MORPHOS:
ADVANCING COASTAL PROCESS RESEARCH AND MODELING

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1. Introduction

The 2004-2005 Hurricane seasons resulted in more than 30 billion dollars in US property loss and damages and nearly 2000 direct fatalities within our coastal communities[1]. This devastation painfully demonstrates that our national coastlines are not adequately protected against recurring extreme weather events, and that there is a significant risk of sustaining high damages and losses from future events. This risk is exacerbated by many factors, including coastal development pressure, increased storm activity, sea level rise, coastal subsidence, and loss of wetlands; and the potential societal and economic consequences of decisions in the area are enormous. Furthermore, the current level of risk cannot be well quantified using existing models, as these major catastrophes transcend our past experiences and exhibit impacts that fall outside the range of model tuning for existing tools (Riley 2007).

Some of the key issues that currently appear to be beyond the state of the art in coastal predictions include wave-current-vegetation interactions (critical to determining the value of wetlands and wetland restoration in coastal areas), estimates of low-volume levee overtopping rates over natural surfaces (critical to levee design), accurate objective specification of bottom friction (critical to surge level prediction and evaluating wetland impacts), accurate estimation of wave-driven radiation stresses in coupled wave-surge models (present models appear to underpredict this surge component), potential baroclinic and 3-D effects in surge predictions (how important is this?), wind field specification in coastal areas (this drives the entire system and presently "neglects" coastal effects), quantitative understanding of the effects of climate variability on expected future extremes (even more critical when sea level rise is also considered), quantitative prediction of coastal response during extreme events and during recovery following these events (can beaches/dunes provide effective protection in extreme events?), statistical characterization of meteorological events that produce coastal hazards (sample size is very small!), and system-wide risk estimation methodologies (typically not performed by people who understand specific coastal problems). This is certainly not an exhaustive list; however, it points out that research needs are very broad and cannot be "pigeon-holed" into a single small niche.

[1] National Hurricane Center Archives, http://nhc.noaa.gov.

A logical question that arises from the previous list of deficiencies is how did we end up with shortfalls in so many key technologies? Probably a large factor contributing to this fact is that most existing modeling systems focus on operational systems and incorporate many empirical factors that can be used to fit local situations. For example, coefficients and even physical systems are changed from site to site in applications. These are typically "tweaked" to provide a reasonable approximation to available measurements and little information is gained, since variations in coefficients and different sets of "physics" allow for very large variations in the results. In short, present systems appear to focus on developing effective empirical tuning methods for optimizing performance. Whereas this approach works relatively well for operational systems, it is not expected to work well in most of the shortfall areas mentioned above.

As a result of the deficiencies noted above and the current approach in modeling systems, there is a critical need within the coastal engineering community for a reliable, physics-based modeling capability for tropical and extra-tropical storm risk assessment. Such a capability needs to incorporate improved objective estimates of winds, waves, currents and water levels, and coastal response (erosion, breaching, and accretion) during extreme events, without having to adjust several coefficients to produce realistic results. Furthermore there is a need for a robust, standardized approach to establishing the risk of coastal communities to future occurrences. Such a system of tools could be used to plan and prepare for weather impacts on our fragile coastal communities and resources.

The Morphos program was established by the US Army Corps of Engineers (USACE) to address these needs. The program was initially funded with emergency appropriations stemming from the destructive 2004 hurricane season, which brought Hurricanes Charlie, Francis, Jeanne and Ivan to the Florida coastlines (Figure 1). Morphos was charged with developing a prototype integrated modeling system for predicting three-dimensional beach morphology changes during hurricane events. To address this charge, USACE assembled an international team of coastal process experts spanning government agencies, academia and private industry. The 2005 hurricane season brought new challenges with Hurricanes Katrina and Rita, resulting in barrier island obliteration, extensive wetlands destruction, levee failure and overtopping, and widespread flooding due to inundation (Figure 2). This total devastation prompted a realignment of the Morphos objectives to address coastal risk in all types of environments. In fact, many of the Morphos investigators shared duel roles on the Hurricane Katrina Interagency Performance Evaluation Task Force (IPET) and are involved with the Louisiana Coastal Protection and Restoration (LACPR) Program and the Mississippi Coastal Improvement Program (MSCIP). In 2007 Morphos became an established component of the System-Wide Water Resources Program (SWWRP). The mission of SWWRP is to assemble and integrate the diverse components of water resources management, providing users access to current and improved technologies for multidisciplinary system-wide assessments[2].

The goals of Morphos are consistent with the mission of several federal agencies, including the National Oceanic and Atmospheric Administration (NOAA), the Federal Emergency Management Agency (FEMA), the US Geological Survey (USGS), and the

[2] https://swwrp.usace.army.mil/_swwrp/swwrp/4-pubs/FactSheets/SWWRPfactsheet.pdf

US Department of Homeland Security (DHS). Partnerships are being established with these organizations on various levels to ensure Morphos will fully meet the national need for an integrated modeling system capable of accessing coastal risk and designing an adequate level of coastal protection. Throughout this work USACE maintains a firm commitment to advancing both model physics and numerical methods in order to field the best possible technology.

Figure 1. Beach front erosion on Hutchinson Island, FL resulting from 2004 Hurricanes Jeanne and Francis.

Figure 2. New Orleans flooding after 2005 Hurricane Katrina.

2. Morphos Approach

Morphos seeks to develop a state-of-the-art modeling system with a variety of tools to address our essential coastal engineering applications. Key program elements include a dedicated community steering group, research and development to advance the state of coastal process modeling technology, rigorous test and evaluation of individual model elements and systems, and development of a community set of tools (Figure 3).

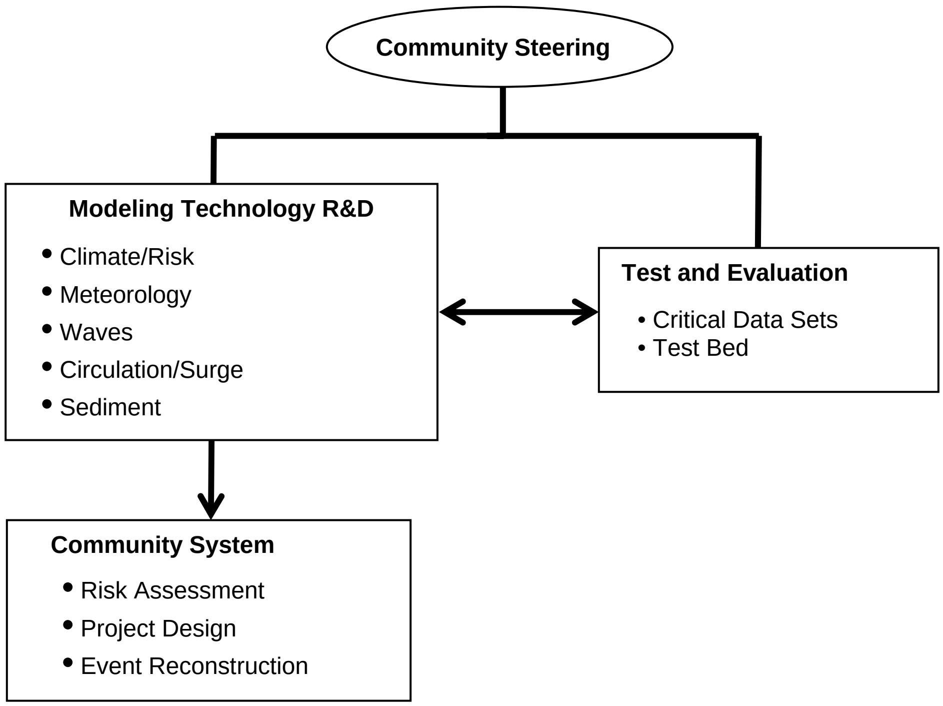

Figure 3. Morphos program elements.

It is vitally important that Morphos development be driven by community needs. These needs are communicated through a dedicated steering group of coastal engineers with representatives from both private industry and Federal Government. The steering group provides program oversight and direction for all phases of product development. Regularly obtaining such community inputs ensures that Morphos developments keep pace with requirements for estimating risk along our evolving coastlines.

Morphos investigators conduct the necessary research and development to advance our physical understanding of important coastal processes and represent them with sufficient accuracy in efficient numerical algorithms. This work can take many forms, including analyzing essential data sets, advancing new and existing theoretical descriptions of coastal behavior, and developing efficient computer applications for engineering use. This aggressive research and development component allows Morphos to continually embrace the latest technology and ensure that Morphos technology obtains, and holds, community acceptance as "state-of-the-art."

A careful assessment of model performance against known standards and real-world scenarios is crucial for the success of Morphos. This need is being fulfilled through an aggressive test and evaluation program component. Elements of this effort include the collection and assimilation of essential data sets, development of a robust statistical package for quantifying model performance, and construction of a model test bed environment to provide Morphos developers convenient access to validation data and model assessment tools.

A primary vision of Morphos is to develop a community system of modeling tools to address modern coastal engineering problems. Specific applications include risk assessment, the design and evaluation of coastal protection, and, as with Hurricane Katrina and other significant disasters, reconstruction of historical events. As coastal change results from complex interactions between various processes including winds, waves, currents and sediment transport; individual modeling technologies are dynamically coupled to adequately replicate the impacts of these events.

Morphos follows a spiral development approach for research and product development. As depicted in Figure 4, a long term research and development program is envisioned with steady progress towards a fully integrated community modeling system. Progress is marked by spin-off products, such as major code releases, specific engineering tools, community documentation, and crucial data sets.

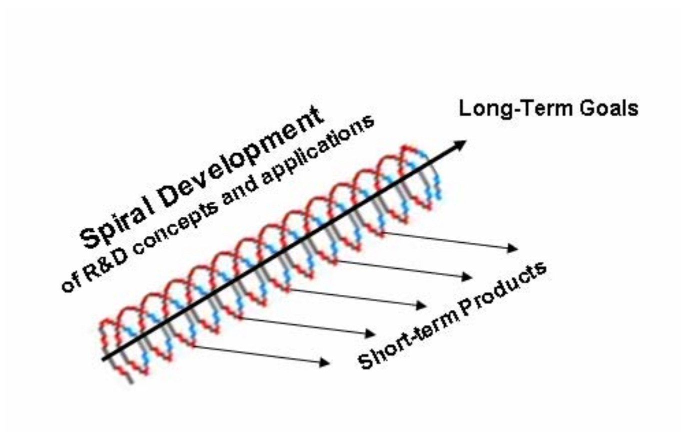

Figure 4. Morphos spiral development approach allows long-term research and development to coexist with short-term goals.

3. Coastal Process Research and Development

The Morphos research and development program seeks to advance our physical understanding of coastal processes, improve our ability to numerically predict the features of coastal impacts, and develop a methodology to quantify the risk of future impacts within a given coastal region. These advances are documented in a variety of journal articles, conference papers and technical notes (see References for samples).

Morphos coastal process research and development is divided into five focus areas as described below.

Climate and Risk

Climate changes must be considered in the assessment of coastal risk and the characterization of hurricane surges. The potential role of climate variations is being quantified through investigation of hurricane frequency-intensity relationship cycles over the past 40 years. Findings suggest that there have been repeating sequences of active and inactive hurricane periods with the active periods rather short in duration yet producing all the major storms. Furthermore, these active periods tend to correlate with principal components of atmospheric forcing and sea surface temperature (Resio et al. 2007).

The estimation of hurricane risk factors is being advanced through a new statistical methodology that is not as strongly tied to the short historical record as the commonly used Empirical Simulation Technique (Scheffner et al. 1999). The Joint Probability Method (JPM) is now gaining acceptance agency-wide as a practical replacement. The JPM approach provides a probabilistic description of the frequency, tracks, and storm characteristics (i.e., pressure deficit, radius of maximum winds, forward velocity, etc.) at or near landfall. It allows for the incorporation of uncertainty due to many factors and can include consideration of climate variability. Furthermore a JPM optimal sampling approach (JPM-OS) determines an optimal combination of storms parameters, and the associated weights, to be used in the calculation of exceedence probabilities with manageable sample sizes and reasonable execution times (Toro 2007).

Meteorology

Because coastal hydrodynamics are forced primarily by the winds and tides, Morphos prediction accuracy is dependant upon the quality of the driving winds. The development of a robust hurricane atmospheric forcing system is an important research and development element of Morphos. Specific research topics include the impact of atmospheric boundary layer height variations on hurricane strength and land-falling effects such as sea-land drag.

Wind field modeling is important for both post-storm reconstructions and in simulating hypothetical future events. Hurricane wind fields can be quite complex with multiple eyewalls and an asymmetric structure around the storm center. Detailed reconstruction of such fields, such as the Hurricane Ivan landfall winds depicted in Figure 5, is accomplished by incorporation of the TC96 planetary boundary layer model (Thompson and Cardone 1996) with an Interactive Objective Kinematic Analysis (IOKA) system (Cox 2007). Furthermore, both the TC96 and other modeling approaches (Vickery et al. 2000) are being developed to simulate future scenarios for risk assessment.

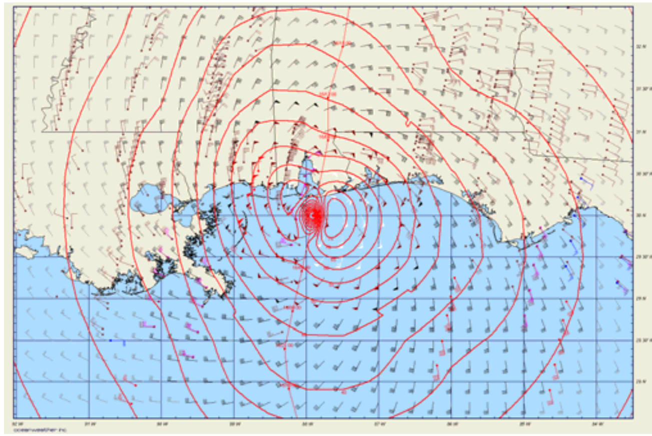

Figure 5. Morphos IOKA reconstruction of Hurricane Ivan windfield at landfall (Cardone and Cox 2007).

Waves

It is widely recognized that the biggest problem in coastal wave modeling is the lack of adequate source terms in the wave balance equation

$$\frac{D(f,\theta)}{Dt} = \sum_k S_k(f,\theta) = wind + Snl + dissipation,$$

which states that the total rate of change of wavefield properties is described by a balance between the wind input (*wind*), nonlinear transfer (*Snl*), and energy loss (dissipation) source terms. Although there are various approximate forms of these source terms that have been used to predict wave evolution in deep water, the enhanced interactions that occur in shallow water drive these approximations to be inaccurate near the coast. As a result, Morphos is advancing nearshore wave modeling technology to include consistently-scaled spectral source terms that operate equally well in deep or shallow water (Badulin et al. 2007, Resio and Perrie 2007, Long and Resio 2007a, van Vledder 2007). For example, comparison of *Snl* computations between the Morphos Two-Scale Approximation (TSA), the commonly applied Discrete Interaction Approximation (DIA), and an exact computation in Figure 6 shows the significant improvement gained with the TSA nonlinear transfer source term.

Advancements are being made in other critical wave modeling areas as well, including the improved representation of bottom friction and diffraction in nearshore wave models (Smith and Grzegorzewski 2007, Long and Resio 2007b), an improved semi-Lagrangian method for numerical simulation of wave propagation across arbitrary bathymetry and current fields (Scott 2007), and an efficient numerical model for deterministic 4-wave resonant interactions using a kinetic equation derived from the Boussinesq equations for arbitrary depth (Onorato 2007, Ousborne 2007). The propagation scheme will be implemented into the new Time-Stepping WAVE model (TSWAVE). The kinetic equation work supports development of an efficient phase-resolving wave modeling technology for deep- and shallow-water applications.

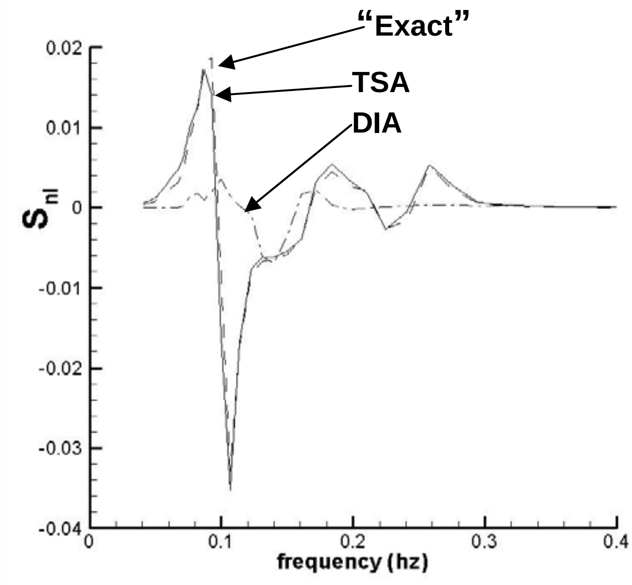

Figure 6. Comparison of TSA and DIA wave-wave interaction source term approximations to the exact computation (Resio and Perrie 2007).

Circulation and Storm Surge

Winds, tides, waves, rainfall and river influx all influence coastal circulation and storm surge levels. To simulate the effect these processes have on inundation, flooding, beach erosion, and sediment transport, Morphos is advancing the development of ADCIRC 2D and 3D modeling systems. Research areas include optimizing the accuracy and parallel efficiency of Discontinuous Galerkin (DG) codes for correctly computing mass transfers across an unstructured grid (Kubatko et al. 2006, Kubatko and Westerink 2007, Kubatko et al. 2007), and adding such enhancements as the robust and accurate wetting and drying of grid elements (Bunya et al. 2007). Furthermore a generic wave coupler is under development that will allow the dynamic information transfers between ADCIRC and wave models in both serial and parallel computations (Shi 2007).

Recent applications of this Morphos-sponsored technology include a reconstruction of hurricane surges for Hurricanes Katrina and Rita along the Louisiana and Mississippi coasts. The peak surge associated with Hurricane Katrina is shown in Figure 7a. This hindcast includes the effects of winds, waves and tidal forcing computed over an unstructured grid of more than 4 million individual elements (Westerink 2007). As Figure 7b depicts, this high-fidelity simulation results in a very good agreement of predicted surge levels with observed high water marks.

(a) (b)

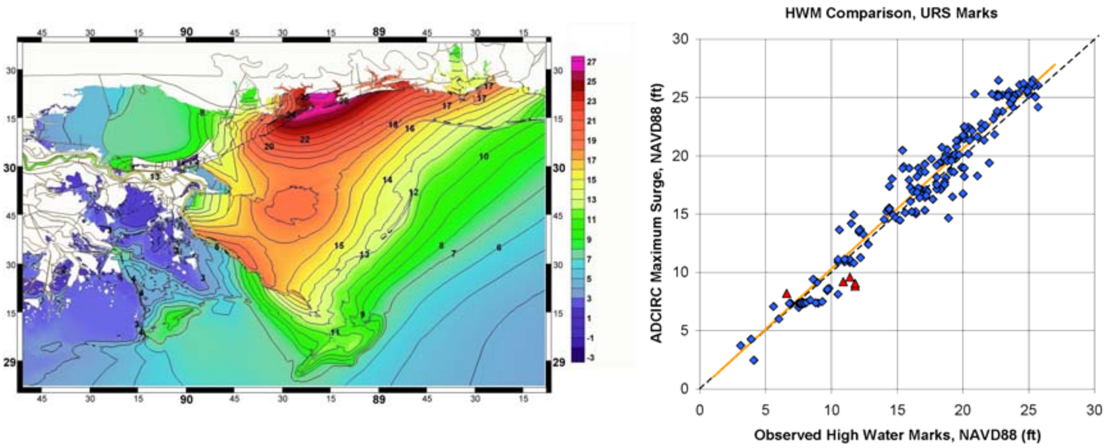

Figure 7. Total surge (ft) hindcast of Hurricane Katrina: (a) Peak surge at storm impact, (b) Comparison of predicted surge levels with observed high water marks (Westerink 2007).

Sediment Transport and Beach Morphology

Event-driven hydrodynamic forcing leads to the entrainment, movement and deposition of coastal sediments. Hurricane-driven transport on open coasts often results in large-scale beach erosion leading to structural damages and loss of property. Furthermore, significant shoaling can occur around inlets and inland waterways, with serious consequences to navigation. Morphos is developing improved prediction tools for nearshore sediment transport and morphological change. Due to the significant impacts of the 2004 Hurricane season (Figure 1), present focus is on the morphological evolution of sandy coasts. Our goal is to use ADCIRC/TSWAVE to force a stand-alone nearshore wave/current/sediment transport model from approximately 10-m depth shoreward.

Nearshore technologies under development include the steady-state nearshore morphology model Sedcirc (Kobayashi et al. 2007a, Kobayashi et al. 2007b) and the low-frequency nearshore morphology model XBeach (Roelvink et al. 2007). Both of these models solve the 2D (horizontal) shallow-water equations and include such features as dune erosion and overtopping. Presently these models are undergoing extensive testing with both laboratory and field data, with typical recent test results appearing in Figure 8 (Johnson 2007). Additional research is leading towards a phase resolving approach for high-fidelity morphological applications. It is anticipated that the resulting suite of tools will fulfill a wide range of coastal engineering needs related to the design of adequate protection along sandy coasts.

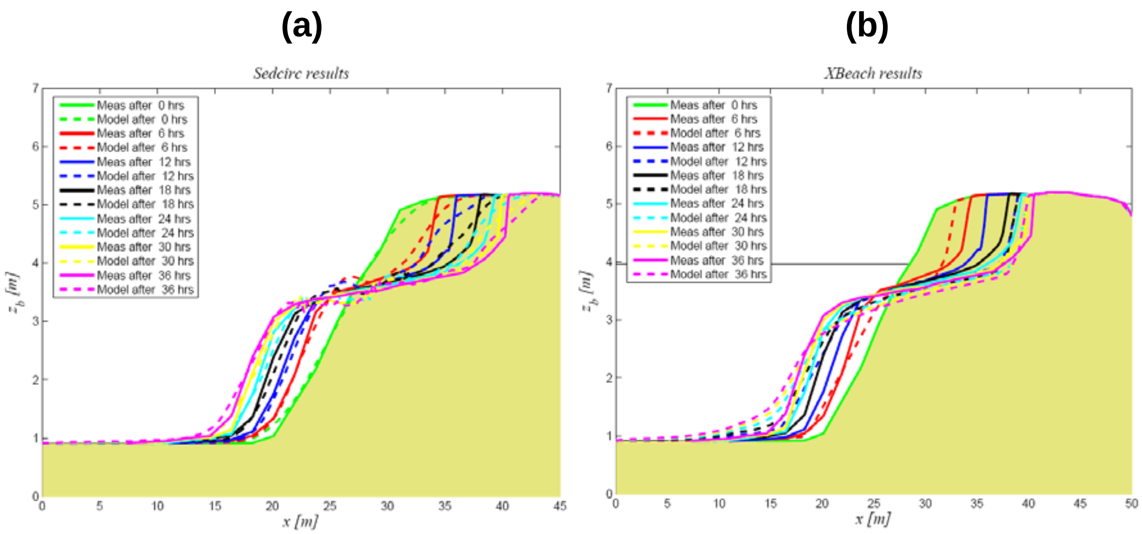

Figure 8. Comparison of cross-shore morphology predictions with Oregon State University wave tank dune erosion data: (a) Sedcirc results, (b) XBeach results (Johnson 2007).

4. Coupled Modeling System

From a simulation perspective, the coastal hydrodynamic environment is difficult to replicate. Multiple driving forces, large variation in boundary conditions and spatial resolution, and difficult problem characterization have prevented a single software approach or system from being developed that can simulate the entire problem. Rather, the software development approach has been to simplify equations and focus on specific components such as longshore or wind-driven currents. The result is a large number of software solutions, each with advantages and disadvantages.

One of the aims of Morphos is to more completely simulate the large number of physical processes occurring within the coastal zone. One approach to doing this would be to develop an all encompassing software code that can solve all aspects of the problem. This approach is avoided, however, because of the complexity and hence cost such a solution would require. Another approach is to link established codes that may focus on a single physical process into a larger software system that can simulate more of the coastal processes. Morphos will adopt the latter technique.

Issues related to Model Coupling

Modeling linking or coupling is not trivial, however. There are certain issues that must be addressed in order to integrate multiple components. These issues include a method of exchanging data between models, tools and databases, a means of setting up the integrated model, the mode of control when the integrated model executes, and decisions on whether the individual models run sequentially or simultaneously. Because of the type of modeling being conducted within Morphos, a number of criteria were established that any model coupling approach must satisfy. These are as follows: (1) system must work in a distributed parallel HPC environment, (2) system must accommodate a combination of modeling structures including structured grids and unstructured meshes, and (3) system must be portable to multiple hardware/software configurations. This section will discuss some of these issues in context of the existing model coupling methodologies available to Morphos.

Definitions

A few definitions are included to help the discussion on model coupling:

Model – The software code developed to simulate the natural environment.
Model Instance – The application of a model to a specific location in the world.
Model Domain – The computational structure on which the model runs. For finite element models, this is would be the unstructured mesh that consists of nodes and elements.
Linking – Passing data in one direction from model A to Model B. Can be done during run time but is typically done as a post-process to Model A and a pre-process to Model B.
Coupling – Passing data bi-directionally between Model A and B during run time. This is also known as feedback modeling.
Model System – One or more model combined together in a simulation environment.

File Based Model Coupling

The simplest method of developing a linked modeling system is to use model output and input files. In this method the output from model instance A is crafted to become the input for model instance B. This requires no modifications to the source code of either model. However, if feedback modeling is required, it can prove to be more difficult. Modifying each model to accept hot-start files can circumvent many of these difficulties. The Surfacewater Modeling System (SMS) (Zundel 2005) Steering Module provides model linking and coupling using a file based approach. SMS is used to create a model instance and to define where the models will be linked. SMS then controls when and for how long model A will run. It then modifies the output from Model A to be used as input to Model B, tells Model B when to run and repeats this until a satisfactory result is obtained.

This approach is very simple to implement but has significant limitations. The primary limitation is the amount of procedural overhead required to manage and manipulate all of the files required for the simulation. Further, computational time is wasted reading and writing to files. This approach is valid for small model instances and will continue to be supported by Morphos.

Framework Based Model Coupling

A more complex method of developing a linked modeling system is transferring data between computational programs during the model run time. This can significantly increase performance, especially when dealing with extremely large model instances that will be executed on HPC resources. A number of approaches have been attempted to accomplish this over the past few years as more organizations attempt to integrate multiple modeling systems. Some of these include the OpenMI initiative spearheaded by the EU (Blind and Gregerson 2005), the Model Coupling Environmental Library (MCEL) (Bettencourt 2002), the Model Coupling Toolkit (MCT) (Larson et al. 2005) and the Earth System Modeling Framework (ESMF) (Collins et al. 2005). While the details of how these systems all work are quite different, none provide a complete solution that would satisfy the model linking criteria described previously. In all cases extensive code changes are required within each model being linked.

The most promising technology for this work was determined to be the ESMF. This system provides a software framework by which data can be shared between model codes during runtime. ESMF provides extensive data aggregation and interpolation routines to transform data between modeling domains. ESMF is based upon the Message Passing Interface (MPI) protocol and therefore can support distributed parallel computing. The primary drawback to ESMF is that it currently (2007) does not support unstructured meshes. This drawback is being addressed by the ESMF community as well as by ERDC researchers and ESMF based solutions that do support this type of model domain should be available in the very near future.

Model Setup

One of the problems with creating an integrated linked system of models is how to setup and organize the entire set of models so that each model knows how it will interact with all others. The problem has been addressed within the SMS Steering Module but no such system exists for ESMF. It is anticipated that Morphos will adapt the model setup provided by SMS to work with an ESMF based model system.

5. Test and Evaluation

Modeling studies typically require many simulations to fully explore output sensitivity to a variety of controlled inputs, source term settings, grid resolutions, etc. This is often a difficult task due to lack of adequate validation data, disparate data formats and the need for established standards, metrics and tools for quantifying prediction error. To address this issue Morphos is constructing a model test bed environment for the assessment of model performance against both known standards and significant coastal events for which we have adequate ground-truth data. The basic architecture of the modeling test bed appears in Figure 9. The test bed brings together a comprehensive validation data archive, an automated validation module and a variety of display and reporting options to provide a structured testing environment for coastal process model developers. Furthermore, coupling the test bed concept with NOAA regional IOOS observational networks has provided a real-time instrumented model test bed for the continuous assessment of model performance over many storm sequences (Devaliere et al. 2007).

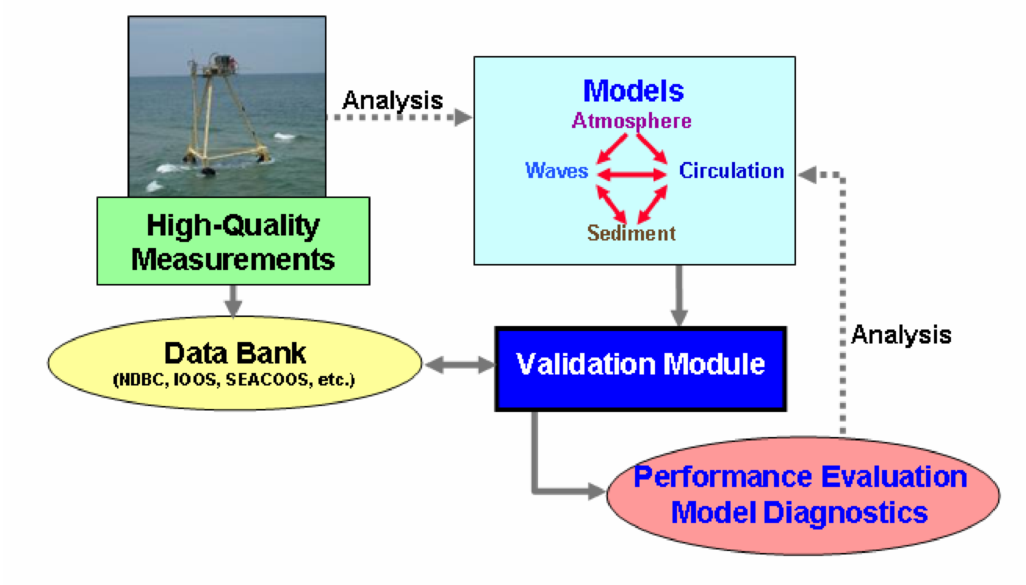

Figure 9. Morphos test bed concept for model performance assessment.

Data Collection

Critical data sets are obtained as required to improve our understanding of the physical processes responsible for coastal change, inundation and flooding. These observations span from controlled laboratory experiments to field measurements during coastal storms and hurricanes. For example, high-resolution wind, temperature and humidity data collected at the end of USACE Field Research Facility (FRF) pier will facilitate development of improved parameterizations of coastal wind drag in extreme wind conditions (Friebel, 2007). Recent results from an extratropical storm, or “nor’easter”, suggest a coastal reduction in atmospheric drag levels over traditional observation sets (Figure 10). In a related effort, high-resolution wind and wave observations obtained by the FRF in Currituck Sound, NC and other locations have supported the formation of a universal scaling relationship for the next-generation wave modeling source terms (Long and Resio 2007a).

Data sets are also obtained for the purpose of verifying Morphos numerical models. As was demonstrated in Figure 8, controlled dune erosion experiments conducted in a wave flume by Oregon State University provided critically needed validation data for the assessment of Morphos cross-shore beach morphology algorithms (Johnson, 2007). Another example results from a partnership with the National Oceanic and Atmospheric Administration Integrated Ocean Observing System program (NOAA/IOOS), where long-term measurements of coastal winds, waves and currents along the Carolinas coast facilitate the quantification of model performance over many sequences of coastal storms and hurricanes (Devaliere et al. 2007).

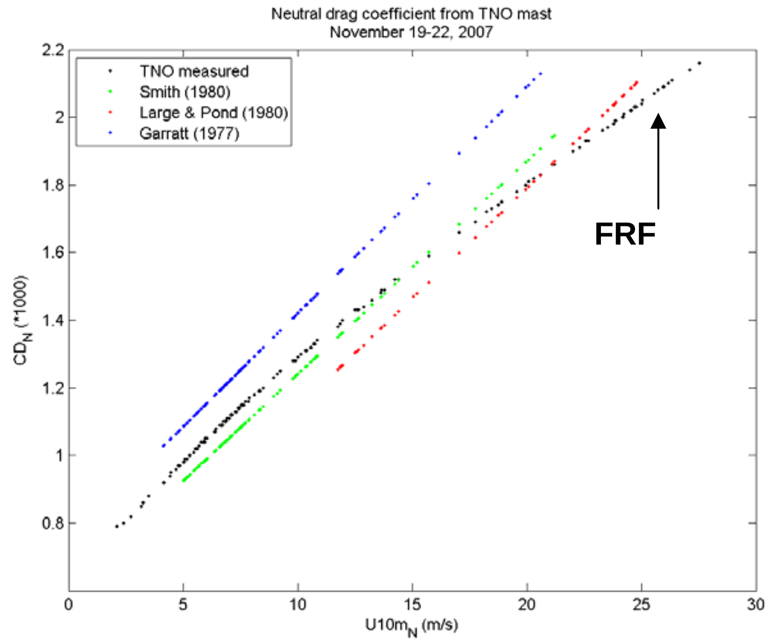

Figure 10. Atmospheric drag coefficients estimated from FRF high-resolution wind measurements during November 2006 nor'easter compared with historical trends (Friebel 2007).

Performance Assessments

The Morphos test bed will include an automated validation module for conducting detailed model skill assessments based on the comparison of model predictions to known standards, benchmarks and ground-truth data (Figure 9). Once model output is generated, the Automated Model Evaluation and Diagnostics System (AutoMEDS) will search a formatted data archive for corresponding ground-truth parameters that coexist in space and time with the predicted parameters. Comprehensive statistical comparisons will yield performance scores on overall model skill as well as a variety of error metrics for diagnostic evaluation of model strengths and weaknesses.

A prototype validation module has already been constructed for numerical wave model assessments (Hanson et al., 2006). The Wave Model Evaluation and Diagnostics System (WaveMEDS) partitions the complex wave field to individual wind sea and swell components. Wave component height, period and direction simulation errors are then quantified from both temporal correlation and quantile-quantile comparisons. Finally, performance scores are computed by normalizing the errors to mean quantities. A summation of performance scores across time, space and wave component type is accomplished using sample size weighting functions. The result is a report-card like scoring of model performance for key attributes. Expansion of this technique to other Morphos modeling technologies (winds, currents, sediment) will provide a standard set of tools for testing new code developments and benchmarking final product performance.

6. Significance

Although a relatively new program, Morphos has significantly impacted several USACE and multi-agency activities. As stated, the Morphos development team made critical contributions to the Hurricane Katrina IPET and the LAPCR and MSCIP studies. As a result, Morphos is helping to lead US agencies to adopt a standardized methodology for assessing coastal risk to inundation flooding. The Morphos team is helping to apply this methodology in a variety of Federal and local programs, such a Floodplain Mapping Program by the State of North Carolina and a Chesapeake Bay Region 3 assessment sponsored by FEMA. Furthermore, the Morphos Modeling Test Bed is being used to help set up and evaluate these coastal storm surge applications as well as provide a key demonstration project for the NOAA Integrated Ocean Observing System (IOOS) program.

Morphos will continue to engage community steering to improve our national capability for coastal risk assessment. Continued progress will require further advances in model physics and numerical coupling strategy. Spin-off engineering tools will support coastal engineering needs. The robust test and evaluation of developing technology will be supported by advancing the test bed infrastructure with critical data archives and model evaluation tools. The Morphos vision is to ultimately integrate these capabilities into a system of high-fidelity tools to fully support our coastal engineering design and assessment needs.

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