WHAT HAS BEEN LEARNED ABOUT STORM SURGE DYNAMICS FROM HURRICANE ISABEL MODEL SIMULATION?

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ABSTRACT

An unstructured grid hydrodynamic model was used to study storm surge in the Chesapeake Bay during Hurricane Isabel. The model-simulated, storm-induced water level compared reasonably well with the measured data collected around the Bay. Calibrated water level was extracted from the model to further analyze the dynamics of the surge as it formed and propagated along the mainstem Chesapeake.

Based on time-series analysis, formation of the surge due to the pumping of coastal waters (hereafter called the primary surge) into the Chesapeake was first identified at the Bay mouth with a peak height of 1.5 m above mean sea level (MSL). Once formed, it propagated northward with gradually diminishing amplitude at a speed of about 5 m·sec^{-1} until reaching Windmill Point, near the mouth of the Rappahannock River in Virginia. Beyond Windmill Point, the surge height increased monotonically toward the northern part of the Chesapeake Bay.

Spatial analysis of surge height revealed that a second-stage surge was induced directly by the southerly wind following Hurricane Isabel's passage inland. The persistent southerly wind induced a setup and a set-down in the upper and lower Chesapeake respectively, with the dividing line near Windmill Point where the water level stayed at approximately 0.5 m above MSL during the event.

Space-time analysis provided further evidence that the abnormally high water in the upper Chesapeake Bay was the result of the primary surge wave as well as the second-stage surge caused by the southerly wind-induced setup.

INTRODUCTION

Hurricane Isabel made landfall in eastern North Carolina at 12:00 Eastern Daylight Time (EDT) on 18 September 2003. It weakened after landfall as it moved across eastern North Carolina, southern Virginia, and western Pennsylvania with an average speed of 9.3 m·sec^{-1}. Sustained winds of about 46 m·sec-1 and a pressure drop of about 56 mb were observed before landfall. Storm surges of 1.4–1.8 m above normal tide level were observed in the lower Chesapeake with 2.0–2.6 m seen in the upper Bay. The unexpected high water in the northern portions of the Bay inflicted significant damage to the City of Annapolis and the Baltimore metropolitan area. Figure 1 shows the storm surge (excluding the normal astronomical tide) and the corresponding wind fields observed at four stations in the Bay during Hurricane Isabel.

The storm surge started at 14:00 on 18 September at the Chesapeake Bay Bridge Tunnel (CBBT) with a peak height of about 1.5 m. The surge dropped initially as it moved northward, then increased again after passing Windmill Point, Virginia. It ultimately reached 2.4 m at Tolchester Beach, Maryland. The duration of high water (using the 75th percentile of water level as a measure) also increased from less than half a day to a full day in the middle and northern portions of the Chesapeake. Based on Bretschneider's [1] surge ratio and Green's Law prediction, Chesapeake Bay geometry alone (including variation of the width and depth) cannot account for the entire increase of the surge from 1.5 m in the lower Bay to 2.4 m in the upper Bay.

Why does the surge amplitude decrease and increase again as it moves north in the Bay? And

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what is the cause for the duration of high-water in the mid-Bay? Displayed alongside time series from four water level stations in Figure 1 are the corresponding wind vector time series. Inspection of the wind vector history during the hurricane shows that the wind initially started with northeast and east winds, followed by prolonged southeast, south, and southwest winds after passage of the storm. The maximum sustained wind speed from south to north reached 15 $m \cdot sec^{-1}$ for an extended period, suggesting that the wind fields may hold the key for answering these questions.

To test the hypothesis, a storm surge hydrodynamic model, along with a parametric wind model, were set up for simulating the response of the Bay to the hurricane wind fields. After model calibration with the observed data, the main Bay results were extracted from the model for a detailed analysis of surge dynamics. The following sections describe the hydrodynamic and parametric wind models, model results and their use for surge dynamics analysis, and conclusions.

HYDRODYNAMIC MODEL AND THE PARAMETRIC WIND FIELD MODELS

An unstructured grid, finite difference/finite volume model ELCIRC (Eulerian Lagrangian CIRCulation) has been used to simulate storm surge in the Chesapeake Bay during Hurricane Isabel. The model can simulate storm surge using a high-resolution grid on a large modeling domain (Figure 2), while still maintaining a relatively large time step. The model is a general three-dimensional model capable of simulating both two-dimensional (vertically averaged) and three-dimensional hydrodynamics and transport processes. The model uses an orthogonal, unstructured grid with mixed triangular and quadrilateral grids in the horizontal and the z-coordinate in the vertical [2]. The Eulerian-Lagrangian (E-L) transport scheme is

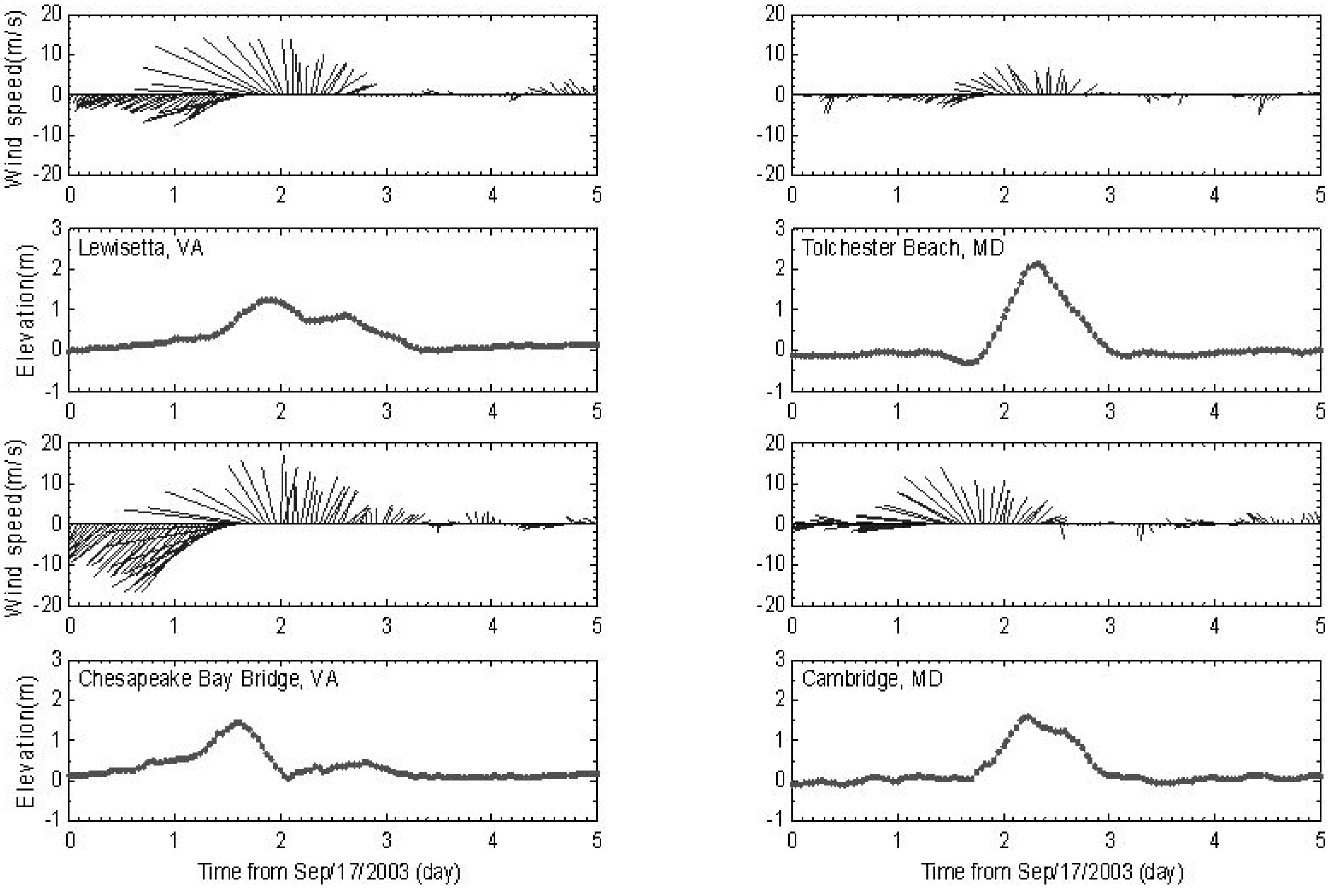

Figure 1. Observed storm surge (excluding astronomical tide) and the corresponding wind vectors in Chesapeake Bay stations during Hurricane Isabel.

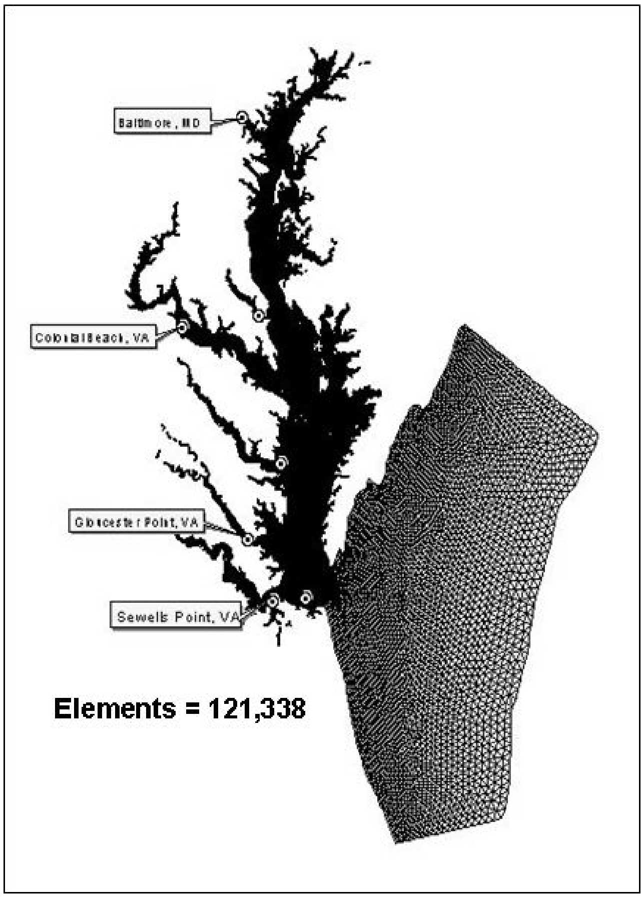

Figure 2. Modeling domain of Chesapeake Bay and the adjacent coastal water using a high-resolution unstructured grid.

used for the convective terms and the semi-implicit, finite-difference method for treating 3-D equations [3]. Due to the E-L transport scheme, the model time step is not restricted by the CFL condition; thus, the high-resolution model grids can represent large model domain without reducing computational efficiency. Zhang et al. [4] provide a detailed description of ELCIRC.

For this study, the wind and atmospheric pressure model implemented is the SLOSH (Sea, Lake, and Overland Surge Hurricane) wind model developed by the U.S. National Weather Service [5, 6]. The wind and atmospheric pressure fields are generated based on the parameters of atmospheric pressure drop and radius of maximum wind speed. The pressure along with wind speed and direction are computed for a stationary, circularly symmetric storm using the balance of forces along a surface wind trajectory and normal to a surface wind trajectory. The governing equations for the wind model are as follows:

$$\frac{1}{p_a}\frac{\partial p}{dr} = \frac{k_s V^2}{\sin\Phi} - V\frac{dV}{dr} \tag{1}$$

$$\frac{1}{p_a}\frac{\partial p}{dr}\cos\Phi = fV + \frac{V^2}{r}\cos\Phi - V^2\frac{d\Phi}{dr}\sin\Phi + k_n V^2 \tag{2}$$

where r is the distance from the storm center, $p(r)$ is the pressure, p_a is the central pressure, Φ is the inflow angle across circular isobars toward the storm center, V is the wind speed, f is the Coriolis parameter, and k_s and k_n are friction coefficients. The wind speed profile for a stationary storm is described as:

$$V(r) = V_M \frac{2(R_M)r}{R_M^2 + r^2} \tag{3}$$

where V_M is the maximum wind speed and R_M is the radius of maximum wind. The derived hurricane wind and pressure fields are obtained by substituting the stationary wind profile specified in (3) into (1) and (2) and solved by an iterative method.

MODEL ANALYSIS OF SURGE DYNAMICS

The model was spun up initially for five days from a quiescent condition and then the five-day, real-time simulation was started. The forcing functions used were pressure and wind forcing obtained from the parametric wind model, along with nine astronomical tidal components obtained from the ADCIRC database [7] at the open boundary. The storm tide, which consists of elevation changes induced by astronomical tide and the wind combined, was obtained first. A second run was then conducted with only astronomical tide forcing (without wind forcing); the results include only elevation changes induced by the astronomical tide. The storm surge, defined as the water level change induced exclusively by wind, was obtained by subtracting the astronomical tide component

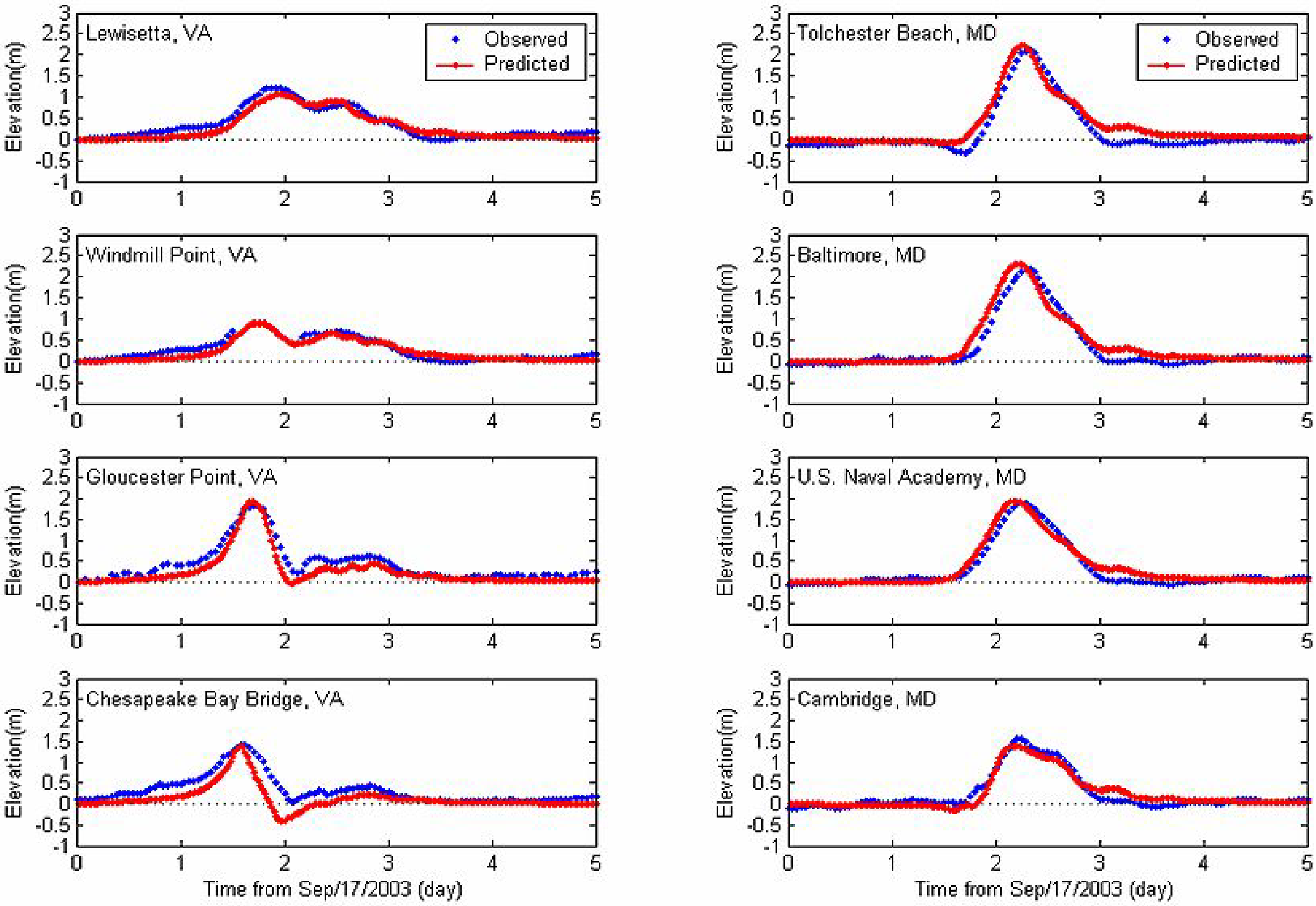

Figure 3. The observed versus modeled storm surge during Hurricane Isabel.

from the total water surface elevation from the first simulation. A similar procedure was used for obtaining observed storm surge data. Figure 3 presents the observed versus model-simulated storm surge during Hurricane Isabel in the Chesapeake Bay. The left panel starts with the southernmost station at CBBT and extends north through Gloucester Point, Windmill Point, and Lewisetta in Virginia. The right panel continues the sequence through the Maryland portion of the Bay, including Cambridge, the U.S. Naval Academy, Baltimore, and Tolchester Beach. The comparison of model-simulated results with observations was quite good for most stations north of Windmill Point. For the Gloucester Point and CBBT stations near the Bay mouth, the model caught the peak of the surge and the trend of the forerunner, but under-predicted the water level during the relaxation period of the storm. This situation appears to be influenced by continental shelf processes and requires further investigation. Despite the discrepancy, the existing model results are sufficiently accurate for use in analyzing the fundamental property of storm surge dynamics.

Temporal Variation of the Surge

Storm surge occurs as a long wave in which the amplitude and phase change continuously in time and space. The simplest way to start the analysis is by simultaneously examining the time series for stations along the mainstem Bay. Twenty stations, separated by approximately equal distances, were selected (Figure 4). The time series for each station was saved from day 1 (00:00 on 18 September) through day 3.5 (12:00 on 20 September) using 00:00, 17 September 2003 (EDT) as the common time origin. They are then plotted jointly on an elevation versus time graph (Figure 5).

The figure indicates that the first major surge, the primary surge, appeared at about 14:00 on 18

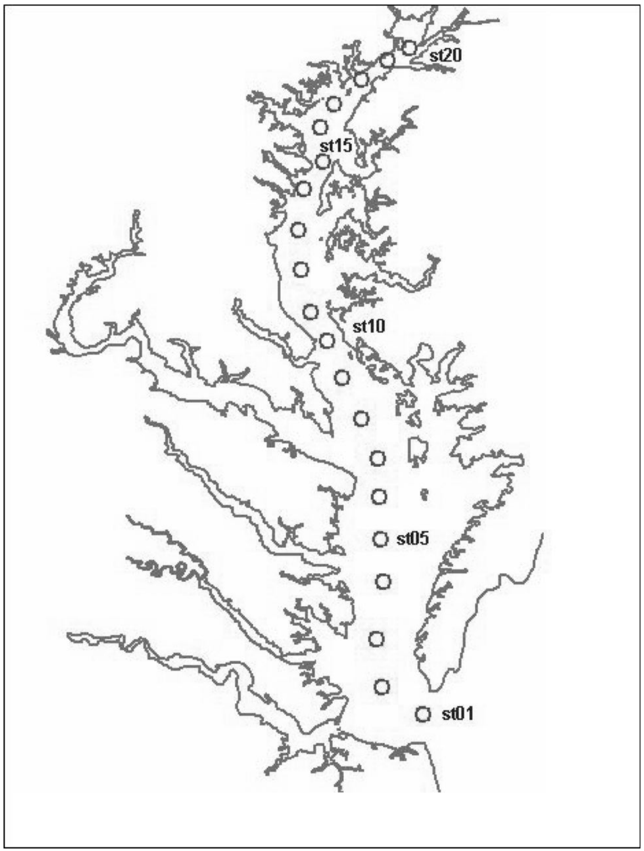

Figure 4. The locations of 20 stations in the Chesapeake Bay model domain selected for storm surge analysis.

September at CBBT with a predicted height of approximately 1.5 m. The amplitude of the primary surge decreased as it propagated northward until it reached the fourth station near the mouth of the Rappahannock River. The amplitude then increased monotonically toward the northern Bay until reaching 2.5 m (modeled) at Tolchester Beach. In terms of temporal variation, the first three stations in the lower Bay responded differently from the remainder of the 17 stations in that the surge for the former stations dropped rapidly and fell below MSL. Their high-water duration, using the 75th percentile as a measure, lasted only for a half day. In contrast, the fourth to twelfth stations in the middle portion of the Bay displayed a much longer high-water duration, exceeding one full day.

Spatial Variation of the Surge

A snapshot of the spatial distribution of water elevation spanning the entire Bay can also be obtained using the previously assigned 20 stations. Figure 6 shows the spatial curves plotted with time intervals of 4 hours starting at 08:00 September 18 and ending at 20:00 on 19 September. From the 12:00 and 16:00 18 September curves, the first-stage surge (primary surge) can be clearly identified in the lower Bay. The next three profiles, namely 20:00 on 18 September, 00:00 on 19 September, and 04:00 on 19 September, revealed that a linear trend of setup in the upper Bay and set-down in the lower Bay was evident with use of a 0.5 m water level as the benchmark mean sea level (see *The Combined Effects* section below for further explanation). The slope of the elevation at 08:00 on 19 September—a fully developed setup—was verified by a steady-state, analytical formula balanced between the hydrostatic pressure gradient and the wind stress (less than the bottom stress). A linear slope of 2.1 m over a 250-km horizontal distance was estimated using a wind speed of 15 $m \cdot sec^{-1}$ and a water depth of 6 m, not much different from the actual observation of 2.4 m at Tolchester Beach.

Careful examination of the 20:00 18 September, 00:00 19 September, and 08:00 19 September curves revealed a pair of wave crests (marked by the arrows) separated by 50 km moving northward. The advancing front in the upstream side toward the upper Bay is the primary wave, which was followed by the second-stage surge generated by southerly wind-induced setup. Eight of nine spatial elevation curves intersect through the Windmill Point station, where the setup and set-down are separated; the elevation there maintains a small variation at approximately 0.5 m above MSL. At 08:00 on 19 September, about 16 hours after the first-stage surge appeared at the Bay mouth, the elevation in the upper Bay finally reached the highest level at 2.5 m and retreated thereafter.

The Combined Effects of Primary Surge and the Wind-induced Setup and Set-down

Based on the description in the previous section, at least two processes were involved in the evolution of the storm surge: namely, the primary surge and the second-stage surge by the southerly

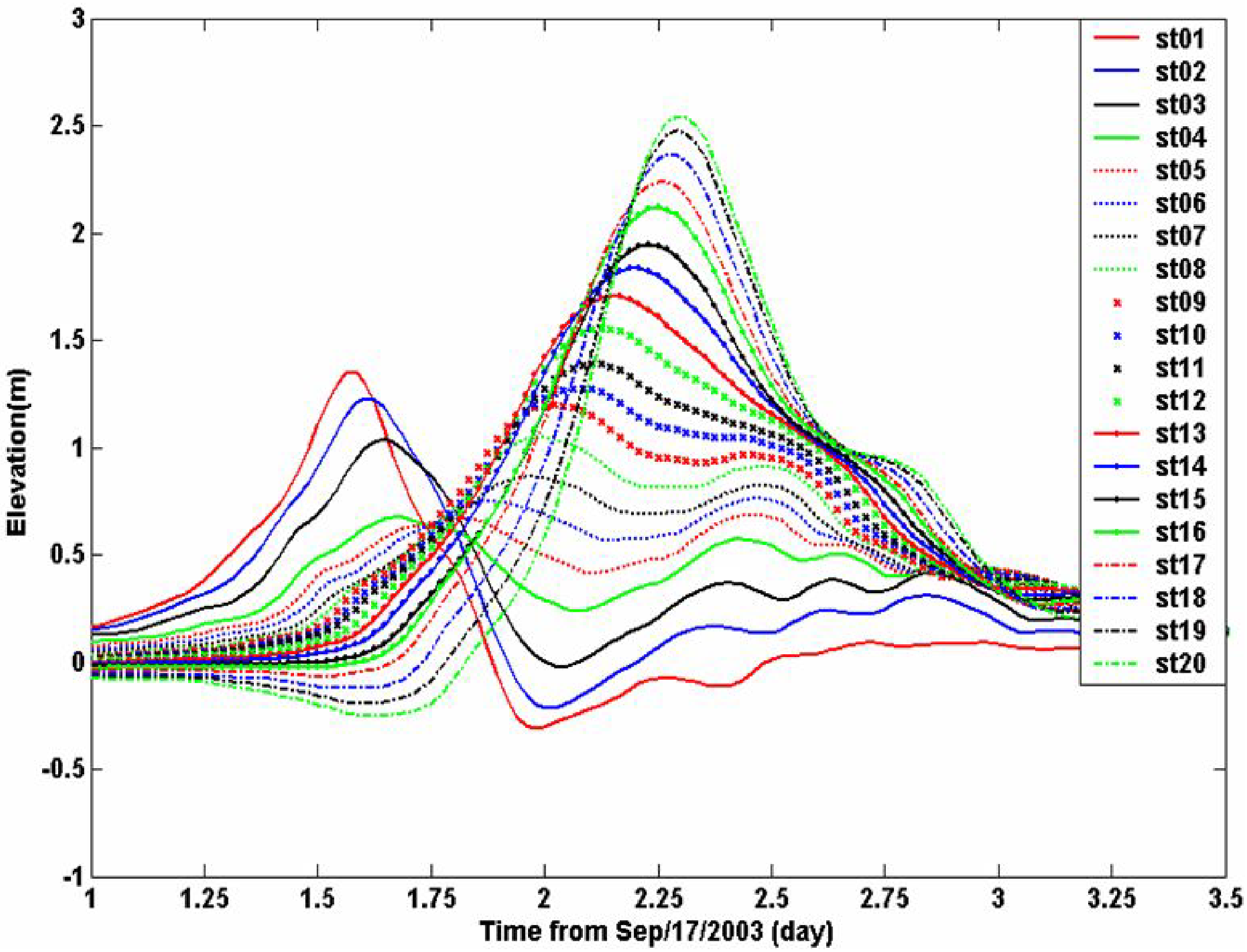

Figure 5. Elevation versus time shown for stations 1 through 20.

wind-induced setup/set-down. Figure 7 shows a distance-time (x-t) plot with isolines contouring surge height. In this x-t diagram, a time history of elevation can be plotted by recording the contour along x_i = constant line at any specific location x_i. If two records are taken synchronously, a characteristic curve (also called a wave ray—the path in which the wave propagates) can be obtained by connecting similar phases (e.g., crest to crest or trough to trough) between the two records. The underlying purpose is to determine the path of the wave ray and the associated phase speed, by using the relationship dx/dt = c (x,t) in the x-t plane, where c is the wave speed.

Starting at x = 0, day = 1.6 day, the first wave ray curve was determined by tracing through the crests of the primary surge; the phase speed was established by its slope as 5.2 $m \cdot sec^{-1}$. The second wave ray curve at x = 0, day = 2.0 was determined by the troughs of the set-down process at a phase speed of 7.6 $m \cdot sec^{-1}$. Similarly, at x = 285 km, day = 2.3 in the upper Bay, the third wave ray curve was obtained at crests with a speed of 6.4 $m \cdot sec^{-1}$. If all three wave rays are plotted on a single x-t diagram, the two from x = 0 merge into the one from x = 285 km (see shaded areas in Figure 7). Physically, this means that the surge wave induced by the setup/set-down process has a higher speed and will catch up to the primary surge and become a single, combined surge wave in the upper Bay.

From shallow-water wave theory, it is well known that when more than one long wave is produced in a non-dispersive condition, one can overtake the other and they combine, continuing as a single wave [7]. Merging of two surge waves causes the wave profile to steepen; the energy of

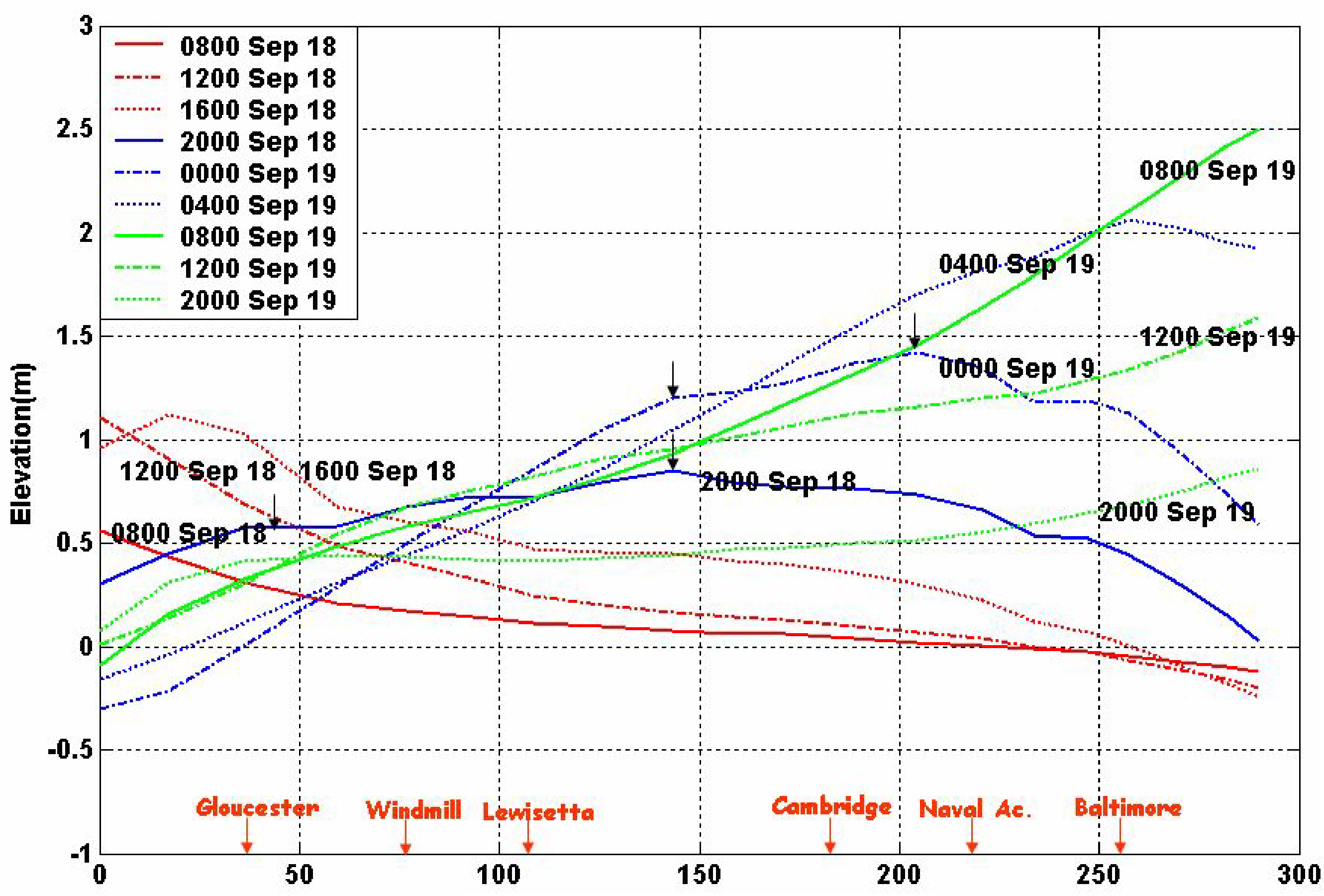

Figure 6. The elevation versus space plot for stations 1 through 20.

the two original waves will refocus and the amplitude of the merged wave increases significantly.

For the mid-Bay region, the time series record along $x_i = 100$ km clearly showed that initially the mean water level was raised by the first-stage primary surge by approximately 0.5 m. After, it stayed above MSL at 0.4–0.6 m throughout the period. The fact that the mean water level can stay above MSL for an extended period suggests that the mid-Bay region must have a net influx of water to compensate for the outflux created by the increasing elevation gradient. A model simulation with and without southerly winds (figure not shown) demonstrated that the prolonged southerly wind after Hurricane Isabel was responsible for the influx of water into the region. The water level in mid-Bay also exhibits a smoother and smaller temporal variation as compared to the lower Bay. Given that the primary surge and the second-stage surge were generated separately (about 6 hours apart), the two waves are certain to have an intrinsic phase lag as they propagate out of the lower Bay. This lag could have created the destructive wave interference in the mid-Bay due to the effect of amplitude modulation. Other mechanisms are possible and should be investigated further.

CONCLUSIONS

A high-resolution, unstructured grid hydrodynamic model (ELCIRC) along with a parametric gradient wind model was applied to simulate storm surge in the Chesapeake Bay during Hurricane Isabel. Good agreement between the model-simulated water level and the real-time observed data was obtained at various sites in the Bay. The model was used further to conduct diagnostic studies for surge dynamics. Several lessons were learned from the analysis of surge dynamics and are summarized as follows:

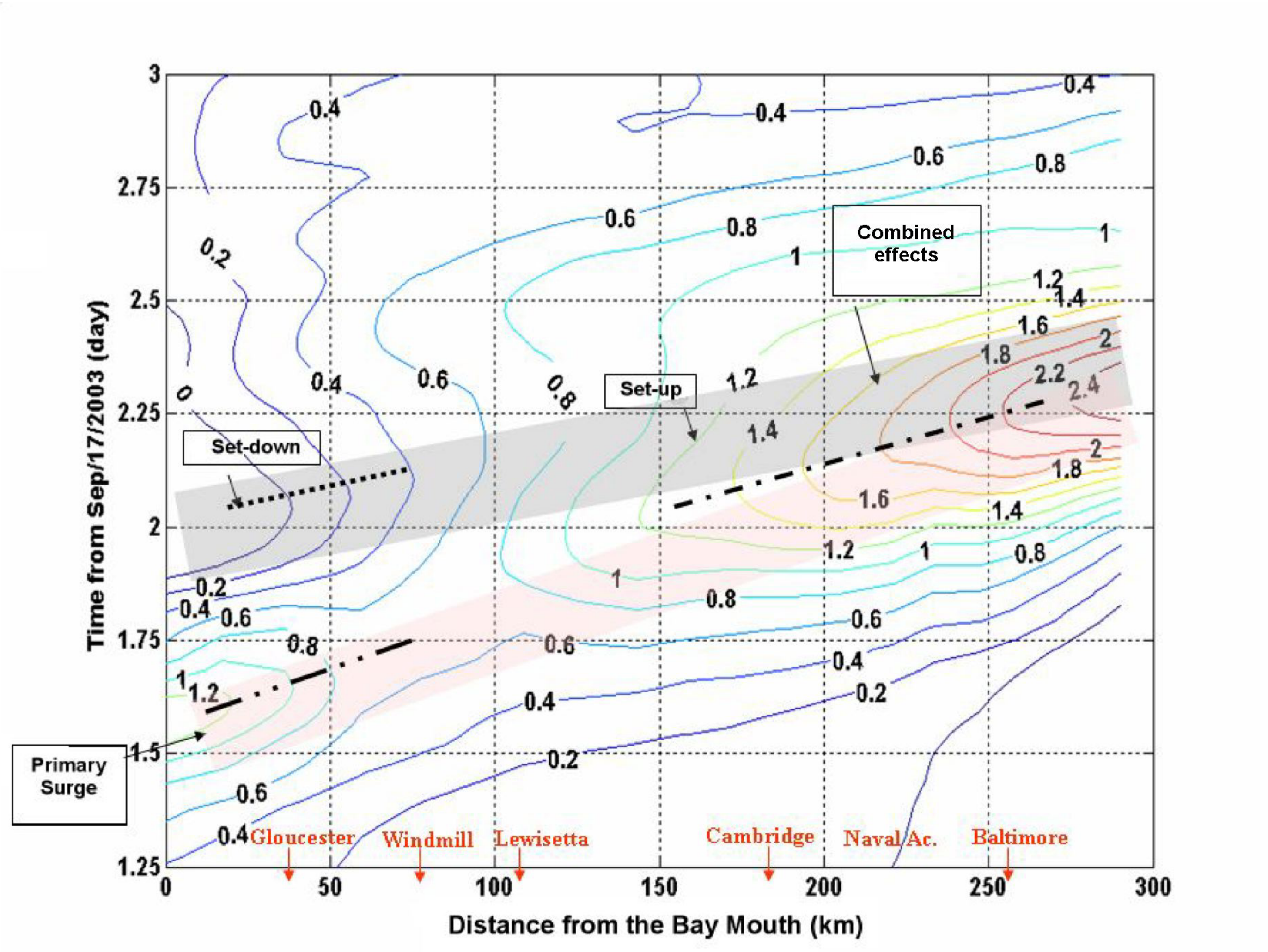

Figure 7. The space versus time plot for stations 1 through 20

1) The evolution of the surge occurred in two stages. In the first stage, the primary surge was generated by the far-field wind from both the north and the east pumping coastal water into the Bay. In the second stage, the local southerly wind prevailed and triggered setup in the upper Bay and set-down in the lower Bay.

2) The response of the Bay differed in the regions south and north of Windmill Point, Virginia. South of Windmill Point, water level variation had a short-lived, high-water stage because wind-induced set-down tended to cancel the effect of the primary surge. North of Windmill Point, on the other hand, a much larger surge occurred in the upper Bay due to reinforcement of the primary surge wave and southerly wind-induced setup.

3) In the mid-Bay, prolonged high-water duration was explained based on mean water level and its temporal variation. Mean water level was raised about 0.5 m by the primary surge initially and subsequently maintained by the prolonged southerly wind. The relatively small temporal variation was due to the destructive physical effects of wave interference when the two waves were superimposed with their intrinsic phase lag. The question of whether the amplification of the surge could be due to the resonant interaction between the long wave and the atmospheric forcing is an interesting one, but beyond the present scope of work.

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