [*Thacker et al*., 2012; *Mattern et al*., 2013]. Uncertainty in physical inputs (river discharge, wind forcing) had the strongest effect on hypoxia predictions among all the inputs that were considered, presumably because of the previously identified sensitivity of hypoxia to stratification and the small signal-to-noise ratio of the summertime salinity field reported by *Marta-Almeida et al*. [2013]. Uncertainty in hypoxia predictions resulting from perturbations in river discharge and wind forcing is much larger than that resulting from uncertainty in initial, boundary and river nutrient concentrations and phytoplankton growth rate parameters [*Mattern et al*., 2013].

[25] Another shelf hypoxia activity attempted to provide data on the behavior and implementation requirements of models that are presently in operational use or that are under serious consideration for such use. A preoperational (now operational) Navy regional ocean nowcast/forecast system of the Gulf of Mexico and Caribbean Sea was evaluated in collaboration with a complementary research effort sponsored by the U.S. Department of Energy and an offshore energy industry consortium. The regional ocean forecast system provides a useful baseline capability for operational applications and a vehicle to evaluate research-derived model improvements for future operational implementation. These multiple evaluation efforts also provided useful examples to the cyberinfrastructure group as they developed visualization and analysis capabilities useful to both research and operational users.

[26] A final complementary effort using the research precursor to the nowcast/forecast capability referenced above combined hydrodynamic model simulations with hydrographic, nutrient and carbon measurements to make budget calculations for the Louisiana shelf. These calculations elucidate the relative importance of the Mississippi and Atchafalaya river loads and show that the Mississippi River delivers roughly twice as much nutrients and organic carbon to the shelf as the Atchafalaya River [*Lehrter et al*., 2013].

5. Coastal Waves, Surge, and Inundation

[27] The goal of this component of the COMT was to provide guidance on the behavior (e.g., accuracy, robustness, execution speed) and implementation requirements (e.g., resolution, parameterization, computer capacity) of models that are presently in operational use, or that are under consideration for such use, for computing waves, storm surge, and inundation. This component of the COMT evaluated model responses to three extratropical storms (May 2005, April 2007, December 2010) and hurricane Bob (1991) in the Gulf of Maine and to two hurricanes (Rita 2005, Ike 2008) that impacted the northwestern Gulf of Mexico. Skill assessment, sensitivity studies, and intra-model/intermodel comparisons provided a basis for defining model accuracy, implementation requirements, and computational performance.

[28] Studies in the Gulf of Maine were conducted at two scales, large-scale (Gulf of Maine/Northwest-Atlantic) and locally in and around Scituate Harbor, MA (using a one-way nested grid that obtained open boundary forcing from a large-scale model).

[29] The Northwest-Atlantic component of this study evaluated the performance of: (1) a composite model system consisting of SWAN implemented within WAVEWATCHIII® (hereafter, WW3) on a traditional nested set of structured grids, (2) an unstructured grid finite-volume version of SWAN, denoted as SWAVE, and (3) WWM, a recently developed, unstructured grid version of WW3. Results indicated that modern source terms for wind input and dissipation give better results than older WAM Cycle3

physics; unstructured grid models appear to offer an attractive alternative to structured grid models; and the higher order propagation scheme used in WW3, does not appear to offer an advantage over the lower order schemes used in SWAN, WWM, and SWAVE.

[30] The impacts of wave-current interaction and stratification on the Gulf of Maine coastal response to hurricane Bob were investigated by *Sun et al*. [2013]. Wave-current interaction created variations in the surge elevation in both space and time, with the more significant effects occurring over the shelf and open coast rather than inside the inner bays. Sea level change along the coast was mainly driven by barotropic dynamics; the highest vertically integrated water transports were essentially the same for cases with and without vertical stratification. However, wave-current interaction generated strong vertical current shear in some of the stratified areas, leading to a strong offshore transport near the bottom and vertical turbulent mixing over the continental shelf. Stratification could also result in a significant difference in current velocities around islands where the water is not vertically well-mixed.

[31] Inundation studies around Scituate Harbor, MA, were conducted using three unstructured-grid, fully coupled surge-wave models (ADCIRC+SWAN, FVCOM+SWAVE, SELFE+WWM) by *Chen et al*. [2013]. For the same unstructured mesh, meteorological forcing and initial/boundary conditions, inter-model comparisons were made for tidal elevation, surface waves, sea surface elevation, coastal inundation, currents, and volume transport. All three models showed comparable tidal accuracy and consistent dynamic responses to storm winds, both with and without the inclusion of wave effects. The three models also showed that wave-current interaction could (1) change the current direction on the shelf to the north of Scituate Harbor from along-shelf to onshore, thereby enlarging onshore water transport and (2) intensify an anticyclonic eddy in the harbor entrance and a cyclonic eddy in the harbor interior, which could push water inside the harbor toward the northern peninsula and the southern end and thus enhance flooding in those areas. Differences in the model results were determined to be due to (1) the specific implementation of wave-current interaction, (2) the different discrete algorithms used in the three wave models and in computing wave-current interaction, and (3) the different algorithms used for the treatment of the flooding/drying process.

[32] Additional studies by *Beardsley et al*. [2013] used FVCOM+SWAVE on two different resolution grids, with and without wave-current interaction, examined the influence of spatial resolution and model dynamics on predicted flooding. In all simulations, a wind driven coastal current flowed southward across the harbor entrance, with an attached separation eddy forming downstream of the northern breakwater and a rapid decrease of wave energy entering the harbor. With wave-current interaction, the southward coastal current was strongly enhanced and currents within the separation eddy increased to more than 1 m/s, making it highly nonlinear with large lateral shears. Comparisons of the model water elevation time series with harbor tide station measurements showed that wave-current interaction increased the peak model surge by $\sim$8 cm, in closer agreement with the observed peak. Increased resolution within the harbor produced greater flooding in several shallow areas but did not significantly change the maximum water level in the main harbor.

[33] Studies in the Gulf of Mexico evaluated wave and surge/inundation results at both the Gulf scale and in the areas of highest impact from hurricanes Rita and Ike. *Huang et al*. [2013] evaluated the effects of wind input parameterizations on hurricane wave estimation in SWAN for Hurricane Ike. The default/recommended setting for the wind input parameterization overestimated the maximum significant wave heights by about 2 m in the deep Gulf of Mexico when compared with observations from moorings. The overestimation could be relieved either by adjusting the maximum value of the surface drag coefficient or by substituting a high-wind-speed bulk formula for the default low-to-moderate one used in SWAN. Because of the dissipative effects of the shallow coastal areas, the overestimation of waves in deep water has limited impact on the waves in near-shore waters. Thus, previous wave model results using a low-to-moderate wind speed bulk formula may still be reliable in waters shallower than 20 m while overestimating significant wave heights in deeper waters for high wind speed conditions such as hurricanes.

[34] *Hope et al*. [2013] provide a careful analysis and skill assessment of Hurricane Ike using ADCIRC+SWAN. While the storm made landfall near Galveston, TX, as a moderate intensity storm, its large wind field in conjunction with the broad Louisiana-Texas shelf and large-scale concave coastal geometry generated waves and surge that impacted over 1000 km of coastline. Ike's complex and varied wave and surge response included: the development of a storm surge "forerunner" 24 h prior to the storm's landfall due to strong shore-parallel, wind-driven currents and the associated across-shelf, geostrophic setup; the resulting early rise of water in coastal bays and lakes facilitating inland surge penetration and inundation; the shore-normal wind-driven peak surge; the southward propagation of a free wave along the Texas shelf; and the appearance of resonant and reflected waves on the adjacent continental shelf. Preexisting and rapidly deployed instrumentation provided the most comprehensive hurricane response data set ever recorded. More than 91 wave parameter time histories, 523 water level time histories, and 206 high water marks were collected in deep water, in the near shore, and up to 65km inland. A comprehensive skill assessment demonstrated the ability of ADCIRC+SWAN to capture the principal aspects of the observed storm response.

[35] *Kerr et al*. [2013a] examine the sensitivity of tides, surge, and waves during hurricane Ike in ADCIRC+SWAN to grid resolution, topographical detail, bottom friction, wave-current interaction, and nonlinear advection at basin, shelf, wetland, and coastal channel scales. Grid resolution requirements were found to be less stringent in the open ocean, however, coarse resolution or the absence of intratidal zones decreased solution accuracy along protected near shore and inland coastal areas due to decreased frictional attenuation. Diurnal tidal amplitudes were more sensitive to the presence of intratidal zones and coarse mesh resolution than semidiurnal tides. The bottom friction parameterization had little effect on tidal skill, however, it had a significant impact on the strength of the alongshore current generated during hurricane Ike and the magnitude

of the resulting geostrophic setup. Nonlinear advection increased the geostrophic set by 15–20 cm and increased resonant shelf waves by 20–30 cm. Wave radiation stress added 20–40 cm to water levels at coastal stations.

[36] *Kerr et al*. [2013b] carefully compare three unstructured, coupled surge-wave models, ADCIRC+SWAN, FVCOM+SWAN, and SELFE+WWM, using identical grids (424,485 nodes) forcing and parameterizations. In addition, NWS's official operational forecast storm surge model, SLOSH, was used on both local (Galveston Basin—46,222 nodes and Sabine Pass—77,827 nodes) and Gulf of Mexico scale (ETSS—185,409) grids. The three unstructured grid models yielded very similar results for both hurricanes Rita and Ike. These models all appeared to reproduce the important physical processes and showed minimal water level or wave height bias and comparable variances versus observations. SLOSH using the local, Galveston Basin grid failed to capture the hurricane Ike forerunner and was therefore biased significantly low. SLOSH performed better on the local, Sabine Pass grid for hurricane Rita, which did not elicit a significant forerunner. SLOSH on the ETSS grid showed minimal bias for either storm, although its accuracy was limited by the nearly 5 km resolution in near shore/onshore areas. In all cases, SLOSH deviations from observations were greater than those from the three unstructured grid models. The largest difference in model performance was observed in execution speed and scalability benchmarks. The implicit time stepping scheme of SELFE+WWM performed well at small numbers of cores, but scaled poorly at larger numbers of cores. ADCIRC+SWAN had better scaling and absolute performance when more than 128 cores were used per run. SLOSH is not configured to utilize modern parallel computing architecture and rather is limited to running on a single core. Runtimes for ADCIRC on a single core were more than 10 times longer than for SLOSH on the ETSS grid, even after the SLOSH runtimes were multiplied by 2.3 (=424,485/185,409) to normalize for the number of grid nodes. Thus, SLOSH remains more efficient for use in probabilistic forecasting that requires ensembles of hundreds to thousands of model runs. However, SLOSH-based probabilistic forecasts should be assessed for accuracy (particularly high or low bias) by comparing select, individual SLOSH runs with similar runs using one of the higher resolution unstructured grid models presented herein.

[37] *Zheng et al*. [2013] provide a detailed analysis of two-dimensional (2-D), vertically integrated, and three-dimensional (3D) model responses using FVCOM for hurricane Ike. Both 2-D and 3-D models were found to accurately predict the surge response although different bottom friction formulations are required by each type of model. Sensitivity studies indicated that hurricane storm surge in both 2-D and 3-D depends critically upon the bottom friction parameterization.

6. Supporting Cyberinfrastructure

[38] The primary goal of the COMT cyberinfrastructure team was to accelerate the development of better tools for model assessment, not only for use by COMT participants but also for the broader IOOS and international geoscience communities, building on the approach already being implemented by IOOS [*Signell*, 2010]. Effective assessment of model results requires: (1) tools for model data providers to easily aggregate, annotate, and serve their data using standard web services, (2) efficient search tools for users to locate model and observed data sets for specific simulations, and (3) tools to access and visualize model and observed data from standardized web services. Significant progress was made on all of these tasks.

[39] To help modelers serve their data using standardized services, custom templates for each modeling group were created using NcML (NetCDF Markup Language), which allowed providers to upload collections of nonstandard model output to the server. A THREDDS Data Server used the NcML to make each collection available as a single standardized dataset through a variety of web data and metadata services. Structured grid data were standardized with CF conventions (http://cf-pcmdi.llnl.gov/documents/cf-conventions) and unstructured grid data were standardized with CF and UGRID conventions (https://github.com/ugrid-conventions), the latter developed by the unstructured grid community with COMT participation. As far as we know, the COMT provides the first example of unified standards and services for both unstructured and structured grid model data. In addition, the COMT cyberinfrastructure team built tools that extend the THREDDS-based infrastructure, for example, providing a new service (ncSOS) that allows collections of observational data in NetCDF files to be delivered via the IOOS-approved OGC Sensor Observation Service.

[40] To facilitate searches by cataloging services, metadata fields were populated in COMT data sets that would translate into ISO metadata using the ncISO tool (developed by National Geophysical Data Center with IOOS funding). Static metadata (e.g., modeler, institution) was specified in the NcML templates, while more dynamic metadata (e.g., description of the particular simulation) was entered by the modeler via a web browser. This allows metadata from COMT to be efficiently searched and integrated with other data using catalog services such as the IOOS Catalog and data.gov.

[41] For map-based browsing of data sets, new Python-based WMS services for both unstructured and structured grids were developed, as the existing ncWMS services built into THREDDS were too slow for curvilinear structured data, and did not work for unstructured grid data [*Howlett et al*., 2012].

[42] To facilitate data access, the NCTOOLBOX for Matlab was extended to take advantage of both CF and UGRID-compliant data, allowing users to access model output along with standardized geospatial and temporal information without the need to implement model-specific code. Custom tools to facilitate model-data comparison were also developed (such as a tool to interpolate model results along a specified glider path) with demos providing examples of model and observed data extraction and comparison. In addition, the COMT significantly enhanced the Interactive Model Evaluation and Diagnostics System (IMEDS) [*Hanson et al*., 2009] providing a powerful, easy-to-use, and stand-alone tool for performing skill assessment on observed and modeled time series data. These tools greatly improved the efficiency of model skill assessment for COMT participants [*Kerr et al*., 2013a, 2013b; *Wilkin and Hunter*, 2013].

[43] The second goal of the cyberinfrastructure was to facilitate access to and the usage of large-scale

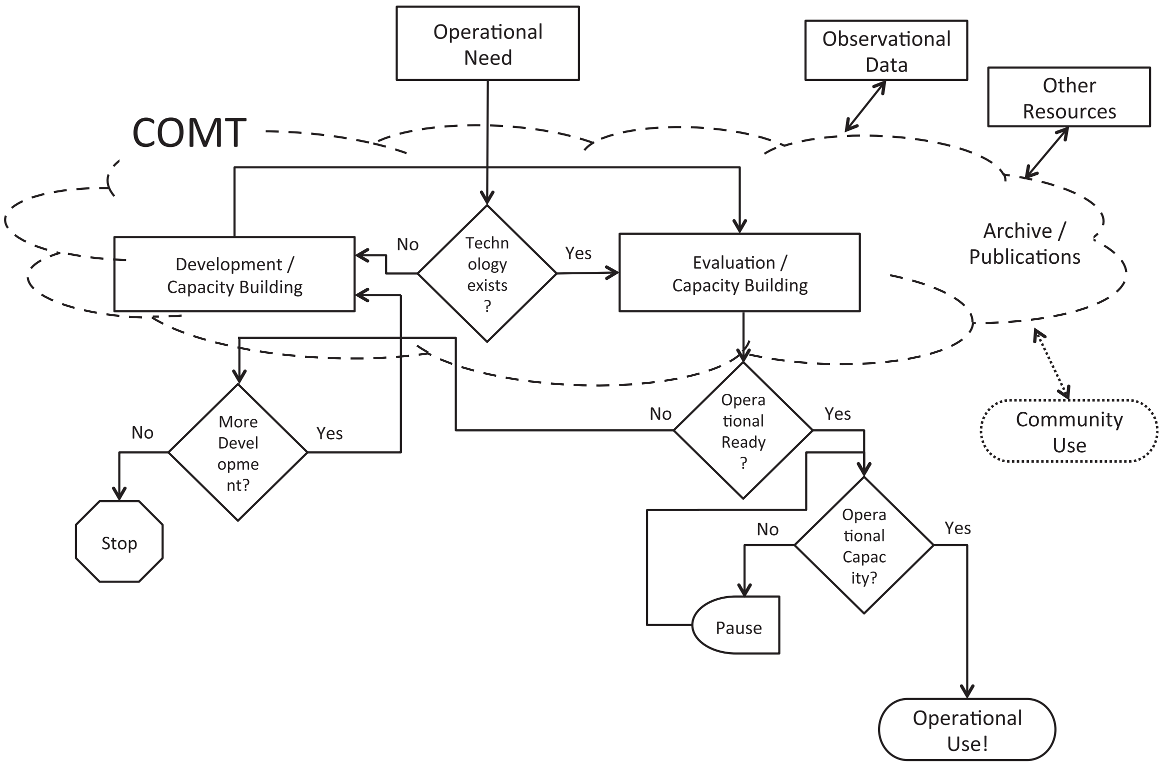

Figure 1. Schematic of the COMT's place in the space of research to operations.

computational resources within the COMT. This was accomplished through the development and submission of successful competitive proposals to LONI, TeraGrid, and XSEDE (TeraGrid's NSF funded successor). Access to these systems was essential to the Coastal Waves, Surge, and Inundation component to enable the use of large, high resolution grids, to evaluate both 2-D and 3-D models, to explore coupled surge and wave models and to demonstrate model performance on computational systems that are similar to those used by major operational users (e.g., National Weather Service, US Army Corps of Engineers, US Navy).

[44] The third goal of the COMT cyberinfrastructure was to serve the specific needs of the scientists participating in the testbed. This involved developing and maintaining a COMT website (testbed.sura.org and www.ioos.noaa.gov/modeling/testbed.html), data archive, computing resources, and custom code to perform tasks such as skill assessment [*Hanson et al.*, 2009] and format conversions. Short descriptions and links for all software tools may be found on the COMT website, all of which are open-source and freely available. The grids, forcing, output, and associated observational data described in the papers contained in this special issue are captured in the COMT data archive and comprise a rich resource for future model evaluation.

[45] While significant progress was made during COMT, there is still important cyberinfrastructure work left to do. For providers, we would benefit from better tools for enabling input and verification of model data. In COMT, errors in metadata commonly resulted in unavailable data. For data search, we need to exercise catalog services to make sure that users are actually finding the data they are looking for, and provide better tools to query catalog services and parse the results. For data browsing, we need to continue to develop tools like PyWMS that will work for all commonly used models. For data access, we need tools that work with CF and UGRID compliant data not only in Matlab, but in Python and other commonly used analysis and visualization environments. The COMT allowed us to take great steps forward, and built a foundation that can be leveraged by future Testbed and community activities.

7. The Role of the Coastal Ocean Modeling Testbed

[46] As stated fully in section 2., the mission of the COMT is principally to accelerate the transition of research to operations in coastal and ocean modeling. Figure 1 illustrates how the COMT fits into research to operations as well as other complementary roles within the coastal and ocean modeling community. Specifically, for an identified *Operational Need*, the primary role of the COMT is to provide a venue for *Evaluation* of technology that currently exists or *Development* of targeted new technology depending on what is available within the research community. *Evaluation* of existing modeling technology may include: (i) comparisons of multiple technologies, (ii) suitability assessment of one or more technologies, (iii) development of technology application guidance including pilot projects, (iv) identification of technology benefits versus current operational capabilities, and (v) determination of resources (e.g., computational, personnel) required to implement identified research modeling technology in an operational setting. *Developing* new modeling technology may be best focused on "missing pieces" that limit the utility of current technology for operational needs, although there is considerable room for discretion in

this aspect of the COMT. Both the *Evaluation* and *Development* activities must be done in an open, objective, and inclusive manner with a commitment to developing an understanding of, and not simply a documentation of, modeling technology performance. Activities should engage meaningful participation from the research and the operational communities; these represent important opportunities for collaboration. Feedback from operational users can help focus and stimulate research efforts (i.e., operations to research), while exposure to the development and/or evaluation of modeling technologies can provide invaluable experience for operational users. This will create important capacity building, both in terms of more efficient research activities and operational users who are better able to use (and therefore transition) the new modeling technology.

[47] The availability of external resources, especially *Observational Data* but also *Other Resources* such as high performance computing, is clearly critical to the activities within the COMT. However, as identified in Figure 1, COMT activities may also affect these external resources, e.g., by pursuing Observing System Simulation Experiments (OSSEs) to optimize data collection systems or by providing demanding, high visibility use cases and data standards to drive resource development (e.g., the NSF EarthCube and DataWay programs for supporting the development of community-guided cyberinfrastructure to integrate data and information for knowledge management across the sciences).

[48] While specific software products may originate from *Development* activities, the most significant contributions expected from the COMT are data or knowledge-based and should be designed to help determine whether a given modeling technology is desirable for operational deployment (i.e., is it *Operationally Ready*) and further whether an interested operational user has the *Operational Capacity* (e.g., personnel computer resources) to use it. Only after clearing these hurdles will the technology achieve actual transition to *Operational Use*. While knowledge can be communicated from the COMT to operational users via numerous means, ultimately significant findings should be captured in refereed publications both to ensure scientific rigor and to achieve dissemination to the broader community. In addition, a well-maintained and easily accessible archive of model inputs and outputs, observational data sets and developed products should be maintained for the benefit of ongoing COMT activities and to enable future modeling technology development and evaluation efforts, whether or not they are conducted within the auspices of the testbed. *Community Use* may occur via the testbed archive or it may utilize the accumulated knowledge (e.g., as reported in presentations, publications) to assist with its own decisions about whether to adopt certain modeling technology. The considerations affecting these decisions may be quite different than those affecting decisions by operation users.

[49] The technical findings and developments discussed in sections 3.–6. of this manuscript and covered in detail in the series of 16 technical papers in this special issue, summarize the knowledge, product development, and archive that have resulted from the initial set of COMT activities. A less tangible product of the COMT, but one that should also have lasting impact, is the community building that resulted from scientists working together in a team environment toward a shared set of goals. For example, in several cases when multiple models were being compared and one model was found to have less skill than others, team members worked together to identify the cause of these differences, and to improve the underperforming model. These interactions and feedbacks resulted in significant improvements to several of the models evaluated in the COMT.

[50] Looking forward, the COMT's role and construct should be sufficiently robust and extensible that it can evolve to meet future needs, e.g., for applications in geographic regions, for prediction challenges and to meet user needs that are all substantially different from the initial set of COMT activities reported herein. By facilitating the advancement of science-based models coordinated with supporting observations, the COMT will significantly enhance the nation's ability to predict and manage coastal and ocean risks arising from severe episodic events as well as from longer term environmental and societal change.

Appendix A: References for Models Used in the U.S. IOOS Testbed

Inundation, Surge and Wave Models	
ADCIRC	General Reference: *Luettich et al.* [1992] As configured for current study: *Dietrich et al.* [2010]
FVCOM	General reference: *Chen et al.* [2003]
SELFE	General Reference: *Zhang and Baptista* [2008]
SLOSH	General Reference: *Jelesnianski et al.* [1992]
SWAN	General Reference: *Booij et al.* [1999] Auxiliary Reference: *Zijlema* [2010]
WWMII	General Reference: *Roland et al.* [2009]
WW3 - WAVEWATCHIII	General Reference: *Tolman* [2009]
Shelf Hypoxia Models	
ROMS	General reference: *Haidvogel et al.* [2008] ROMS biological module: *Fennel et al.* [2006] Physical-biological configuration for the Northern Gulf of Mexico: *Hetland and DiMarco* [2008] and *Fennel et al.* [2011]
FVCOM	General reference: *Chen et al.* [2003]
NCOM	General reference: *Martin* [2000] NCOM for regional domains: *Ko et al.* [2008]
IASNFS	NCOM for Intra-America Seas: *Ko et al.* [2003]
HYCOM	General reference: *Bleck and Boudra* [1981] Gulf of Mexico Regional Application: *Prasad and Hogan* [2007]
NGOM – Princeton Ocean Model	General Reference: *Oey* [1996] Specific Reference: *Lanerolle and Patchen* [2011]
Estuarine Hypoxia Models	
ChesROMS—Chesapeake Bay ROMS	Physical Model: *Xu et al.* [2011] Biological (BGC) Model: *Brown et al.* [2012], *Scully* [2013], and *Constantin de Magny et al.* [2009]
CBOFS – Chesapeake Bay Operational Forecast System	Physical Model: *Lanerolle et al.* [2011]
EFDC	Physical model: *Hong and Shen* [2012]
CH3D-ICM	For Chesapeake Bay: *Cerco et al.* [2010]
1-term DO model	*Scully* [2013]

[51] **Acknowledgments.** This project was supported by NOAA via the IOOS Office, award NA10NOS0120063 and NA11NOS0120141, and used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant OCI-1053575. We thank Zdenka Willis and Doug Levin of the U.S. IOOS Office for their support and guidance throughout this project. We are also grateful for the support and encouragement provided by SURA president Jerry Draayer and for the untiring technical and managerial assistance provided by SURA staff members Jeri Marie Cravens, Linda Akli, Russell Moy, Peter Bjonerud, and Thanh Quach. The members of the Testbed Advisory and Evaluation Group deserve special thanks for their expert guidance. These members are

1. Frank Aikman, NOAA/National Ocean Service
2. Art Allen, U.S. Coast Guard
3. Larry Atkinson, Old Dominion University
4. Eric Bayler, NOAA/NESDIC
5. Yi Chao, Remote Sensing Solutions, Inc.
6. Bruce Ebersole, U.S. Army Corps of Engineers
7. Denny Kirwan, University of Delaware
8. Chris Massey, U.S. Army Corps of Engineers
9. Chris Mooers, Portland State University
10. Rick Signell, U.S. Geological Survey (Chair)
11. Aijun Zhang, NOAA/NOS

References

Beardsley, R., C. Chen, and Q. Xu (2013), Coastal flooding in Scituate (MA): A FVCOM study of the Dec. 27, 2010 Nor'easter, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/2013JC008859.

Bever, A. J., M. A. M. Friedrichs, C. T. Friedrichs, M. E. Scully, and L. W. J. Lanerolle (2013), Combining observations and numerical model results to improve estimates of hypoxic volume within the Chesapeake Bay, USA, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20331.

Bleck, R., and D. Boudra (1981), Initial testing of a numerical ocean circulation model using a hybrid (quasi-isopycnic) vertical coordinate, *J. Phys. Oceanogr.*, *11*, 755–770.

Booij, N., R. C. Ris, and L. H. Holthuijsen (1999), A third-generation wave model for coastal regions: 1. Model description and validation, *J. Geophys. Res.*, *104*(C4), 7649–7666, doi:10.1029/98JC02622.

Brown, C. W., R. R. Hood, W. Long, J. Jacobs, D. L. Ramers, C. Wazniak, J. D. Wiggert, R. Wood, and J. Xu (2012), Ecological forecasting in Chesapeake Bay: Using a mechanistic-empirical modeling approach, *J. Mar. Syst.*, *125*, 113–125.

Cerco, C.F., S. C. Kim, and M. R. Noel (2010), The 2010 Chesapeake Bay Eutrophication Model, A report to the US Environmetal Protection Agency Chesapeake Bay Program, US Army Eng. Res. and Dev. Cent., Vicksburg, Miss.

Chen, C., H. Liu, and R. C. Beardsley (2003), An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries, *J. Atmos. Oceanic Technol.*, *20*, 159–186.

Chen, C., et al. (2013), Extratropical storm inundation testbed: Intermodel comparisons in Scituate, Massachusetts, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20397.

Constantin de Magny, G., W. Long, C. W. Brown, R. R. Hood, A. Huq, R. Murtugudde and R. R. Colwell (2009), Predicting distribution of Vibrio spp. in the Chesapeake Bay: Vibrio cholerae case study, *EcoHealth*, *6*(3), 378–389, doi:10.1007/s10393-009-0273-6.

Dietrich, J. C., M. Zijlema, J. J. Westerink, L. H. Holthuijsen, C. Dawson, R. A. Luettich Jr., R. Jensen, J. M. Smith, and G. S. Stelling (2010), Modeling hurricane waves and storm surge using integrally-coupled, scalable computations, *J. Coastal Eng.*, *58*, 45–65, doi:10.1016/j.coastaleng.2010.08.001.

Fennel, K., J. Hu, A. Laurent, M. Marta-Almeida, and R. Hetland (2013), Sensitivity of hypoxia predictions for the northern Gulf of Mexico to sediment oxygen consumption and model nesting, *J. Geophys. Res. Oceans*, *118*, 990–1002, doi:10.1002/jgrc.20077.

Fennel, K., R. Hetland, Y. Feng, and S. DiMarco (2011), A coupled physical-biological model of the Northern Gulf of Mexico shelf: Model description, validation and analysis of phytoplankton variability, *Biogeosciences*, *8*, 1881–1899, doi:10.5194/bg-8–1881-2011.

Fennel, K., J. Wilkin, J. Levin, J. Moisan, J. O'Reilly, and D. Haidvogel (2006), Nitrogen cycling in the Mid Atlantic Bight and implications for the North Atlantic nitrogen budget: Results from a three-dimensional model, *Global Biogeochem. Cycles*, *20*, GB3007, doi:10.1029/2005GB002456.

Friedrichs, M. A. M., et al. (2009), Assessing the uncertainties of model estimates of primary productivity in the tropical Pacific Ocean, *J. Mar. Syst.*, *76*(1–2), 113–133, doi:10.1016/j.jmarsys.2008.05.010.

Friedrichs, M., K. G. Sellner, and M. A. Johnston (2012), Using multiple models for management in the Chesapeake Bay: A shallow Water Pilot Project, *Chesapeake Bay Program Scientific and Technical Advisory Committee Rep. 12-003*, 11 pp., Edgewater, Md.

Haidvogel, D.B., et al. (2008) Regional ocean forecasting in terrain-following coordinates: Model Formulation and skill assessment, *J. Comput. Phys.*, *227*, 3595–3624, doi:10.1016/i.jcp.2007.06.016.

Hanson, J. L., B. Tracy, H. Tolman, and R. Scott (2009), Pacific hindcast performance of three numerical wave models, *J. Atmos. Oceanic Technol.*, *26*, 1614–1633.

Hetland, R., and S. DiMarco (2008), How does the character of oxygen demand control the structure of hypoxia on the Texas-Louisiana continental shelf?, *J. Mar. Syst.*, *70*, 49–62.

Hofmann, E. E., J.-N. Druon, K. Fennel, M. Friedrichs, and the U.S. ECoS team (2008), Eastern U.S. continental shelf carbon budget: integrating models, data assimilation, and analysis, *Oceanography*, *21*(1), 86–104.

Hong, B., and J. Shen (2012), Responses of estuarine salinity and transport processes to potential future sea-level in the Chesapeake Bay, *Estuarine Coastal Shelf Sci.*, *104–105*, 33–45, doi:10.1016/j.ecss.2012.03.014.

Hong, B., and J. Shen (2013), Linking dynamics of transport timescale and variations of hypoxia in the Chesapeake Bay, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/2013JC008859.

Hope, M. E., et al. (2013), Hindcast and validation of Hurricane Ike (2008) waves, forerunner, and storm surge, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20314.

Howlett, E., et al. (2012), The US IOOS Coastal and Ocean Modeling Testbed for Advancing Research to Applications, Mar. Technol. Soc./IEEE, Virginia Beach, Va.

Huang, Y., R. H. Weisberg, L. Zheng, and M. Zijlema (2013), Gulf of Mexico hurricane wave simulations using SWAN: Bulk formula-based drag coefficient sensitivity for Hurricane Ike, *J. Geophys. Res. Oceans*, *118*, 3916–3938, doi:10.1002/jgrc.20283.

Jelesnianski, C. P., J. Chen, and W. A. Shaffer (1992), SLOSH: Sea, lake, and overland surges from hurricanes, *NOAA Tech. Report NWS 48*, 77 pp., Natl. Weather Serv., NOAA, Silver Spring, Md.

Jolliff, J., J. C. Kindle, I. Shulman, B. Penta, M. A. M. Friedrichs, R. Helber, and R. A. Arnone (2009), Summary diagrams for coupled hydrodynamic-ecosystem model skill assessment, *J. Mar. Syst.*, *76*(1–2), 64–82, doi:10.1016/j.marsys.2008.05.014.

Kerr, P. C., R. C. Martyr, A. S. Donahue, M. E. Hope, J. J. Westerink, R. A. Luettich Jr., A. B. Kennedy, J. C. Dietrich, C. Dawson, and H. J. Westerink (2013a), U.S. IOOS coastal and ocean modeling testbed: Evaluation of tide, wave, and hurricane surge response sensitivities to mesh resolution and friction in the Gulf of Mexico, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20305.

Kerr, P. C., et al. (2013b), U.S. IOOS coastal and ocean modeling testbed: Inter-model evaluation of tides, waves, and hurricane surge in the Gulf of Mexico, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20376.

Ko, D. S., P. J. Martin, C. D. Rowley, and R. H. Preller (2008), A real-time coastal ocean prediction experiment for MREA04, *J. Mar. Syst.*, *4*, 17–28, doi:10.1016/j.jmarsys.2007.02.022.

Ko, D. S., R. H. Preller, and P. J. Martin (2003), An experimental real-time Intra-Americas Sea Ocean Nowcast/Forecast System for coastal prediction, paper presented at the AMS 5th Conference on Coastal Atmospheric and Oceanic Prediction and Processes, *Seattle, Wash.*, pp. 97–100, AMS, Boston, Mass.

Lanerolle, L. W. J., R. C. Patchen, and F. Aikman III (2011), The second generation Chesapeake Bay Operational Forecast System (CBOFS2): Model development and skill assessment, *NOAA Tech. Rep. NOS CS 29*, Silver Spring, Maryland.

Lanerolle, L. W. J., and R. C. Patchen (2011), The design, calibration and validation of a coupled numerical ocean modeling system for the West Florida Shelf, *NOAA Tech. Rep. NOS CS 31*, 45 p, Silver Spring, Maryland.

Lehrter, J. C., M. C. Murrell, and J. C. Kurtz (2009), Interactions between freshwater input, light, and phytoplankton dynamics on the Louisiana continental shelf, *Cont. Shelf Res.*, *29*, 1861–1872.

Lehrter, J. C., D. S. Ko, M. C. Murrell, J. D. Hagy, B. A. Schaeffer, R. M. Greene, R. W. Gould, and B. Penta (2013), Nutrient distributions, transports, and budgets on the inner margin of a river-dominated continental shelf, *J. Geophys. Res. Oceans*, *118*, doi:10.1002/jgrc.20362.

Luettich, R. A., J. J. Westerink, and N. W. Scheffner (1992), ADCIRC: An advanced three-dimensional circulation model for shelves, coasts and estuaries, Report 1: Theory and methodology of ADCIRC-2DDI and ADCIRC-3DL, *Tech. Rep. DRP-92-6*, Dep. of the Army, US Army Corps of Eng., Washington, D. C.

Marta-Almeida, M., R. D. Hetland, and X. Zhang (2013), Evaluation of model nesting performance on the Texas-Louisiana continental shelf, *J. Geophys. Res. Oceans*, *118*, 2476–2491, doi:10.1002/jgrc.20163.

Martin, P. J. (2000), Description of the navy coastal ocean model version 1.0, *NRL/FR/7322-00-9962*, Nav. Res. Lab., Stennis Space Cent., Miss.

Mascret, A., T. Devogele, I. Le Berre, and A. Henaff (2006), Coastline Matching Process based on the discrete Frechet distance, *Prog. Spatial Handling*, Springer, 383–400, doi:10.1007/3–540-35589-8_25.

Mattern, J. P., K. Fennel, and M. Dowd (2013), Sensitivity and uncertainty analysis of model hypoxia estimates for the Texas-Louisiana shelf, *J. Geophys. Res. Oceans*, *118*, 1316–1332, doi:10.1002/jgrc.20130.

Ocean.US (2008), The Integrated Ocean Observing System (IOOS) Modeling and Analysis Workshop Report, *Ocean.US Publ. 18*, 21 pp. [Available atwww.ioos.gov/library/mast_report2008.pdf.].

Oey, L.-Y. (1996), Simulation of mesoscale variability in the Gulf of Mexico, *J. Phys. Oceanogr.*, *17*, 145–175.

Prasad, T. G., and P. J. Hogan (2007), Upper-ocean response to Hurricane Ivan in a 1/25° nested Gulf of Mexico HYCOM, *J. Geophys. Res.*, *112*, C04013, doi:10.1029/2006JC003695.

Roland, A., A. Cucco, C. Ferrarin T. W. Hsu, J. M. Liau, S. H. Ou, G. Umgiesser, and U. Zanke (2009), On the development and verification of a 2-D coupled wave-current model on unstructured meshes, *J. Mar. Syst.*, *78*(Suppl. 1), 244–254, doi:10.1016/j.jmarsys.2009.01.026.

Scully, M. E. (2013), Physical controls on hypoxia in Chesapeake Bay: A numerical modeling study, *J. Geophys. Res. Oceans*, *118*, 1239–1256, doi:10.1002/jgrc.20138.

Signell, R. P. (2010), Model Data Interoperability for the United States Integrated Ocean Observing System (IOOS), in *Proceedings of the 11th International Conference on Estuarine and Coastal Modeling*, *Seattle, Wash.*, edited by M. Spaulding, pp. 221–238, ASCE, Reston, Virginia.

Sun, Y., C. Chen, R. C. Beardsley, Q. Xu, J. Qi, and H. Lin (2013), Impact of current-wave interaction on storm surge simulation: A case study for Hurricane Bob, *J. Geophys. Res. Oceans*, *118*, 2685–2701, doi:10.1002/jgrc.20207.

Thacker, W., A. Srinivasan, M. Iskandarani, O. Knio, and M. Le Hna (2012), Propagating boundary uncertainties using polynomial expansions, *Ocean Modell.*, *4344*, 52–63, doi:10.1016/j.ocemod.2011.11.011.

Tolman, H. L. (2009), User manual and system documentation of WAVEWATCH III TM version 3.14. [Available at http://polar.ncep.noaa.gov/mmab/papers/tn276/MMAB_276.pdf.].

U.S. IOOS (2010), U.S. Integrated Ocean Observing System: A Blueprint for Full Capability, Version 1. U.S. IOOS Office, November. [Available at http://www.iooc.us/wp-content/uploads/2010/11/US-IOOS-Blueprint-for-Full-Capability-Version-1.0.pdf.].

Wilkin, J. L., and E. J. Hunter (2013), An assessment of the skill of real-time models of Mid-Atlantic Bight continental shelf circulation, *J. Geophys. Res. Oceans*, *118*, 2919–2933, doi:10.1002/jgrc.20223.

Wilmott, C. J. (1981), On the validation of models, *Phys. Geogr.*, *2*, 184–194, doi:10.1080/02723646.1981.10642213.

Xu, J., W. Long, J. D. Wiggert, W. J. Lanerolle, C. W. Brown, R. Murtugudde, and R. R. Hood (2011), Climate forcing and salinity variability in the Chesapeake Bay, USA, *Estuaries Coasts*, doi:10.1007/s12237-011-9423-5.

Zhang, Y. L., and A. M. Baptista (2008), SELFE: A semi-implicit Eulerian-Lagrangian finite-element model for cross-scale ocean circulation, *Ocean Modell.*, *21*(3–4), 71–96.

Zheng, L., R. H. Weisberg, Y. Huang, R. A. Luettich, J. J. Westerink, P. C. Kerr, A. S. Donahue, G. Crane, and L. Akli (2013), Implications from the comparisons between two- and three-dimensional model simulations of the Hurricane Ike storm surge, *J. Geophys. Res. Oceans*, *118*, 3350–3369, doi:10.1002/jgrc.20248.

Zijlema, M. (2010), Computation of wind-wave spectra in coastal waters with SWAN on unstructured grids, *Coastal Eng.*, *57*, 267–277.