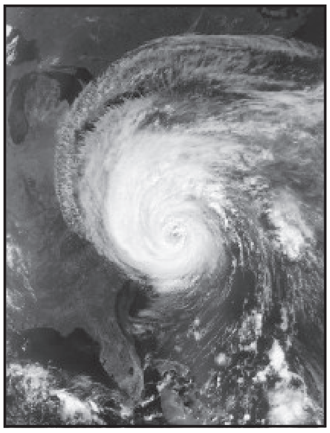

Regional Storm and Hurricane Models, Forecasts, and Physics

PHYSICAL RESPONSE OF CHESAPEAKE BAY TO HURRICANES MOVING TO THE WRONG SIDE: REFINING THE FORECASTS

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ABSTRACT

The Chesapeake Bay's storm surge created by Hurricane Isabel bears remarkable similarity to the hurricane storm surge of August 1933. The scale and configuration of the Bay render it particularly vulnerable to these rare events, when the eye of the cyclone advances on the western side. The Bay's geometry is large and complex, so spatially limited, time-varying cyclones produce an intricate variety of water level, current, and wave responses, with both surges and depressions. Isabel arrived with a strength, timing, and wind-stress distribution that forced the water column northward as a single layer—destratifying the main-stem water column as it proceeded. Where normally this response to wind forcing is two-layered, such unusually strong winds drive the entire water column in a single layer as the initial phase of a quarter-wave seiche. The Bay's long-wave propagation speed is of the same order as the advancing cyclone, setting up the possibility of a seiche resonance. Bay volume changes associated with the seiche enhance estuary-shelf exchange and significantly modulate the buoyant plume and coastal current on the shelf.

Analysis of both the observational and damage data from Hurricane Isabel, along with comparisons to the 1933 storm, provide lessons for observing systems, forecasting, and emergency management of the coastal ocean. In particular, improving storm-surge forecasting will require incorporating data assimilation of pre-storm water levels both within the Bay and over the continental shelf, especially in the shelf-wave propagation region. Furthermore, stress formulations for the fetch-limited reaches of Chesapeake Bay will likely require refinement for accurate storm-surge forecasting on the scale appropriate for emergency management.

INTRODUCTION

The enclosed reaches of Chesapeake Bay offer protection from tropical storms that usually pass on the eastern side. This enclosure limits fetches, so waves are usually less destructive than along the open coast. Although the Bay's shallow depths confine the wind's applied momentum, rendering it especially prone to wind driving, the northeast winds associated with the typical cyclone drive water out of the Bay and lower water levels even as they build a dangerous surge along the coast.

But such conditions are only typical. In the rare circumstance when cyclones pass to the west of the Bay's axis, the confined nature of the Bay becomes a liability and storm surges are likely to exceed those on the open coast. This shift from protection to vulnerability is not simply due to the strong winds of the western storm blowing water into the Bay or up the shallow western tributaries. The shift is also the result of the Bay's size, depth, and geometry, which render it particularly responsive to these extreme forcings. The same shallow and enclosed aspects of the Bay that protect during typical hurricanes facilitate seiche and resonance phenomena for storms moving up the western side. Only two hurricanes in the last 100 years have taken such a path; in both cases, a large storm surge ensued. In August 1933, a hurricane propagated over the western side of the Bay, flooding low-lying lands as it moved. Extensive flooding on the Eastern Shore damaged agricultural fields with salt contamination. Seventy years later, in September 2003, Hurricane Isabel moved to the west of the Bay, also creating widespread flooding. The Isabel surge reached a maximum of 2.7 m above normal high tide in Washington, D.C. and caused significant damage.

Hurricane Isabel's strike in the presence of fledgling observing systems provided both scientific insight and practical lessons on how to observe, forecast, and manage emergency situations—lessons ranging from the mundane to the state of our scientific art in describing the coupling of the atmosphere to the ocean.

The following discussion will focus on the responses of the Chesapeake Bay to cyclones moving on the wrong, or western, side of the Bay. In particular, it will attempt to explain why the Bay's geometry amplifies the surges produced by these storms. Finally, lessons from Hurricane Isabel will be used to outline measures that can be taken to improve both the observing and forecasting of these responses.

RESPONSE

Both the August 1933 storm and Hurricane Isabel made landfall over the Outer Banks of North Carolina. After reaching land, the eye of the August 1933 storm turned slowly to the right, traversing the upper reaches of the western tributaries of Chesapeake Bay (Figure 1). In contrast, Hurricane Isabel showed little deviation from a straight-line path that began three days before landfall and continued until weakening over the Great Lakes.

Despite the difference in paths, the Bay's response to both the 1933 storm and Hurricane Isabel was remarkably similar. This similarity is especially evident when the four Bay water-level gauges common to both storms are juxtaposed (Figure 2). The initial surge in the south end of the Bay, recorded by the Hampton Roads gauge, was approximately 1.5 m above normal high tide. The alignment of the strong southeasterly winds in the northeast quadrant of the storms with the long fetch of the lower Potomac River (Figure 1) created the largest surge in Washington, D.C., reaching 2.7 m above normal high tide during Hurricane Isabel.

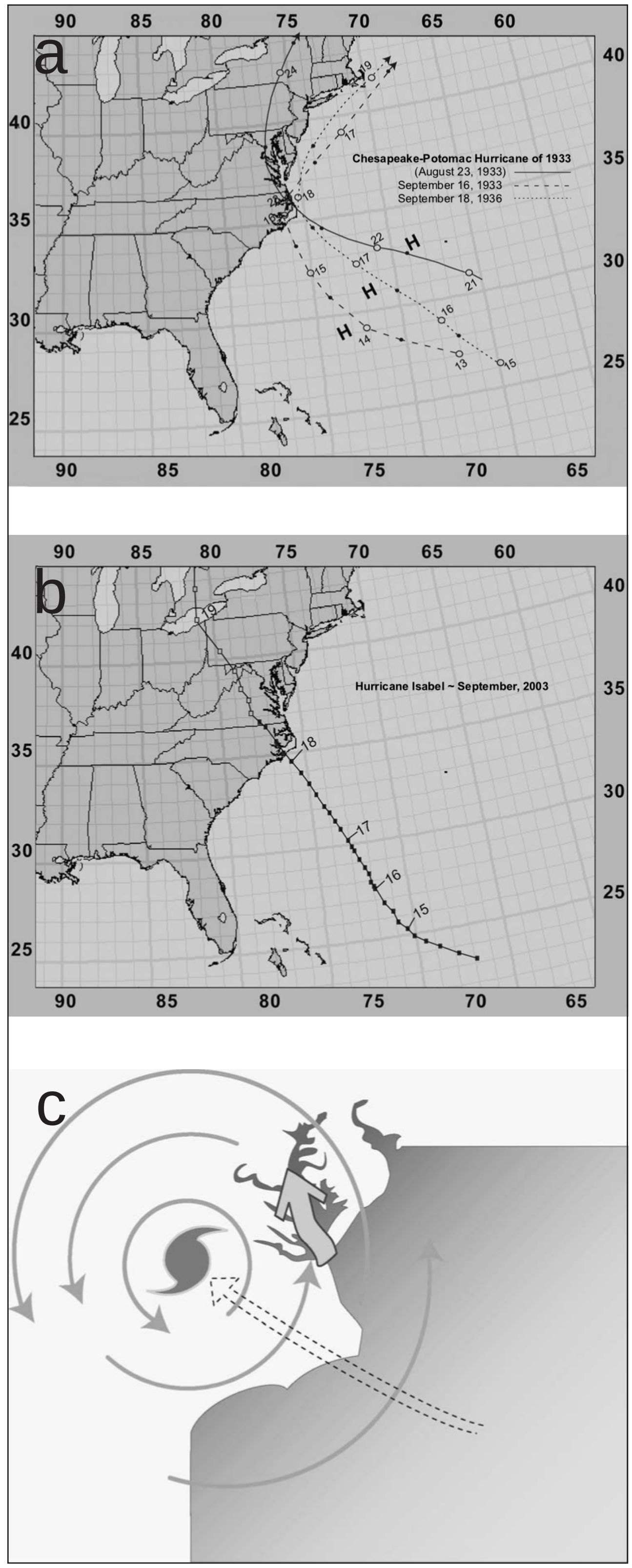

Figure 1. Hurricane tracks: a) 1933, b) 2003 (courtesy of NOAA National Weather Service), and c) wind pattern schematic of hurricanes traversing to the west of Chesapeake Bay.

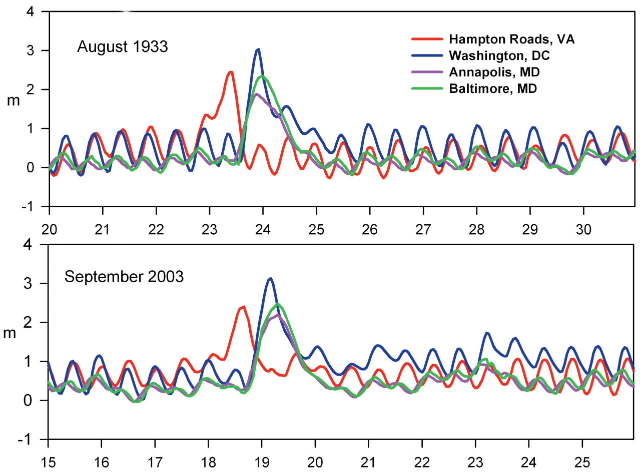

Figure 2. Water gauge records from Chesapeake Bay tide gauges common to 1933 and 2003. The time axis has been adjusted to facilitate comparison of the two hurricanes.

These same southeast winds produced surges over the northern main stem of the Bay, recorded at Annapolis and Baltimore, Maryland. The northern surges peaked a few hours after the Washington maximum (Figure 2). In contrast to other gauge locations, the water level in the upper Potomac River at Washington remained elevated long after the two storms. This elevation appears to be the result of the storm-swelled discharge from the Potomac River following the high rainfall from the two hurricanes, which passed directly over the Potomac watershed. The tidal river is sufficiently narrow in this reach that discharge surges can markedly elevate water level.

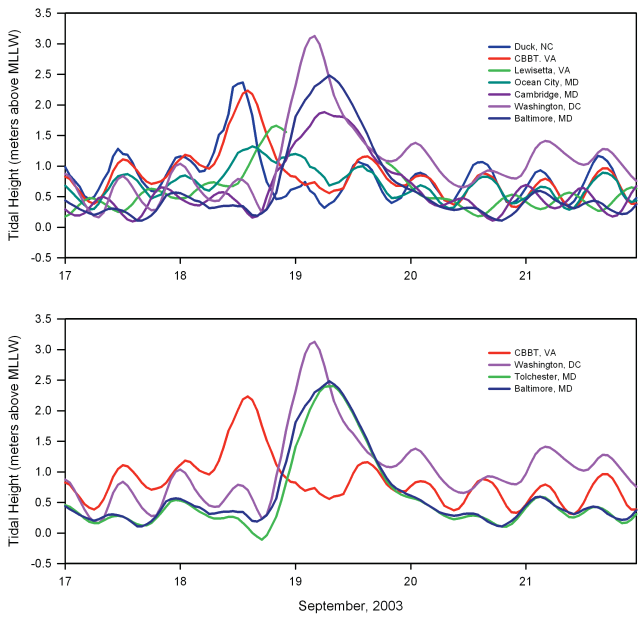

Figure 3. Water-level records from Chesapeake Bay region prior to and during Hurricane Isabel. Upper panel includes most available records, while lower panel includes only selected stations at Chesapeake Bay Bridge Tunnel, Washington, D.C., in the northern Bay, Tolchester Beach, and Fort McHenry in Baltimore. Heights are meters above Mean Low Low Water (MLLW).

The increase in the number of water level gauges since the 1933 hurricane affords a more detailed look at the Bay's response to Hurricane Isabel (Figure 3). In the days preceding Isabel's landfall, northerly winds drove surface waters out of the Bay and depressed sea level over the northern half of the estuary. Isabel arrived with strong southeasterly winds on 18 September, creating an initial storm surge at the Bay entrance. The Bay is sufficiently large that the cyclone produced strong northeasterly winds over the upper Bay at the same time. These winds further depressed water levels and created a strong cross-Bay slope. This slope, indicated by the difference in water levels between the Tolchester and Baltimore gauges, persisted until late in the storm.

Similar, or even greater cross-Bay slopes would be expected from the strong southeasterly winds over the southern Bay; no gauges were in place on the Eastern Shore between Kiptopeake, Virginia and Cambridge, Maryland. Interesting standouts in the tide gauge records are the Lewisetta, Virginia gauge on the southern shore of the Potomac River near its junction with the mainstem Bay and the Ocean City, Maryland gauge on the open coast (Figure 3). The Lewisetta gauge shows a smaller surge than even at Hampton Roads and markedly smaller than those at the gauges to the north. Here, southeasterly winds were not as strong as winds seaward of Hampton Roads, nor would they be as effective in driving a surge. The Ocean City gauge's comparatively modest response to the hurricane in comparison to the Bay's surge is partly a result of lower wind forcing in that region and partly due to the lack of the Bay's magnification effects.

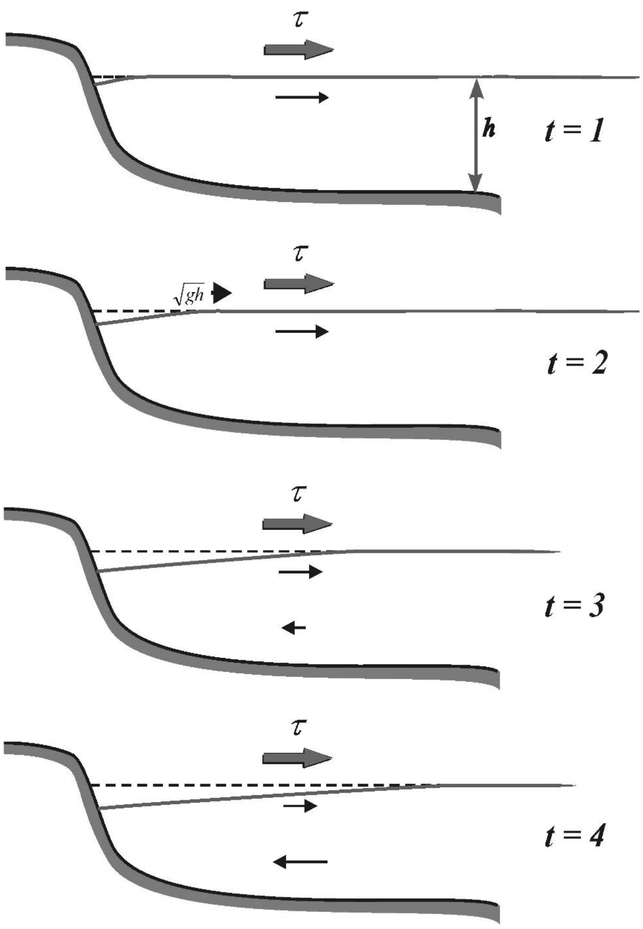

Figure 4. Schematic diagram of response to wind forcing (seaward wind case). Wind stress T drives surface layer in direction of wind, creating a slope in sea level (t = 3, 4). The pressure gradient created by sea level slope drives water in opposite direction to wind. In surface layers, frictional driving by applied wind stress overcomes this pressure gradient, while in lower layers, frictional driving pressure gradient drives landward flow.

To create a storm surge, horizontal movements of water are necessary to fill the additional volume. Winds along the axis of the Bay drive such a motion. The normal response of wind forcing is a phased, two-layer current structure (Figure 4). Initially, the applied wind stress drives the surface layer in the direction of the wind. This motion, in turn, forms an along-axis slope. The response time for this slope depends on the shallow-water gravity wave speed

$$c = \sqrt{gh}$$

where h is the water depth and g is gravity. The resulting slope represents a barotropic pressure gradient opposing the wind. If the wind is still active, then this opposing pressure gradient may not reverse the flow at the surface, but decreases the frictionally driven flow. At depth, however, this pressure gradient creates a strong answering flow (Figure 4). The phase delay between applied wind and lower-layer response for the middle reaches of Chesapeake Bay is typically 18 to 24 h [1, 2]. The response of an estuary to wind forcing is enhanced in such large water bodies as Chesapeake Bay, where the axial component of wind stress has a long, unobstructed fetch to transfer momentum to the water. In contrast, meandering channels can even create opposing pressure gradients in adjacent reaches of an estuary [3].

Currents measured at the Chesapeake Bay Observing System's (CBOS; *www.cbos.org*) mid-Bay buoy (latitude 38.3º N) revealed strong flows associated with Hurricane Isabel superimposed on the regular ebb and flow of the semidiurnal tide (Figure 5). Prior to the storm, northerly winds drove a typical two-layer, wind-forced flow, with the upper-layer flow moving out of the Bay and the lower-layer flow moving in. On the afternoon of 18 September, the storm's southeasterly and southerly winds and associated pressure deficit became sufficiently strong to force the entire water column up the Bay at speeds in excess of 1.5 $m \cdot s^{-1}$. This slab-like response is unusual in the Chesapeake Bay, not only because weaker winds drive two-layer flows, but also because the typically strong stratification decouples the upper and lower layers. As will be discussed, the strong winds created sufficient mixing energy to destroy this stratification. After the storm, the Bay relaxed with a strong movement of the entire water column in the opposite direction that subsequently reverted to a more typical two-layer structure late on 19 September (Figure 5). The one-layer movement of 18 September, with its associated storm surge, indicates long advective scales and a strong intrusion of shelf water into the Bay. Speeds of 1.0 $m \cdot s^{-1}$ imply transports on the order of 100 $km \cdot d^{-1}$, or one-third the Bay's length. Bay volume increases from this intrusion event would amount to approximately 10% of the Bay's normal volume.

The storm surge created by Hurricane Isabel increased in magnitude from south to north, from 1.5 m at Hampton Roads to 2.7 m at Washington and 2.2 m at Baltimore. This increase occurred despite diminishing maximum winds from south to north. Maximum sustained winds (measured near or over land) decreased from >30 $m \cdot s^{-1}$ at Gloucester Point, Virginia to 14 $m \cdot s^{-1}$ at Horn Point Laboratory in Cambridge, Maryland. The long, unobstructed fetch for Isabel's southeast winds along the lower Potomac River may help explain the high storm surge in Washington. But such an explanation does not account for the large surge in Annapolis and Baltimore in northern Chesapeake Bay, especially when compared with Lewisetta and Hampton Roads (Figure 3).

Two driving components of the seiche oscillation may have contributed to the large surge in both Washington and Baltimore. A clue to one may be the low stand of water in the northern Bay prior to Hurricane Isabel's landfall (Figure 2). The subsequent surge with the onset of the hurricane may have benefited from a seiche rebound. Chuang and Boicourt [4] described an interval of near-resonant seiche activity in Chesapeake Bay in 1986. Regular passages of atmospheric low-pressure systems forced the Bay at near the free-oscillation period of approximately 2 d creating 1-m amplitude fluctuations in water level in the upper Bay. The second process that may have contributed to the large surge is also related to the seiche, the progressive nature of the hurricane. After landfall, Hurricane Isabel moved northwestward on its track at speeds of about 10 $m \cdot s^{-1}$ (Figure 1). This speed is similar to that of the Bay's long-wave propagation speed of ~7 $m \cdot s^{-1}$. The coincidence of storm (with its dual forcing of wind stress and low pressure) moving along with a propagating surge would create conditions for efficient transfer of energy. Although the response to the lower pressure is unlikely to be sufficiently rapid to match the inverted barometer effect, the low-pressure field is likely to contribute to the surge as it moves.

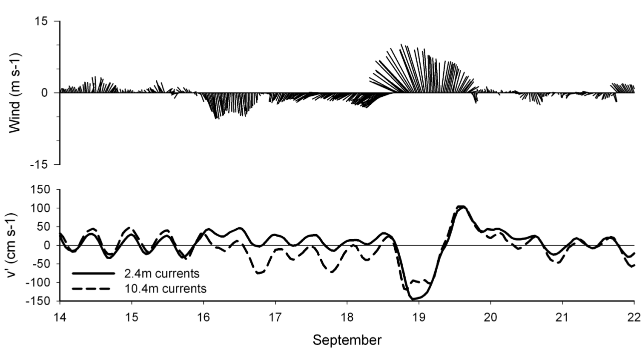

Figure 5. Wind and current records from Hurricane Isabel, 14 to 22 September 2003. Current records are from 2.4-m and 10.4-m depth at the CBOS mid-Bay station (38.3° N 76.2° W). Wind records are from the Horn Point Laboratory weather station in Cambridge, Maryland. For winds, northward winds are positive and parallel to the ordinate axis. For currents, positive flow is directed seaward.

As Hurricane Isabel progressed up the western side of the Bay, building a storm surge, its winds also created large waves. The strong currents and high waves mixed the water column in the process, destratifying its layers and re-aerating the summertime anoxic lower layer. Stratification prior to Isabel was well developed because the 2003 water year (1 October 2002 to 30 September 2003, including Isabel runoff) was the highest freshwater input to Chesapeake Bay since 1937. The EPA Chesapeake Bay Program survey prior to Isabel in late August 2003 showed strong stratification and resulting extensive hypoxia (Figure 6). Hypoxic water (<2 $mg \cdot L^{-1}$) penetrates 30 km landward of the central deep trough paleochannel and well onto Rappahannock Shoals (beginning at km 210, Figure 6), forming a mid-depth oxygen minimum in the pycnocline. This oxygen minimum is the result of the lower-layer flow supplying oxygenated water from the adjacent continental shelf.

Fortuitously, an Aanderaa RCM-9 current meter equipped with a PerSens optical oxygen sensor was deployed on the CBOS mid-Bay buoy in August, approximately a month prior to Hurricane Isabel. This instrument was mounted at 10-m depth, in the upper portion of the anticipated hypoxic zone to ensure a range of conditions for sensor testing. For three weeks, recorded oxygen levels seldom rose above recorded anoxia (Figure 7). A southerly wind event on August 12 was sufficiently strong to drive both upper and lower layers of the water column northward for two days.

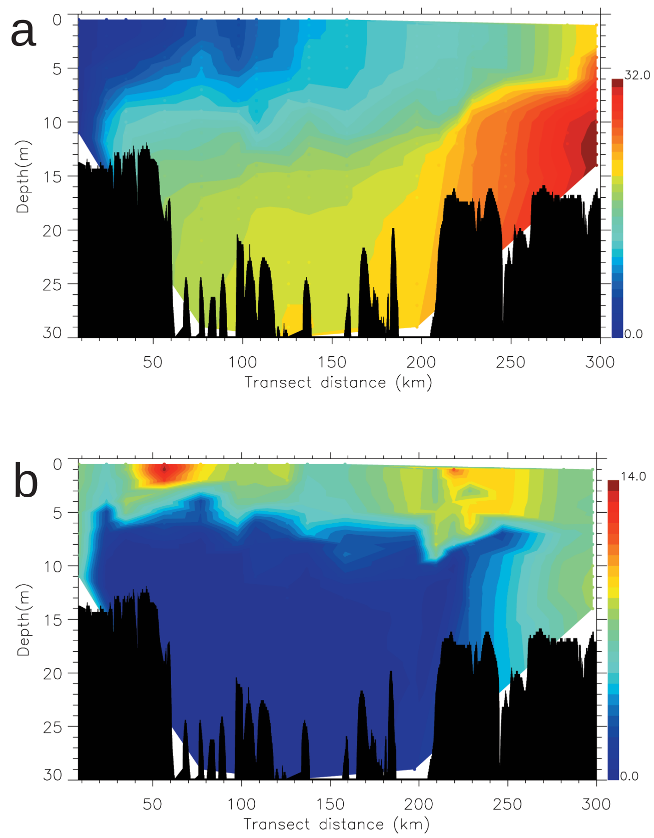

Figure 6. Axial salinity (a) and dissolved oxygen (b) distributions during 18–20 August 2003 for Chesapeake Bay. Data are from EPA Chesapeake Bay Program surveys.

The mixing resulting from this wind event increased oxygen levels at 10 m to approximately 50% saturation. However, oxygen levels quickly declined to hypoxia following the event. The salinity sensor at 19 m showed little evidence that mixing penetrated to that depth. During the approach of Hurricane Isabel, northeast winds over the Bay created a strong current shear and began to mix oxygen down to 10 m at the mid-Bay station. These winds increased the up-Bay transport of salty water in the lower layer, thereby elevating salinities at 19 m. Upon the arrival of Hurricane Isabel, vertical mixing overcame this horizontal advection. Salinities at this depth at the mid-Bay CBOS buoy decreased markedly (Figure 7), despite both the intrusion of ocean water and the unusually strong wet-year stratification. Here, the drop in salinity was approximately 10 practical salinity units (PSU).

The net result of this combination of intrusion and subsequent destratification event in the northern Bay (latitude >39° N) was an *increase* in salinity at the surface from 0 to 11 PSU. As is typical of mixing events [5], the Bay's longitudinal salinity gradient enabled rapid recovery of stratification. In turn, this stratification diminished vertical mixing and allowed oxygen consumption in the deeper layers to aggressively draw down concentrations to <1 mg·L^{-1}. A survey using a towed, undulating vehicle (Scanfish) on 5–6 October (approximately two weeks after destratification) shows the rapid recovery of stratification (Figure 8a) and hypoxia (Figure 8b), historically quite uncommon this late in the season. With increased eutrophication, however, fall oxygen depletions have become increasingly common in recent decades.

The causes and consequences of a storm surge in Chesapeake Bay are not limited to the Bay proper. Large fluctuations in the Bay's volume, associated with the storm-induced seiche, translate into fluctuations in the amount of water imported to the Bay from the shelf and in the size of the buoyant discharge plume and coastal current on the continental shelf. This coastal current can move water parcels southward along the coast at speeds in excess of 50–150 cm·s^{-1} for typical times of 1–5

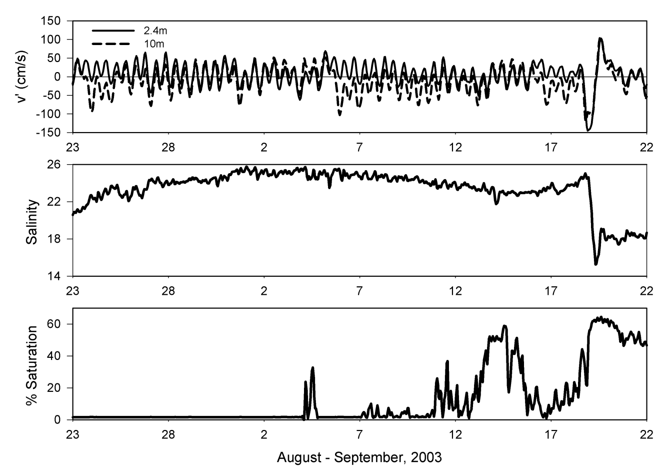

Figure 7. Current, salinity, and oxygen records from the CBOS mid-Bay station. Currents are from 2.4-m and 10.4-m depths. Salinity and oxygen saturation are from 10.4-m depth.

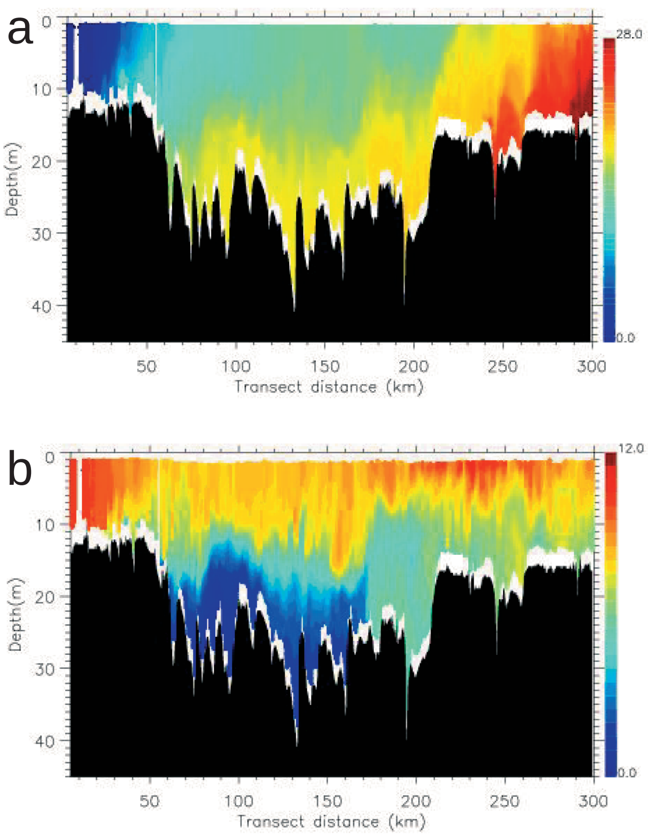

Figure 8. Axial distribution of (a) salinity and (b) oxygen from Scanfish survey on 5 to 6 October 2003, approximately two weeks after Isabel.

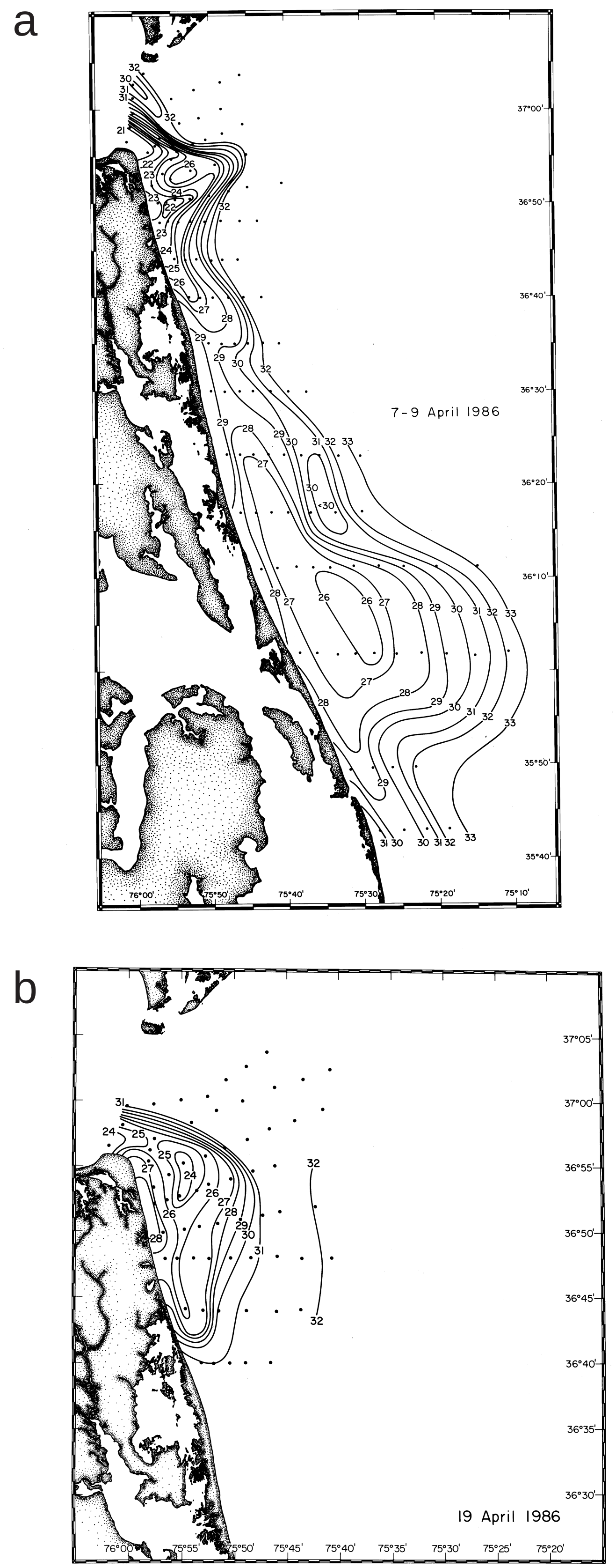

Figure 9. Surface salinity patterns of Chesapeake Bay plume in April 1986.

d, or until winds favorable for upwelling drive the plume offshore.

Examples of possible variations in shelf-estuary exchange under conditions of strong wind forcing can be inferred from two surface salinity maps during the interval of resonant seiche activity described by Chuang and Boicourt [4] in 1986. One of the smallest plumes observed during the month-long survey occurred on 19 April 1986 during a storm surge in northern Chesapeake Bay (Figure 9b). This small plume stands in contrast to a larger and more typical spring runoff plume earlier in the study (Figure 9a). Such fluctuations in exchange at the mouth of Chesapeake Bay are created not only by the local effects of the wind stress and pressure fields acting on the Bay alone, but also through water-level fluctuations over the inner continental shelf. These variations are also driven by winds on the continental shelf, forcing Ekman drift toward and away from the coast. The north-south orientation of the Bay creates a situation whereby the two responses are qualitatively opposing—a north wind lowering water levels in the Bay while elevating water levels along the coast. Phase differences between coastal Ekman setup and Bay seiches create a situation for the Bay in which the initial response is local setup and seiche generation [6, 7]. If the applied wind stress persists, the coastal setup propagates into the Bay. Although rare, the case in which a hurricane slows or stalls could enable a superposition of these responses and an even greater surge over the Bay region. Coastal sea-level variations are primarily produced by local Ekman drift in the offing of the Chesapeake Bay mouth, but they also can be generated far upcoast from the Bay, from where they can propagate southward as a continental shelf wave [8]. The Bay's response to wind forcing is, therefore, a complex mix of local and remote processes, both within the Bay and over the entire domain of the Middle-Atlantic Bight continental shelf.

LESSONS LEARNED

Hurricane Isabel provided scientific insight into the response of the large, semi-enclosed Chesapeake Bay ecosystem to strong forcing. The shape (size, depth, linearity), orientation, and enclosed nature of the basin amplify the response in a manner analogous to a Helmholtz resonator. The strength of the forcing, the speed of its progression, and the spatially limited pattern of its wind stress and pressure field were sufficiently different from typical wind conditions to provide an opportunity for a comparative ecology of extreme versus moderate responses. For instance, the marked cross-Bay water-level differences produced by Hurricane Isabel were of a size to be noticed, whereas more typical cross-Bay slopes might not be included in an analysis of longitudinal transport. The similarity of the response to Isabel with that of the 1933 storm gives motivation for further analysis as well as distinction between the local and remote components.

In addition to the lessons provided by Hurricane Isabel concerning the physical response of Chesapeake Bay, there were lessons for improving our observation and forecasting of storm surges. With the advent of the U.S. Integrated Ocean Observing System (IOOS), much has been made of the value of real-time observations for improving forecasts and warnings for the coastal ocean via data assimilation into numerical models. A mundane, but nonetheless crucial, aspect of this assimilation process is that the data stream must be maintained, even in the presence of the storm forcing. Hurricane Isabel damaged both buoys and water level gauges on the Bay. The data records shown in Figure 5 and Figure 7 terminated because storm waves battered the solar panels on the mid-Bay buoy until they were torn off their mounts (Figure 10).

Armoring water-level gauges, providing automatic backups, and designing less-vulnerable platform superstructures are relatively straight-forward tasks. Improvements in our storm surge forecasting, however, will require additional efforts. The question arises as to whether improvements in storm surge forecasts are necessary, given that the NOAA SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model provided good estimates of Hurricane Isabel storm surges for the Chesapeake Bay region. The stated accuracy of the model is approximately 20% if the hurricane wind field is accurately forecast [9, 10]. For low-lying regions of Chesapeake Bay, especially on the Eastern Shore of Maryland and Virginia, 20% uncertainty in water level translates into substantial uncertainties in inundation forecasts, especially when the present Digital Elevation Models contain widespread errors. Inundation forecasts are crucial for emergency management in regions such as Dorchester County, Maryland, where approximately 50% of the county was under water during Hurricane Isabel [11]. Furthermore, given the spatial structure in Hurricane Isabel's storm surge, forecasts should be delivered on both regional and local scales to aid emergency in such decisions as evacuation orders.

Reducing uncertainties in storm surge forecasts, especially in large embayments such as Chesapeake Bay or Long Island Sound, will require incorporation of antecedent water-level histories, river flow, and wave-dependent stress formulations in the forecast models. Of these, the most important is likely to be the seiche activity in the day(s) prior to hurricane arrival. Providing adequate warnings on county scales will depend on improvements in local setup descriptions.

While incorporation of antecedent water level histories, both within these bays and along the adjacent coast, is essential for improving surge forecasts, sufficient time may not be available to assimilate real-time data of waves and winds into forecast models for rapidly moving storms. However, research to improve wind-stress and drag-coefficient formulations in forecast models should be conducted for these fetch-limited waters. Over-water measurements of winds, along with incorporation of waves and wave-dependent stress formulations into the models, are efforts likely to foster progress in storm-surge forecasting. Targeted observational investigations will be necessary to support these efforts. Ultimately, improvements such as time-dependent wind-stress formulations may well be governed by the law of diminishing returns unless a truly coupled atmosphere-ocean model of both the estuary and regional continental shelf is applied to the forecast problem.

Figure 10. Damage to CBOS mid-Bay buoy after Isabel.

REFERENCES

1. D.W. Pritchard and M.E.C. Vieira. 1984. Vertical variations in residual current response to meteorological forcing in the mid-Chesapeake Bay. In: *The Estuary as a Filter*, V.S. Kennedy (ed.). Academic Press, Orlando, FL. pp. 27–65.
2. M.E.C. Vieira. 1986. The meteorologically driven circulation in mid-Chesapeake Bay. *J. Mar. Res.* 44: 473–493.
3. W.C. Boicourt. 1982. Estuarine larval retention mechanisms on two scales. In: *Estuarine Comparisons*, V.S. Kennedy (ed.) Academic Press. New York. pp. 445–457.
4. W.S. Chuang and W.C. Boicourt. 1989. Resonant seiche motion in the Chesapeake Bay. *J. Geophys. Res.* 94: 2105–1220.

5. D.M. Goodrich, W.C. Boicourt, P. Hamilton, and D.W. Pritchard. 1987. Wind-induced destratification in the Chesapeake Bay. *J. Phys. Oceanog.* 17: 2232–2240.
6. D.P. Wang. 1979. Subtidal sea level variation in the Chesapeake Bay and relation to atmospheric forcing. *J. Phys. Oceanog*. 9: 413–421.
7. D.P. Wang. 1979. Wind-driven circulation in the Chesapeake Bay, winter 1975. *J. Phys. Oceanog*. 9: 564–572.
8. H.W. Ou, R.C. Beardsley, D. Mayer, W.C. Boicourt, and B. Butman. 1981. An analysis of subtidal current fluctuation in the Middle Atlantic Bight. *J. Phys. Oceanog.* 11: 1383–1392.
9. S.H. Houston, W.A. Shaffer, M.D. Powell, and J. Chen. 1995. Comparisons of SLOSH parametric and HRD analyzed surface wind fields in recent hurricanes. *A.M.S. 21st Conf. on Hur. And Trop. Met.* 24–28 Apr. 1995, Miami FL, pp. 619–621.
10. S.H. Houston, W.A. Shaffer, M.D. Powell, and J. Chen. 1996. Incorporating HRD surface wind fields into the SLOSH model. *A.M.S. 21st Conf. on Hur. and Trop. Met.* 24–28 Apr. 1995. Miami FL. pp. 265–267.
11. A.E. Luscher. 2005. Improving utilization of geospatial information in coastal hazard planning in Maryland. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium. CRC Publication 05-160, Edgewater, MD. pp. 233-241.