PHYSICAL RESPONSE OF THE YORK RIVER ESTUARY TO HURRICANE ISABEL

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ABSTRACT

After making landfall on the North Carolina coast on the morning of 18 September 2003, Category 2 Hurricane Isabel tracked northward parallel to and slightly west of the Chesapeake Bay. At Gloucester Point, near the mouth of the York River estuary, strong onshore winds with speeds in excess of 20 $m \cdot s^{-1}$ persisted for over 12 hours and peak winds reached over 40 $m \cdot s^{-1}$, causing a sustained up-estuary wind stress. Storm surge exceeded 2 m throughout most of the lower Chesapeake Bay. A 600 kHz acoustic Doppler current profiler (ADCP), deployed at a depth of 8.5 m off Gloucester Point, provided high-quality data on waves, storm surge, currents, and acoustic backscatter throughout the water column before, during, and after the storm. Pressure and salinity sensors at three additional sites further up the estuary provided information on water surface slope and saltwater excursion up the estuary. A first-order estimate of three terms of the along-channel momentum equation (barotropic pressure gradient, acceleration, and friction) showed that the pressure gradient appeared to be balanced by the wind stress and the acceleration during the storm. The storm's path and slow speed were the primary causes of the extremely high storm surge relative to past storms in the area.

INTRODUCTION

Hurricane Isabel caused extensive flooding in many parts of the Chesapeake Bay region, including the York River estuary. This flooding was partially due to the slow speed of the storm as it moved north and west of Chesapeake Bay, causing high winds (greater than 25 $m \cdot s^{-1}$) for almost 10 hours in the York River estuary. Strong onshore winds and storm-associated rain runoff contributed to a storm surge that equaled or exceeded the surge experienced during the hurricane of 1933. As a result, this storm was labeled as a "hundred-year" event in the region.

The York River is a sub-estuary of the Chesapeake Bay, located on the western side of the Chesapeake about 50 km from the Bay's mouth. It is a partially mixed estuary and generally exhibits a fortnightly stratification-destratification cycle [1, 2]. The river is approximately 50 km in length from the mouth to West Point where it splits into the Pamunkey and Mattaponi rivers. A constriction and bend in the river occur at Gloucester Point, approximately 10 km from the mouth. Here, orientation changes from east-west in the lower river to southeast-northwest in the upper river (Figure 1). At Gloucester Point (GP), the typical spring tide maximum currents are 0.9 $m \cdot s^{-1}$ and neap tide maximum currents are 0.7 $m \cdot s^{-1}$. The usual tidal range here is 0.5 m (neap) to 1.0 m (spring) [1]. This paper describes the response of the York River estuary to the local winds and storm surge caused by the hurricane.

MATERIALS AND METHODS

Several instruments already deployed in the York River and at the Bay mouth were used in conjunction with an acoustic Doppler current profiler (ADCP) deployed specifically to capture the storm event. This suite of instruments was used to measure water levels, water currents, salinity and

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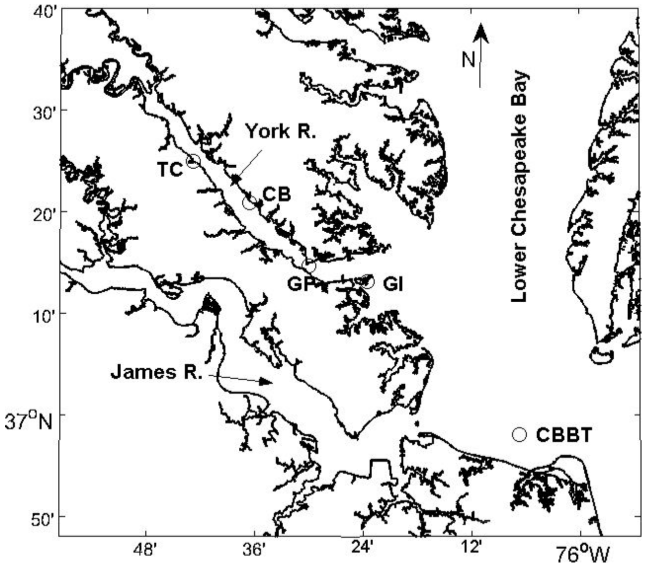

Figure 1. Site map of observation stations in the lower Chesapeake Bay and York River. Stations are marked with an "o." Abbreviations are defined in the text.

temperature, and meteorological conditions in the York River before, during, and after the passage of Hurricane Isabel. These data were supplemented by wind data obtained from airports in Yorktown and Portsmouth, Virginia, at the Chesapeake Bay Bridge Tunnel (CBBT), and at the Virginia Institute of Marine Science (VIMS).

The 600 kHz RDI ADCP was deployed at Gloucester Point from 16 to 25 September 2003. Velocity data were collected in 0.50 m-depth bins starting 1.8 m above the bed. The water depth minus 10% was the limit used for the topmost bin. The water depth varied between 8 and 10 m. A 1-minute average velocity profile was collected every 5 minutes. The ADCP was also configured to measure directional wave spectra: 10-minute bursts sampled at 2 Hz were collected every hour for the estimates of wave height, period, and direction. Velocity data from the ADCP were rotated to an along- and across-channel orientation based on the direction that maximized the velocity variance [3]. Backscatter intensity data from the ADCP were range-corrected and converted to relative concentrations of suspended solids for both time and depth comparisons.

The water level at Gloucester Point was tracked during the storm by a NOAA tide gauge at this location until the NOAA gauge was washed away at 15:36 EDT on 18 September. The pressure sensor on the ADCP, however, provided a complete record of water level estimates throughout the storm. After the hurricane, the ADCP pressure gauge was adjusted to height above MLLW using the NOAA gauge for the 30 hours that both instruments were operational. A further correction for atmospheric pressure based on barometric pressure from a weather station in Portsmouth, Virginia was made to the ADCP water level record. Additional water level information was obtained from a NOAA tide gauge at the CBBT and at the Chesapeake Bay National Estuarine Research Reserve (CBNERR) gauges at Clay Bank (CB) and Taskinas Creek (TC) (Figure 1). The NOAA gauges at the CBBT and at GP are referenced to NAVD88; for this study, both were adjusted to MLLW at GP.

Temperature, salinity, turbidity, and other water quality parameters were obtained every 15 minutes from YSI-6600 sondes at fixed stations at GP, CB, and TC maintained by CBNERR. Only the first three parameters will be discussed in this paper. Additional water column structure information was obtained on 16 September and 2 October 2003 from surveys up the river using a Falmouth Scientific CTD mounted on a Sea Sciences, Inc., Acrobat undulating tow body. This instrument allows data to be collected while the vessel is moving at speeds up to 4 m·s^{-1}, allowing a 20-km section of the polyhaline region of the York River to be sampled in under 2 hours and presenting a near-synoptic view of its water column properties.

RESULTS AND DISCUSSION

Wind data from the Chesapeake Bay Bridge Tunnel show the effects of the storm passing to the west of the Bay. During the storm, the wind changed direction from northeasterly to southeasterly. The strong southeasterly winds (Figure 2) during the latter part of the storm forced a large surge of water up the Bay and its tributaries. In the York River, this surge peaked at 1.86 m in height at 16:09 EDT on 18 September 2003 (Figure

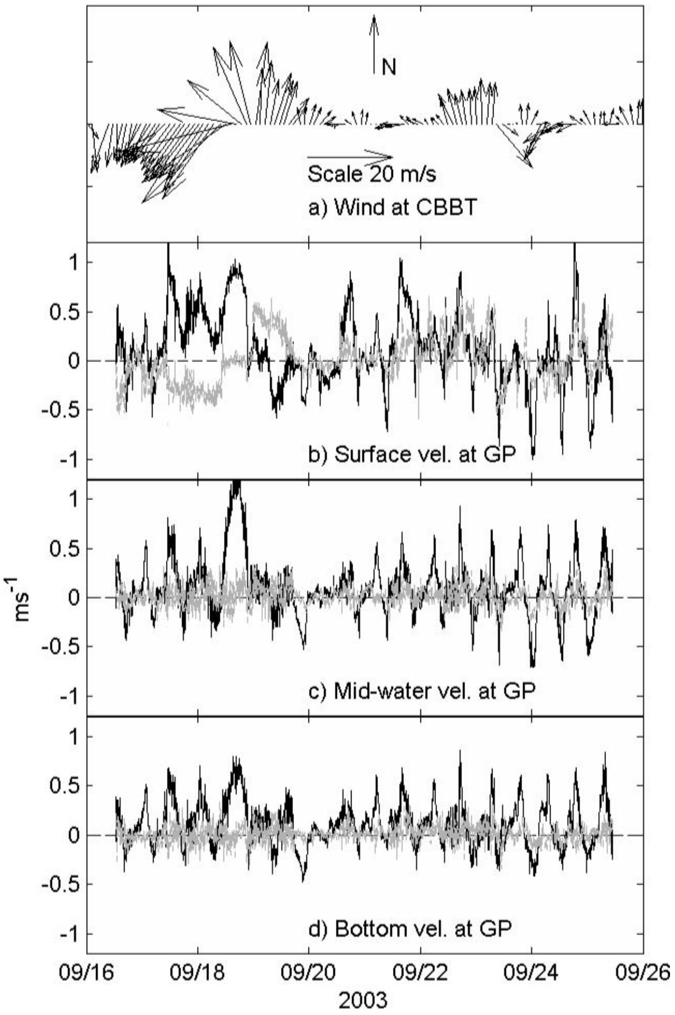

Figure 2. Surface wind data from the CBBT in Panel a shows the rotation and speed of the wind generated by Isabel (wind convention is the direction the wind is blowing towards). Panels b, c, and d show water velocities for surface, mid-water, and bottom depths from the ADCP at GP. Black lines represent along-channel flow with positive toward the west (upriver); gray lines are across-channel flow with positive toward the north (across river).

3). The maximum wave height occurred at 17:38 EDT, and the astronomical tides were at a maximum at 15:31 EDT (Figure 3). The nearly coincident times of high water and the surge and wave effects from the storm resulted in more destructive damage to piers, homes, and waterfront property along the York River compared to damage recorded for either Tropical Storm Agnes or the hurricane of 1933 [5]. Isabel occurred during the last quarter moon; consequently, the astronomical tide was lower than maximum. Had the storm occurred a week later, overall flooding damage from the storm could have been worse. The effects from the wind-induced surge and waves were seen throughout the Chesapeake Bay and many of its sub-estuaries. The location and orientation of the York River sub-estuary made it especially susceptible to wind effects during the height of the storm.

Both the constriction and bend in the river at GP force water velocities into more complicated interactions than the more rectilinear flows evident farther up the river at CB [4]. The ADCP at GP was located on the north side of the channel in about 8.5 m of water. The along-channel rotated velocity

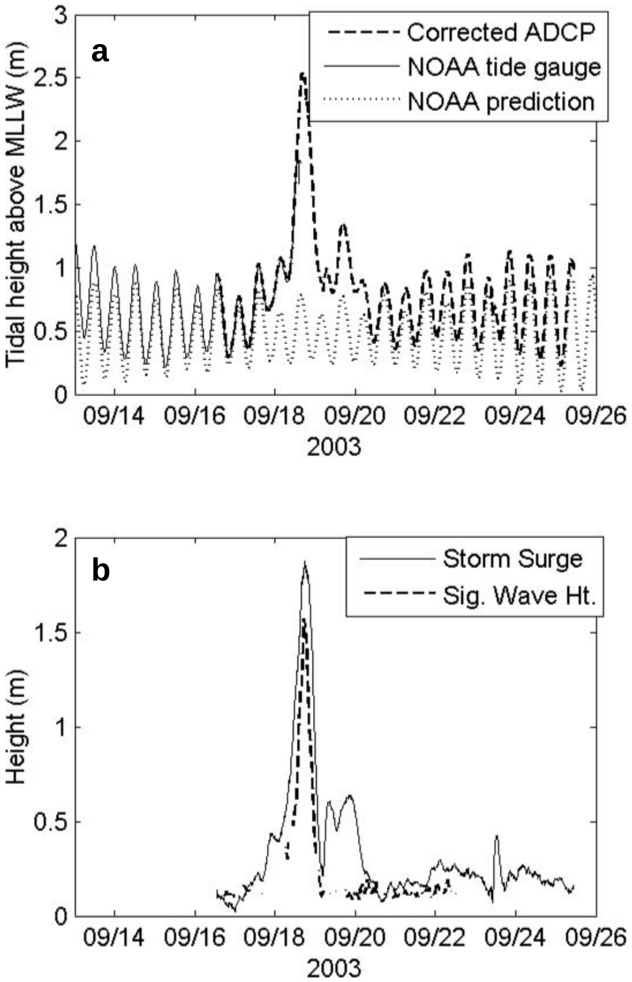

Figure 3. Panel a: comparison of predicted tidal elevation and observed water level at Gloucester Point from NOAA's destroyed tide gauge and the ADCP pressure record. Panel b: storm surge above astronomical tides and significant wave height (Hs) at Gloucester Point.

coincided with the east-west orientation of the river downstream of GP. Across-channel velocities were rather large in the surface bins, especially during the first hours of the storm when the wind did not blow straight up the river (Figure 2). When wind velocities were maximal, however, the dominant direction compared favorably with the alignment of the York River just below GP and, therefore, amplified the surface currents in the along-channel direction.

Due to this congruence, the surface water velocity showed an entirely along-channel orientation for a time. Both before and after this time, the surface water was not flowing directly up the river as it was partially realigned by the strong winds of the storm that were not in line with the channel. The quick reaction of the surface water velocity to the changing wind direction has been observed in the York River and similar estuaries both during the storm and at other times of high winds [5, 6].

The tidal signal in both the water level and the water velocity was completely dominated by the wind-driven flow for the duration of the storm; as a result, normal ebb tides were not seen for over 12 hours. A mid-depth velocity maximum was also observed during this time (Figure 2), which may have been caused by the changing wind direction slowing the along-channel surface currents or by the underlying tidal and gravitational forces. Before and after the storm, the semidiurnal tide showed a clear, strong signal, especially towards spring tide on 25 September (Figure 2). The maximum water velocity during the storm was 1.0 $m \cdot s^{-1}$ at the surface and 1.6 $m \cdot s^{-1}$ at 4 m depth, almost twice the maximum spring tide values. Also of interest is the rebound of the currents on the day after the hurricane, as the ebb tide was much stronger than the flood tide to accommodate relaxation of the forcing after the winds abated.

The ADCP measured waves with significant wave heights (Hs) of 1.6 m (Figure 3) and maximum wave heights ($H_{1/10}$) of 2 m with an average period of 5 sec. The dominant wave direction was consistent with the orientation of the channel below GP. Typical waves in the York River estuary have a significant height of 0.1– 0.3 m and a period of 1–3 sec.

Water temperature, salinity, and turbidity observations from the GP, CB, and TC CBNERR stations within the York River sub-estuary also showed the effects of Isabel's passage. The influx of cooler Bay stem water into the estuary caused a pronounced drop in water temperature in the estuary during the storm and a rebound effect in the following days, especially up the estuary. During the storm, the longitudinal salinity gradient was reduced between GP and TC, primarily due to the more dramatic rise in salinity further from the estuary's mouth (Figure 4). After the storm, salinity throughout the system was reduced due to the freshet associated with rainfall within the catchment basin and to the re-equilibration of the York River following the storm surge. After Tropical Storm Agnes in 1972, sub-estuaries of the Chesapeake Bay took almost 2 months to increase to typical salinity levels [5]. Surface and bottom salinities from two neap tide cruises up the thalweg of the York River from its mouth (GI on Figure 1) almost

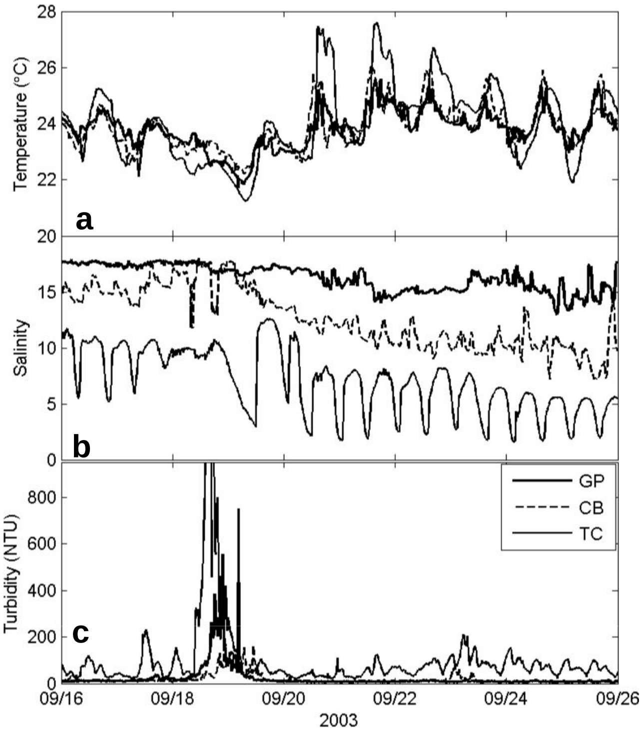

Figure 4. Temperature, salinity, and turbidity observations from fixed, near-bottom sondes maintained by CBNERR Virginia.

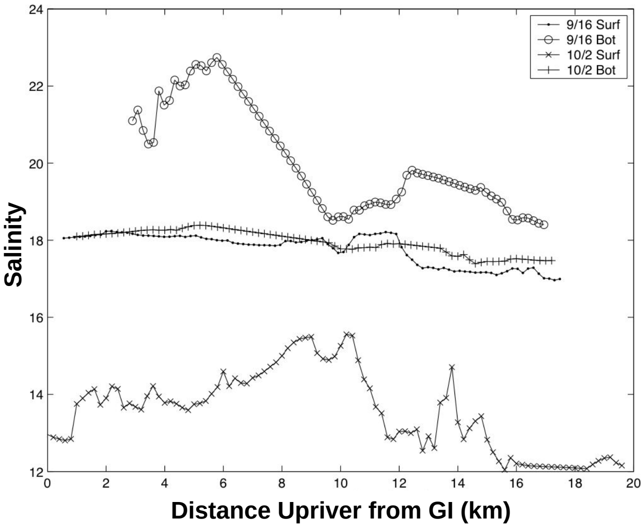

Figure 5. Surface and bottom salinity values for the York River from GI at the mouth to CB. Measures were taken with an Acrobat undulating CTD profiler on 16 September and 2 October 2003. Note the overall lower salinity in the estuary several weeks after the storm's passage, even though stratification had returned.

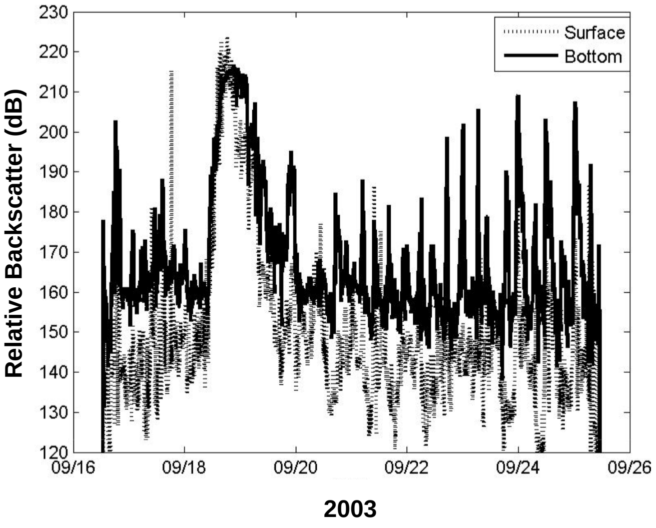

Figure 6. Relative backscatter as recorded by the ADCP for bottom and surface bins.

to CB on 16 September and 2 October 2003 showed depressed salinities in both surface and bottom water that persisted two weeks after the storm passed, although stratification had returned (Figure 5). No water column measurements were taken during or just after the storm due to the destruction of piers and lack of available research vessels at that time. Other evidence, such as the ADCP backscatter record, suggests near-complete mixing.

The ADCP backscatter signal can be used as a proxy for suspended solids in the water column under certain conditions [7]. Figure 6 shows the near-surface and near-bottom backscatter measurements during ADCP deployment. The near-surface values were taken from about 2 m below the surface to reduce the spurious signal caused by breaking waves. Bubbles throughout the water column are another source of contamination; however, it is impossible to separate the bubbles from other internal signals that contribute to the backscatter without ancillary information from other instruments.

The backscatter signal during the storm, therefore, can only be evaluated for suspended solids in a qualitative sense. Before the storm, the surface values were consistently lower than the bottom values, reflecting the resuspension of sediment in the water column from the bed.

During the storm, the relative backscatter increased dramatically and the surface values equaled the bottom values, indicating probable increased suspended solids throughout the water column, despite the bubble contamination. The forces necessary to suspend sediment uniformly from bottom to surface were sufficient to mix the water column completely during the storm and into the following day. The surface backscatter signal also indicates that the higher levels of suspended solids in the water column did not return to pre-storm levels for at least a week following passage of the storm. Turbidity observations from the fixed stations show a similar trend (Figure 4c) and also indicate that higher levels of suspended matter were found farther up the sub-estuary during Isabel.

A simple longitudinal momentum balance (Equation 1) was calculated using wind data from the CBBT, linearly calculated surface slope from water levels at GP and the CBBT (about 45 km apart), and the along-channel acceleration measured by the ADCP at Gloucester Point.

$$\frac{\partial u}{\partial t} + g\frac{\partial \eta}{\partial x} = \frac{(\tau_s - \tau_b)}{\rho_w h} \qquad (1)$$

In Equation 1, g is gravitational acceleration, t is time, h is mean water depth (10 m), x is distance

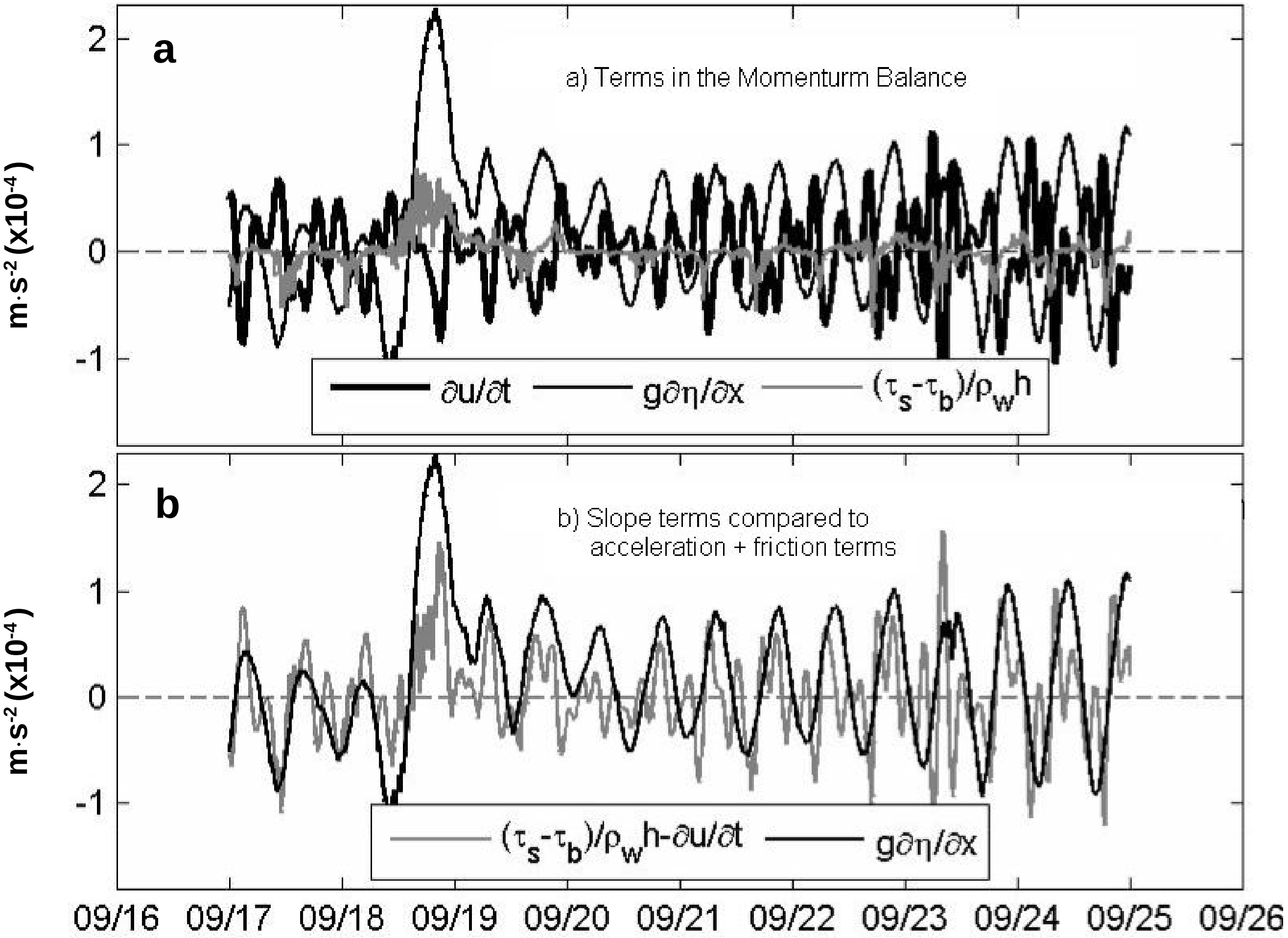

Figure 7. Panel a shows the three main terms in a simple-along channel barotropic momentum balance between acceleration, surface slope, and friction. Panel b shows the balance between the slope term and the acceleration and friction terms combined. To do this, the acceleration term is moved to the right hand side of Equation 1.

along the estuary, u is up-estuary velocity and h is the surface slope. The surface stress (t_s) was estimated using the wind stress calculated as $\tau_s \approx \rho_{air} C_{D(air)} U_{10}^2$where air density ($\rho_{air}$) and the drag coefficient ($C_{D(air)}$) were assumed to be constants (1.25 kg·m^{-3} and 0.01, respectively) and the wind velocity at 10 m (U_{10}) was estimated from the wind recorded at the CBBT. The bottom stress, $\tau_b \approx \rho_w C_{D(water)} U_b^2$ was estimated in a similar fashion, where U_b, the bottom velocity, was estimated from the lowest ADCP bins and water density (ρ_w) and drag coefficient ($C_{D(water)}$) were assumed to be constants of 1010 kg·m^{-3} (reflecting a mean salinity of 17 and a mean temperature of 26º C) and 0.001, respectively.

The slope term represents the barotropic pressure gradient and is the signal representative of the storm surge. The magnitude of this term is about 2.5 times the other two terms during the height of the storm (Figure 7a), and nearly balances the combined acceleration and friction terms (Figure 7b). Some of the variability in this balance arises from the tidal phase difference between the two locations. It is also likely that the friction term is underestimated throughout the passage of Hurricane Isabel since the drag coefficient for wind increases with increasing wind velocity [8]. The bottom stress term, while possibly underestimated, is likely to have remained relatively stable as compared to the surface stress, since the wind increase was at least an order of magnitude greater, while the water velocity increase was not nearly as large.

CONCLUSIONS

Near the mouth of the York River, the local storm surge from Isabel was 2 m and the maximum wave height ($H_{1/10}$) was also 2 m with a peak period of 5 sec. At this location, currents at all levels flowed up estuary without reversal for approximately 12 hours. Near the peak of the storm, the magnitude of the water velocity exceeded 1 $m \cdot s^{-1}$ at all depths with the maximum velocity occurring 4 m below the surface. After the storm passed, water levels and velocities did not return to normal for over 24 hours. Horizontal and vertical salinity gradients and absolute values were affected by the storm both during and for some time after, showing a reduction of the local salinity gradient, an increase in salinity during the storm, and a decrease in salinity after the storm that persisted for several weeks. This outcome is similar to the response of the Chesapeake Bay and its sub-estuaries after Tropical Storm Agnes in 1972 [5]. Backscatter and turbidity measurements provide evidence for full mixing of the water column and a greatly increased suspended sediment concentration during the storm that persisted for over 24 hours. The surface slope term in the momentum balance appeared to be almost balanced by wind stress and acceleration terms, although further refinement is necessary, especially in estimating the friction term. The destructive force of Hurricane Isabel in the York River estuary was directly related to the duration of the up-estuary winds and the concurrent high water and relatively long period and large waves. The effects from the storm's passage were evident in salinity and temperature observations in the weeks following the storm.

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