THE EFFECT OF HINDCASTED WAVES ON COASTAL STORM WATER LEVELS DURING THE BLIZZARD OF 2003

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1. INTRODUCTION

A shore protection and storm damage reduction study for the south shore of Long Island, New York, USA, from Fire Island Inlet to Montauk Point is being conducted by the U.S. Army Corps of Engineers. The study area includes the barrier islands, Atlantic Ocean shorelines, and adjacent back bays. These low-lying areas are subject to flooding by tropical and extratropical storm surge from the Atlantic Ocean, surge propagation through tidal inlets, wave setup and runup, and barrier island overwash and breaching. By using meteorological hindcasts and coupling hydrodynamic, wave, and sediment transport models, accurate storm surge levels can be calculated throughout the study area.

This paper discusses the application and performance of hindcasted wind fields and wave models to simulate ocean wave setup and its impact on back-bay water levels during storm events by presenting model simulations and measurements from the blizzard of 2003.

2. STUDY AREA

The project area is located entirely in Suffolk County, Long Island, along the Atlantic and the bay shores of the towns of Babylon, Islip, Brookhaven, Southampton, and East Hampton (Figure 1). The overall study area is approximately 135 km long and includes three large estuarial bays: Great South Bay (connected to the ocean by Fire Island Inlet), Moriches Bay (connected to the ocean by Moriches Inlet), and Shinnecock Bay (connected to the ocean by Shinnecock Inlet). The westernmost portion of the overall study area, the Nassau/Suffolk County border at Great South Bay, is located about 75 km east of The Battery, in New York City.

3. STORM SURGE MODELING METHODOLOGY

Coastal storm water levels are governed by a number of complex physical processes: wind conditions, barometric pressure, astronomic tide, wave conditions, and morphologic response. The numerical modeling strategy for this study addresses all of these processes by combining a number of numerical models, some with external communication and others with integrated dynamic communication. The strategy also employs state-of-the-art meteorological methods. Figure 2 illustrates the complexity of the numerical modeling strategy. The numerical models and methods used to simulate storm water levels resulting from ocean stage, wave setup, surge propagation

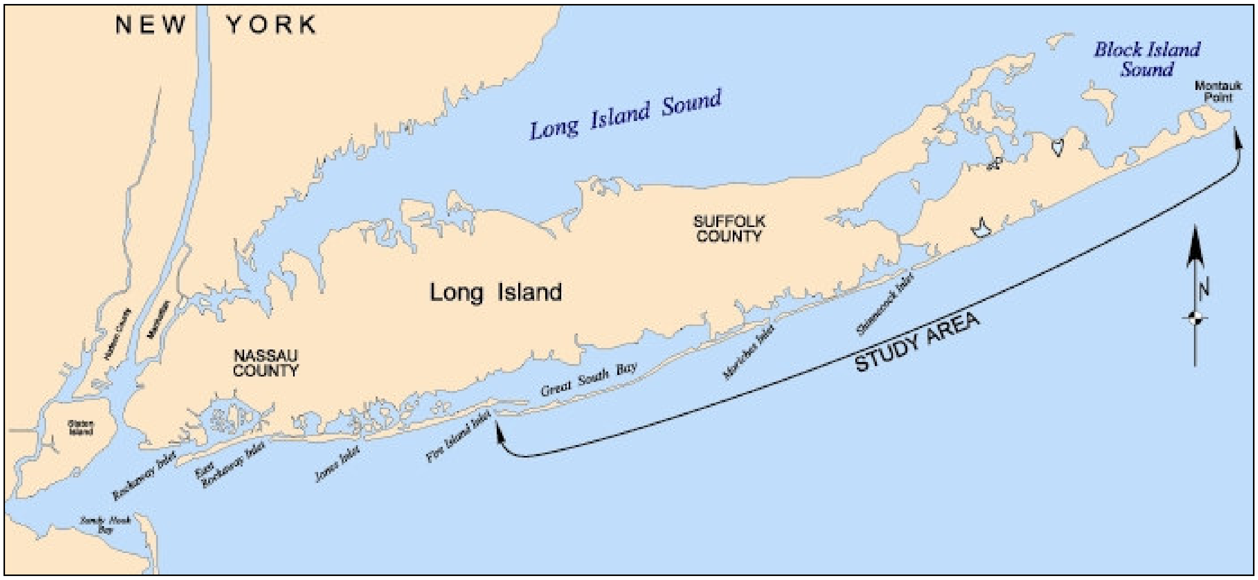

Figure 1. Study area.

through the tidal inlets into the bays, and localized wind setup are*:

- Planetary Boundary Layer model (PBL)
- Interactive Kinematic Objective Analysis (IKOA)
- ADvanced CIRCulation model (ADCIRC)
- WISWAVE
- DELFT3D-FLOW
- DELFT3D-WAVE (HISWA)

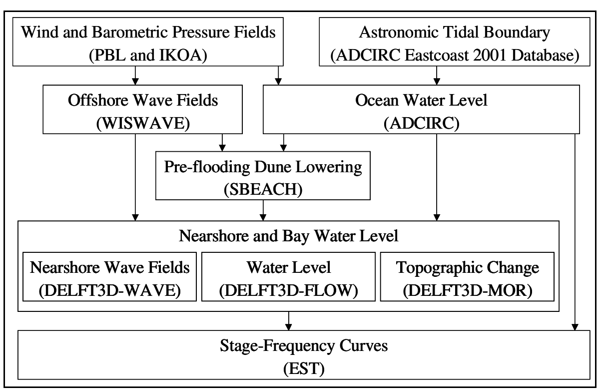

Figure 2. Modeling strategy.

* The impact of morphological response on storm water levels is beyond the scope of this paper. See Cañizares *et al.* (in press) for a discussion of morphological impacts on storm water levels for this study.

3.1 Meteorological Forcing

For this study, Oceanweather, Inc developed meteorological forcing for 37 tropical and extratropical storms. Tropical wind velocity fields, 10-m above the water surface, and barometric pressure fields were developed using PBL, a tropical cyclone model (Thompson and Cardone, 1996). PBL describes the vortex pressure field using existing historical information on storm track, scale radius of the storm radial pressure profile, and other parameters.

Storm tracks and initial estimates of intensity of an historical North Atlantic basin tropical storm to be analyzed were taken, with some modification, from the NOAA Tropical Prediction Center's database (Jarvinen *et al.*, 1984). Surface winds generated from PBL are then imported into a graphical interface at 6-hourly intervals and evaluated against available surface data and aircraft reconnaissance wind observations adjusted to the surface as described by Powell and Black (1989). This process is iterated until a solution for the surface wind fields that is most consistent with all of the available data is achieved. The final wind field is this best fit model solution.

Wind fields, 10-m above the water surface, for extratropical storm events were developed using IKOA. The benefits of IKOA enhancement to the performance of ocean response modeling over wind fields produced by strictly automated methods for extratropical storms are well established (e.g., Cardone *et al.*, 1995). The IKOA starts from a first-guess background wind field and then proceeds to assimilate observations of surface winds from ships, buoys, coastal stations, and remote sensing sources. If available, background winds were taken from the AES40 hindcast (Swail and Cox, 1999).

For extratropical events, barometric pressure fields were taken directly from NOAA's NCEP (National Center for Environmental Prediction) database (www.ncep.noaa.gov).

Tropical and extratropical wind and pressure fields were produced on a grid domain extending from 30° N to 47° N and from 64° W to 82° W to capture far-field surge and wave field generation (Figure 3). Wind fields were reported at a grid spacing of 0.0625° latitude by 0.0625° longitude (about 7 km) and 0.625° latitude by 0.833° longitude, for tropical and extratropical events respectively. Temporal resolution for tropical and extratropical events was 30 minutes and 3 hours, respectively.

No land effects were considered during wind field development. Therefore, a 30 percent reduction in wind speed for all offshore-directed winds in nearshore areas was adopted for this study (Resio, personal communications).

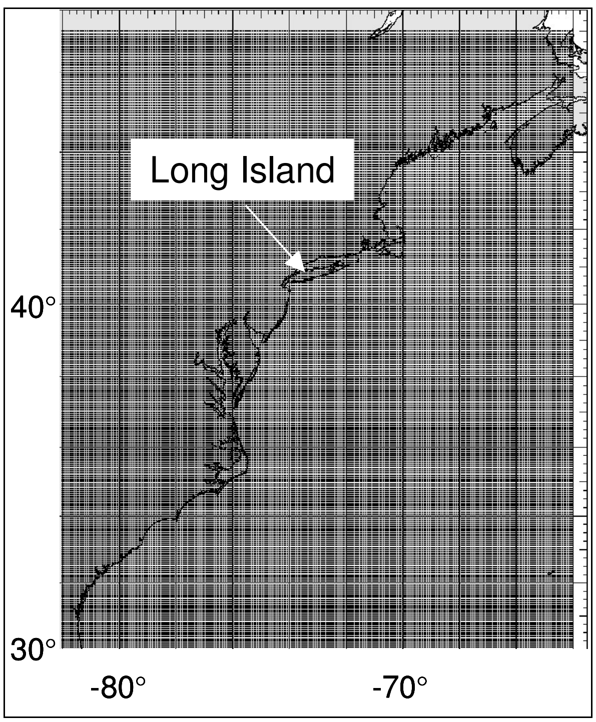

Figure 3. Wind field grid for tropical events.

3.2 Offshore Hydrodynamic Modeling

Using ADCIRC, ocean and nearshore, outside the surf zone, storm water levels for this study were simulated by the US Army Corps of Engineers and Coastal Analysis LLC (Luettich *et al*., 1992; Irish *et al.*, in press). ADCIRC is a long-wave hydrodynamic numerical model that simulates water surface elevations and currents from astronomic tides, wind, and barometric pressure by solving the two-dimensional, depth-integrated momentum and continuity equations.

The ADCIRC model's finite-element grid is presented in Figure 4. Grid resolution varies from very coarse at the open ocean boundaries to 50-m in some nearshore locations. ADCIRC was forced with the hindcasted storm wind and barometric pressure fields to capture meteorological effects on water levels. ADCIRC was also forced with astronomic tidal constituents from the ADCIRC East Coast 2001 Tidal Constituent Database for seven main tidal constituents (Mukai *et al*., 2002). Water level time series were output, at 6-minute intervals, at 20-m depths offshore of the study area. These time series were used to force a nearshore hydrodynamic model, DELFT3D-FLOW (WL| Delft Hydraulics, 2001).

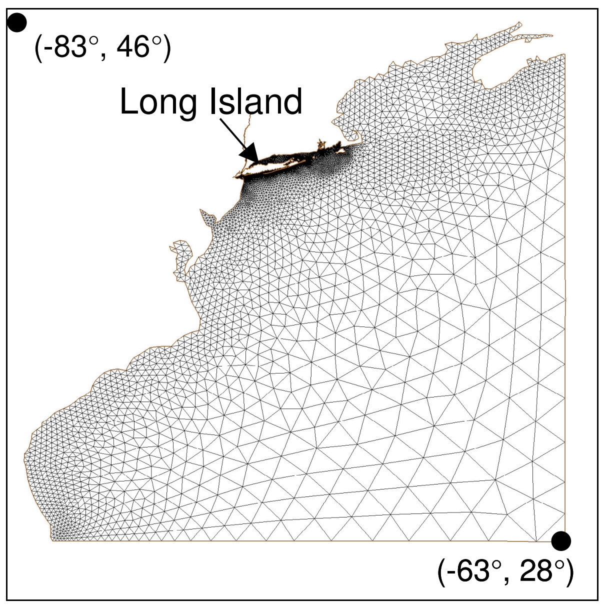

Figure 4. ADCIRC finite-element grid.

3.3 Offshore Wave Modeling

Offshore and Coastal Technologies, Inc, used WISWAVE (also WAVAD), a directional spectral, temporally sensitive wave model, to simulate bulk directional spectra, at hourly intervals, at 30-m depths (Resio and Perrie, 1989; Hubertz, 1992). WISWAVE solves the time-dependent wave action balance equation and simulates wave growth from wind following the combined Phillips and Miles mechanism. The model includes weak nonlinear wave-wave interaction and accounts for linear refraction, shoaling, and dissipation.

For this study, WISWAVE was forced with the hindcasted storm wind fields discussed in section 3.1. WISWAVE computed directional wave spectra using 15 frequency bands, 0.03 to 0.31 Hz, and 16 direction bands. To capture both far-field generation and the spatial resolution desired inshore, a nested-grid approach was adopted. The coarsest grid, at 1° resolution, extended from 50° to 80° west longitude and from 20° to 45° north latitude while the finest grids, at 0.083° resolution, cover inshore areas from west of Fire Island inlet to Montauk Point (Figure 5).

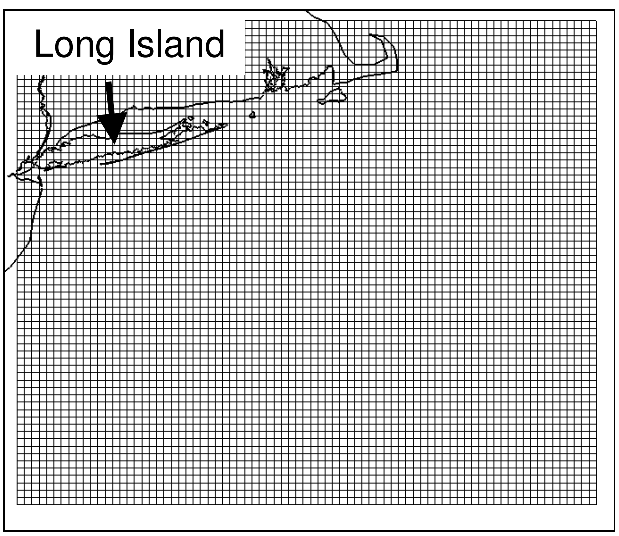

Figure 5. WISWAVE 0.083° fine grid.

3.4 Nearshore Hydrodynamic Modeling

Water levels in the nearshore and in the back bays were computed by Moffatt and Nichol (Cañizares, 2004) using DELFT3D-FLOW (WL| Delft Hydraulics, 2001). DELFT3D-FLOW simulates water level and currents from tidal, meteorological, and wave forcing by solving either the two-dimensional depth-integrated or three-dimensional flow and transport phenomena. The two-dimensional mode was adopted for this study.

The DELFT3D-FLOW orthogonal curvilinear grid for this study extends from East Rockaway Inlet eastward to the east side of Shinnecock Bay (Figure 6). The model grid includes Great South, Moriches, and Shinnecock Bays, and their inlets, and extends up to 5 km from across the nearshore. The model grid (top pane of Figure 6) has variable resolution throughout the domain. The cross-shore resolution varies from values of 15-20 m at the barrier island and the intertidal zone, to around 350 m at the offshore boundary. The typical model's longshore resolution is around 200-300 m. At Moriches and Shinnecock inlets (lower center and right panes of Figure 6) the grid size is in the order of 30 m. Grid resolution is on the order of 75 m at Fire Island inlet (lower left pane of Figure 6). To simulate storm water levels, DELFT3D-FLOW was forced along its offshore boundary with water level time series from ADCIRC, throughout its domain with the storm wind and pressure fields, and with wave radiation stress fields simulated with HISWA (discussed below).

3.5 Nearshore Wave Modeling

Moffatt and Nichol used the stationary wave model HISWA (DELFT3D-WAVE) to compute nearshore wave climate and resulting surf-zone radiation stresses (Holthuijsen *et al.*, 1989). HISWA is a second generation wave model that computes wave propagation; wave generation by wind; non-linear wave-wave interactions and dissipation for a given bottom topography; and stationary wind, water level, and current field in waters of deep, intermediate and finite depth. The model accounts for the following physics: wave refraction over a bottom of variable depth and/or spatially varying ambient current; depth and current induced shoaling; wave generation by wind; dissipation by depth-induced breaking and/or bottom friction; and wave blocking by strong counter currents. HISWA is based on the action balance equation and wave propagation is based on linear wave theory (including the effect of currents).

HISWA wave computations are carried out on a rectangular grid. A nested grid approach was also used for nearshore wave modeling and spans from East Rockaway Inlet to Montauk Point (Figure 7). The offshore grid, with 250 m alongshore by 50 m across-shore resolution, was forced on its offshore boundary with significant wave height, peak period, and mean wave direction. These inputs were

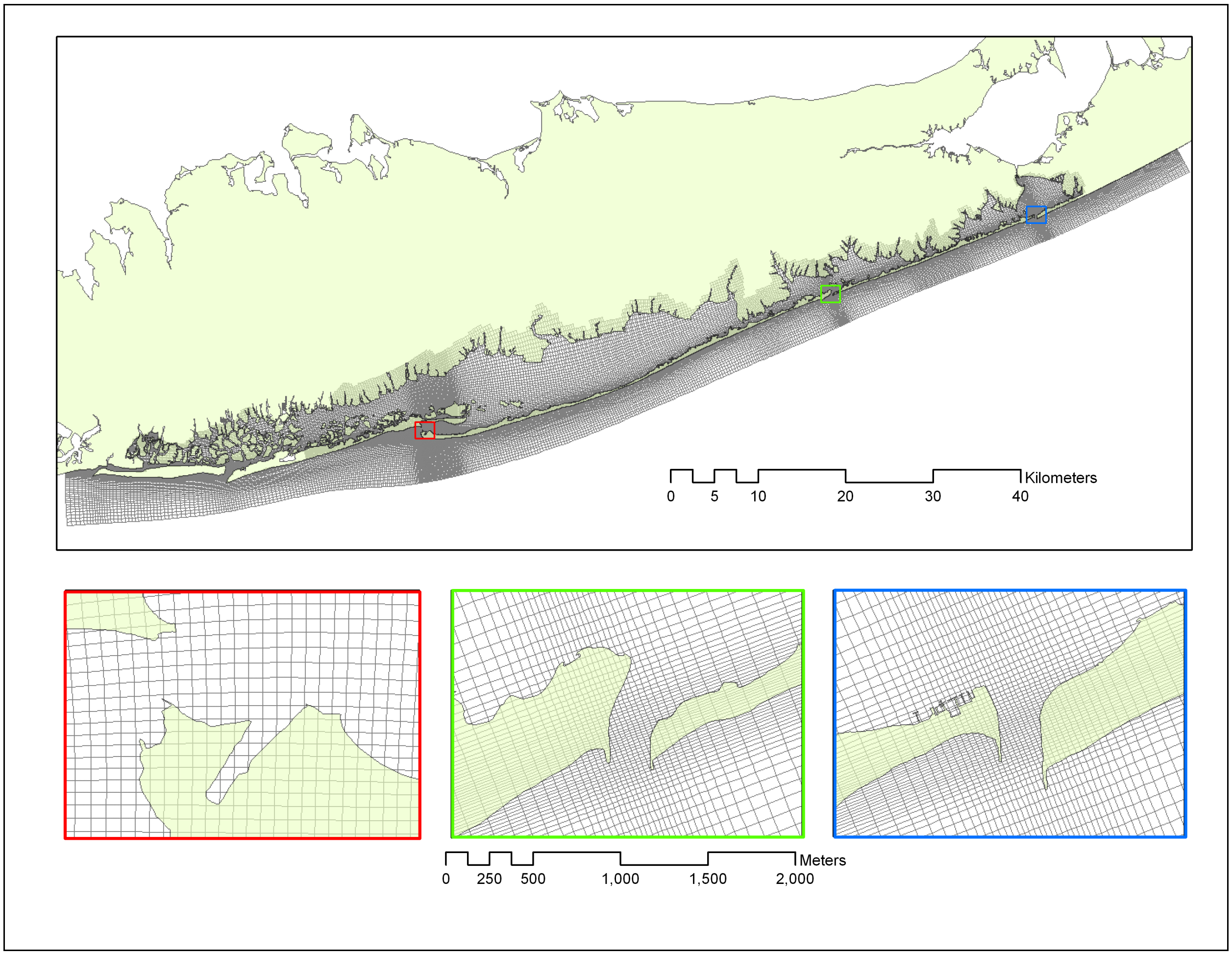

Figure 6. DELFT3D-FLOW computational grid.

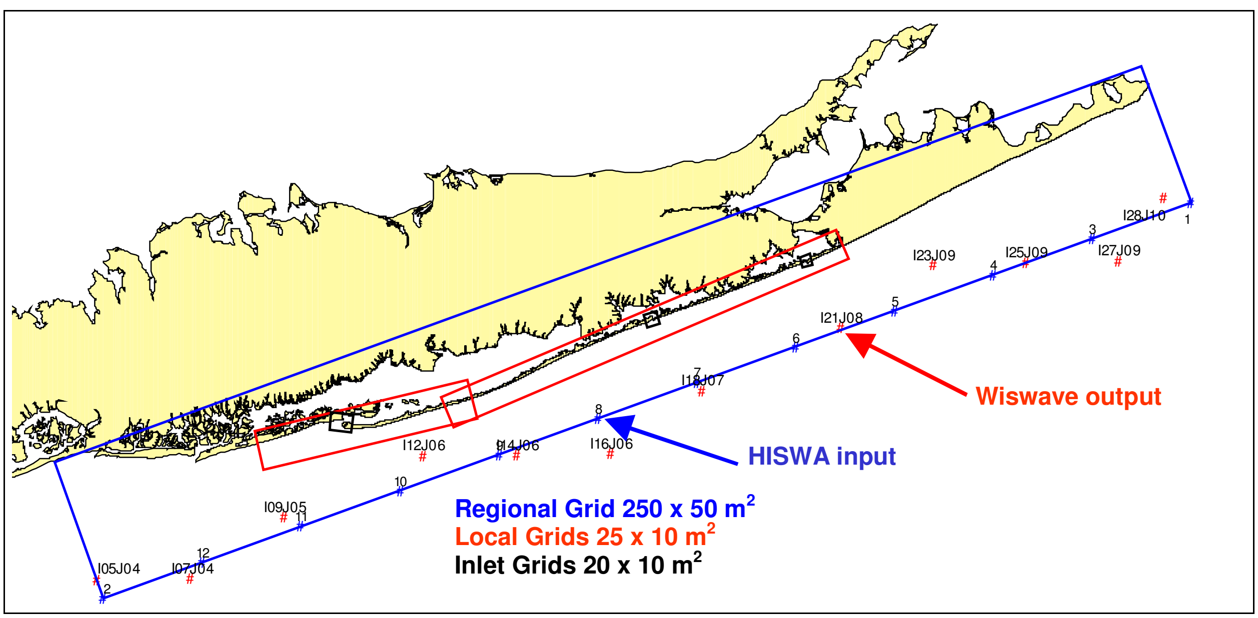

Figure 7. HISWA (DELFT3D-WAV) computational grid.

computed from the bulk spectra from WISWAVE simulations.

Non-stationary conditions may be simulated with HISWA as quasi-stationary with repeated model runs. For this study, HISWA simulated wave conditions for each hourly input condition from WISWAVE.

3.6 Nearshore Wave and Water Level Coupling

The HISWA model has a dynamic interaction with DELFT3D-FLOW (i.e. two way wave-current interaction). By this, the effect of waves on current and the effect of flow on waves, including wave setup, are accounted for. The resulting radiation stresses obtained from the HISWA local rectangular grids are automatically transferred to DELFT3D-FLOW, which simulates the flow on a curvilinear grid. This process allows direct simulation of the impacts of wave setup on hydrodynamics, specifically water level at the coastline and in the estuarial bays.

This modeling strategy uses high quality wind hindcasts to drive offshore wave and hydrodynamic models and coupled nearshore wave and hydrodynamic models. This allows major physical processes, as they impact water level, to be effectively simulated in the study area.

4. BLIZZARD OF 2003 MEASUREMENTS

A field investigation conducted in February 2003, afforded the opportunity to assess the performance of the modeling approach for simulating storm water levels. Offshore and Coastal Technologies, Inc. installed water level gages at six locations in Great South and Moriches Bays (Figure 8). In addition, water level measurements were also available for NOAA stations at Sandy Hook, New Jersey; The Battery, New York; Montauk Fort Pond, New York; and Newport, Rhode Island. Finally, NDBC Buoy 44025, offshore of Long Island, provided measurements of wave characteristics, wind speed, and barometric pressure.

The blizzard in mid-February 2003, impacting the entire northeastern USA, occurred during the field deployment and resulted in minor coastal flooding and significant snowfall. This extratropical event was characterized by peak offshore wind speeds near 20 m/s resulting in elevated ocean water levels that were as much as 0.5 m above astronomical predictions for 1.5 days. Offshore wave heights over 4 m were sustained for 1 day with maximum wave height around 6 m.

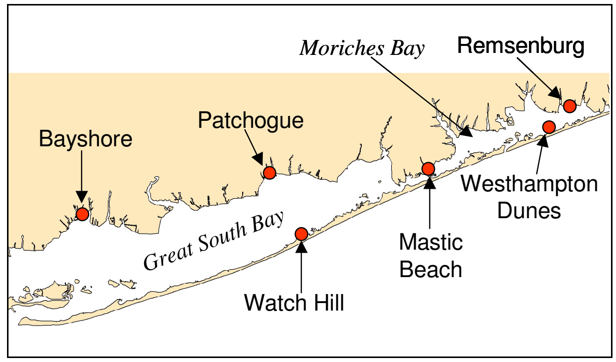

Figure 8. Location of bay water level gages.

5. BLIZZARD OF 2003 SIMULATION COMPARISON TO MEASUREMENTS

Following the meteorological hindcasting and storm surge modeling methodology outlined in Section 3, water levels were simulated for the blizzard of 2003. Computed wind speed, barometric pressure, wave characteristics, and water levels were compared with measurements at a number of locations.

5.1 Meteorology

Wind fields developed using IKOA and barometric pressure from NCEP for the 2003 storm were compared with offshore measurements at NDBC Buoy 44025 (Figure 9 and Figure 10). Wind speed time series shape and magnitude matches well with measured time series, showing that the IKOA performs well for this storm. Peak wind speed comparisons with the offshore buoy are very good, with peak speed differing by less than 1 m/s. NCEP barometric pressure compares very well with measured pressure at the offshore buoy with the peak NCEP pressure only 0.03 m, water, below the measured peak.

5.2 Wave Characteristics

Spectral wave height, period and direction computed with WISWAVE were compared with measurements at NDBC Buoy 44025 (Figure 11, Figure 12, and Figure 13). Time series for all three wave parameters compare well with measurements. Differences in maximum significant wave height and peak period are 0.8 m and 2.5 s, respectively.

5.3 Offshore Water Levels

ADCIRC simulated storm water levels were compared with NOAA measurements at the four NOAA measurement locations near the study area. Time series comparisons at Sandy Hook and Montauk Fort Pond are given in Figure 14 and Figure 15, respectively. ADCIRC performs well for simulating water levels for this storm. Differences between measured and simulated peak water levels are 9 cm (9%) or better at all four locations. Further, hydrograph shape is very similar to measured hydrograph shape at all four locations.

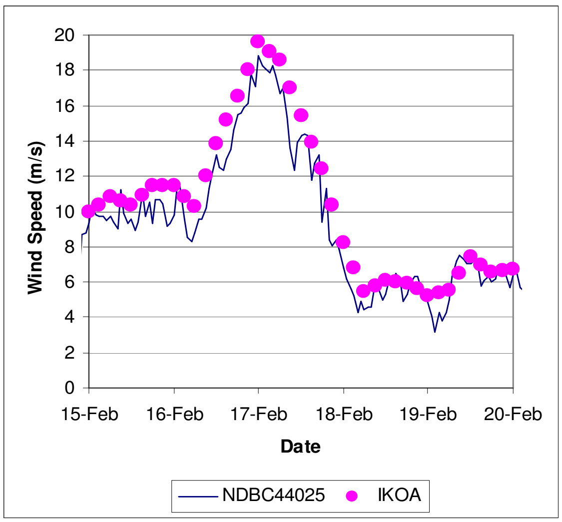

Figure 9. Wind speed comparison at offshore NDBC buoy 44025.

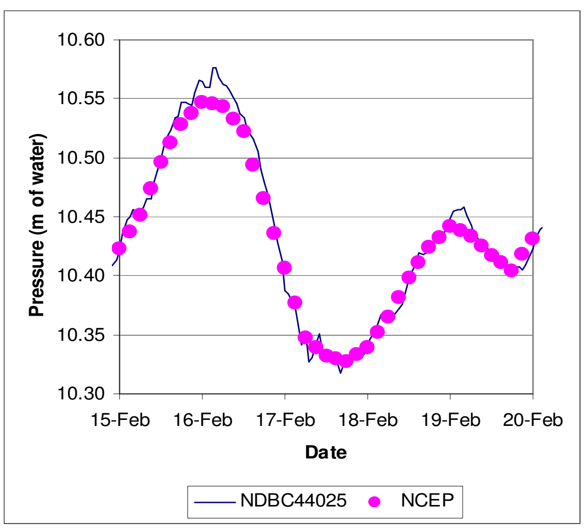

Figure 10. Barometric pressure comparison at offshore NDBC buoy 44025.

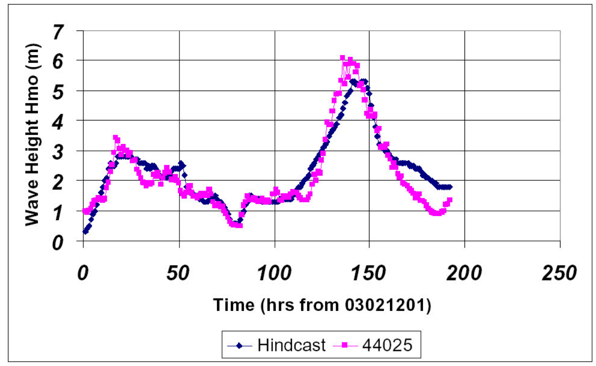

Figure 11. Significant wave height comparison at offshore NDBC buoy 44025.

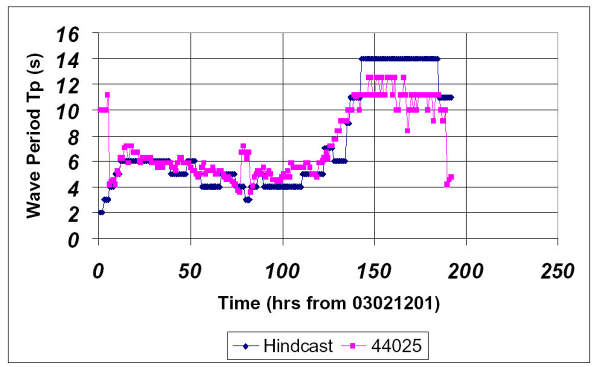

Figure 12. Peak wave period comparison at offshore NDBC buoy 44025.

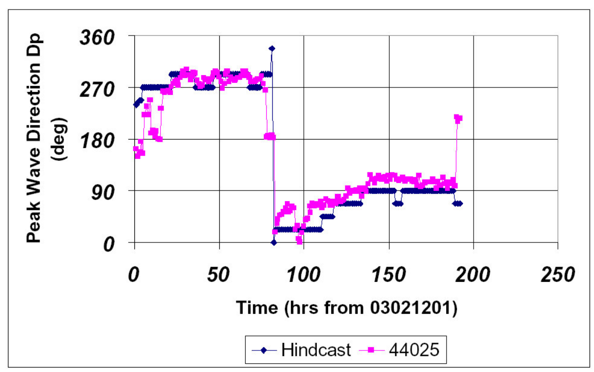

Figure 13. Wave direction comparison at offshore NDBC buoy 44025.

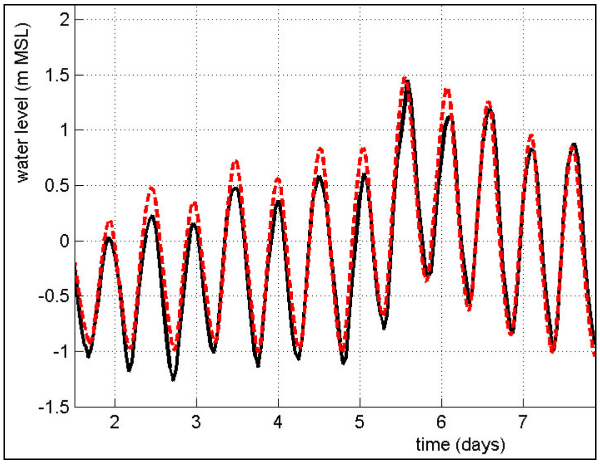

Figure 14. Water level at Sandy Hook, New Jersey starting at 0000 GMT on 12 February 2003.

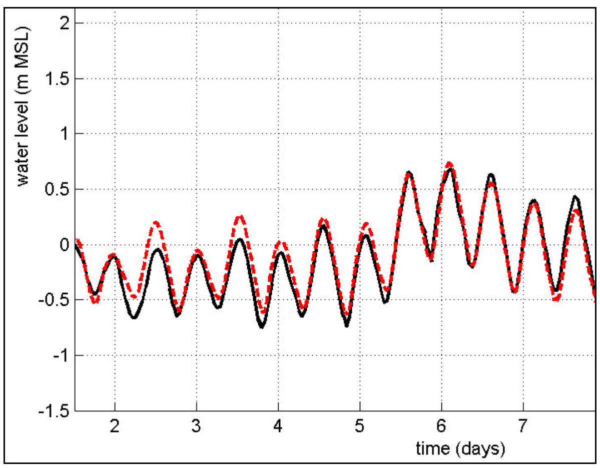

Figure 15. Water level at Montauk Fort Pond, New York starting at 0000 GMT on 12 February 2003.

5.4 Bay Water Levels

The DELFT3D-FLOW simulation of the 2003 blizzard included ocean surge, local wind and pressure fields, and ocean waves. The simulation water levels were compared with the measured water levels at the six bay locations. Figure 16 shows the simulated and measured results at Watch Hill in Great South Bay. Simulated hydrograph shapes at all locations compare well with measured hydrograph shape, showing that DEFLT3D-FLOW performs well for this storm. This storm is characterized by two peak water levels. Simulated peak water levels for the first peak at the three measurement stations in Moriches Bay are within 3 cm, or 4%, of the measured peak water levels. The model also performs well at Watch Hill and Bayshore, in Great South Bay, with simulated peak water levels for the first peak within 5 cm, or 9%, of measured peak water levels. Maximum water level comparisons at Patchogue are within 2 cm, or 4%.

Comparisons between measured data and simulation results for meteorological forcing, wave characteristics, and ocean and bay water levels show that the modeling strategy performs well for the blizzard of 2003.

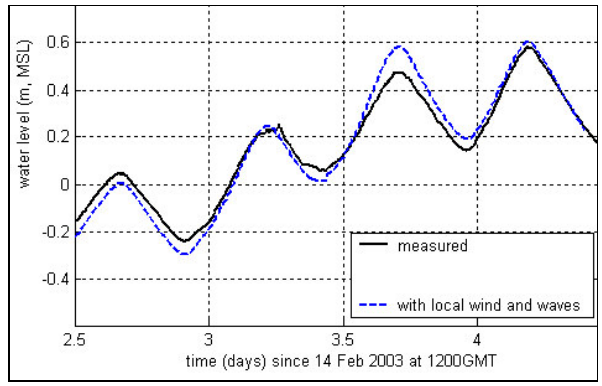

Figure 16. Water level at Watch Hill, Great South Bay, during blizzard of 2003.

6. BAY WATER LEVEL CONTRIBUTIONS

To understand the water level contributions of individual physical processes, a series of DELFT3D-FLOW simulations were performed for the blizzard of 2003:

1. Only offshore boundary forcing with ocean hydrographs from ADCIRC.
2. Simulation 1 plus local wind and barometric pressure forcing throughout the DELFT3D-FLOW model domain.
3. Simulation 2 plus ocean wave forcing from HISWA.

These three simulations allow separation of the effects on bay water levels from: astronomical tide; propagation of ocean surge through tidal inlets; propagation of flow generated by ocean wave setup through tidal inlets; and localized wind setup and setdown.

Figure 17 and Figure 18 compare the water level time series for three test simulations to measured bay water levels, and Figure 19 and Figure 20 summarize water level contributions from each process. For the blizzard of 2003, the combined effect of tidal amplitude and tidally generated superelevation makes

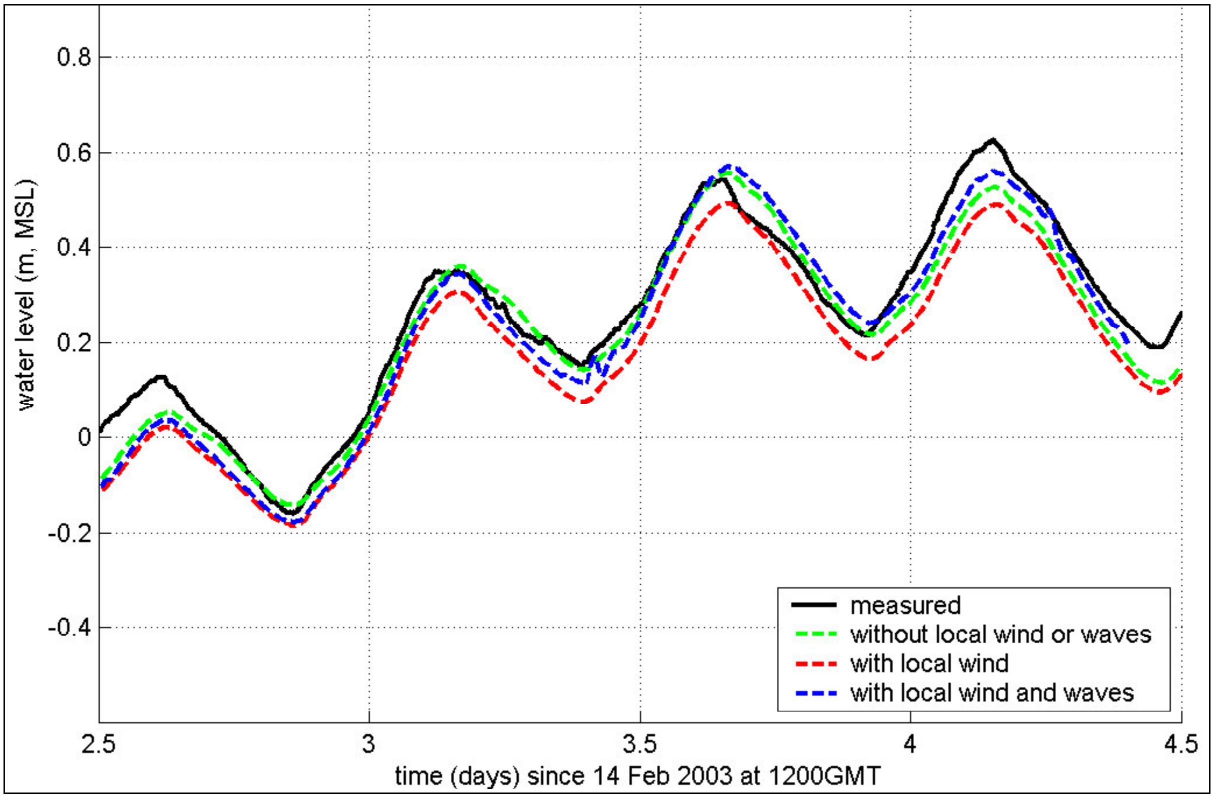

Figure 17. Water level contributions from physical processes at Bayshore, Great South Bay.

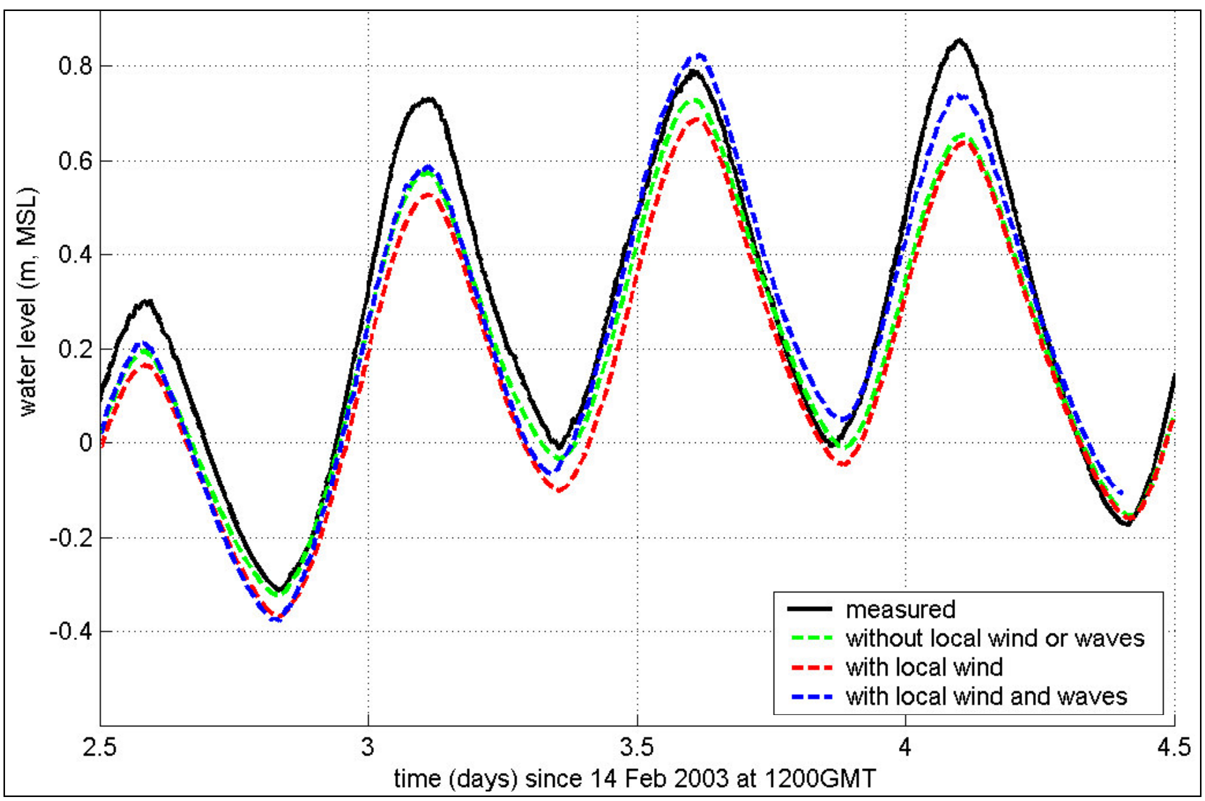

Figure 18. Water level contributions from physical processes at Westhampton Dunes, Moriches Bay.

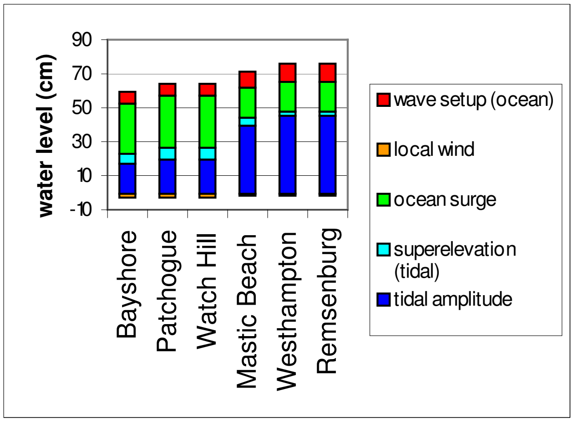

Figure 19. Water level contributions from physical processes for peak occurring 18 February 2003 at 0300 GMT.

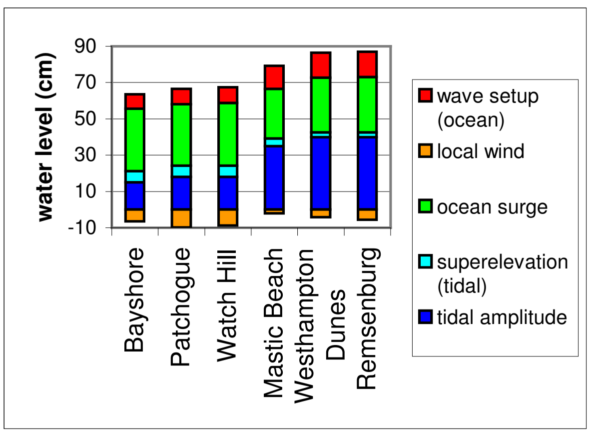

Figure 20. Water level contributions from physical processes for peak occurring 18 February 2003 at 1500 GMT.

up about 40% (25cm) of the total peak water level in Great South Bay and 50% (40 cm) of the peak water level in Moriches Bay. Water level contributions from ocean surge alone are about 35 cm in Great South Bay and 30 cm in Moriches Bay.

The addition of local wind has only a small effect on Moriches Bay water levels: DELFT3D-FLOW predicts a small setdown, on the order of 5 cm, at Westhampton Dunes and Remsenburg, on the eastern side of the bay, while the contribution from local wind at Mastic Beach, on the western side of the bay, is negligible. In contrast, the model predicts setdown of 10 cm at Patchogue and Watch Hill, at the eastern end of Great South Bay, and setdown of 6 cm at Bayshore, near the center of Great South Bay.

Wave setup from ocean waves is a significant contributor to water levels in both Great South and Moriches Bays. At all three measurement locations in Great South Bay, water level contribution from wave setup is around 9 cm. At all three measurement locations in Moriches Bay, water level contributions are around 14 cm. For the same offshore wave height, water level contribution from ocean wave setup is 50% larger in Moriches Bay than in Great South Bay. This indicates that inlet and bay geometry, and its effects on hydrodynamics, are important for accurate prediction of bay water levels associated with ocean wave setup. For the blizzard of 2003, flow through the inlets created by ocean wave setup accounts for 15% of the total water levels in the bays.

7. CONCLUSIONS

Model simulation comparisons with measurements during the blizzard of 2003 prove the modeling strategy, and its individual model components, accurately simulate storm water levels. In particular, high-quality wind and wave hindcasts are essential for accurately simulating storm water levels. This modeling approach was adopted for storm surge analysis of the south shore of Long Island. In total, 14 hurricanes and 23 extratropical storms were simulated using this modeling strategy. Peak simulated water levels will be used for economic analyses and engineering design.

Additionally, model simulations indicate that propagation of ocean wave setup into back bays is a major contributor to total water level within the study area. For the blizzard of 2003, sustained wave heights over 4 m for 1 day, with peak height over 5 m, increased bay water levels by a measurable 10 to 15 cm. For more severe storms, the increase in bay water levels is likely to be even more, perhaps as much as 30 cm. When considering economic damages, an increase as little as 15 cm in bay water level translates to a significant increase in damages. Therefore, small changes in water level for small events are important for economic analyses and design.

The results from the blizzard of 2003 indicate that the impact of ocean wave setup propagation through the tidal inlets is dependent on the inlet and bay geometry. This finding demonstrates the importance of simulating nearshore wave conditions and including the resulting radiation stresses when computing hydrodynamic response in estuarial bays.

8. REFERENCES

Cañizares, R., Alfageme, S., and M. Gravens, in press: Modeling of storm induced barrier island overwash and breaching in the Atlantic coast of Long Island. Proceedings, 29th International Conference on Coastal Engineering, Lisbon, Portugal.

Cardone, V.J., Graber, H.C., R.E. Jensen, Hasselmann, S., and M.J. Caruso, 1995: In search of the true surface wind field in SWADE IOP-1: ocean wave modeling perspective. The Global Ocean Atmosphere System, 3, 107-150.

Holthuijsen, L.H., Booij, N. and T.H.C Herbers, 1989: A prediction model for stationary, short-crested waves in shallow water with ambient currents. Coastal Engineering, 13, 23-54.

Hubertz, J. M., 1992: User's guide to the Wave Information Studies (WIS) Wave Model, Version 2.0. WIS Report 27, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Jarvinen, B.R., Neumann, C.J., and M.A.S. Davis, 1984.: A tropical cyclone data tape for the North Atlantic basin, 1886-1983: Contents, limitations, and uses. NOAA Technical Memorandum NWS NHC 22 (1984).

Irish, J.L., Williams, B.P., Militello, A., and D.J. Mark, in press: Regional-scale storm-surge modeling of Long Island, New York, USA. Proceedings, , 29th International Conference on Coastal Engineering, Lisbon, Portugal.

Luettich, R.A., Westerink, J.J., and N.W. Scheffner, 1992: ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL. Technical Report DRP-92-6, November 1992, U.S. Army Engineer Waterways Experiment Station, Vicksburg MS.

Mukai, A.Y., Westerink, J.J., and R.A. Luettich, 2002: Guidelines for using Eastcoast 2001 Database of Tidal Constituents within western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea. ERDC/CHL CHETN-IV-40, US Army Corps of Engineers.

Powell, M.D. and PG. Black, 1989: The relationship of hurricane reconnaissance flightlevel wind measured by NOAA's oceanic platforms. 6th National Conference on Wind Engineering.

Resio, D.T. and W. Perrie, 1989: Implication of an f^{-4} equilibrium range for wind-generated waves. Journal of Physical Oceanography, 19(2), 193-204.

Swail, V.R. and A.T. Cox, 2000: On the use of NCEP/NCAR reanalysis surface marine wind fields for a long term North Atlantic wave hindcast. Journal of Atmospheric and Oceanic Technology, 17, 532-545.

Thompson, E.F., and V.J. Cardone, 1996: Practical modeling of hurricane surface wind fields. Journal of Waterway, Port, Coastal, and Ocean Engineering, July/August 1996, 195-205.

WL | Delft Hydraulics, 2001: User Manual Delft3D-FLOW. Delft, The Netherlands.