Tidal Prediction Using the Advanced Circulation Model (ADCIRC) and a Relocatable PC-based System

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Introduction

The tide-generating forces that result from the gravitational attraction between the Earth, Sun, and Moon can be precisely formulated. In contrast, the response of the oceans to these forces is subject to modification by non-astronomical factors such as configuration of the coastline, local depth of the water, ocean floor topography, and other hydrographic and meteorological influences. These influences may play an important role in altering the tidal height range, the interval between high and low water, and times of arrival of the tides at a particular location.

The importance of such tidal information is well known to all who work or recreate in or around coastal waters. Knowledge of the times, heights, and extent of the ebb and flood of tidal waters is of importance in a wide range of practical applications, including navigation through intra-coastal waterways; construction of bridges, docks, breakwaters, and deep water channels within bays and harbors; commercial fishing; and recreational boating, surfing, and swimming. The military, in particular the Navy, relies on tidal predictions for operational planning and execution in marine environments. Water depths at high tide can facilitate a beach landing, while later at the same location low tides may strand amphibious vehicles on muddy tidal flats. Tidal currents affect the positioning and/or movement of subsurface mines and Navy SEAL swimmers must gauge their heading based on the strength and direction of the tidal current.

A capability for predicting sea surface elevations and currents forced by the tides is clearly advantageous. Existing tide tables created from historical elevation data are often used for tidal prediction, but their information is either sparsely located or based on outdated coastal geometry and/or topography. Most certainly, tide tables contain little information for coastal waters that extend beyond the shoreline. Modern advances in computing bring to the forefront the numerical model as an alternative means to obtain high resolution, up-to-date forecasts of tidal elevations and currents. Such models can ingest recent bathymetric measurements and include transient meteorological effects such as wind and atmospheric pressure. The spatial and temporal density of the forecast information can be readily tailored to specific applications and needs.

This paper contains details regarding the design of a tidal forecast system subject to the constraints of an operational environment. Specifics of the Navy's tidal prediction system are addressed with descriptions of the numerical prediction models, examples of operational products and results from recent validation tests of the operational forecast system. The paper concludes with a look at recent developments of the modeling system that will likely advance the future operational tidal prediction capability of the Navy.

Tidal Prediction Strategy

Design Criteria

A number of desired criteria come to mind in considering the design of a tidal forecast system. Foremost, a model forecast system should produce accurate values of the tidal heights and currents where accuracy is defined by some predefined range of error. A second characteristic of a successful prediction system is its portability across computer platforms. A machine-independent numerical modeling system can adapt readily to rapid changes in the availability of computer platforms due both to technological advances and user resources. A final criterion is one of mobility. A relocatable model forecast system affords more flexibility to meet the needs of multiple users in relation to the variety of geographic regions and spatial scales desired.

The operational environment poses a number of

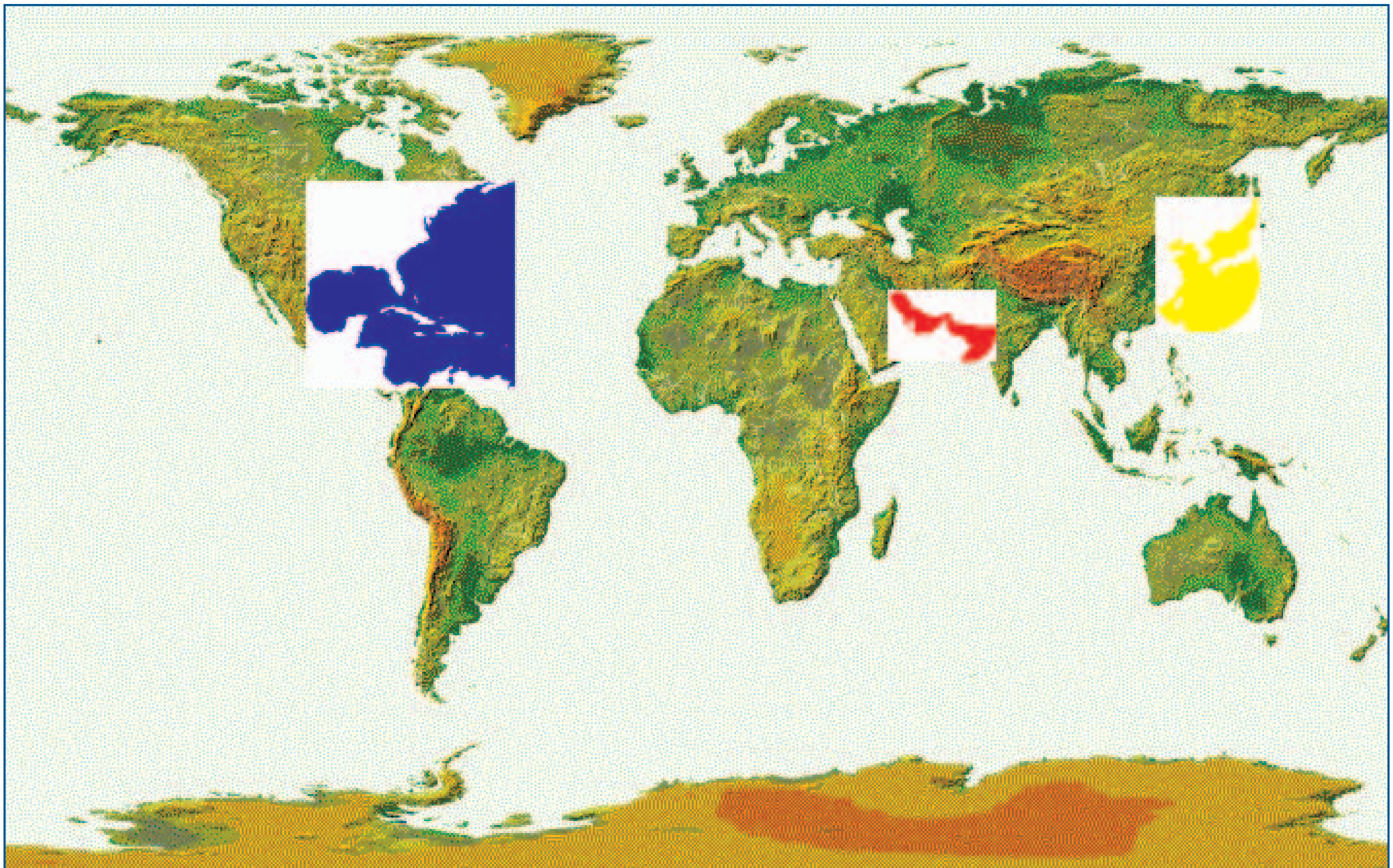

Figure 1. Regions around the world for which the ADCIRC model is run operationally, producing forecasts of tidal heights and currents for the Navy.

additional constraints upon a forecast system. The generation of hourly or daily forecasts of sea surface height and currents must be executed in a fully automated manner, implying all tasks are performed without human intervention. This automation encompasses such tasks as the retrieval of forcing field products (e.g. wind stress, pressure) produced by operational meteorological models, the generation of a computational grid, model set-up and execution, and the creation of forecast products. Furthermore, the model prediction system must have computational run times and interfaces that are consistent with a real-time framework and the user's operational environment. Forecasts of sea surface elevation and currents must be timely and not outdated with respect to real time. Timeliness further constrains computational run-time when time zone differences between the physical location of an executing forecast model and the location of those receiving the forecast information differ substantially.

Navy Tide Prediction

The tidal forecast system currently employed by the Naval Oceanographic Office (NAVOCEANO) and Navy Regional Operational Centers consists of two models, the finite element-based Advanced Circulation Model (ADCIRC; Luettich et al., 1992) and a finite difference, relocatable, PC-based system, PCTides (Hubbert et al., 2001). This model combination is implemented in such as way as to satisfy the goals outlined above for a successful operational tidal prediction system. The ADCIRC model as configured is portable, executing on all available supercomputer and workstation platforms, and computationally efficient. Accuracy of the model is corroborated by years of successful tidal prediction well documented in the literature, making the ADCIRC model a logical component of any tidal prediction system (Westerink et al., 1994; Luettich and Westerink, 1995; Grenier et al., 1995; and Blain and Rogers, 1998). The grid flexibility of the unstructured mesh afforded by the finite element method is unparalleled. However, such flexibility comes at a price. In the recent past, the generation of unstructured grids has been tedious, with considerable human intervention and skill required. Automated grid generation utilities are under development in a variety of forms, but none are presently suitable for the operational environment. Consequently, limitations exist on the capability to rapidly relocate ADCIRC model applications. Thus, in the context of the Navy's tidal prediction system, the ADCIRC model is applied regionally over pre-existing computational meshes. Currently operational forecasts are produced for three regions around the globe (Figure 1). One application is an oceanic basin adjacent to U.S. coastal waters, the western North Atlantic Ocean. The remaining two regions encompass semi-enclosed seas, the Yellow Sea and the Sea of Japan in Asia, and the Arabian Gulf and Gulf of Oman in the Middle East. Computational grids for these regions are created such that their open ocean boundaries extend into deep ocean waters, where water depths are greater than 1000 m. This strategy facilitates an interface with established databases for global tidal models utilized for open ocean tidal forcing, while simultaneously minimizing the influence of these boundary values on coastal tide predictions.

To address the issue of relocatability, the Naval Research Laboratory (NRL) has developed a rapidly relocatable, global prediction capability for tidal heights. The capability is utilized for locations where neither observations nor a regularly run operational tidal prediction model, such as ADCIRC, exists. Requirements for such a model are that it be rapidly configured for the location of interest and that it execute quickly on the available computers. The resultant prediction system, called PCTides, executes on both PC and UNIX-based platforms. Whereas the ADCIRC model is configured for regions covering more than 10 degrees of latitude and longitude, the PCTides system is usually applied over much smaller areas. Typical regions for a PCTides application span a box of dimension 300 km to 1000 km with a typical resolution range between 3 km and 10 km. PCTides with its structured and regular grids is inherently rapidly relocatable. As such PCTides is employed as the need arises in areas external to ADCIRC applications.

Description of the Forecast Models

ADCIRC

Operational tidal forecasts of sea level and currents are derived first, if regionally available, from computations of the fully nonlinear, two-dimensional configuration of the constant density coastal circulation model, ADCIRC (Luettich et al., 1992). The ADCIRC model is based on the well known shallow water equations (Le Mehaute, 1976) that are derived from vertical integration over the water column of the three-dimensional mass and momentum balance equations and subject to the hydrostatic and Boussinesq approximations. The frictional stress at the seabed is represented using a standard quadratic law based on the current magnitude squared. For tidal dynamics at scales currently considered (i.e. one half to tens of kilometers), lateral mixing effects are not important and are thus not considered. While shoreline inundation and dewatering can be of significance in nearshore and estuarine environments, this mechanism is inconsequential at the spatial scales of present operational applications and is not activated. The interested reader can find further details of the derivation and numerical discretization of the ADCIRC model equations in Kolar et al. (1994). For a complete listing of publications relating the development and implementation of ADCIRC see the current ADCIRC User's Manual online: http://www.unc.edu-/depts/marine/C_CATS/adcirc/.

Tidal forcing for the operational implementation of ADCIRC consists of body forces (astronomical gravitational and acceleration forces) that account for the Newtonian equilibrium tidal potential and Earth tides, a measure of the rigidity of the Earth's surface (Reid, 1990), and open-ocean boundary elevations derived from eight tidal harmonic constituents (M2, S2, K2, N2, O1, K1, Q1, 2N2). Data for the open ocean boundary forcing are extracted from Finite Element Solutions (FES) versions 95.1/2.1 (Shum et al., 1997), an archive of global tide predictions generated by the model of Le Provost et al. (1994). Surface wind stress and atmospheric pressure fields produced by the Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond, 1991) are also applied as forcing. Resolution of the NOGAPS products is rather coarse at 1.0 degree. Higher-resolution operational products, such as the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS; Hodur, 1997; Hodur and Doyle, 1999) exist but often do not completely cover the domain of an ADCIRC application. For the latest information on the NOGAPS and COAMPS operational models, the reader is referred to articles by Rosmond et al. (NOGAPS) and Hodur et al. (COAMPS) in this issue of Oceanography.

The ADCIRC model has an extensive and successful history of both tide and storm surge prediction in coastal waters and marginal seas (Westerink et al., 1994; Blain et al., 1994; Luettich and Westerink, 1995; Blain, 1998; Fortunato et al., 1998; Luettich et al., 1999). The model is well suited to tidal prediction because of its computational efficiency that is in part due to implementation of the finite element method and the use of an iterative sparse matrix solver. One can expect to complete simulations that extend from months to a year and employ 30-second time-step increments expediently and without unreasonable storage requirements. For example, a model of the western North Atlantic Ocean containing 36,185 points completed a 250-day simulation of the tides after using only 103 hours of CPU on a CRAY SV1 (single-processor speed of 500 MHz). As such, real-time forecasting (e.g. 48 hour forecasts) is well within reach of the ADCIRC model. A schematic depicting the configuration of the ADCIRC model as implemented at NAVOCEANO is presented in Figure 2.

The finite element method utilized by the ADCIRC model is a technique that converts the model equations to a discrete form and allows computation of the solution over irregular, spatially unstructured meshes. The unstructured mesh partitions the region of application into elements of variable horizontal size; ADCIRC

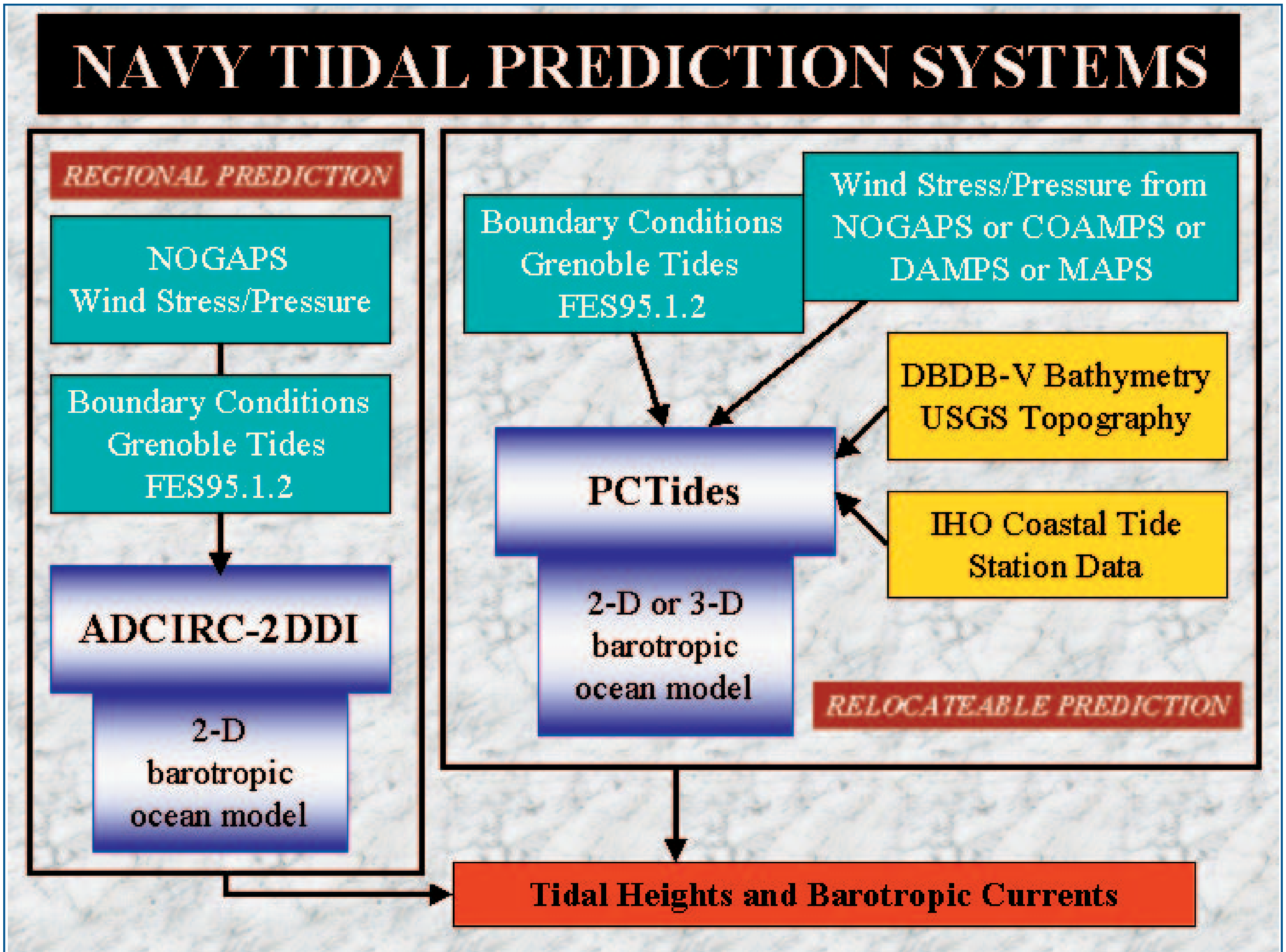

Figure 2. *A schematic depicting operational configurations of the Navy Tidal Prediction Systems.* ***(Left)*** *a regionally focused finite element model, ADCIRC, and* ***(Right)*** *the relocatable, PC-based system, PCTides. Forcing input to the system is colored green, databases for assimilation or bathymetry are colored yellow, the models are blue, and the computed products are in red.*

employs triangular elements. The primary advantage of this approach is that the detail of the coastline can be more accurately represented and topographic features better resolved by using many small elements. A further advantage is the ability to define computational domains that are substantially larger than those typically constructed for a structured grid model for the same computational cost. The reason for this is that in regions of the domain where the tidal dynamics are not highly variable, e.g., smooth topography or deep waters, large elements can be used. The result is a larger domain whose ocean boundaries are located in the deep ocean, where tides are small and their specification will have a lesser impact on the shallow-water regions of interest. Figure 3 illustrates the powerful nature of unstructured triangular meshes. A remaining feature of the ADCIRC model is its facility for timely and complete run-time harmonic decomposition for specified components of the tidal signal. This feature facilitates model comparisons to historical tide station data that are primarily archived in terms of the amplitudes and phases of various tidal frequencies. Ultimately, the ADCIRC model formulation leads to an accurate, physically realistic, and expedient prediction capability for tides.

Relocatable PC-based Model

The second component of the Navy's operational tide prediction capability is the PC-based relocatable modeling system, PCTides. Figure 2 depicts a schematic of the PCTides forecast system. At the core of the PCTides system is a constant density ocean model that can be exercised in either a two-dimensional (2-D) or a three-dimensional (3-D) form. The 2-D version is a

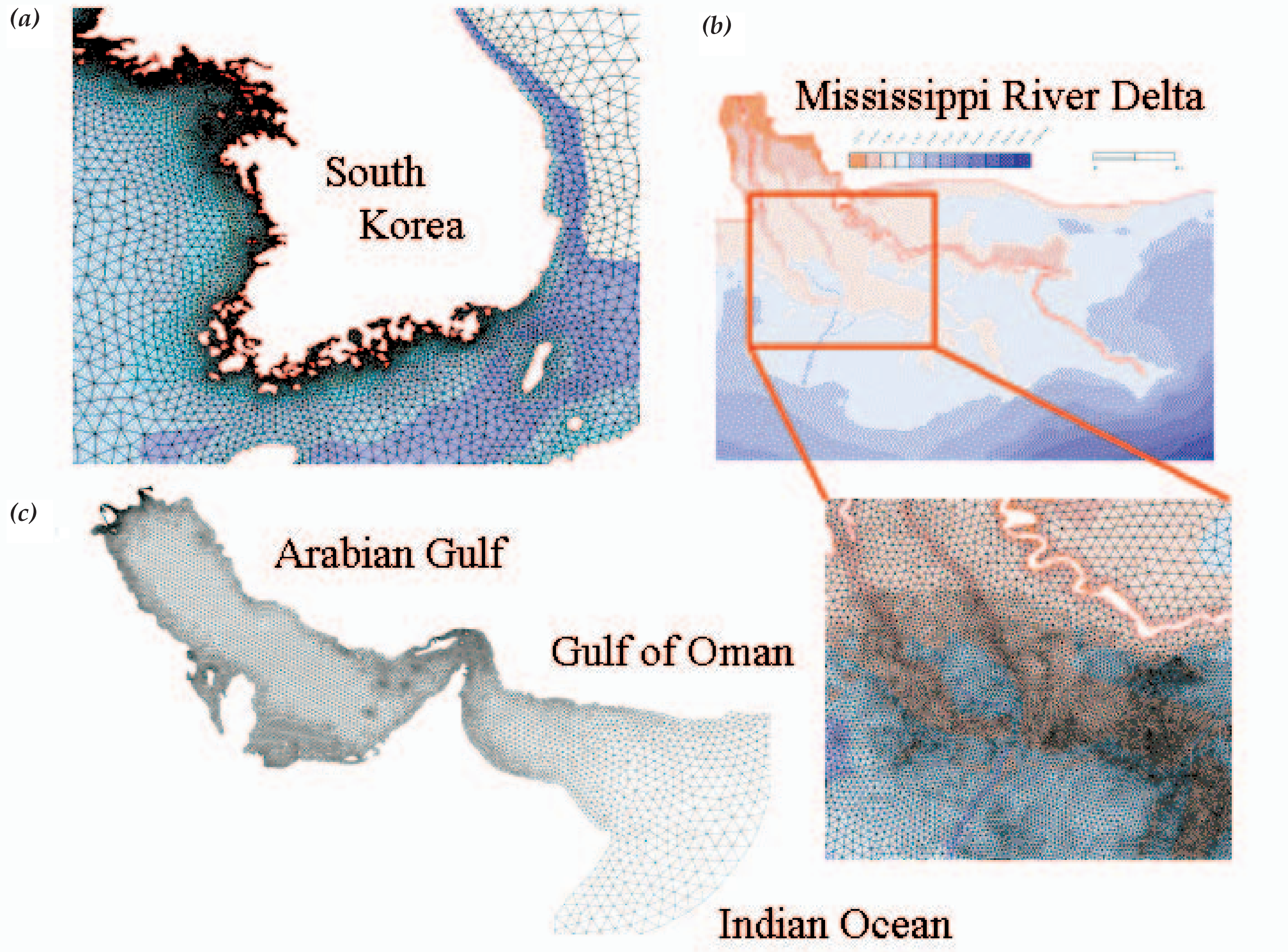

Figure 3. Examples illustrating the flexibility of an unstructured mesh for: ***a)*** *resolution of fine-scale coastline detail,* ***b)*** *resolution of bathymetric complexities, and* ***c)*** *utilization of large domains with deep ocean boundaries.*

depth-integrated shallow-water model (similar in theory to the ADCIRC model equations) designed to model both currents and sea level heights on or near continental shelves. It contains a wetting and drying algorithm for the simulation of coastal flooding due to tides and/or storm surge. The 3-D model is used when current structure with vertical depth is required for locations where tide and wind forcing dominate. A data-assimilative component is present within PCTides so as to loosely constrain (via a weighted nudging approach described by Hubbert et al., 2001) computed tidal heights using known sea-level elevations at available tidal stations. The user has the option to activate or inactivate the 3-D mode, wetting and drying, and/or the data assimilation capabilities. The most prevalent implementation of PCTides is in its 2-D mode using data assimilation with no wetting/drying mechanism active.

All databases required for operation, except for the wind forcing, are internal to the PCTides system. This is an important feature that defines PCTides as a "stand-alone system," providing global tidal-height forecasts without any external input. The types of databases necessary and those contained within PCTides include bathymetry, tidal boundary forcing data, and tidal station data for assimilation. The bathymetry database is a 3-minute interpolated version of the U.S. Navy's DBDB-V database (NAVOCEANO, 1997) that includes the higher-resolution bathymetry data at their native resolution. Similar to ADCIRC, eight tidal harmonic constituents (M2, S2, K2, N2, O1, K1, Q1, 2N2) located at the open water boundaries of the ocean model are extracted from FES95.1/2.1 solutions (Shum et al., 1997). Although the total "tide" is defined by a much larger set of harmonic constituents, these eight constituents provide a large percentage of the total tide. Lastly, tidal station data are taken from the International Hydrographic Office (IHO) database

(IHO, 1979). The IHO data, approximately 4,500 coastal stations, are used for either model validation or for data assimilation.

PCTides also contains a mesoscale atmospheric prediction system (MAPS) that uses the NOGAPS fields for boundary and initial conditions. This model can be run to produce high-resolution winds that drive the ocean model. However, a special MAPS forecast is not usually generated. Instead, winds from either the NOGAPS or the higher-resolution COAMPS or the Distributed Atmospheric Mesoscale Prediction System (DAMPS), a system similar to COAMPS that is operated at Navy regional centers, are available in real-time for use in PCTides forecasts. These real-time operational wind fields are available via the Navy's Metcast system. This system allows a user to request specific real-time atmospheric forecast products. For additional information on Metcast, see http://zowie.metnet.navy.mil/spawar/.

PCTides was specifically designed to be user friendly. It contains a graphic user interface (GUI) that allows the user to select a region from a global map using a "point and click" technique and to select the resolution of the model grid. Bathymetry and open water boundary conditions are interpolated to this grid. The user inputs the latitude and longitude of station locations where he/she requires a forecast as well as the starting date and length of the forecast. In a case where wind forcing is desired, the length of the available wind forecast determines the length of the tidal height forecast. Output from the system may be viewed as a graphic or a text file of the tidal height time series at specified locations. The average PCTides 48 hour forecast takes anywhere from 3 to 10 minutes of run time on a 500 MHz PC.

Operational Validation

Models that are developed toward operational use must go through a rigorous evaluation. This operational evaluation (OPTEST) determines if the accuracy of the model forecasts is acceptable for Navy use and if the model can "operate" within the operational runtime requirements. The parameters of an OPTEST, such as the model configuration, location of testing, form of the model-data comparisons, and criteria for determining success, are agreed upon a priori and are defined according to the purpose of the forecasts and the overall operational forecast strategy. Both tidal models, PCTides and ADCIRC, have gone through or are currently undergoing (as in the case of PCTides) this evaluation.

OPTEST Descriptions

A side-by-side evaluation of both ADCIRC and PCTides was conducted in the western North Atlantic Ocean during the ADCIRC OPTEST. For ADCIRC, the domain of application (Figure 4) includes coastal regions off the eastern United States and Canada, the Gulf of Mexico, the Caribbean Sea and extends out to 60°W in the deep waters of the Atlantic Ocean. Resolution varies from 0.5 km to 45 km. For PCTides, a large domain (large rectangle depicted in Figure 4) similar in coverage to the ADCIRC model domain was used along with two higher-resolution (4 km versus 9 km for the large domain) nested grids covering smaller local regions (e.g. small rectangle shown in Figure 4). The two regional grids were centered on Chesapeake Bay (shown in Figure 4) and the New York/New Jersey coasts and are more representative of typical PCTides applications. The OPTEST period ran for approximately one month, July 19-August 17, 2000. Operational wind stress and surface pressure fields from the NOGAPS model were applied over this same period. For the OPTEST, each of the models ran daily, generating forecasts of tidal heights and currents. Model predictions were compared to real-time coastal observations of tidal deviation from the mean water level made available through the following National Oceanic and Atmospheric Administration (NOAA) website: http://www.co-ops.nos.noaa.gov/. The ten coastal stations identified for evaluation purposes are Sandy Hook and Atlantic City, NJ; Windmill Point, Kiptopeke, Sewells Point, and Chesapeake Bay, VA; Duck, Springmaid Pier and Fort Pulaski, NC; and St Augustine Beach, FL.

The ADCIRC model forecasts consist of a six-day run that includes a three-day ramp-up of the applied forcing, a one-day nowcast, and two days of forecast. The ADCIRC operational run stream completes within 2.5 hours on a 500 MHz CRAY SV1 for a grid composed of 31,435 computational points. Hourly and half-hourly elevations and depth-averaged currents are saved at all computational points in the mesh as well as at the preselected station locations. Figure 5 contains an example of an operational tidal elevation product that is generated for pre-defined stations. For PCTides, on each day of the OPTEST, a 48-hour forecast of tidal height deviations from mean sea level are produced on all three grids. A 24-hour "spin-up" period prior to the forecast is included. The PCTides run stream for all three grids completes within 30 minutes on a 300 MHz Pentium II, Windows 98 desktop PC. Three-hourly elevations and depth-averaged currents are saved at every grid point while at the pre-defined stations, elevations and depth averaged current values are saved every 12 minutes. An example of an operational product generated by PCTides is shown in Figure 6 for the Chesapeake Bay region.

OPTEST Results

The computed 24-hour forecasts for both models were evaluated qualitatively, by visual inspection of predicted tidal time series plotted against the observed tidal deviations, and quantitatively, by calculating standard statistical error measures. Accuracy of the model predictions was labeled acceptable if the root-mean-square error (RMS; squared difference between computed and observed sea levels) for each station was less

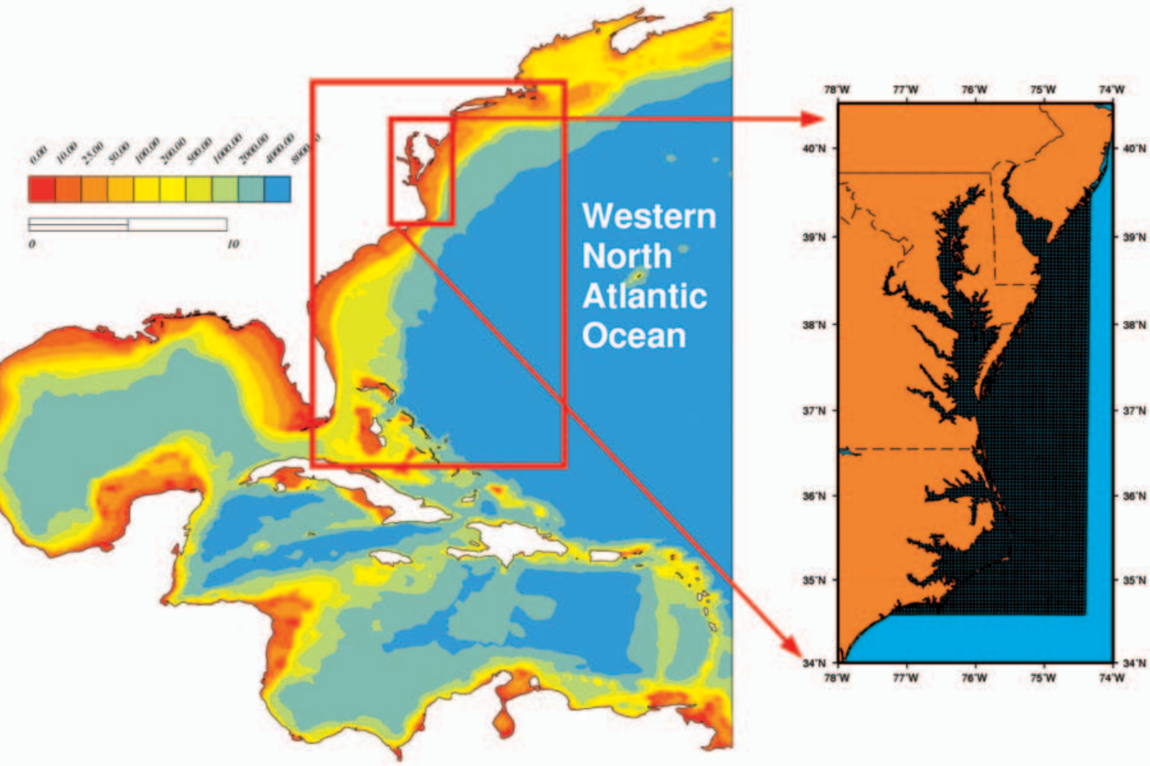

Figure 4. Relative domain sizes for the ADCIRC and PCTides operational model applications. Bathymetry for the ADCIRC OPTEST region in the western North Atlantic ocean is overlaid by boundaries of the PCTides OPTEST nested grids. The PCTides high resolution (4 km) grid centered on Chesapeake Bay is also shown. ADCIRC model resolution ranges from 0.5 to 45 km.

than 20 cm. The interpretation of this error level would vary, depending upon the tidal climate in a given region of application. Another criterion, the relative error (e.g. predicted tidal heights must be within 20% of observed sea-level magnitudes) offers an independent indication of model skill when comparing predictions across different regions.

At the ten coastal stations identified for the OPTEST, the mean RMS errors associated with the ADCIRC model predictions ranged between 9 and 15 cm for tidal amplitude with a mean amplitude of 11 cm (Figure 7a). The ADCIRC predictions also contained a mean phase error, related to the timing lag, of 23 minutes (see Figure 7b). For PCTides, the RMS error in the tidal amplitude was approximately 10 cm, and the error in the phase, or the timing of the high and low water, was approximately 24 minutes. These errors for both models fall within the acceptable Navy standard.

For PCTides, a similarly constructed OPTEST was repeated for a domain covering coastal waters off the western coast of the United States. Evaluations of the model were based on comparisons at four NOAA coastal stations. In this case, the RMS error in the tidal amplitude was 10 cm and the RMS phase error was 20 minutes. Further testing was conducted at several additional locations around the globe where NRL personnel constructed sample grids and compared model forecasts to tidal predictions generated from IHO coastal tide station data. These extensive evaluations provided confidence in the forecast skill of the model when utilized in a relocatable mode.

Upon completion of these evaluations, the PCTides system was installed at two of the U.S. Navy's regional forecasting centers (Norfolk, VA and San Diego, CA) and is presently running through an operational evaluation (OPTEST) at these centers. Each center is exercising the PCTides model at locations where they have interest in forecasting and have NOAA observations for evaluation. During this OPTEST period, NRL is replicating these PCTides applications and posting forecast tidal heights and observations to a website accessible by the centers (see Figure 6 as an example). The primary purpose of this duplication is to provide the centers with a means to check their implementation of the PCTides and conduct a qualitative evaluation of the forecast against the observations. Such "sample" websites also assist the operational centers in assessing how best to display model forecast products. Upon comple-

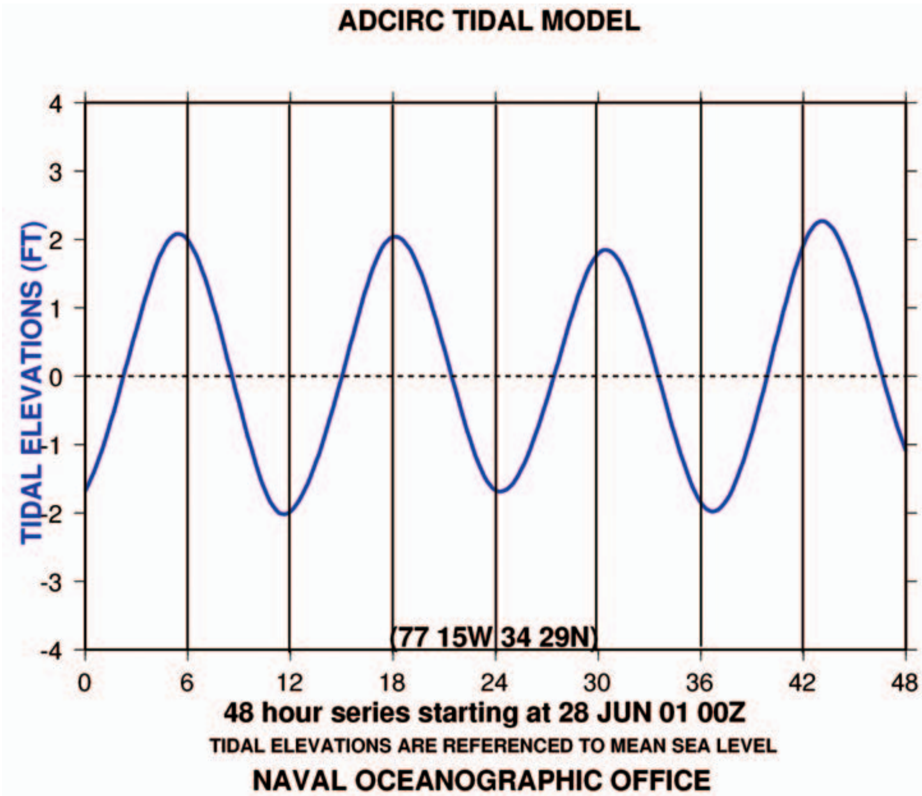

Figure 5. *Sample ADCIRC operational forecast product for tidal elevation. Predicted 48 hour tidal elevation time series starting June 28, 2001, 0Z at station location 77°15'W, 34°29'N.*

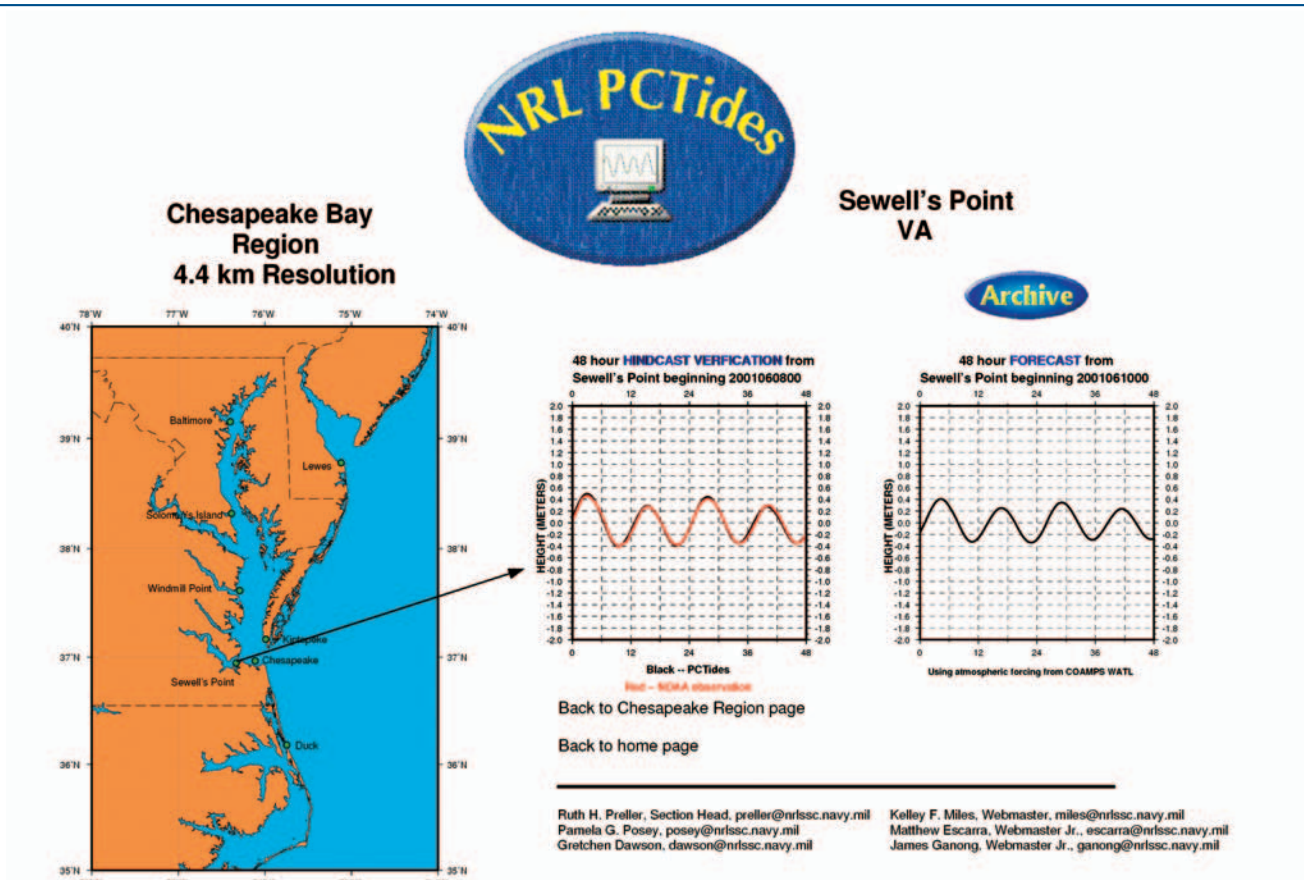

Figure 6. *Sample PCTides operational product for the Chesapeake Bay regional grid including a map of the Chesapeake Bay model domain and the 48-hour forecast and hindcast with observations overlaid for June 10, 2001, at the Sewell station.*

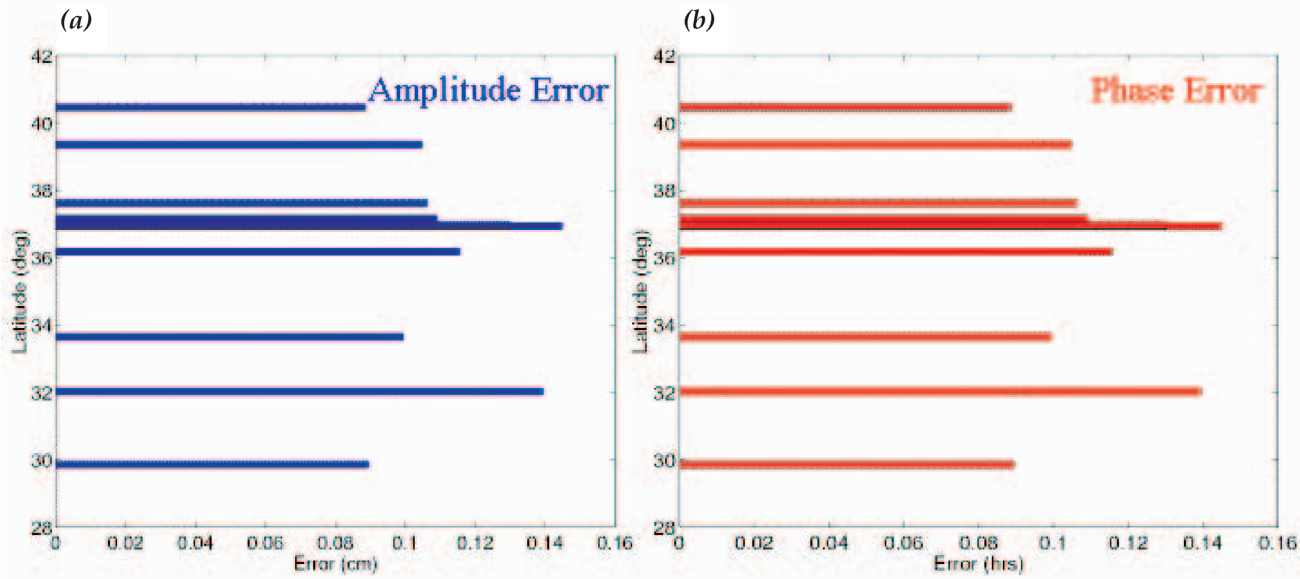

Figure 7. The OPTEST errors for tidal ***a)*** *amplitude and* ***b)*** *phase associated with ADCIRC model tidal elevation predictions at 10 coastal stations located in the western north Atlantic ocean.*

tion of the formal OPTEST, the centers provide NRL with feedback on both the model skill and its products. NRL, in turn, uses these comments to revise and tailor the PCTides system to more directly meet the needs of its operational users. Evaluation for final operational acceptance follows.

Recent Advances in Modeling Capability

In the shallow waters of coastal regions, tidal effects comprise only one portion of the circulation dynamics present. Wave action in the nearshore leads to the generation of longshore and rip currents. Sea breezes and offshore winds directly affect both the wave climate and local currents while freshwater river discharge can create gradients in water density that also drives flow. The variability of the bathymetry and complex shorelines further add to the complexity of coastal circulation. The nonlinearity inherent in coastal dynamics results in intricate interactions between each of these processes. A comprehensive coastal model that can accurately represent the full range of dynamical scales and forcing will lead to considerably better forecasts of the coastal environment.

The ADCIRC model strives to be such a model, and thus, contains mechanisms for shoreline inundation and dewatering of tidal flats, the inclusion of freshwater river inflows, and wave-current interaction. Most recently ADCIRC has been shown to be effective at simulating wave-induced flows in the surf zone, e.g. longshore currents and rip currents, generated by breaking waves (Blain and Cobb, 2002; Cobb and Blain, 2001). While flooding/drying is currently represented by switching on/off individual grid elements, an approach to allow infiltration into the porous substrate at the seabed is under investigation. The result will be a more physical approach that conserves water and can more readily interface with groundwater and overland flow models. Baroclinic dynamics that govern the influence of density gradients produced by river inflow or evaporative heating is also under testing in coastal embayments.

As the drive to forecast small-scale dynamics necessitates computational mesh resolutions on the order of meters, limited area domains become a requirement. Such regions of application contain large open water boundaries located in the midst of dynamically active regions, making the specification of boundary values difficult. One would like to utilize available observations in defining appropriate boundary values for sea level and currents. A data assimilative capability based on the use of linear adjoint models provides just such a tool. The methodology of Lynch et al. (2001) is being applied in a variety of coastal regions to generate appropriate open ocean boundary forcing based on available observations. This approach not only facilitates the use of limited area models but also allows general improvement of predictions of coastal circulation. At this time, considerable testing is required to fully understand the ramifications and appropriate use of this data-assimilative capability within an operational setting.

Lastly, the relocatability of unstructured grid models is being addressed through the development of automated grid-generation techniques. Zhang and Baptista (2001) have constructed a means to generate unstructured grids that are optimal in terms of the uniformity and minimization of errors associated with the discrete mesh. This approach neutralizes errors associated with the computational mesh for any given application. Error measures may be defined by any number of criteria, including mass conservation, energy conservation, and truncation errors associated with the discrete model equations. Other semi-automated tools for mesh generation have been developed at NRL, but for all techniques several components still impede full automation. The mismatch of bathymetric and shoreline data is an ever-present problem. Delineating the land-water interface in regions of tortuous coastline and a final sweep to eliminate elements whose angles are too skewed for reasonable numerical computations remain difficult tasks to automate in the context of mesh generation. Still motivation is high to achieve full relocatability for unstructured mesh models. These ongoing developments associated with unstructured mesh coastal circulation models, and ADCIRC in particular, will ultimately improve the operational capabilities of such models.

Though the Navy will continue to use PCTides in its present form as a rapidly relocatable, self-contained, constant density tide-surge forecast system, future model development, particularly with regard to advances in the physics of coastal ocean models, will focus on ADCIRC. Future changes to the PCTides system will consist only of upgrades to the existing databases as higher resolution bathymetry, more accurate global tidal solutions, and additional tide station data become available. These upgrades will ultimately improve the operational forecasts from PCTides.

Summary

The current Navy tidal prediction system, comprised of the models ADCIRC and PCTides, addresses the need for timely forecasts of sea level and currents in coastal waters. ADCIRC provides forecasts over predefined regions that span more than 10 degrees, i.e. the western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea; the Yellow Sea, Sea of Japan, and western Pacific Ocean; and the Persian Gulf, Gulf of Oman, and portions of the Indian Ocean. The unstructured computational grid associated with the finite element-based ADCIRC model presently is not capable of being rapidly relocated around the globe. A PC-based 2-D and 3-D constant density ocean model, PCTides, serves in this capacity. The structured finite difference grid associated with this model is inherently relocatable. Both models have been tested in the operational environment and are found to produce sea-level forecasts that are within 10 cm of observed values and are no more than 30 minutes in error from the actual times of high and low tide.

Advanced developments in the coastal dynamics of the ADCIRC model together with the implementation of data assimilative techniques, and the creation of an automated grid-generation utility for unstructured meshes will greatly enhance the forecast capability of the Navy in coastal environments.

An additional challenge for operational forecasting is how best to represent the products of increasingly sophisticated and complex coastal ocean models. Forecast products must remain informative, address user needs, and be readily interpreted. Possibilities for future products include the use of probabilistic data alongside the deterministic forecasts. Means, ranges, and maximum likelihood of exceedance are some examples. Scenario-based products may be more practical for use in the field. One example of such a product would be a series of current field predictions derived using a variety of wind conditions. The user would then select the appropriate forecast given local wind information. It is not enough to develop state-of-the-art numerical prediction models for sea level and coastal currents. Forecasts from these models must be communicated in an efficient and appropriate manner to the user community.

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