PAPER

High Resolution Modeling of Coastal Inundation: User Requirements and Current Practice, a Navy Perspective

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ABSTRACT

The impact of coastal flooding and inundation on Navy operational missions and the existing Navy requirements for resolution and accuracy relevant to coastal inundation are presented. High resolution (less than 500 m) coastal models exercised operationally at the Naval Oceanographic Office are reviewed, summarizing the advantages, disadvantages and typical spatial resolutions of each. The present state of Navy coastal inundation modeling from a research and development perspective is presented along with highlights of planned advances in the near-future. Lastly, the gaps between users, products, data and research and development are illuminated. Fine-scale bathymetry and topography as well as *in situ* currents for validation are required for accurate, high resolution inundation modeling. Gaps between the needs of Navy users and the type and form of operationally available inundation products are identified and discussed. The need for usability, relocateability, and expediency in the operational setting contribute in large part to the delay in transitioning model capabilities from research and development to operations.

1. Introduction

Throughout modern history, amphibious assaults and landings have been a mainstay of U.S. Navy operations. The vulnerability of these landing craft to capsizing, swamping, stranding, and filling with sand and water was clearly realized following a post-World War II review of amphibious operations reports (USACE, EM 1110-2-1100, Part I, 2002). Many amphibious landing casualties and problems during World War II could be attributed to the waves, currents, and water levels of the local environment. During the U.S. invasion of Incheon Harbor in the Republic of Korea September 15, 1950, SeaBees constructed pontoon causeways and piers that compensated for the extreme tidal range (-.60 meters to +9.80 meters) and extensive mud flats in the harbor. Even so, a U.S. Navy Tank Landing Ship (LST) was stranded during low tide near the Tidal Basin on Incheon's waterfront, during the post-assault buildup, Sept. 20, 1950 (Figure 1).

More than fifty years later, the Navy still finds inundated environments challenging for operations. Since the declaration of a "Global War on Terror" following the events of September 11, 2001, military operations are increasingly focused on special operations that take place in coastal environments such as estuaries, shallow waterways, and inland rivers. The occurrence of inundation in these operational theaters is typically caused by extreme tidal ranges, precipitation-induced flooding events, and/or wind-induced setup that directly affect the insertion and movement of Special Forces. Navy Special Forces routinely insert themselves into riverine and estuarine environments where the only known information may be an outdated,

FIGURE 1

Tank Landing Ship (LST) stranded at low tide, Incheon, Korea, September 20, 1950. *Official U.S. Navy photograph, now in the National Archives Collection.*

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perhaps 30-year old, topographic map. No information regarding the river banks, heights, vegetation, water depth, or upstream discharges are available. Furthermore, areas that are subject to inundation processes are often located at the cusp of the land–sea interface where algorithms for processing satellite imagery break down or are sub-optimal.

Inundation from storm surge is also a concern for stateside Navy installations. The two major homeports for the Navy's East Coast Fleet (Norfolk, VA, and Mayport, FL) are both vulnerable to Atlantic hurricanes. A decision to relocate the Norfolk harbor fleet, for example, could cost $5 million and would need to take place three days in advance of a predicted landfall in order to recall personnel and ready ships in maintenance or overhaul for evacuation (USWRP Program Plan, 2003). The Naval base at Pascagoula, MS, located on the Gulf of Mexico was directly impacted by Hurricane Katrina, August 29, 2005. Major infrastructure damage was sustained (Navy Newsstand, 9/17/2005, Story Number NNS050917-09, www.news.navy.mil). Additionally, two destroyers and an amphibious assault ship under construction at Litton-Ingalls Shipbuilding were significantly impacted by Hurricane Katrina (Navy Newsstand, 8/20/2006, Story Number NNS060820-01, www.news.navy.mil). Furthermore, the recommendation for closure of the Pascagoula Navy Station by the Base Realignment and Closure Committee (BRAC) 2005 noted the hurricane hazard as a contributing factor for closure.

The current need for accurate prediction of inundation fortunately coincides with the availability of significantly increased computational capacity, one that accommodates very realistic, high resolution numerical model simulations. High spatial resolution (10 – 100 m) is necessary to capture the topographic variations that are so fundamental to inundation processes. Other factors affecting inundation are surface and bottom frictional effects. Traditional uncertainties in model parameterizations of the bottom friction and surface wind drag are just now being addressed through the use of fine-scale remotely-sensed data. Many of these advances are found only in the research and development realm. The challenges of transitioning these advances into an operational mode for Navy applications lie in automation and robust application to multiple geographic regions worldwide.

Within this paper the general role of inundation processes in Navy operations is first discussed, citing known requirements and articulating existing needs. Following is a survey of current Navy modeling practices for inundation prediction, from both an operational and research and development perspective. Lastly, gaps between Navy needs and requirements and operational practice are identified. A way forward is presented based on existing and planned research and the technology needed to bridge the gap to operations. From the Navy perspective, high fidelity prediction of inundation-related events is the path for cost reduction with regard to inundation, where cost is defined by the loss of life and equipment.

2. User Requirements

Inundation affects Navy operations throughout the coastal environment from rivers to estuaries to open coasts. Inundation processes are quite sensitive to the underlying bathymetry and topography, the type and height of vegetation, and sediment properties. Since the Navy operational theater is worldwide, typically in non-U. S. waters, such detailed information is often unavailable. Operational planning can be affected not only by the extent and magnitude of the inundation, but also by the timing of an inundation event. For example, tidal flats or river banks that are not currently wet but were recently wet by inundation processes will have different trafficability and soil strength properties than if they had remained dry over the same time period. These changes in the operational terrain are critical to the successful deployment of Navy landing craft and Special Forces moving on foot or by shallow draft boats.

Navy requirements for inundation, specified in the context of water levels, tidal heights and times, and currents, are very fine-scale in their spatial and temporal resolutions to account for the variability of coastal processes relevant to mission operations and the consequences of failure that include loss of life.

Despite the acknowledgement that inundation events and processes affect Navy operations, the prediction of inundation *per se* has not been a priority for the development of Navy operational products or modeling. As such, there are no explicit resolution requirements for inundation or inundated areas. The Functional Area Analysis (FAA) for Department of Defense (DOD) Requirements for Natural Environment Parameter Collection (CNMOC, 2006) does address specifics for the characterization of tides, water levels and currents in the coastal nearshore and littoral environment. Table I summarizes the user requirements set forth in this document. The "Accuracy Value" in Table I refers to the percent error of the prediction at any location relative to the observed value while the "Accuracy Mapping" error is the tolerance in space for simulated minus observed differences. "Timeliness" references currency of the predicted value. The opera-

TABLE 1

A Summary of Navy Operational Requirements for Tides, Water Levels and Currents*

Element	Resolution			Accuracy	Timeliness
	Horizontal	Vertical	Temporal	Value, Mapping	
Tide Height	1.0 m	0.5 m	1 hr	10%, 5 km	3 hr
Tide Time	1.0 m	0.5 m	1 hr	10%, 5 km	3 hr
Water Depth	25 m	0.5 m	daily	5%, 10 m	4 hr
Current direction	1 deg	10 deg	1 hr	5 deg, 100 m	15 min
Current Speed	12.8 cm/s	12.8 cm/s	1 hr	12.8 cm/s, 100 m	15 min
Current Time	10 m	10 m	1 hr	15 min, 1 km	10 min

*Extracted from the Functional Area Analysis (FAA) for Department of Defense (DOD) Requirements for Natural Environment Parameter Collection, CNMOC 2006.

tional run time of a predictive simulation directly impacts the timeliness of the predicted variable. Other military requirements relating to water visibility, vegetation, and soil moisture will certainly be influenced by inundation processes but, interestingly enough, these parameters are often defined as Air Force requirements and have not received much emphasis in the support of Navy operations. This can be understood in the context that the written requirements for environmental variables sometimes evolve more slowly than do the actual needs of the operational forces. Aside from the formal process that generates written requirements, there are only *ad hoc* avenues for the forces or "end users" to communicate actual needs to the operational modeling community.

3. Current Practice

A. Operational Modeling

The Naval Oceanographic Office (NAVOCEANO) is the primary operational center for execution of Navy operational oceanographic prediction systems and the dissemination of resulting model products to the fleet. Operational oceanographic support at NAVOCEANO is divided by scale into global, regional, and local systems with two primary modes of operation, scheduled and rapid-response. Scheduled applications run every day, producing pre-defined oceanographic products (often graphical in nature) at specific intervals. At present, there are no high resolution (defined by spatial scales less than 500 m) coastal prediction systems run as scheduled operations at NAVOCEANO. Coarser resolution operational coastal systems, run daily, are regional models based on the Shallow Water Analysis and Forecast System (SWAFS) (Horton et al., 1997) and the Navy Coastal Ocean Model (NCOM) (Martin, 2000). One example, the regional, 1/16 degree prediction system for the East Asian Seas, NCOM-EAS16 (Riedlinger et al., 2006), produces a 2-day hindcast and 3-day forecast of three-dimensional fields for temperature, salinity, currents and sea surface height. For this system, inundation and recession processes are not supported necessitating the imposition of a 5 m minimum water depth.

The rapid-response coastal models provide operational products that address specific requests from the fleet (the "end users") within a relatively short time frame (days to weeks). Often these requests are for oceanographic information in localized coastal areas where inundation processes would likely influence environmental conditions. NAVOCEANO at present uses several operational model systems to meet the wide range of requested coastal variables including tidal elevations, two- and three-dimensional currents, transport and dispersion of contaminants, and the wave environment. (Note that details regarding the current state of Navy operational wave modeling and the important contribution of waves to coastal inundation are beyond the scope of this paper and are not included herein.) Current operational models are RMA-2 (Donnell et al., 2006), the Water Quality and Mapping Analysis Package, WQMAP (Spaulding et al., 1999), PC-Tides (Hubbert et al., 2001), ADCIRC (Luettich et al., 1992), and Delft Hydraulics' Three-Dimensional Integrated Modeling package, Delft3D (Lesser et al., 2004). These systems are applied using a variety of spatial resolutions ranging from hundreds of meters down to tens of meters. Brief descriptions of each model and their operational role are discussed below.

RMA-2 is a 2D depth-averaged finite element hydrodynamic model originally developed at the Army Corps of Engineers, Waterways Experiment Station (now the Engineering Research and Development Center, ERDC). RMA-2 computes water surface elevations and horizontal velocity components for 2D flow fields. At NAVOCEANO, RMA-2 is primarily used for river and estuarine applications. The representation of wetting and drying within RMA-2 is handled either by element elimination where dry elements are removed from the computation or marsh porosity which parameterizes the gradual wetting and drying of elements much like a sponge. An additional feature permits the storage of water in regions located off the main channel. For river applications, a bendway or vorticity correction is applied to the computation of velocities around curved channels. The engineered modeling approach of RMA-2 may be attractive to non-expert users in situations where the scope and goals of the model application are narrow and *in situ* observations are available for model calibration. Packaging of the RMA-2 model within the Surface Modeling Software (SMS) (Zundel, 2005) facilitates interactive, rapid model set-up. The result of highly engineered RMA-2 computations is that neither mass is conserved nor the underlying physics of the flow preserved. Historically, RMA-2 would be considered a first-generation finite element model since its numerical formulation is based on a Galerkin finite element discretization of the primitive conservation equations (King and Norton, 1978). Galerkin finite element solutions to these equations are known to have folded dispersion relations (Lynch and Gray, 1979) which lead to oscillatory, unstable solutions. Consequently, applications of RMA-2 are often accomplished using very large values (100 m^2/s or higher) of the lateral viscosity which can result in over-damped, inaccurate solutions. While other models may also have inaccuracies in their numerics or physics representations, those associated with RMA-2 are rather fundamental and their occurrence is antiquated by modern standards.

WQ-MAP is an integrated system for modeling the circulation and pollutant transport in estuarine and coastal waters. It includes three basic components, a boundary fitted coordinate grid generation module, a three-dimensional, time-dependent hydrodynamic model that solves the salt and temperature transport equations, and three separate water quality or pollutant transport and fate models. This latter capability makes this model unique among the operational models at NAVOCEANO and defines its primary purpose. Inundation is not specifically handled by WQ-MAP. The WQ-MAP model system is designed for execution on personal computers (PCs) and allows for simple and fast set-up of new geographical regions. Disadvantages of the system are simplified physics and low-order numerics of the model. For example, the upwind, first-order advection scheme adds notable artificial numerical diffusion to the computed solution and the turbulence closure is represented by a simple, one-equation turbulent kinetic energy model.

PC-Tides is a PC-based, relocatable tidal modeling system that accommodates 2D barotropic circulation. NAVOCEANO exercises PC-Tides when quick tidal solutions are needed at kilometer scales. The wetting and drying algorithm is based on pressure gradient differentials between adjacent cells (Hubbert and McInnes, 1999) without consideration of mass conservation. A data-assimilative component loosely constrains (via a weighted nudging approach described by Hubbert et al., 2001) computed tidal heights using known sea-level elevations at available tidal stations. The most prevalent implementation of PC-Tides uses data assimilation with no active wetting/drying mechanism. The data-assimilative component of this system generally insures a higher level of accuracy for the predicted tidal heights.

ADCIRC, the Advanced CIRCulation Model for Shelves, Coasts and Estuaries, solves the shallow water equations in a Galerkin finite element framework. The numerical discretization of the model yields a second order accurate solution for tides, currents and wind-driven surge and inundation. Presently at NAVOCEANO, only the 2D, depth-integrated (2DDI) version of ADCIRC is utilized. The ADCIRC model has a non-conservative inundation scheme that activates and de-activates grid elements using criteria based on a simplified momentum balance between the pressure gradient and bottom friction. The unstructured triangular meshes associated with ADCIRC provide a significant advantage when modeling coastal regions at scales of ten to one hundred meters. Another advantage is the parallelization of ADCIRC computations, making possible very large computational problems. Large domain problems have been shown as optimal for specifying remote boundary forcing and retaining high resolution in local coastal areas of interest (Blain et al., 1994). Disadvantages in using the ADCIRC model are the time and degree of user sophistication required for grid generation and model set-up. The SMS visualization software does contain an ADCIRC module. However, without control of the embedded ADCIRC code within SMS, NAVOCEANO has opted not to exercise ADCIRC from the SMS software. Further limitations of ADCIRC stem from its lack of three-dimensional buoyancy-driven dynamics and transport. Applications of ADCIRC at NAVOCEANO have been limited to wind and tidally-driven water levels and 2D circulation (Blain et al., 2002).

Delft3D is an integrated nearshore, currents, wave and surf modeling system with a sophisticated GUI interface for model set-up and execution. Since Delft3D is presently in early transition to operations and is being used initially for waves and surf, further details of the system are not presented here.

The rapid-response operational capabilities detailed above for high resolution coastal prediction at NAVOCEANO reflect the current Concept of Operations emphasizing expediency in military decisions based on observation, orientation, decision, and action within the battlefield environment (Burnett et al., 2002). The high temporal and spatial variability of coastal dynamics when coupled with its influence on the success of Special Operations missions places priority on the quick turnaround of operational products. The worldwide venue for Navy operations also requires these operational prediction systems to be easily relocateable to a variety of geographic locations. So while accuracy of the predictions is clearly necessary, the ease of set-up and time-to-solution for the modeling capabilities have taken precedence. The operational systems that are in use have friendly, GUI-driven interfaces that lead to more rapid model configuration and are often executed using desktop computational resources. These systems, however, do not represent the best technology for realistic and accurate prediction of coastal processes and inundation. The challenge remains to rapidly transition the most advanced modeling technology into an operational framework that combines accuracy, ease of use and minimal turnaround times.

B. Research and Development

The Naval Research Laboratory (NRL) is the Navy's corporate laboratory, and within NRL's Oceanography Division at Stennis Space Center, MS basic and applied oceanographic research and development (R&D) is focused on understanding ocean processes through the use of models and remotely-sensed and *in situ* observations. An integral aspect of the NRL mission is to merge R&D with the reality of fleet operations so that technical advances and developed model systems are transitioned to operations, primarily at NAVOCEANO.

Inundation modeling at NRL has evolved as spatial resolutions in most coastal model applications have increased. Models having kilometer scale resolutions had shorelines represented as an "impermeable wall" located at some minimum water depth (i.e., 3 m and 10 m were commonly used values, e.g., Blain, 2000; Naimie et al., 2001). This approach was also used when two-way coupling coastal circulation and surface wave effects in Bay St. Louis, MS (Cobb and Blain, 2002). The inclusion of inundation processes would have significantly complicated the coupling process. As coastal model applications approach resolutions on the order of hundreds of meters, model domains include very shallow, nearshore waters necessitating implementation of a wetting and drying mechanism to avoid the instability associated with dry computational cells (e.g., Blain et al., 1998; Blain and Edwards, 2002; Preller et al., 2005). This application of wetting and drying was not intended to realistically simulate the processes associated with inundation rather the wetting and drying algorithm provides stability for computations in very shallow water. Coastal model results using numerical wetting and drying to ensure numerical stability typically do not focus on the verification of inundated areas or the position of the wetting front.

The most recent NRL coastal studies of riverine environments and storm surge are beginning to specifically examine inundation processes. At NRL, an operational prototype of the ADCIRC model, focused on the KAA waterway in the northern Persian Gulf, was developed to support Navy forces during *Operation Iraqi Freedom* in May of 2003 (Blain, 2003). With water depths of 5 m or less and topography not more than 6 m above sea level within the upper KAA waterway, inundation and recession were expected to significantly modulate water level and current values. In this area, near Um Qsar, the spatial resolution was approximately 5 m. Comparison of depth-integrated currents computed by the ADCIRC model for inundation ex-

FIGURE 2

Model predicted depth-integrated currents near Um Qsar, Iraq for inundation and recession processes a) not included and b) included.

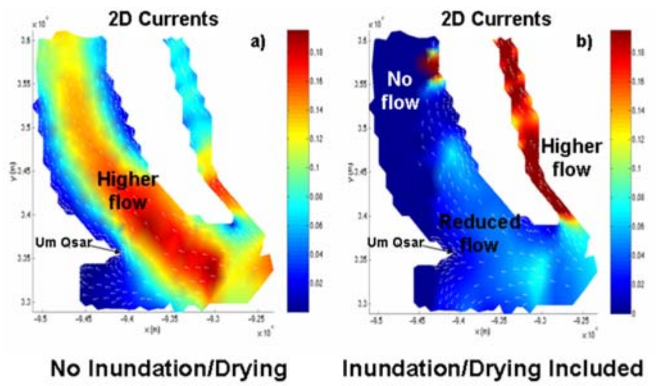
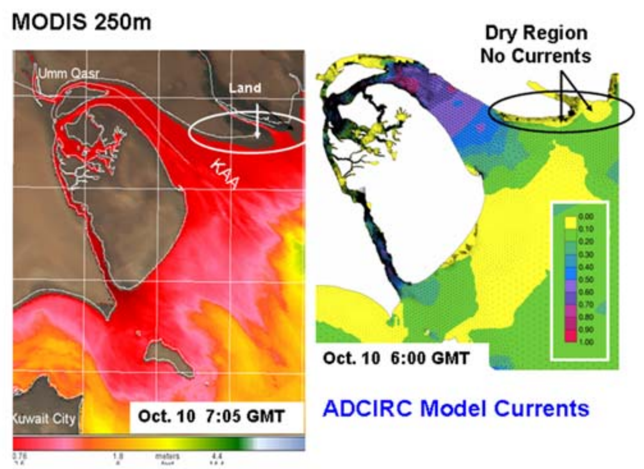


FIGURE 3

Correspondence is demonstrated between a) exposed land as seen using the MODIS 250 m beam attenuation coefficient and b) ADCIRC modeled coastal drying east of the KAA waterway in Iraq on October 10, 2004.



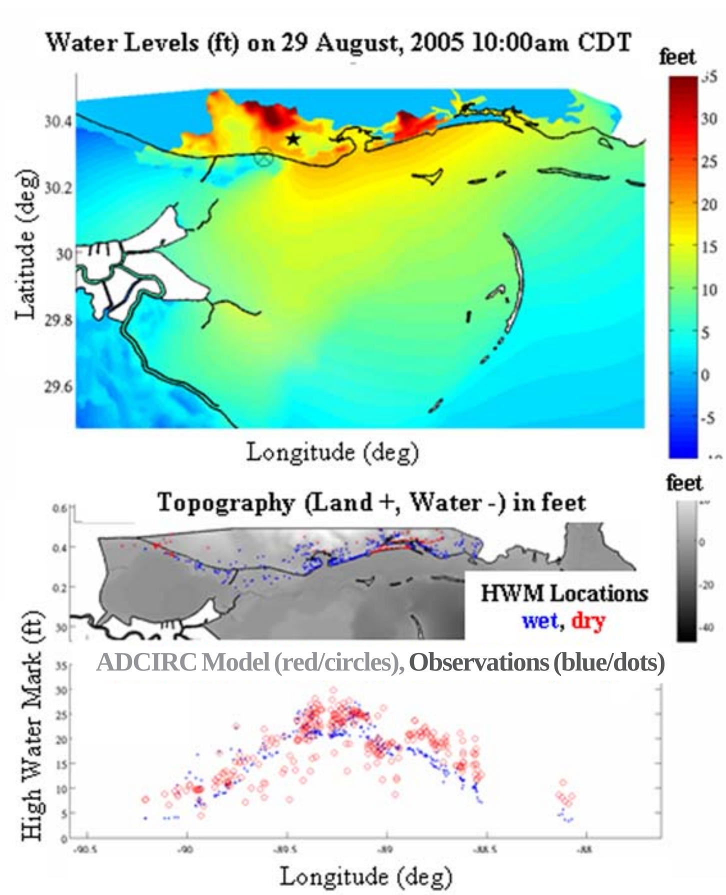
cluded and included (Figure 2) demonstrate the significance of the tidal inundation and drying on local circulation. Without ground truth measurements, however, we can only assume that the realism provided by wetting/drying provides the more accurate result.

Limited comparisons of exposed land areas seen in the MODIS 250 m satellite imagery for the same application show a correspondence to the dry areas computed by the ADCIRC model east of the KAA waterway, as shown for October 10, 2004 in Figure 3. (Note that other regions of zero current [yellow/white] are present in Figure 3 and indicate the occurrence of slack tide). Resolution throughout the KAA ranges between 5 m and 20 m. The spatial scales simulated by this northern Persian Gulf model highlight not only the potential impacts of inundation on military operations but expose needs for detailed bathymetry/topography data and a means for verifying accuracy of the inland inundation.

Most recently, storm surge and coastal flooding along the Mississippi Gulf coast resulting from the landfall of hurricane Katrina on August 29, 2005 were successfully simulated using the ADCIRC coastal ocean model (Figure 4a). (Note that the mesh excludes New Orleans, LA, and surrounding coastal areas eliminating the effect of Katrina's storm surge and flooding on these regions. A more comprehensive benchmark for hurricane Katrina

FIGURE 4

Storm surge and inundation along the Mississippi Gulf coast predicted by the ADCIRC model during the landfall of hurricane Katrina on August 29, 2005. Location of the storm center is indicated by the symbol ⊗ Comparisons to 458 USGS high water marks reveal an average model error of 1.2 feet, an excellent result considering the coarse 225 m inland resolution and the neglect of wave effects.



storm surge and inundation has been presented by the Interagency Performance Evaluation Taskforce (IPET, 2006).) This work exclusively focused on the inundation component of the storm surge and used technology and information that would be typically available for Navy operations worldwide. The unstructured mesh for this problem contained 375,479 nodes and 730,431 triangular elements providing 225 m of spatial resolution in coastal and inland areas, resulting in the largest Navy application of unstructured grid models to date. Comparisons of computed high water values to USGS high water mark measurements at 458 locations along the Gulf coast indicate very good agreement between observed and predicted water levels with average errors of only 1.2 feet (0.37 m) (Figure 4b). The experience gained from this hurricane Katrina hindcast revealed a high degree of model sensitivity to movement of the wetting front inland and was indicative of an inter-relationship between spatial resolution, complexity of the topographic gradients and the model time step. Topographic smoothing and coarsened resolution were ultimately required for a reasonable model solution. Deficiencies in the wetting and drying algorithm will be necessary to improve the fidelity and robustness of the inundation modeling.

Several Navy research and development initiatives addressing inundation and coastal flooding are anticipated to begin within the next several years. The first is focused specifically on improving tidal inundation prediction by combining models and remotely-sensed data. Goals include the development of a more robust, conservative inundation algorithm based on a full suite of physics. The model targeted is a new discontinuous Galerkin form of the ADCIRC model. Mesh adaptivity, to better capture wetting and drying fronts, and a more realistic representation of bottom frictional effects are planned. Westerink et al. (2006) have already shown in hindcasts of hurricanes Betsy and Andrew that storm surge and inundation are extremely sensitive to vegetation types, canopy height of the landscape, and wind direction relative to the terrain (land or water). Expected results include more robust computations of inundation and recession that have the capability to simulate higher resolution more efficiently.

A second proposed effort specifically addresses Navy needs in riverine environments. The project objective is to automate (a) the extraction of river properties from high resolution multi-spectral and hyperspectral remotely-sensed data, and (b) the utilization of this data in the configuration of an advanced hydrodynamic river model. River characteristics include shoreline features, areas of shallow water, vegetation classes, and optical properties. The modeling of inundation and riverine currents is inseparable in many instances, particularly since it is often difficult to clearly delineate river banks from the surrounding topography.

The Office of Naval Research also recently announced the Coastal Geosciences Departmental Research Initiative (DRI) on Tidal Flats scheduled for the FY07-FY11 time period. The goals of this DRI are to develop and improve the capability to predict hydrodynamics and sediment dynamics in macro-tidal muddy river-estuary-coastal environments. The region selected for the focused study is Kyunggi Bay located on the western Korean peninsula. Features of the bay include wide tidal flats, deep tidal channels and tidal sand ridges running in parallel to tidal flows. A macro-tidal range of nearly 9 m results in a dramatic exposure of the tidal beds at low tide. Both observations (remotely sensed and *in situ*) and modeling activities are planned for this intensive study. Another ONR sponsored research project focuses on incorporating the Delft Hydraulics Simulating Waves and Nearshore (SWAN) model into the ADCIRC hydrodynamic model so that surge, inundation and wave processes can be fully and realistically integrated in future predictions.

Clearly, future Navy research and development efforts are indicating a shift of emphasis to address inundation and related concerns in coastal and riverine environments. This is likely a response to the needs of Navy mission planners and military forces whose operations are increasingly occurring in these same environments.

4. Assessing the Gaps

The hostility of the marine environment during a storm surge event results in a lack of water level time series and a scarcity current observations within the primary region of surge generation leading to a gap in our ability to validate model predictions for storm surge (see Luther et al., this volume). In U.S. waters, historical observations have been limited to water heights with little recorded information available on currents (magnitude and direction). More recently both IOOS Regional Associations and the National Data Buoy Center are working to address this gap by providing a growing amount of data on surface currents. Despite these efforts, coastal currents remain largely under-sampled and the survivability of observing networks during a tropical storm event is an issue. Where foreign waters are concerned, the primary domain for Navy activity, measurements of water levels and currents are sparse at best.

Inundation events are often measured only by high water mark values which provide no temporal information. Lacking are details of the temporal and spatial evolution of an inundation and/or recession event (see Luther et al., this volume). Remotely-sensed data may provide some means of validating inundation predictions but their temporal resolution (typically twice daily) is limiting. Two additional yet critical pieces of data are the bathymetry and topography at scales of tens of meters. High resolution model predictions are not possible without high resolution bathymetry and topography across the land–sea interface. The use of remotely-sensed LIDAR data is beginning to fulfill this requirement for U.S. applications (see Stockdon et al., 2007) but it will not meet all Navy needs worldwide. The Navy must continue to pursue the exploitation of a variety of satellite sensors to obtain high resolution bathymetry and topography in very shallow, near-coastal regions.

The technology to accurately represent inundation and drying via numerical modeling is largely available. Sufficient computational resources, including utilities for parallel processing, load balancing and distributed computations, are in place to achieve very high resolution simulations of wetting and drying events. Proposed work that advances inundation algorithms and utilizes refinements to the surface and bottom drag specification through the interpretation of remote sensed imagery (described Section III B) should begin to address known deficiencies in existing research models. Despite these imperfections the high resolution modeling capability within the research community far exceeds current operational capabilities. The gap between research and operational applications can be attributed to both *de facto* and imposed constraints of the operational environment. For example, user-friendly interfaces, automated model relocateability, and expediency of the solution are all of significant importance in the operational environment. Transitioning research models into an operational mode in a more efficient and timely fashion will require effective collaboration between research and operational modelers that benefit both communities. Emphasis on education and training with regard to emerging technologies will also ease some of the existing operational constraints.

A final gap is evident in comparing the current form of operational products and their ability to meet user needs. At present most operational products generated by the Navy operational center at NAVOCEANO are time-stamped graphical maps depicting color-fill contours or directional vectors. This type of product is decidedly research-oriented and requires skill and experience to interpret. Oceanographic operational products are only one among several data sources that are synthesized by mission planners and tactical users. Maps of geospatial information depicting existing structures, vegetation, and so forth in the form of Geographic Information Systems (GIS) are often used by military planners but such information is not typically merged with predicted water levels for inundation and recession. The diversity of tactical decision aids, computer resources, and "reachback" capability available within the various operational commands of the Navy, (e.g., special warfare, mine warfare, and anti-submarine warfare), render a uniform interface for operational products impractical. The development of targeted and useful operational products will require more effective communication between the vast array of "end users" and data providers outside of the formal requirements process. Certainly, the utilization of GIS information is one area that could improve the interpretation of existing operational products though GIS software has potential limitations handling temporal changes. Aside from format, to make inundation products more operationally relevant, measures of uncertainty or statistical information that place the operational product within the context of expected values require development by the R&D community. Though accuracy levels are already established via the Navy requirements (Table I), the accuracy or uncertainty associated with an operational product is rarely communicated creating a gap in the user's ability to assess the suitability of an operational product for a specific purpose. Effective two-way collaboration between the R&D, operational and user communities is essential for the innovation of more informative, targeted products that better reflect both the sophistication and limitations of the predictive capability available. One final observation is the binary nature of existing operational products. Given that a coastal model requires timely environmental input (such as wind forcing) for a forecast, the forecast and its products tend to be either realistic because the applied forcing represents observed conditions or the forcing is invalid and the significance of the operational products is devalued. For example, if the operational wind field used to drive an operational coastal model is not representative of the wind conditions experienced on a particular day, the forecast is not credible and little can be gained from that operational product. A more robust operational product may be one that presents multiple scenarios or realizations of the coastal environment. To further exploit the wind forcing example, operational forecasts under varying wind conditions would constitute the operational product. For this type of product, the user has pertinent information irrespective of the operational wind field fidelity. This approach could also be interpreted in terms of ensemble modeling, a regular practice in meteorological forecasting (Tracton and Kalnay, 1993).

Though considerable gaps exist with regard to the scale and type of available data and the form of operational products, the capability for accurate high resolution inundation and recession modeling is largely in place. This technology must be more rapidly pushed to operations which will require careful consideration of issues and constraints within the operational environment and more effective communication between the R&D and operational communities. The renewed interest in inundation processes by Navy interests lends encouragement that gaps between research and operations, and operational products and the user can be closed within the short term.

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