Simulation of Wind, Storm Surge, and Wave in Hurricane Sandy

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ABSTRACT

In the study, the storm surges and waves driven by Hurricane Sandy (2012) were computed by using an integrated coast-ocean process model, CCHE2D-Coast. The surface wind and air pressure fields of the cyclone were reconstructed by a parametrical cyclonic wind model, which was developed to include the decay effect of hurricane landfall. The simulated wind, wave, and water elevations were compared with the observation data by NOAA and USGS. This preliminary numerical result indicates that this coast-ocean model reproduced well the storm surge tides and waves in the entire east coast of the US.

INTRODUCTION

Hurricane Sandy was formed in the southwestern Caribbean Sea at the late October of 2012, which is a classic late-season hurricane. The cyclone made landfall as a category 1 hurricane in Jamaica, and gained strength to a 100-kt category 3 hurricane in eastern Cuba. Sandy underwent a complex evolution and grew considerably in size while over the Bahamas, and continued to grow despite weakening into a tropical storm north of those islands. The system restrengthened into a hurricane while it moved northeastward, parallel to the coast of the southeastern United States, and reached a secondary peak intensity of 85 kt while it turned northwestward toward the mid-Atlantic states. Although at the landfall of Hurricane Sandy (2012), this cyclone weakened to a post-tropical storm near Brigantine, New Jersey at about 2330 UTC, Oct. 29, 2012, due to its tremendous size (winds grew to about 870 n mi prior to landfall), Sandy drove a catastrophic storm surge into the New Jersey and New York coastlines. The atmospheric structure of Sandy is also very complex. When the cyclone moved up to the high latitude of the east Atlantic Ocean, it merged into the Gulf Stream and encountered the trough of the jet stream from the west of the North American continent. This complex weather system made the surface wind fields around the cyclone being asymmetric, which is different from the symmetrical structure of surface wind of hurricanes in the Gulf of Mexico (Halverson and Rabenhorst 2013).

The strong wind and air depression lift the waters of the entire east coast of the US from Florida to Maine. When Sandy made its landfall, it induced catastrophic storm surges and waves into the New Jersey and New York coastlines which
inundated low-lying land areas in the two states. The highest water elevation of storm tide measured by an NOAA-NOS tide gauge at King Point in New York was 14.311 ft (4.362 m) above Mean Lower Low Water (MLLW) at 0206 UTC 10/30/2012. The storm surge at this NOS station was up to 8.54 ft above the normal tide level at this moment. Surveyed high-water marks from the United States Geological Survey (USGS) indicate that the highest water levels in New York occurred on Staten Island. The highest direct measurement of inundation was 7.9 ft above ground level, in the Oakwood neighborhood of Staten Island. Significant flooding due to storm surge (with some contribution from rainfall) occurred in parts of the Hudson River Valley as far north as Albany. In New Jersey, the highest water elevation of storm tide measured at Sandy Hook, NJ was 10.416 ft above NAVD 88, at 2342 UTC 10/29/2012. The surge at this moment reached to 8.567 ft above the normal tide level. After this record, this station failed and stopped reporting the data.

As storm surge from Sandy was pushed into New York city and Raritan Bays, sea water piled up within the Hudson River and the coastal waterways and wetlands of northeastern New Jersey, including Newark Bay, and the Passaic and Hackensack Rivers. Significant inundations occurred along the Hudson River in Weehawken, Hoboken, and Jersey City, where many high-water marks indicated that inundations were between 4 and 6.5 ft above ground level. Inundations of 4 to 6 ft were also measured across Newark Bay in Elizabeth and the area around Newark Liberty International Airport.

The high wind of Sandy generated huge ocean waves along the storm track. The highest significant wave height at NDBC Station No. 44065 was 32.35 ft (9.86 m), recorded at 0050 UTC 10/30/2012. Wave action on the east coast caused beach erosion, damage to coastal structures such as bridge piers and houses near the shores, and highways. Preliminary U.S. damage estimates are near $50 billion, making Sandy the second-costliest cyclone to hit the United States since 1900. In the United States, 72 direct deaths were noted, making Sandy the deadliest U.S. cyclone outside of the southern states since Agnes (1972). (Blake et al. 2013).

This research is to apply an integrated coast-ocean model, CCHE2D-Coast, to simulate meteorological and hydrodynamic processes during Hurricane Sandy such as wind, air pressure, surface water elevations, tidal currents, and waves in the U.S. Atlantic coast. CCHE2D-Coast consists of a multi-directional wave action model, depth-averaged hydrodynamic model, a tropical cyclonic wind and air pressure model, and sediment transport model (not used for this study). The cyclonic wind model is a newly developed parametric wind model which contains the effect of hurricane landfall. All the submodels for meteorological and oceanographic processes use a single mesh which is a structural non-orthogonal quadrilateral grid. This integrated model has been verified and validated by simulating several hurricanes which made landfall in the Gulf of Mexico (Ding et al. 2013). The integrated model has high efficiency in simulating large-scale wind-storm-surge processes during tropical storms in a laptop computer with a relatively short CPU time.

This study includes mesh generation covering the entire East Coast, tidal condition specification, model spin-up, storm data collection, and model validation (hindcasting). Simulated physical parameters, i.e. wind speed, water surface elevations, significant wave heights, peak wave periods, and wave spectral energy in
several NOAA gauge stations are carefully compared with the observations by NOAA. Hindcasting results are in good agreement with NOAA’s observation data. Using this computationally-efficient model, one-week storm surge simulation (without wave-current interaction) took 3 hours on a single CPU of Intel(R) Core (TM) i7 CPU@2.22GHz; fully-coupled wave-current simulation took 8 hours on the single CPU on a laptop computer. It indicates that this integrated coast-ocean model is capable of performing real-time prediction of wind, tide, water elevations, and waves in tropical cyclones with a good accuracy.

INTEGRATED HURRICANE-INDUCED STORM-SURGE MODEL

A Cyclonic Wind-Pressure Model with Landfall Decay Effect

To predict storm surges induced by tropical cyclonic wind and low pressure, spatio-temporal variations of air pressure and wind fields are needed to calculate wind energy input into ocean water column. The widely-used tropical cyclonic wind-pressure model, Holland’s wind model (Holland 1980) is a parameterized wind-pressure model. This simple model only needs a few parameters for defining hurricane track, size, intensity, and central pressure to determine the air pressure and wind tangential velocity. However, this simple model doesn’t include the decay effect of wind after a hurricane makes its landfall.

Hazardous wind and storm surges occur around the coastal area where hurricane makes its landfall and during the period right after its landfall. It is, therefore, important to predict the location and the intensity of storm wind at hurricane landfall. Mainly due to loss of thermal energy input from warm ocean waters, storm wind speed usually decays quickly after landfall. In general, hurricane intensity decay is influenced by a complex combination of physical factors, including the ocean structure prior to landfall, surface heat capacity of water and soil, surface roughness and moistures of soil and vegetation, and variations between day and night (e.g. DeMaria et al. 2006).

Kaplan and DeMaria (1995) approximate hurricane maximum velocity decay by a linear differential equation with respect to time after landfall. Their linear decay model only takes into account the decay due to energy loss of heat input from the ocean. Correlation analyses of various hindcast storms found that the linear decay model was inadequate in simulating the decay process; in particular, sharp drops in wind velocity immediately following landfall of numerous storms suggested that one or more additional physical factors induce a nonlinear pattern of hurricane decay. Thus, to predict the maximum wind speed and air pressure after hurricane landfall, Ding (2012) developed a new decay model with an additional non-linear decay term to account for increased surface roughness as the storm moves over land.

\[
\frac{d(V_{\text{max}}-V_b)}{dt} = -\alpha(V_{\text{max}}-V_b) - \frac{C_D}{h} (V_{\text{max}}-V_b)^2
\]  

(1)

where \( t = \) time after landfall, \( V_b = \) background wind velocity, \( V_{\text{max}} = \) maximum wind velocity, \( \alpha = \) parameter of linear decay (1/s), \( C_D = \) non-dimensional drag coefficient and \( h = \) mean height of the planetary boundary layer (m), the lowest layer of the troposphere in which wind is influenced by land surface friction (Vickery et al. 2000). Because the last term in Eq. (1) is nonlinear, this equation does not have an analytical
solution. A time-marching semi-implicit Euler’s scheme is used for computing the maximum wind speed. The empirical parameters, the decay parameter \( \alpha \) and the drag coefficient \( C_D \), have been calibrated by computing the historical post-landfall data of the hurricanes landed in the northern Gulf Coast.

Holland’s tangential wind field equation (Holland 1980) was used to derive a direct relationship between the decay in maximum velocity and central barometric pressure. This parameterized formula boils a hurricane’s complex atmospheric processes down to a fixed vortex of rotating winds that create a central region of low atmospheric pressure – the eye (Mattocks and Forbes 2008).

\[
V(r) = \sqrt{(B / \rho)(R / r)^\beta (P_a - P_c)e^{-\left(\frac{rf}{2}\right)} + \left(\frac{rf}{2}\right) - \left(\frac{rf}{2}\right)}
\]

where \( V(r) \) = tangential wind speed (m/s) at a distance of \( r \) (m) from the center, \( R \) = radius of the band of maximum sustained winds from the eye’s center, \( P_a \) = ambient pressure (both in pascals), \( B \) = empirically determined parameter, \( f = 2\Omega \sin(latitude) \) is the Coriolis force, and \( \Omega \) is the rotational frequency of the earth. An explicit relationship between maximum wind and pressure was derived by setting \( R \) equal to \( r \) in Holland’s equation (2):

\[
V_{\text{max}} = \sqrt{(B / \rho)(P_a - P_c)e^{-\left(\frac{rf}{2}\right)}}
\]

Combining Eq. (2) with Eq. (3), thus the tangential wind field at any locations can be expressed as a function of maximum velocity and a position function of \( r \).

\[
V(r) = \sqrt{V_{\text{max}}^2 (R / r)^\beta e^{\left(\frac{rf}{2}\right)} + \left(\frac{rf}{2}\right) - \left(\frac{rf}{2}\right)}
\]

In Hurricane Sandy, the decay model produced very accurate prediction results for hurricane maximum wind and the central pressure after its landfall (see Figure 1).

![Figure 1 Comparisons of wind speed (left) and central air pressure (right). The observation data are from the best track of Hurricane Sandy (2012) by NOAA.](image)

**Integrated Hurricane-Induced Storm-Surge Model**

Storm surges are induced by wind and low air pressure during a storm or a hurricane. Coastal flood and inundation are driven by multiple hydrodynamic processes (coastal and oceanographic processes) such as wind-induced currents, tidal
flows, waves, wave setup, earth rotation, river flows, etc. To simulate storm surges during a hurricane driven by the Coriolis force and all the hydrological force such as winds, waves, tides, and river flows, a coast-ocean model, called CCHE2D-Coast, is used in this study. This model consists of a multidirectional wave spectral model and a coastal hydrodynamic model (Ding et al. 2013). It is capable of simulating hydrodynamic processes in coasts, estuaries, rivers, and oceans such as (1) storm surges and waves driven by cyclonic wind, (2) irregular wave deformations and transformation, (3) tidal and river flows, and (4) nearshore currents and wave setup/setdown. This model generally employs a non-orthogonal grid that can model complex coastlines.

The surface wind stress is a major driven force of storm surges, which represents the portion of wind energy input into water columns. Even though the interaction between air and sea water is complex, this wind stress $\mathbf{\tau}_s$ can be modeled by the conventional bulk formula (e.g. Large and Pond 1981),

$$\mathbf{\tau}_s = \rho C_d \mathbf{\hat{V}}_w \mathbf{\hat{V}}_w$$

where $\mathbf{\hat{V}}_w = $ vector of wind velocity at 10 meters above ground, and $C_d =$ drag coefficient.

In the wave action model, the energy input by wind forcing is modeled as separated sink and source terms proposed by Lin and Lin (2004). The coefficients in the wind energy input are calibrated by hindcasting Hurricane Gustav (2008) which made landfall at the southern Louisiana coast (see Ding et al. 2013 for the details).

**CONDITIONS FOR SIMULATING STORM SURGES OF SANDY**

**Computational Domain and Mesh**

As shown in Figure 2, the computational domain covers the entire US east coast from Florida to Maine. The bathymetric data of the Atlantic Ocean were obtained from two data sources: one is the NOAA National Geographic Data Center (NGDC) (the resolution is about 100m); another is an existing grid used in the ADCIRC storm-surge simulations, which is a finite elemental mesh data. This ADCIRC depth grid called SL15 contains 2,137,978 nodes and 4,184,778 triangular elements in total, which covers a very large area including Gulf of Mexico, Caribbean Sea and part of the Atlantic Ocean up to Maine and Nova Scotia. The topographical data is from the USGS DEM. In the areas of New York and New Jersey, the 3-m DEM data was used for creating the computational grid. A non-orthogonal structural grid was generated by using CCHE2D-Mesh (Zhang and Jia 2009). It consists of 1,008,018 nodes (1679×594) with spatially-varying resolutions: high resolution in coastal regions and low-lying land in New Jersey, lower resolution at deepwater of the ocean. Figure 2 (right) shows the computational grid only covering the coastal regions of New York and New Jersey, including the Hudson River and the wetland in northeast New Jersey.

The bottom roughness coefficients, i.e. Manning’s $n$ values, are obtained by interpolating the values from the SL15 mesh data. The values in the SL15 have considered the sea bottom roughness, coastal structures (i.e. dikes, roads, sea walls etc.), and vegetation at wetland. The roughness values are set as 0.02 in the water area and 0.03 in inland area, respectively.

**Computational Conditions of Storm Tracks, Tides, and Waves**
The best track of Sandy provided by NOAA’s National Hurricane Center (NHC) is used as the storm track. The information of the storm track includes the coordinates of the cyclone centers at different recorded time, the central air pressure, and the radii of the cyclone (Figure 1).

**Figure 2** Left: Computational domain and Bathymetry and Topography of the US East Coast; Right: computational grid in NY and NJ coasts

Based on the observations of tides at NOAA’s tide gages in the Atlantic Ocean (http://tidesandcurrents.noaa.gov/gmap3/), the tidal elevations at Bermuda is used as the tidal boundary condition at the deepwater open boundary of the Atlantic Ocean.

Wave set-up induced by storm winds can cause an additional increase in water surface elevation and increases the extent of inundation area and depth. By using the wave model in CCHE2D-Coast, the wind-induced wave fields are computed over the entire computational domain as shown in Figure 2. In the simulations of storm surge by coupling the wave model with the hydrodynamic model, the wave field was recomputed every one hour based on the latest flow results. On the offshore boundary, wave parameters as the wave boundary conditions are computed by a deep water wave model, Young’s hurricane wave model (Young 1988).

**Model Spin-up and Initial Conditions**

Before a storm surge simulation starts, the model has to be initialized, or spun up, so that a well-developed sea state is created for flow dynamic simulations driven by tides and storm winds. This model was spun up by simulating the tidal flows over the US east coast for 10 days, i.e. from 0000 UTC 10/15/2012 to 0000 UTC 10/25/2012. The time-step size is 120 seconds. An eddy-viscosity model was used for calculating the eddy viscosity in the flow model. During the spin-up period of the simulation, the effect of surface wind was neglected.

**SIMULATION RESULTS OF WIND, WAVE, AND STORM SURGE IN HURRICANE SANDY**
The simulation of storm surges and waves started at 0000 UTC 10/25/2012, 5 days before Hurricane Sandy made landfall at the New Jersey coast. It was carried out till 0000 UTC 11/01/2012, for a week.

The surface wind fields of Hurricane Sandy were reconstructed by using the Holland’s wind model. However, after the cyclone made it landfall in New Jersey, the decay of landfall was considered by modifying the maximum wind speed and the central air pressure based on Eq. (1) and Eq. (5) of the nonlinear surface wind model developed by Ding (2012). α and $C_D$ decay parameter regressions, i.e. Eqs. (2) and (3) were used to estimate Sandy’s decay process from forecasted maximum winds and minimum pressure at landfall (see Figure 1). The cyclonic wind fields were represented by the modified Holland’s wind model with a variable hurricane strength parameter (B); rotational velocities were scaled by 0.7 to match surface wind speeds. After comparing a few formulations for calculating the drag coefficient $C_D$ in Eq. (12), Large and Pond (1981) was used to calculate the drag coefficients for surface wind stress.

The frequency of wave-current interaction was two hours, namely, the wave field driven by the cyclone wind was updated every 2 hours during the storm-surge simulation. In the computation of wave-action equation of the spectral wave energy, the total 21 frequency bins and 25 wave directions were used to discretize the wave spectra for computations of irregular wind-induced waves. The effect of wave breaking in shallow waters and the whitecapping in deepwaters were included. The unsteady wave action was performed.

In the simulation of surge tide, the wave-induced radiation stresses, surface wind stresses, and the bottom friction stresses were considered. A strongly implicit scheme was used for solving the time-dependent flow equations. The time-step size for computing flows is 120 seconds. Using this computationally-efficient model, one-week storm surge simulation (without wave-current interaction) took 3 hours on a single CPU of Intel(R) Core (TM) i7 CPU@2.22GHz; fully-coupled wave-current simulation took 8 hours on the single CPU on a laptop computer. All the computed results of wind, wave, current, and water elevations can be visualized by applying CCHE2D-GUI. The animations of these physical variables can be generated by this user interface.

As two examples, Figure 3 presents comparisons of wind speed at NOAA gages at Ocean City Inlet, MD, and NDBC44065. The first station recorded the wind parameters every 6 minutes; the NDBC station provides hourly wind data. This parametric wind model produced a good result of wind at the Ocean City Inlet, but an overestimated wind speed at the NDBC Station. Due to the “hybrid storm” structure of Sandy (Halverson and Rabenhorst 2013), to obtain better prediction of wind, a meso-scale numerical weather model such as the weather research and forecasting (WRF) Model is needed. Nevertheless, the wind fields generated by the present parametric wind model have produced good results of waves and storm surges, as discussed below.
As shown in the left of Figure 4, the New Jersey coast, the Hudson River, and the south beach of Long Island received most storm surge waters. The maximum water elevation, up to 5 m above NAVD88 was computed at the west of the Raritan Bay, NJ. In comparison with the USGS-observed high water marks (HWMs) in the coasts of New York and New Jersey (USGS 2013), the value of $R^2$ of the maximum water elevations is 0.7293 (shown in the right of Figure 4). Considering the resolution of the grid and the accuracy of the DEM data, the computed water elevations are acceptable.

Figure 5 further presents the comparison of time series of water elevations between computation and NOAA’s Observations at two selected NOAA tide gages at Montauk, NY, and Sandy Hook, NJ. The storm-surge model reproduced the dynamic variations of surface water elevations at the US east coast.
The wave actions were computed along with the simulation of storm surges every two hours from 10/25 to 11/01/2012. As the cyclone was approaching to the east coast, high waves traveled to the seashores of New York and New Jersey. As shown in the left of Figure 6, the offshore significant wave height wave at this area reached 10 meter. The right plot of Figure 6 presents the comparisons of wave heights at NOAA’s NDBC buoy No. 44065, which is located at the offshore of the south beach of Long Island, NY. The simulation of wave actions has caught well the variation of the wave features in the ocean.

CONCLUSIONS AND DISCUSSIONS

In the study, the storm surges and waves driven by Hurricane Sandy (2012) were computed by using an integrated coast-ocean process model, CCHE2D-Coast. The surface wind and air pressure fields of the cyclone were reconstructed by a parametrical cyclonic wind model, which was developed to include the decay effect of hurricane landfall. The simulated wind, wave, and water elevations were compared with the observation data by NOAA and USGS. This preliminary numerical result
indicates that this coast-ocean model reproduced well the storm surge tides and waves in the entire east coast of the US. To further improve the accuracy of the hindcast results of wind and wave, a mesoscale numerical weather model is needed to take into account the hybrid system of this late-season hurricane interacting with the Gulf Stream and cold storm.

REFERENCES


