# NEW YORK CITY'S VULNERABILITY TO COASTAL FLOODING

## Storm Surge Modeling of Past Cyclones

BY BRIAN A. COLLE, FRANK BUONAIUTO, MALCOLM J. BOWMAN, ROBERT E. WILSON, ROGER FLOOD, ROBERT HUNTER, ALEXANDER MINTZ, AND DOUGLAS HILL

Advances in high-resolution storm surge modeling for the New York City metropolitan region should help forecasters and emergency managers during an impending storm.

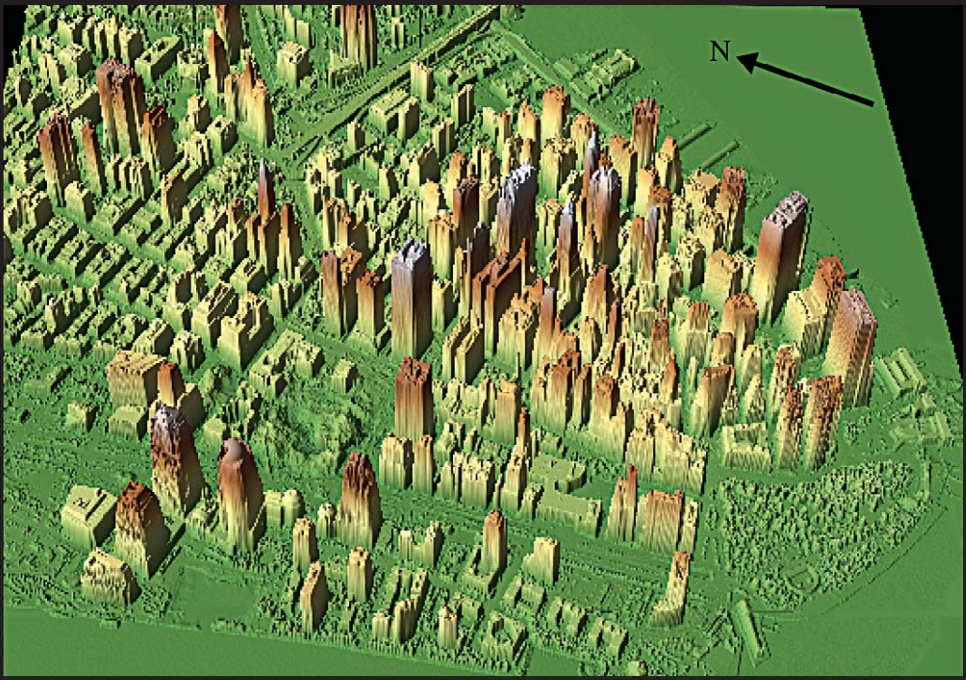


**FIG. 1. Three-dimensional image of the business district of Manhattan using lidar taken by the NOAA's Citation jet on 27 Sep 2001. The imager is flying over the Hudson River looking to the east. The seawalls surrounding Manhattan are 1–1.75 m above MSL. (Photo courtesy of NOAA/U.S. Army JPSD).**

New York City, New York (NYC), and the adjacent region of northern New Jersey and Long Island, New York, are built around a complex of narrow rivers, estuaries, islands, and waterways that are strongly influenced by tides and weather. Much of the Metropolitan region is less than 5 m above mean sea level (MSL), with about 260 km$^2$ at risk from storm surge flooding by a 100-yr flood event for both tropical systems and nor'easter cyclones (Bowman et al. 2005). For example, Fig. 1 shows a lidar image taken from aircraft for the business district of southern Manhattan.[1] Much of the seawall that surrounds lower Manhattan in this lidar image is only ~1.5 m above MSL, which offers little protection against major storm surge events. In fact, if a category-3 hurricane hit NYC, it is estimated that nearly 30% of the south side of Manhattan ▶

[1] The spatial accuracy of the lidar system is ±3 m, with depth accuracy of about 15 cm (Irish et al. 2000).

would be flooded (U.S. Army Corps of Engineers 1995). To make matters worse, sea level has been rising at about 0.3 m century$^{-1}$ in this area (Rosenzweig and Solecki 2001). This is a conservative estimate, because global warming is expected to increase the rate at which sea level rises to 0.50–0.75 m century$^{-1}$ (Rosenzweig and Solecki 2001). As sea level increases during the next century this will favor more frequent and severe storm surge flooding around NYC.

The catastrophic loss of life and property by several hurricanes across Florida in 2004 and along the Gulf of Mexico coast during the summer of 2005 emphasizes the importance of accurate storm surge forecasts in highly populated coastal environments. On 20 September 2005, the director of the National Hurricane Center, Max Mayfield, testified before Congress and stated that several urban–coastal cities are extremely vulnerable to hurricane storm surge, one of which is the NYC–Long Island area (information online at www.legislative.noaa.gov/Testimony/mayfieldfinal092005.pdf). Considering the millions of people who live in NYC and the billions of dollars at risk, current modeling and observational technologies need to be evaluated in order to improve forecasts of coastal flooding around this region.

Although landfalling hurricanes are usually the primary concern, extratropical (ET) cyclones also cause significant coastal flooding problems along the U.S. east coast. For example, during the December 1992 nor'easter event, water levels at Battery Park (the Battery) on the southern tip of Manhattan peaked at ~2.5 m (8 ft) above mean sea level. Sea level overtopped the city's seawalls for only a few hours, but this was enough to flood the NYC subway and the Port Authority Trans-Hudson Corporation (PATH) train systems at the Hoboken train station in New Jersey (Fig. 2a), thus precipitating a shutdown of these transportation systems for several days. Sections of FDR Drive in lower Manhattan were flooded with ~1.5 m (~4 ft) of water (Fig. 2b), which stranded more than 50 cars and required scuba divers to rescue some drivers (National Weather Service 1994).

Coastal flooding around NYC during cool season wind events is considered a major forecast problem for the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS). The NWS had an 85% false-alarm rate for coastal flood warnings for the NYC–Long Island area during the 2002–06 period (R. Watling, NWS Eastern Region Headquarters, 2006, personal communication). The high false-alarm rate results from large uncertainties in the water level forecast guidance along the complex shoreline surrounding NYC and Long Island (J. Tongue, Upton NWS Office, 2007, personal communication).

*Storm surge models.* Storm surge models are frequently utilized for determining coastal water levels associated with landfalling hurricanes. One example is the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, which was developed by the Techniques Development Laboratory (now called the Meteorological Developmental Laboratory) of the National Weather Service (Jelesnianski et al. 1992). The SLOSH model forecasts a coastal surge with limited observations of the storm's internal structure by using 6-h storm central pressures, storm position, and the storm's size measured from the center to the region of maximum radial winds. SLOSH also includes the effects of topography, such as underwater sills, channels, sand dunes, and levees, and it is run on a stretched finite-difference grid. Surface wind speed is not an input parameter, because SLOSH calculates the wind field based on the central pressure and storm size using a combination of cyclostrophic and frictional balances (Houston and Powell 1994).

Jarvinen and Lawrence (1985) demonstrated that SLOSH could forecast storm surge to within 0.5 m using several-hundred storm surge observations archived from 10 hurricanes along the U.S. east coast. The SLOSH model assumes a radially symmetric storm, which is reasonable for some hurricanes, but not when hurricanes move northward toward southern New England and develop more ET characteristics (Atallah and Bosart 2003). During an ET event, such as Floyd (1999), the area of maximum winds tends to elongate northward along a coastal baroclinic zone (Colle 2003). Wind asymmetries along fronts also exist during nor'easters, which likely prevents SLOSH from making accurate storm surge forecasts over New England, especially during

**AFFILIATIONS:** Colle, Buonaiuto, Bowman, Wilson, Flood, Hunter, Mintz, and Hill—Storm Surge Research Group, School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, New York
**CORRESPONDING AUTHOR:** Dr. Brian A. Colle, School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11794-5000
E-mail: brian.colle@stonybrook.edu

*The abstract for this article can be found in this issue, following the table of contents.*
DOI:10.1175/2007BAMS2401.1

In final form 9 December 2007

the cool season. As a result, NOAA has developed an extratropical storm surge model for the U.S. east coast (Chen et al. 1993; Shaffer et al. 1997). This surge model has been forced with the Aviation [AVN; now the Global Forecast System (GFS)] model since the mid-1990s and 48-h surge predictions are made twice daily using the NWS GFS model as forcing (see information online at www.nws.noaa.gov/mdl/etsurge/). Unfortunately, even with 25,000 nodes along the U.S. east coast, this system has limited resolution (> 3-km grid spacing) around Long Island, which is not enough to resolve the complex flows in the narrow bays and channels of the south coast. Also, the nearest online forecast point that forecasters and emergency managers can use for the Long Island south shore is Sandy Hook, New Jersey.

The National Ocean Service (NOS) of NOAA also recently developed a real-time ocean modeling system for the NYC metropolitan region (Wei 2003). Their Physical Oceanographic Real-Time Systems (PORTS) provides nowcast (0–6 h) and forecast (30 h) water level and currents for inside New York harbor. Based on the Princeton Ocean Model (POM), it predicts water level and current nowcasts using several real-time water level and surface wind observations around NYC as forcing. The longer 30-h forecast utilizes the National Centers for Environmental Prediction (NCEP) 12-km North American Mesoscale (NAM) model for wind forcing of POM, and the NOS tidal harmonics and forecast guidance from the NWS extratropical storm surge model are used for the open boundary conditions around Sandy Hook (Wei 2003). However, these real-time efforts have been focused primarily as an aide to local ship navigation into the harbor and not on regional flooding from major storm events.

*Objectives.* There have been relatively few studies in the formal literature evaluating storm surge (ocean) models that obtain surface wind and pressure forcing from an atmospheric forecast model (one-way coupled). Blier et al. (1997) evaluated the NWS extratropical storm surge model for three storm surge events for Nome, Alaska, and they found that the model realistically predicted the storm surge, although the predicted surges were somewhat weaker than those observed. Li et al. (2006) evaluated the Regional Ocean Modeling Systems (ROMS) coupled with the fifth-generation Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) in the Chesapeake Bay for Hurricane Isabel (2003). Meanwhile, there have been no formal studies evaluating storm surge models that are forced by atmospheric forecast models over New England for past major storm events, which is a motivation of our study.

The goal of this project is to demonstrate the utility of using a state-of-the-art atmospheric model combined with an ocean model in the Stony Brook Storm Surge (SBSS) system to predict storm surges for the NYC metropolitan region. The MM5 has been used for real-time weather predictions at Stony Brook University (SBU) down to 4-km grid spacing across coastal New England for several years (Colle et al. 2003; Jones et al. 2007). The MM5 has been shown to realistically simulate the ET transition of tropical systems along the East Coast, such as Floyd (1999) over the Northeast (Colle 2003), thereby providing

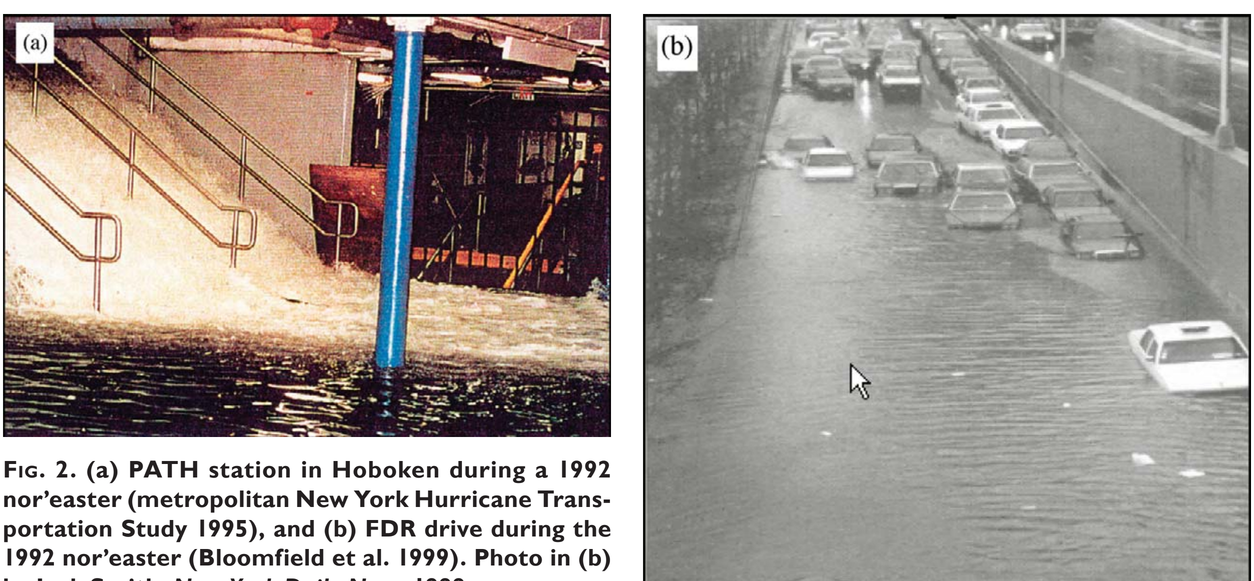

**Fig. 2. (a) PATH station in Hoboken during a 1992 nor'easter (metropolitan New York Hurricane Transportation Study 1995), and (b) FDR drive during the 1992 nor'easter (Bloomfield et al. 1999). Photo in (b) by Jack Smith, *New York Daily News* 1999.**

an opportunity to evaluate storm surge predictions for such events. This paper highlights storm surge responses around NYC produced by the Advanced Circulation Model for Coastal Ocean Hydrodynamics (ADCIRC) ocean model for the December 1992 nor'easter and Tropical Storm Floyd. The MM5 simulations for both storms are compared with surface observations and analyses from the North American Regional Reanalysis (Mesinger et al. 2006).

The next section describes the setup of the storm surge modeling system for NYC. The simulation results for the two storms are presented in the "11–12 December 1992 nor'easter" and "Hurricane Floyd (16–17 September 1992)" sections. The results and recommendations for future work are provided in the "Discussion and conclusions."

**STONY BROOK STORM SURGE (SBSS) MODEL.** The MM5 is a terrain-following sigma coordinate model used to predict regional atmospheric circulation and precipitation (Grell et al. 1994). Since 1999, SBU has been running MM5 in deterministic (Colle et al. 2003) and ensemble configurations (Jones et al. 2007) at 36-, 12-, and 4-km grid spacing. This paper utilizes the deterministic MM5 forecasts from the 12-km domain for two major storm events (Fig. 3a). The SBSS system also utilizes output from the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005). A future paper will explore the benefit of using ensembles as applied to storm surge prediction, derived by varying initial conditions and model physics in the MM5 and the WRF models. The deterministic surge predictions utilize twice-daily MM5 runs at 0000 and 1200 UTC, which are integrated using initial and boundary conditions derived from the NCEP NAM model forecasts (Colle et al. 2003). The real-time MM5 and simulations for this paper use the Grell convective parameterization (Grell et al. 1994), simple ice microphysics (Dudhia et al. 1989), and the Medium-Range Forecast (MRF) planetary boundary layer scheme (Hong and Pan 1996).

For the 10–12 December 1992 nor'easter, the MM5 initial and bound-

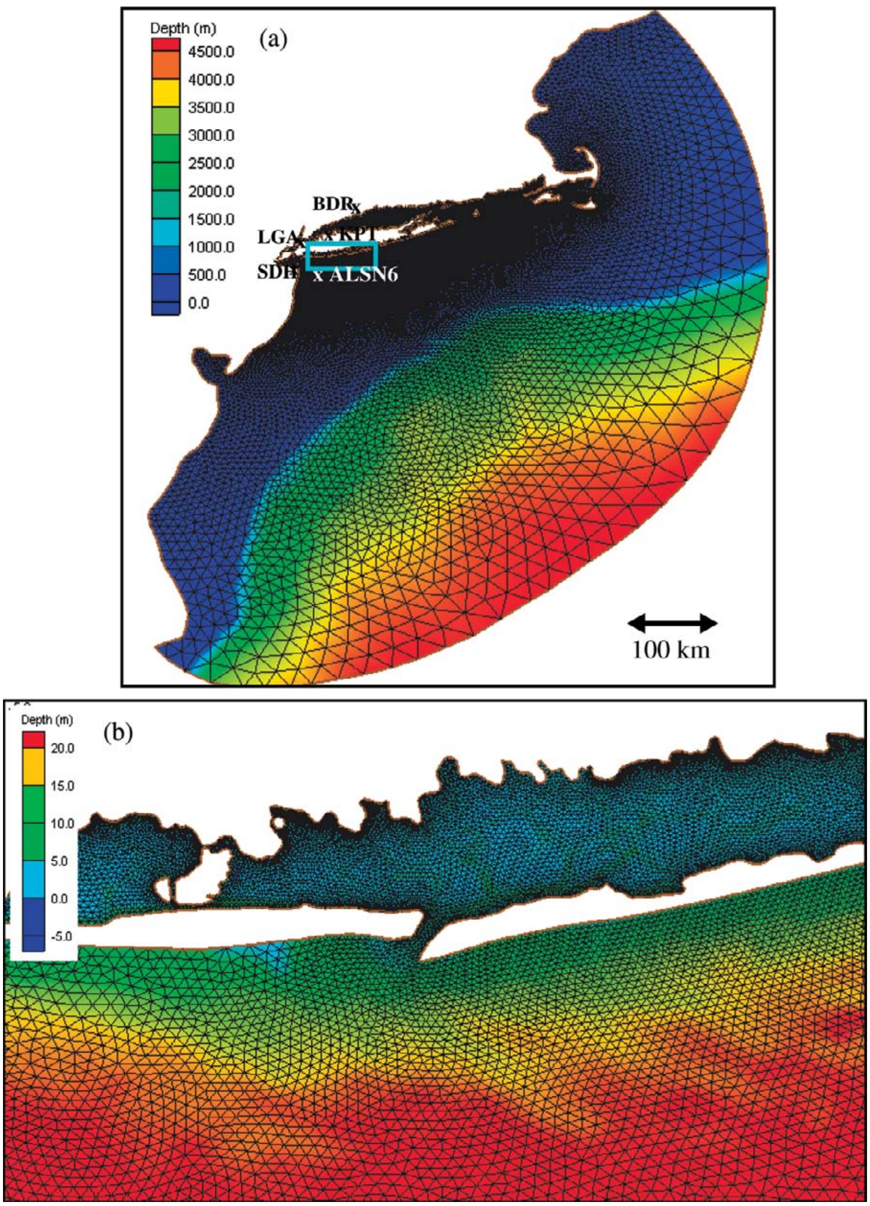


**Fig. 3. (a) Full domain used for the storm surge model (ADCIRC) showing the unstructured grid and bathymetry (color shaded in meters). The grid overlaps the 12-km MM5 domain. (b) A portion of the ADCIRC domain for the blue box in (a) along the south shore of Long Island. The station locations for the time series in Figs. 7, 10, and 12 are shown at the "x" locations.**

ary conditions originated from the 3-h NCEP regional reanalysis (Mesinger et al. 2006). Two simulations were completed for the 48-h event: one run from 1200 UTC 10 December to 0000 UTC 11 December, and the other from 0000 UTC 11 December to 1200 UTC 12 December. The first simulation was relatively short, because the model wind errors were >10 $m\ s^{-1}$ by hour 24. For the September 1999 Floyd event presented in Colle (2003), the MM5 initial and boundary conditions were obtained from the NCEP 32-km Eta Model run at 0000 UTC 16 September 1999. By 2100 UTC 16 September, the 12-km MM5 forecast of Floyd's central pressure along the mid-Atlantic coast was within 1–2 mb of that observed (cf. Fig. 4 of Colle 2003).

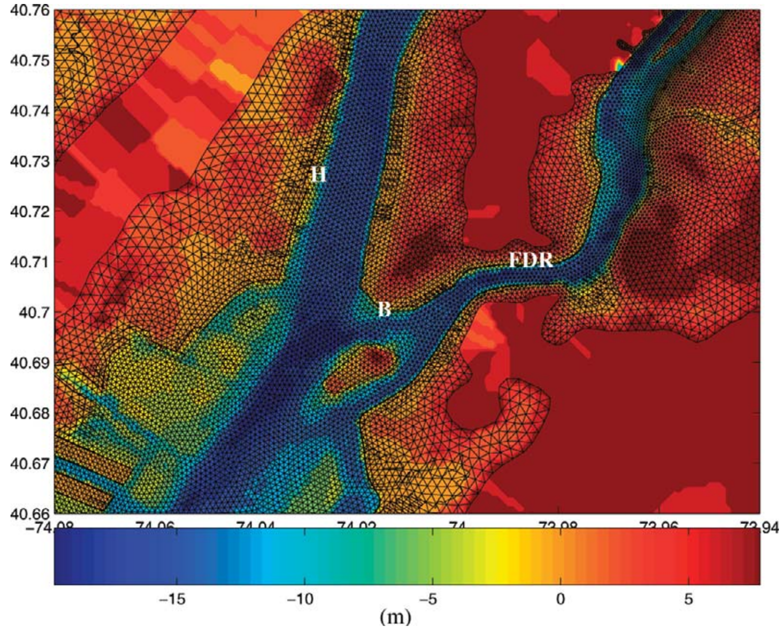


**Fig. 4. The triangular elements of ADCIRC grid are overlaid on the bathymetry and topography (color shaded in meters) for the region that surrounds Manhattan Island and parts of Brooklyn and New Jersey. The model is gridded up to the 8-m level above mean sea level to allow for the most serious coastal flooding. The locations of Hoboken, the Battery, and FDR Drive are given by "H," "B," and "FDR," respectively.**

The hourly surface winds and sea level pressure from the 12-km MM5 domain were used to force the ADCIRC model, which solves time-dependent, free-surface circulation and wind-driven transport problems in a barotropic configuration on a finite element grid (Luettich et al. 1992; Westerink et al. 2008).[2] ADCIRC was forced by tidal constituents along the ocean boundary. Five principal constituents were considered for these surge events, including the $M_2$, $K_1$, $O_1$, $N_2$, and $S_2$ (Westerink et al. 1993). ADCIRC has been recently applied to hurricane storm surge predictions for New Orleans, Louisiana (Brouwer 2003; Westerink et al. 2008). For example, Westerink et al. (2008) used ADCIRC and the wind forcing from Hurricanes Betsy (1965) and Andrew (1992), and showed that the model could predict storm surge within about 10% at many gauge stations.

The triangular elements for the SBSS setup of ADCIRC range from 70 km to several hundred kilometers offshore (Fig. 3a) to ~10 m around portions of Long Island (Fig. 3b) and NYC (Fig. 4). The ADCIRC grid contains ~110,000 grid nodes (Figs. 3a,b), with the highest resolution near the coast in order to use ADCIRC's wetting and drying scheme (Westerink et al. 2008). This approach allows ADCIRC to simulate flooding of coastal areas above sea level during storm surge events. The coastal geometry surrounding NYC is very complex, and includes numerous piers and bulkheads (seawalls). Because the detailed heights of all these structures are not yet documented, and we are most concerned about the south coast of Manhattan in the financial district, we used a nominal seawall height around New York Harbor of 1.75 m above MSL. This height is conservative, because most of the seawall ranges from 1.25 to 1.75 m above MSL. ADCIRC was gridded to 8 m above MSL in order to accommodate the worst-case (category 4) flooding around NYC (Fig. 4). The bathymetric dataset originated from the NOS database of coastal hydrographic surveys, supplemented by data from the U.S. Army Corps of Engineers nautical charts, and multibeam data collected by Stony Brook University ship surveys. The NOS hydrographic dataset (online at www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) consists of discrete bathymetric soundings that are generally referenced to mean lower low water. A vertical offset was applied to the hydrographic dataset so that both the land and water have a common vertical origin. The hydrographic data were interpolated to the ADCIRC grid.

[2] The details of the ADCIRC model and its governing equations can be found in Westerink et al. (2008).

**11–12 DECEMBER 1992 NOR'EASTER.** *MM5 simulation.* On 1200 UTC 10 December 1992, cyclogenesis began along the southeast Virginia coast in response to the approach of a deeper upper-level trough and a low-level baroclinic zone near the coast (not shown). By 1200 UTC 11 December (Fig. 5a), this cyclone had deepened to 990 mb, and was located over southeast Maryland. There was a coastal baroclinic zone that stretched from Cape Cod westward toward NYC at this time. Easterly surface winds of 15–20 m s$^{-1}$ were present around Long Island, with this direction favoring a long fetch down Long Island Sound as well as toward the New York Bight. The 12-km MM5 correctly predicted the ~990-mb cyclone and was within 50 km of the observed position at this time (Fig. 5b). The model surface winds were within 5 m s$^{-1}$ of observed at many locations.

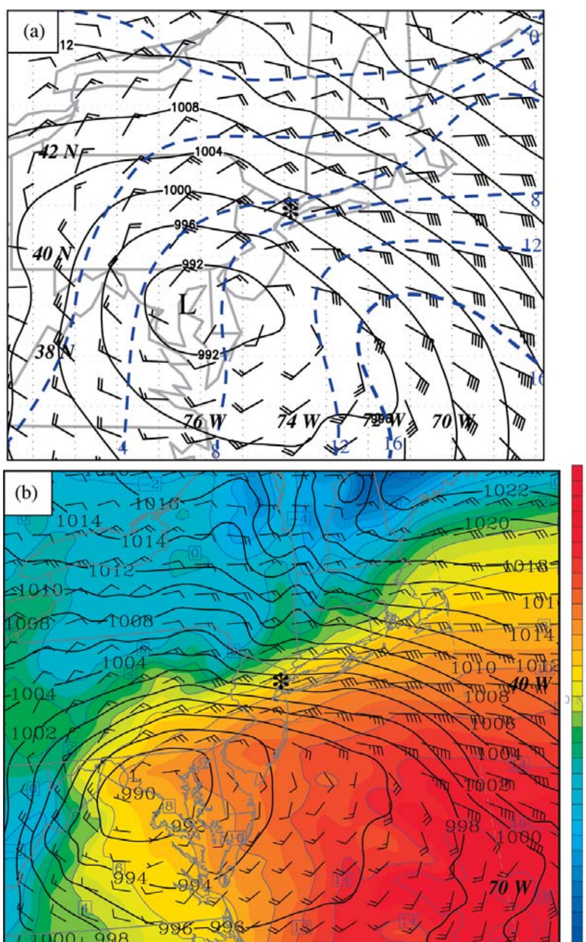


**FIG. 5. (a) NCEP regional reanalysis around the Northeast and mid-Atlantic at 1200 UTC 11 Dec 1992, showing sea level pressure (solid black every 2 mb), surface temperature (blue every 4°C), and winds (full barb = 10 kts). (b) MM5 12-h forecast from the 12-km grid valid at 1200 UTC 11 Dec 1992, showing sea level pressure (solid black every 2 mb), 2-m temperature (blue every 2°C and shaded using scale), and winds (full barb = 10 kts).**

By 1200 UTC 12 December 1992 (Fig. 6a), the cyclone had moved slowly to a few hundred kilometers southeast of Long Island and had filled gradually to 994 mb. The 12-km MM5 was ~2 mb too deep with the cyclone at this time (Fig. 6b), but the storm position and surface winds were fairly accurate around Long Island. The winds around Long Island had slowly veered to a north-northeasterly direction and decreased to 12–17 m s$^{-1}$, which favors less easterly fetch and surge entering Long Island Sound; however, the north-northeast wind direction still does not allow water to leave Long Island Sound easily, thus potentially prolonging the coastal flooding in the NYC area.

The 12-km MM5 winds were compared with hourly winds observed at La Guardia Airport (LGA) and Ambrose Tower (ALSN6) from 1200 UTC 10 December to 1200 UTC 12 December (Fig. 7). Because LGA is located at the coast and it is not well resolved by the 12-km MM5, the closest water grid point in the MM5 was used for comparison. At

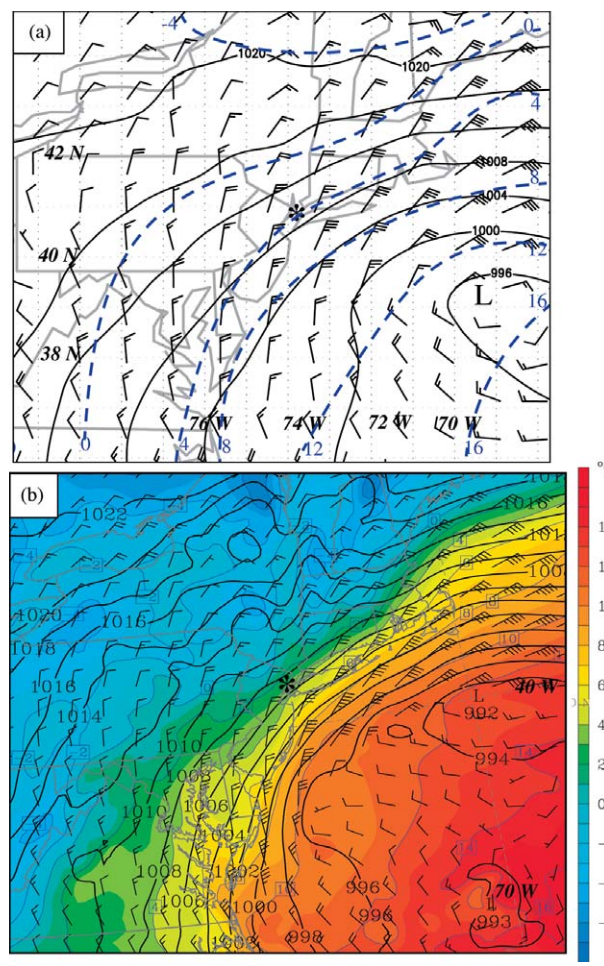


**FIG. 6. (a), (b) Same as Fig. 5, except for 1200 UTC 12 Dec 1992.**

LGA (Fig. 7a), the observed and simulated surface winds from 1200 UTC 10 December to 1200 UTC 11 December increased steadily and the wind directions veered from easterly to northeasterly as the cyclone approached. Both the MM5 and regional reanalysis could not reproduce this more northeast component, and the sustained 20–22 m s$^{-1}$ winds at LGA at 1200–2100 UTC 11 December were underpredicted by ~5 m s$^{-1}$ in the MM5. During the peak of the wind event between 1200 and 1700 UTC 11 December, the wind gusts at LGA reached 25–30 m s$^{-1}$ (not shown). The winds became more northeasterly and weakened a few meters per second after 1800 UTC 11 December as the surface low slowly drifted well southeast of Long Island (cf. Fig. 5).

At ALSN6, to the south of western Long Island (Fig. 7b), the wind sensor is at 30 m above MSL, which was compared with the MM5 at this same height. The observed northeast winds at ALSN6 reached hurricane force (36 m s$^{-1}$, with gusts to 41 m s$^{-1}$) at 1600 UTC 11 December. The MM5 was within 3 m s$^{-1}$ at ALSN6 at most times, but underestimated the peak winds by ~6 m s$^{-1}$. The strong winds, combined with the local high tide for New York Harbor at around 1300 UTC 11 December, resulted in the flooding problems in the region.

*ADCIRC simulation.* The ADCIRC model was spun up using the astronomical tides for several days before the MM5 winds and sea level pressure were applied, starting on 1200 UTC 10 December. Figure 8 shows the water levels predicted by the ADCIRC for the coastal waters of the mid-Atlantic and southern New England coasts at 0400, 1300, and 1700 UTC 11 December 1992. At 0400 UTC (Fig. 8a), there were east-southeasterly winds of ~15 m s$^{-1}$ and water levels were 0.5–1.5 m above MSL along the coast, with the highest predicted water levels within the Chesapeake Bay, western Long Island Sound, and the Gulf of Maine. By 1300 UTC (Fig. 8b), which is the time of maximum flooding in New York Harbor, the 20–25 m s$^{-1}$ easterly winds over coastal New Jersey and Long Island, combined with the approaching high tide in this region, resulted in water levels of 1.5–2.0 m above MSL in the New York Bight region. The bight region is a vulnerable location for storm surge given the sharp bend in the coastline, which helps funnel water toward New York Harbor. At 1700 UTC (Fig. 8c), the winds weakened somewhat along coastal New Jersey while the tide was receding. Meanwhile, the water levels exceeded 2.0 m above MSL in western Long Island Sound and the Gulf of Maine given the eastward movement of cyclone and the 3–4-h-later high tide in these regions.

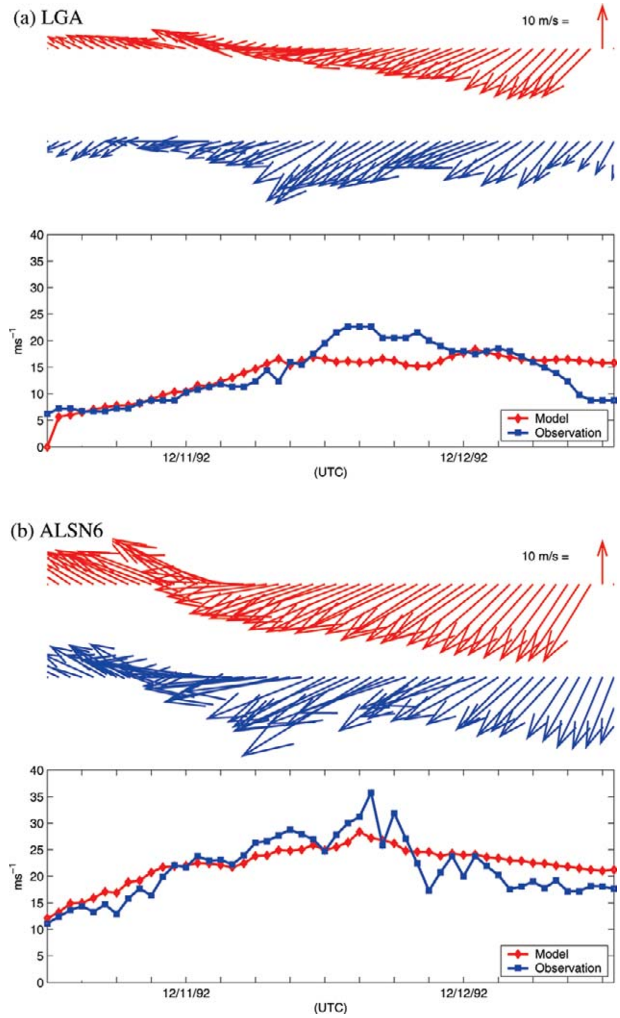


**Fig. 7. Meteorological wind time series for (a) LGA and (b) ALSN6 showing wind speed (m s$^{-1}$) for the observed (red) and 12-km MM5 (blue) wind vectors. Station locations are on Fig. 3a.**

Figure 9 shows the water levels and currents around New York Harbor at 0900 and 1300 UTC 11 December as the coastal flooding occurred in lower (southern) Manhattan. At 0900 UTC (Fig. 9a), there was a 0.5–1.0 m s$^{-1}$ current from the Atlantic northward into New York Harbor. The current split around the south side of Manhattan, with flow accelerating to nearly 1 m s$^{-1}$ northward up the East River to the east of Manhattan; in addition, there was flow up the Hudson River to the west. The water levels at this time had increased to ~1.0 m above MSL on the south and west sides of Manhattan. Because the ADCIRC seawall was set at 1.75 m above MSL, at this time there was no flooding.

Four hours later, at 1300 UTC 11 December (Fig. 9b), the simulated water levels increased to 2–2.5 m above MSL across New York Harbor as the

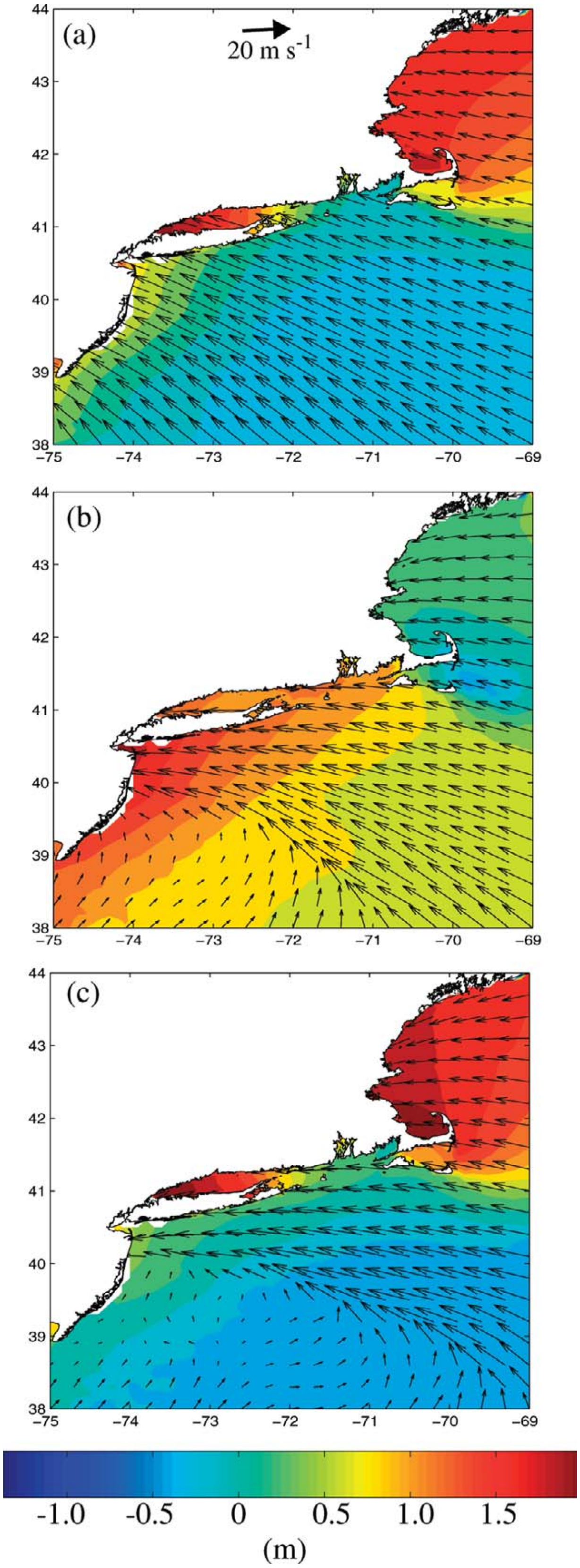


**Fig. 8. Surface 12-km MM5 winds (vectors in m s$^{-1}$) and water height relative to sea level (shaded in meters) for (a) 0400, (b) 1300, and (c) 1700 UTC 11 Dec.**

onshore currents with the surge continued. This resulted in fairly extensive flooding over the seawalls on the west and south sides of Manhattan and across the Hudson River around Hoboken, New Jersey (cf. Fig. 4b for location). Much of the simulated flooding on the lower west side of Manhattan was associated with the pier locations, but the water did penetrate to the 2-m above sea level point in the terrain. Meanwhile, the flooding on the south and lower east sides of Manhattan was consistent with the observed flooding of FDR Drive during the event (cf. Fig. 2b), while the flooding near Hoboken corresponded with the flooding in the PATH subway station (cf. Fig. 2a). During the next few hours the tidal currents in New York Harbor switched from the south to the north as the low tide approached (not shown). Meanwhile, high tide and associated flooding occurred in western Long Island Sound at 1700 UTC 11 December (not shown), but not enough of this surge could propagate quickly enough through the East River to cause any further flooding problems within New York Harbor (not shown).

ADCIRC was quantitatively compared with several NOS water level gauges around the region (cf. Figs. 3a and 4 for locations). In contrast with a fast-moving tropical storm, the December 1992 surge event slowly increased over three tidal cycles as the winds slowly increased on 10–11 December 1992 (Fig. 10). At the Battery (Fig. 10a), the model predictions were within 10–20 cm of the observed for the three high-water periods associated with the surge and high tide. The peak surge (~1.0 m) occurred around the time of the flooding noted above at 1300 UTC 11 December.

The ADCIRC simulation also accurately predicted the high water levels observed at Sandy Hook and Bridgeport, Connecticut (Figs. 10b,c). The Sandy Hook (SDH) peak surge at 1300 UTC 11 December was similar to that of the Battery, with the ADCIRC predictions of the peak water level running 1–2 h too early compared with that observed. At Bridgeport, the peak water level of 2.2 m above MSL and associated surge of ~1.0 m occurred at 1700 UTC 11 December.

**HURRICANE FLOYD (16–17 SEPTEMBER 1999).** *Model forecasts.* Hurricane Floyd made landfall along the southern North Carolina coast at 0900 UTC 16 September 1999 with 50 m s$^{-1}$ surface-sustained winds, making it a category 2 on the Saffir–Simpson scale (Simpson and Riehl 1981). The winds associated with Floyd weakened rapidly to tropical storm force as the storm moved quickly northeastward along the U.S. east coast during a

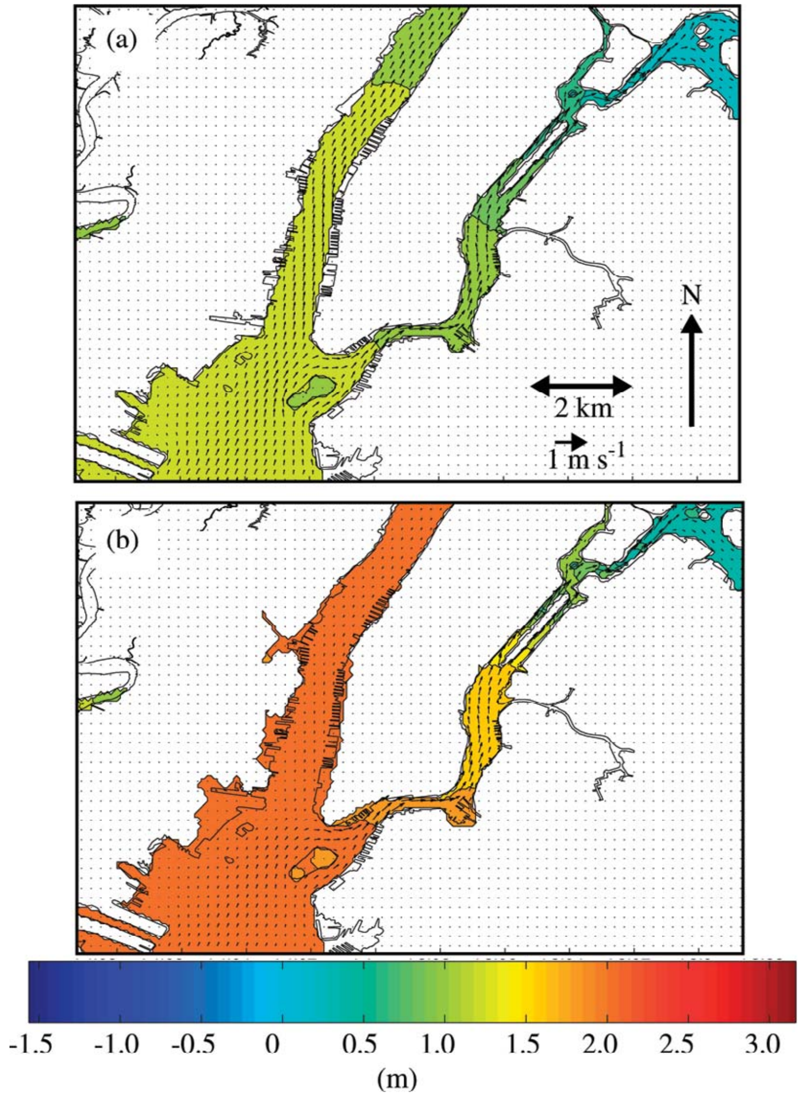


**Fig. 9. NYC spatial storm surge evolution at (a) 0900 and (b) 1300 UTC 11 Dec 1992, showing ADCIRC current vectors and water elevation (color shaded in meters) above MSL.**

12–18-h period. Atallah and Bosart (2003) describe the observational evolution of Floyd, while Colle (2003) illustrates the high-resolution MM5 simulations of the event.

The MM5 winds and sea level pressure were applied to the ADCIRC model starting at 0000 UTC 16 September 1999. The 12-km MM5 forecast of Floyd's central pressure (982 mb) along the mid-Atlantic coast was within 1–2 mb of the observed (not shown), and the simulated cyclone was located about 30 km south of the observed position by 1800–2100 UTC 16 September (cf. Fig. 4 of Colle 2003). At 1800 UTC 16 September 1999, the simulated position of Floyd was located over southern Virginia, which resulted in water levels of 1.0–1.5 m above MSL along the mid-Atlantic (Fig. 11a), and a weak to moderate storm surge of 0.5–1.0 m above local tidal level (not shown). By 2100 UTC (Fig. 11b), Floyd's center was located along the southeast New Jersey coast, with the highest water level (1.0–1.5 m) and surge (~1.0 m) located in western Long Island Sound. The winds then veered to northwesterly after Floyd traversed across Long Island during the next 6 h (Fig. 11c). This offshore flow forced water away from the coast, resulting in depressed water levels of about 0.5 m below mean tidal level around Long Island (not shown).

Figure 12 illustrates that the time series of the water levels for Floyd are much different than the 1992 December nor'easter. The surge for Floyd occurred quickly during one tidal cycle, and luckily the peak surge at the Battery at 2200 UTC 16 September occurred as low tide approached

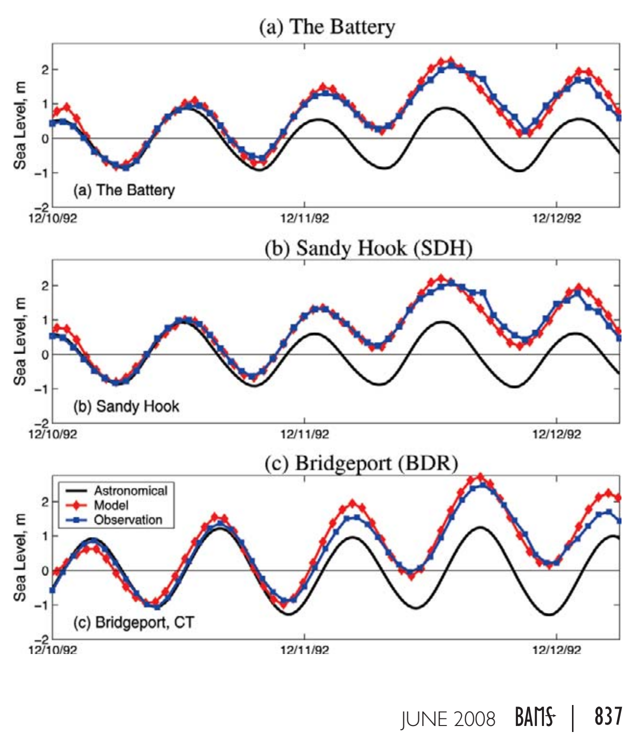


**Fig. 10. Time series of water level above MSL for (a) the Battery, (b) Sandy Hook (SDH), and (c) Bridgeport (BDR) for the model (red), observed (blue), and astronomical tide (black). The station locations are on Figs. 3a and 4.**

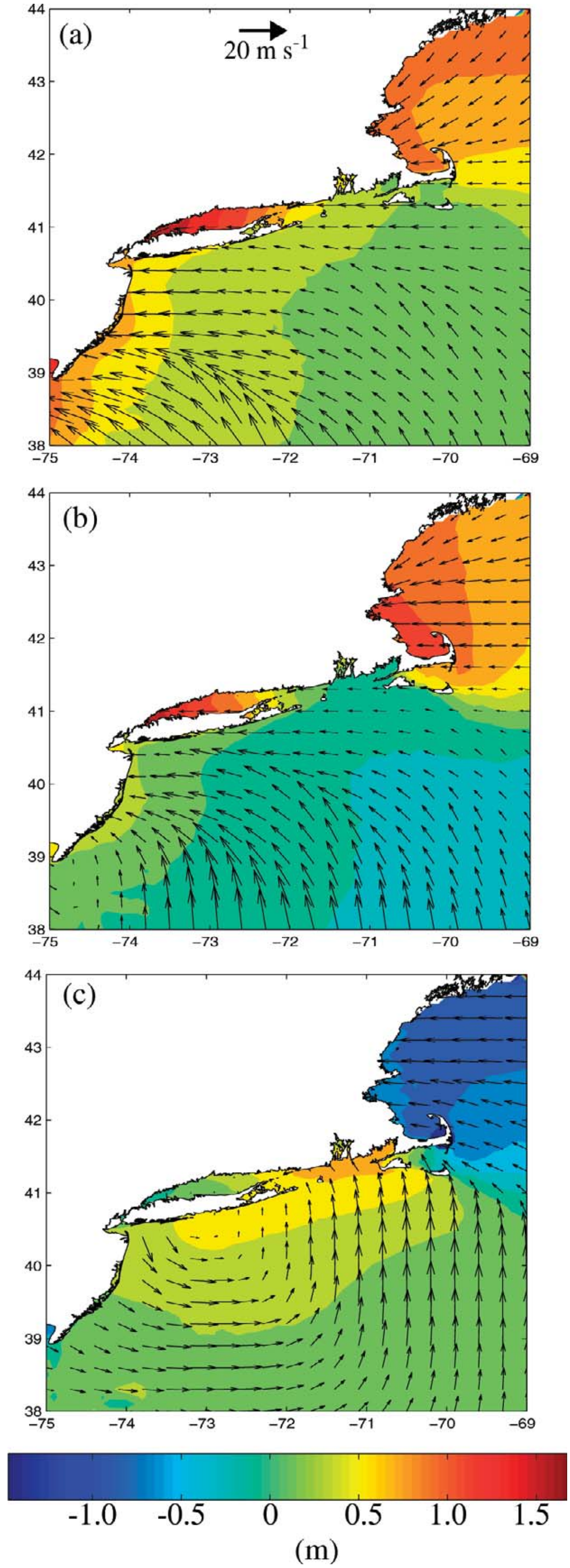


**FIG. 11. The 12-km MM5 surface winds and water height above MSL (shaded in meters) for (a) ADCIRC water height, (b) 2100, and (c) 0300 UTC 17 Sep 1999.**

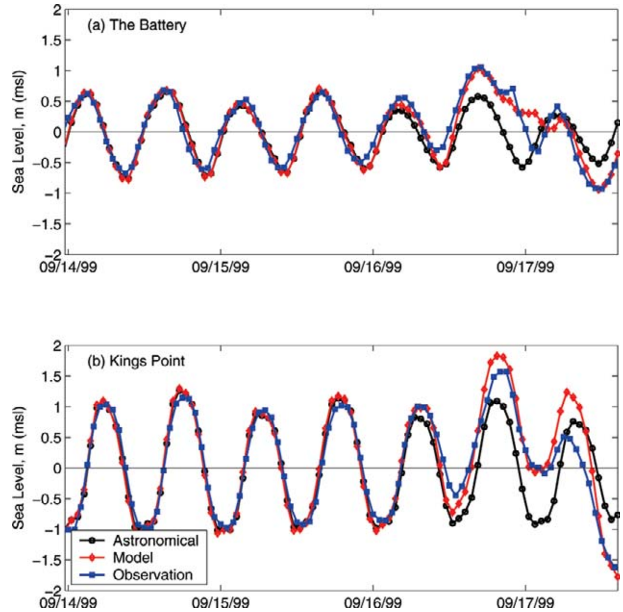


**FIG. 12. Time series of water height versus time (h) for (a) the Battery and (b) Kings Point (KPT) for the model predicted (red), observed (blue), and astronomical tides (black). The station locations are on Figs. 3a and 4.**

(Fig. 12a). The SBSS model predicted the maximum water height within 10% for many of the tidal reference stations around NYC. For example, at the Battery, the model correctly predicted both the phase and the amplitude of the highest water level at 1800 UTC 16 September (Fig. 12a); however, the model water levels were too high during the next 6 h as a result of the late (2–3 h) arrival of the simulated storm. This phase error created excessive easterly wind forcing between 2100 and 0000 UTC 17 September, which resulted in higher storm surge around NYC during the next low tide at 0000 UTC 17 September. At King's Point along the north shore of Long Island ("KPT" on Fig. 3a), the water level exceeded 1.5 m above mean sea level, or about 0.75 m above mean tidal level (Fig. 12b). Accordingly, the model tidal phase was advanced by 1–2 h during the storm event, suggesting a slight model bias in predicting the tide at this location.

*Sensitivity simulations.* Flooding over some of the southern Manhattan Island seawalls requires water levels of 1.5–1.75 m above MSL, which occurred briefly for the December 1992 nor'easter, but not during Floyd. The NYC area was spared of any flooding during Floyd because of the fortuitous phasing of the strongest winds at local low tide, as well as the rapid weakening of Floyd down to a tropical storm event as it propagated northward along the U.S. east coast. In order to illustrate these factors, additional sensitivity studies were conducted by i) increasing the intensity of Floyd's winds up to a category-1 hurricane in the NYC area, and ii) varying the timing of Floyd's landfall in the NYC Metropolitan area.

First, a simulation was conducted in which the intensity of MM5's wind predictions used as forcing for ADCIRC was increased by a factor of 2 (HURRFLOYD), but the tidal phasing and sea level pressure were left the same as the control run (CTL). This provided a peak wind of HURRFLOYD near NYC of ~35 m s$^{-1}$ (70 kts), which is equivalent to a weak category-1 hurricane. This resulted in a peak water level at the Battery of 1.3 m above sea level (Fig. 13), which is about 40 cm greater than the CTL, although this water level would likely not have resulted in significant coastal flooding, given the low tide.

Another experiment was conducted in which the timing of the maximum simulated surge in the CTL at near–low tide (2200 UTC 16 September) was shifted back in time to coincide with a spring high tide a week earlier at 1300 UTC 9 September (SHIFTFLOYD). This spring high tide was 60–80 cm higher than the tidal level during the time of maximum surge on 16 September 1999. The SHIFTFLOYD water levels approached 1.7 m above mean sea level, ~70 cm higher than the CTL run (Fig. 13). Some minor flooding would have occurred for this scenario, thus illustrating the impact even a relatively weak storm can have if it occurs during a spring (fortnightly) high tide.

Finally, a third experiment was conducted in which the doubling of Floyd's winds was combined with a time shift to spring high tide experienced a week earlier (MAXFLOYD). This resulted in peak water levels over 2.3 m above MSL at the Battery (Fig. 13), which is 1.3 m greater than the CTL run and it is comparable to the December 1992 nor'easter water levels at the Battery. Thus, significant flooding would have likely occurred across coastal southern and western Manhattan Island for a scenario similar to the MAXFLOYD run.

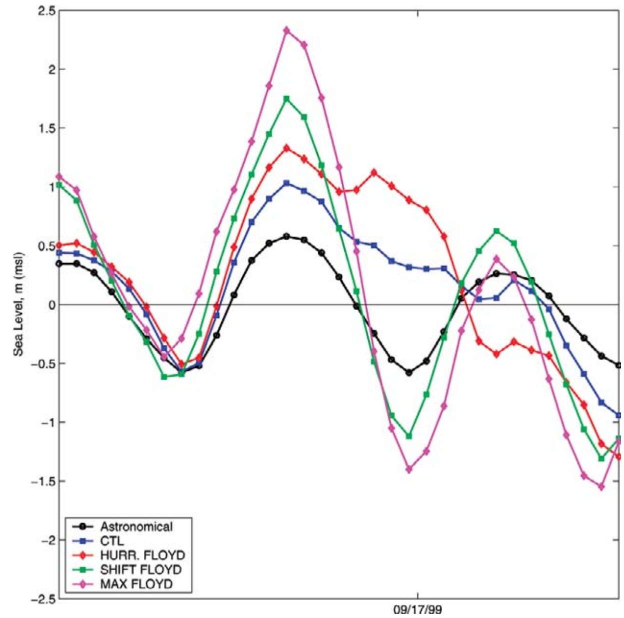


**Fig. 13. Time series of water height (m) at the Battery for the CTL, HURRFLOYD, SHIFTFLOYD, and MAXFLOYD simulations, as well as the astronomical tides. The time series starts at 0300 UTC 16 Sep, with each run labeled in the inset box.**

**DISCUSSION AND CONCLUSIONS.** This study highlights the capability of the Stony Brook Storm Surge (SBSS) modeling system. It utilizes surface winds and sea level pressures from the fifth-generation PSU–NCAR Mesoscale Model (MM5) at 12-km grid spacing to drive the Advanced Circulation Model for Coastal Ocean Hydrodynamics (ADCIRC), to simulate storm surge events for New York City (NYC). The system was tested around NYC for the 11–12 December 1992 nor'easter and Tropical Storm Floyd on 16 September 1992. The peak water levels for these events were predicted within 10% at several stations around NYC. This offers promise that storm surge predictions will continue to improve as hydrodynamic models such as ADCIRC are further developed.

In order to evaluate the skill of the SBSS model for longer time horizons, a real-time storm surge modeling system has been developed for the NYC area. It produces 60-h forecasts after being initialized early at 0000 UTC using ADCIRC coupled to the 12-km MM5. The forecasts are posted and updated twice daily (information online at http://stormy.msrc.sunysb.edu), in which the forecast of water level, winds, and sea level pressure are shown for several coastal sites, as well as NOAA astronomical tides and observations. The SBSS system is also currently being coupled with a wave model [Simulating Waves Nearshore (SWAN)], and the skill of the storm surge model is being evaluated over a seasonal period for several significant storm events.

Ensemble storm surge 48-h predictions are also being produced for the 0000 UTC cycle using five MM5 members and three WRF members at 12-km grid spacing as input, with the results displayed on the same Web page noted above. The atmospheric ensemble uses a variety of initial conditions [NCEP GFS, NAM, Canadian, U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS)] combined with various convective, boundary layer, and microphysical parameterizations. This ensemble is helping to determine how a suite of nor'easter forecasts can increase the forecast skill of the storm surge predictions.

Overall, this study reemphasizes the vulnerability of NYC to storm surge flooding and reemphasizes the need for accurate information on the timing and effects of storm surge flooding. It also illustrates that even moderate nor'easter events, such as the December 1992 cyclone, can cause significant flooding, especially if they occur during a high tidal cycle. As mean sea level continues to rise during the next 50–100 yr, flooding problems in the metropolitan New York region will only be exacerbated. Therefore, we believe that both state and city authorities in NYC and coastal northern New Jersey should begin exploring the feasibility of constructing European-style storm surge barriers across the major connections of New York Harbor to the ocean as protection against serious storm surge flooding.

There are already several storm surge barriers currently in operation in New England, the United Kingdom, the Netherlands, and Europe, constructed following severe and fatal flooding events in the past. For example, the September 1938 "Long Island Express" hurricane left 300 dead on Long Island and 600 dead in Providence, Rhode Island. This event was followed by Hurricane Carol in 1954, when 60 died in this same region (Bowman et al. 2005). As a result, the U.S. Army Corps of Engineers led efforts to construct a 7.6-m-high and 88-m-wide concrete barrier across the Providence River in 1966. Unfortunately, it usually takes a major disaster to provide the motivation for such barriers to be built.

We have performed additional simulations of Tropical Storm Floyd and the December 1992 nor'easter in which we installed three storm surge barriers located at Perth Amboy (behind Staten Island, west of Sandy Hook), across the Narrows (south entrance to New York Harbor), and across the upper end of the East River (east entrance to New York Harbor). The preliminary simulations with barriers show that metropolitan New York can be effectively protected from devastating storm surges (Bowman et al. 2005). Additional cases need to be simulated to investigate the surrounding impacts of these storm surge barriers as well as the sensitivity of NYC flooding to storm track and intensity.

**ACKNOWLEDGMENTS.** This publication is a resulting product from project [NYSG R/CCP-13] funded under award NA07OAR4170010 from the National Sea Grant College Program of the U.S. Department of Commerce's National Oceanic and Atmospheric Administration, to the Research Foundation of State University of New York on behalf of New York Sea Grant. The statements, findings, conclusions, views, and recommendations are those of the author(s) and do not necessarily reflect the views of any of those organizations. Support to run the MM5 in real-time was provided by UCAR-COMET (Grant S0238662).

## REFERENCES

Atallah, E., and L. F. Bosart, 2003: The extratropical transition and precipitation distribution of Hurricane Floyd (1999). *Mon. Wea. Rev.,* **131,** 1063–1081.

Blier, W., S. Keefe, W. A. Shaffer, and S. C. Kim, 1997: Storm surges in the region of western Alaska. *Mon. Wea. Rev.,* **125,** 3094–3108.

Bloomfield, J., M. Smith, and N. Thompson, 1999: Hot nights in the city. Global Warming, Sea-Level Rise and the New York Metropolitan Region. *Environmental Defense Fund,* 36 pp.

Bowman, M. J., B. A. Colle, R. Flood, D. Hill, R. E. Wilson, F. Buonaiuto, P. Cheng, and Y. Zheng, 2005: Hydrologic feasibility of storm surge barriers to protect the metropolitan New York–New Jersey region: Final report. Marine Sciences Research Center Tech. Rep., Stony Brook University, 28 pp.

Brouwer, G., 2003: The creeping storm. *Civil Eng.,* **73,** 46–88.

Chen, J., W. A. Shaffer, and S.-C. Kim, 1993: A forecast model for extratropical storm surge. *Advances in Hydro-Science and -Engineering,* S. S. Y. Wang, Ed., Academic Press, 1437–1444.

Colle, B. A., 2003: Numerical simulations of the extratropical transition of Floyd (1999): Structural evolution and responsible mechanisms for the heavy rainfall over the northeast U.S. *Mon. Wea. Rev.,* **131,** 2905–2926.

——, J. B. Olson, and J. S. Tongue, 2003: Multi-season verification of the MM5. Part I: Comparison with the Eta over the central and eastern United States and impact of MM5 resolution. *Wea. Forecasting,* **18,** 431–457.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.,* **20,** 3077–3107.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth-generation Penn State/

ENCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 138 pp.

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast model. *Mon. Wea. Rev.,* **124,** 2322–2339.

Houston, S. H., and M. D. Powell, 1994: Observed and modeled wind and water-level response from tropical storm Marco (1990). *Wea. Forecasting,* **9,** 427–439.

Irish, J. L., J. K. McClung, and W. J. Lillycrop, 2000: Airborne lidar bathymetry: The SHOALS system. *PIANC Bull.,* **103,** 43–53.

Jarvinen, B. R., and M. B. Lawrence, 1985: An evaluation of the SLOSH storm surge model. *Bull. Amer. Meteor. Soc.,* **66,** 1408–1411.

Jelesnianski, C. P., J. Chen, and W. A. Shafer, 1992: SLOSH: Sea, lake, and overland surges from hurricanes. NOAA Tech. Rep. NWS 48, 71 pp.

Jones, M., B. A. Colle, and J. Tongue, 2007: Evaluation of a short-range ensemble forecast system over the northeast United States. *Wea. Forecasting,* **22,** 36–55.

Li, M., L. Zhong, W. C. Boicourt, S. Zhang, and D.-L. Zhang, 2006: Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay. *Geophys. Res. Lett.,* **33,** L02604, doi:10.1029/2005GL024992.

Luettich, R. A., J. J. Westerink, and N. W. Scheffner, 1992: ADCIRC: Advanced three-dimensional circulation model for shelves, coasts, and estuaries. Report #1: Theory and methodology. U.S. Army Eng. Waterways Exptl. Station, Coastal Hydraul. Laboratory, Tech. Rep. DRP-92-6, 143 pp.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.,* **87,** 343–360.

National Weather Service, Eastern Region, 1994: The Great Nor-easter of December 1992. Disaster Survey Rep., 59 pp. [Available from the National Weather Service, Eastern Region Headquarters, 630 Johnson Ave, Bohemia, NY 11716.]

Roebber, P. J., D. M. Schultz, B. A. Colle, and D. J. Stensrud, 2004: Towards improved prediction: High resolution and ensemble modeling in operations. *Wea. Forecasting,* **19,** 936–949.

Rosenzweig, C., and W. D. Solecki, Eds., 2001: *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change—Metro East Coast.* Columbia Earth Institute, 224 pp.

Shaffer, W. A., J. P. Dallavalle, and L. D. Burroughs, 1997: East Coast extratropical storm surge and beach erosion guidance. Tech. Procedures Bulletin 436. [Available at www.nws.noaa.gov/om.]

Simpson, R. H., and H. Riehl, 1981: *The Hurricane and Its Impact.* Louisiana State University Press, 398 pp.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. Gill, D. Barker, W. Wang, and J. Powers, 2005: A description of the advanced research WRF version 2. NCAR Tech. Note 468+STR, 94 pp.

U.S. Army Corps of Engineers, 1995: Metro New York hurricane transportation study. Interim Tech. Rep., 74 pp.

Wei, E., 2003: The new port of New York and New Jersey operational forecast system. *Bull. Amer. Meteor. Soc.,* **84,** 1184–1186.

Westerink, J. J., and Coauthors, 2008: A basin- to channel-scale unstructured grid hurricane storm surge model applied to southern Louisiana. *Mon. Wea. Rev.,* **136,** 833–864.