Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay

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[1] Semi-enclosed bays and estuaries are usually protected from hurricane-generated storm surges. When a hurricane travels on the land side, however, it may induce high storm surges, strong currents and destratification in the water column. Real-time observations and numerical model prediction both show a slab-like sloshing in Chesapeake Bay when it was hit by Hurricane Isabel in September 2003. Strong southeasterly winds in the right front quadrant of the storm forced water in Chesapeake Bay to move northward as a single layer, producing high sea levels and flooding in the northern Bay region including Baltimore and Annapolis. Furthermore, the strong landward winds erased water-column stratification and caused a strong intrusion of high-salinity shelf water into the Bay. After Isabel's passage, the longitudinal salinity gradient produces restratification and two-layer circulation in the Bay. **Citation:** 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.

1. Introduction

[2] U.S. East and Gulf Coasts are incised by a number of semi-enclosed bays and estuaries where many metropolitan cities are located. These coastal water bodies support highly productive marine ecosystems. Depending on their orientation and location, their enclosed reaches may either increase or decrease their vulnerability to tropical cyclones (TCs). For the Chesapeake Bay, the normal offshore passages of TCs and the north-south orientation of the channel create the situation in which the northerly winds from TCs drive water out of the Bay. In contrast, when a TC passes on the land side, the confined nature of the bay becomes a liability and storm surges may exceed those on the open coast. This shift from protection to vulnerability arises because the southeasterly winds in the northern semicircle of a TC blow water into the bay and pile it up against the bay's head. This interesting scenario happened on 18 September 2003 when Category 2 Hurricane Isabel made landfall over the Outer Banks of North Carolina and moved poleward on the west side of Chesapeake Bay (Figure 1a), creating widespread flooding in several highly populated areas. To our knowledge, such a scenario has never been documented, and its impacts on storm surges, water quality and marine ecosystems were poorly understood. Although we address the unusual case where the storm departed from the usual offshore pathway and propagated northward on the land side of Chesapeake Bay, it is relevant to the general problem of semi-enclosed bays enhancing storm surges and clearly warrants investigation.

[3] As Hurricane Isabel reached the Chesapeake Bay, an array of tide gauges monitored the storm-surge response. The mid-Bay buoy of Chesapeake Bay Observing System (CBOS) survived the passage of Isabel and provided rare current measurements during a storm surge (see http://www.cbos.org). The trajectory and intensity of Hurricane Isabel as well as all the meteorological fields, including wind stress field over Chesapeake Bay, were well predicted by the Mid-Atlantic Regional Atmospheric Forecasting Model (MM5) at the horizontal resolution of 4 km (see http://www.atmos.umd.edu/~mm5 [*Grell et al.*, 1995]). Furthermore, a new 3D hydrodynamic model, based on the state-of-art Regional Ocean Modeling System (ROMS) [e.g., *Shchepetkin and McWilliams*, 2005], showed considerable skill in predicting the sea level, salinity distribution, tidal and subtidal currents in the Bay [*Li et al.*, 2005]. Thus, Hurricane Isabel's (2003) strike provided an unprecedented opportunity to observe, understand and predict storm surges in Chesapeake Bay. Although models have been developed to simulate storm surges in coastal oceans [*Davies et al.*, 1998; *Jarvinen and Neuman*, 1985], few have been tested about their ability in reproducing observed currents [*Jones and Davies*, 2003]. These models typically ignore the effects of density stratification, but water in estuaries occupies a wide salinity range. While NOAA's SLOSH (Sea, Lake and Overland Surges from Hurricanes) model provides forecasts for storm surges at U.S.'s East and Gulf coasts, including Chesapeake Bay (see http://www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml), the stated model error is about ±20% [*Houston et al.*, 1995]. For low-lying regions, the 20% uncertainty in water level translates into substantial uncertainties in inundation forecasts. Thus, the purposes of this study are to (i) explore the use of high-resolution regional atmospheric and oceanic models to improve the prediction of hurricane-generated storm surges and currents, (ii) gain insight into the barotropic and baroclinic processes in Chesapeake Bay under hurricane-forcing conditions, and (iii) discuss the implications for water quality and marine ecosystem in Chesapeake bay and possible consequences to other semi-enclosed bays and estuaries in today's climate warming era.

2. Storm Surges

[4] Hurricane Isabel travelled northwestward along a nearly-straight line that began three days before landfall and lasted until its eventual dissipation over the Great

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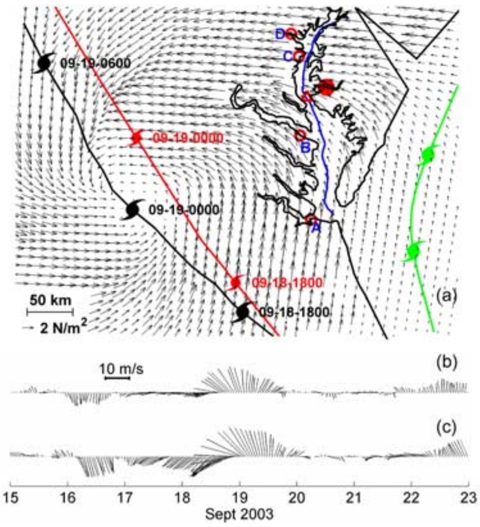

Figure 1. (a) MM5-predicted surface wind stress over Chesapeake Bay at 0000 LST 19 September 2003, superposed by observed (red) and predicted (black) Isabel's track and a hypothetical track for a storm moving on the ocean side of the Bay (green). A blue line along the Bay denotes the Bay's center axis, red open circles are used for tidal gauge stations (A-Hampton Road, VA; B-Lewisetta, MD; C-Annapolis, MD; D-Baltimore, MD), a red triangle for CBOS mid-Bay buoy and a red solid circle for a mid-Bay weather station. Comparison of (b) observed and (c) predicted horizontal wind vectors at the weather station.

Lakes. Since Isabel passed Chesapeake Bay on its west (land) side (see Figure 1a), the dominant wind direction switched from northeasterly to southeasterly. The highest sustained wind in the Bay reached 30.8 m s^{-1} at Gloucester Point, Virginia, with gusts up to 40.7 m s^{-1}. If this storm had moved on the Bay's east side, the wind direction would have switched from northeasterly to northwesterly. This difference in wind direction would lead to dramatic differences in the barotropic response of the Bay, as discussed before. Figure 1a shows that the predicted track is in close proximity to the observed until 0600 LST 19 September when the storm's influence on the Bay starts to diminish. MM5 predicts the observed wind speeds and directions reasonably well (Figures 1b and 1c), especially the switching from the northeasterly to southeasterly during the passage of Isabel. Pronounced differences in wind stress can be seen between land and water surfaces (Figure 1a).

[5] Hourly wind stress field produced from the MM5 model is used to drive the ROMS model configured for Chesapeake Bay. Figure 2a provides a 3D view of the sea-level distribution over the Bay at 0400 LST 19 September. The alignment of southeasterly winds with the long fetch of the lower Potomac River created the largest surge in Washington, DC, which reached 2.7 m above normal high tide. Sea levels in the northern Bay were also rising rapidly at this time. Obviously, Isabel's strong southeast-to-southerly winds blew water into the Bay and piled it against the Bay's head. However, other mechanisms might have also contributed to the high sea levels. The Bay's long-wave propagation speed is of the same order of magnitude as the advancing storm, setting up the possibility of a seiche resonance [*Boicourt*, 2005] which was previously observed

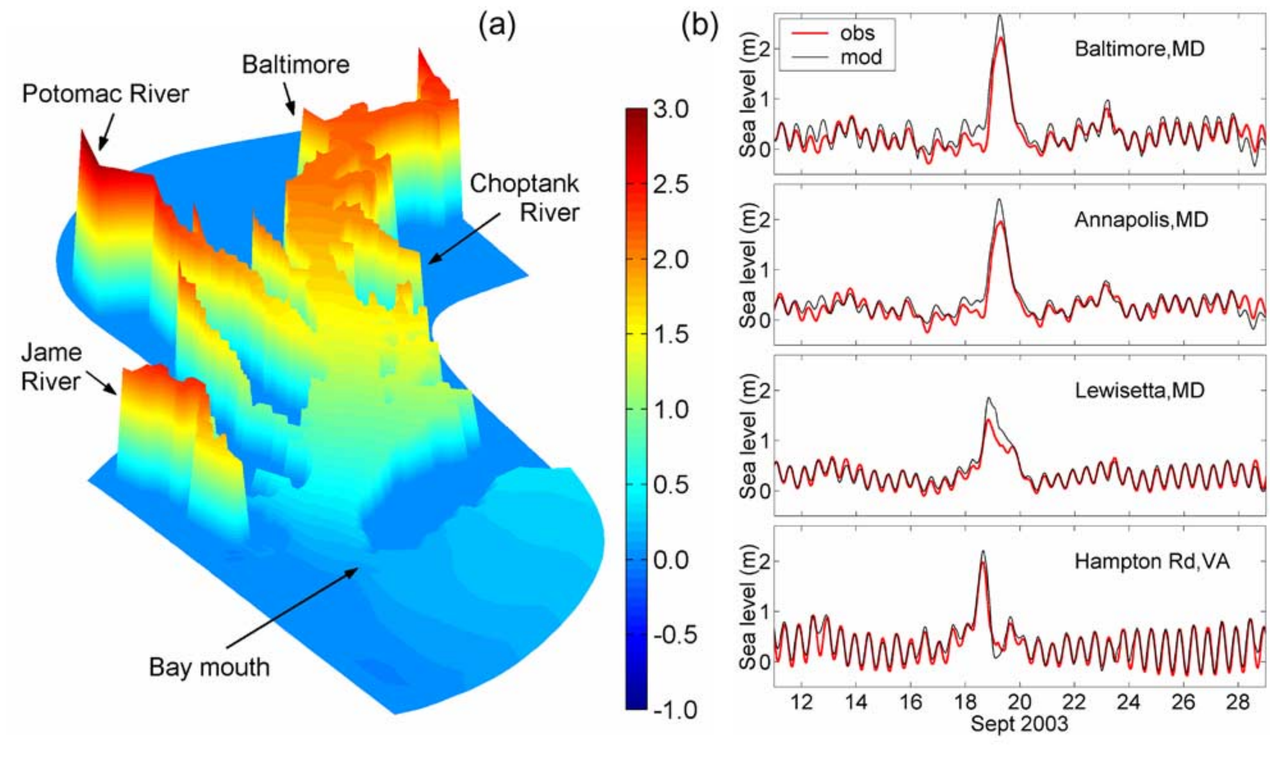

Figure 2. Storm surges in Chesapeake Bay and its tributaries. ROMS-predicted sea-level distribution: (a) a 3D view showing high storm surges in the Potomac River and northern Bay at 0400 LST 19 September; (b) comparison of time series of the predicted (black) and observed (red) sea levels at a few selected tidal gauge stations (given in Figure 1a).

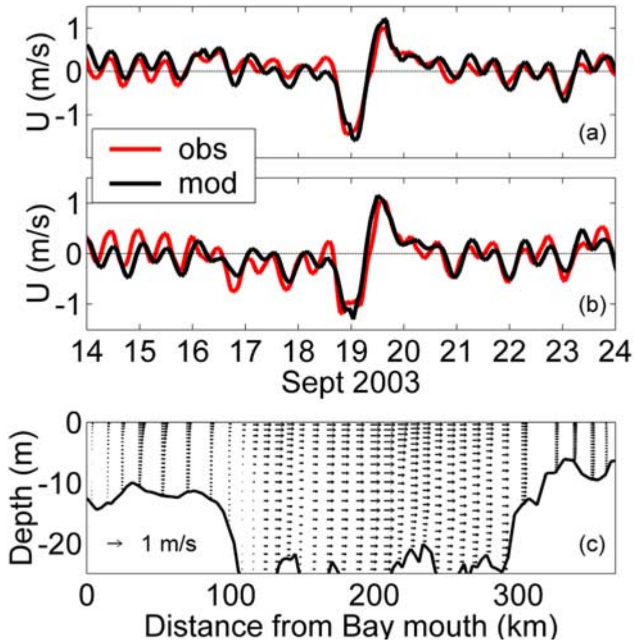

Figure 3. Generation of slab-like sloshing in Chesapeake Bay. Comparison of the predicted (black) and the buoy-observed (red) currents (positive for the seaward direction) at (a) 2.4-m and (b) 10-m depths at CBOS's mid-Bay buoy. The large oscillation seen on 18 and 19 September indicates a bay-wide sloshing generated by Hurricane Isabel. (c) Predicted non-tidal along-channel velocity distribution in a vertical cross section aligned with the center axis of the Bay at 0000 LST 19 September. Tidal velocity component was removed through a 34-hour Lanczos (low-pass) filter.

in the Bay [*Chuang and Boicourt*, 1989]. Although there were two episodes of sea-level depression in the northern Bay on September 16 and 17, they were about 10 cm below the local mean sea level and could not contribute significantly to the sea-level rebound. Therefore, the high storm surges appear to be a direct result of Isabel's strong southerly winds. The observed temporal evolution of sea levels at 4 selected tidal stations was well captured by the model (Figure 2b). The Root-Mean-Square (RMS) error averaged over 8 stations in the Bay is 0.13 m. The model's predictive skill as defined by *Warner et al.* [2005] has a high score of 0.96; a detailed discussion of the model skill will be presented in a forthcoming paper. It is worth noting that the storm surges reached 2.2 m at Baltimore and 2.0 m at Annapolis (Figure 2b), causing flooding there.

3. Wind-Driven Currents and Destratification

[6] Besides causing high storm surges, Isabel's winds drove strong currents. Chesapeake Bay responds to both local wind forcing and coastal sea-level setup/down associated with remote wind forcing [e.g., *Wang*, 1979]. The typical response to the local wind forcing is a phased, two-layer current structure superimposed on the regular ebb-and-flood of the semidiurnal tide. Prior to the storm, northerly winds drove a two-layer, wind-forced flow, with the upper-layer flow moving out of the Bay and the lower-layer flow moving into the Bay, as shown in Figures 3a and 3b. During the evening of 18 September, however, the storm's southeast–to-southerly winds became sufficiently strong to force the entire water column up the Bay at speeds in excess of 1.5 m s^{-1}. After the storm's passage, the Bay relaxed with a rapid movement of the entire water column in an opposite direction, thereby reverting to its more typical two-layer structure on 21 September. This current variability was well captured by the model. The associated RMS error is about 0.19 ms^{-1} with a model-predictive skill of 0.93. Hence, water in Chesapeake Bay was sloshed forth by the storm's southeast-to-southerly winds but subsequently sloshed back due to the presence of a seaward pressure gradient generated by the sloping sea surface. Figure 3c shows that the water movement was not only synchronised from the surface to bottom but also from Bay's mouth to Bay's head. This slab-like response is unusual in Chesapeake Bay, not only because weaker winds could drive two-layer flows, but also because the typically strong stratification would act to decouple the upper and lower layers. As will be discussed next, the strong winds produced by Isabel created sufficient mixing energy to destroy this stratification.

[7] Prior to Isabel's landfall, water was highly stratified (Figure 4a) because 2003 was one of the wettest years on record. However, strong turbulent mixing generated by Isabel's winds quickly erased the stratification in the water column, as shown by nearly vertical isohalines in Figure 4b.

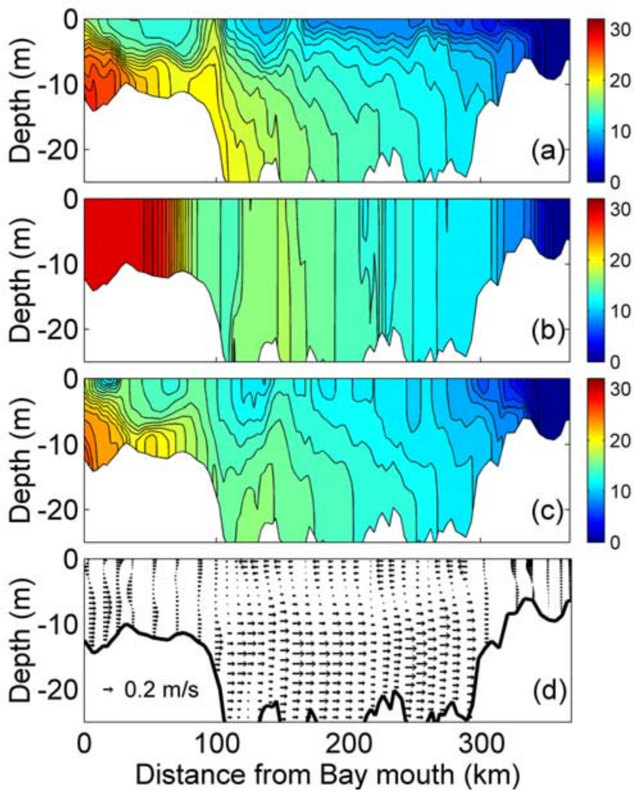

Figure 4. Water-column destratification due to wind mixing. Predicted along-channel salinity distributions (a) before (0000 LST 16 September), (b) during (0000 LST 19 September), and (c) after (0000 LST 22 September) Isabel's passage, and (d) predicted non-tidal velocity after Isabel's passage (0000 LST 22 September).

Thus, Hurricane Isabel temporarily transformed the partially mixed estuary into a vertically homogeneous one. Moreover, the one-layer water movement resulted in a strong intrusion of high-salinity shelf water into the wide lower-Bay, occupying roughly one-fifth of the Bay's total volume. After the passage of the storm, the large horizontal salinity gradient between the head and mouth, together with the enhanced stream flows from tributaries, produced restratification in the water column (Figure 4c) and a two-layer estuarine flow except near the Bay's mouth where the flows might still undergo adjustment following the storm surge (Figure 4d). The longitudinal salinity gradient averaged to about 10^{-4} psu/m (Figure 4b) and resulted in a gravitational adjustment when the wind subsided. The buoyancy frequency averaged over the bay increased linearly with time and reached 0.03 s^{-1} at 17 hours after the destratification. The numerical result for the initial phase of stratification increase is in good agreement with the theoretical prediction by *Simpson and Linden* [1989]. Subsequently, turbulent diffusion works against the longitudinal advection to produce a quasi-steady salinity distribution. More detailed investigations into the destratification and restratification processes will be presented in a separate paper.

4. Concluding Remarks

[8] In this study, we have shown that the high-resolution regional atmospheric and oceanic models have the remarkable predictability for Isabel-generated surface stress, storm surges and currents in Chesapeake Bay, as verified against the real-time data recorded on the observation systems. The hurricane-force winds destratified the Bay's water columns through strong vertical mixing. It should be mentioned that the effects of surface waves and wave-current interactions were not included in this work. Since Chesapeake Bay has an elongated geometry, waves tend to be well developed for southerly or northerly winds but fetch-limited for easterly or westerly winds. We anticipate more accurate predictions if these effects were incorporated; this will be worthwhile to pursue in the future.

[9] Nevertheless, the above results have important implications for the water quality and marine ecosystems in the Bay. For example, because of excessive nutrient loading, a large volume of the Bay's bottom water becomes hypoxic or anoxic during the summer [*Smith et al.*, 1992]. The strong vertical mixing may re-aerate the bottom water and inject nutrients into the sunlit upper water column. Indeed, post-Isabel observations showed that Isabel led to enhanced plankton and fish abundance in Chesapeake Bay [*Roman et al.*, 2005]. Aircraft remote sensing showed a large post-Isabel phytoplankton bloom over the middle and lower Bay. Near the Bay's mouth there was a dramatic increase in the abundance of ecologically-important bay anchovy, possibly associated with the intrusion of shelf water as shown in Figure 4b. However, the rapid recovery of stratification diminished vertical mixing and allowed biological consumption to draw down oxygen concentration, resulting in a return of hypoxia in the Bay [*Boicourt*, 2005].

[10] Given warmer-than-normal global sea-surface temperature, both the number and proportion of intense TCs have increased notably since 1970 [*Emanuel*, 2005; *Webster et al.*, 2005]. Thus, more hurricanes with stronger intensity might hit bays and generate storm surges as seen during the passage of Isabel. The problem of storm surge is exacerbated by the prospect of accelerated global sea-level rise in the 21st century [*Church et al.*, 2001], and compounded by continuing subsidence of low-lying lands surrounding bays and estuaries [*Kearney and Stevenson*, 1991]. Scientific insights gained from this case study are relevant not only to bays and estuaries on the U.S. East and Gulf Coasts but also to those in South and East Asia that are frequently hit by TCs.

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