SIMULATION OF HURRICANE ISABEL USING THE ADVANCED CIRCULATION MODEL (ADCIRC)

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ABSTRACT

Hurricane Isabel made landfall near Drum Inlet, about 240 km south of the Chesapeake Bay mouth, on the Outer Banks of North Carolina at 17:00 UTC (GMT 12:00), 18 September 2003. Hurricane Isabel is considered one of the most significant tropical cyclones to affect portions of northeastern North Carolina and east-central Virginia. The ADvanced CIRCulation Model (ADCIRC) model was applied to the Chesapeake Bay to simulate Hurricane Isabel. High-resolution grids were placed inside the Bay and tributaries; coarse grids were placed outside the Bay. The spatial grid resolution in the Bay mainstem is about 200–1000 m and the spatial grid resolution in the tributaries ranges from 50–700 m. A parametric wind model was used to drive the model. The model results show that, with the use of a parametric wind model, the model can predict the peak surge and storm tide histories along the Bay mainstem and tributaries. The model was used to analyze the impact of sea level rise on surge and inundation prediction.

INTRODUCTION

Chesapeake Bay is one of the largest estuaries in the United States. The Bay comprises many tributaries and numerous interconnected embayments, marshes, islands, and channels. The bathymetry of the Bay is very complex and the shorelines are very irregular. The model grid resolution applied in the previous storm surge studies of the Bay was on the order of kilometers [1], which is not sufficient to resolve the irregular shorelines and tributaries. To allow for a better prediction of storm surge and inundation, a high-resolution model grid is needed to represent both estuary bathymetry and adjacent low-lying land.

In 2003, Hurricane Isabel made landfall in eastern North Carolina on 18 September (GMT 12:00). Although it was only classified a Category 2 storm (Saffir-Simpson scale), Isabel had a significant impact on the Chesapeake Bay with a 1.5–2.0 m (above mean sea level) storm surge. The surge and inundation caused huge damage in the region, with many flooded areas in the tributaries and headwaters of the estuary. To study the influence of storm surge on the Chesapeake, the ADCIRC model has been applied to the Bay to simulate storm tide and inundation. A high-resolution, unstructured grid was used to represent the model area. The flexibility of the grid layout allows the model to cover a large modeling domain while maintaining high resolution in areas with complex topographic and bathymetric features. Simulations show that the model successfully predicts the peak surge and inundation along the Bay mainstem and tributaries. Preliminary studies of the influence of sea level change on inundation prediction were also conducted.

MODEL DESCRIPTION

The ADvanced three-dimensional CIRCulation model (ADCIRC) is a finite element model developed by Westerink and Luettich et al. [2, 3]. The model was developed specifically to simulate long time periods of hydrodynamic circulation along shelves and coasts and within estuaries. The intent of the model is to produce long numerical

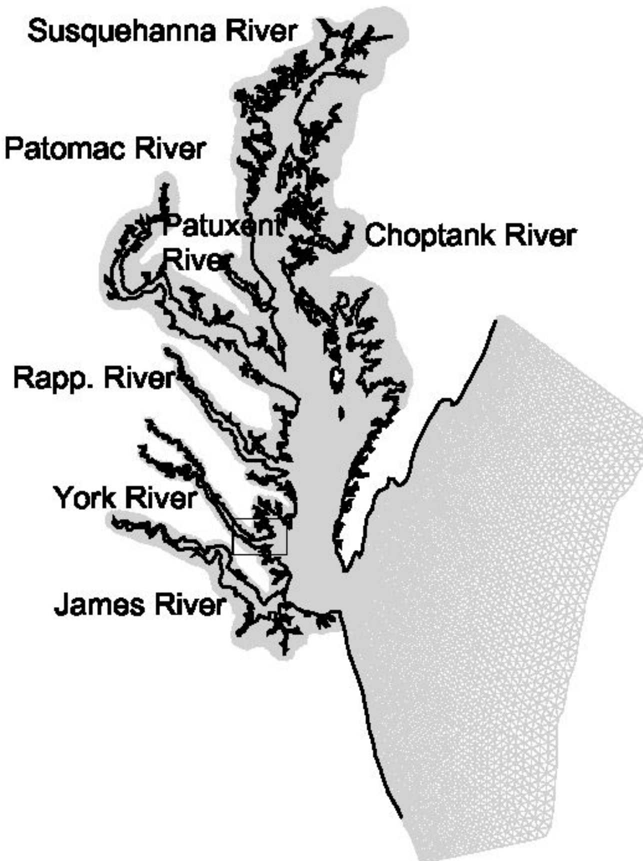

Figure 1. High-resolution model grid.

simulations for very large computational domains in a unified and systematic approach. This finite element model allows users to place a grid with fine resolution flexibly near the coast or in complex bathymetric areas while using coarser resolution in the open ocean. The model can be forced with surface elevation at the open boundary, zero land boundary flux, variable spatial and temporal free surface stress, and atmospheric pressure. The model can simulate wetting-drying processes in low-lying areas along with the influence of waves. The model has been extensively applied over the past decade by both the U.S. Army Corps of Engineers and the U.S. Navy [4] for tidal and hurricane storm surge predictions in many regions [5, 6, 9, 10] as well as for wave-tide circulation [7].

MODEL GRID

To take full advantage of the finite element model's ability to represent complex estuarine geometry, a high-resolution model grid was generated for the ADCIRC model. The grid includes both the water body and adjacent low-lying land areas. The model open boundary is located at approximately 74.5 degrees west longitude along the 200-m isobath (Figure 1).

The total number of horizontal grid elements is 239,541. High-resolution was placed inside the Bay and tributaries with coarse resolution placed outside of the Bay. The spatial grid resolution in the Bay main channel is about 0.2 to 1 km. The spatial grid resolution ranges from 150–500 m in the tributaries with a range of approximately 50–150 m in tidal rivers such as the Mattaponi and Pamunkey rivers. Figure 2 shows an example configuration of the grid near the mouth of the York River, indicating that an irregular shoreline can be well represented by model grids.

The 3-second Coastal Relief Model bathymetric data were used to obtain water depth

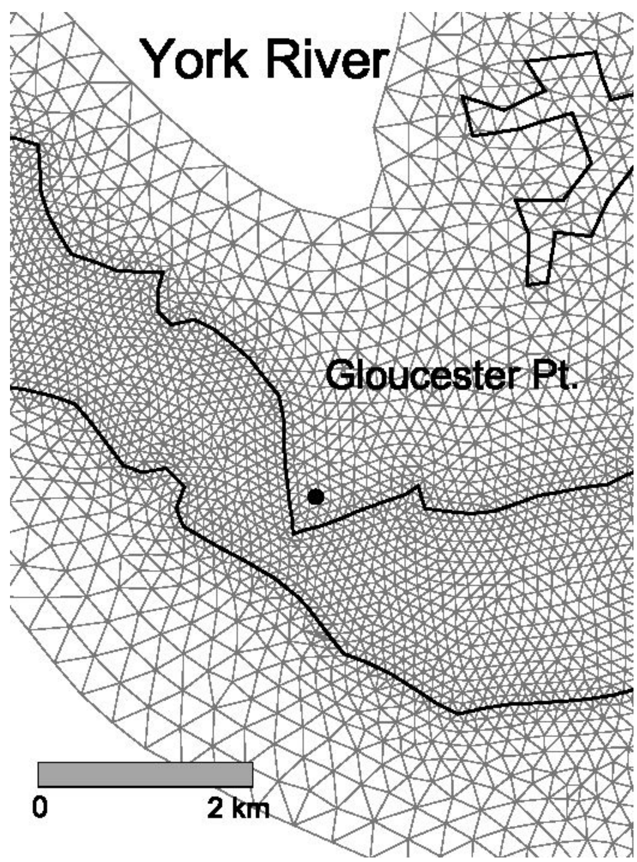

Figure 2. Grid layout at the mouth of York River.

inside the Bay and NOAA's 2-minute Global Relief Model (ETOPO2) bathymetric data were used for the remainder of the grid cells near the coast. The mean sea level was used as the datum for the model. Data from USGS 30-meter Digital Elevation Models (DEM) were used to obtain the elevation of adjacent low-lying land. The DEM data, based on the NGVD datum, were adjusted to mean sea level based on the gauge stations inside the Bay. Six tidal gauge stations with available datum information inside the Bay were used as reference stations—Sewells Point at Hampton Roads, Gloucester Point, Lewisetta, Annapolis, Baltimore, and Kiptopeke.

The difference between mean sea level and NGVD29 ranges from 0.23 m at Baltimore to 0.17 m at Hampton Roads. The difference at Kiptopeke is about 0.10 m. Therefore, elevations of adjacent low-lying land are adjusted based on the stations in the drainage basins. Elevations in the James River and York River basins were adjusted based on the data from Hampton Roads and Gloucester Point stations, respectively. The elevations in the Rappahannock River and Potomac River basins were adjusted based on data from the Lewisetta station. The elevation adjacent to the upper Bay above the Potomac River was adjusted based on the Baltimore stations. The elevation adjacent to the Eastern Shore region was adjusted based on the Kiptopeke station.

MODEL SIMULATION

Hurricane Isabel

Hurricane Isabel made landfall near Drum Inlet, about 240 km south of the Chesapeake Bay mouth, along the Outer Banks of North Carolina at 17:00 UTC (12:00 GMT) on 18 September 2003. Figure 3 shows the hurricane's track. Isabel was classified as a Category 2 storm (Saffir–Simpson Hurricane Scale) with sustained winds of about 85–90 kt before landfall.

Figure 3 shows the locations of NOAA tidal stations and values of the available observed maximum surface elevation in the Chesapeake Bay. Storm tides of 1.0–1.5 m were recorded over the central portion of the Chesapeake Bay and 1.5–2.1 m over the southern portion of the Bay in the vicinity of Hampton Roads, Virginia. In the upper reaches of the Chesapeake Bay, near Annapolis and Baltimore, Maryland, surface elevations of 1.9–2.2 m were observed. High surges were also observed at the headwater of the tributaries, reaching 2.5 m above normal level at the Richmond City lock along the James River in Virginia and nearly 2.4 m along the Potomac River in Washington, D.C. During Hurricane Isabel, the surge time series were recorded at several NOAA tide gauges along the U.S. East Coast and the Chesapeake Bay, a rare occurrence during past hurricane events. These observations provide useful information for model evaluation. Although large portions of low-lying areas of the Chesapeake were flooded during Isabel, a reliable data set from inundation areas has not yet become available. Therefore, time series of water level data, together with maximum surge data, were used for model evaluation.

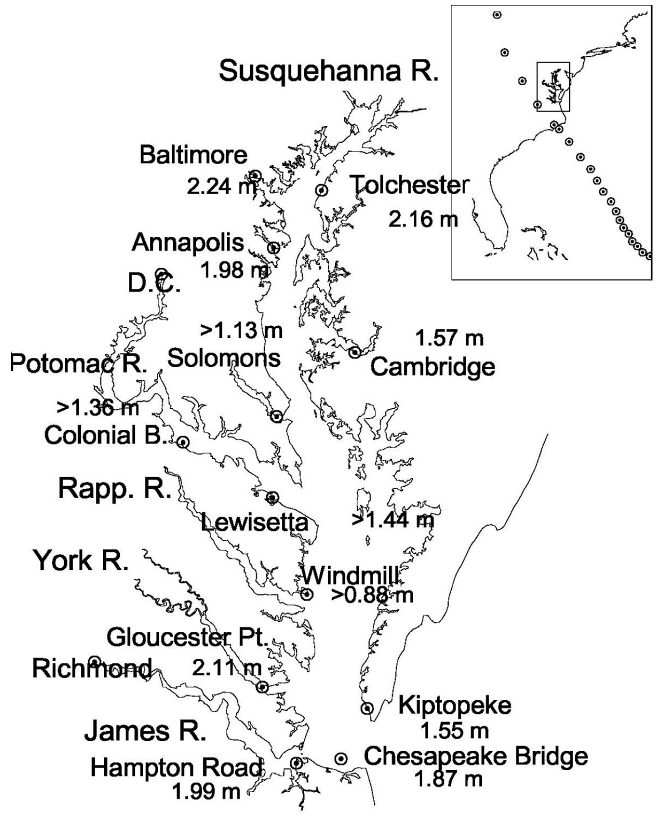

Figure 3. Map of tidal gauge stations and maximum storm tide during Hurricane Isabel.

Hurricane Simulation

For storm tide simulation, the model was run in a two-dimensional, depth-averaged mode. The model was forced by a parametric wind model similar to the Sea, Lake, and Overland Surges from Hurricanes model (SLOSH) used by NOAA's National Weather Service [1]. The model can reproduce the wind field with meteorological parameters including hurricane path, atmospheric pressure, and radius of maximum wind. The best hurricane track and meteorological data were obtained from the National Hurricane Center. The surface wind patterns analyzed by the Hurricane Research Division (HRD) were available before Isabel made landfall. These wind field data were downloaded from the National Hurricane Center and used to estimate the maximum radius of wind. The hourly wind field parameters were input into the model and the wind field was then calculated every 0.2 hours to drive the model using linear interpolation of the hourly wind parameters. Nine tidal constituents—M_2, S_2, K_1, O_1, Q_1, K_2, N_2, M_4, and M_6—forced the ADCIRC model at their open boundaries. The forcing harmonic constants were obtained from the U.S. Army Corps of Engineers' East Coast 2001 database of tidal constituents [9]. The model was run for four days for tidal spin-up starting 12 September 2003 at 24:00 EDT and 96 hours for storm surge simulation. Results from the last three days, staring 17 September 2003 at 24:00 EDT, were analyzed.

The measured pressure near landfall was 957 mb [13] and the estimated maximum radius was approximately 56 miles based on the HRD wind field before Hurricane Isabel made landfall. The estimated pressure drop was about 56 mb. The initial model tests of surge simulation using these parameters indicated that the model did not predict well the peak surge in the upper Bay area and the water retreat was too rapid in the lower Bay area

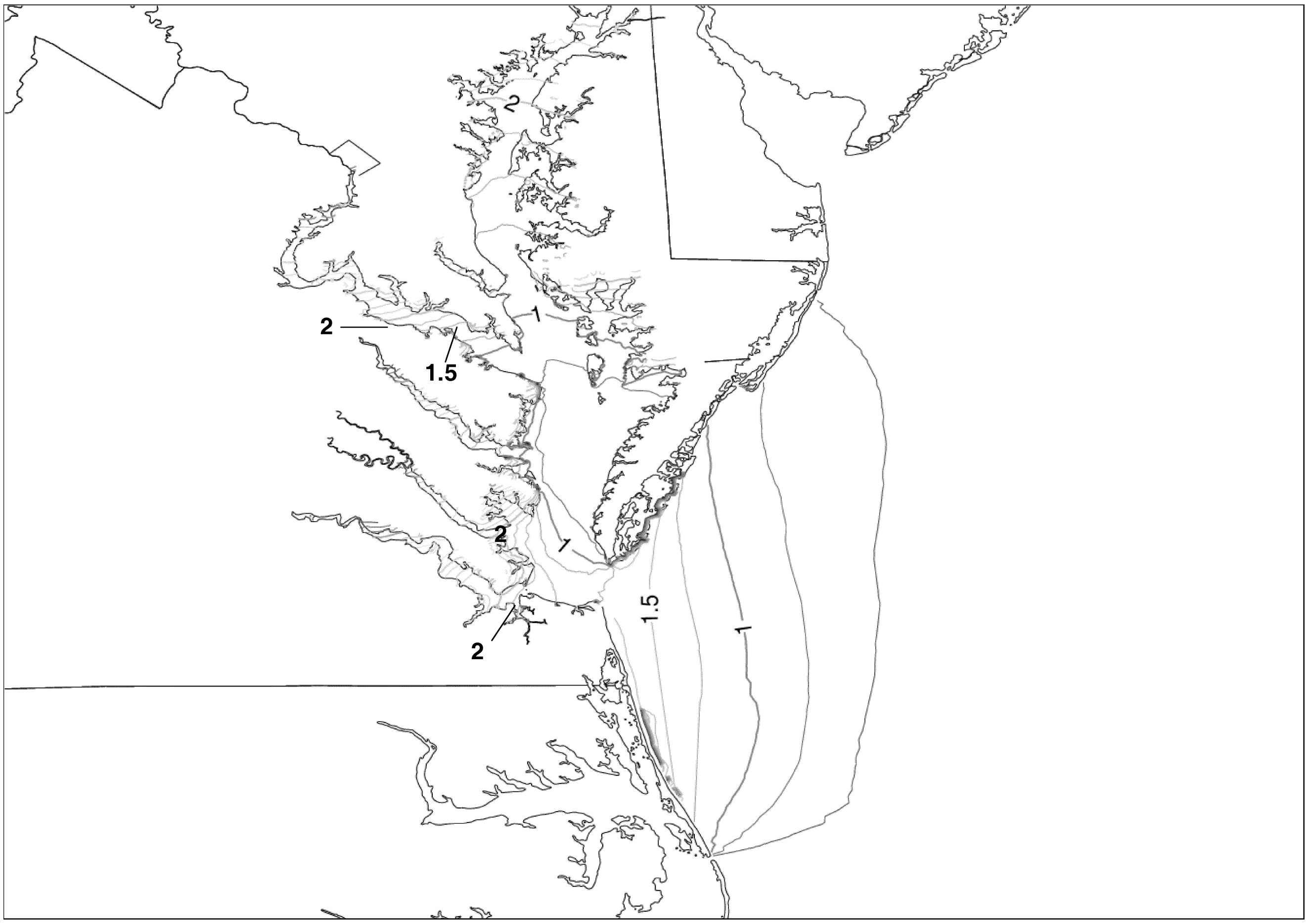

Figure 4. Contours of maximum surge predicted by ADCIRC in Chesapeake Bay (contour interval is 0.25 m).

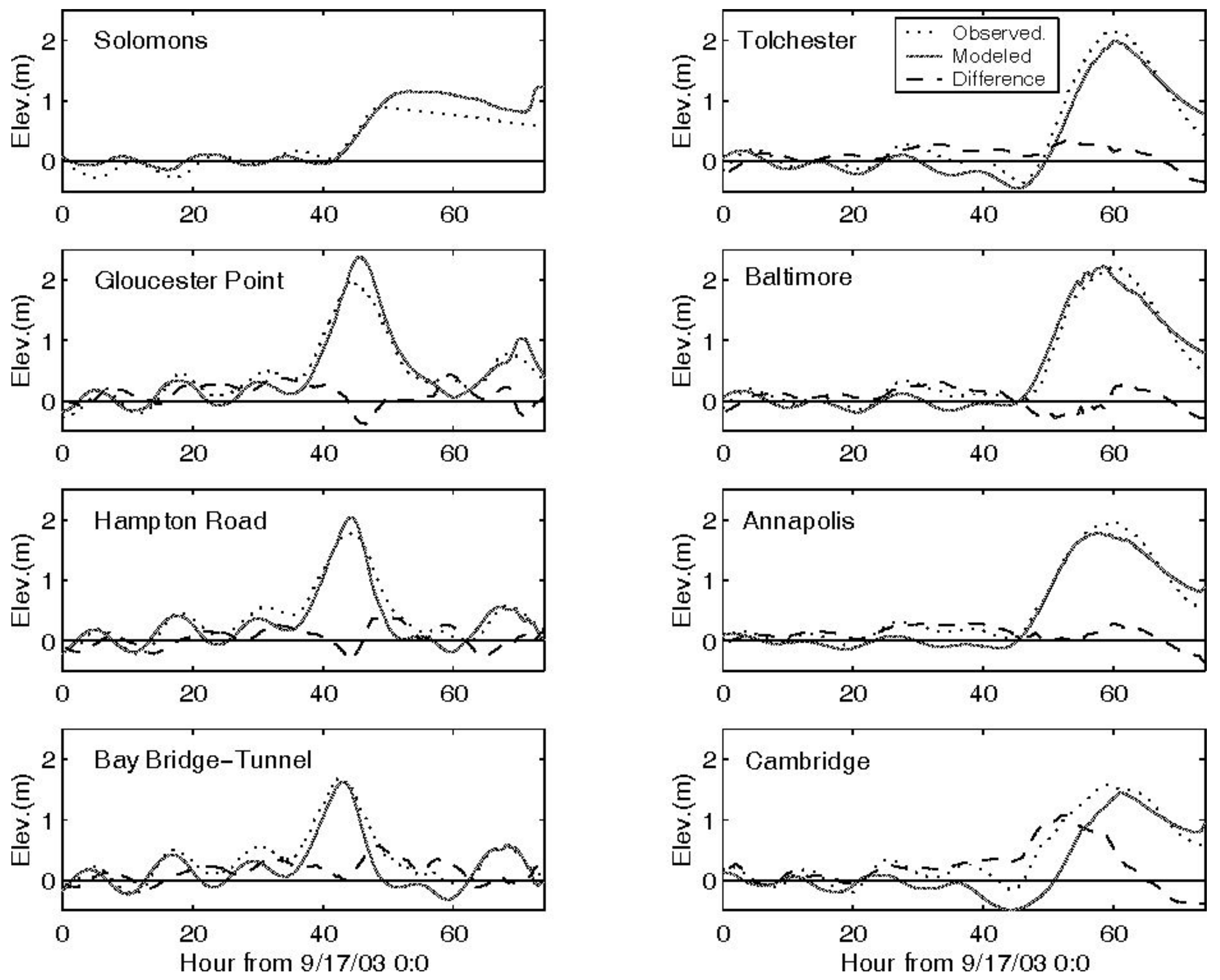

Figure 5. Time series comparison of ADCIRC model simulations with observations at different stations (dotted lines are observations, solid lines are model results, and dashed lines are differences).

after the peak surge. By comparing model predictions and wind observations at the Tolchester and Hampton roads tidal gauge stations, it was found that the parametric wind model under-predicted the magnitude of the wind at these stations 6 hours after Isabel made landfall. To better simulate the wind field, the pressure drop and maximum radius were adjusted 6 hours after the hurricane made landfall. The pressure drop and maximum radius were increased by about 10% and 12% of the observed values, respectively.

Figure 4 presents the maximum storm tide predicted by the ADCIRC. The high surge occurs in both the lower and upper Bay and relatively lower surge occurs in the middle portion of the Bay. It is also visible that surge in all western tributaries is higher relative to the surge occurring in the Bay main channel. Model predictions of peak storm tide distribution agree well with the observations (Figure 3), showing that the accurate prediction of surge in tributaries becomes possible with the use of high-resolution model grids.

Figure 5 shows the time series comparisons of computed storm tide from ADCIRC to observations at eight selected stations. It also shows the difference between model simulations and observations. In general, model results agree well with the observations in the Bay. Table 1 lists both modeled and observed peak storm tide at seven tidal gauge stations. The differences over a 72-hour

Table 1. A summary of modeled and observed storm tide during Hurricane Isabel.

Location	Peak Storm Tide* (m)		Difference	RMS (m)
	Observed	Modeled	(m)	72 hr. time series
Bay Bridge Tunnel	1.87	1.63	0.24	0.22
Hampton Roads	1.99	2.05	-0.05	0.17
Gloucester Pt.	2.11	2.39	-0.28	0.21
Annapolis	1.98	1.78	0.20	0.17
Baltimore	2.24	2.24	0.00	0.17
Cambridge	1.57	1.46	0.12	0.43
Tolchester	2.16	1.99	0.17	0.18
Mean RMS Error (m)			0.19	0.26

** Reference to mean sea level*

Table 2. A summary of model predictions of storm tide under current conditions and storm tide during lower sea level.

Location	Peak Storm Tide (m)		Difference	RMS (m)
	2003	Lower Sea Level	(m)	72 hr. time series
Bay Bridge Tunnel	1.63	1.70	-0.07	0.07
Hampton Roads	2.05	2.06	-0.01	0.04
Gloucester Pt.	2.39	2.43	-0.04	0.02
Windmill Point	1.07	1.09	-0.02	0.03
Solomons	1.31	1.25	0.05	0.04
Colonial Beach	2.64	3.03	-0.39	0.16
Annapolis	1.78	1.93	-0.15	0.11
Baltimore	2.24	2.35	-0.11	0.08
Cambridge	1.46	1.56	-0.10	0.06
Tolchester	1.99	2.15	-0.16	0.10
Mean RMS Error (m)			0.16	0.08

period of storm tide histories between model predictions and observations are quantified by RMS errors. The model appears to overpredict surge at Gloucester Point by about 0.28 m and underpredict surge at Annapolis by about 0.2 m. Time series RMS errors range from 0.17–0.43 m. The largest error occurs at Cambridge. The mean RMS errors for peak storm tide and time series are 0.19 and 0.26 m, respectively. The predicted peak surge at Baltimore occurs slightly earlier than the observations, whereas the prediction of peak surge lags observations by about three hours at Cambridge (Figure 5). One possible cause of the discrepancy at Cambridge is the wind field. The parametric wind model was used to generate the wind field. The model assumes that the circular wind pattern and the influence of topography and surface friction on the wind field are not considered. Despite adjustment to the model parameters to match the wind at Hampton Roads and Tolchester, the wind field may deviate from the wind field locally. The cause of the phase shift at Cambridge is not clear. Although the wind field used to drive the model appears too strong at the Cambridge station, this does not explain the phase delay at that location. The interactions of surge and local bathymetry can also play an important role contributing to the phase lag.

The model predictions of surface elevation in the lower Bay regions are also lower before the peak surge. It appears that the forerunner is under-predicted, especially at the Bay Bridge tunnel near the Bay mouth. Since a limited model domain is used, the open boundary condition specification can directly influence the interior model simulation. The model applications in other areas show that surge histories at the shore depend highly on offshore conditions [6, 8]. Different boundary conditions, such as using an inverse pressure adjustment or a radiation boundary condition [6, 8, 11], have been reported to improve the open boundary condition specification of model applications. For the current modeling exercise, the still water boundary condition was used, where surface elevation at the boundary was set to equal the base astronomical tide. To better simulate surge time histories, an improved boundary condition and wind field should be implemented. Overall, the model successfully captured the general surge processes in the Bay area with the use of the parametric wind model.

INFLUENCE OF SEA LEVEL CHANGE ON SURGE SIMULATION

Hurricane intensity and its induced inundation depend on the path of the hurricane, wind speed, and local bathymetry. Boon [12] points out that tidal phase and long-term sea level change are also key factors for assessment of future hurricane influence on the region. Based on Boon's analysis [12] of long-term tidal data from Hampton Roads, a secular rate of sea level rise of 4.25 $mm \cdot yr^{-1}$ predicted an increase of 29.8 cm over 70 years. Flooding will be more severe as sea level rises. It was assumes that sea level of 100 years ago was 40 cm lower than current sea level. A model run was conducted assuming Isabel occurred 100 years ago by setting the sea level 40 cm lower than the current level. Figure 6 shows a comparison of predicted storm tide at current sea level and that predicted at the lower sea level.

Table 2 shows the comparison of peak storm tide under current conditions and the peak during lower sea level. The difference of storm tide histories is quantified by RMS errors. It is noteworthy that the surge is increased (relative to sea level) when sea level is lowered. The mean RMS error of the peak storm tide is 0.16 m and the mean RMS error for time series is approximately 0.06 m. It appears that the differences increase in the upper Bay region. The cause of increase in storm tide during lower sea level can be attributed partly to lower inundation.

Figure 7 compares the difference in predicted inundation with respect to sea level change. The model results show that the estimated flooding area increases approximately 37% as sea level increases (shaded areas around the shoreline). Since the vertical resolution of DEM data is not sufficiently fine to represent appropriately the local topography in the adjacent low-lying land, overprediction or

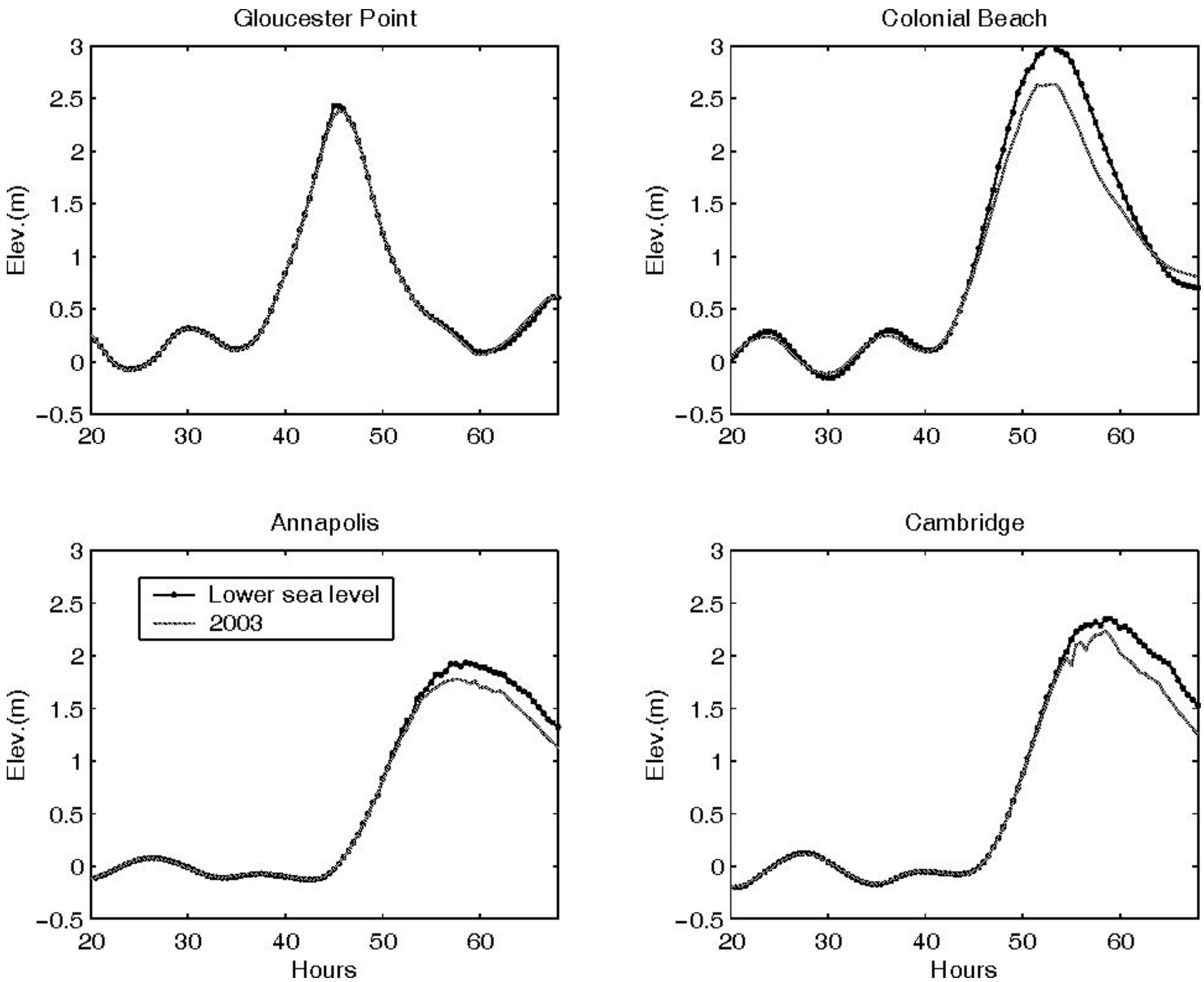

Figure 6. Comparison of model predicted surge under different sea level condition (lines with dots are results for low sea level (40 cm lower) and solid lines are the results under the current sea level).

underprediction of inundation may be occurring in some local areas. Nevertheless, the model simulation suggests that sea level rise is an important factor in assessment for the impact of storm surge in the coastal zone, particularly with respect to the increased inundation.

CONCLUSION

The ADCIRC model was applied to Chesapeake Bay for simulating Hurricane Isabel. With the use of high-resolution model grids, the model can represent irregular shoreline and complex bathymetry well. The model simulation shows the capability to predict peak surge in the Bay mainstem and tributaries under the forcing of a parametric wind model. The differences of peak storm tide simulation and observation range from 0.0–0.28 m. The mean RMS error of peak storm tide between model simulation and observation is 0.19 m. The mean RMS error of a 72-hour simulation is about 0.26 m. A preliminary model simulation suggests that sea level rise is an important factor in assessing inundation.

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Figure 7. Difference in inundation from model flood prediction using current sea level and low sea level conditions (shaded area indicates the increased flooding at current sea level).

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