DEVELOPMENT AND VALIDATION OF INTEGRATED COASTAL PROCESS MODELS FOR SIMULATING HYDRODYNAMICS AND MORPHOLOGICAL PROCESSES

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ABSTRACT

Understanding coastal processes is increasingly important because the majority of the world's shoreline are eroding. Global warming and storm surges due to extreme weather conditions further threat human lives; and the resulting erosion problem makes beaches vulnerable. Numerical simulation of coastal processes driven by waves and currents can assist engineers and researchers to assess the environmental impact of coastal engineering projects, e.g. planning of harbors, designing erosion control structures, dredging for waterway maintenance, etc. The researches on coastal process modeling conducted in the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi have a wide spectrum of topics covering irregular wave deformations, wave-induced currents, tidal currents, currents driven by combined tides and storm surges (hurricanes), and sediment transport in wave and current environments. A process-based approach has been adopted to integrate the multi-scale physical processes in coasts, for which computations of waves, currents, sediment transport, and morphodynamic change are modulized. These numerical modules have been intensively verified and validated both individually and combined. By using this advanced integrated model, the long-term (yearly) simulations of bathymetrical changes in coasts under the varying conditions of waves and currents are achieved. This numerical approach provides engineers and researchers with an efficient tool to assess the long-term impact of coastal engineering projects, and therefore to find a cost-effective engineering plan for longevity of service in protecting erosion and/or preserving sustainable coastal system.

1. INTRODUCTION

In 2001 over half the world's population lived within 200km of a coastline. The rate of population growth in coastal areas is accelerating and increasing tourism adds to the pressure on the environment. In the United States, around 53% of the population lives near the coast and since 1970 there have been 2000 homes per day erected in coastal areas. In China alone, where the urban population is expected to increase by over 125% in the next twenty five years, over 400 million live on the coast (UN Atlas of the Ocean, 2005).

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Understanding coastal processes driven by wave and current is crucial to marine environmental management, coastal ecological rehabilitation, and sustainable development of marine ecosystem. Coastal hydrodynamics and morphological processes are typical physical phenomena in coastal/estuarine areas which consist of transformation and deformation of surface gravity waves propagating across the continental shelf to the beach, wave-induced currents in surf zone, tidal currents, as well as longshore and cross-shore sediment movements. Modeling of the coastal processes can significantly facilitate planning of coastal projects and designing of coastal structures for shoreline erosion protection, navigation channel maintenance, coastal environmental assessment, and so on.

In the past decades, significant progress has been made in the studies of coastal processes by means of physical experiments and computational simulations (De Vriend et al. 1993; Ding et al. 2000; Reniers et al. 2004). With the aid of the advanced numerical techniques, the simulation of the wave-breaking process has been achieved by solving the Reynolds averaged Navier-Stokes equations with a turbulence closure model. However, due to the extreme complexities of natural morphological processes, the mechanisms of sediment transport have neither been fully understood nor described adequately by physical principles and mathematical analyses. Direct simulation of long-term (daily to yearly) morphological evolutions in a real-scale coast coupled with irregular waves and wave-induced currents has been a challenging goal. With the process-based approach having been employed to the development of the coastal area morphological model, the simulation of morphodynamic changes and shoreline evolutions has become feasible. In general, this is accomplished by computing sequentially tidal circulation, wave field, current field, sediment transport, and seabed changes. Then a new bathymetry is fed back to modify the computations of the wave and current fields in the next time step (Figure 1). By this iterative procedure going through the wave-current-morphological models, it is possible to simulate the long-term morphological process by using an empirical sediment transport model for the fine time-scale morphological process.

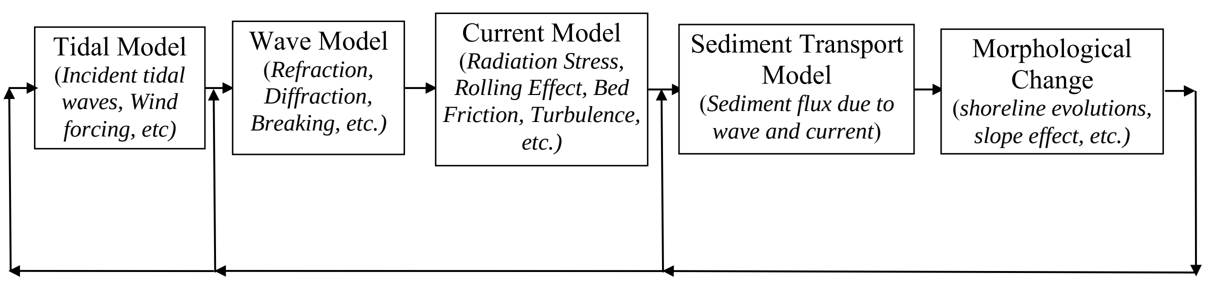


Figure 1. Flow chart of feedback system in a coastal area morphological model

By means of the process-based approach, an integrated coastal process model has been developed in the NCCHE, which consists of three major submodels for modeling irregular wave deformations, wave-induced currents, and morphological changes of seabed in a coast. First, the temporal/spatial variations of wave heights and directions due to wave refraction, diffraction, and breaking were described by a multi-directional wave spectral equation. Then, the two-dimensional (2-D) depth-averaged, shortwave-averaged momentum equations of currents with the radiation stress model were employed to simulate the wave-induced currents. In order to take into account the non-uniformities of the vertical current structures (e.g. the surface rollers) in surf zone in the depth-averaged wave-induced current, the improved formulations of the radiation stresses derived from the non-sinusoidal wave assumption (Svendsen et al. 2003) were used in the momentum equations. Finally, in the sediment transport model, the cross-shore and longshore sediment transport rates were calculated by means of an energetic sediment flux model, and the morphological changes of seabed were computed by a sediment balance model with the downslope gravitational effect included. The shoreline evolutions were simulated synchronistically by monitoring the wetting-and-drying processes with the seabed change computation. To develop a comprehensive numerical analysis tool providing end-users with a user-friendly interface, these coastal process submodels have been built in a software package called CCHE2D (NCCHE 2005), which is a comprehensively verified and validated tool to analyze 2-D shallow water flows, morphological processes, water quality, etc. Since this model also provides a user-friendly interface (CCHE2D-GUI) and a non-orthogonal mesh generator, it is very convenient to generate a grid system to cover a natural coastal zone with complex shorelines.

Through developing and refining the state-of-the-art numerical techniques for simulating tidal processes in coasts and estuaries, the researchers in the NCCHE have also conducted the research of tidal process modeling to understand tidal flows and coastal/estuarine circulation processes and their impact on exchange of freshwater and saltwater, water quality, and sediment transport. The CCHE2D-TIDE is an add-in module for the CCHE2D which extends the use of the CCHE models for simulating tidal waves, tidal currents, and residual currents under the conditions of incident tidal waves (non-reflective), tributary flows, non-uniform wind force, and the Coriolis force. This model can also simulate the variations of water elevations due to the combined forcings of tides and hurricane. The hurricane is represented as a hurricane cyclone model to simulate air pressure, wind speed, etc. One of ongoing projects in the research group is to develop a module for the CCHE3D model for simulation of three-dimensional tidal flows in large-scale and complex bathymetries. The CCHE3D hydrodynamic model together with the tide simulation module can simulate three-dimensional tidal waves, tidal currents, and residual currents under the conditions of incident tidal waves (non-reflective), tributary inflows, wind field, and the Coriolis force. Both 2D and 3D tidal models can simulate long-wave tidal flows and short-wave oscillatory free-surface flows.

In the paper, some basic features in the coastal morphological models and tidal process models are introduced. Several numerical examples for validation of individual process submodel in the integrated coastal process model and tidal process model are presented. The interactions of those submodels for modeling waves, currents, and seabed changes, are also discussed. The results indicate that this comprehensively validated coastal process model is capable and reliable in the applications to the study of marine environmental impact assessment for coastal/estuarine management and coastal structure planning.

2. DESCRIPTIONS OF MODELS

2.1 Wave-Current-Morphology Models

The coastal research in the NCCHE aims at the development of comprehensive numerical models for simulating coastal processes in large-scale coasts. The modular models, CCHE2D-COAST, for adding in the CCHE2D models are developed to extend the capabilities of the CCHE models for investigating irregular wave deformations, nearshore currents, sediment transport under the combination of waves and currents, and morphological processes. The main features of the coastal process models are as follows:

- Flexible non-orthogonal mesh available for simulating complex coastlines;
- Irregular wave deformations including refraction, diffraction, transmission through coastal structures, wave breaking, etc.;
- Nearshore currents including the surface roller effect in the surf zone;
- Sediment transport due to combination of wave and current,
- Morphodynamic change;

- Description of a variety of coastal structures, e.g., groin, offshore breakwater, artificial headland, jetty, artificial reef (submerged dike).

The wave module integrated in the CCHE2D-COAST is a multi-directional spectral wave transformation model built in a non-orthogonal mesh. It provides users with several options for input wave spectra at offshore boundary. This module has been extensively validated in the NCCHE (Ding et al. 2003, 2004, 2005; Ding and Wang, 2005). The current module based on the shallow water equations is used to simulate the depth-averaged wave-induced currents driven by the radiation stresses. This module provides users with a surface roller model as an option to take into account the effect of undertow current and wave breaking inside surf zone. This consideration of 3D flow structure in computation of currents can improve further the accuracy of morphological process modeling. The sediment transport and morphology modules have been integrated into the CCHE2D-COAST model. The offshore wave climate process can be parameterized by incident wave spectra and an adjustable feedback frequency. By implementing the wave-current-morphological feedback cycle, the modeling of long-term coastal processes with multi-scales can be achieved. The comprehensive validations for waves, currents, and mophodynamic changes have shown that this integrated model has high accuracy, robustness, high efficiency in the long-term simulation of coastal morphological processes (Ding et al. 2005). The applicability and efficiency of the CCHE2D-COAST can be applied by end-users in coastal engineering to select a cost-effective solution in coastal management, planning coastal projects, and designing coastal structures.

2.2 Tidal Flow Models

Through developing and refining the state-of-the-art numerical techniques for simulating tidal processes in coasts and estuaries, the long-range goals of the research are to understand tidal flows and coastal/estuarine circulation processes and their impact on exchange of freshwater and saltwater, water quality, and sediment transport. The CCHE2D-TIDE is an add-in module for the CCHE2D which extends the use of the CCHE models for simulating tidal waves, tidal currents, and residual currents under the conditions of incident tidal waves (non-reflective), tributary flows, non-uniform wind force, and the Coriolis force. This model has been tested and validated using various laboratory and field data. One of ongoing projects in the research group is to develop a module for the CCHE3D model for simulation of three-dimensional tidal flows in large-scale and complex bathymetries. The CCHE3D hydrodynamic model together with the tide simulation module can simulate three-dimensional tidal waves, tidal currents, and residual currents under the conditions of incident tidal waves (non-reflective), tributary inflows, wind field, and the Coriolis force. Both 2D and 3D tidal models can simulate long-wave tidal flows and short-wave oscillatory free-surface flows.

Storm surge is a meteorologically forced long wave motion, which can produce sustained elevations of the water surface above the levels caused by the normal astronomical tides. Storm surge modeling has assumed an important role in coastal engineering design. The CCHE2D-TIDE provides users with a hurricane model to take into account the effects of surface pressure, wind fields, and the route of a storm.

3. NUMERICAL APPROACHES

The partial differential governing equations in the integrated coastal process model are discretized by means of a numerical method called the Efficient Element Method (Jia and Wang 1999). The mesh for simulating waves, currents, and morphological changes are generally non-orthogonal; it is therefore capable of modeling the coastal processes in coastal zones with complex shorelines. The wave energy equation about the irregular wave deformation is solved by means of the parabolic approximation, by which the waves are assumed to propagate in a principal direction from offshore toward onshore (downwave direction). The wave-induced currents are obtained by solving the shallow water equations with the radiation stresses, for which a time-marching algorithm with a velocity correction method (Jia and Wang 1999) is employed. The morphological changes of seabed are solved by using the explicit Eulerian forward scheme. The seabed levels are calculated at each time step by updating the local sediment transport rate due to the variations of bathymetry and bottom friction. To predict the shoreline changes in coastal zones, a moving boundary treatment is capable of handling these complex and dynamic wetting-and-drying processes (Jia and Wang 1999). After the simulation of morphological processes over a period, the wave and current fields were computed according to the updated bathymetry. Thus, this integrated model has considered the interaction of wave, current, and sediment transport by adjusting the feedback period for repeating this feedback cycle (see Figure 1). This consideration is important to speed up the simulation of the long-term morphological process.

In addition, this integrated coastal model was developed on a software platform called CCHE2D (NCCHE 2005), which is a general analysis tool for simulating 2-D currents, sediment transport, water quality, etc, and also provides a user-friendly interface called CCHE2D-GUI and a non-orthogonal mesh generator. On the basis of the CCHE2D software platform, this coastal process model can serve immediately as a general analysis tool for simulating waves, currents, and morphological changes, and further support researchers and engineers for making decision of coastal project planning and environmental management.

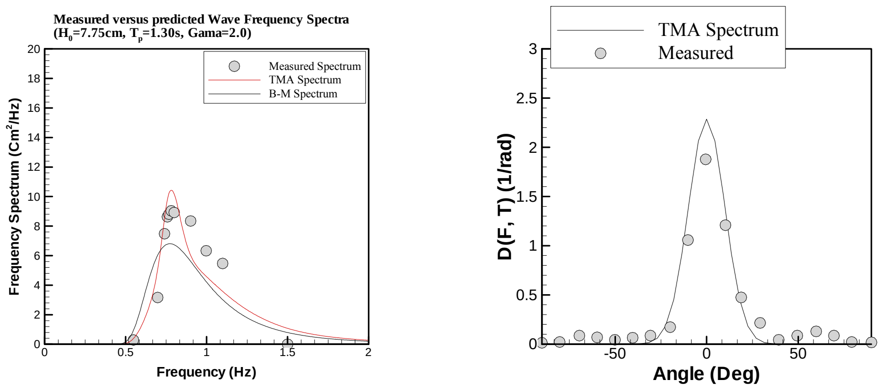
4. NUMERICAL EXAMPLES FOR MODEL VERIFICATION AND VALIDATIONS

4.1 Validations of Wave-Current-Morphology Models

The integrated submodels in the wave-current-morphology models can be validated individually or combined. For instance, the performance of wave transformation processes (e.g. refraction, diffraction, wave breaking, etc) in wave model may be confirmed separately by using simplified laboratory experimental data. However, complex processes such as coastal morphological processes should be validated systematically, because coastal sediment transport can not be solely simulated without information of wave and current.

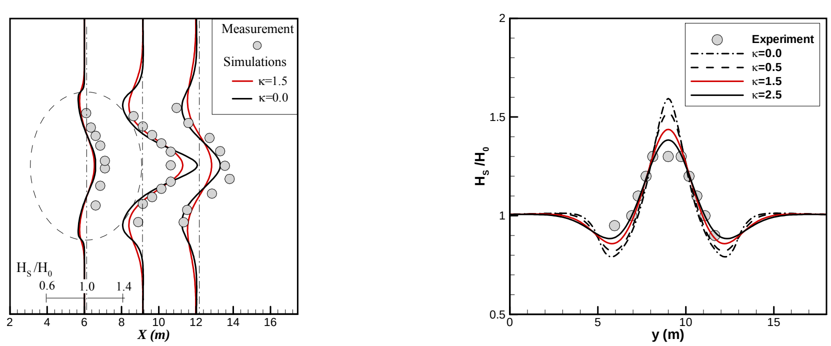
The wave deformation experiments conducted by Vincent and Briggs (1989) were utilized for validating the multi-directional spectral wave transformation model in the CCHE2D-COAST to confirm the effectiveness of refraction-diffraction terms in the model. In the paper, the results for the case of the narrow directional spreading spectrum are presented, in which the incident wave height H_0 was 7.75cm, the period was 1.3s. Figure 2 compares (a) two narrow wave frequency spectra and (b) a directional spreading function with the measured ones, respectively. These wave frequency spectra, i.e., TMA spectrum and Bretschneider-Mitsuyasu (B-M) spectrum, reproduced very well the experimental offshore wave conditions. Figure 3 plotted the wave height profiles along three transects behind the shoal with the corresponding measured values. In Figure 3(a), the red lines stand for the wave height computed with the diffraction effects (the diffraction coefficient κ=1.5), and the black lines are the results without the diffraction effects (the diffraction efficient κ=0.0). It implies that the diffraction terms in the wave equation can improve the accuracy of the simulated wave heights behind the shoal. Figure 3(b) shows the calibration of the κ value; it has been found that a calibrated κ value, i.e. κ =1.5, is suitable for the simulation of the wave deformations in the cases.

The integrated coastal model has been validated systematically by simulating sequentially waves, currents, and morphological evolutions in a movable bed laboratory experiment conducted by Mimura et al. (1983). This experiment was carried out in a wave basin being 14-m long, 7.5-m wide, and 0.42-m deep. A beach with 1/20 slope was initially covered with 10-cm thick sand, which had a uniform diameter of 0.2mm. The still water depth in the experiments was 25cm. The incident irregular wave with 5.7cm height and 0.9s period attacked normally the beach for approximately 12 hours. Then, an offshore breakwater of an iron plate with 1.5m long and 0.5m height was installed at 1.8-m offshore from the initial shoreline. The experiment of the morphodynamic changes lasted more than twelve hours after the installation of the offshore breakwater. The simulation by this model was started just from the installation of the structure and terminated after six hours. The measured beach topography at the initial time of the breakwater installation by Mimura et al. (1983) was used for generating a computational mesh with 0.1m uniform spatial increment.



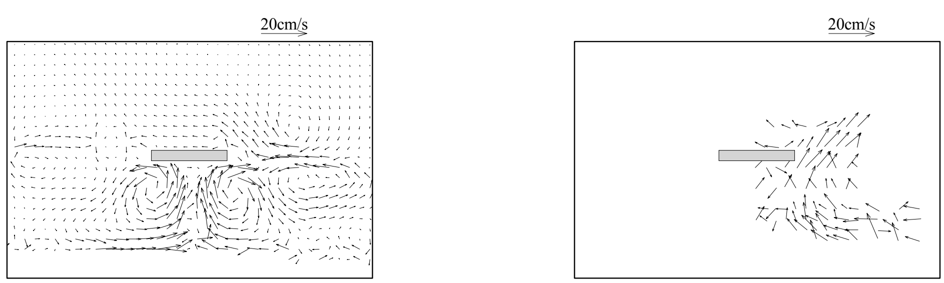
(a) Wave Frequency Spectra (b) Narrow Directional Spreading (σ_m=10)

Figure 2. Comparison of frequency spectra and directional spreading functions between measurements and simulations (B-M = Bretschneider-Mitsuyasu)



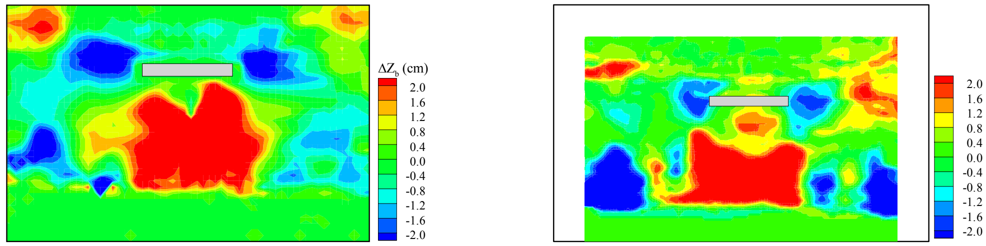
(a) H/H_0 in three transects (b) Calibration of diffraction at the second transect

Figure 3 Comparisons of normalized wave heights with and without diffraction term



(a) Simulation (b) Observation (Mimura et al. 1983)

Figure 4 Comparison of wave-induced currents at t=6 hours between simulation and observation



(a) Simulation (b) Observation (Mimura et al. 1983)

Figure 5 Comparison of seabed changes after six hours between simulation and observation

The wave-induced current fields for driving the morphological process were thus computed by solving the shallow water equations with the improved radiation stresses (Ding et al. 2005). The simulations of waves and currents were repeated after every 12 minutes of morphological change computations. Figure 4 compares (a) the computed currents at t=6 hours with (b) the measurements at the same time. The computed currents reproduced the circulations and the currents in front of the breakwater. Figure 5 compares the distributions of seabed changes after six hours between the simulations and the observations. This integrated model predicted quantitatively the sand depositions behind the breakwater, the scour at the tips of the breakwater, and offshore bars. The reasonable agreement in the morphological change results between the simulation and the observation was obtained.

4.2 Validations of Tidal Flow Models

The validation of the CCHE2D-TIDE model was done by using the real-time data provided by the USGS sites in the Hudson River, NY. The computational domain covered the tidal river reach from HASTING (USGS Site# 01376304) to GREEN ISLAND (USGS Site# 01358000). The validation of the tidal model has been carried out by simulating the tidal flows during a 10 day period from 0:00am, 05/29/2004 to 0:00am, 06/08/2004. The tidal elevations at the Hastings-on-Hudson cross section were used as the downstream boundary condition of incident tidal wave, which were download from the USGS website. The upstream discharge at Green Island was estimated as 6,000ft^3/s (169.92m^3/s) based on the historical data during the same days in 2003. The average wind velocity and direction, i.e. 5.73mph and NNW, collected at Poughkeepsie during the 10 days computational period, were inputted in the tidal model as a steady wind field. The simulations of the tidal flows in the area were started from a status of still water at the beginning, i.e. cold start. The data of tidal elevations, discharge, and stream velocities at the other three sites, i.e. Albany, Poughkeepsie, and West Point, have been used for comparisons of the numerical results with these measurements.

The computed tidal currents around the Hastings-on-Hudson are shown in Figure 6 for an ebb tide at 7:30am, 6/07/2004, and for a slack tide at a lower water level (LWL) at 10:30am, 6/07/2004. The computed tidal elevations above the National Geodetic Vertical Datum (NGVD) at Albany have been compared with these observations in Figure 7. The comparison of discharge at Poughkeepsie was also carried out. Figure 8 shows the computed discharge and observed ones in the section, and excellent agreement of the discharges was made.

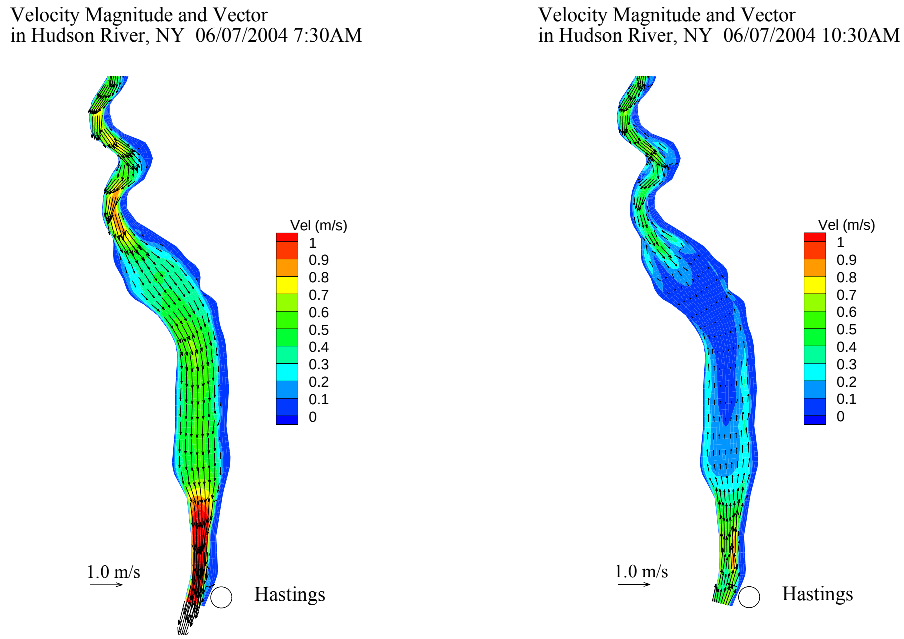


Figure 6 Computed tidal currents in the lower Hudson River, NY (Left: Ebb tide at 7:30am, 06/07/2004; Right: Slack tide at 10:30am, 06/07/2004)

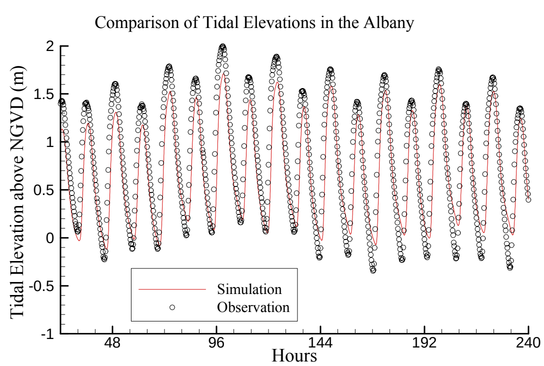


Figure 7 Comparison of tidal elevations between simulation and observation at Albany in the upper Hudson River, NY (USGS Site#: 01359139)

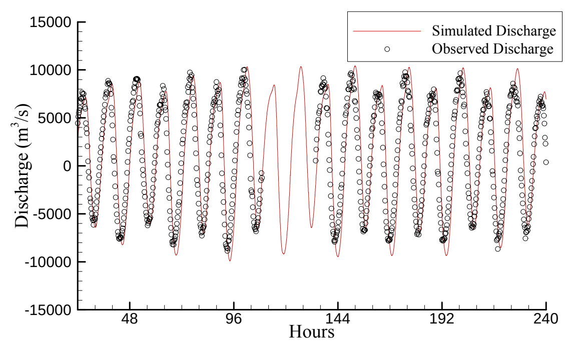


Figure 8 Comparison of stream discharge between simulation and observation at Poughkeepsie in the middle Hudson River, NY (USGS Site #: 01372058). Sign of discharge: (+) ebb tide, (-) flood tide

The NCCHE has conducted the research on the hydrodynamic simulation due to the hurricane's impact. The hurricane can be modeled as the so-called cyclone model proposed by Holland (1980). The movement and the potential of a hurricane are parameterized in the model by considering hurricane pressure (central pressure and ambient pressure), wind speed, radius of maximum wind, etc. The decay of a hurricane after landfall can also be included. Figure 9 shows the simulated wind fields of the Hurricane Ivan in the Gulf of Mexico during the period from September 7 -24, 2004. The Hurricane Ivan made landfall in the U.S. near Gulf Shores, Alabama. The decay of the wind speed after its landfall was taken into account in the simulation along the Ivan's path.

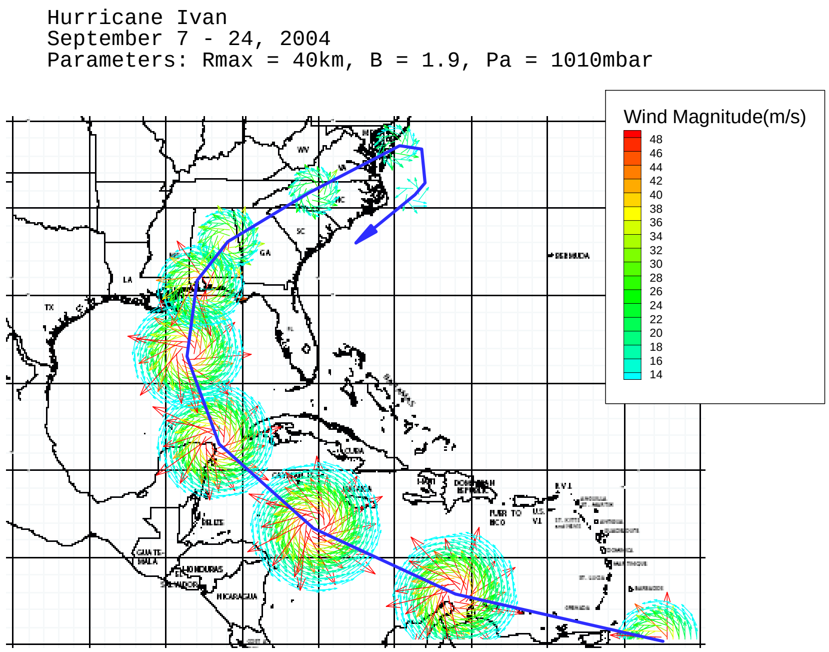


Figure 9 Simulated wind fields of the Hurricane Ivan during September 7 – 24, 2004

5. CONCLUSIONS

The integrated coastal process model has been developed for simulating the natural coastal processes such as irregular wave deformations, wave-induced currents, tidal currents, sediment transport, and morphodynamic changes. These submodels for simulating the corresponding coastal processes were systematically integrated into a comprehensive numerical analysis tool to predict the interactions among waves, currents, and seabed changes. The offshore wave climate process can be parameterized by an incident wave spectrum and an adjustable feedback frequency. By implementing the wave-current-morphological feedback cycle, the modeling of long-term coastal processes of multi-scales can be achieved.

The submodels about waves, currents, and morphological processes were systematically tested by simulating the relevant laboratory cases. The integrated model also can be applied to simulate long-term seabed changes with installations of coastal structures in coasts. The NCCHE tidal model is capable of simulating tidal currents under natural geometrical condition. The hurricane cyclone model has been developed for assessing the impact on the increasing of water elevation and the flooding in coasts and estuaries. Because of these achievements of validation and application of the model, it can be concluded that this numerical tool is available for assisting researchers and engineers for the marine environmental impact assessment for coastal/estuarine management and coastal structure planning.

Moreover, this model has been built in a software package called CCHE2D, which is an extensively verified and validated tool to analyze 2-D shallow water flows, morphological processes, water quality, etc. The included user-friendly interface further facilitates the simulations of coastal processes in coasts with complex shorelines (NCCHE 2005). The applicability and efficiency of the model can be applied by end-users in coastal engineering to select a cost-effective solution in coastal management, planning coastal projects, and designing coastal structures.

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