Hurricane Isabel in Perspective

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Hurricane Isabel crossing the U.S. East Coast

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Why a Conference on Hurricane Isabel?

Downtown Annapolis, Alexandria, and Fells Point in Baltimore under water; piers and docks destroyed, cars parked several hundred yards inland inundated; year-plus frustrations with federal and personal insurance recoveries for storm damage. What was so different about this hurricane versus others that have blown over the Bay?

In fact, Isabel was not a hurricane when she arrived but a tropical storm, yet she still caused devastating damage in the tidal areas of the Bay and its tributaries. Why, with the best hurricane projections possible, was the region caught unprepared? Why was there so much damage when everyone knew the storm was approaching and where she would track?

These questions have motivated managers, local government officials, and the scientific community since Isabel visited in September 2003 and inspired a cross-community conference, "Hurricane Isabel in Perspective" held at the Maritime Institute in Linthicum, Maryland in November 2004. Sponsored by the Chesapeake Research Consortium (CRC) and the University of Maryland Center for Environmental Science (UMCES), the conference encouraged participation by scientists, managers, and many emergency responders to explore the reasons for the devastating impacts of the hurricane and to discuss openly why the advanced forecasting tools and preparedness teams were unable to protect property throughout the region.

The conference topic raised sufficient interest in the region that several institutions and organizations co-sponsored the meeting: CRC, UMCES, the Virginia Institute of Marine Sciences, the U.S. Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the MD Department of Natural Resources (MD DNR), the Chesapeake Bay National Estuarine Research Reserves, and the Keith Campbell Foundation. Over 160 participants met for two days to listen to technical presentations by leading national and regional scientists and to participate in open discussion among state and county government officials and emergency response personnel.

Isabel was not unique; she mimicked a hurricane that traversed the Chesapeake Bay in 1933. The fundamental property shared by Isabel and the earlier storm was that both tracked northward along the western side of the Chesapeake, resulting in counterclockwise winds that drove water up the Bay and its tributaries. The storm surge from Isabel, coupled with tide- and wind-induced waves, reached far inland, particularly in the low-lying regions adjacent to the Bay. Even with advanced warning and media-delivered predictions of storm-surge height, the regional population did not grasp the storm surge concept. As a result, citizens did not fully prepare for the flood waters that accompanied the storm's passage. Had the storm tracked to the east of the Chesapeake's main stem, with the modest rains that fell during and after the storm, far less property damage and flooding would likely have occurred.

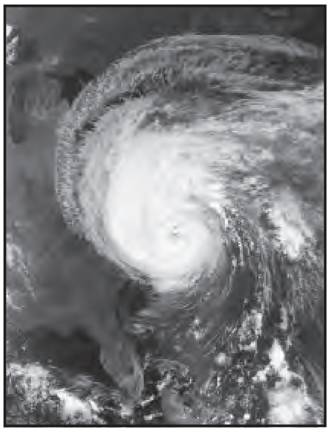
An obvious outcome of the conference has been the recognition that more informative descriptions are needed on the height of storm surge and likely areas of inundation expected in low-lying areas around the Bay and its tributaries. Recognizing the importance of effective and continuous regional distribution of surge and inundation forecasts prior to a storm's arrival may reduce future storm impacts in the basin.

Planners, scientists, emergency responders, and academics alike agreed that the numerous lessons learned from Hurricane Isabel will greatly assist our society's ability to prepare for, respond to, and recover from the next major storm event. The presentation of these lessons forms the contents of this proceedings volume. Most notable, however, is the lesson that planning does reduce impacts. While some need for improvement in terms of regional decision-making processes and institutional response still exists, use of the tremendous amount of scientific and academic research, along with forecast and model outputs, proved invaluable and will remain indispensable into the future.

This proceedings volume includes 31 peer-reviewed manuscripts covering: the history of hurricanes and storms from colonial times along with colonial and late-'70's responses to these major meteorological events; the physics and models describing the hurricane's passage and the effects on water levels; the biological responses in the water and on the land; and management and emergency responder capacities for Isabel and the future.

The region was severely flooded and is still recovering. Hopefully, although the flooding has receded, the effects of this storm will remain in our collective memory to ensure better preparedness in the coming years.

Kevin Sellner (CRC), Zoe Johnson (MD DNR), and Bill Dennison (UMCES)



Hurricane Isabel in Perspective: Keynote Address

ECOLOGICAL EFFECTS OF A RECENT RISE IN ATLANTIC HURRICANE ACTIVITY ON NORTH CAROLINA'S PAMLICO SOUND SYSTEM: PUTTING HURRICANE ISABEL IN PERSPECTIVE

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ABSTRACT

The intensity and frequency of hurricanes have varied historically in the Mid-Atlantic region. Since the mid-1990's, this region has witnessed a sudden rise in hurricane landfalls. During this period, eastern North Carolina has experienced seven Category 2 or higher hurricanes: Fran and Bertha in 1996, Bonnie in 1998, Dennis, Floyd, and Irene in 1999, and Isabel in 2003. These storms have had distinctive hydrologic and nutrient loading effects on the Pamlico Sound and its tributaries, including large changes in nutrient enrichment that led to variable phytoplankton biomass and compositional responses. These contrasting effects were accompanied by biogeochemical (hypoxia, nutrient cycling) and habitat alterations. Food web changes may also have occurred.

While floodwaters from the two largest hurricanes, Fran and Floyd, exhibited long-term (months) effects on hydrology, nutrient loads, and algal production, windy but relatively low rainfall hurricanes such as Isabel led to strong vertical mixing, storm surges, but relatively little flushing. Each storm type influenced algal growth and compositional dynamics; however, their respective ecological impacts differed substantially. Isabel made landfall near Drum Inlet on the Outer Banks of North Carolina, transected Pamlico Sound, and tracked onto the Virginia-Maryland tidewater region west of Chesapeake Bay. In the sound, strong vertical mixing and sediment resuspension caused injection of nutrients into the water column, which affected phytoplankton composition and growth. This effect was minor and short-lived (< 2 weeks), however, compared to the larger, lengthy (>6 months) effects of Floyd. The effects of Hurricane Isabel on phytoplankton production and composition in the relatively shallow (~ 5 m), well-mixed Pamlico Sound proved marginal compared to the deeper, stratified mainstem Chesapeake Bay (>15 m), where a large amount of hypolimnetic water was introduced into near-surface waters. Hydrological and wind forcing are important factors and must be integrated with nutrient loading effects when assessing the ecological effects of hurricanes on large estuarine ecosystems.

INTRODUCTION

Hurricane Isabel struck the Mid-Atlantic coastline near Drum Inlet on the Outer Banks of North Carolina on 18 September 2003. After making landfall, Isabel traveled northward across Pamlico Sound and then west of the Chesapeake Bay. This storm is among the most recent of a spate of hurricanes that reflects a projected 10- to 40-year increase in North Atlantic hurricanes that began in the mid-1990's [1]. In Eastern North Carolina, seven major hurricanes (Category 2 or higher) have made landfall since 1996: Bertha and Fran in 1996; Bonnie in 1998; four visits from three hurricanes (Dennis, Floyd, and Irene) in 6 weeks from September to October 1999; and Hurricane Isabel in 2003 (Figure 1). Hurricanes Fran and Floyd led to unprecedented 100- to 500-year flood events [2], inundating coastal rivers and estuaries and impacting the Pamlico Sound system—the second largest estuary in the United States and the country's largest lagoonal ecosystem [2, 3, 4, 5] (Table 1). Prior to 1996, coastal North Carolina had not been seriously affected by a large hurricane

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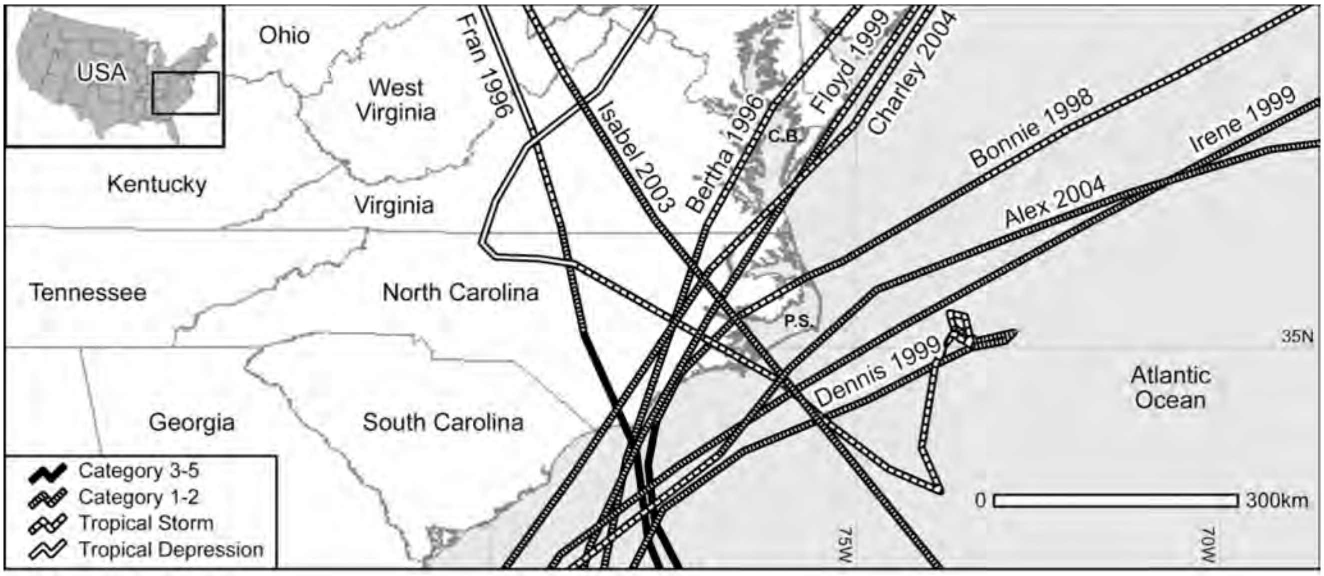

Figure 1. Tracks and intensities of hurricanes that have struck eastern North Carolina since 1996.

since mid-October 1954, when Hurricane Hazel made landfall in South Carolina.

Hurricane Hazel was followed by a 40-year hiatus in major hurricane impacts on eastern North Carolina. This lull was suddenly broken in 1996 with the arrival of hurricanes Bertha and Fran. This lengthy gap in hurricane landfalls is not unusual however. Analysis of weather records for coastal North Carolina indicates that this region has experienced repeatable 10 to 40-year periods of elevated Atlantic hurricane activity. For example, the late 1800's (1880's–1900) and early to mid-1900's (1930's–1950's) were particularly active periods interspersed with calm. During the 1890's, there were several years when multiple Category 2 or higher hurricanes struck the North Carolina coast (Figure 2). The 1940's and 1950's were also very active years, with hurricane landfall frequencies matching those of the late 1990's (Figure 3).

Even as a Category 2 (40–45 $m \cdot s^{-1}$) hurricane, Isabel is considered one of the most significant hurricanes to affect portions of coastal North Carolina and the Virginia-Maryland tidewater region since hurricanes Dennis and Floyd in 1999 [3], Hurricane Hazel in 1954, and the Chesapeake-Potomac Hurricane of 1933 [6]. In North Carolina, Hurricane Isabel's most notable physical effects were storm surges on the Outer Banks and throughout the Albemarle-Pamlico Sound system, including its estuarine tributaries (Neuse, Tar-Pamlico, and Chowan-Roanoke). Perhaps most notable, this storm caused a breach at Hatteras Island between Hatteras Village and Frisco, North Carolina, creating a new 518-m-wide inlet with depths ranging to 6 m (Figure 4). This breach persisted for approximately two months, at which time the U.S. Army Corps of Engineers and the North Carolina Department of Transportation (DOT) filled the inlet. During its brief lifetime, the inlet had a significant impact on water exchange

Table 1. Water residence time (in days) calculated from monthly mean flow for two key tributaries (Neuse and Pamlico) and the Pamlico Sound proper. Values are shown for September and October, 1999, during the hurricane flood period. Average residence time is based on mean flow data obtained from the 1989–1999 USGS upstream river gauging records.

Waterbody	September		October	
	1999	Ave.	1999	Ave.
Neuse River Estuary	7	69	11	81
Pamlico River Estuary	7	133	19	175
Pamlico Sound	36	219	79	313

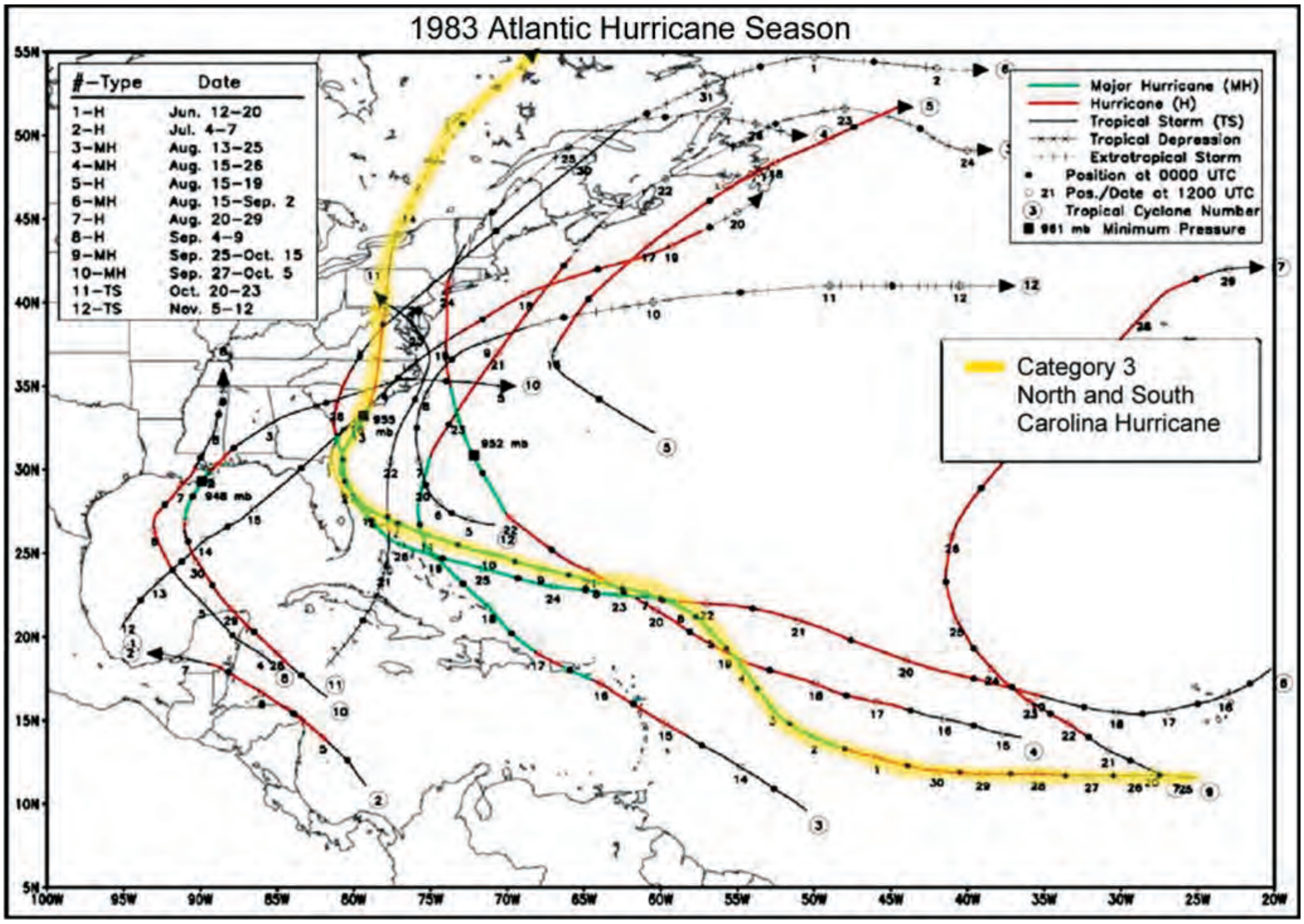

Figure 2. The 1983 North Atlantic hurricane season when four hurricanes co-existed in September. All four hurricanes eventually made landfall in eastern North Carolina (courtesy of NOAA).

between the Atlantic Ocean and the lagoonal Pamlico Sound system, as witnessed by altered salinity regimes in the sound. These hydrologic and chemical changes were documented by the North Carolina Ferry-Based Water Quality Monitoring Program, FerryMon *(www.ferrymon. org)*.

The purpose of this paper is to place the ecological effects of Isabel on North Carolina estuaries in perspective with regard to the effects of recently preceding hurricanes, most notably Hurricane Frances in 1996 and hurricanes Dennis, Floyd, and Irene in 1999. Specific emphasis will be on the phytoplankton community, forming the base of the food web. We used data from temporally and spatially intensive water quality monitoring programs that have been in place since the early 1990's on a key tributary of the Pamlico Sound, the Neuse River Estuary. In addition, ferry- and small-vessel-based water quality monitoring programs on the sound proper have been used to examine hydrologic and water quality impacts of these storms. In recent years, these programs have proven timely and essential for assessing the combined ecosystem-level effects of growing anthropogenic nutrient loads and what appears to be a new era of elevated hurricane frequency and intensity.

METHODS AND MATERIALS

The Pamlico Sound System

North Carolina's Pamlico Sound system is comprised of five major watersheds—the Tar-Pamlico, Neuse, Roanoke, Chowan, and Pasquotank—covering an area of approximately 80,000 km^2 (Figure 5). The sound has a surface area of 4,350 km^2 and estimated volume of about 21 km^3. Together, these basins drain approximately 40% of North Carolina and about 10% of Virginia.

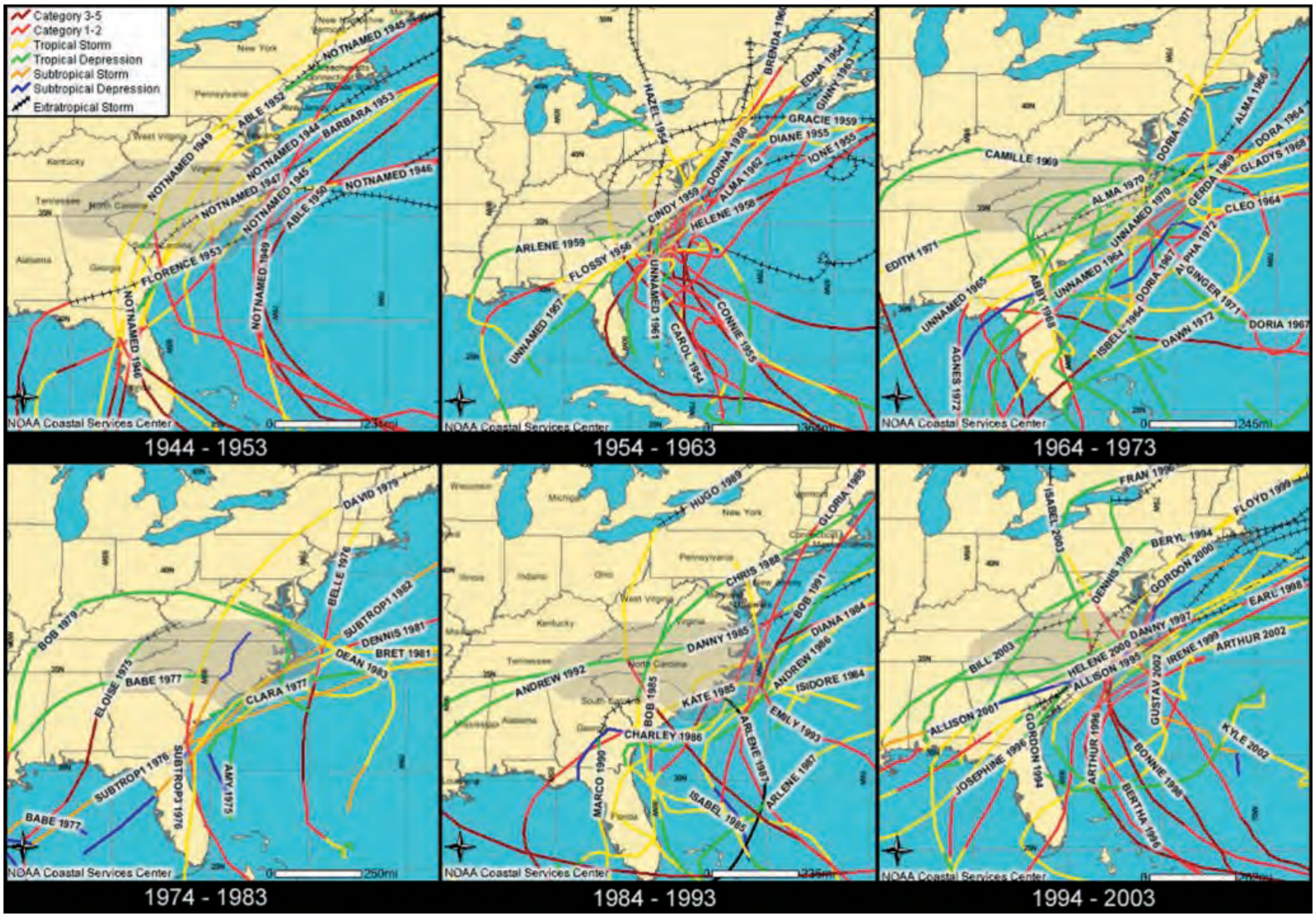

Figure 3. Decadal records for tracks of major Atlantic storms from 1944 to 2003.

A geologically and ecologically important feature of the sound is its lagoonal nature, attributable to the surrounding barrier islands, the Outer Banks. Water exchange with the coastal Atlantic Ocean and nearby Gulf Stream is restricted to three narrow, shallow inlets, leaving the sound with a relatively long residence time (~1 yr) during average years [7]. This provides ample time for resident phytoplankton and vascular plants to assimilate nutrient inputs and is a critical ingredient for the sound's high productivity per unit nutrient input and fertility. However, the long residence time also makes the sound sensitive to excessive nutrient loading and eutrophication [3]. The Pamlico Sound is an important fishing ground and provides critical nursery and foraging habitats for the surrounding Mid-Atlantic fishery [8].

Development in the sound's watershed came later than in some other major estuaries, such as the Chesapeake Bay. Recent (since the early 60's) conversion of watersheds to agricultural crops, intensive livestock, silviculture, and urbanization has greatly increased nutrient loading to the river estuaries of the sound [9, 10, 11].

The Neuse River Estuary is the largest (in terms of water discharge) tributary of the sound. It drains a rapidly growing urban, industrial, and agricultural watershed and illustrates the plight of many coastal river systems under the influence of accelerating nutrient loading. This estuary is approximately 100 km long from its fresh headwaters to the mesohaline (15–25 psu) waters of Pamlico Sound (Figure 5). Its physical, chemical, and biological characteristics have been intensively monitored and are the focus of modeling studies [12, 13]. Primary production in the Neuse River Estuary is strongly controlled by nitrogen inputs [14, 15, 16], which have nearly doubled in the past three decades [9, 10, 11]. Within this time frame, the estuary has experienced multiple symptoms of

Figure 4. Hurricane Isabel struck the North Carolina coast on 18 September 2003. Upper frame: The new inlet that was cut by Isabel's storm surge and overwash of Hatteras Island. Shown are before and after images (courtesy of USGS). Lower left frame: NOAA rainfall intensity image showing Isabel making landfall near Drum Inlet on the Outer Banks. Lower right frame: Hurricane Isabel's northwesterly track across the Pamlico Sound after making landfall.

eutrophication, including nuisance (i.e., toxic and food-web-disrupting) dinoflagellate and cyanobacterial blooms, extensive bottom-water hypoxia, and periodic shellfish and finfish kills [14, 17, 18]. Nonpoint sources contribute about 75% of the external or "new" nitrogen loads, much of it from agricultural activities. Agricultural expansion—including creation of new farm land, widespread use of nitrogen fertilizers, proliferating livestock (swine, cattle) and poultry (chicken, turkey) operations, coastal urbanization, and increasing contributions from groundwater and atmospheric deposition—have led to unprecedented increases in nitrogen loading [19]. Industrial-style farms have increased the region's hog population from approximately 1 million to over 12 million between 1989 and 1999 alone. As a result, land-applied and atmospherically deposited nitrogen inputs to this estuary constitute a large and growing source of externally supplied "new" nitrogen [20].

Eutrophication and algal bloom formation have been linked to enhanced deposition of organic matter [21], leading to growing frequencies, magnitudes, and aerial coverage of large-scale, bottom-water hypoxia and anoxia (Figure 6) [24]. Relatively long water-residence times (from 30 to over 70 days) and persistent stratification

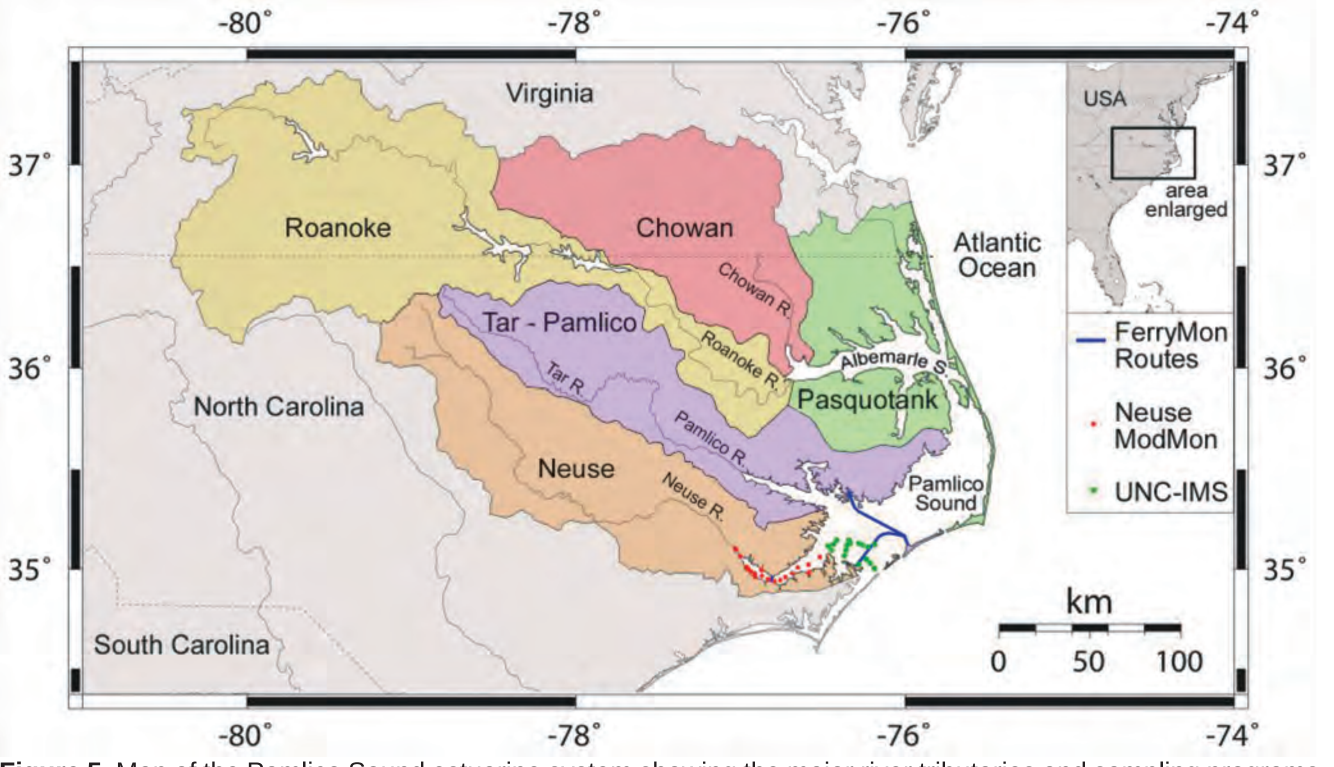

Figure 5. Map of the Pamlico Sound estuarine system showing the major river tributaries and sampling programs for the Neuse River estuary and sound proper.

exacerbate low dissolved oxygen conditions during summer, which can cover at least half the bottom of the estuary [12, 22]. Finfish and shellfish kills have been linked to these events [23, 24].

The water quality monitoring programs used to examine hydrologic and nutrient effects on the Pamlico Sound and Neuse River Estuary (Figure 5) are: 1) The Neuse River Estuary Monitoring and Modeling Program, ModMon (*www.marine.unc.edu/neuse/modmon)* and 2) the Ferry-Based Water Quality Program, FerryMon (*www.ferrymon.org)*. The ModMon program collects near-surface (upper 0.5 m) and near-bottom (0.5 m from the bottom) water quality samples at 19 locations (reduced to 13 in 2003) along the main stem of the estuary. Water quality parameters include: temperature, salinity, dissolved oxygen, turbidity, transparency (vertical attenuation of photosynthetically active radiation), dissolved inorganic nutrients (nitrate/nitrite and ammonium-N, orthophosphate-P, silicate), dissolved organic carbon (DOC) and nitrogen (DON), particulate C and N, chlorophyll *a* (*in situ* fluorescence and extracted), and diagnostic algal photopigments (chlorophylls and carotenoids).

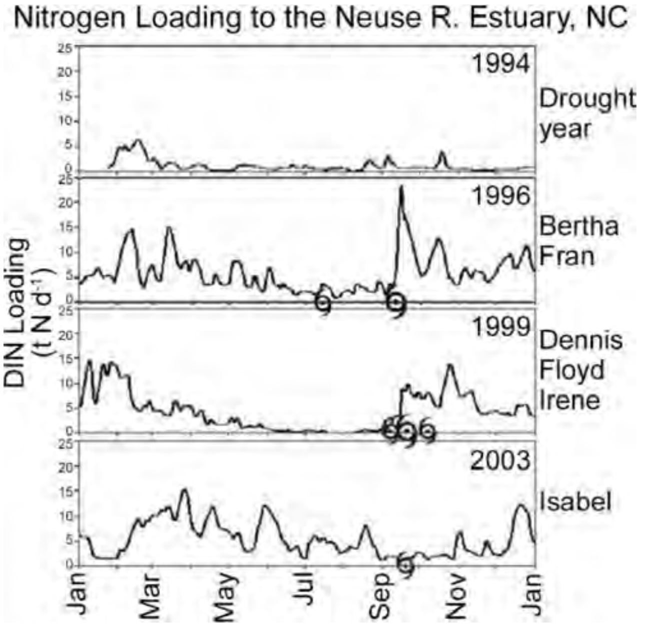

Figure 6. Dissolved inorganic nitrogen (DIN) loading to the Neuse River estuary during selected years reflecting different storm and hydrologic discharge conditions. Loading was calculated by multiplying water discharge at the Kinston gauging station by DIN concentrations at Streets Ferry, the most upstream Modmon sampling site. A relatively dry year (1994) was chosen for comparison. Hurricane landfalls and names are indicated.

Additional data were obtained from the Neuse River FerryMon route with 40 crossings per day (05:00–01:00) between Cherry Point and Minnesott Beach. This representative, mid-estuarine location has periodic algal blooms, low-oxygen bottom waters, and periodic fish kills. It is also a major water and nutrient input source for the Pamlico Sound. Near-surface water quality data were obtained from a continuous flow, automated system using a YSI 6600 multi-probe sensor, which monitored surface waters along the ferry route for temperature, salinity, pH, dissolved oxygen, turbidity, chlorophyll *a*, and geographic position.

ModMon and FerryMon also serve as platforms for collecting data on diagnostic photopigments as indicators of the major taxonomic groups comprising the phytoplankton community (i.e., diatoms, dinoflagellates, chlorophytes, cyanobacteria, and cryptomonads). High-performance liquid chromatography (HPLC), coupled to photodiode array spectrophotometry (PDAS), was used to determine phytoplankton group composition based on the diagnostic photopigments [25]. Pigments include specific chlorophylls (*a, b, c*), carotenoids, and phycobilins. A statistical procedure, ChemTax [26], partitions chlorophyll *a* (i.e., total microalgal biomass) into the major algal groups, to determine the relative and absolute contributions of each group. In the Neuse River Estuary, key photopigment markers include chlorophyll *b* and lutein (chlorophytes); zeaxanthin, myxoxanthophyll, and echinenone (cyanobacteria); fucoxanthin (diatoms); peridinin (dinoflagellates); and alloxanthin (cryptomonads) [27]. The HPLC measurements were also used to calibrate remotely sensed (aircraft, satellite) phytoplankton distributions on the ecosystem and regional scale [13].

RESULTS AND DISCUSSION

The recent period of elevated hurricane landfalls started in 1996 with the arrival of hurricanes Bertha and Fran. Hurricane Bertha made landfall near Wilmington, North Carolina on 14 July 1996, then rapidly moved north just inside the coastline. While its high winds caused significant storm surges, beach erosion, and structural damage, Bertha was a relatively low rainfall storm. The Neuse River freshwater discharge record at Kinston (USGS Station No. 02089500), located approximately 25 km upstream from the entrance to the estuary, showed little impact on hydrologic or nutrient loading to the estuary (Figure 6). In contrast, Hurricane Fran, which struck the coast near Wilmington on 5 September 1996, moved inland and stalled over the Piedmont region. This large, Category 2 hurricane delivered up to 50 cm of rainfall in areas of the Pamlico Sound watershed, causing extensive, long-lasting (4 weeks) flooding in the Neuse River Estuary drainage basin. Discharge from Hurricane Fran contained high levels of nutrients, as reflected in nitrogen loading (Figure 6), and low dissolved oxygen concentrations, with stressful (to finfish and shellfish) hypoxic (<2 mg $O_2 \cdot L^{-1}$) conditions persisting throughout the water column of the estuary for nearly 3 weeks [24] *(www.marine.unc.edu/neuse/modmon).* During this period, fish kills were reported along the entire length of the estuary [24] (Figure 7). Two months after the event, the estuary returned to pre-Fran oxic (>4 mg $O_2 \cdot L^{-1}$) conditions, although higher-than-seasonally-normal freshwater discharge prevailed well into the spring months. This discharge most likely resulted from floodwaters still draining swamps and wetlands, as well as recharge from saturated groundwater sources [28, 29]. Significant residual discharge lasted at least 6 months after Fran. Increased estuarine nutrient loads also resulted. Dissolved inorganic nitrogen (DIN) loading to the Neuse River associated with Fran's floodwaters approximately doubled the annual nitrogen load to this estuary [13] (Figure 6). Fran's nutrient load occurred after the summer optimal phytoplankton production period [24]. Hence, much of this load was not use and flushed into the Pamlico Sound. Unfortunately, the sound was not routinely monitored for water quality until late 1999 (following hurricanes Dennis, Floyd, and Irene).

Hurricane Bonnie, which made landfall near Wilmington as a Category 3 hurricane, was another coastal storm. It rapidly moved up the North

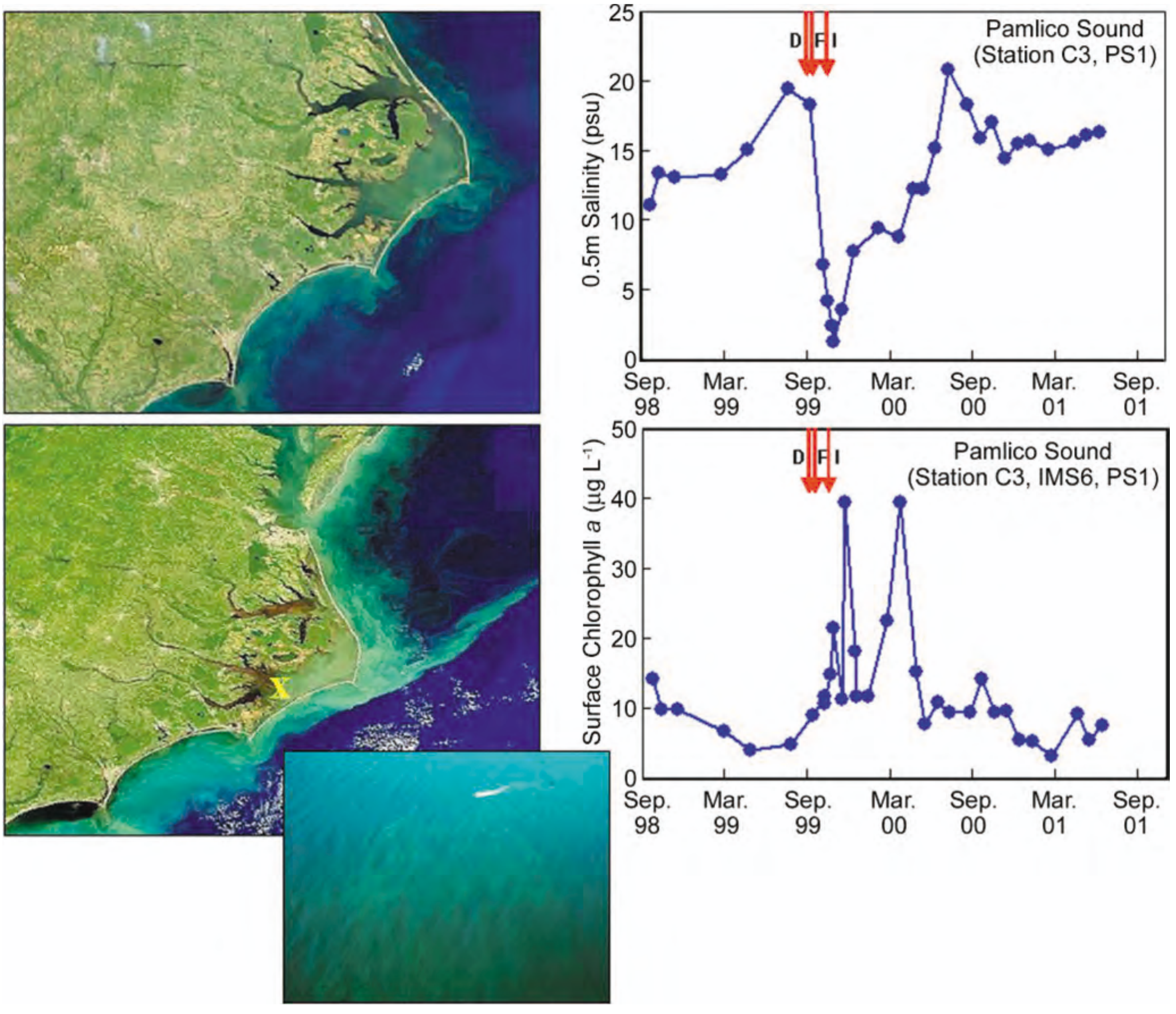

Figure 7. Effects of hurricanes Dennis (D), Floyd (F), and Irene (I) on salinity (psu) and phytoplankton production (chlorophyll *a* concentration) of Pamlico Sound. Upper left frame is a NASA SeaWiFS image of the sound on 16 September 1998, almost 1 year before the hurricanes. Middle left frame is the sound and adjacent coastal ocean on 23 September 1999, approximately 1 week after Floyd made landfall. Note the brown-stained freshwater runoff entering the sound as well as the sediment-laden water flowing from the sound into the ocean following post-Floyd flooding in the watershed. Salinity did not return to pre-hurricane levels at the sampling location (x) for approximately 9 months and elevated chlorophyll *a* concentrations occurred for at least 6 months after this event. Lower left frame shows one of several algal blooms occurring in response to Floyd's floodwaters in Pamlico Sound (note the fishing boat). Figure adapted from [3].

Carolina coast and crossed the western sound with over 45 $m \cdot s^{-1}$ winds, causing widespread structural damage, downed trees, and coastal erosion. Bonnie took a path similar to Hurricane Bertha and likewise proved to be a windy but relatively low rainfall storm. The hydrograph at Kinston showed relatively little freshwater discharge associated with Bonnie. As a result, this hurricane had no detectable impact on either seasonal or annual nitrogen loads to the Neuse River Estuary. While Bonnie completely mixed the waters of the estuary, no significant stimulation of primary production or phytoplankton biomass and no development of hypoxia or fish kills were evident after her passage.

During a six-week period from early September to mid-October 1999, hurricanes

Dennis, Floyd, and Irene inundated eastern North Carolina with up to 1 m of rainfall, exceeding the 30-year average rainfall value by more than 50 cm in some regions of the Pamlico Sound watershed [28] (Figure 7). This led to the "flood of the century" in the eastern part of the state [2]. The sediment- and nutrient-laden floodwaters turned the sub-estuaries of the sound fresh and were equivalent to more than 80% of the volume of the sound [2, 3] (Table 1). The floodwaters caused the sound's water residence time to drop from ~1 year to ~2 months, depressing salinity by 70%. The floodwater freshet entering the sound caused strong vertical salinity stratification, which "locked in" high salinity, nutrient-enriched bottom waters and triggered a very large hypoxia event. An estimated one third or more of the sound's bottom waters was hypoxic to anoxic during the 1- to 2-month period of stratification that followed the flooding [3]. This hypoxic condition would have probably lasted longer if it had not been for Hurricane Irene's winds completely mixing the sound's water column by mid-October. Stressful conditions on finfish and shellfish and an increase in fish disease were reported during the post-Floyd hypoxic period in the sound [3].

The nitrogen load associated with the floodwater was equivalent to at least the annual nitrogen load to this nitrogen-sensitive system [3]. In addition, the floodwaters were highly enriched with organic matter, quantified as dissolved and particulate organic carbon (DOC and POC). Floodwaters transiting the Neuse River Estuary contained up to three times higher DOC and POC concentrations than pre-floodwater discharge [3]. Between September and October 1999, roughly 2000 metric tons of particulate nitrogen (PN) or 60% of the annual freshwater external load entered the estuary [3, 4]. External loading of particulate N was likely an important contributor at the estuary head where productivity rates are typically the lowest [18]. Primary productivity and chlorophyll *a* (Chl *a*) concentration decreased during peak flow. Given the rapid flushing rates and dramatic decrease in residence time, much of this production was likely exported to the sound [4].

In the sound, phytoplankton biomass (Chl *a*) showed a sudden and sustained increase above pre-hurricane levels. This increase was initially documented in monthly surveys using small boats in the western sound and then (starting in 2000) by ferry-based continuous water quality monitoring across the sound [30]. On average, Chl *a* concentrations increased approximately ten-fold, from pre-hurricane levels of 2–5 $\mu g \cdot L^{-1}$ to well over 25 $\mu g \cdot L^{-1}$ after the floodwaters fertilized the sound (Figure 7). Elevated Chl *a* concentrations were observed in the sound as well as the Neuse River Estuary until mid-2000, indicating at least a 6-month period of phytoplankton biomass enhancement. The stimulation of phytoplankton production was accompanied by changes in community composition [4, 27], discussed in the context of the 1996–2003 hurricanes.

These observations indicate that the nutrient load associated with Hurricane Dennis' and Floyd's floodwaters strongly affected primary production, nutrient cycling, and overall water quality of the sound. While hurricane-related floodwaters appeared to have a strong flushing effect on the estuarine tributaries of the sound [3, 4], the Pamlico Sound acted like a trap for the accompanying nutrient loads. These results indicate that hurricanes do not always or consistently have "cleansing" effects on estuarine ecosystems. Rather, they can become nutrient loading sinks or sources, depending on hydrologic, nutrient loading, and within-system cycling characteristics [3, 4].

Most recently, Hurricane Isabel made landfall as a Category 2 storm on 18 September 2003 between Cedar and Ocracoke islands on the Outer Banks. The storm crossed the Pamlico Sound on a northwesterly track, taking it through northeastern North Carolina and the Virginia Tidewater and Chesapeake Bay regions (Figure 4). Isabel's storm surges and high waves caused a breach in the Outer Banks, creating a new inlet near Hatteras Village (Figure 4). Her storm surges also caused extensive flooding and property damage throughout the Bay area. Despite the violent winds, rainfall amounts from Isabel were relatively small (less than 6 cm in coastal North Carolina) (NC Climatology Office,

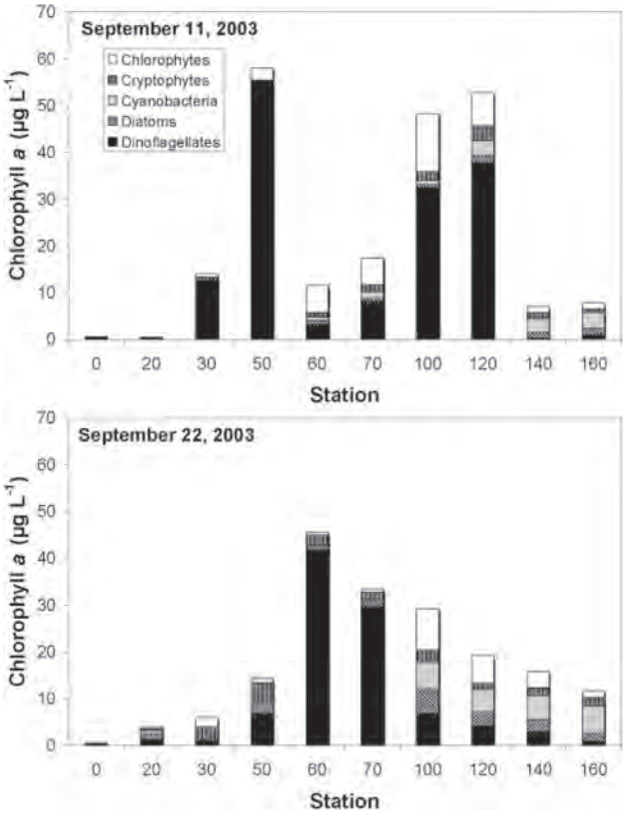

Figure 8. Effects of Hurricane Isabel on phytoplankton biomass (as total chlorophyll *a* concentration) and composition (as the absolute abundance of major taxonomic groups) in the Neuse River Estuary. Values were determined by HPLC-Chemtax analysis. Shown are data for ModMon station locations ranging from the freshwater head of the estuary (0) to the entrance to Pamlico Sound (160). Data are shown for the week prior to and 4 days following Isabel's passage.

NC State University, Raleigh), largely because it was a fast-moving storm. As a result, freshwater discharge associated with Isabel was quite low—comparable with more localized summer-fall thunderstorm activity.

Phytoplankton productivity and biomass responses to Isabel were measurable but small, because little freshwater discharge and nutrient enrichment resulted from this storm. No significant increases in Chl *a* were observed in the Neuse River Estuary following Isabel (Figure 8). Most likely, the lack of phytoplankton growth response to the storm was attributable to the lack of external nutrient loading due to low runoff and the fact that the water columns of these systems were already vertically well-mixed prior to Isabel's arrival. As a result, little, if any, nutrient enrichment of the euphotic, upper water column took place [13].

A different scenario occurred in response to Isabel's passage in the Chesapeake Bay. Aircraft remote sensing and two baywide cruises after this hurricane showed a significant phytoplankton bloom in the mainstem Bay between the York and Patuxent rivers (L. Harding and J. Adolf, personal communication). This bloom appears to have resulted from water column mixing and reintroduction of nutrients to the surface layer. Approximately 7 weeks after Isabel, a large dinoflagellate bloom was observed in the mainstem Bay between the Patuxent and Choptank rivers. This bloom, which lasted for several weeks, proved unusual when compared to historic analyses of the same region during this period (L. Harding and J. Adolf, personal communication) [13]. Mixed-layer depths increased after Isabel, substantially exceeding the mixed-layer depths in a long-term average dataset for some regions of the Bay (W. Boicourt, personal communication). This increase suggests that significant water column mixing occurred, leading to the introduction of subpycnocline nutrients, which helped trigger and sustain this bloom. Although it remains unclear why dinoflagellates specifically took advantage of these conditions, it is evident that long-term averages for the rich and well-documented Chesapeake Bay hydrologic and phytoplankton data can be overwhelmed by episodic events such as hurricanes [13, Roman et al. submitted]. The overall effects of Isabel on phytoplankton dynamics in the Neuse River Estuary/Pamlico Sound and Chesapeake Bay were short-lived, a striking contrast to >6-month stimulation of primary production and phytoplankton biomass in response to nutrient enrichment from Floyd's floodwaters during 1999 to 2000 in both the estuary and the sound.

Impacts of Hurricanes on Phytoplankton, Trophic State, and Habitat Conditions

Data from 1994 to the present show that North Carolina's estuarine systems have experienced the combined stresses of anthropogenic nutrient enrichment, droughts (reduced flushing combined with minimal nutrient inputs), and elevated hurricane activity (high flushing accompanied by elevated nutrient inputs) since 1996. These distinct perturbations have allowed us to examine impacts of anthropogenic and natural stressors on phytoplankton community structure. Seasonal and/or hurricane-induced variations in river discharge with resulting changes in flushing rates (and hence, estuarine residence times) have differentially affected phytoplankton taxonomic groups as a function of their contrasting growth characteristics. For example, the relative contribution of chlorophytes, cryptophytes, and diatoms to the total Chl *a* pool appeared to be strongly controlled by periods of elevated river flow in the Neuse River Estuary (Figure 9). These effects are most likely due to the rapid growth rates and enhanced nutrient uptake rates of these groups [31]. Cyanobacteria, which generally have slower growth rates, were more abundant when flushing was minimal (i.e., longer residence times) during summer (Figure 9).

Historic trends in dinoflagellate and chlorophyte abundance provide additional evidence that hydrologic changes have altered phytoplankton community structure, at least on a seasonal scale, in the Neuse River Estuary. Both decreases in the occurrence of winter-spring dinoflagellate blooms and increases in the abundance of chlorophytes coincided with the increased frequency and

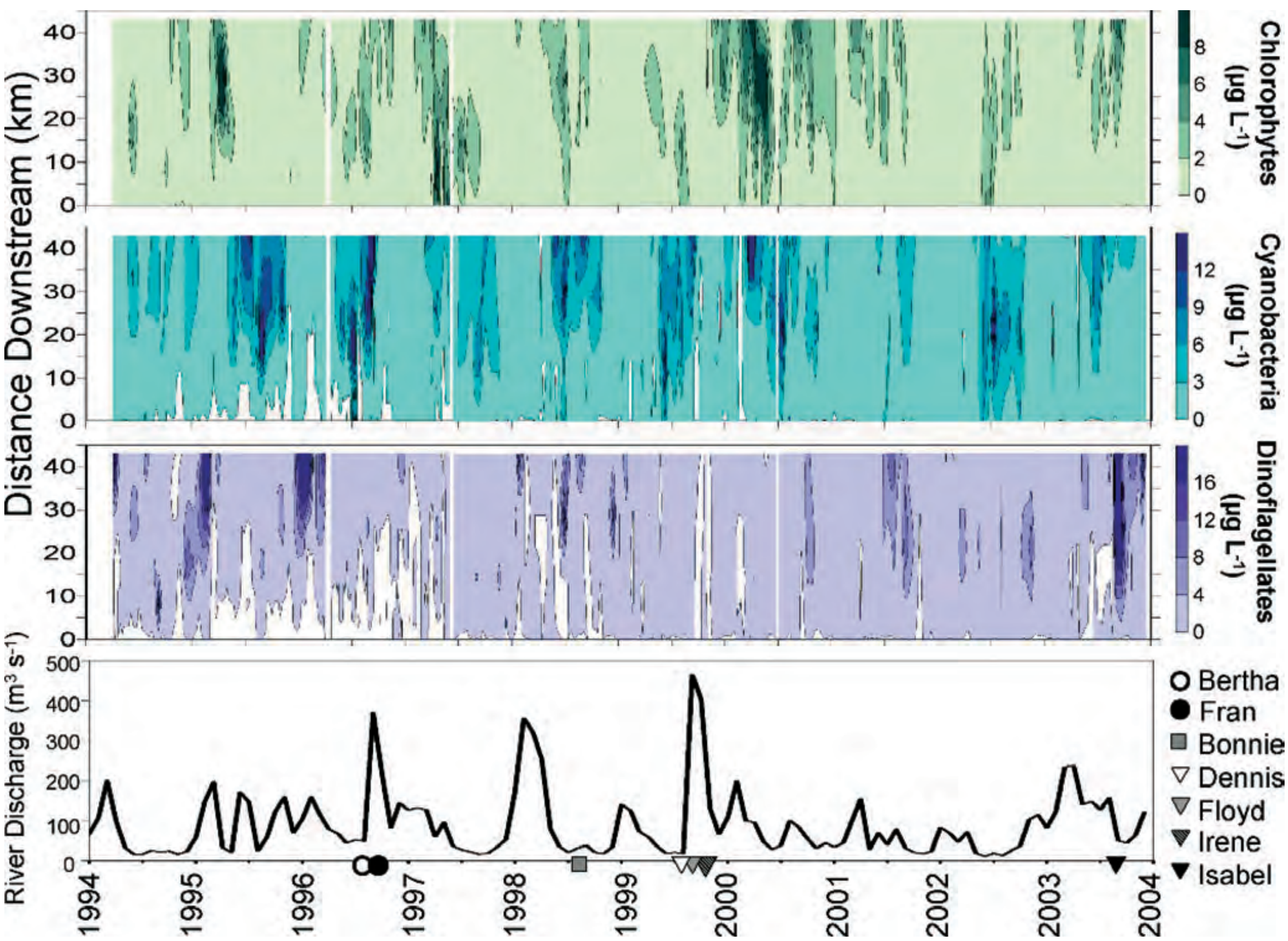

Figure 9. Phytoplankton taxonomic group biomass distributions, based on diagnostic photopigments, from 1994 to 2003 in the Neuse River estuary. Shown are changes in biomass of chlorophytes, cyanobacteria, and dinoflagellates along a segment of the estuary stretching from the most upstream, freshwater location (0 km) to a downstream, mesohaline location (40 km). Also shown is freshwater discharge from the Kinston, NC gauging station and the times of hurricane landfalls. Figure adapted from [13].

magnitude of hurricanes since 1996 (Figure 9). The relatively slow growth rates of dinoflagellates appear responsible for their reduced abundance during the ensuing high-river discharge events. Overall, phytoplankton composition has been altered since 1994 in conjunction with major hydrologic changes, specifically floods following major hurricanes such as Fran and Floyd [13]. These phytoplankton community changes signal potential trophic shifts and biogeochemical alterations.

CONCLUSIONS

Phytoplankton communities are sensitive, relevant indicators of hydrologic and nutrient changes accompanying a recent upward shift in the frequency of Atlantic hurricanes making landfall along the U.S. East and Gulf coasts. A large proportion, from 50% to well over 80%, of primary production sustaining estuarine food webs in these regions is attributable to phytoplankton. Because they dominate within-system production of organic matter, phytoplankton communities supply the "fuel" for respiration and decomposition, the oxygen-consuming processes underlying hypoxia and anoxia in estuarine and coastal waters. Phytoplankton communities also strongly influence the *qualitative* aspects of production and fertility of these waters since not all phytoplankton taxa are alike in how they are consumed and used by consumers, starting with the zooplankton and benthic invertebrate grazers and terminating with finfish and shellfish. In addition, some species of dinoflagellates and cyanobacteria may be toxic, posing additional water quality and habitat problems.

On the whole, hurricanes and other large climatic perturbations—including frontal passages and intense winter-spring lows such as such nor'easters—can have profound effects on altering phytoplankton primary production, composition, and biogeochemical cycling. Some events have more profound and long-lasting effects. These events and critical "drivers" from the ecosystem-response perspective are the duration and amounts of rainfall associated with these events. Storm intensity is another important factor. Clearly, Category 2 or higher storms that move slowly once they make landfall are the most catastrophic from both human infrastructure and ecological perspectives. Overall, results from this synthesis indicate that hydrological and wind forcing assume relatively high levels of importance and must be integrated with nutrient-loading effects in assessing the ecological effects of hurricanes on large estuarine ecosystems.

Because ecosystem response and recovery can take months, if not years, following large storms, careful attention should be paid to the potential long-term, ecosystem-altering effects of the protracted period of elevated hurricane frequency that seems to be taking place [1]. Thus, while estuarine ecosystems are still recovering from one storm, they may be impacted by a new one, leading to long-term biogeochemical and trophic instability. Such instability may mandate close attention from fisheries and habitat managers; unstable conditions may require greater protection of fisheries stocks and resources until a more stable period of fewer and reduced frequency of climatic perturbations is entered.

Based on the findings from Pamlico Sound and prior studies of hurricane impacts in other large estuaries (e.g., Hurricane Agnes on the Chesapeake Bay in 1972 [32]), an increase in major storm activity can cause increased nutrient loading (both external and internal), enhanced algal bloom activity, expansion of low-oxygen conditions, and potential impacts on fisheries. While primary production and standing stocks of phytoplankton may sporadically increase in response to the large nutrient loads accompanying hurricane flood-waters, little short-term evidence suggests that the observed, enhanced primary production of Pamlico Sound translated into increased production at higher trophic levels [3, 17]. If anything, the increased production of phytoplanktonic organic matter adds more "fuel" to support hypoxia and anoxia in the sound's bottom waters and sediments [3]. While increased river discharge can enhance shelf fisheries or anadromous fishes in oligotrophic estuaries, high-discharge events are more likely to have a negative effect in lagoonal estuaries. Flooding not only adds nutrients, organic materials, sediments, and toxic chemicals to estuaries, it also leads to strong stratification of the water column—a prerequisite to low-oxygen concentrations in the bottom water [22], which has proven true for both the Pamlico Sound system and the Chesapeake Bay.

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REFERENCES

1. S.B. Goldenberg, C.W. Landsea, A.M. Mestas-Nunez, and W.M Gray. 2001. The recent increase in Atlantic hurricane activity: Causes and Implications. *Science* 293: 474–478.
2. J.D. Bales. 2003. Effects of Hurricane Floyd inland flooding, September–October 1999, on tributaries to Pamlico Sound. *Estuaries* 26: 1319–1328.
3. H.W. Paerl, J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, J.M. Fear, M. Go, B.L. Peierls, T.L. Richardson, and J.S. Ramus. 2001. Ecosystem impacts of 3 sequential hurricanes (Dennis, Floyd and Irene) on the US's largest lagoonal estuary. *Proc. Natl. Acad. Sci.* 98(10): 5655–5660.
4. B.L. Peierls, R.R. Christian, and H.W. Paerl. 2003. Water quality and phytoplankton as indicators of hurricane impacts on large estuaries. *Estuaries* 26: 1329–1343.
5. P.M. Tester, S.M. Varnam, M.E. Culver, D.L. Eslinger, R.P. Stumpf, R.N. Swift, J.K. Yungel, M.D. Black, and R.W. Litaker. 2003. Airborne detection of ecosystem responses to an extreme event: Phytoplankton displacement and abundance after hurricane induced flooding in the Albemarle-Pamlico Sound system. *Estuaries* 26: 1353–1364.
6. NOAA Natl. Hurricane Ctr. Archives, Miami.
7. L.J. Pietrafesa, G.S. Janowitz, T-Y Chao, T.H. Weisberg, F. Askari, and E. Noble. 1996. The Physical Oceanography of Pamlico Sound. Univ. of North Carolina Sea Grant Publication UNC-WP-86-5. 125 pp.
8. B.J. Copeland and J. Gray. 1991. Status and Trends Report of the Albemarle-Pamlico Estuary. J. Steel (ed.). Albemarle-Pamlico Estuarine Study Report 90-01. North Carolina Dept. Environment, Health and Natural Resources. Raleigh, NC.
9. D.W. Stanley. 1988. Historical trends in nutrient loading to the Neuse River Estuary, NC. In: W. Lyke and T. Hoban (eds.). Proc. American Water Resources Assoc. Symp. on Coastal Water Resources, AWRA Tech. Publ. Ser. TPS-88-1. AWRA, Bethesda, MD. pp. 155–164.
10. R.C. Dodd, P.A. Cunningham, R.J. Curry, and S.J. Stichter. 1993. Watershed Planning in the Albemarle-Pamlico Estuarine System, Report No. 93-01, Research Triangle Institute, Research Triangle Park, NC. Dept. Environment, Health and Natural Resources. Raleigh, NC.
11. C.A. Stow, M.E. Bursuk, and D.W. Stanley. 2001. Long-term changes in watershed nutrient inputs and riverine exports in the Neuse River, North Carolina. *Water Res.* 35: 1489–1499.
12. R.A. Luettich, J.E. McNinch, H.W. Paerl, C.H. Peterson, J.T. Wells, M. Alperin, C.S. Martens, and J.L. Pinckney. 2000. Neuse River Modeling and Monitoring Study (ModMon); Phase 1, 1997–1999. Water Resources Research Institute Report 325B, Water Resources Research Institute of the Univ. of North Carolina, Raleigh, NC. 172 pp.
13. H.W. Paerl, L.M. Valdes, J.E. Adolf, B.M. Peierls, and L.W. Harding, Jr. In press. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. *Limnol. Oceanogr.*
14. H.W. Paerl. 1987. Dynamics of blue-green algal (*Microcystis aeruginosa*) blooms in the lower Neuse River, NC: causative factors and

potential controls. Report No. 229. Univ. of North Carolina Water Resources Research Institute, North Carolina State Univ. Raleigh, NC. 164 pp.

15. J. Rudek, H.W. Paerl, M.A. Mallin, and P.W. Bates. 1991. Seasonal and hydrological control of phytoplankton nutrient limitation in the lower Neuse River Estuary. *Mar. Ecol. Progr. Ser*. 75: 133–142.
16. J.N. Boyer, D.W. Stanley, and R.R. Christian. 1994. Dynamics of NH_4^+ and NO_3^- uptake in the water column of the Neuse River Estuary, North Carolina. *Estuaries* 17: 361–371.
17. R.R. Christian, W. Bryant, and D.W. Stanley. 1986. The relationship between river flow and *Microcystis aeruginosa* blooms in the Neuse River, NC. UNC Water Resources Research Institute. Rep. No. 223. Raleigh, NC.
18. H.W. Paerl, M.A. Mallin, C.A. Donahue, M. Go, and B.L. Peierls. 1995. Nitrogen loading sources and eutrophication of the Neuse River Estuary, NC: Direct and indirect roles of atmospheric deposition. Water Resources Research Report No. 291, Univ. of North Carolina Water Resources Research Institute, North Carolina State Univ., Raleigh, NC. 119 pp.
19. H.W. Paerl, and D.R. Whitall. 1999. Anthropogenically derived atmospheric nitrogen deposition, marine eutrophication and harmful algal bloom expansion: Is there a link? *Ambio* 28: 307–311.
20. D.R. Whitall, and H.W. Paerl. 2001. Spatiotemporal variability of wet atmospheric nitrogen deposition in the Neuse River Estuary. *J. Environ. Qual.* 30: 1508–1515.
21. E.J. Clesceri. 2004. Fate of Watershed-based Organic Matter in the Neuse River Estuary, NC. Ph.D. Thesis, Univ. of North Carolina at Chapel Hill. 215 pp.
22. C.P. Buzzelli, S.P. Powers, R.A. Luettich, Jr., J.E McNinch, C.H. Peterson, J.L. Pinckney, and H.W. Paerl. 2002. Estimating the spatial extent of bottom water hypoxia and benthic fishery habitat degradation in the Neuse River Estuary, NC. *Mar. Ecol. Progr. Ser.* 230: 103–112.
23. H. Lenihan and C.H. Peterson. 1998. How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. *Ecol. Applic.* 8: 128–140.
24. H.W. Paerl, J.L. Pinckney, J. Fear, and B.L. Peierls. 1998. Ecosystem response to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse River Estuary. *Mar. Ecol. Progr. Ser.* 166: 17–25.
25. D.F. Millie, H.W. Paerl, and J. Hurley. 1993. Microalgal pigment assessments using high performance liquid chromatography: A synopsis of organismal and ecological applications. *Can. J. Fish. Aquat. Sci.* 50: 2513–2527.
26. M. Mackey, D. Mackey, H. Higgins, and S. Wright. 1996. CHEMTAX - A program for estimating class abundances from chemical markers: application to HPLC measurements of phytoplankton. *Mar. Ecol. Progr. Ser.* 144: 265–283.
27. H.W. Paerl, L.M. Valdes, J.L. Pinckney, M.F. Piehler, J. Dyble, and P.H. Moisander. 2003. Phytoplankton photopigments as indicators of estuarine and coastal eutrophication. *BioScience* 53(10): 953–964.
28. J.D. Bales, C.J. Oblinger, and A.H. Sallenger. 2000. Two months of flooding in eastern North Carolina, September–October 1999: Hydrologic, water-quality, and geologic effects of Hurricanes Dennis, Floyd, and Irene: U.S. Geological Survey Water Resources Investigations Report 00-4093, 47 pp.
29. H.E. Mew, D.K. Hirth, D. Lewis, R.B. Daniels, and A.J. Keyworth. 2002. Methodology for compiling ground water recharge maps in the Piedmont and Coastal Plain provinces of North Carolina: NC Dept. Envir. and Nat. Res. Ground Water Bulletin Number 25, 68 pp.
30. C.P. Buzzelli, J.R. Ramus, and H.W. Paerl. 2003. Ferry-based monitoring of surface water quality in North Carolina estuaries. *Estuaries* 26: 975–984**.**
31. J.L. Pinckney, H.W. Paerl, M.B. Harrington, and K.E. Howe. 1998. Annual cycles of

phytoplankton community structure and bloom dynamics in the Neuse River Estuary, NC. *Mar. Biol.* 131: 371–382.

32. E.P. Ruzecki, J.H. Schubel, R.J. Huggett, A.M. Anderson, M.L. Wass, R.J. Marasco, and M.P. Lynch (eds.). 1976. *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*, Chesapeake Research Consortium Publication No. 54, Johns Hopkins University Press, Baltimore, MD.

History of Regional Storms and Hurricanes

STORMS: A LONG PERSPECTIVE FROM HISTORY

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ABSTRACT

Historical accounts from early seafarers and regional inhabitants of the Mid-Atlantic suggest that hurricanes and storms posed grievous conditions for the first settlers in the region. Seafarers were at the mercy of winds and waves, often surviving only through diligent and continuous bailing and luck, ultimately to ground near hospitable islands, such as Bermuda or barrier islands such as Assateague, Virginia. Recounts of colonial storm surges describe mass flooding and extensive sediment deposition. More recent Chesapeake reports rely on a vanishing oral history and accompanying local landmarks of flood heights, indicating the importance in recording regional history as baseline data for contrasting the most recent effects of large storms with those of the last century. Even until the 1930's, these storms came as an unpredicted surprise. With the ongoing practice of constructing buildings in vulnerable shoreline areas, future hurricanes and other large storms will likely continue to periodically wreak havoc on personal property and communities.

INTRODUCTION

Many modern citizens of the Mid-Atlantic region suffered major personal property loss during Hurricane Isabel for the first time in their lives. Isabel, however, was certainly not the first major storm to affect the Chesapeake area. This paper compares Isabel with other storms in Bay history, but since it is based on a talk than rather than a documented manuscript, it differs from other contributions in this proceedings volume.

The paper highlights several points based on Isabel's passage. First, early Chesapeake visitors registered shock to the major weather events they encountered, similar to the reactions of today's citizens to Isabel. Their valor and strength under adversity are models to compare with our pampered existence today. Second, the escalation of storm impacts measured in the colonial literature seems to have increased the severity of flooding as settlement density and the value of coastal property increased, the number of people recording incidents multiplied, and damage to the naturally resilient ecosystem mounted. Third, within the memory of living persons, it is possible to reach back before real understanding of storm tracks and beyond the social warning systems of radio and television relied upon today. The perspectives of individuals coping with the damage of hurricanes coming as a complete surprise are useful in interpreting modern outcries against meteorological uncertainty.

Although arguments continue about the credibility and reliability of modern forecasting, people of the 17th century had not a clue about such things. John Smith, the English explorer who is generally credited with opening the Chesapeake to European eyes, did not have to deal with this kind of second-guessing. He told his life history and embellished his record of personal valor as the occasion warranted; *everybody* remembers him. But, he had no idea in 1607 what a hurricane actually was nor had he, or any of the Virginia colonists, any sense of where major storms originated or how they traversed the region.

None of the early explorers possessed the knowledge to read the signatures of tropical storm effects in the Chesapeake forests around them. With modern eyes, the satellite image records for the past 20 years show the signature claw marks within the region's forest that denote the passage of tornados. Although highly localized, tornadoes are catastrophic events that radically alter the immediate ecosystem for decades and perhaps centuries. Unlike the early colonial era, when such touchdowns land atop residential and commercial properties today, the strikes become marks of human and personal property devastation.

THE WRITTEN RECORD

Sea Venture and The Tempest

It is fortunate that several written records survive from the early years of European contact with the East Coast. They come to us mostly as harrowing personal accounts. William Strachey wrote of one storm late in July of 1609—a storm that was apparently recurving away from this coast and centered east of Bermuda by the time Strachey encountered it.

Because they are largely encircled by reefs impassable even to small vessels in heavy weather, the Bermudas were known to mariners as the "Devil's Isles," an area much feared as a place of disaster rather than salvation. The *Sea Venture,* the ship on which Strachey sailed, cruised into the "dangerous quarter" of the storm at about 33 degrees north latitude. The storm pounded the vessel for three days and four nights. To preserve the ship, they ran before the gale, which (without knowledge of the storm's structure) kept them trapped in the strongest winds swirling about the eye and spiraling towards the center. The tale makes for fearful reading as Strachey attempts to describe the tumult [1]:

. . .if at any time we bore but (a scrap of sail). . .to guide her before the sea, six and sometimes eight men were not enough to hold the whipstaff in the steerage, or the tiller below in the gunner room: by which may be imagined the strength of the storm, in which the sea swelled above the clouds and gave battle unto Heaven."

The violent wrenching literally worked the caulking out of *Sea Venture's* seams; the crew was sent creeping below decks with candles to look for leaks and staunch them with anything at hand. In the gunner's room, one huge leak was stuffed with "I know not how many pieces of beef," but somewhere deep in the ship, a massive leak kept the waters rising.

The pumps began bringing up pieces of biscuit, from the 10,000 pounds of stores the ship was carrying to starving Jamestown. The ship's carpenter "tore apart the whole breadroom but found (the leak) not." Along with the crew of 30, 120 additional people (most of whom had never been to sea) were desperately bailing and trying to stay alive. The water was five feet deep above the ship's ballast. A huge rogue wave—an unpredictable and abnormally large surface wave—completely buried the ship from her forecastle over the entire waist or central decks. The crew thought the ship was so long submerged that she would simply sink, but slowly *Sea Venture* labored up again, still floating.

When the superstitious seamen saw electrical discharges at the rigging, "St. Elmo's fire," they thought it forebode inevitable death. Every hour, the passengers bucketed 7200 to 8000 gallons of water overboard and they had three deep pumps in continual operation pumping 4000 strokes at each 4-hour watch. Strachey estimates this freed the ship of a hundred tons of water six times a day! And *still* she was sinking. Only one person flagging of resolve, Strachey said, and the ship would instantly sink. The water in the ship's hull was 10 feet deep.

By Friday, the fourth morning, they were close to exhaustion. They agreed by that night, they would simply shut up the hatches and:

"commending our sinful souls to God, committed the ship to the mercy of the gale. Surely that night we must have done it, and that night had we then perished. But see the goodness and sweet introduction of better hope by our merciful God given unto us: Sir George Somers, when no man dreamed of such happiness, had discovered and cried land."

Chance, along with the circling path of hurricane winds, brought them to the east side of

Bermuda. They ran *Sea Venture* between two rocks, where she jammed and remarkably failed to break up. The lot of them—men, women, and children "to the number of about 150"—dragged ashore with tools and made numerous trips back to salvage parts of the ship.

They found the Bermudas not at all the Devil's Isles, but hospitable and mild of climate. They provisioned on hogs presumably turned loose by Spanish rovers years before to forage and breed there for future mariners. But they also harvested a strange and foolishly tame burrowing bird, the cahow, from a few of the isolated Bermuda islets where the hogs, those "invasive, non-native introduced predators" could not reach.

The group encamped there well into the following year, eventually building two small ships from what they had salvaged from *Sea Venture*. Provisioning for their subsequent voyage to Jamestown, they salted down a bunch of cahows and set off, expecting to join a thriving colony in the Chesapeake. Instead they found the settlers near death from starvation, disease, and harassment by the Native Americans at Jamestown. Ever resourceful, the new arrivals shared what remained of their travel provisions, including the salted birds, with their distressed brethren. In the last few years, archaeologist Bill Kelso and colleagues excavated the old 1600's fort and found the bones of some of these birds in a garbage pit—provisions shared with the starving Jamestown colonists by their miraculously preserved and resourceful countrymen.

The poor, oceanic nesting cahow birds (*Pterodroma cahow* or Bermuda petrel), were simply hunted and smashed by future generations of Bermudans until no more existed. Then, in 1951, David Wingate discovered 18 nesting pairs on a rocky islet off Bermuda and subsequently devoted his life to nursing the species back to a modestly successful colony (about 180 individuals in 2003).

As a postscript, Smokey Wingrove, a scuba diver and amateur historian, stared out at the east coast rocks in Bermuda for many years and finally determined which ones had caught the hull of *Sea Venture* that July day centuries before. He found the wreck and participated in the archaeology of the ship, helping to uncover the full effects of a hurricane almost 400 years ago. Bill Dennison (co-host of this conference) was at the Bermuda Biological Station some years ago. He SCUBA-dove to the wreck of *Sea Venture* and, from the underwater perspective, confirmed how extraordinary it was that the ship became cradled between these two supporting rocks [2].

Strachey ultimately stayed in turbulent and politically unstable Virginia for a year or so and was appointed secretary of the colony. In this capacity, he left us with one of the best period records of colonial business, the environment, and Native American customs. At the excavation of the Jamestown Fort in 1996, a brass finger-ring was found in carefully sifted soil from the street. The find was a signet ring used to press into the wax dripped to seal official correspondence. The logo on the ring—a displayed eagle with a cross on its breast—turned out to be the family emblem of William Strachey.

The storm and survival of the ship's crew and passengers, described by William Strachey, was published in 1610 in London from a manuscript that he sent back by sea as a "true reportory" of the voyage [1]. The story created a sensation in England and was key in the creation of a play *The Tempest* by one William Shakespeare. Shakespeare refers to the dreaded "Barmoothos" isles and almost quotes Strachey's words in describing *his* tempest.

Norwood's Storm

Col. Henry Norwood wrote about a huge storm that also apparently missed the East Coast in late autumn 1649 [3]. The storm could have been a hurricane or a late extratropical cyclone. Norwood, his servants, and a party of colonists about *The Virginia Merchant* were also pounded at sea for days on end with every soul aboard bailing with buckets day and night with no food. The crew abandoned hope and breached the rum casks, intent on drinking themselves into a stupor to dull the prospects of drowning.

They stopped a leak discovered far below by the bos'n as he listened for the rush of water with a rod pressed to his ear. In all that turmoil, the ship barely made it with hardly a mast or sail left. The captain had aimed for capes Charles and Henry to enter the Chesapeake, but ended up against the Delmarva barrier islands close to Assateague. Norwood and several passengers, ashore for fresh water, were literally abandoned by the crippled and still sinking ship as it fled south to Jamestown.

Several of them died—and some were eaten by their fellows—before Indians rescued them. Their rescuers led them on an arduous 50-mile trek by foot through the wetlands in January, finally arriving at an English plantation. Norwood, in addition to providing a rousing tale of survival at sea and an epic journey in the depth of winter, also gives us our first written record of the trackless cypress swamps and wet woodlands of the Maryland and Virginia Eastern Shore. He was glowing in his praise of the humanity, generosity, and heartfelt sympathy shown them by these Native American tribes.

The Tobacco Coast

In his epic book *Tobacco Coast* [4], the premier maritime historian for the Chesapeake, Arthur Pierce Middleton, wrote about the river basins being settled and put under tobacco cultivation as well as the impact of major storms and freshets that tested the wisdom of how far down on the floodplains colonists dared develop. It is not known, of course, how many of the storms recorded by early colonists were really hurricanes, though the dates give a good idea. Whether the storms turned into extratropical cyclones or maintained their structure and wind velocities is unanswerable.

Hurricano is thought to be an Arawak (that is, Caribbean Native American) word picked up by the Spanish. Middleton reports the worst storm of the period, which they called the great "Hurry-Cane," occurred in August 1667 with a 24-hour dwell time over the Chesapeake. The wind started northeast, backing north, and then to the southeast. One estimate was that 10,000 houses in the tidewater region were destroyed along with two-thirds to four-fifths of the crops by flooding and some hail.

The Damage Grows

"A most dreadful hurricane [modern spelling]," the worst since 1667, came in 1769. By this time, damage began taking a larger toll especially on shipping with nine ships and all the small craft driven upon shore, in addition to agricultural losses. As the basin was opened to agriculture and logged of its forests, flood heights seem to have increased. When John Smith first visited the fall line of the James River, he very perceptively estimated (using marks visible on trees and rocks) that the river rose about 8 feet in flood. By 1771, the Gazette documented a flood "20 feet higher than the one in 1766," "the greatest fresh in James River ever known" [4]. The 1771 flood deposited 10 to 20 feet of sand, covered with a near-pavement of stones, on former farm fields. A ship at Warwick sounded at the peak and found the water exceeded "the common tides by more than 40 feet," having risen at one point at the rate of 16 inches per hour.

Through correspondence with friends in different cities during the 1700's, Ben Franklin worked out that a storm experienced in New York was the same one that had been to the southwest over Philadelphia a couple days earlier. Even by the 1933 and 1938 hurricanes, however, the impact on waterfront communities here in the Chesapeake was still largely one of surprise. The networks to predict storm paths were simply not there; while someone might telephone New York about a storm, there simply was no way at the time to tell where it was headed.

MODERN MEMORY

Homegrown Stories

Annie Murphy Jones today runs tiny Tom Jones' Store at Wingate on the Honga River. During Isabel, several inches of water had come into the store and a boat had floated up and been stranded beside the road outside.

"I got it mostly dried out now, except in there," Annie said, gesturing to a lower room where the water had been deeper. Everything was similar to the year before, except where the floorboards had swelled and buckled from the water, a neighbor had taken a plane to level the boards off so the cat's bowl would sit square next to the kerosene stove.

Annie is a well of information about the early 20th century on this part of the "shore." In the very earliest days of radio here, Annie's father had a tuner that he would fire up using storage batteries in the back room (eventually recharged by a little windmill), and the children were shushed while the vacuum tubes glowed and he sat in his easy chair to listen to the crackly news. He focused even more intently on the evening comedy broadcasts, laughing in sync with thousands of families all over America to the jokes of "Fibber McGee, Lum 'n' Abner" and, Annie says: "what was that last one? "Amos and Andy. Oh! He loved them shows. . . ."

Radio provided no warning in 1933 when one August morning Mr. Murphy readied, as usual, to go off to his job at the little branch bank. There was a nor'easter, Annie said, some wind, but not much rain. "Oh no you're not," his wife lectured, "(unless) I'm going with you." Mr. Murphy looked out the window and saw the tide had already surrounded their chicken house. He told Annie's brother to go out and get the chickens, but before he could, Annie said: "a wave of water came out of the ditch and rolled the little coop over."

They thought their four cows must be drowned, but the animals swam up and rested their heads on the roof of a shed. Murphy's house was a bit higher than a neighbor's where water was coming through the windows. They dragged the non-swimming wife over, towing her through armpit-deep water while she wailed, "I won't live! Oh! I'm gone," and up the front walk where there were two gates, about 5 feet high. "Only this much was showing," Annie shows, measuring an inch and a quarter with her fingers. A buy-boat (one of the big-decked brogans or bugeyes, rigged down with power to transport oysters) floated up nearby and the men all went down to push her back into the creek before the tide went out.

Since she was living in the same house during both storms, Annie tried to compare the '38 storm with Isabel. The gates were gone, so she could not compare sea level rise based on that criterion, but a few years ago when she broke a hip, a small third step was put in at the top of her entry. During Isabel, the tide rose up high enough that this step, level with the flooring inside, floated off. The water was just at the height of the floor joists—about what is expected given a sea level rise of some 6 to 8 inches over the previous 69 years—but it did not seep inside to soak her rugs. She shook her head, contemplating a next time. "I'm too old to haul all that stuff outside to dry at my age!"

One difference: back then residents didn't have electricity for lights or refrigerators in their home. They had literal iceboxes to which blocks of ice were carried by hand from the soft crab packing house in Wingate. Even the rare wealthier families with refrigerators had "Kelvinators" in which the motor, condenser, and washbasket-sized coils were on top. Today, wise engineers (who have never been through a flood) place the motors on the bottom, where even a few inches of salt water spell doom.

Back then, coal furnaces or woodstoves both operated entirely on mechanical principals, with no electricity needed. Lighting was by kerosene; the best was an Aladdin lamp with a high-temperature mantle replacing the usual wick. As rural electrification expanded in later years, much of the wiring and heating plants in older homes was placed in basements with outlets sometimes a mere 10 to 12 inches off the floor. A foot of flooding means salt water in the junction boxes. Sheetrock at floor level is also a disaster. Whole-house air-conditioning units are mostly on concrete pads at ground level. Neighborhood electrical transformers, for small housing clusters where the wiring is underground, are also at ground level.

One of the classic books on the Chesapeake is Gilbert Klingel's *The Bay* [5], a touchstone of what this great estuary was in the early decades of the 20th century. Klingel's daughter, the remarkable Marcia Benouameur, lived on the water at Gwynn Island in a century-old waterman's house that she and her husband Clint White had upgraded. Their home was devastated by Isabel. They had never dreamed that water could rise high enough to enter the house, taking out electricity, water, and buckling the wide board floors that they had just sanded and varnished. An oriental chest that her father had brought back from the Far East, full of family linens and lace from generations ago, had swelled shut, trapping all these soaking wet treasures to fester and mold. A year later, the two were just beginning to get back on their feet after the expenditure of many thousands beyond insurance coverage.

Of Piers and Such

Recent hurricanes have also affected other structures, such as piers. Modern piers are often built without regard to long-term tide records. Many boats, essentially unsecured atop their electric boatlifts, floated away or were holed and sunk during Isabel. Tide staff records taken for 26 years at Osborn Cove in southern Maryland indicate that the pier there flooded just a few times in more than 2.5 decades. When the pier did flood, the poorly nailed boards flopped up and down like piano keys.

The wood making up the pier planks bears mentioning. It was heartwood red oak. At the time of the dock's death, 75 of the 50-year-old planks were still original. One has 42 annual rings across a diameter of 104 mm, showing growth of 2.4 $mm \cdot yr^{-1}$ and indicative of old growth forest. Modern 2 x 4's have 13 rings in the same diameter.

In the early 70's, boatbuilder Billy Kinnon at Benedict on the Patuxent replaced his dock and specified only heartwood oak. The "sapwood" that someone had used the previous time had quickly rotted away. He paid 23 cent a board foot for the new stuff from a sawmill up the road. Outside of some fine woods purveyor, you would have a hard time trying to buy that quality wood today. The similar modern dock plank is fast-grown plantation pine or fir, about 20% thinner in cross-section and with approximately 13 rings in the same diameter. It costs about $1.80, a little more than two times the price for 20% less wood and less than one-third the quality.

In the old days men built their own docks. Now, the number of docks belonging to passive, unhandy owners is astronomical. About 100 Patuxent River docks in the first six miles above Solomons, Maryland were hammered to pieces by Isabel-generated waves, probably a half-million dollars worth of damage for the docks alone.

In reconstructing the author's pier, a safe margin was left to protect against flooding, building a foot or so higher than either the original pier or the neighbor's dock built in 1932. Isabel still exceeded the chart by a couple of feet, so the perspective for planning has to be extraordinarily long.

Recent Reports

By 50 years ago, newspapers were reporting named storms. Some newspapers from Calvert County, Maryland reported the devastation from Hurricane Hazel in 1954. In one, the reporter noted that she caused "thousands of dollars in damage" [6] and when the weekly paper went to press, the list of barns blown over and trees toppled onto houses was still growing. Many losses may never have been reported, so the total number of wrecked farm structures or lost boats was probably never fully reckoned. A week or two later, the same paper wrote about farm loans available from the government to help those who sustained farm losses [6]. By and large though, people simply dug in and rebuilt things on their own, dried out their salvageable possessions, and went on with it.

Looking back to Gordon Whitney's estimates of storm habitat disruption in the primeval forest, he suggests that in the northeast the blowdown cycle for an individual section of forest occurred over hundreds of years. Maryland forester Dan Boone says that the tree crowns of virgin timber stands were so high that they were subject to wind throws at the rate of about 2% to 3% each year; this downing of trees kept enough forest openings so that edge habitat and successional species made the woods diverse and always in some kind of flux.

But, clear away 40% of the tree cover for agriculture and other uses, and later convert a good portion of this land into urban and suburban development, and there is a serious problem. The same forces of destruction now visit $300,000 and higher-value houses along with $10,000,000 big-box stores. The region is certainly dealing with significant sea level rise (Annie Jones' front porch demonstrates that!) and global warming may be increasing the frequency and intensity of tropical cyclones, but independent of those factors our decisions underwrite our own fates.

ON TO THE FUTURE

The NOAA's Michael Glantz, who writes for the ENSO Signal Newsletter, says that the Weather Channel probably coined the notion of "superstorms" in describing the March 1993 blow that struck the East Coast. He tended to pooh-pooh that notion a bit, but then conceded that the storm had indeed been more severe than anything in the previous century in terms of overall impact. He concludes that with advance forecasts as well as satellite and instrument records, it is now possible to set criteria and really evaluate these signal events. He hopes, as we all do, that such analyses can remain independent of political posturing on the reality or fiction of global warming and climate change. He has a good point.

As a society, as well as from the federal, state, municipal, and individual perspectives, our stupidity and stubbornness are incredible. More and more valuable property is placed close to the shoreline, where hazards even from normal erosion exist, thus assuring catastrophe whenever natural events decree.

All across the landscape of this watershed, the unwise and apparently uncontrollable sprawl of development practices have heightened the probability that communities will be in harm's way, and that we will all hear of these events and disasters in real time. Modern communication virtually assures that most of the disasters will be sensationally publicized and that the dollar costs of damage well documented. Unfortunately, the region seems trapped in this conundrum with little remedy in sight.

REFERENCES

1. W. Strachey. 1964. In: *A Voyage to Virginia in 1609*. L.B. Wright (ed.). University of Virginia Press. Charlottesville, VA.
2. S. Wingrove. 1996. Pers. interview. Bermuda.
3. Col. H. Norwood. 1649. A Voyage to Virginia. In: *Tracts and Other Papers Relating Principally to the Origin, Settlement and Progress of the Colonies in North America*. P. Force (ed.). 1844. Washington, D.C.
4. A.P. Middleton. 1984. *Tobacco Coast*. Johns Hopkins Press. Baltimore, MD.
5. G.C. Klingel. 1951. *The Bay*. Dodd. Mead and Co. New York. 278 pp.
6. *Calvert Independent*. 2004. Reprint of 50-year-old front pages.

AN UNPRECEDENTED SCIENTIFIC COMMUNITY RESPONSE TO AN UNPRECEDENTED EVENT: TROPICAL STORM AGNES AND THE CHESAPEAKE BAY

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ABSTRACT

In June 1972, the remnants of Hurricane Agnes brought destructive floods to the watershed of the Chesapeake Bay basin. Unlike Hurricane Isabel, Agnes did not strike Chesapeake Bay directly, but deposited a record amount of rainfall on the watershed. The evening that the Agnes rainfall began in earnest coincided with a meeting of the Citizens Program for the Chesapeake Bay. The directors of the three largest Chesapeake Bay research institutions, Drs. Donald W. Pritchard, L. Eugene Cronin, and William J. Hargis Jr., were in attendance at this meeting. The potential magnitude of the Agnes rainfall was readily apparent at the meeting as one of the planned evening events had to be moved due to a foot of water in the meeting room. The following morning at breakfast, the three directors committed their institutions to "Operation Agnes," extensive studies of the biological, chemical, and physical impacts of this event.

Hargis, Cronin, and Pritchard were good friends and strong competitors of long standing. Since 1949, Pritchard had been the first full-time director of the Chesapeake Bay Institute (CBI); Cronin had headed the Chesapeake Biological Laboratory (CBL) since 1951; and Hargis had been director of the Virginia Institute of Marine Science (VIMS) (and its predecessor the Virginia Fisheries Laboratory-VFL) since 1959. In 1964, the three directors had set up an informal Chesapeake Bay Research Council (CBRC) to coordinate some of their Chesapeake Bay research activities. They used the CBRC mechanism to coordinate "Operation Agnes," a commitment that was made without any assurance of financial support for these studies. The gamble taken by the three laboratory directors was successful, eventually resulting in a peer-reviewed book published by The Johns Hopkins University Press entitled *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*.

Operation Agnes was the last project undertaken by the CBRC. Reorganization by two of the parent institutions and incorporation of the Chesapeake Research Consortium (CRC) resulted in a realignment of Chesapeake Bay scientific leadership and the leadership of Operation Agnes moved from CBRC to CRC.

The scientific community's response to Tropical Storm Agnes—an unprecedented event—was in itself unprecedented. A number of coincidences came into play: recent (1969) experience with flooding from Hurricane Camille; fortuitous attendance of the leaders of the three largest Chesapeake Bay research institutions at a meeting directly affected by Agnes; and the prior mobilization of the three institutions to conduct extensive hydrographic studies throughout Chesapeake Bay. The most important factor, however, was the strong commitment of three laboratory directors to the understanding of the Chesapeake Bay system.

The Event[1]

In June 1972, the remnants of Hurricane Agnes reached the Chesapeake Bay region as a tropical depression with winds of less than 39 mph

[1] *Information in this section was primarily developed from the summaries of Agnes impacts produced by the Chesapeake Bay Research Council and the Chesapeake Research Consortium [1, 2].*

(63 km. As it passed through the Chesapeake region, it picked up strength from coastal waters and again became a tropical storm. From 21 through 23 June, rains directly attributed to Agnes reached the Chesapeake basin, falling on a watershed already saturated with precipitation dropped by a cold front that produced rainfall of 2.5–7.5 cm with isolated stations reporting up to 15 cm. Agnes produced measured rainfall over the entire watershed in excess of 13 cm with about a third of the area receiving more than 30 cm from June 21–23, 1972. Other storms, such as Hurricane Camille (August 1969), had produced greater rainfall at selected stations, but no recorded storms had produced the amount of rainfall that fell over such a large area as Agnes.

This record rainfall resulted in immediate flooding of the major Bay tributaries; most rivers crested at record levels. Peak normalized flow [Normalized flow = (average flow for a period)/(normal average for the same period)] was rapid and exceeded 60 in the James and Rappahannock rivers, slowed to 30–40 in the Susquehanna and York rivers, with the Potomac falling between the two. Flow rates also decreased faster in the James and Rappahannock rivers compared to the York and Susquehanna rivers. Salinities were depressed throughout the system for extensive periods of time. The floods of Agnes were estimated to be a 1-in-200 year event.

Unlike Isabel, winds were relatively low during Agnes, seas were not unusually high, and shore erosion in the tidal Chesapeake remained relatively low. Large quantities of sediment, however, were stripped from the watershed and transported to the tidal Chesapeake. In ten days, an estimated 31 million metric tons, compared to an average annual discharge of .5–1 million metric tons, flowed down the Susquehanna River over the Conowingo Dam at the head of the Bay. Deposition over some areas of the upper Bay was 15–25 cm, with up to 1 meter in channels. Rappahannock River sedimentation from Agnes amounted to between 2 and 7.5 mm, equivalent to about one-third of annual deposition. The extensive runoff also resulted in unseasonably large increases in nutrients, particularly nitrogen. This nitrogen was rapidly tied up in the sediments, with the majority of nitrogen remaining in the estuary and not transported to the Atlantic. Release of nutrients from the sediments in the following year resulted in extensive blooms. Dissolved oxygen concentrations were depressed both in the Bay and its tributaries, with the extent of depressed-oxygen waters much greater than normally found in summer months.

The entire biological community was disrupted to some extent. Soft-shell clams and oysters were the hardest hit shellfish. Blue crabs were initially thought to be displaced like finfish populations, but subsequent analyses of blue crab reproductive patterns indicated a major shift in 1972. Oyster drills, molluscan predators of oysters and other shellfish, were essentially eradicated in the Rappahannock and Piankatank rivers and severely depleted in the James and York rivers.

Aquatic vegetation was severely impacted. Hardest hit was eelgrass, which was reduced by about 89%. For all species combined, reduction was about 67%. In the tributaries to the lower Bay, eelgrass has not recovered to pre-Agnes levels through 2004.

Impacts to benthos and phytoplankton were most severe in the polyhaline zones. Many of these species were eliminated from their normal range. Fewer organisms from the mesohaline and oligohaline zones were as severely impacted and many actually extended their normal ranges downstream.

Economic losses in the tidal Chesapeake and its tributaries related to Agnes were estimated at $42.7 million in 1972 dollars (about $185.4 million in 2003 dollars.)

THE SCIENTIFIC COMMUNITY RESPONSE

In 1972, research in the Chesapeake Bay was dominated by three institutions: the Chesapeake Biological Laboratory (CBL) founded in 1925, the oldest of the three and the largest unit of the University of Maryland's Natural Resource

Institute; the Virginia Institute of Marine Science (VIMS), which had been founded in 1940 as the Virginia Fisheries Laboratory; and the Chesapeake Bay Institute (CBI), a unit of The Johns Hopkins Institute which had been formed in 1948 with equal funding from Maryland, Virginia, and the Office of Naval Research.

In 1964, the long-time heads of these three institutions—Dr. Donald W. Pritchard, the first permanent director of CBI (appointed 1949); Dr. L. Eugene Cronin, second permanent director of CBL (appointed 1951); and Dr. William J. Hargis, Jr., the fourth permanent director of VIMS (appointed 1959)—executed a memorandum of agreement which established a Chesapeake Bay Research Council (CBRC). This agreement replaced the compact that governed the funding and operations of CBI, which had by then fallen into disuse.

Under this collaboration, the three institutions developed several agreements related to data collection, data storage, and data sharing. With the advent of the US Army Corps of Engineer's (CoE) Chesapeake Bay Study in 1965, the council developed a major cooperative program to collect prototype data for the hydraulic model of the Chesapeake Bay that was eventually built at Matapeake, Maryland.

The three laboratory directors, although strong competitors, were very good friends and shared a common goal of doing the best science possible in the Chesapeake Bay. Each recognized that good science required good funding and that good funding came as a result of strong public and political support. All three directors maintained close ties with organized citizens groups. They were all on the Board of Directors of the Chesapeake Bay Foundation and had formed an *ad-hoc* Science

Figure 1. The Chesapeake Bay's "Big Three." From left to right: Bill Hargis, Don Pritchard, and Gene Cronin. Photo taken at the Bi-State Conference on Chesapeake Bay 1977, Patuxent Naval Air Station, Maryland.

Advisory Committee for the Citizen's Program for Chesapeake Bay (now known as the Alliance for Chesapeake Bay), an umbrella organization of Chesapeake Bay organizations started in 1971.

The Citizens' Program was holding its 1972 meeting in Fredericksburg, Virginia when the rains from Agnes began falling on the watershed. By the evening of the first day of the meeting, it became apparent that a flood event was underway as the rooms scheduled for the evening's event flooded. The following morning at breakfast the "Big Three," (Pritchard, Cronin, and Hargis, Figure 1) realized the storm presented them with a unique opportunity to study a major flood event. They agreed to put their institutions' resources out in the Bay and tributaries as soon as possible to capture the hydrographic results of the expected floods. By that afternoon and the following day, all three institutions had personnel on the water.

This commitment was made without any identified funding. The institutions had the personnel, supplies, and equipment available because they were prepared to do extensive hydrographic data collection for the CoE's model during the summer of 1972. The CoE, however, had directed this effort be postponed until later in the summer when low salinities from the wet winter would return to more normal conditions. Dr. W. Jackson Davis, VIMS Assistant Director for Fisheries Science, who along with the writer of this paper had accompanied Hargis to the Fredericksburg meeting, was assigned the task of overall Operation Agnes coordination. The author was assigned the task of trying to beg, borrow, or otherwise cajole logistic and financial support for the operation.

The words "unprecedented scientific community response" are used in the title. In 1972, there were essentially no regular surveys conducted within the Bay region except for fish and shellfish monitoring. No continuous data monitoring stations existed except for NOAA tide gauges, National Weather Service weather stations, and U.S. Geological Survey stream gauges. The only significant quantities of instrumentation to collect quality hydrographic data were the instruments purchased for CoE model data collection. Yet despite this lack of equipment and resources, the most extensive study of the impact of a major storm event was successfully mounted based on the determination of three scientists that such an endeavor was an opportunity not to be missed.

The response to the CBRC initiative was extremely gratifying. Several federal agencies committed funding within a few days of the event, bypassing normal lengthy reviews. The CoE, Philadelphia District was the first agency to provide new funding. The CoE, Norfolk District also contributed new money. Eventually the CoE, Baltimore District was persuaded that the Agnes expenditures were appropriate for this CoE study and fully funded the CBRC hydrographic studies. The fact that Drs. Pritchard, Cronin, and Hargis were on the Scientific and Technical Advisory Committee for this CoE study and Bill Hargis represented the Commonwealth of Virginia on the CoE Study Steering Committee may have helped persuade the Baltimore District.

New or reprogrammed funds were made available by the National Science Foundation's (NSF) Research Applied to National Needs (RANN) program and Oceanographic section. NOAA's Sea Grant Program and National Marine Fisheries Service's (NMFS) Anadromous Fish (PL 88-903) and Jellyfish (PL 89-720) programs provided some new funds and allowed substantial reprogramming of committed funds. In Maryland, the state's Department of Natural Resources and the U.S. Fish and Wildlife Service allowed reprogramming of the Bureau of Sport Fisheries Dingle Johnson funds. Financial support was also provided by the U.S. and Virginia offices of Emergency Preparedness, the Environmental Protection Agency, the Food and Drug Administration, and Columbia Natural Gas Corporation.

At the time of Agnes, the only large, fast vessels dedicated to oceanography in the CBRC institutions were the R/V *Ridgely Warfield*, a catamaran operated by CBI specifically designed for coastal and estuarine oceanography along with two oil field crew boats operated by CBI. VIMS had several very large, slow boats (including a car/

passenger ferry and a converted Landing Craft Utility) and several smaller converted work boats and sport fishing boats. The existing combined fleet and assigned vessel operators were insufficient to handle the daily slackwater runs in the tributaries and mainstem Bay, as well as the continuous anchor stations desired and the desired sampling in the coastal Atlantic. There was also concern that the floodwaters would bring down large quantities of debris that could endanger small craft.

Fortunately several organizations in the region provided extensive vessel support. The Naval Ordnance Laboratory, Solomons, Maryland; Coastal River Squadron TWO, U.S. Naval Amphibious Base (USNAB), Little Creek, Virginia; Assault Craft Unit TWO, USNAB; U.S. Coast Guard Cutter, *Cuyahoga*, Yorktown, Virginia; and Fort Eustis, Virginia provided both fast and sturdy vessels to meet these needs. The U.S. Coast Guard also provided the Buoy Tender, *Red Cedar*, Portsmouth Virginia to set current meter arrays and the Cutter, *Point Martin*, Little Creek, Virginia to recover and re-establish stations run over by commercial shipping. Support for equipment recovery was also provided by the Navy's Explosive Ordnance Disposal Unit TWO, Fort Story, Virginia (diving) and the Naval Ordnance Laboratory, White Oak, Maryland (magnetometer). The National Aeronautic and Space Administration's Langley Research Center in Hampton, Virginia provided helicopters, remote sensing instrumentation, and personnel to measure Bay surface hydrographic conditions.

Shelf observation support was provided through NOAA by the NMFS's R/V *Albatross* from Woods Hole, Massachusetts and vessels and personnel from NMFS's Sandy Hook, New Jersey laboratory. The U.S. Coast Guard also supported shelf studies by providing personnel to make round-the-clock hydrographic observations at the Diamond Shoals, Five Fathom, and Chesapeake Light towers.

Operation Agnes caught the attention of others in the Bay scientific community and many scientists added an Agnes component to their studies. The first report detailing the effects of Agnes on the Chesapeake Bay was a report to the CoE, Philadelphia District prepared by the CBRC [1].

In addition to seeing Agnes visit the Chesapeake region, 1972 saw the formal start of a new organization that assumed the role of facilitation of inter- and multi-university projects that had been informally provided by the CBRC. This new organization, the Chesapeake Research Consortium, Inc. (CRC), grew out of a project funded by the NSF's RANN program. The original participants in the project were the University of Maryland, The Johns Hopkins University, and VIMS. These three institutions were joined soon after by the Smithsonian Institution (at the recommendation of NSF). The only principal in the CRC who was a member of the CBRC was Bill Hargis, director of VIMS. At both the University of Maryland and The Johns Hopkins University, the principals were drawn from the academic side of the organization as opposed to the Chesapeake Bay-oriented research institutions. The formal document establishing the CRC was signed in February 1972, but it had not yet become fully functional when Agnes struck.

After initiating Operation Agnes and coordinating the initial report [1], the CBRC essentially turned over completion of the project to the CRC. The CRC co-sponsored a conference on Agnes, *"A Symposium on the Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System,"* with the CoE, Baltimore District. The results of this symposium were published as a two-volume CoE report containing about 47 technical papers. In 1976, The Johns Hopkins University Press published a 639-page report detailing the effects of Tropical Storm Agnes on the Chesapeake Estuarine System [2] for the CRC. This volume contained not only studies performed as part of Operation Agnes by CBI, CBL, and VIMS staff, but also studies by several other Chesapeake Bay scientists, notably those involved in coordinated studies at the Smithsonian Institution's Chesapeake Bay Center for Environmental Studies, now known as the Smithsonian Environmental Research Center.

Several reports on the effects of Agnes on the Chesapeake estuarine system were presented at conferences and symposia and eventually in peer-reviewed journals as well as in the CRC book. The honor of producing the first peer-reviewed paper [3] went to Dr. J.D. Andrews[2] of VIMS who published his study of Agnes' impacts on epifauna in a 1973 issue of *Chesapeake Science*.

AFTER AGNES

In 1973, Dr. Pritchard resigned from the directorship of CBI for health reasons, but remained as a senior scientist. In 1974, he took a one-year sabbatical. After returning to The Johns Hopkins University, he became director of CRC in 1976. In 1977, he retired from The Johns Hopkins University and joined the staff of the State University of New York, Stony Brook. Dr. Pritchard died in 1999.

In 1975, the University of Maryland's Natural Resource Institute was merged into the newly formed Center for Estuarine and Environmental Studies. Dr. Cronin served as assistant director of CEES until becoming director of CRC, replacing Dr. Pritchard. He remained director from 1977 until his retirement in 1984. Dr. Cronin died in 1998.

Dr. Hargis remained as director of VIMS and a principal in CRC. He served part of the time as chairman of the CRC board until 1981 when he returned to full-time teaching and research. In 1991, he retired and remains active as an emeritus faculty member. VIMS was placed under the control of the Board of Visitors of the College of William & Mary in 1979.

WILL WE SEE ANOTHER OPERATION AGNES?

Will we see the equivalent scientific response to an "unexpected environmental event" in the future? I doubt it. The scientific infrastructure in the Chesapeake Bay has become more complex. There is no longer a "Big Three" that controls or oversees the major resources devoted to Bay research. Two of the institutions or successor institutions led by the "Big Three" are much larger now than in 1972. One has disappeared. Many other institutions have developed an interest and capability to study the Chesapeake Bay. The leadership of the Bay scientific community is not as centralized or as close (some might say "closed" instead of "close") as in 1972. The largest non-governmental organization, the Chesapeake Bay Foundation, has developed its own in-house scientific capability. The Bay is now being looked at with many more eyes.

In some ways, communication at the scientist level is better. The Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program and CRC have convened groups of scientists to address different problems over the years. The Chesapeake Bay Stock Assessment Committee, instituted by NOAA as part of its contribution to the Chesapeake Bay Program, has greatly improved communications between fisheries scientists working in the Bay. Communication among scientists at different institutions does not now flow through the institution's leadership.

In the 30-plus years since Agnes, however, it appears that the scientific leadership has been more and more constrained by non-scientific business managers in their own institutions and, more importantly, by business as opposed to scientific consideration in the funding agencies. In the early 1970's, a program officer in a federal agency such NSF, NOAA, or the CoE could make a commitment to a scientist that a study would be funded if the scientist began a project without a signed grant or contract and the money would materialize within a reasonable length of time. By the end of the 1970's, program officers would state up front they could not make any commitments until a grant or contract was signed by the contracts office.

A legitimate concern for "accountability" has led to a strong curtailment of the flexibility once possessed by laboratory directors and individual scientists. So many "sign-off" steps currently exist in the process to obtain reprogramming approval or to acquire funds on extremely short notice that

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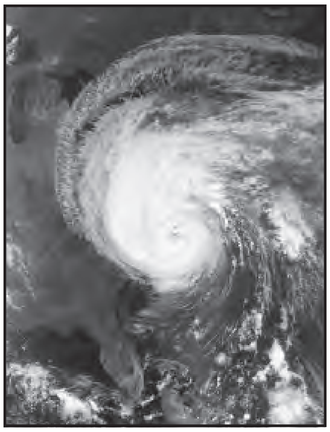
[2] *Dr. Andrews retired from VIMS in 1983. He died October 28, 2004.*

most "unexpected events" will have come and gone before approval is obtained

Fortunately, as was seen in Isabel's aftermath, advances in monitoring technology and practices allow us to track system responses to unusual events without the need to immediately launch major field efforts to capture the event.

REFERENCES

1. A.M. Anderson, J. Davis, M.P. Lynch, and J.R. Schubel. 1973. The Effects of Hurricane Agnes on the Environment and Organisms of Chesapeake Bay: Early Findings and Recommendations. A report to the Philadelphia District, U.S. Army Corps of Engineers. Chesapeake Bay Research Council. 172 pp.
2. J. Davis, B. Laird, E.P. Ruzecki, J.R. Schubel, R.J. Huggett, A.M. Anderson, M.L. Wass, R.J. Marasco, and M.P. Lynch (eds.). 1976. *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD. 639 pp.
3. J.D. Andrews. 1973. Effects of Tropical Storm Agnes on epifaunal invertebrates in Virginia estuaries. *Ches. Sci*. 14: 223–234.



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.

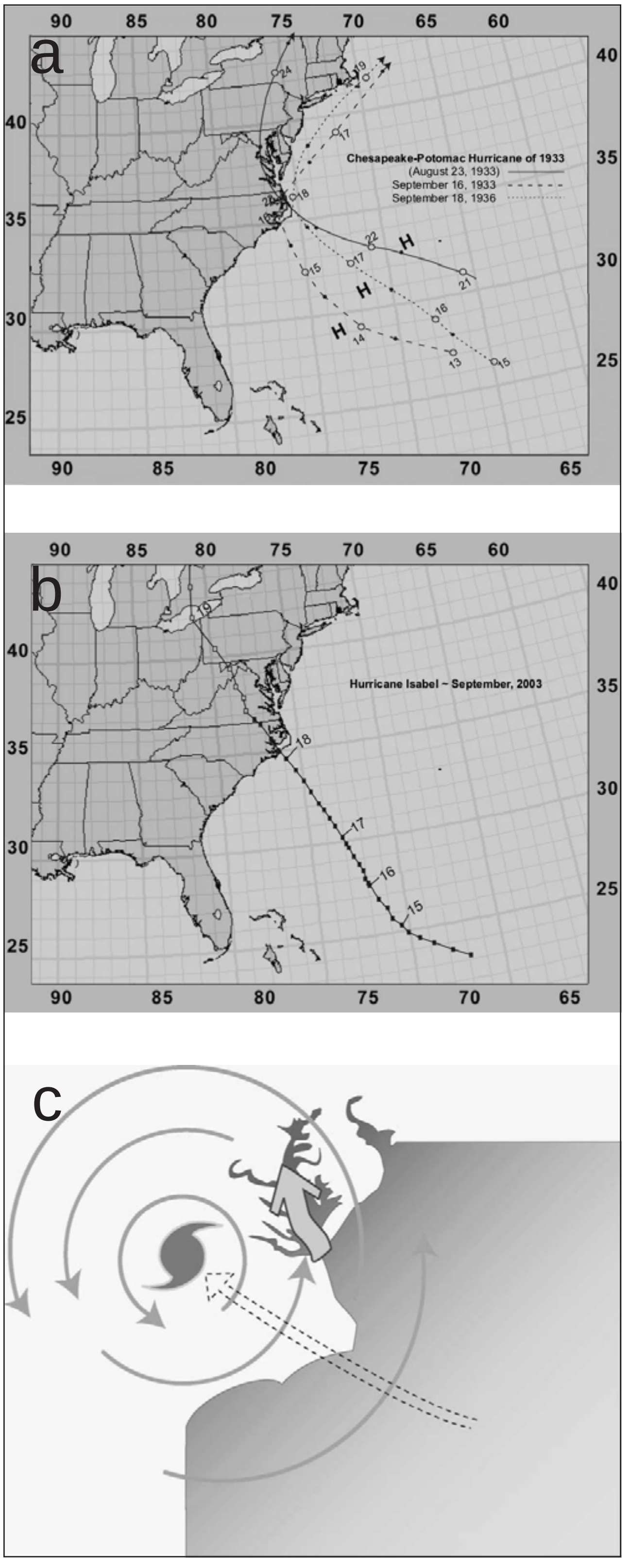

Figure 1. Hurricane tracks: a) 1933, b) 2003 (courtesy of NOAA National Weather Service), and c) wind pattern schematic of hurricanes traversing to the west of Chesapeake Bay.

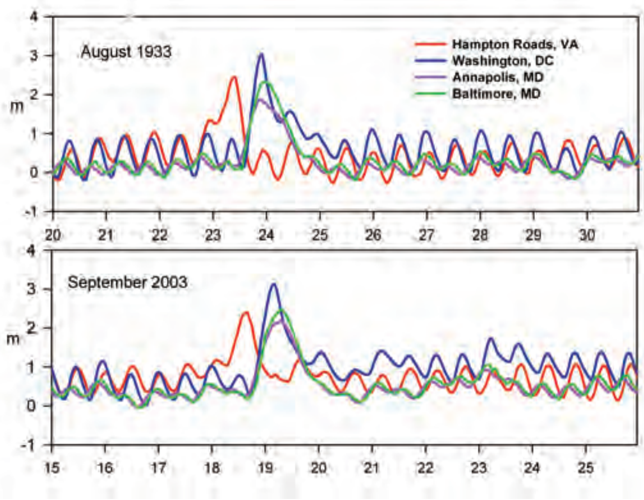

Figure 2. Water gauge records from Chesapeake Bay tide gauges common to 1933 and 2003. The time axis has been adjusted to facilitate comparison of the two hurricanes.

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.

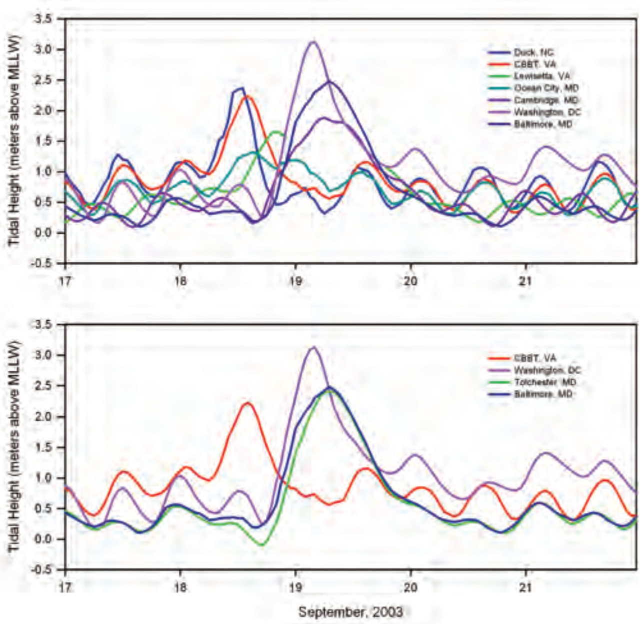

Figure 3. Water-level records from Chesapeake Bay region prior to and during Hurricane Isabel. Upper panel includes most available records, while lower panel includes only selected stations at Chesapeake Bay Bridge Tunnel, Washington, D.C., in the northern Bay, Tolchester Beach, and Fort McHenry in Baltimore.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

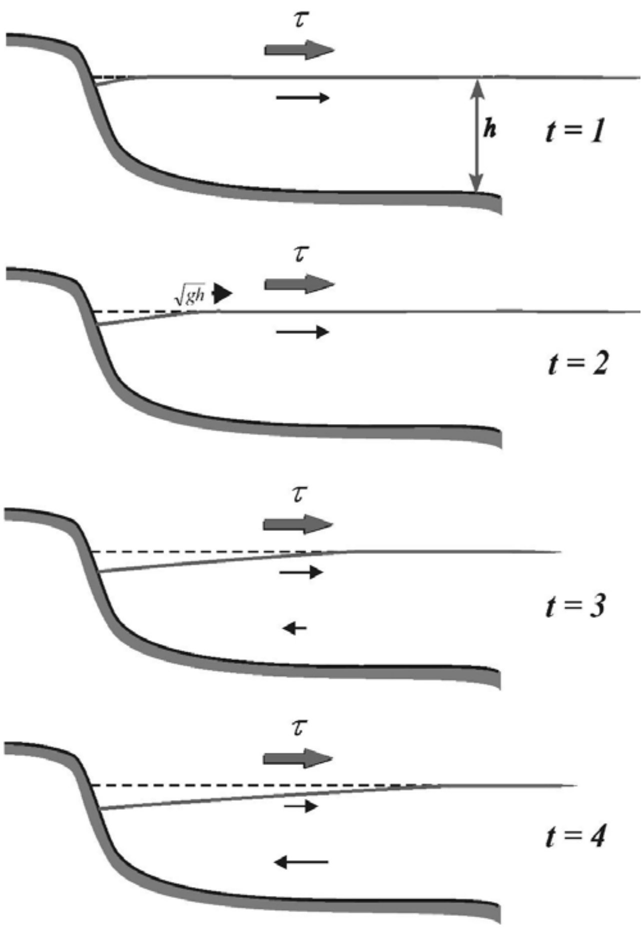

Figure 4. Schematic diagram of response to wind forcing (seaward wind case). Wind stress T drives surface layer in direction of wind, creating a slope in sea level (t = 3, 4). The pressure gradient created by sea level slope drives water in opposite direction to wind. In surface layers, frictional driving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

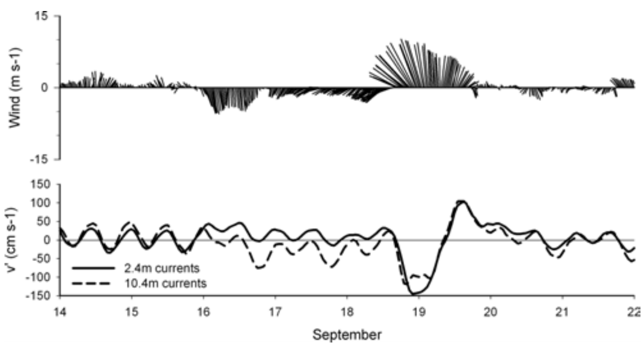

Figure 5. Wind and current records from Hurricane Isabel, 14 to 22 September 2003. Current records are from 2.4-m and 10.4-m depth at the CBOS mid-Bay station (38.3° N 76.2° W). Wind records are from the Horn Point Laboratory weather station in Cambridge, Maryland. For winds, northward winds are positive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

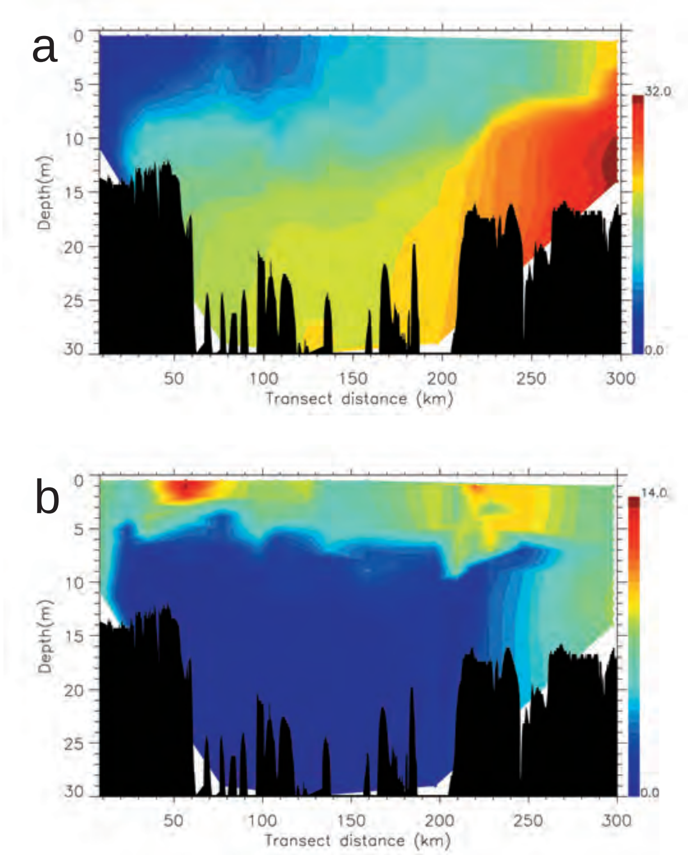

Figure 6. Axial salinity (a) and dissolved oxygen (b) distributions during 18–20 August 2003 for Chesapeake Bay. Data are from EPA Chesapeake Bay Program surveys.

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 $mg \cdot L^{-1}$. 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 $cm \cdot s^{-1}$ for typical times of 1–5

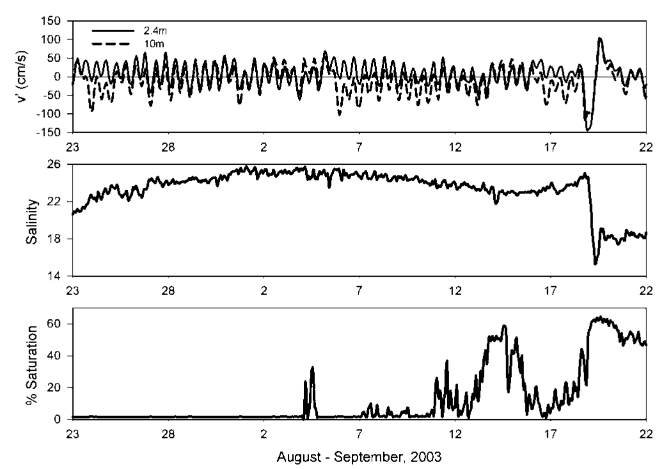

Figure 7. Current, salinity, and oxygen records from the CBOS mid-Bay station. Currents are from 2.4-m and 10.4-m depths. Salinity and oxygen saturation are from 10.4-m depth.

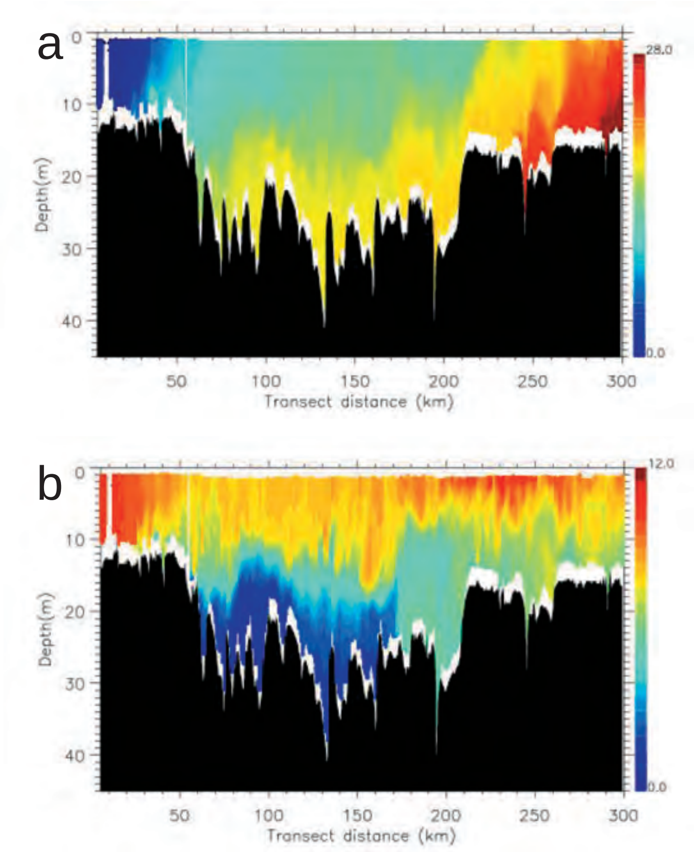

Figure 8. Axial distribution of (a) salinity and (b) oxygen from Scanfish survey on 5 to 6 October 2003, approximately two weeks after Isabel.

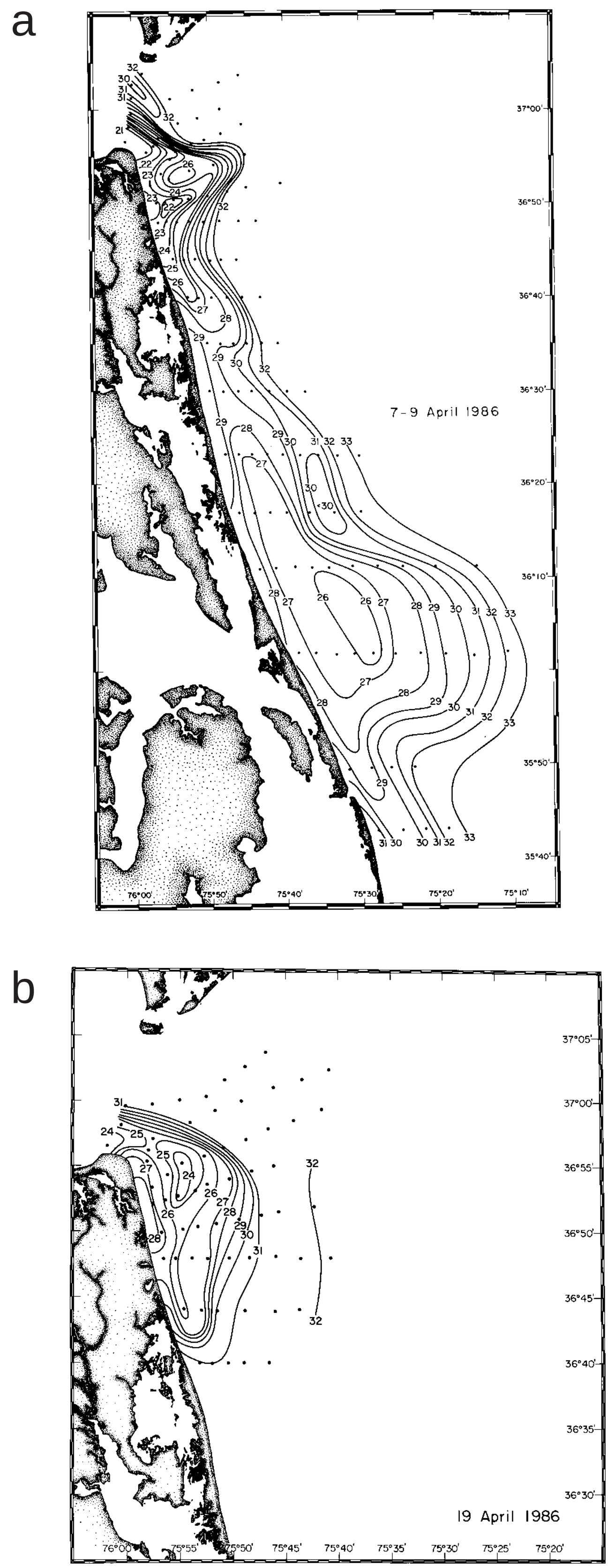

Figure 9. Surface salinity patterns of Chesapeake Bay plume in April 1986.

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

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

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.

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.

ISABEL'S SILENT PARTNERS: SEASONAL AND SECULAR SEA LEVEL CHANGE[1]

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ABSTRACT

Tidal conditions fail to explain a paradoxical similarity in water level extremes induced by Hurricane Isabel on 18 September 2003, and the 23 August 1933 storm of record at Hampton Roads, Virginia. Storm surge peaks occurred near astronomical high tide during both storms, but Isabel arrived during neap tides while tides during the 1933 storm were nearer to spring. In addition, Isabel produced a lesser storm surge, yet she yielded a storm tide, or high-water mark, roughly equal to that of the 1933 hurricane. The answer to the paradox lies in observed sea level—water level measured relative to the land—and its movement during the 70 years between these events. Water level analysis shows that the sea level change observed can be divided into three categories at three different time scales: daily (astronomical tides), monthly (seasonal change), and yearly (secular trend in sea level). At Hampton Roads, a secular rise rate of 4.25 mm·yr^{-1} (1.39 ft/century) predicted an increase of 29.8 cm in 70 years; mean sea level for the month of September stood an additional 21.9 cm above the annual mean for 2003. These numbers are comparable to the mean semi-range of tide (37.0 cm) at Hampton Roads. Thus seasonal and secular change are both factors of key importance in evaluating storm tide risk at time scales attributable to major hurricanes (100 years). Adoption of a new vertical reference, *projected monthly mean sea level*, is proposed to facilitate their inclusion in storm tide predictions at decadal time scales.

[1] *Contribution No. 2639, Virginia Institute of Marine Science and School of Marine Science*

INTRODUCTION

Hurricane Isabel made landfall on 18 September 2003, preceded by threats of severe coastal flooding in North Carolina, Virginia, and Maryland. A Category 2 hurricane at landfall [1], Isabel could be expected to generate a storm surge of between 1.8 and 2.4 m (6–8 ft) according to the Saffir-Simpson scale. Instead, the storm produced a lesser surge of approximately 1.45 m (4.8 ft) at Hampton Roads, Virginia in the lower Chesapeake Bay. However, Isabel created a storm tide equal to that of the Category 3 hurricane on 23 August 1933, which produced a surge of about 1.78 m (5.8 ft) at Hampton Roads. Post-storm analysis reveals that the sea level base that existed on 18 September 2003, as Hurricane Isabel approached the lower Bay, was considerably higher than the base level presented to the 1933 hurricane that produced the largest storm surge on record in Hampton Roads. This result explains how Isabel, reduced to a Category 1 hurricane by the time of her arrival in Virginia [1], could produce a maximum storm tide that may have equaled or even exceeded in places the high water marks left by the 1933 hurricane 70 years ago.

To understand the result and its future implications, storm tide and storm surge definitions [2] must be revisited in the context of sea level dynamics, a goal that leads to the study of both deterministic variations in water level (secular trends, seasonal cycles) as well as random (stochastic) variations that occur at decadal time scales [3]. To separate these variations from short-term (tidal and sub-tidal) variations, it is convenient to use monthly averages of sea level (monthly mean sea level) tabulated at primary tide stations with long record lengths. These averages will be used "as-is" in the analyses that follow (i.e., no attempt is made to adjust the means for the effects of individual storms).

To evaluate the threat of flooding in advance of storms likely to impact the coastal zone in the long term (decadal time scale), the long-term sea level change components that yield a representative base water level for a given place and time when combined must be isolated. To this representative level or vertical datum, the astronomical tide (water level oscillations resulting from gravitational interactions between sun, moon, and earth) is normally added to the storm surge (water level change resulting from the storm). Adding astronomical tide and storm surge superposed to the datum elevation yields the observed water level at tide stations or the storm tide history with their peak sum defining the storm tide maximum [2].

Measured storm surge is often derived as the difference between observed and predicted water level histories. Both histories must refer to corresponding time intervals and the same vertical datum; it is assumed that predictions can be made with an acceptable model of the astronomical tide allowing for its interaction, if any, with the surge. Since it is derived as the difference between two referenced water levels, storm surge is a relative measure and has no inherent reference of its own. A storm tide, on the other hand, is dependent on its elevation above a specified vertical datum. The vertical reference used in the United States and its territories for storm and other tides is customarily an established tidal datum as defined in the next section.

METHODS

Water level data for Hampton Roads (Sewells Point), Virginia were obtained from the National Ocean Service (NOS) website (*http://co-ops.nos.noaa.gov/*). Several reference datums may be selected on this site, including mean lower low water (MLLW), the average of the lower low water height of each tidal day over the National Tidal Datum Epoch (NTDE)[2], mean sea level (MSL), the average of all hourly heights over the NTDE, and the station datum (STND). Station datum is the zero point of the vertical measurement scale fixed in position when a tide station is first established. Although STND does not change thereafter, MLLW, MSL, and other tidal datums are periodically revised in relation to it whenever the NTDE is updated in response to observed sea level change [4]. Another datum not commonly used to reference tidal heights is mean higher high water (MHHW), the average of the higher high water height of each tidal day over the current NTDE. The final section of the paper contains additional information about this datum.

Least squares harmonic analysis [5] was applied to a 29-day series of hourly height data to obtain the harmonic constants (amplitude and phase) for nine tidal constituents (M_2, S_2, N_2, K_1, O_1, M_4, M_6, S_4, and MS_4). The resulting time-local model of the astronomical tide subsequently accounts for the maximum possible variance (in the least squares sense) present in the data at these tidal frequencies. Although the nine constituents above are only a subset of the 26 tidal constituents used in NOS predictions for Hampton Roads, many of the latter represent "perturbations" on the major constituents (e.g., K_2 on S_2). These perturbations are unimportant in a time-local model of the tide. The 29-day analysis also provides the equivalent of monthly mean sea level (MMSL) conveniently tabulated at most NOS tide stations. Although MMSL can be referenced to other tidal datums or to the station datum STND, 1983–2001 MLLW will be used in all of the sea level evaluations and comparisons that follow.

DATA ANALYSIS AND RESULTS

Figures 1 and 2 show a comparison of storm surge and storm tide for the 1933 hurricane and Hurricane Isabel at Hampton Roads. Both storms produced almost the same storm tide height: 2.44

[2] *A specific 19-year period adopted by NOS for tidal datum averaging. Currently the years 1983–2001 are used.*

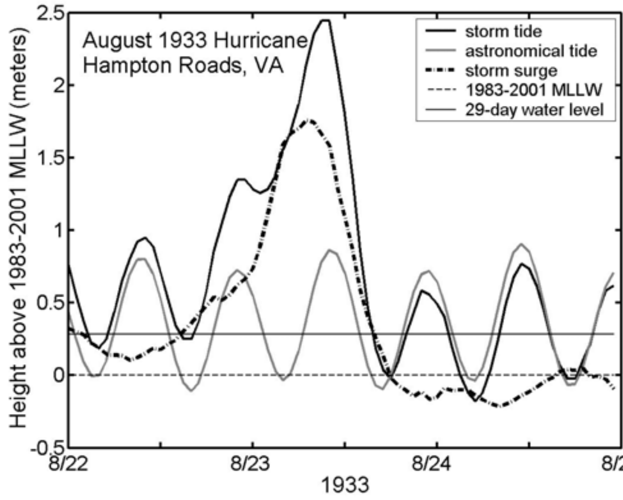

Figure 1. Water levels at Hampton Roads, Virginia during the hurricane of August 1933.

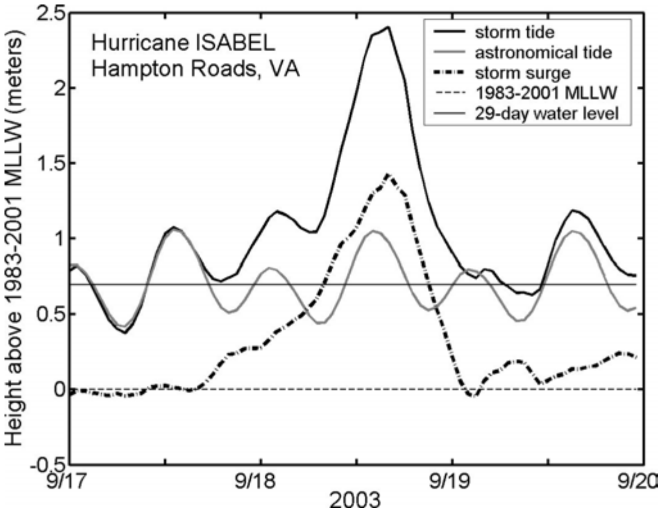

Figure 2. Water levels at Hampton Roads, Virginia during Hurricane Isabel in September 2003.

m (8.0 ft) MLLW for the 1933 event versus 2.40 m (7.9 ft) MLLW for Isabel. However, the storm surge for Isabel was estimated to be 1.45 m (5.8 ft) as compared to 1.78 m (4.8 ft) for the 1933 hurricane.

Examining the monthly (29-day) mean water levels for both storms (Figures 1 and 2), it is immediately clear that Isabel's smaller storm surge capitalized on the higher water level average for September 2003, a level about 40 cm higher than the average for August 1933 (water levels on both occasions refer to MLLW for the 1983–2001 NTDE). Other factors had secondary influence on storm tide outcome: Isabel's 40-cm "boost" in mean water level was slightly offset by a smaller (neap) tidal range on 18 September 2003 compared to a larger (near-spring) range on 23 August 1933 (mean range of 74 cm). Peak surge occurred about two hours after peak astronomical tide during Isabel and about three hours before it during the 1933 event. The comparison underscores the importance of sea level change when dealing with major storm tide events.

Long-term sea level change is easily evaluated by MMSL plots of the type shown in Figure 3. The sea level trend indicated by the slope of the linear regression line in this figure (4.25 ± 0.27 mm·yr^{-1} at the 95% level of confidence) is based on 74 years of record at Hampton Roads. It projects a sea level rise of 29.8 cm over a 70-year interval, about 10 cm less than the 40-cm change seen in Figures 1 and 2. The 10 cm difference appears in the MMSL deviation from trend for the months in question (August 1933, September 2003, Figure 3). The MMSL for other storms of record during this interval, including the Ash Wednesday extratropical storm (March 1962, Figure 3), show variable but consistently positive deviations from trend. Although the MMSL values shown are unadjusted, tests were run that indicate some means may have increased by 2 to 3 cm because of major individual storms.

Combinations of meteorological and hydrological factors are responsible for the MMSL deviation from regression in Figure 3. One set produces the seasonal cycle depicted by the curve in Figure 4; it shows that average MMSL is higher than annual MSL (12-month MMSL average) during the months of August, September, and October. Highest extremes (black diamonds in Figure 4) occurred then and in February and November as well.

The seasonal tide cycle in Figure 4 is approximated in tidal predictions by the seasonal tide constituents, Sa and Ssa. Most of the water level variance attributed to these "tidal" constituents with annual and semiannual periods is, in fact, non-tidal in origin. This variance results largely from seasonal heating cycles producing thermal

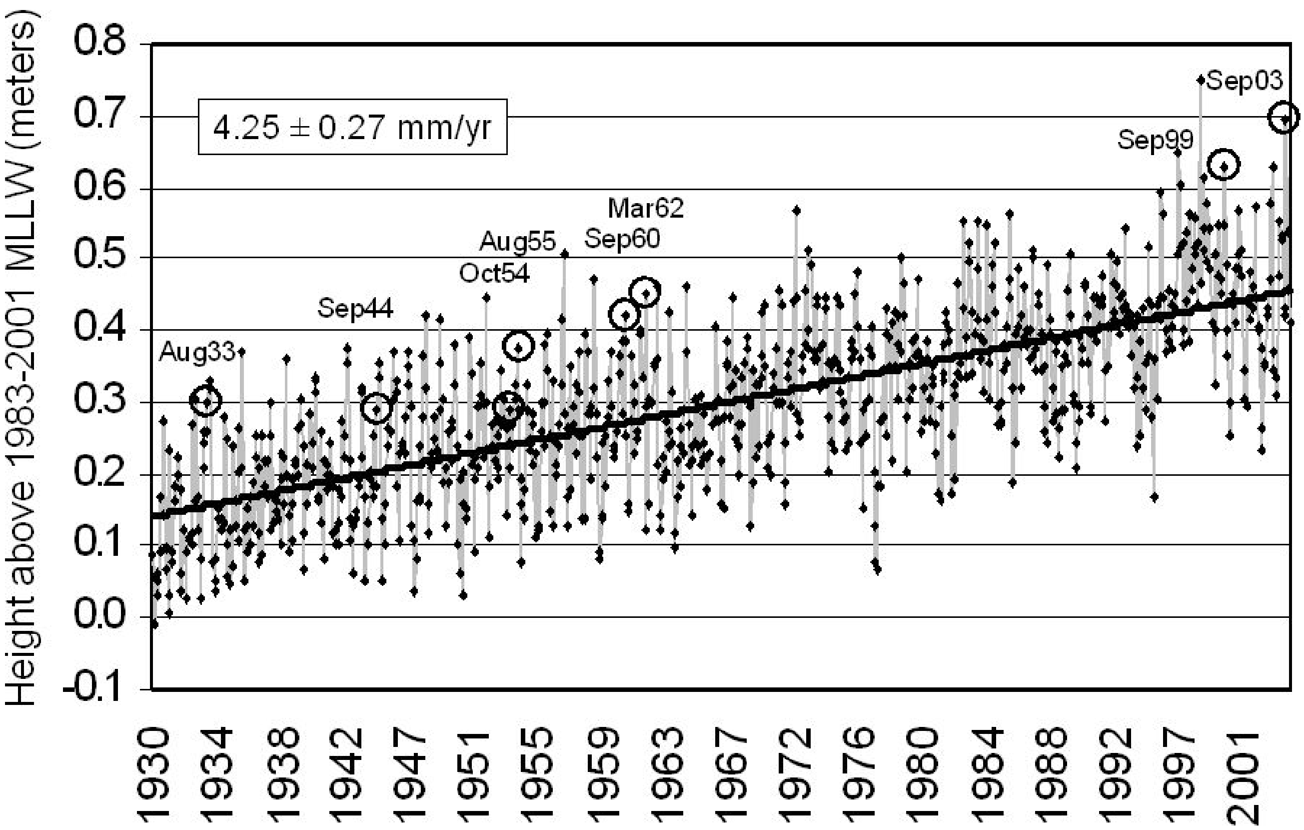

Figure 3. Plot of monthly mean sea level (MMSL), 1930–2003, at Hampton Roads, Virginia. The MMSL for September 2003 lies 21.9 cm above annual mean sea level for 2003. Storms of record during this period are circled and indicated by month and year.

expansion and contraction of the water column and, in some coastal areas, is due to seasonal river discharge [6]. Consequently, unlike other tidal constituents with more precise predictive capabilities, seasonal predictions made specifically with Sa and Ssa are likely to vary substantially from the actual MMSL in any given month and year.

The last assertion is substantiated by the large spread in the distribution of MMSL values about each monthly mean plotted in Figure 4. One standard deviation above and below the mean is indicated by vertical bars, assuming the 74 data points comprising each mean are normally distributed. Equally important, the MMSL distribution about each mean represents a time series with its deterministic components (seasonal variation and secular trend) removed. For example, the September MMSL series shown in Figure 5 approximates a stationary stochastic process with constant mean and variance over time.

Source of Variation

While surges caused by major storms are included in MMSL determinations, they are not the primary reason for high MMSL values. The MMSL values for September 2003 and August 1933 increased by only 2% of the surge maximum (2 and 3 cm, respectively) due to the hurricane and its effects over a 24-hour period. Probably the major source of sea level variation in this case is the interannual or decadal variability believed to arise from Rossby waves in the North Atlantic Ocean—irregular waves characterized by periods between 1 and 10 years or longer. Interestingly, “broad-band” sea level fluctuations of this type are more commonly seen on western Atlantic shores, a fact consistent with westward-only movement of the Rossby waves [3].

Figure 6 is a histogram displaying the frequency distribution of recorded MMSL values at Hampton Roads for the month of September,

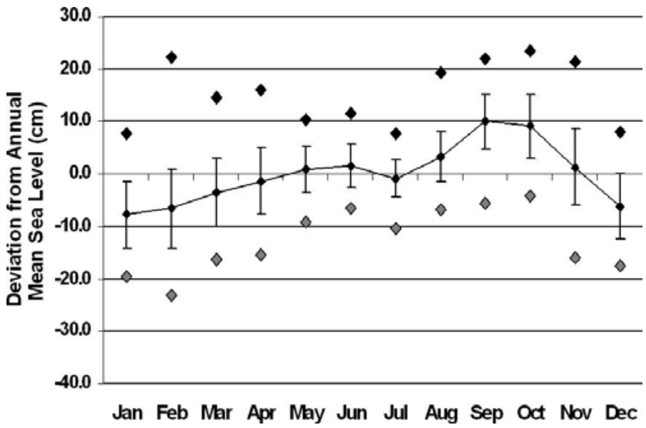

Figure 4. MMSL means and extremes at Hampton Roads (Sewells Point), Virginia (1930–2003). One standard deviation is indicated by the vertical bars about each mean (N=74).

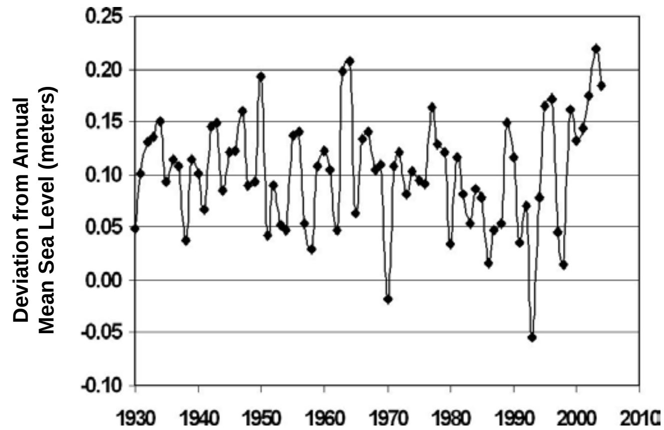

Figure 5. September MMSL series at Hampton Roads (Sewells Point), Virginia (1930–2004). Graph shows decadal variations absent secular trend and seasonal change.

fitted by a normal distribution curve. The abscissa values are deviations from annual MSL with the mean (Dm = 10.10 cm) representing the seasonal change. Assuming a normal distribution, the average MMSL in September plus two standard deviations is Dm+2s = 20.46 cm (the projected seasonal change), a value that is likely to be exceeded in approximately 2% of all instances of September MMSL at Hampton Roads.[3] The September projected seasonal change has, in fact, been exceeded twice at Hampton Roads in 74 years—in 1964 (20.7 cm) and again in 2003 (21.9 cm).

The results for Hampton Roads, Virginia are not unique. A 101-year water level record (1903–2003) at Baltimore, Maryland yields similar data (Figures 7 and 8). The sea level trend at Baltimore is 3.09 ± 0.20 $mm \cdot yr^{-1}$ and for the month of September, Dm = 10.65 cm, and Dm+2s = 18.48 cm, a value exceeded six times in 101 years including a 21.1 cm seasonal change for September 2003. The four highest seasonal extremes at Baltimore (black diamonds in Figure 7) occurred in June, August, September, and October, the latter three being the most common months in which major tropical storms and hurricanes have impacted the Chesapeake Bay.

CONCLUSIONS

Comparative evaluation leaves little doubt that ongoing seasonal and secular changes in sea level become increasingly important to flood risk assessments at time scales approaching 100 years. Authorities charged with determining that risk in the past have largely ignored long-term sea level change while seeking to define the 100-year flood as a level with 0.01 annual probability of occurrence irrespective of time [7]. Only the NOS has recognized sea level as dynamic by responding to it with a series of four NTDE updates (1924–1942, 1941–1959, 1960–1978, and 1983–2001) that have

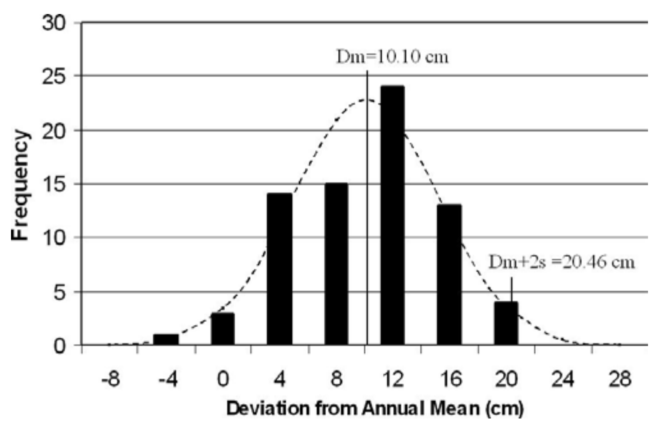

Figure 6. September MMSL distribution at Hampton Roads (Sewells Point), Virginia (1930–2003).

3 *The probability for a normally distributed value to fall more than two standard deviations above the mean is 0.0227.*

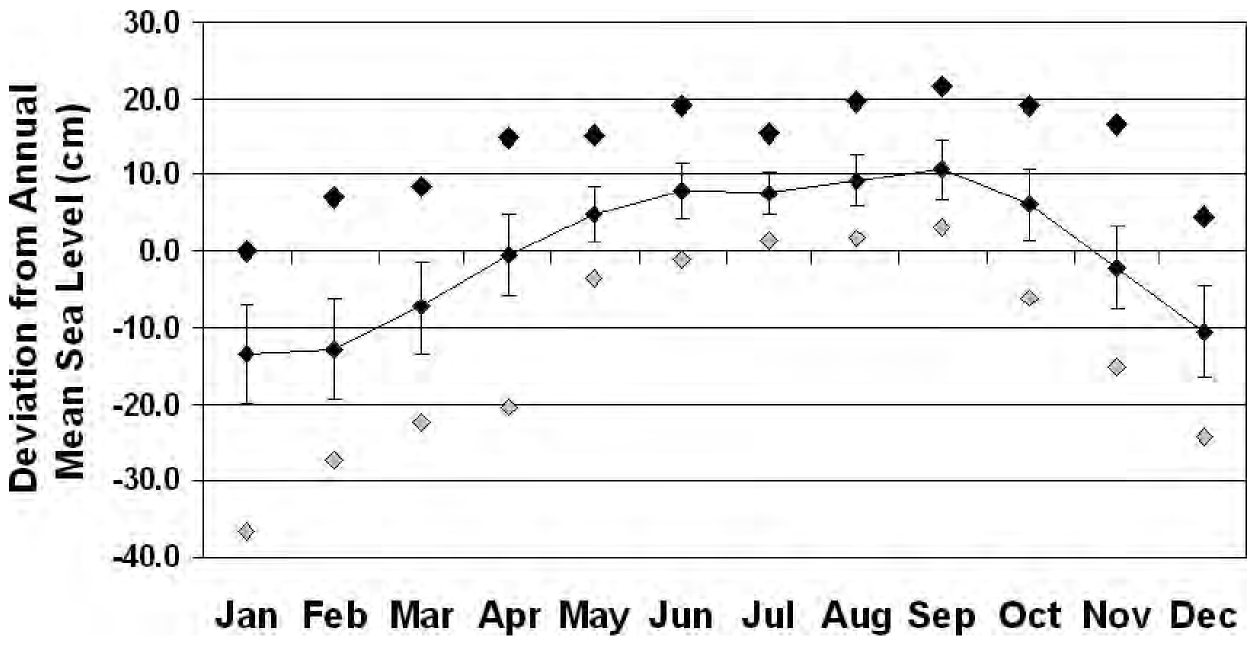

Figure 7. MMSL means and extremes at Baltimore (Fort McHenry), Maryland (1903–2003). One standard deviation is indicated by the vertical bars about each mean (N=101).

revised tidal datum elevations at intervals ranging from 17 to 23 years. Although a specific interval for updating has not been prescribed, the NTDE and resulting tidal datums remain an indispensable component of storm tide forecasts that actively consider sea level change. The extremes of projected sea level change described above were, in fact, realized during Hurricane Isabel. Although there is no certainty that a similar combination will reoccur in the future (even sea level rise, to a degree, is uncertain), the evidence strongly suggests that it

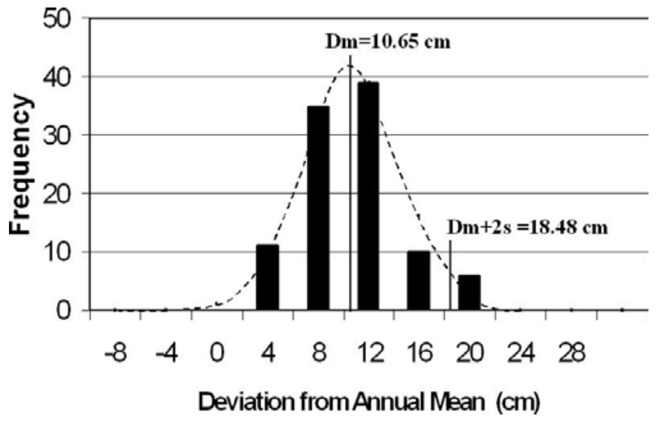

Figure 8. September MMSL distribution at Baltimore (Fort McHenry), Maryland (1903–2003).

will if past trends continue in conjunction with seasonal and decadal variations in sea level.

Outlook

After the disastrous hurricane seasons of 2003 and 2004, few can doubt the immense threat posed by even a Category 1 storm or the dramatic impact that extreme winds and high tides can have on coastal communities. Although sea level change has clearly played a role in shaping that impact over time, the threat it poses is not perceived as an imminent one and has received little attention as a result. Historically, NTDE updates are driven by vessel navigation and marine safety issues rather than coastal flooding concerns, with nautical charts being the focus rather than flood maps. In the belief that it is time to change this policy, this paper makes a contribution through the recommendations presented below.

RECOMMENDATIONS AND RATIONALE

It is recommended that the projected secular change from the midpoint of the current NTDE to a given year of prediction and the projected seasonal change (e.g., Dm+2s) for the month of

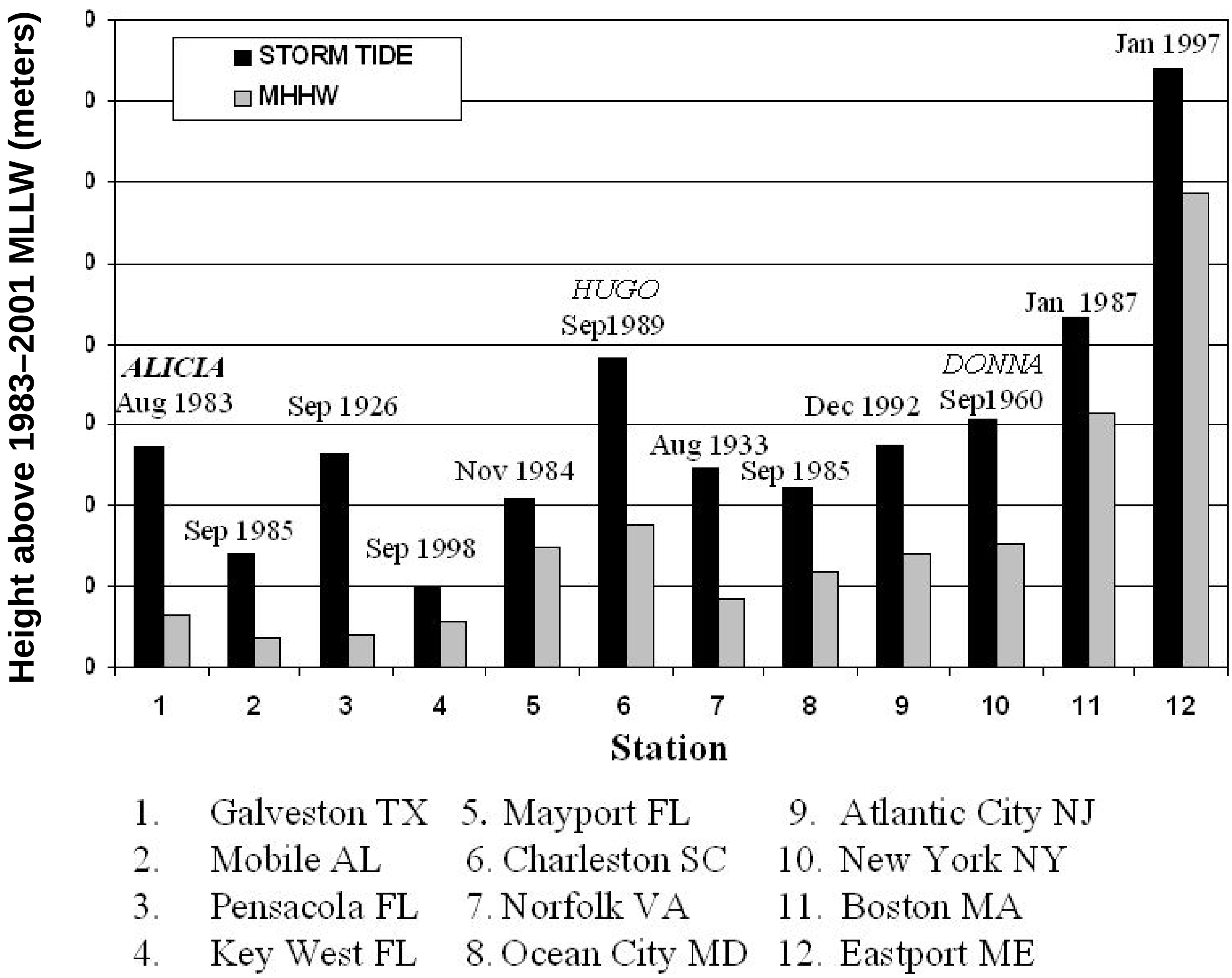

Figure 9. Record storm tides measured above 1983–2001 MLLW at 12 NOS tide stations along the U.S. Gulf and Atlantic coasts.

prediction be combined, with the total change determining the projected monthly mean sea level at that location when referenced to a suitable tidal datum. It is proposed that the predicted storm surge from any source, such as a hydrodynamic model, be added to the projected monthly mean sea level to obtain the predicted storm tide height above datum for any specified event (e.g., the 10-year or 100-year storm). Emergency management planning—for example, determining whether to raise the first-floor elevation of homes flooded during Isabel (and by how much)—requires this or a similar approach to be effective at decadal time scales.

It is further recommended that long-term observations and predictions of storm tide height reference the tidal datum of mean higher high water (MHHW) rather than the chart datum of MLLW. Figure 9 shows the relationship between these datums and record storm tides at 12 NOS tide stations from Galveston, Texas to Eastport, Maine. In this figure, Eastport appears to have the largest storm tide of any station but this is a rather biased view, directly resulting from the greater tidal range (MHHW-MLLW) at this location. If the storm tides are referenced to MHHW, the range effect is removed. Stations located in hurricane zones, such as Galveston, Pensacola, or Charleston, then receive their proper recognition as stations with the highest risk from storm tides, noting that MHHW itself is likely to be exceeded several times by astronomical tides alone in the course of a year.

The possibility of confusing similar sounding terms could also lead one to mistakenly report a 7.5-m storm surge at Eastport due to the way the information is presented in Figure 9.

The MHHW accounts conservatively for the astronomical tide contribution to storm tide heights during all but the spring astronomical extremes. Just as the mariner may rely on charted depths below MLLW even at the lowest levels of the tide, the property owner may rely on storm tide heights forecast above MHHW even at the highest levels of the tide. The MHHW line is arguably a more recognizable contour on land and lies nearer to coastal infrastructure most likely to be impacted by storm tides.

REFERENCES

1. J. Beven and H. Cobb. 2004. *Tropical Cyclone Report, Hurricane Isabel*. NOAA National Weather Service, National Hurricane Center, Tropical Prediction Center. Miami FL, 30 pp.
2. C.P. Jelesnianski. 1993. In: *The Global Guide to Tropical Cyclone Forecasting WMO/TD-560*, Ch.4, World Meteorological Organization, Geneva. 342 pp.
3. W. Sturges and B.G. Hong. 2001. In: *Sea Level Rise: History and Consequences*. B.C. Douglas, M.S. Kearney, and S.P. Leatherman (eds.). Academic Press, New York. pp. 165–180.
4. S.D. Hicks. 1999. *Tide and Current Glossary*, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service. Silver Spring MD. 34 pp.
5. J.D. Boon. 2004. *Secrets of the Tide: Tide & Tidal Current Analysis and Predictions, Storm Surges and Sea Level Trends*. Horwood Publishing, Chichester. 212 pp.
6. D.T. Pugh. 2004. *Changing Sea Levels*. Cambridge University Press, Cambridge. 265 pp.
7. J.D. Boon, C.S. Welch, H.S. Chen, R.J. Lukens, C.S. Fang, and J.M. Zeigler. 1978. *Storm Surge Height-Frequency Analysis and Model Prediction for Chesapeake Bay*. Special Rep. No. 189 in Applied Mar. Science, Vol. 1, Virginia Institute of Marine Science, Gloucester Point, VA. 155 pp.

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

K.G. Sellner (ed.). 2005. Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.

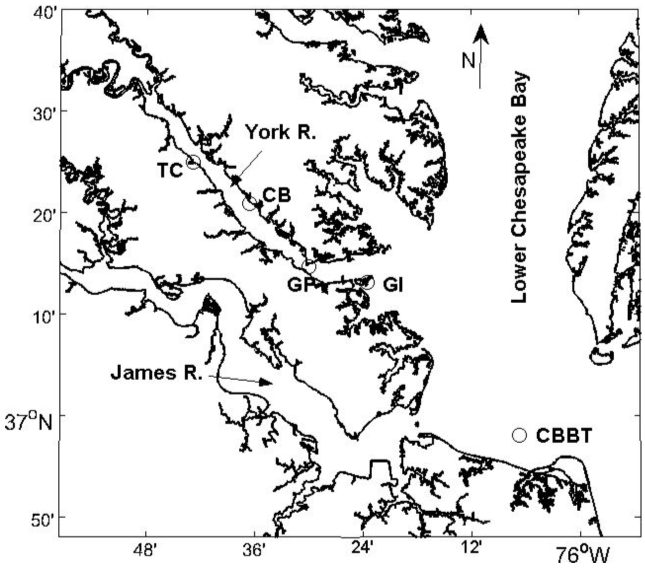

Figure 1. Site map of observation stations in the lower Chesapeake Bay and York River. Stations are marked with an "o." Abbreviations are defined in the text.

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 $m \cdot s^{-1}$, 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

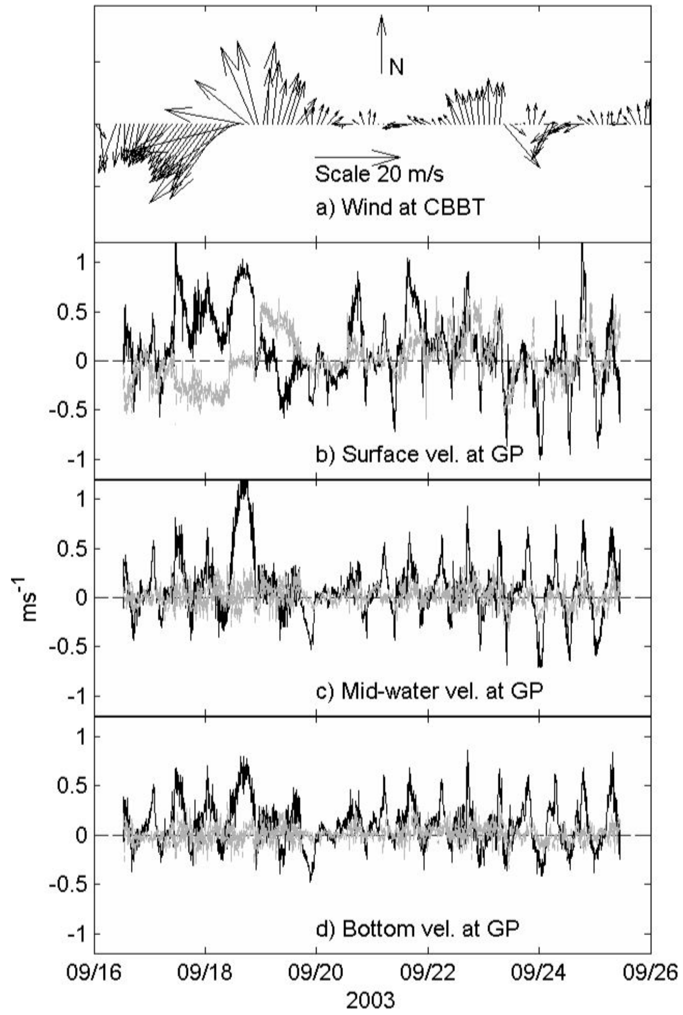

Figure 2. Surface wind data from the CBBT in Panel a shows the rotation and speed of the wind generated by Isabel (wind convention is the direction the wind is blowing towards). Panels b, c, and d show water velocities for surface, mid-water, and bottom depths from the ADCP at GP. Black lines represent 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

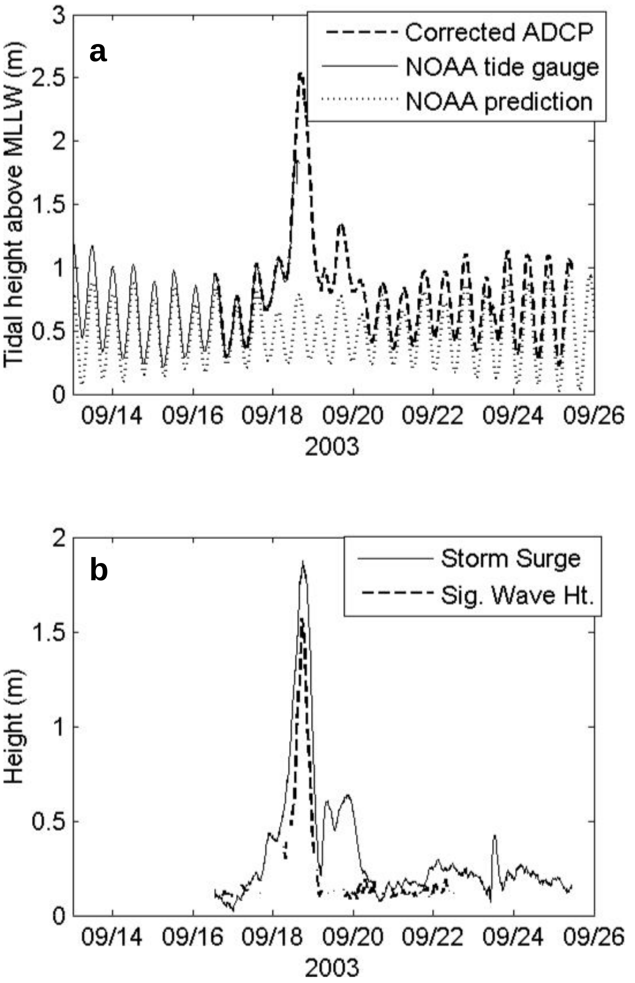

Figure 3. Panel a: comparison of predicted tidal elevation and observed water level at Gloucester Point from NOAA's destroyed tide gauge and the ADCP pressure record. Panel b: storm surge above astronomical tides and significant wave height (Hs) at Gloucester Point.

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

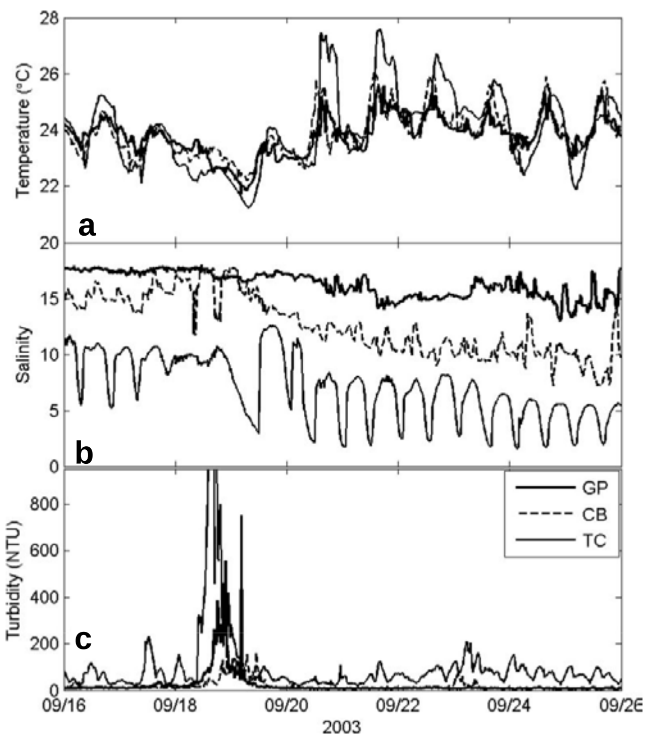

Figure 4. Temperature, salinity, and turbidity observations from fixed, near-bottom sondes maintained by CBNERR Virginia.

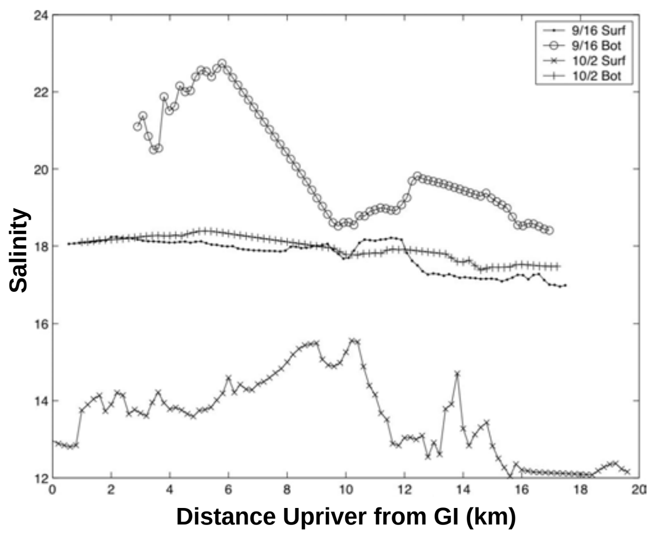

Figure 5. Surface and bottom salinity values for the York River from GI at the mouth to CB. Measures were taken with an Acrobat undulating CTD profiler on 16 September and 2 October 2003. Note the overall lower salinity in the estuary several weeks after the storm's passage, even though stratification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

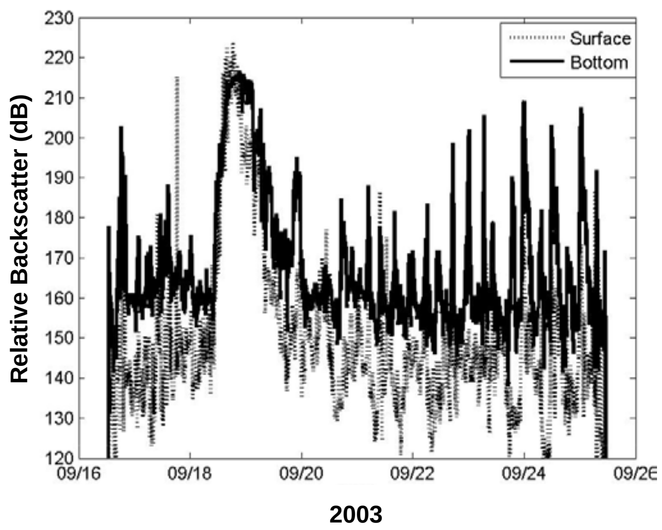

Figure 6. Relative backscatter as recorded by the ADCP for bottom and surface bins.

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

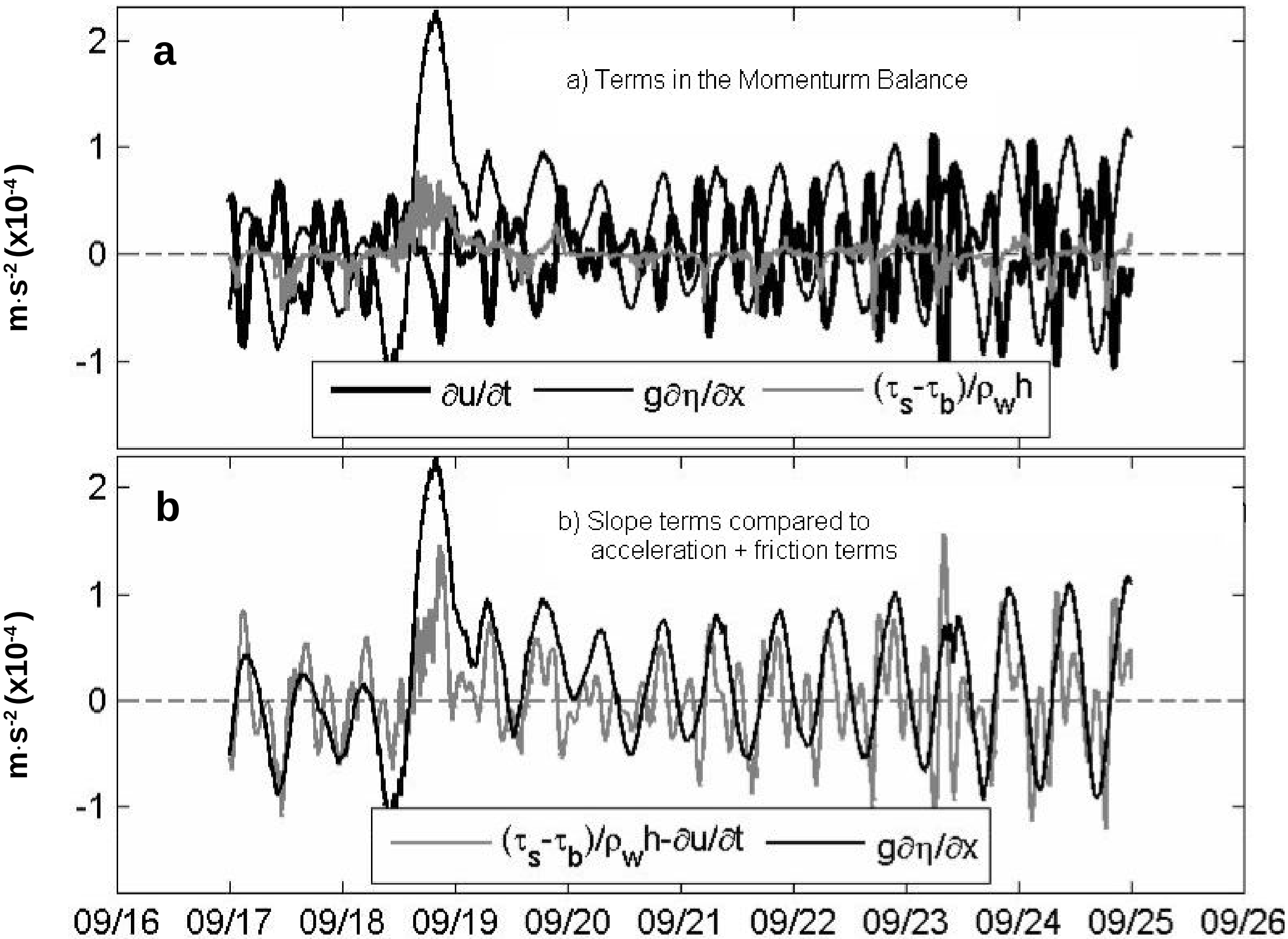

Figure 7. Panel a shows the three main terms in a simple-along channel barotropic momentum balance between acceleration, surface slope, and friction. Panel b shows the balance between the slope term and the acceleration and friction terms combined. To do this, the acceleration term is moved to the right 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 (ρ_{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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REFERENCES

1. L.W. Haas. 1977. The effect of the spring-neap tidal cycle on the vertical structure of the James, York and Rappahannock rivers, Virginia, U.S.A. *Est. Coast. Mar. Sci.* 5: 485–496.
2. J. Sharples, J.H. Simpson, and J.M. Brubaker. 1994. Observations and modeling of periodic stratification in the upper York River estuary, Virginia. *Est. Coast. Shelf Sci.* 38: 301–312.
3. W.J. Emery and R.E. Thomson. 1998. *Data Analysis Methods in Physical Oceanography*. Elsevier Science, Inc. New York.
4. J.H. Simpson, E. Williams, L.H. Brasseur, and J.M. Brubaker. 2005. The impact of tidal straining on the cycle of turbulence in a partially stratified estuary. *Cont. Shelf Res.* 25: 51–64.
5. P.V. Hyer and E.P. Ruzecki. 1976. Changes in salinity structure of the James, York and Rappahannock estuaries resulting from the effects of Tropical Storm Agnes. *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). The Johns Hopkins University Press. Baltimore, MD.
6. D.P. Wang and A.J. Elliot. 1978. Non-tidal variability in the Chesapeake Bay and Potomac River: Evidence for non-local forcing. *J. Phys. Oceanogr.* 8(2): 225–232.
7. C.T. Friedrichs, L.H. Brasseur, M.E. Scully, and S.E. Suttles. 2003. Use of backscatter from Acoustic Doppler Current Profiler to infer eddy diffusivity of sediment and bottom stress. *Proc. Coast. Sed. 2003*, American Society of Civil Engineers.
8. S.D. Smith. 1980. Wind stress and heat flux over the ocean in gale force winds. *J. Phys. Oceanogr.* 10: 709–726.

OCEANOGRAPHIC FACTORS AND EROSION OF THE OUTER BANKS DURING HURRICANE ISABEL

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ABSTRACT

The meteorological and oceanographic processes responsible for erosion of the Outer Banks of North Carolina during Hurricane Isabel have been simulated using a suite of numerical models. The computed wind, wave, current, and water level fields are used to drive a three-dimensional numerical sedimentation model that calculates nearshore sediment transport and erosion potential. The erosion potential is the quantity of sand that can be transported by the coastal transport system, which is the maximum volume that can be eroded. The potential erosion of the dunes is discussed by comparing the erosion potential to dune-beach volumes, which are not known in this study.

It is proposed that breaching is dependent on prior dune erosion and the difference in water levels between the open ocean and lagoon sides of the islands. Thus breaching will occur where the erosion potential is high and a large water level difference exists across the barrier island. The results are consistent with coastal erosion patterns observed in the aerial photographs taken after landfall.

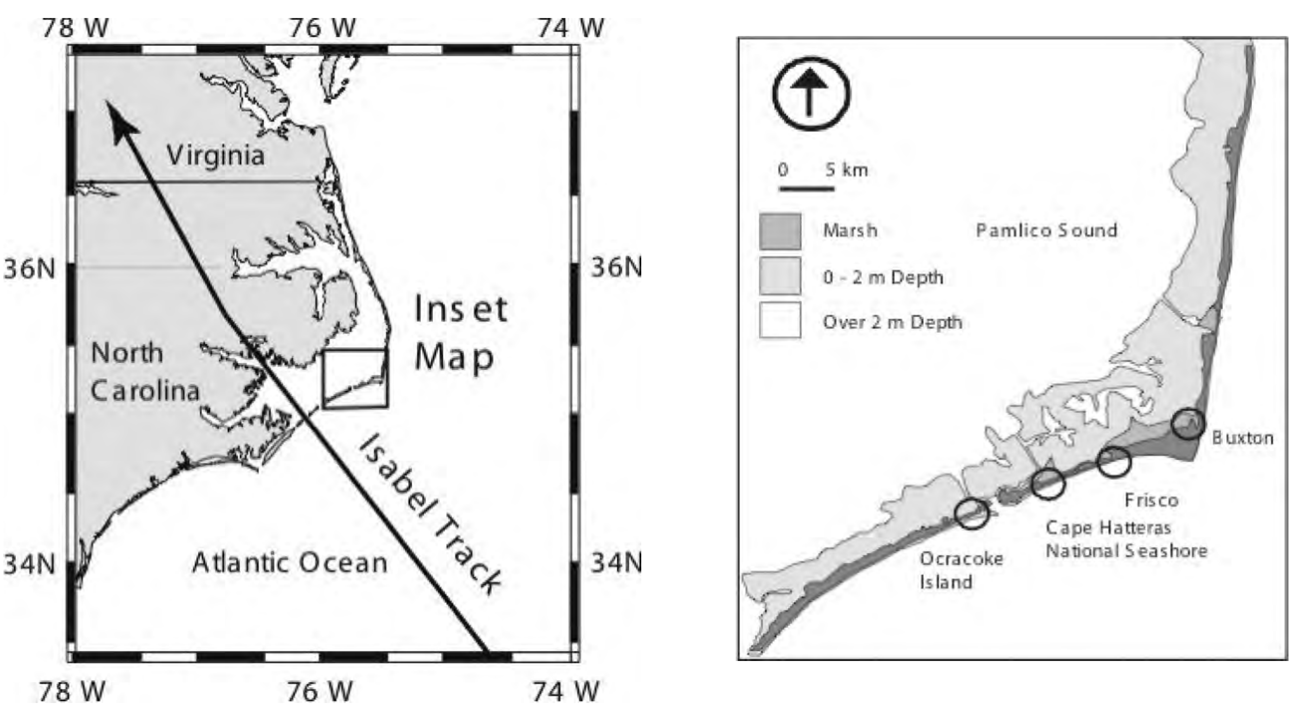

Figure 1. Map of the Outer Banks showing the path of Hurricane Isabel on 18 September 2003. The inset map shows the Cape Hatteras locations (circled) discussed in the text.

INTRODUCTION

The morphological response of a barrier system to a severe storm consists of distinct erosion and deposition phases [1]. The erosion phase is characterized by dune scarp erosion, channel incision, and washout. Deposition comprises construction of perched fans, washover terraces, and sheetwash lineations. Maximum washover penetration and erosion for hurricanes occurs in the right, front quadrant within 20 to 50 km of the eye [2].

This study examines the response of the barrier islands making up the Outer Banks of North Carolina to Hurricane Isabel, which made landfall west of Ocracoke Island at 11:00 UT on 18 September 2003 (Figure 1). From what is known of barrier island response to hurricanes [3], the severe overwash and breaching of Hatteras Island during Isabel are not surprising. Nevertheless, the relationships between atmospheric, oceanographic, and sedimentological processes during hurricanes are poorly known. If the complex response of a barrier island system such as the Outer Banks is to be understood, demonstrating a direct relationship between oceanographic forcing and patterns of barrier island erosion becomes necessary.

This paper identifies these links and uses them to predict erosion patterns during Hurricane Isabel. The use of numerical models to simulate atmospheric, oceanographic, and sedimentological processes during a hurricane can reveal the causes of specific erosional responses. It remains for the coastal research community to improve this ability further through the use of more-detailed coastal erosion models that use these simulated processes to make specific predictions for future storms.

METHODS

The National Oceanic and Atmospheric Administration (NOAA) flew several reconnaissance flights over the Outer Banks after Hurricane Isabel to assess the damage. Images were taken between 19 and 21 September with an Applanix-Emerge Digital Sensor System (DSS) mounted on a NOAA Twin Otter aircraft flying at an altitude of 1875 m (7500 ft). The ground sample distance for each pixel is approximately 0.37 m. The DSS system has a built-in GPS system that allows geo-referencing of the images [4]. The geo-referenced images were not available for this study, however; instead high-resolution jpeg images were used. The magnitude of washover penetration can be estimated from the photographs, using vehicles and road markings for scale.

The model system in this study couples individual models so that key information can be passed between them [5, 6, 7]. A parametric cyclone wind model [8] is used to calculate the wind field. The wave field is calculated by the SWAN (Simulating WAves Nearshore) wave model [9], developed for use in coastal areas. This study uses the Navy Coastal Ocean Model [10] (NCOM), to calculate coastal currents. NCOM is initialized using temperature and salinity data from a global circulation model [11], and forced with tidal elevations and transports at open boundary points from a global tide model [12]. The interaction of waves and currents near the seabed is represented using a model that calculates the combined wave and current shear stresses [13, 14] (BBLM). The BBLM is coupled to the TRANS98 sedimentation model [15], which has been applied to several sedimentation studies during severe storms [6, 16, 17, 18, 19]. The models use a cell size of 3.02 km and 3.71 km along the x (easting) and y (northing) axes, respectively. The hindcast interval is from 00:00 UT on 16 September to 15:00 UT on 19 September 2003. The model operation sequence is: 1) Holland wind model; 2) SWAN wave model; 3) NCOM circulation model; and 4) coupled BBLM and TRANS98 model.

A bed conservation equation is solved using the sediment transport vectors from TRANS98 [19]. Erosion is predicted at grid cells where a transport divergence results from the storm currents; converging currents result in deposition. Observations in the Gulf of Mexico and the Atlantic coast indicate that the inner shelf (deeper than about 3–5 m) is either a site of deposition or no change over long time intervals and during storms [20, 21, 22, 23, 24]. If a divergence occurs in the sediment transport field at a boundary cell adjacent to land, therefore, the eroded sand is replaced by sediment from the adjacent land point. This boundary condition assures that no erosion will occur at coastal water cells and has been implemented with the TRANS98 model for a northeaster at the Field Research Facility at Duck, North Carolina [16]. The results were consistent with measurements of bed elevation, indicating that it constitutes a reasonable first approximation of beach and dune erosion. The volume of sediment removed from the adjacent land point is referred to as potential erosion (e) in this study.

RESULTS AND DISCUSSION

The Morphological Response of Ocracoke and Hatteras Islands

Washover terraces and perched fans were deposited 650 m inland at the eastern end of Ocracoke Island (Figure 2a) at a distance of 50 km from landfall. Newly incised channels, in addition to dune erosion and washover deposition (Figure 2b), are evident at the western end of Hatteras Island, which is 60 km east of the storm track. At the town of Frisco on Hatteras Island, 70 km from the storm track, coastal dunes were severely eroded and washover terraces, perched fans, and sheetwash lineations were deposited 500 m from the water line (Figure 2c). Hurricane Isabel's impacts at Buxton, just north of Cape Hatteras and approximately 75 km from the storm path, were primarily dune erosion and the construction of washover terraces and perched fans (Figure 2d) as far as 400 m inland.

Predicted Atmospheric and Oceanographic Conditions

The predicted meteorological and oceanographic factors all reach their maximum intensities along Hatteras Island during the 12-hour period surrounding landfall. The predicted hurricane winds become easterly and strengthen to more than 20 m·s^{-1} by 18 September. A peak wind speed of 35 m·s^{-1} occurs just before the eye makes landfall when the wind is onshore at south Hatteras Island (Figure 3a). The hindcast waves near Hatteras Island exceed 7 m at landfall (Figure 3b), in agreement with coastal observations during Hurricane Andrew [25].

The hindcast currents along south Hatteras Island are westerly during the storm build-up and peak at more than 2 m·s^{-1} prior to landfall. Due to the shift in wind direction to onshore, however, they weaken at landfall (Figure 3c) before reversing direction as the eye moves inland and the wind becomes westerly. The storm surge is superimposed on the astronomical tides and these water surface anomalies can reinforce each other if their relative timing is correct. The tidal signal dominates the regional pattern of predicted water level (Figure 3d). The storm setup extends from Ocracoke Island eastward and northward along Hatteras Island—consistent with the predicted wind field prior to landfall, which pushes water into Pamlico Sound and piles it against the coast. Low water levels are predicted in southeast Pamlico Sound because the easterly wind at landfall pushes lagoon water to the western side of the estuary.

Barrier Island Potential Erosion

The majority of published morphological data for hurricane impacts on mid-latitude coasts demonstrates that the overwhelming response of beaches to these events is a net sediment loss [26]. Coastal dunes are typically eroded several meters during severe storms and beaches evolve to form a storm profile that stores sand on the inner shelf [1, 2]. The dune-beach system is thus the primary source of sand for the coastal transport system.

The carrying capacity of the coastal sediment transport system is the potential coastal erosion (e), which is the maximum volume of sediment mobilized by erosional processes [27, 28]. The dune erosion potential can be evaluated by comparing the cross-sectional area of the dune-beach system, $A_D = L \cdot H_D$, to the potential erosion, e, where H_D is the mean height of the dune-beach system and L is its width. Potentially, the dune-beach system will be removed when $A_D <$ e. When H_D is unknown, as in this study, the potential for dune erosion can be estimated by calculating the average height, $H_{AC} = e/L$, that would produce a beach-dune volume that equals e. The storm surge effectively reduces the dune height by h; thus H_{AC} is increased by the total setup h (Figure 3d); $H_{AC} = H_{AC} + h$. For example, L is approximately 250 m at Ocracoke, 100 m at the western end of Hatteras Island, 200 m at Frisco, and 150 m at Buxton. The predicted values of e (Figure 4) decrease eastward; consequently, H_{AC} = 1.04 m, 1.58 m, 0.9 m, and 0.6 m at Ocracoke, Cape Hatteras National Seashore (a larger predicted h), Frisco, and Buxton, respectively. The model is capable of predicting deposition but it does not occur along this coast during Hurricane Isabel

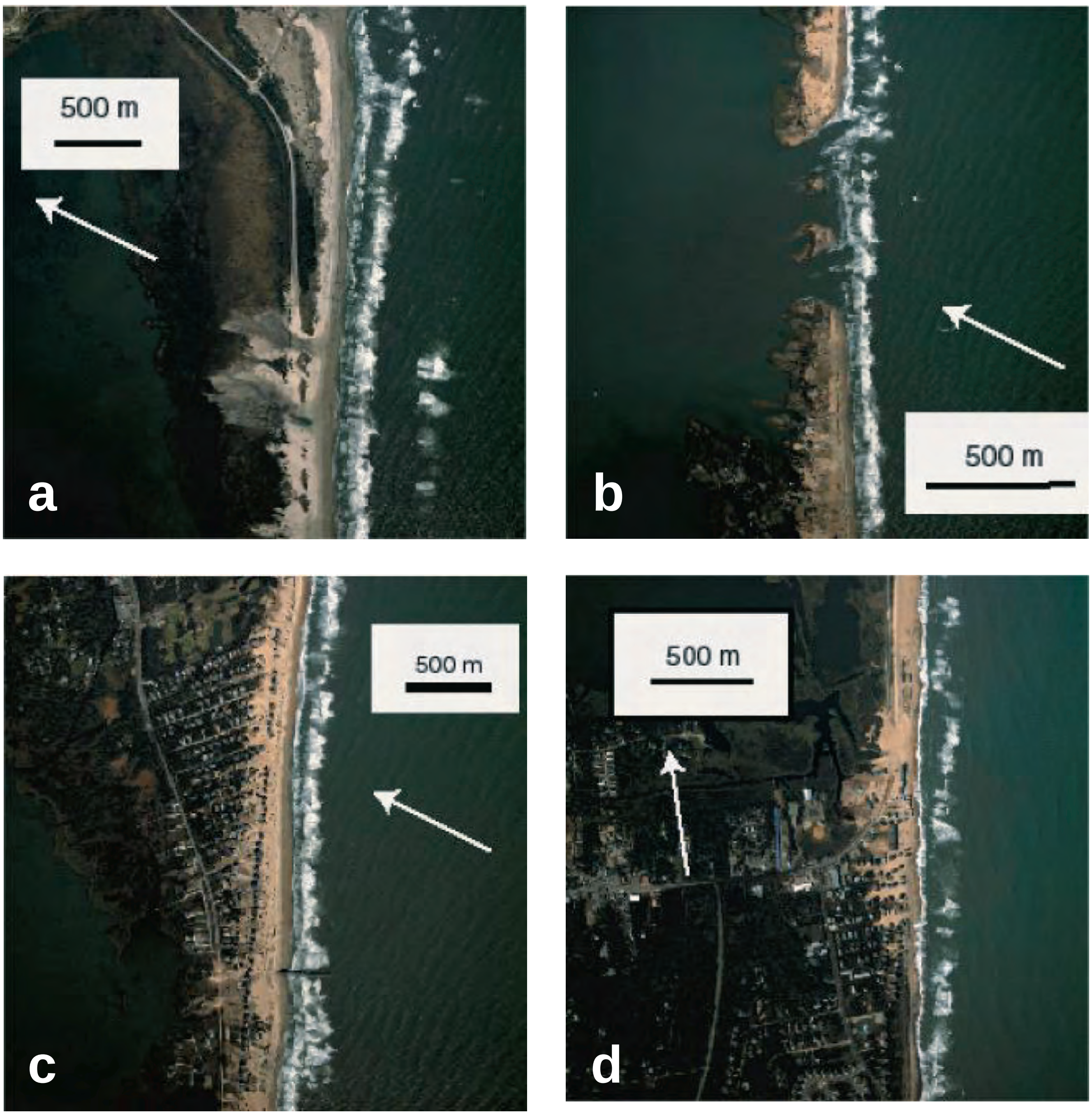

Figure 2. Aerial photographs taken after Hurricane Isabel on the Outer Banks: a) Ocracoke Island; b) Cape Hatteras National Seashore; c) Frisco; and d) Buxton. See Figure 1b for locations. The photographs are oriented with Pamlico Sound to the left.

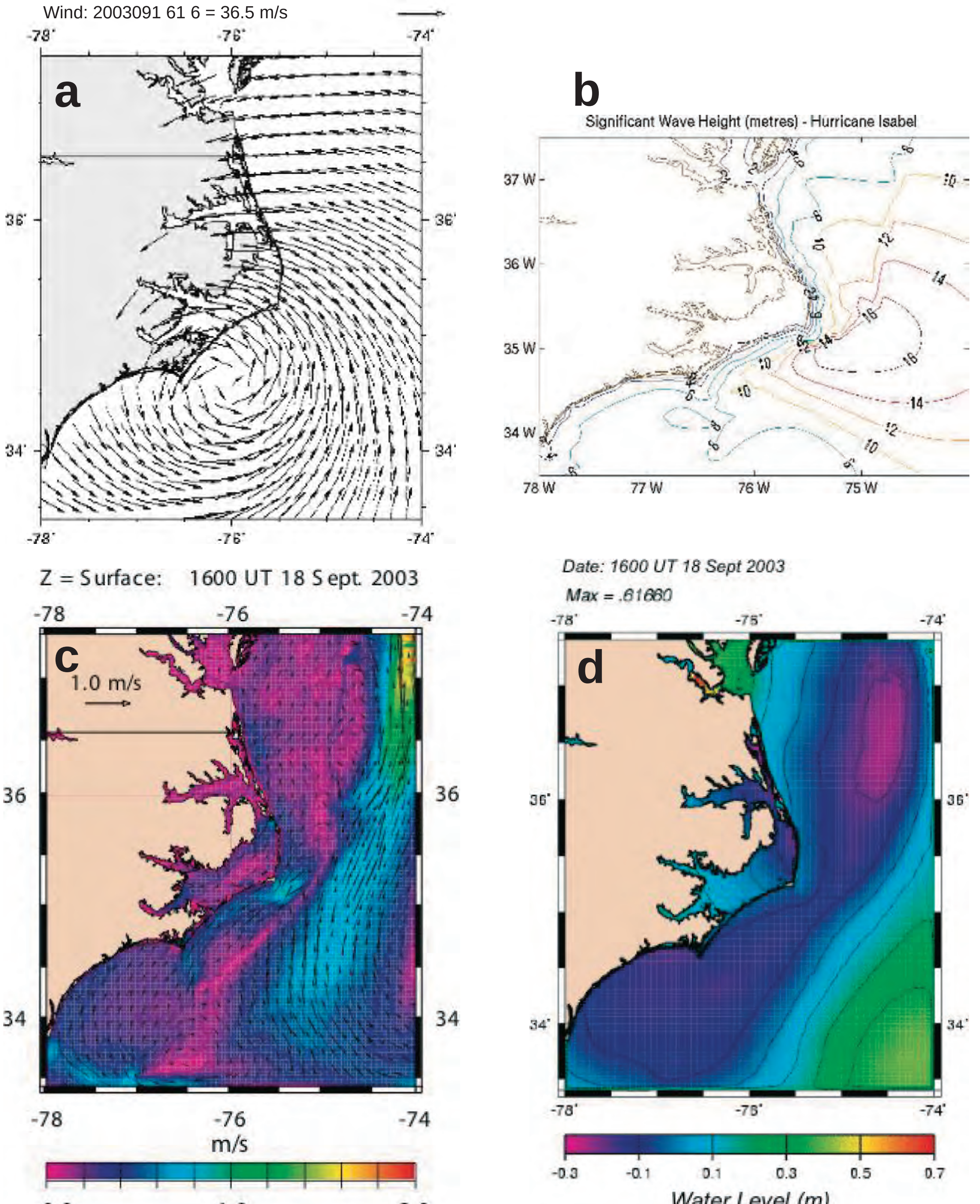

Figure 3. Predicted environmental conditions at landfall (16:00 UT 18 September 2003): a) The wind velocity computed by the Holland Model; b) The significant wave height from SWAN; c) The surface currents calculated by NCOM; and d) The water level anomaly calculated by NCOM (contour interval is 0.1 m).

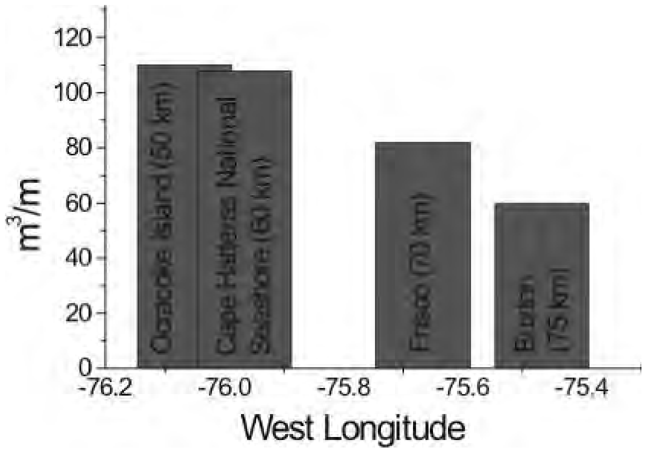

Figure 4. Potential erosion (m^2) predicted by TRANS98 during Hurricane Isabel at the locations shown in Figure 1b. The distance from landfall is given in parentheses. The units are cubic meters of sand eroded per meter of coastline.

because of the storm surge, waves, and nearshore currents.

Analysis of the available aerial photographs revealed that dune penetration was the exception at Ocracoke Island (Figure 2a), although overwash occurred locally at spatial scales below the resolution of the hydrodynamic and sedimentation models. This situation indicates that, overall, $e < A_D$ and $H_{AC} < H_D$. The lower dunes and smaller volume of sand at Cape Hatteras National Seashore would have allowed significant erosion for the same value of e as at Ocracoke. The amount of damage to the barrier island (Figure 2b) supports this conclusion and indicates that $H_D < H_{AC}$. The dunes at Frisco are as low as those at Cape Hatteras National Seashore, but coastal erosion was reduced due to its longer distance from the storm track and the greater width of the island.

The observed water levels during Hurricane Isabel (measured $h < 2$ m) did not exceed the dunes on Hatteras Island and submergence would have been unlikely. For channel incision to occur, therefore, the dune-beach system must first have been substantially eroded by waves. A second source of energy is the pressure head associated with the difference in water levels on the ocean and lagoon sides of the island. If the dunes are locally removed at weak points, this pressure gradient can drive a steady current landward, which in combination with storm waves can rapidly erode a channel to the lagoon.

The potential for breaching can be evaluated using the water level differences across the islands (Dh), the potential erosion of the dune-beach system (e), and the island width. The predicted Dh at Ocracoke at landfall is 0.65 m. Because of set-down in southeast Pamlico Sound (Figure 3d), however, the hindcast water level at Hatteras National Seashore is -1.8 m and Dh is 2.3 m. This large gradient, in combination with significant dune erosion and a narrow width (less than 250 m), caused breaching at this location. A similar pressure gradient is predicted at Frisco, but no channel was incised, partly because of somewhat lower dune erosion (e = 80 m^2) and greater width (more than 500 m). Although the hindcast water level inside the sound is lower at Buxton (-2.4 m), the low setup on the open coast results in a difference of 2.6 m. The dunes were entirely removed, but the width of the island prevented breaching despite a large Dh.

These results are somewhat qualitative due to a lack of beach-dune profiles, the coarse resolution of the numerical models, and the importance of several nearshore processes not included in these models, such as wave-driven flow and island inundation. Nevertheless, we consider these results robust because of their dependence on fundamental physics rather than parameterizations of diverse observations. The models predict a strong current system and large waves along the ocean side of the islands, where erosion of the inner shelf would occur if not for the supply of sand from the beach-dune sand reservoir. The comparison between the model results and the observed erosion indicates that the dunes were removed and breaching occurred in areas where this sand reservoir was insufficient. A more detailed simulation of the timing of these erosional processes will require significant additional research effort.

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photographs of the Outer Banks were acquired from the North Carolina Geodetic Survey.

REFERENCES

1. R.A. Morton and A.H. Sallenger. 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *J. Coast. Res.* 19: 560–573.
2. J.E. Fucella and R. Dolan. 1996. Magnitude of subaerial beach disturbance during northeast storms. *J. Coast. Res*. 12: 420–429.
3. S.P. Leatherman. 1983. Barrier dynamics and landward migration with Holocene sea-level rise. *Nature* 301: 415–417.
4. NOAA. 2003. NOAA News Online Story 2091. *www.noaanews.noaa.gov/stories.*
5. T.R. Keen and R.L. Slingerland. 2003. A numerical study of sediment transport and event bed genesis during Tropical Storm Delia. *J. Geophys. Res*. 98: 4775–4791.
6. T.R. Keen, S.M. Glenn, and R.L. Slingerland. 1994. Coastal circulation and sedimentation during severe storms. In: *Proc. Third Int. Conf. Estuarine Coastal Mod.* M.L. Spaulding, K Bedford, A. Blumberg, R. Cheng, and C. Swanson (eds.). American Society of Civil Engineers, NY. pp. 279–293.
7. R.A. Allard, L. Smedstad, M. Bettencourt, C.A. Blain et al. 2003. High fidelity simulation of littoral environments: Applications and coupling of participating models. In: *Proc. High Perf. Comp. 2003 Users Group Conf.*, R.E. Peterkin, Jr. (ed.) IEEE Computer Society, Washington D.C. pp. 306–313.
8. G.J. Holland. 1980. An analytic model of the wind and pressure profiles in hurricanes. *Mon. Weather Rev.* 108: 1212–1218.
9. N. Booij, R.C. Ris, and L.H. Holthuijsen. 1999. A third-generation wave model for coastal regions-1. Model description and validation. *J. Geophys. Res.* 104: 7649–7666.
10. S.L. Morey, P.J. Martin, J.J. O'Brien, A.A. Wallcraft, and J. Zavala-Hidalgo. 2003. Export pathways for river discharged fresh water in the northern Gulf of Mexico. *J. Geophys. Res.* 108: Article No. 3303.
11. C.N. Barron, A.B. Kara, H.E. Hurlburt, C. Rowley, and L.F. Smedstad . 2004. Validation of the 1/8º Global Navy Coastal Ocean Model nowcast/forecast system. *NAVO MSRC Navigator* Spring, 5–8.
12. G.D. Egbert, A.F. Bennett, and M.G.G. Foreman. 1994. TOPEX/POSEIDON tides estimated using a global inverse model. *J. Geophys. Res*. 99: 24821–24852.
13. S.M. Glenn and W.D. Grant. 1987. A suspended sediment stratification correction for combined wave and current flows. *J. Geophys. Res.* 92: 8244–8264.
14. T.R. Keen and S.M. Glenn. 1994. A coupled hydrodynamic-bottom boundary layer model of Ekman flow on stratified continental shelves. *J. Phys. Oceanogr.* 24: 1732–1749.
15. T.R. Keen and S.M. Glenn. 1998. Resuspension and advection of sediment during Hurricane Andrew on the Louisiana continental shelf. In: *Proc. Fifth Int. Conf. Estuarine Coastal Mod.* M.L. Spaulding and A.F. Blumberg (eds.). American Society of Civil Engineers. NY. pp. 481–494.
16. T.R. Keen, R.L. Beavers, P.A. Howd, and K. Hathaway. 2003. Shoreface sedimentation during a northeaster at Duck, North Carolina, U.S.A. *J. Coast. Res.* 19: 24–40.
17. T.R. Keen, S.J. Bentley, W.C. Vaughan, and C.A. Blain. 2004. The generation and preservation of multiple hurricane beds in the northern Gulf of Mexico. *Mar. Geol.* 210: 79–105.
18. T.R. Keen and S.M. Glenn. 2002. Predicting bed scour on the continental shelf during Hurricane Andrew. *J. Waterw. Port Coast. Ocean Eng.* 128: 249–257.
19. T.R. Keen and R.L. Slingerland. 1993. Four storm-event beds and the tropical cyclones that produced them: A numerical hindcast. *J. Sed. Pet.* 63: 218–232.
20. R.L. Beavers. 1999. Storm sedimentation on the surf zone and inner continental shelf, Duck,

North Carolina. Ph.D. Thesis, Duke University. Durham, NC.
21. E.L. Gallagher, S. Elgar, and R.T. Guza. 1997. Observations and Predictions of Sand Bar Motion, In: *Proc. 25th Int. Conf. Coastal Eng.* 205–216, A.S.C.E.
22. R.A. Morton, J.C. Gibeaut, and R. Gutierrez. 1995. Pre-Project Surveys of Beach and Nearshore Conditions Galveston Beach Nourishment Project. Report prepared for the City of Galveston by the Bureau of Economic Geology at the University of Texas at Austin.
23. J.H. Vazquez. 1996. Galveston Beach Nourishment Project Post Monitoring Beach and Nearshore Surveys, Report Prepared for the Park Board of Trustees of the City of Galveston by Texas A&M University–Galveston.
24. S.L. Douglass, B. Pickel, and B. Greathouse. 1999. State of the Beaches of Alabama: 1998. College of Engineering Report No. 99-1 to Coastal Programs Office, Alabama Dept. of Economic and Community Affairs, U. South Alabama, Mobile, AL.
25. V.J. Cardone et al. 1994. Hindcast Study of Wind Wave and Current Fields in Hurricane Andrew–Gulf of Mexico, Minerals Management Service, Herndon, VA.
26. G.W. Stone and C.W. Finkl (eds.). 1995. Impacts of Hurricane Andrew on the coastal zones of Florida and Louisiana, 22–26 Aug., 1992. *J. Coast. Res.* Special Issue No. 21.
27. P.L. Lawrence and R.G.D. Davidson-Arnott. 1997. Alongshore wave energy and sediment transport on southeastern Lake Huron, Ontario, Canada. *J. Coast. Res.* 13: 1004–1015.
28. P. Ruggiero, P.D. Komar, W.G. McDougal, J.J. Marra, and R.A. Beach. 2001. Wave runup, extreme water levels and the erosion of properties backing beaches. *J. Coast. Res.* 17: 407–419.

LANDSCAPE MODIFICATIONS BY HURRICANE ISABEL, FISHERMAN ISLAND, VIRGINIA

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ABSTRACT

Fisherman Island, an emergent barrier island situated at the southern tip of the Delmarva Peninsula and the entrance to the Chesapeake Bay, is the most rapidly accreting barrier on the Virginia coast. The island has developed in the past 200 to 250 years in a sequence of emergence, divergence, and bipolar spreading. Past storms have left records of accretion events, punctuated by truncation from overwash and channel plugging. This study sought to assess the impact of Hurricane Isabel on the geomorphology and vegetation of the island. Hurricane Isabel produced a 1.3-m storm surge and 3-m wave runup in the vicinity, resulting in submergence of much of the island during elevated water levels. Augmenting a long-term spatial study of island evolution, Landsat Enhanced Thematic Mapper images collected pre- (3 September 2003) and post-Isabel (20 October 2003) were classified for analysis of changes to island morphology and vegetation. Results document localized accretion, interdune flooding and overwash, and minor erosion from Isabel. The island subaerial surface area increased by 3.3%, an observation bolstering its emergent nature, although significant changes were also noted *between* terrestrial cover types (15% of the pre-storm island changed among landform and vegetation types). The greatest morphological changes were spit development, overwash sediment deposition from the beach to shrub-dune areas, and redistribution and accumulation of wrack and storm debris. The island maintained its pre-storm record of sequence morphodynamics.

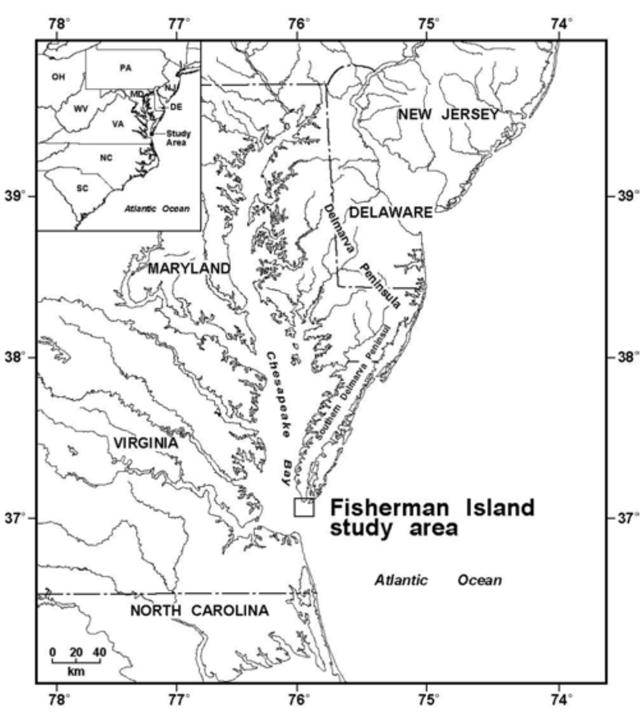

Figure 1. Study area location, Fisherman Island, southern Delmarva Peninsula.

INTRODUCTION

Fisherman Island is the southernmost island in the Delmarva Peninsula chain of barrier islands and marks the northern boundary of the Chesapeake Bay entrance (Figure 1). The island exhibits landscape features distinct from other islands in the Delmarva coastal compartment. The paleogeography and emergence of Fisherman Island from the shoreface are detailed in Oertel and Overman [1]. The distinguishing landscape features of the island complex today reflect its emergence, bipolar spreading and divergence, and modern and periodic hiatus in the depositional record caused by truncation from storm overwash and erosion. The ultimate sand sources of this emergent island are thought to be relatively deep shoreface environments. Deep bay and coastal currents seaward of the nearshore breaker zone transported and deposited sand in a convergence zone at the Chesapeake Bay mouth. This accumulation rose to the level of wave base, resulting in wave refraction of ocean swell. Refracting wave crests are primarily responsible for driving sand onto the Fisherman Island shore [1]. The present-day morphology of the island is a unique emergent pattern with a "collar" shape due to wave refraction recurving spits at both ends of the major axis of the island.

Fisherman Island forms part of the U.S. Fish and Wildlife Service's (FWS) Eastern Shore of Virginia National Wildlife Refuge and is bisected by Route 13 and the causeway of the Chesapeake Bay Bridge-Tunnel. The landscape provides habitats for endemic and migratory waterfowl, shorebirds, and summer nesting waterbirds [2]. Habitat diversity on a relatively low elevation and youthful emergent island is substantially controlled by geomorphic processes. The landform mosaic includes shorelines, ridges, swales, ponds, subaerial flats, tidal flats, sand bars, and spits. In addition, part of the island was developed during World War II and contains relic installations.

Prompted by experience with the site and the opportunity to study potential rapid changes on an emergent barrier island, a remote sensing analysis of surficial and land cover change was initiated. Although shoreline delineation from remote sensing is problematic even using aerial photographs [3], satellite remote sensing to detect change of coastal environments is useful in characterizing and measuring changes of erosion and accretion [4] or zonal variations over moderate distances [5]—particularly where changes are rapid and a long history of shoreline observations is available [6].

METHODS

Isabel Surge, Wave, and Profile Analyses

Observations of the storm event on the uninhabited island are not available, but water-level monitoring stations and buoy data are useful proxy sources. Beach profile measurements were also taken as part of an annual observation program, including 2003 and updated in 2004. First, to characterize Isabel's storm surge on Fisherman Island, water level monitoring data from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) (*http://tidesandcurrents.noaa.gov/data_res.html*) were acquired. Although no direct storm surge measurements were made on Fisherman Island, the proximity to Kiptopeke (a long-term, water-level monitoring station) and numerous tidal benchmarks in the vicinity suggest an appropriate surrogate. In addition, detailed wave observations from the National Data Buoy Center (*http://www.ndbc.noaa.gov/*), primarily from the nearby Chesapeake Light Tower (station # CHLV2) located on the inner shelf, were analyzed. Wind direction, sustained wind speed, and peak gusts were recorded.

Detailed wave data included the wind- and swell-wave significant wave heights (Ho), swell direction (azimuth), and dominant wave period(s). Given the swell height, the breaker height and distance from shore was approximated using an assumed nearshore gradient. Wave runup elevation could be estimated from these data and compared to surface observations and aerial photograph interpretation of the storm's effects. Beach profiles have been collected annually at a site on the western, leeward bayside of Fisherman Island over the past few years as part of a study of the island's morphodynamics and for a course on coastal landscape ecology at Old Dominion University in Virginia. In addition to profiles from 2001 and 2002, a profile was obtained immediately before Hurricane Isabel in September 2003 and again in September 2004.

Remote Sensing

Remote sensing was used to measure shoreline accretion/erosion and net changes in the landscape composition of Fisherman Island. Erosion/accretion is analyzed in a discrete fashion with the classification and movement of shorelines, controlling for tidal asynchrony in the imagery.

Shifts in vegetation and geomorphic features of the island require a more complex analysis using remote sensing, including complementary field data or high-resolution aerial photography (both available in only limited extent). Two cloud-free Landsat-7 ETM+ satellite images were acquired from the USGS Eros Data Center. The pre-Isabel image was taken 3 September 2003 with the post-Isabel image taken 20 October 2004. Both images were geometrically corrected to <0.5 pixel RMS error and co-registered to a common earth coordinate system (UTM WGS84). Since change detection requires consideration of exogenous effects such as atmosphere, solar illumination, and viewing geometry, the images were radiometrically corrected by converting the digital numbers to radiance and then reflectance values. Thus, true reflectance data could be analyzed and corrected for between-scene atmospheric differences with calculation of a set of spectral enhancements that highlight changes on the island. Prior to analyzing changes, the imagery was subset to the general area of Fisherman Island, focusing on nearshore and terrestrial features.

The remote sensing approach used three methods of change detection: image differencing, change vector analysis (CVA), and post-classification change detection. Image differencing —along with multi-image display— highlighted macro-changes on the island, including major erosional/accretional areas, overwash, and ecological changes to vegetated features. Change vector analysis was chosen to refine the basic changes identified by image differencing and to classify pixels into types of change that would typify storm impacts (areas of erosion, accretion, denuded dunes, or overwash areas). Finally, post-classification change detection was used as a discrete, albeit coarse, measurement tool to derive measures of net change on the island (land loss or accretion and amount of change between vegetation and landform types). Post-classification requires the separate classification of two or more images and subsequent overlay analysis. Although this method is the most straightforward change-detection method and is useful for showing discrete changes, it also potentially compounds errors in the individual classified images.

RESULTS AND DISCUSSION

Surge, Wave, and Beach Profiles

The Kiptopeke water levels (Figure 2) deviated markedly from predictions, reflecting the impact of storm surge on the area. Located several kilometers northwest of the island on the eastern Chesapeake Bay shore, Kiptopeke indicated a storm surge maximum of 1.3 m. As a proxy for storm overwash observations, detailed wave data were acquired from Chesapeake Light Tower (CHLV2), which is located approximately 20 km southeast of the island. Wave observations included dominant wave heights (H_o) of 5–6 m over 16 hours, dominant period of 16 sec, and surface winds of 72 mph (116 $km \cdot hr^{-1}$) sustained with gusts to 93 mph (150 $km \cdot hr^{-1)}$. Using the wave data, we estimated breaker heights of up to 7 m, approximately 250 m offshore, which could produce a wave runup height of approximately 3 m. This runup would be superimposed upon the storm surge, approximately equal to the Kiptopeke water level observation (Figure 2). The combination of moderate storm surge and extreme wave action upon the island and its nearshore area prompted further study of the pre- and post-storm landscape. The annual beach profiles (Figure 3) on the southern left-hand spit near the Chesapeake Bay Bridge-Tunnel indicate only moderate shoreline retreat and possible net accretion on the dune, but a more synoptic view via satellite images would complement this observation.

Change Detection

Pre- and post-Isabel images showed a variety of spectral changes owing to geomorphic processes and vegetation disturbance. Image differencing highlighted areas of gross spectral change, identifying areas for more detailed investigation. These areas included: right-hand spit progradation on the northern end of the island; areas of erosion, overwash, and accretion; and inundated dune swales. Change vector analysis was used to

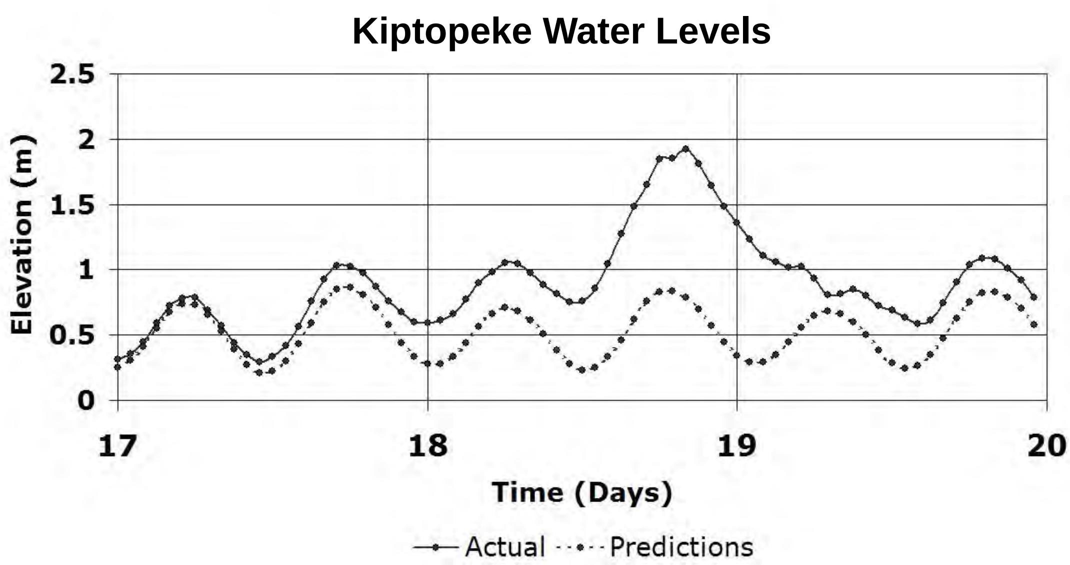

Figure 2. Kiptopeke water levels showing an estimated 1.3 m storm surge.

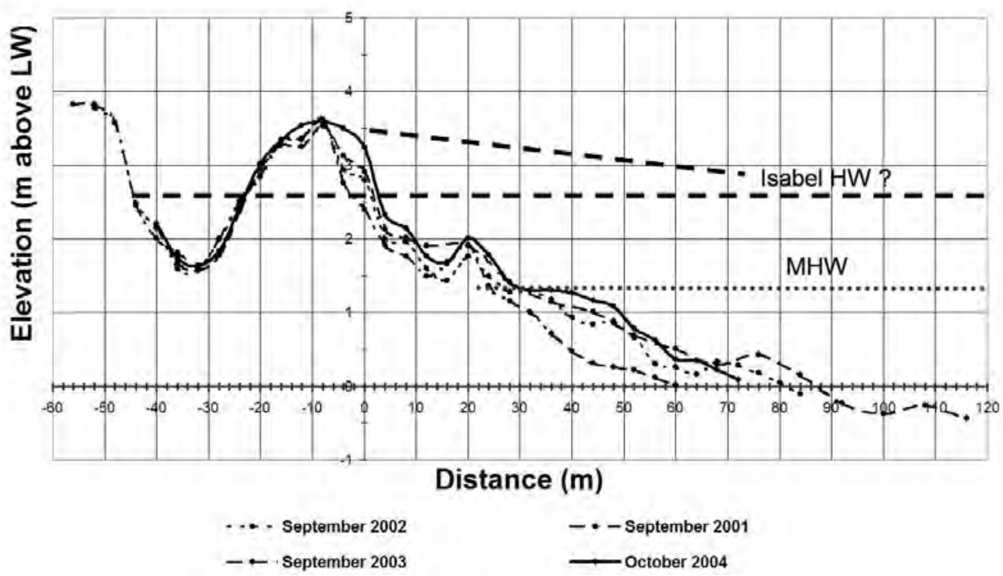

Figure 3. Annual beach profiles taken on the leeward, bay side of Fisherman Island in September 2001, 2002, and 2003 as well as October 2004.

delineate training sites for these areas of known change and to classify the remainder of the image into change/no-change. These areas are depicted as overlays of accretional sands (Figure 4) and eroded beaches and denuded dunes overwashed during the storm (Figure 5). Observations were confirmed by visual image interpretation, ground observations, and oblique aerial photographs of sites (e.g., Figure 6).

For post-classification change detection, we sorted each image into one of four classes using an ISODATA unsupervised classification algorithm (water, marsh/wrack/forest, dune/shrub/grass, and sand/bare). Pre-/post-storm images were overlaid as raster grids and a tally matrix used to tabulate class change/no-change. Table 1 shows the result of classified changes in terms of land area of classes (hectares). Table 2 reports the percentage change for each class. In both tables, cells in the diagonal represent no change. On the northeast side of the island, significant erosion of the beach was indicated, with additional adjacent overwash and

Figure 4. Accretion areas identified by supervised CVA, vectorized into polygons, and displayed over Landsat satellite data (ETM+ 4 September 2003 band 1). Polygons on the island would be overwashed and denuded from vegetated to bare sand. The offshore bars south and east of the island were substantially eroded. The large spit platform on the northern side of the island would subsequently expand longitudinally downdrift (e.g., Figure 5 and Figure 6).

deposition of wrack from possible submerged aquatic and dune vegetation (Figure 6). In terms of percentage change, the island accreted 3.3% additional sand area (~32 ha that were water were classified as bare sand after the storm). A shift also occurred from marsh to water, however, as a result of ponding or possible mixed pixels (accounting for 3.5% of the change or ~34 ha). Erosional and denudational changes were indicated by a shift from marshes, shrub, and dune vegetation to bare sand (3.9% or ~37 ha). Overwash caused the change from bare, sandy beach to wrack and shrub-dune debris deposits (3.7% or ~35 ha).

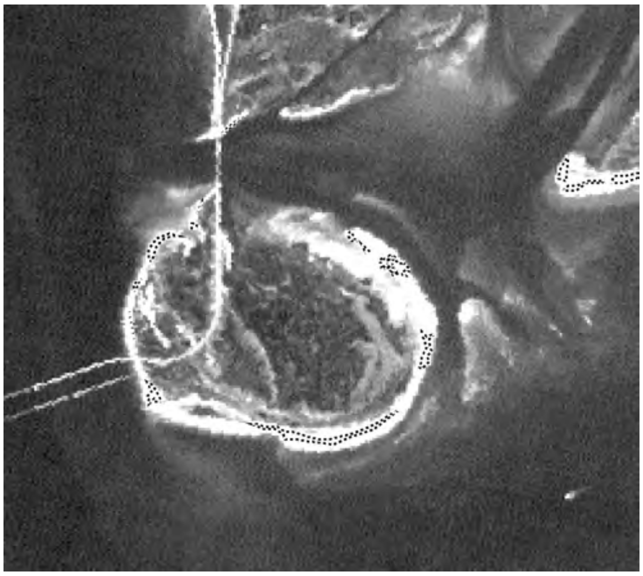

Figure 5. Overwash and erosional areas classified by supervised CVA, displayed over Landsat ETM+ 20 October 2003 band.

The pattern of interdune flooding suggests inundation from the landward/mainland side of the island, with surge water backing up from the interstitial marshes. Northeast winds and the lack of major breaching of primary dunes corroborate this interpretation. This interpretation of change requires the significant caveat that only casual field observations were available to "groundtruth" the changes prior to Isabel and immediately afterward. However, the oblique aerial photography and long-term familiarity with processes and vegetation patterns on the island nonetheless provide confidence in the interpreted results. In addition, accuracy assessment of the individual land cover classifications yields overall accuracy in the 90–95% range among classes (with the lowest being marsh and the highest water).

Figure 6. Oblique aerial photograph of eastern Fisherman Island looking south-southeast after Hurricane Isabel illustrating overwash, erosion, and accretion patterns (Photo courtesy of John Porter, University of Virginia, Virginia Coast Reserve LTER).

Table 1. Area change/no-change matrix (hectares) for Fisherman Island landscape classes.

From 2 Sept '03 \ To 20 Oct '03	Water	Marsh/wrack/ forest	Dune/shrub/ grass	Sand/bare
Water	210	11.8	0.9	32.7
Marsh/wrack/ forest	34.1	247.2	6.4	14.5
Dune/shrub/ grass	0	20.6	205.9	22.4
Sand/bare	3.9	11.1	24.1	134.9

Table 2. Percent change/no-change matrix for Fisherman Island landscape classes.

From 2 Sept '03 \ To 20 Oct '03	Water	Marsh/wrack/ forest	Dune/shrub/ grass	Sand/bare
Water	21.4	1.2	0.1	3.3
Marsh/wrack/ forest	3.5	25.2	0.6	1.5
Dune/shrub/ grass	0.0	2.2	21.7	2.4
Sand/bare	0.4	1.2	2.5	14.2

SUMMARY AND CONCLUSIONS

This project sought to quantify the impact of a hurricane on an emergent barrier island and to gauge the utility of alternative remote sensing change-detection algorithms. Changes between land-surface types represented processes that are typical of other barrier islands, including overwash, erosion and accretion downdrift along inlets and recurved spits, and backbarrier flooding. Despite the high wave energy and moderate surge estimated to have impacted the island, no major breach of primary dunes occurred. Even with significant alterations in vegetation and geomorphic surfaces, the island retained its record of sequence morphodynamics. The project also demonstrated that rather than the application of stand-alone algorithms for change detection, sequential analyses using image differencing, CVA, and post-classification change detection can provide complementary information. Image differencing excels as an exploratory technique. Change Vector Analysis allows for specific process, state, or gradational changes to be mapped. Post-classification provides an overall synoptic assessment of landscape structure and change among island surfaces.

ACKNOWLEDGMENTS

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REFERENCES

1. G.F. Oertel and K. Overman. 2004. Sequence morphodynamics at an emergent barrier island, middle Atlantic coast of North America. *Geomorphology* 58: 67–83.
2. Fish and Wildlife Service. 2004. Eastern Shore of Virginia National Wildlife Refuge (*http://easternshore.fws.gov/*).
3. R.A. McBride, M.W. Hiland, S. Penland, S.J. Williams, M.R. Byrnes, K.A. Westphal, B.E. Jaffe, and A.H. Sallenger Jr. 1991. Mapping barrier island changes in Louisiana: Techniques, accuracy, and results. *Proc. Coast. Sed. '91*, American Society of Civil Engineers, New York. 1011–1026.
4. M. El Raey, S.H. Shawat El-Din, A.A. Khafagy, and A.I. Abo-Zed. 1999. Remote sensing of beach erosion/accretion patterns along Damietta-Port Said, Egypt. *Int. J. Remote Sens.*, 20: 1087–1106.
5. O.E. Frihy, S.M. Nasr, M.M. El Hattab, and M. El Raey. 1994. Remote sensing of beach erosion along Rosetta promontory northeastern Nile Delta, Egypt. *Int. J. Remote Sens.* 15: 1649–1660.
6. F.J. Anders and R.J. Byrne. 1991. Accuracy of shoreline change rates as determined by maps and aerial photographs. *Shore Beach*, 591: 17–26.

HURRICANE ISABEL AND EROSION OF CHESAPEAKE BAY SHORELINES, MARYLAND

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ABSTRACT

Hurricane Isabel resulted in spotty, uneven erosion of the Chesapeake Bay shoreline in Maryland. In the aftermath of the storm, the Maryland Geological Survey (MGS) polled local officials and county planners throughout the state and estimated the amount of sediment contributed by shore erosion to the Bay based on limited quantitative information. In Maryland, erosion was largely limited to the Bay's western shore. Among the affected counties, Baltimore County conducted the most extensive assessment of shore erosion, using aerial surveys. To approximate the area and volume of sediment lost, the authors extrapolated Baltimore County shoreline losses to the western shore of the Maryland Chesapeake Bay and assumed a value of 5 ft (1.5 m) for both shoreline retreat and average bank height. In sum, Isabel washed away approximately 20 acres (8 hectares) of coastal uplands and contributed about 81,000 metric tonnes of fine-grained sediment to the Bay.

From photographs, MGS deduced that: 1) erosion varied in occurrence and amount; 2) the storm surge afforded two opportunities for erosion—once as water inundated low-lying coast lands and again as floodwaters ebbed; 3) erosion control structures commonly remained intact but failed to prevent bank erosion; 4) the storm disrupted nearshore sedimentary structures; and 5) not all changes were erosional.

INTRODUCTION

In the early afternoon of 18 September 2003, Isabel—a tropical cyclone—made landfall as a Category 2 hurricane in the vicinity of Drum Inlet on the Outer Banks of North Carolina. The storm then tracked northwestward through North Carolina and Virginia, west of the Chesapeake Bay. Within 24 hours after landfall, the storm had dissipated, but not before ravaging coastal communities all along the western shore of Maryland's Chesapeake Bay. In addition to extensive property damage, shoreline erosion was an unmistakable and widely reported effect of Isabel's passage over Maryland. State officials estimated the cost to repair damaged shoreline structures, primarily piers and bulkheads, at $84 million [1]. Government agencies and citizens groups were concerned about the possible deleterious effects of an influx of suspended sediments and nutrients on the Bay ecosystem, particularly given the near-record extent of the summer's anoxic "dead zone." The Governor's Chesapeake Bay cabinet requested an estimate of sediment input contributed by shoreline erosion. The Maryland Geological Survey (MGS) endeavored to supply that estimate. Relying on others' photographs and firsthand observations, MGS: 1) examined the effects of the storm on the shoreline to understand the processes responsible for erosion; and 2) estimated the length of affected shoreline, the area of land lost, and the volume of fine-grained sediment delivered to the Bay as a result of the storm.

BACKGROUND

The Storm

Hurricanes are distinguished by their most damaging forces, operating singly or in combination. In Maryland, Isabel will be remembered, not

K.G. Sellner (ed.). 2005. Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.

for her intensity or heavy rains, but for the size of her wind field and especially her high storm surge. At landfall, the radius of hurricane-force winds extended 115 miles (185 km) from the eye; tropical storm-force winds extended 345 miles (555 km). Although wind speeds gradually diminished after landfall, the radius of the wind field remained unchanged for almost as long as Isabel remained a tropical cyclone [2]. Maximum sustained winds and wind gusts measured in the vicinity of the Maryland Bay were all of tropical storm force: 39–73 mph (63–117 $km \cdot hr^{-1}$[3].

The storm surge, a bulge of water generated by the hurricane's swirling winds and low pressure within the eye, made its way from the Atlantic Ocean into the Chesapeake Bay. In the northern hemisphere, winds associated with tropical cyclones (including tropical storms and hurricanes) rotate counterclockwise. The most damaging winds are those in the right front quadrant of the storm, as defined by the direction of the storm's forward motion. As the storm, with its enormous wind field, tracked north-northwest and to the west of the Chesapeake Bay, the right-front-quadrant winds blew from the south-southeast, pushing the storm surge up the Bay and piling water onto the western shore.

Output from the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) computer model, run with actual storm data, depicted probable maximum water levels reached over the course of the surge [4]. Along the western shore, highest maximum levels occurred along the main Bay shorelines of Baltimore and Harford counties, the headward reaches of the Patuxent and Potomac rivers, and minor tributaries draining the north shore of the Potomac River. For 88 better-than-poor-quality, coastal, high-water marks (e.g., mud lines, debris lines, eyewitness accounts) surveyed in western shore counties following Isabel, flood elevations ranged from 0.9–2.4 m (3.0–7.9 ft) and averaged 2.0 m (6.5 ft) (NAVD 88) [5].

Shoreline Erosion in Chesapeake Bay

For its size, Maryland has an inordinately long shoreline, of which 10,905 km (6,776 miles) border the Chesapeake Bay and its tributaries. Based on changes in shoreline position over a 50-year period ending between 1988 and 1995, the 3,511 km (2,182 miles) of shoreline bordering the Bay's western shore retreat at an average annual rate of 0.16 $m \cdot yr^{-1}$ (0.52 $ft \cdot yr^{-1}$) [6].

Both long- and short-term climatic changes and events drive shoreline erosion. Over the long-term—on the order of centuries or millennia—fluctuations in sea level establish the water level at which erosive forces operate. Over the short-term (daily, monthly, or yearly) winds, particularly those associated with storms, propel the waves that impinge on the shore. The energy of the attack depends on wind speed and duration, water depth, and fetch, or the distance the wind blows over water. Tied to storms, particularly nor'easters in the winter and hurricanes in the summer and fall, erosion is episodic. Unlike open ocean coastlines, the Bay shoreline tends not to recover from these events; once fastland sediments are eroded, they are seldom replaced [7].

Finally, shoreline change occurs, not just at the line of contact between land and water, but within a broader zone that extends for some distance both offshore and onshore. In addition to wearing away fastland, shoreline erosion also operates in the nearshore to the base of wave action [8]. For any given year, an estimated 1.99 million metric tonnes of sediment are eroded from fastland bordering the Maryland Chesapeake Bay, and an estimated 2.95 million metric tonnes are eroded from the nearshore.

METHODS

In the months following Isabel, MGS contacted coastal managers, planners, and engineers in most of the counties bordering the Maryland Chesapeake Bay and requested an account of local shoreline losses due to Isabel. County contacts confirmed that damage to shorelines was largely restricted to the western shore. All willingly shared available information. That information, however, was largely qualitative, mostly in the form of photographs and firsthand anecdotal accounts. Only Baltimore County had quantitative data. The county's Department of Environmental Protection and Resource Management (DEPRM) had: reissued permits to rebuild or replace damaged or destroyed structures, including bulkheads, seawalls, etc.; and estimated the length of eroded shoreline for 60% of the county's shoreline.

Assuming that wherever an erosion control structure had been damaged or destroyed, sediment had washed away, MGS reviewed DEPRM's Hurricane Isabel Building Permit Log and constructed a database of locations where such damage had occurred. Within days after the storm, DEPRM surveyed the county's shoreline by plane and estimated that roughly 3,350 m (11,000 ft) of shoreline had undergone erosion [9]. DEPRM, however, made direct observations of only 60% of the county's shoreline. Adjusting for the eroded length of the unobserved (40%) shoreline, MGS calculated the total length of eroded shoreline in Baltimore County as 18,300 ft (5.6 km or 3.5 miles).

Several years before the storm, MGS had updated shoreline change information for the state's tidal water bodies. One phase of the project entailed acquiring a modern, digital representation of the shoreline based on photo interpretation of 1988–1995 orthophotography [10]. From that digital shoreline, MGS determined the length of tidal shoreline bordering Baltimore County: 367 km (228 miles). Of that total, 5.6 km (3.5 miles), or 1.5%, experienced erosion during Isabel. Applying that percentage to the total length of shoreline bordering western shore coastal counties, MGS calculated that approximately 53 km (33 miles) of shoreline eroded during the storm.

In terms of its track and the magnitude of its storm surge, Hurricane Isabel has been compared to the Chesapeake-Potomac Hurricane of 1933. Following that storm, the most severely damaged shorelines comprised a total of 23 km (14 miles or 74,700 ft) in Anne Arundel, Calvert, and St. Mary's counties [11]. The definition of "severe damage" is unclear. Nonetheless, for both storms, the estimated length of affected shoreline is of the same order of magnitude.

In addition to shoreline length, one or two other linear measures are needed to determine the area and volume of sediment lost: shoreline retreat and height of the eroded bank. These two varied widely from site to site. For example, in November 2003, MGS conducted a GPS survey of a 283.5-m (930-ft) stretch of shoreline at Todds Point on the Choptank River. Compared to a pre-storm survey in October 2002, shoreline retreat at the site averaged about 2.4 m (8 ft), ranging up to 6.1 m (20 ft). Considering such variability, MGS assigned an approximate value of 1.5 m (5 ft) to both shoreline retreat and bank height. That is, MGS assumed that along eroded reaches, a 1.5-m high bank retreated 1.5 m. Based on that assumption, the area of eroded sediment roughly equaled 20 acres, and the volume of eroded sediment was 122,000 m^3 (4.3 x 10^6 ft^3).

In 2003, Hill and others evaluated shoreline erosion as a source of sediments and nutrients to the Maryland Chesapeake Bay [12]. Field crews sampled 12 bluff sites on the western shore, in Baltimore, Anne Arundel, Calvert, and St. Mary's counties. They collected sediment samples from the beach and from each of the visually distinctive horizons on the bluff face and subsequently analyzed them for dry bulk density and grain size. Based on site descriptions, the authors of this report extracted a total of 35 bluff samples, averaged results for replicate samples, and calculated mean bulk density and the mean percentage of the various grain size classes.

To convert the volume of eroded sediment to sediment mass, MGS multiplied sediment volume (m^3) by 1.30 metric tonnes·m^{-3}, the mean dry bulk density measured for western shore bluff samples. A total of 159,000 metric tonnes of sediment were eroded during the storm.

Generally, when fastland sediments erode, only the finer-grained constituents (silt and clay) remain suspended in the water column; coarser-grained sands and gravels form a lag deposit near the toe of the bluff. The average western shore bluff consists of nearly equal parts fine-grained (51%) and coarse-grained (49%) sediments [12]. The fine-grained fraction is of particular interest to this study.

Of the 159,000 metric tonnes of eroded sediment, 51% (81,000 metric tonnes) is the estimated suspended sediment load contributed by storm-induced shore erosion to the Bay.

RESULTS AND DISCUSSION

Shoreline Vulnerability

Given the storm surge elevation, virtually the entire western shore shoreline was vulnerable to erosion. In Baltimore County, DEPRM reissued permits for erosion control structures that had been damaged or destroyed by the storm. Assuming that bulkhead damage and erosion were linked, MGS mapped the sites for which those permits had been reissued (Figure 1). The map, biased in favor of densely developed, protected shorelines, confirmed the long reach of the surge. Erosion control structures built in the normally quiet coves of minor tributaries were damaged, not just those lining more exposed reaches of shoreline.

Despite the ubiquity of storm surge flooding, shore erosion was irregular. Seemingly identical reaches of shoreline behaved differently. Some were unaffected. Others experienced greater or lesser sediment losses.

Processes of Erosion

Along shorelines eroded by the action of wind-generated waves, the storm surge's main effect was to expand the zone of wave influence both vertically and laterally (Figures 2a and 2b). Along high banks and bluffs, the surge elevated wind waves, extending the line of wave attack progressively higher up, and then down, the bluff face. At the bluff's base, both manmade and natural protection (e.g., a narrow beach at the bluff base) were overtopped. Laterally, the waves reached much further inland than normal. Upland areas not usually subject to wave attack were eroded during Isabel. Flooding also increased fetch.

Once the storm surge had peaked, floodwaters flowed back into the Bay. This storm surge ebb produced uncommon effects. Receding floodwaters scoured fastland sediment. Small freestanding structures, such as sheds, obstructed the ebbing flow. Along protected reaches, the ebb produced selective failure of erosion control structures that had been overtopped by the flood (Figure 2c).

Although many erosion control structures remained intact after the storm, most were overtopped by the surge. Bulkheads and similar structures constructed higher than the land surface failed selectively from behind as the surge ebbed. Once a structure was breached, water channeled through the opening, commonly scouring a semi-conic section—wider at the top and narrower at the base—from the exposed bank. During the storm surge flood, structures backed by higher banks or bluffs directed the wave attack higher up the bluff face; sediments were gouged from there, rather than from the toe of the slope.

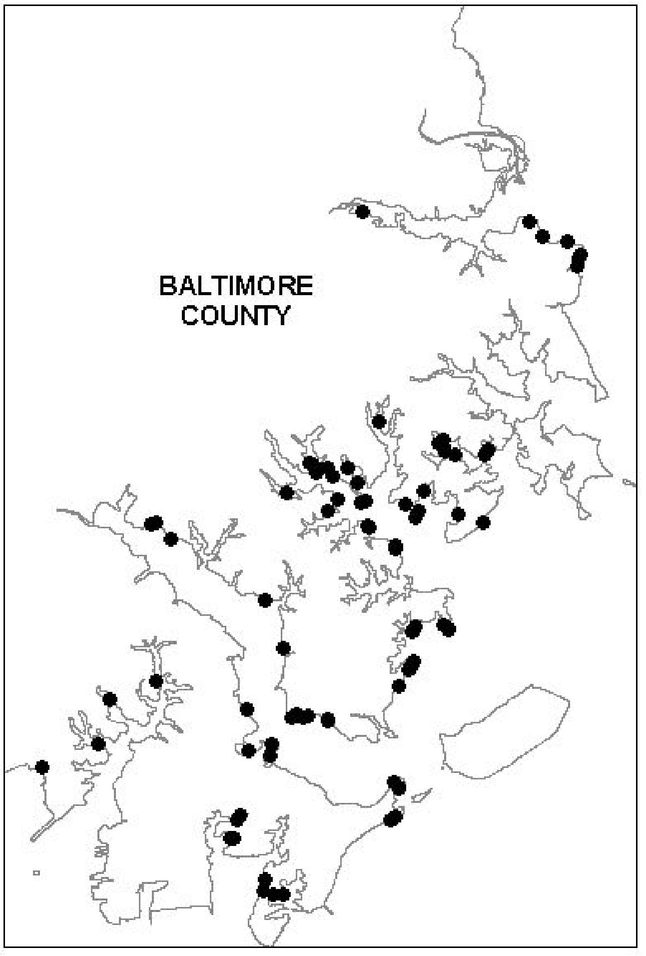

Figure 1. Baltimore County issued nearly 100 permits to replace or repair destroyed or damaged erosion control structures.

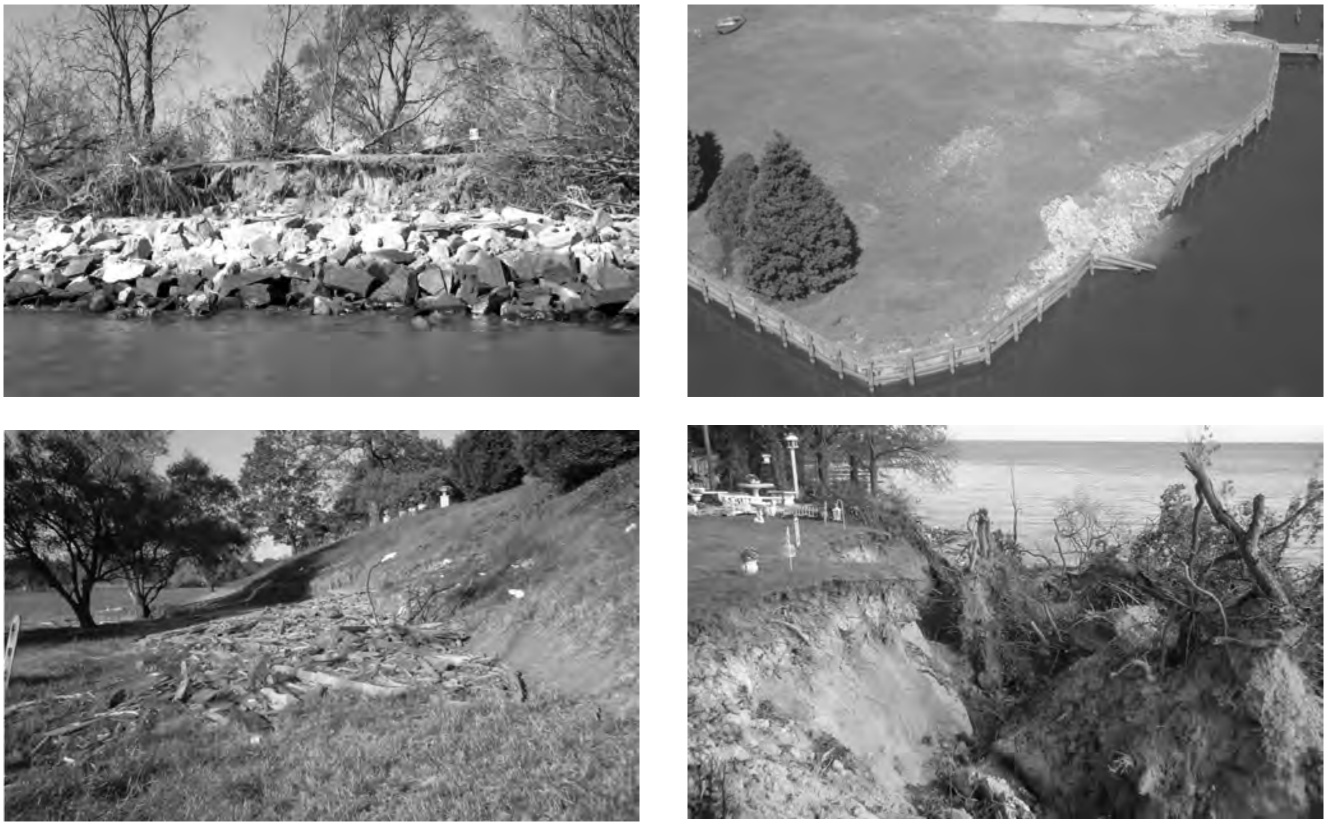

Figure 2. Processes of erosion. Bank erosion due to: a) vertical and b) lateral expansion of zone of wave influence; c) bulkhead failure and fastland scour associated with storm surge ebb; and d) undermining of mature trees. (Photos courtesy of Scott Alexander, St. Mary's County Dept. of Public Works (a); Jim Stein, Anne Arundel Soil Conservation District (b & d); Candy Croswell, Baltimore County DEPRM (c))

Some of the most dramatic examples of storm-induced erosion involved the uprooting of trees (Figure 2d). Generally, the extensive root systems of large trees stabilize the upper part of a slope, until the root mat is undermined. When a tree falls, it can pull away as much as 5–10 m^3 of bank material [13]. During the storm, other factors may have contributed to the collapse of trees along the shoreline: the high soil moisture due to above average precipitation in 2003; the sail effect produced by trees in full canopy acting like sails to catch the tropical-storm-force winds; and, on the shoreward side, the absence of shielding that would have been afforded by neighboring trees. For a while, the downed trees and the mounds of eroded sediment will shield newly exposed banks from wave erosion. Once the eroded sediment washes away and the trees disintegrate or float away, though, direct wave attack will resume. Longer term, the effects of brackish water flooding and spray on trees growing near the shore may lead to their eventual demise. To the extent that dead trees are more likely to fall than live ones, Isabel may have a long-lasting (decadal) effect on shoreline erosion [14].

The forces responsible for coastal erosion operate beyond the shoreline in a broader coastal zone. In addition to actively eroding upland sediments, those forces (magnified by the storm) were directly responsible for extensive reconfiguration of the Bay margin, redistributing sediments temporarily stored on beaches and in shallow nearshore waters. Redistribution of sediment, often sand, took several forms. Observing the exposed roots of marsh vegetation, Baltimore County reported a foot of sand removed from the surface of Pleasure Island [9]. In Anne Arundel County, the entire beach at Herrington Harbor South washed away [15]. At Piney Point, along the Potomac River in St. Mary's County, bulldozers were brought in to remove several feet of sand transported from the beach to a nearby road. In the same county, along the western shore of the Bay, nearshore bars parallel to the shoreline appear to have been disrupted by the storm, and sand-trapping groins seem to have garnered additional sand set in motion by the storm [16].

Estimated Quantity of Eroded Sediment Delivered to the Chesapeake Bay

From a rough approximation of the length of Baltimore County shoreline eroded by Isabel, MGS extrapolated the length of shoreline affected along the entire western shore. In all, about 53 km (33 miles) of shoreline experienced erosion, resulting in a worst-case estimate of 8 hectares (20 acres) of land lost from the western shore.

Isabel resulted in the erosion of about 159,000 metric tonnes of sediment from western shore shorelines. Of that, 81,000 metric tonnes were fine-grained sediment (silt and clay). As a point of comparison, during Hurricane Agnes (1972)—a storm characterized by torrential rainfall in the Bay watershed—the Susquehanna River alone discharged over 31 million metric tonnes of suspended sediment into the Bay, about 30 times the annual average input [17].

Severe as it was, erosion might have been worse. Given the storm surge elevation, the entire western shore was potentially vulnerable. Had the hurricane been stronger at landfall, the storm surge generated in the Chesapeake Bay might have been larger. Had Isabel stalled along its path and lingered through several tidal cycles, prolonged surge conditions, exacerbated by high winds, might have caused more severe erosion. Had rainfall been higher, as was the case during Hurricane Agnes, bank erosion caused by slope failure might have been more common [18], particularly given the wetter than normal months that preceded the hurricane.

ACKNOWLEDGMENTS

The authors would like to thank all of the county planners and coastal engineers who so willingly shared their stories and photos of Isabel's effects on the state's shorelines. For allowing access to their Hurricane Isabel Building Permit Log, for providing an estimate of affected shoreline miles, and for snapping numerous photos, the authors are particularly indebted to Pat Farr, Betty Kelley, and Candy Croswell of the Baltimore County Department of Environmental Protection and Resource Management. Likewise, Jim Stein and Chris Maex-Murphy of the Anne Arundel County Soil Conservation District and Scott Alexander of the St. Mary's County Department of Public Works supplied photographs of shoreline damage in their respective counties and provided valuable insights into the nature of Isabel-related erosion.

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REFERENCES

1. Maryland Department of Planning. 2004. Lessons learned from Tropical Storm Isabel. Baltimore, MD. 29 pp.
2. National Hurricane Center. 2003. Hurricane Isabel Advisory Archive. *www.nhc.noaa.gov/archive/2003/refresh/ISABEL+shtml/forecast.shtml.*
3. J. Beven, and H. Cobb. *Tropical Cyclone Report: Hurricane Isabel* (6–19 September 2003), National Hurricane Center. *www.nhc.noaa.gov/2003isable.shtml* (23 January 2004).
4. W. Shaffer. Pers. comm. National Oceanic and Atmospheric Administration.
5. URS Group, Inc. 2003. Hurricane Isabel rapid response coastal high water mark (CHWM) collection. Gaithersburg, MD. 197 pp.

6. L. Hennessee, M.J. Valentino, and A.M. Lesh. 2003. Updating shore erosion rates in Maryland. MGS, Baltimore, MD. 26 pp.
7. K.F. Nordstrom. 1989. Erosion control strategies for bay and estuarine beaches. *Coast. Manage.* 17: 25–35.
8. T. Cronin, J. Halka, S. Phillips, and O. Bricker. 2003. Estuarine sediment sources. In: *A Summary Report of Sediment Processes in Chesapeake Bay and Watershed*. M. Langland and T. Cronin (eds.). U.S. Geological Survey Water - Resources Investigations Report 03-4123. pp. 49–60.
9. C. Croswell. Pers. comm. Baltimore Co. DEPRM.
10. L. Hennessee. 2001. *Acquiring a modern digital shoreline for Maryland from recent (1988-1995) orthophotograph*y. MGS, Baltimore, MD. 18 pp.
11. J.T. Singewald and T.H. Slaughter. 1949. Shore Erosion in Tidewater Maryland. MD Dept. of Geology, Mines, and Mineral Resources, Baltimore, MD. 141 pp.
12. J.M. Hill, G. Wikel, D. Wells, L. Hennessee, and D. Sailsbury. 2003. Shoreline Erosion as a Source of Sediments and Nutrients, Chesapeake Bay, Maryland. MGS, Baltimore, MD. 24 pp.
13. A.J. Miller. 1985. *Shore erosion as a sediment source to the tidal Potomac River, Maryland and Virginia*. U.S. Geological Survey Water-Supply Paper 2234-E. 45 pp.
14. A. Hairston-Strang. Pers. comm. MD Dept. Natural Resources.
15. B. Lambrecht, D. Bell, S. Carr, and J. Clemenko. 2003. *Bay Weekly.com*., v. XI, no. 39, Sept. 25–Oct. 1, 2003, *www.bayweekly.com/year03/issuexi39/dockxi39.html*.
16. S. Alexander. Pers. comm. St. Mary's Co. Dept. of Public Works.
17. J.R. Schubel. 1976. Effects of Tropical Storm Agnes on the suspended sediments of the northern Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). The Johns Hopkins University Press, Baltimore, MD. pp. 179–187.
18. B.G. McMullan. 1976. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD. pp. 216–222.

HURRICANE ISABEL STORM SURGE SIMULATION FOR CHESAPEAKE BAY

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ABSTRACT

On 18 September 2003, Hurricane Isabel made landfall on the Outer Banks of North Carolina between Cape Lookout and Cape Hatteras as a Category 2 hurricane. This storm caused substantial flooding in the lowland areas of North Carolina, Maryland, Washington, D.C., and Virginia. High storm surge was observed along the Outer Banks and in the Chesapeake Bay. Measured water levels showed a 1.5-m storm surge above normal tide levels at the coastline about 125 km north of the landfall (*http://coastal.er.usgs.gov/hurricanes/isabel*) and a 2.2-m surge near the center of the west bank in Chesapeake Bay (*www.mgs.md.gov/coastal/isabel/isabel2.html*).

This paper presents numerical modeling of the wind field and water surface elevation time series associated with Hurricane Isabel for Chesapeake Bay. The numerical modeling served as one of several calibrations for the prediction of extreme water levels based on major tropical and extratropical storms occurring in the Bay for the last 150 years. The paper describes meteorological and oceanographic input parameters used and compares model results with measured data. Surface wind fields were generated from a Planetary Boundary Layer (PBL) model [1, 2]. The storm track for Isabel was obtained from the North Atlantic Hurricane Track Database *(http://weather.unisys.com/hurricane)*. Water surface elevations were calculated with the ADvanced CIRCulation (ADCIRC) model [3]. Calculated winds and water levels were compared to data from 12 NOAA meteorological stations along the perimeter of the Bay. Model results show overall agreement with measured wind and water levels [4, 5]. A key to successful modeling was topographic representation of the river tributaries that flooded during the storm and are areas that store large quantities of water at peak surge. Comparisons of model results around the Bay are given.

INTRODUCTION

The numerical modeling of Hurricane Isabel was performed by the U.S. Army Engineer Coastal & Hydraulics Laboratory for the U.S. Army District, Baltimore as part of a life-cycle analysis for restoration of three island sites in Chesapeake Bay [4]. The life-cycle analysis required water level information from a suite of storms. Hurricane Isabel was selected as one of 95 tropical and extratropical storms studied in this analysis.

Tasks for the numerical modeling effort were: 1) identifying historical tropical and extratropical storms that passed through the Chesapeake Bay region; 2) acquiring wind fields for historical storms identified as potential storms to model; 3) adjusting wind fields over the land and over the Chesapeake Bay as necessary to represent overland wind adjustments and over-Bay wind adjustments; 4) analyzing existing historical data from regional anemometers to develop local winds over Chesapeake Bay; 5) developing a high-resolution numerical finite element grid of Chesapeake Bay, including overland areas; 6) validating the hydrodynamic model ADCIRC to several historical storm events; 7) applying ADCIRC to the suite of historical storm events to compute storm water levels; and 8) extracting water levels at the three island sites.

SELECTION OF STORMS

The North Atlantic Hurricane Track Database *(http://weather.unisys.com/hurricane)* was used to determine the set of tropical storms that traversed the Chesapeake Bay region. Fifty-two hurricanes were selected from the database from 1851 to 2003 for simulation based upon the following criteria: storms with maximum wind speeds greater than 50 knots in the area between 75 and 79 degrees W longitude and 36 and 39 degrees N latitude.

The database contained the maximum wind speed and minimum pressure as each storm tracked across the Atlantic Ocean and/or Gulf of Mexico. Wind and pressure fields were generated for a given track using the Planetary Boundary Layer (PBL) model [1, 2]. Adjustments for overland and over-Bay were made to the wind fields as follows:

$$U_L = U_W / R_L$$

where U_L is the wind speed over land, U_W is the wind speed over water, and R_L is an adjustment factor. Procedures described in Part II, Coastal Engineering Manual (*http://chl.erdc. usace.army. mil/CHL.aspx?p=s&a=ARTICLES;104)* were followed. The factor R_L ($1 < R_L < 1.5$) is a function of wind speed and percentage of overland and over-water areas in a rectangular wind field cell. Both wind and pressure fields were applied in the ADCIRC model simulations for the Chesapeake to attain the response of the Bay to each storm.

NUMERICAL MODEL ADCIRC

ADCIRC is documented in technical reports and technical notes, as well as in the literature of study applications and engineering projects. A short description of the model is given here for broad understanding of the model's function. The references provide additional details.

ADCIRC is a highly developed numerical model for solving the equations of motion for a moving fluid on a rotating earth [3, 6, 7]. It serves as the Corps of Engineers' regional oceanographic and storm surge model as certified by the Federal Emergency Management Agency. The equations are formulated with hydrostatic pressure and Boussinesq approximations and are made discrete in space with the finite-element method and in time with the finite difference method. ADCIRC can be run either as a two-dimensional depth-integrated (2DDI) model or as a three-dimensional (3D) model. Water elevation is obtained from the solution of the depth-integrated continuity equation in the generalized wave-continuity equation (GWCE). Velocity is solved from 2DDI or 3D momentum equations with all nonlinear terms retained. ADCIRC has robust wetting and drying algorithms for lowland flooding predictions.

ADCIRC can be operated in either a Cartesian or a spherical coordinate system. ADCIRC boundary conditions include specified elevation (harmonic tidal constituents or time series), specified normal flow (harmonic tidal constituents or time series), zero normal flow, slip or no-slip conditions for velocity, external barrier overflow out of the domain, internal barrier overflow between sections of the domain, surface stress (wind and/or wave radiation stress), atmospheric pressure, and outward radiation of waves (Sommerfeld condition). ADCIRC can be forced with elevation, normal flow, or surface stress boundary conditions, tidal potential, and earth load/ self-attraction tide.

Recently, regional-scale ADCIRC studies were completed on high-performance computers to provide accurate tidal constituents for the Atlantic coast, Gulf of Mexico coast, and Pacific coast of the United States to furnish reliable tidal constituents for project-scale simulations [8, 9]. In the present study, the 2DDI ADCIRC is used to predict wave levels and all nonlinear terms (including wetting/drying function for circulation dynamics) are retained in the model. The forcing at the ocean boundary consists of eight tidal constituents (K1, O1, M2, N2, S2, K2, P1, and Q1). The model was run using a 1-second time step with default control parameters (weighting factor of 0.01 in GWCE and drag coefficient of 0.0025 for quadratic bottom friction) and Coriolis term.

ADCIRC GRID DEVELOPMENT

A regional scale ADCIRC grid with a rudimentary representation of Chesapeake Bay was developed through previous studies by the Coastal Inlets Research Program and Offshore and Coastal Technologies, Inc. This grid was refined in Chesapeake Bay and far-field areas for the present study using National Ocean Service Digital Navigation Charts. In this hydrodynamic study, the existing-condition bathymetry was assembled from three sources: Virginia Institute of Marine Science (VIMS) bathymetric data, the GEOphysical DAta System (GEODAS) database, and survey data from the US Army Corps of Engineers. Detailed Chesapeake Bay coastline and bathymetric data were obtained from VIMS and incorporated into the refined ADCIRC grid. Chesapeake & Delaware Canal bathymetric data were obtained from the US Army Engineer District, Philadelphia. Further grid development included the incorporation of overbank areas into the Chesapeake Bay tributaries to predict storm surge accurately in these relatively narrow branches of the Bay (Figure 1). The

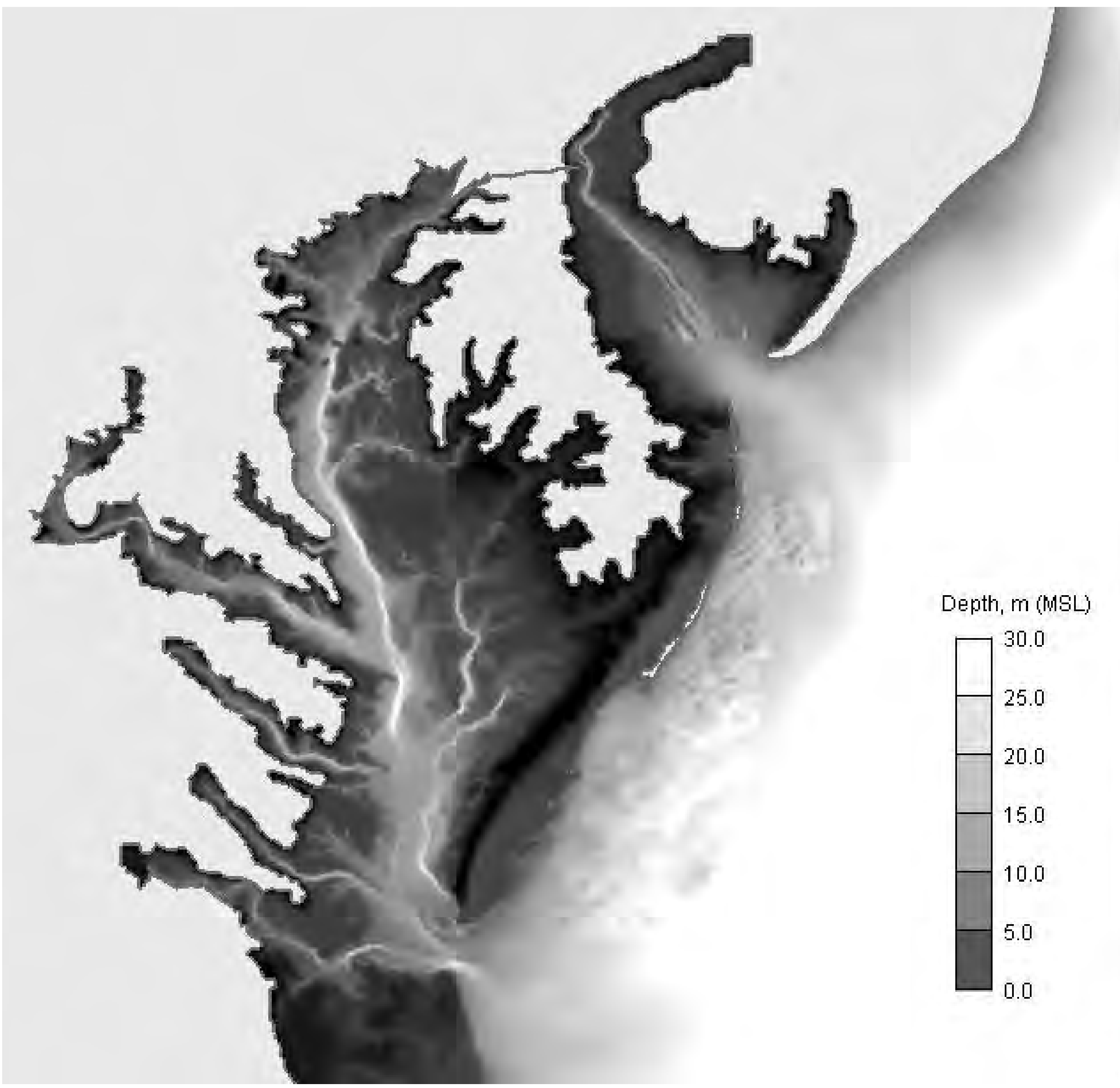

Figure 1. The portion of the ADCIRC grid showing overland bathymetry around the Chesapeake Bay.

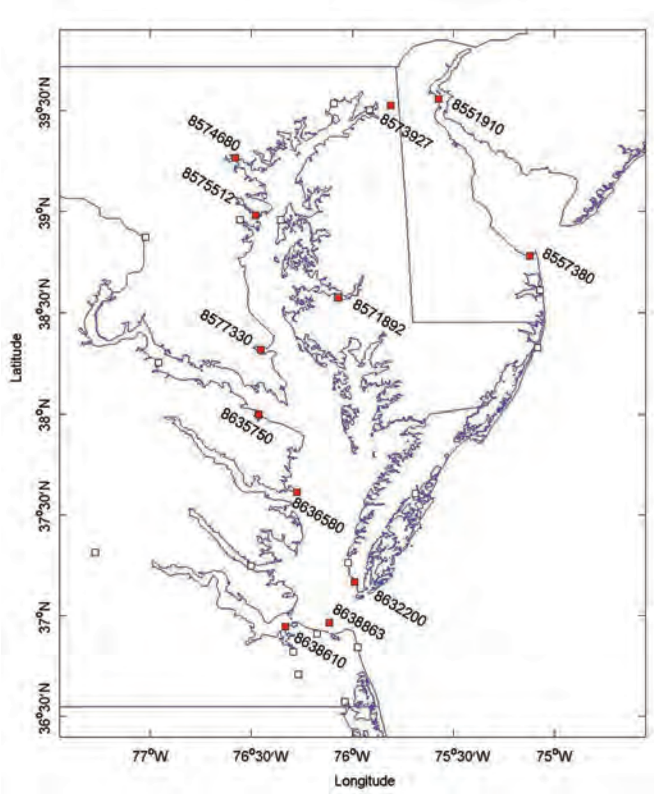

Figure 2. NOAA stations.

ADCIRC grid was extended to include lowland topography data to +10 m, mean tide level, from USGS Digital EEM database GTOPO30—30-second arc resolution *http://edcdaac.usgs.gov/gtopo30/gtopo30.asp*. The grid was constructed with a minimum resolution (node-to-node spacing) of 50 m at shallow water areas and a maximum resolution of 500 m in the open ocean. The grid contained 180,684 elements and 93,095 nodes. The ADCIRC grid generated in this process was applied to tidal current and storm surge simulations to calculate water level at the three island sites for the main project study. The numerical grid was developed to represent the existing Bay condition as closely as possible, especially at the three island study sites. This paper focuses on the simulation of Hurricane Isabel.

VALIDATION TO TROPICAL STORMS

The validation process for tropical storms (hurricanes) applying PBL wind and pressure fields involved comparison of water levels at twelve NOAA stations (Figure 2 and Table 1) to water levels produced by ADCIRC for two major hurricanes—Fran (1996) and Isabel (2003)—and four moderate hurricanes—Bertha (1996), Bonnie (1998), Earl (1998), and Floyd (1999). Fran and Isabel approached the Bay from the ocean with similar storm tracks nearly perpendicular to the coastline and made landfall south of the Bay. They continued in a northwest course to move further

Table 1. NOAA stations for wind/water level measurements (1996–2003), Chesapeake Bay, and Delaware Bay.

Station No.	Station Name	Coordinates
8551910	Reedy Pt, C&D Canal, DE	39^{o} 33’ 30” N, 75^{o} 34’ 26” W
8557380	Lewes, Ft. Miles, DE	38^{o} 46’ 54” N, 75^{o} 07’ 12” W
8571892	Cambridge, Choptank River, MD	38^{o} 34’ 24” N, 76^{o} 04’ 06” W
8573927	Chesapeake City, MD	39^{o} 31’ 36” N, 75^{o} 48’ 36” W
8574680	Baltimore, MD	38^{o} 16’ 00” N, 76^{o} 34’ 28” W
8575512	US Naval Academy, MD	38^{o} 59’ 00” N, 76^{o} 28’ 48” W
8577330	Solomons Is, MD	38^{o} 19’ 00” N, 76^{o} 27’ 12” W
8632200	Kiptopeke Beach, VA	37^{o} 10’ 00” N, 75^{o} 59’ 18” W
8635750	Lewisetta, Potomac River, VA	37^{o} 59’ 48” N, 76^{o} 27’ 48” W
8636580	Windmill Pt, VA	37^{o} 36’ 42” N, 76^{o} 16’ 30” W
8638610	Sewells Pt, VA	36^{o} 56’ 48” N, 76^{o} 19’ 48” W
8638863	Chesapeake Bay Bridge Tunnel, VA	36^{o} 58’ 00” N, 76^{o} 06’ 48” W

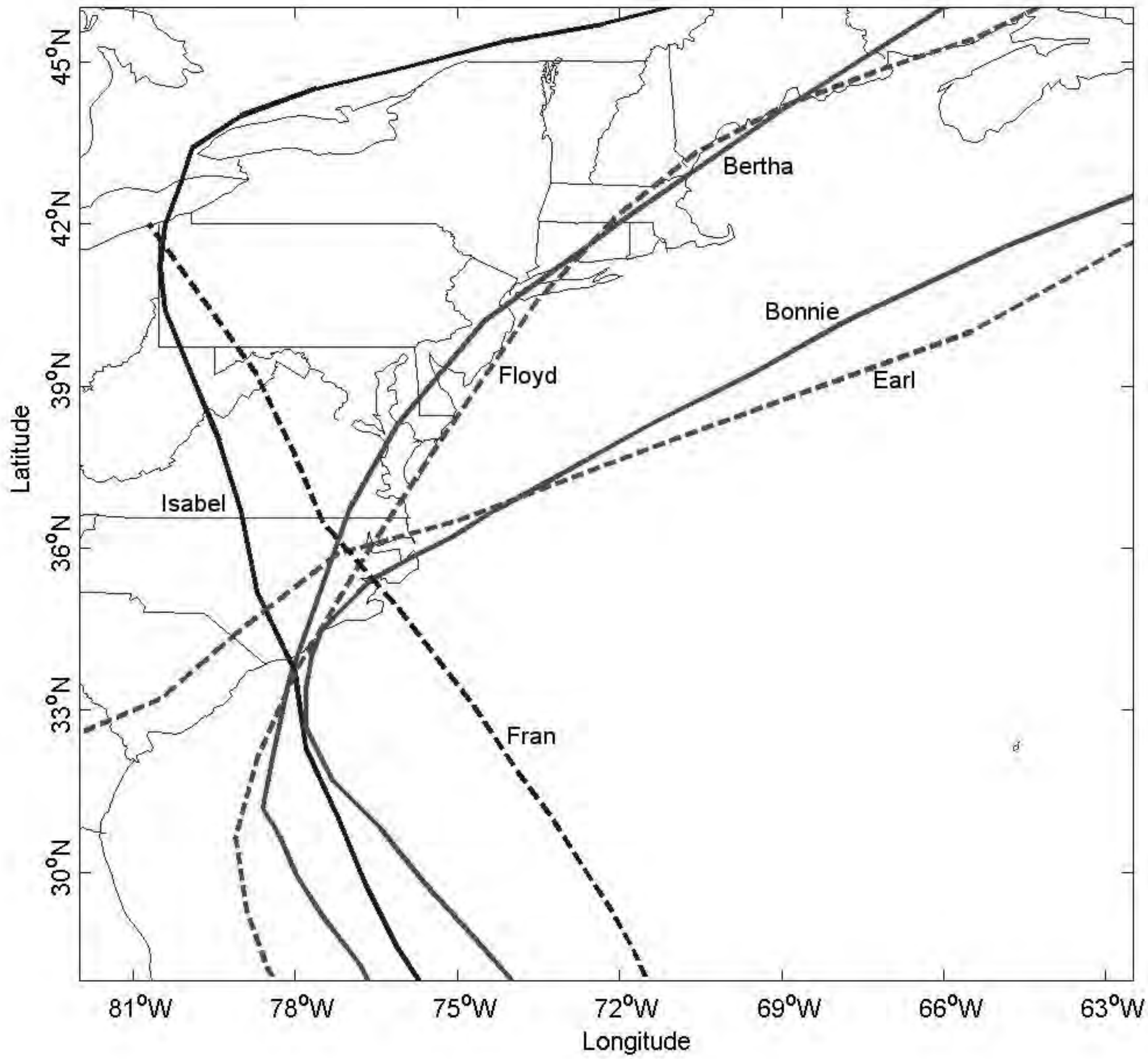

Figure 3. The storm tracks of Bertha (1996), Fran (1996), Bonnie (1998), Earl (1998), Floyd (1999), and Isabel (2003).

inland west of the Bay. The passage of Bertha was similar to Floyd; both hurricanes approached and passed the Bay paralleling the Atlantic coastline east of the Bay. Bonnie and Earl, on the other hand, followed a northeast track from land to ocean crossing the coastline south of the Bay. Figure 3 shows storm tracks of these six hurricanes. Hurricanes of similar track to Fran and Isabel can generate higher storm surge as the onshore wind traps more water along the coastline and in the Bay.

As part of the validation process, NOAA historical water level data (1996–2003) for Chesapeake Bay were extracted from *http://co-ops.nos.noaa.gov/data_res.html* to determine seasonal water level variations and for validation of numerical model results. The mean water level (non-tidal signals) is generally higher from the spring to the fall compared to winter, but this is not modeled in the ADCIRC. In the present study, an average water level increase of 0.1 m in the interval

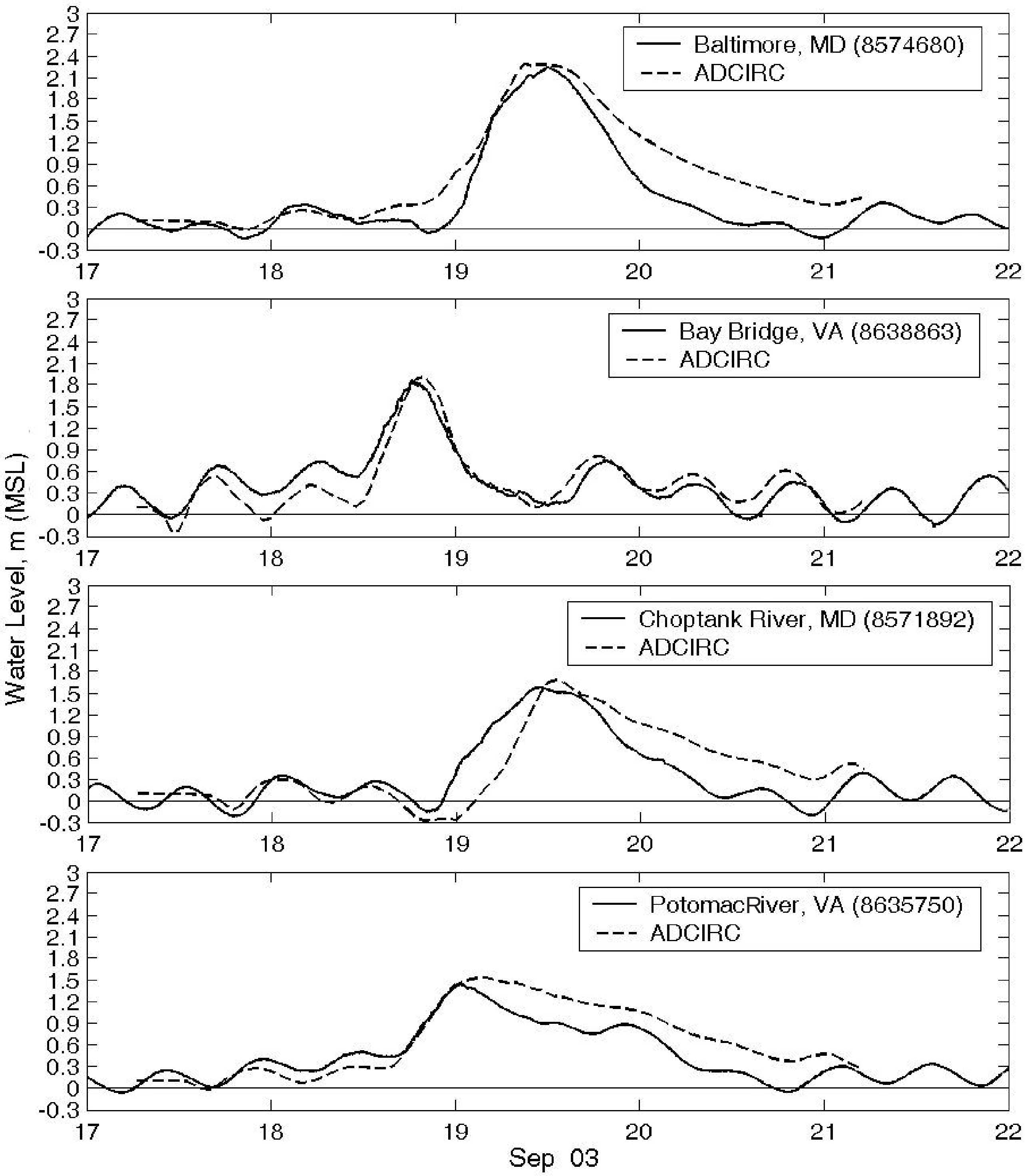

Figure 4. Measured and modeled water levels for Hurricane Isabel at four stations in Maryland and Virginia.

of March to November has been added to model results to account for the seasonal variation [4, 5].

Figures 4 and 5 show the measured and modeled water level time series at eight stations for Hurricane Isabel. Model results agree well with measured data. At Station 8574680 (Baltimore, Maryland), measured and modeled peak water levels are 2.2 and 2.3 m, respectively. At Station 8638863 (Bay Bridge Tunnel, Virginia), both measured and modeled peak water levels are 1.9

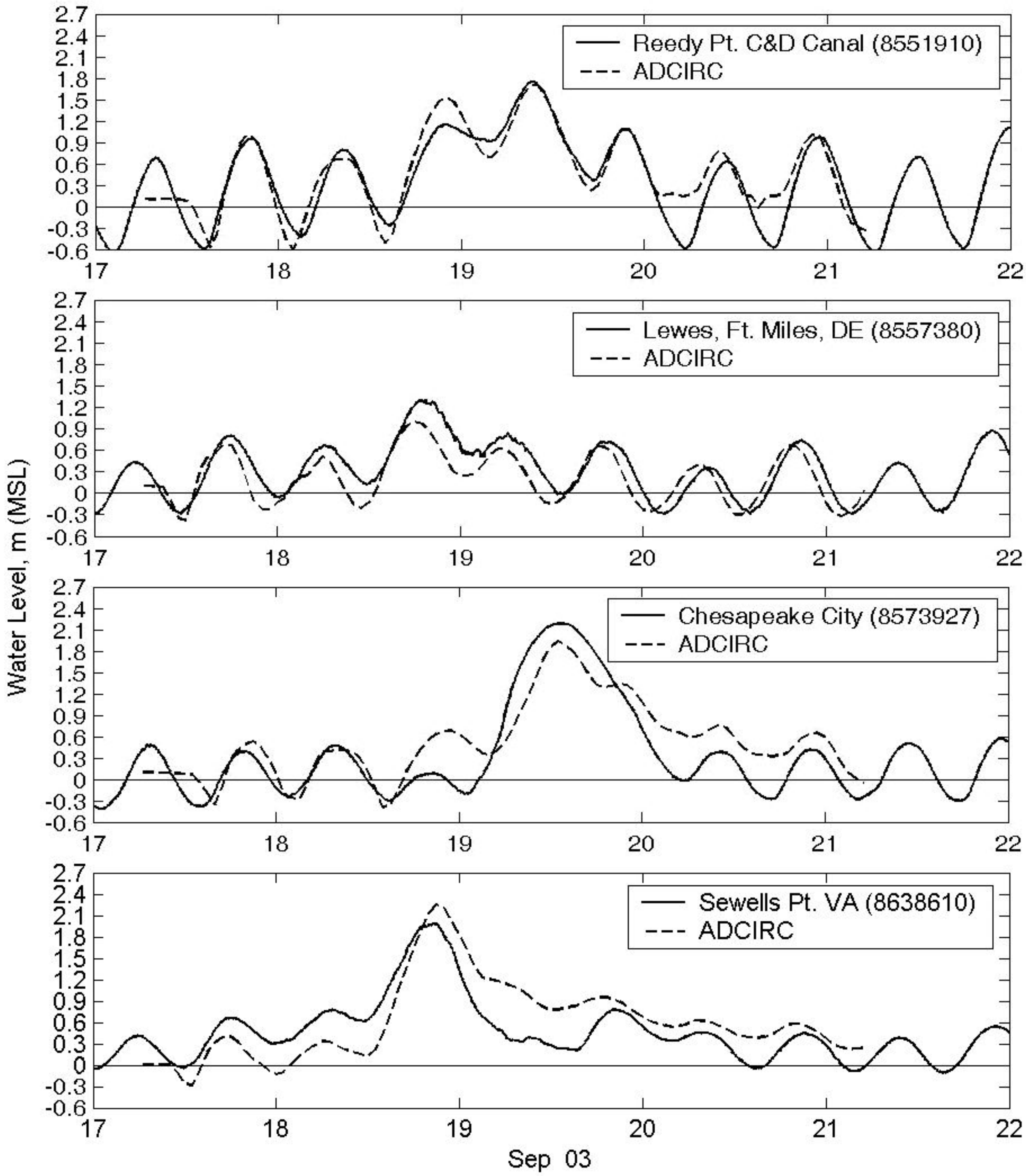

Figure 5. Measured and modeled water levels for Hurricane Isabel at four additional stations.

m. Table 2 compares measured and modeled peak water levels for Hurricane Isabel. The difference of predicted and measured peak water level, ranges between –0.31 and 0.36 m. The root-mean-square error of predicted peak water level versus measured data was 0.20 m. The bias of the predicted peak water level is 0.02 m. The largest errors were at stations 8557380 (Lewes, Ft. Miles, Delaware) and 8638610 (Sewells Point, Virginia). Differences can be attributed to applied model bathymetry, grid resolution, or accuracy of the input wind field (particularly at great distances from the track). Using correct water depth at and around NOAA stations in the model grid is critical for water level prediction as compared to the data. Model results tend to overestimate water levels for Isabel after the surge peak, particularly in the upper Bay. This overestimation occurred when the storm started to weaken and moved further inland in the NNE direction west of the Bay. It is suspected that the PBL model overpredicts wind fields for the weakened storm and error can be induced by the uncertainly of storm parameters used in generation of the wind field. Other factors not modeled in this study (river discharge, non-tidal oceanic setup, variable quadratic friction coefficients for more damping in the shallow northern Bay area) may improve estimations of water levels.

Model water levels are generally more reliable for hurricanes with tracks similar to Fran (1996) and Isabel (2003) than for those with storm tracks similar to Bonnie (1998) and Earl (1998) as compared to the measured data. Hurricanes Isabel and Fran tracked along the main axis of the Bay, whereas Bonnie and Earl skirted away such that the Bay was on the weaker side of the hurricane path. Hurricanes with tracks similar to Fran and Isabel can generate higher storm surge, as the onshore wind tends to trap more water along the coastline and in the Bay.

SUMMARY

Numerical modeling of Hurricane Isabel was performed by the US Army Corps of Engineers Coastal & Hydraulics Laboratory for the U.S. Army District, Baltimore as part of a life cycle analysis for restoration of three island sites in Chesapeake Bay. The modeling served as the calibration for the prediction of extreme water levels based on historical tropical and extratropical storms occurring in the Bay for the last 150 years. Model results show overall reasonable agreement with measured water levels, especially at the peak of surges. The difference of predicted and measured peak water levels ranged between -0.31 and 0.36 m. The largest errors were at Lewes, Deleware and Sewells Point, Virginia. Differences can be attributed to inaccurate bathymetry, grid resolution, or accuracy of the input wind field (particularly at great distances from the track).

A key to the successful modeling was representation of the topography of river tributaries —which flooded during the storm and store large

Table 2. Comparison of measured and predicted peak water levels during Hurricane Isabel.

Station name	Measured (m)	Predicted (m)	P-M, (m)
Reedy Pt, C&D Canal, DE	1.75	1.69	-0.06
Lewes, Ft. Miles, DE	1.31	1.00	-0.31
Cambridge, Choptank River, MD	1.58	1.68	0.10
Chesapeake City, MD	2.18	1.94	-0.26
Baltimore, MD	2.24	2.28	0.04
US Naval Academy, MD	1.98	2.30	0.32
Solomons Is, MD	1.85	1.80	-0.05
Kiptopeke Beach, VA	1.55	1.70	0.15
Lewisetta, Potomac River, VA	1.44	1.53	0.09
Windmill Pt, VA	1.48	1.30	-0.18
Sewells Pt, VA	1.99	2.35	0.36
Chesapeake Bay Bridge Tunnel, VA	1.87	1.91	0.04

Root-mean-square error of predicted peak water level = 0.20 (m) Bias = mean of (predicted – measured) = 0.02 (m) quantities of water at peak surge. Model water levels were generally more reliable for hurricanes with tracks similar to Fran and Isabel than those with tracks similar to Bonnie and Earl (as compared to the measured data). Hurricanes Isabel and Fran tracked along the main axis of the Bay, whereas Bonnie and Earl skirted away such that the Bay was on the weaker side of the hurricane path.

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REFERENCES

1. V.J. Cardone. 1977. An experiment in forecasting hurricane generated sea states. *Proc. 11th Tech. Conf. on Hurricanes and Tropical Meteorology of the American Meteorological Society*, Miami Beach, FL. pp. 688–695.
2. V.J. Cardone, C.V. Greenwood, and J.A. Greenwood. 1992. Unified Program for the Specification of Hurricane Boundary Layer Winds over Surfaces of Specified Roughness. Contract Report CERC-92-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
3. R.A. Luettich, J.J. Westerink, and N.W. Scheffner. 1992. ADCIRC: An Advanced Three-dimensional Circulation Model for Shelves, Coasts, and Estuaries; Report 1: Theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. Dredging Research Program Technical Report DRP-92-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
4. J.A. Melby, E.F. Thompson, M.A. Cialone, J.M. Smith, L.E. Borgman, Z. Demirbilek, J.L. Hanson, and L. Lin. 2005. Life-cycle Analysis of Mid Bay and Poplar Island Projects, Chesapeake Bay, Maryland. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-05-xx (in prep.), U.S. Army Engineer Research and Development Center, Vicksburg, MS.
5. Z. Demirbilek, L. Lin, and G.P. Bass. 2005. Prediction of Storm-induced High Water Levels in Chesapeake Bay. ASCE Conf. Solutions to Coastal Disasters 2005. Charleston, SC. May 8–11, 2005.
6. R.A. Luettich, J.L. Hench. C.W. Flucher, F.E. Werner. B.O. Blanton, and J.H. Churchill. 1999. Barotropic Tidal and Wind-driven Larval Transport in the Vicinity of a Barrier Island Inlet. *Fish. Oceanogr.* 8 (Suppl. 2): 190–209.
7. R.A. Luettich and J.J. Westerink. 2003. Formulation and Numerical Implementation of the 2D/3D ADCIRC Finite Element Model Version 43.XX. Internal Report. *www.marine.unc.edu/C_CATS/adcirc/doumant/theory_report/adcirc_3D_02_07_03.pdf*
8. A.Y. Mukai, J.J. Westerink, R.A. Luettich, and D.J. Mark. 2002. Eastcoast 2001, A tidal constituent database for Western North Atlantic, Gulf of Mexico, and Caribbean Sea. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-02-24, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
9. E.A. Spargo, J.J. Westerink, R.A. Luettich, and D.J. Mark. 2004. ENPAC 2003: A Tidal Constituent Database for Eastern North Pacific Ocean. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-04-12, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

UTILIZING A MESOSCALE MODEL FOR SHORT-TERM FORECASTING DURING HURRICANE ISABEL

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ABSTRACT

Hurricane Isabel caused considerable damage across the National Weather Service (NWS) Wakefield, Virginia county warning area (CWA), including major storm surge damage along parts of the Chesapeake's western shore and major tributaries. In addition, thousands of trees were downed from strong wind gusts. Site surveys conducted by the Wakefield office indicated that several areas within the CWA had greater damage than others. This locally enhanced damage could be attributed to a combination of storm surge, wave action, and high wind gusts. An examination of the performance of the workstation Eta (WSEta) model [1] during Hurricane Isabel was conducted, using model output up to 24 hours before Isabel affected the Wakefield CWA, to identify mesoscale features that contributed to greater damage. Wind direction and speed were examined to assess the duration and fetch of winds over open water and to determine the potential impact of wave heights on storm surge. Atmospheric stability was also examined to evaluate when gust potential was maximized as Isabel moved through the area. The passage of a coastal front was studied to assess further the mixing of higher wind speeds to the ground. The results of this study will be used to suggest a method of how to use mesoscale models effectively before hurricane landfall to assess potential impacts.

INTRODUCTION

Hurricane Isabel caused extensive damage across the Wakefield county warning area (CWA; Figure 1), including areas along the Chesapeake Bay and its tributaries. Surveys of damage caused by Isabel revealed mesoscale structure to the damage with some locations receiving substantially more damage than others. Various meteorological factors contributed to this damage pattern. Specifically, prolonged winds directed up tributaries on the western Chesapeake combined with over-water trajectories of 32 to 97 km (20 to 60 miles), increasing the storm surge and producing higher waves on top of this surge. Although emergency managers, through training and experience, know that significant storm surge augmented by wave action will occur in this situation, more specific information and advanced warning as the storm develops and moves through the area will enhance their ability to respond to the storm effectively. While real-time observations and radar data provide some specifics, this information offers limited value beyond short-term forecasts (1 to 2 hours from observation time). This study examines the Workstation Eta's ability to provide detailed, small-scale information on Isabel's wind, temperature, and precipitation substructures that can improve storm surge and wind forecasting several hours before damage occurs.

MATERIALS AND METHODS

WSEta model output for 00:00 UTC, 06:00 UTC, and 12:00 UTC on 18 September 2003 were examined. The WSEta runs the full physics of its larger-scale parent Eta model [2, 3] with 39 vertical levels, initial conditions through an interpolation of isobaric GRIB data from the Eta or GFS model [1], and lateral boundary conditions supplied by the Eta or the Global Forecast System (GFS) [4,

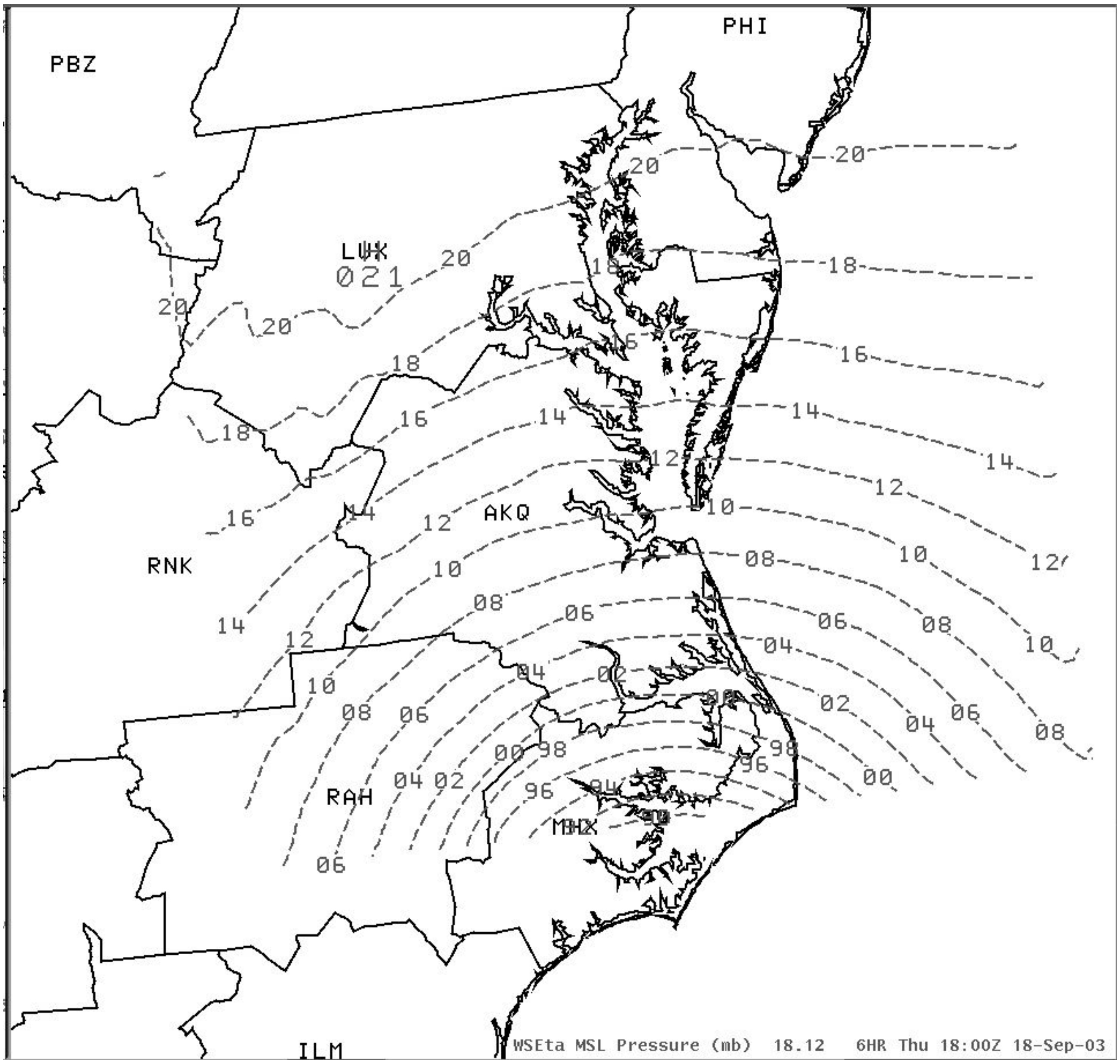


Figure 1. Forecast mean sea level pressure (mslp) contoured every 2 hPa (dashed) from the 12:00 UTC WSEta run, valid at 18:00 UTC on 18 September 2003. Three-letter identifier AKQ is located in the middle of the Wakefield, VA CWA (middle of figure). Area covered by contours of mslp shows the domain of the WSEta.

5]. The model was run initially over a larger, outer (coarse) grid of 15-km grid spacing with a Kain-Fritsch convective scheme [6]. A nested run was then made over a much smaller grid with a spacing of only 5 km (Figure 1). Various runs used different configurations over the inner (nested) grid. These different configurations were evaluated to determine which one best simulated wind, temperature, and precipitation substructures that appeared to be associated with the enhanced damage.

The Kain-Fritsch convective parameterization was always used on the outer domain. Explicit convection was used over the inner domain, except for one run for which the Kain-Fritsch parameterization was also applied to the inner grid. Weisman et al. [7] showed that explicit convective schemes can be used at 4 km, but not at 8 km (no testing was conducted at intermediary resolutions). Since the inner grid resolution (5 km) was close to this threshold, it warranted trying an explicit convection scheme. All runs were hydrostatic, except for one run (Eta initial/boundary conditions and explicit convection over nested grid) for which non-hydrostatic equations were used over the inner grid.

RESULTS AND DISCUSSION

Evaluation of WSEta Output

The various configurations of the WSEta were evaluated with runs at 00:00 UTC, 06:00 UTC and 12:00 UTC on 18 September 2003 using the Weather Event Simulator (WES) [8], which mimics the Advanced Weather Interactive Processing System (AWIPS) graphical display system, to determine if any mesoscale features—frontal boundaries, banded structures, and small-scale wind trajectories and speed maximums—were present and forecasted by the model runs. Any identified features were then examined to determine the impact they had on potential damage.

While the run using the GFS initial/boundary condition had a better overall track and intensity for Isabel when compared to runs with Eta initial/boundary conditions, the broader grid spacing in the GFS caused a loss of the finer detail that this study was attempting to capture. Though using the Eta to provide initial and lateral boundary conditions produced varying tracks and intensity for Isabel (depending on initialization time), these were generally less accurate than those from runs initialed from the GFS. The Eta did, however, provide more detail about the storm's structure. Figure 2 shows this detail through two distinct bands of ascent at 700 hPa in the run using the Eta for boundary conditions; the WSEta run using GFS initial/boundary conditions has one large area of ascent at 700 hPa over southeast Virginia.

The run using Kain-Fritsch convective parameterization on the nested grid provided less structure than runs using explicit convection. A non-hydrostatic run over the nested grid using the Eta boundary conditions, Kain-Fritsch scheme on the initial run and explicit on the nested grid showed slightly more structure. It was felt, however, that the small run time and the barotropic nature of the main feature of interest would make the difference between non-hydrostatic and hydrostatic runs over the 5-km domain small. The slight gain in detail was sufficiently substantial to outweigh the increased runtime (runtime more than doubled, from an average of just shy of 2 hours using hydrostatic equations to over 4 hours using non-hydrostatic equations). The best runs to use for the purpose of this study, therefore, were those

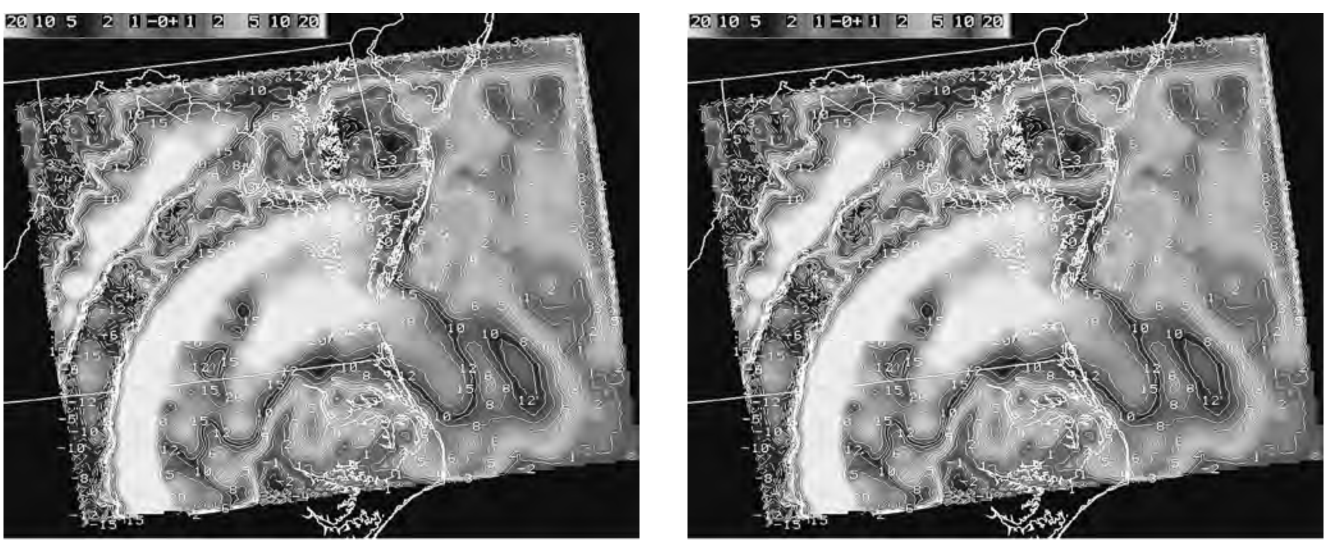
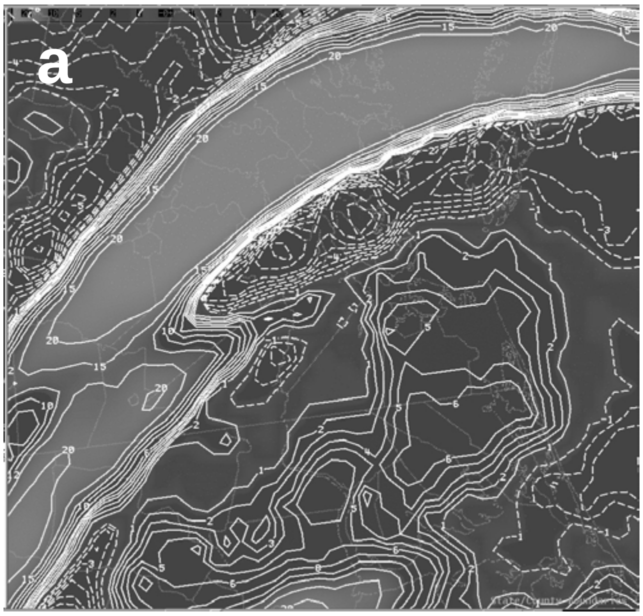
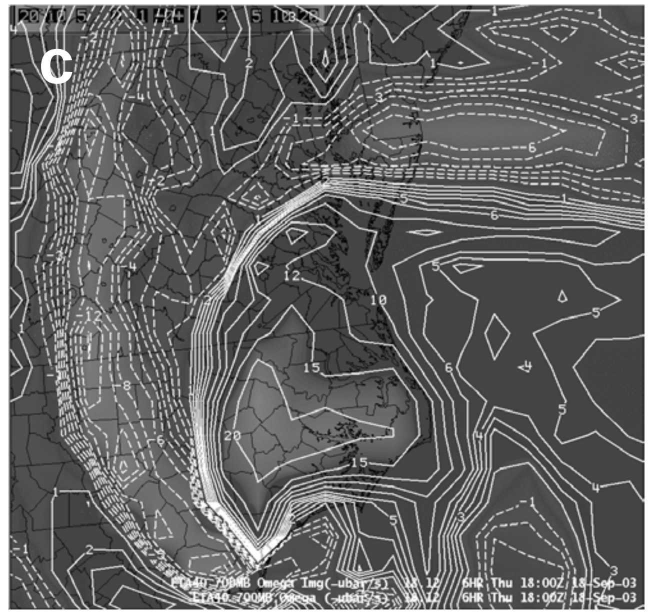


Figure 2. Forecast 700 hPa vertical motion from the 00:00 UTC WSEta run with the Eta boundary conditions (left) and GFS boundary conditions (right), valid at 22:00 UTC 18 September 2003.





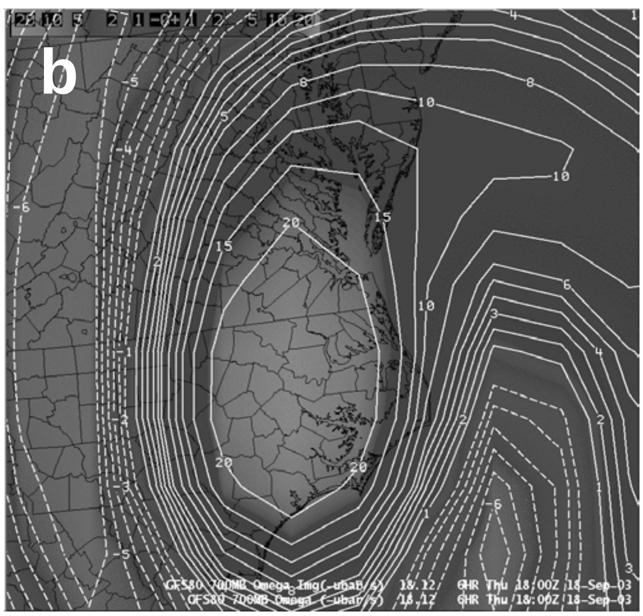


Figure 3. Forecast 700 hPa vertical motion at 18:00 UTC, from WSEta (a), Eta (b), and GFS (c) (respectively) run at 12:00 UTC 18 September 2003. Solid contours represent upward vertical motion; dashed contours represent downward vertical motion. The brighter whites indicate the strongest upward vertical velocity where the stronger bands in a tropical system are expected.

incorporating Eta boundary conditions with hydrostatic equations and explicit convection over the inner grid. This configuration provided detailed output, while enabling more efficient use of limited computer resources. These advantages outweighed any advantage gained by having a more realistic storm track and intensity.

Finally, a comparison of the best configuration and the two operational models (Eta and GFS) was made. As expected given the differences in resolution, a comparison of the WSEta output (5-km resolution) with that of the Eta (20-km resolution in AWIPS) and GFS (about 80-km resolution in AWIPS), the WSEta showed much more detail about the hurricane's banded structure. The Eta depicted some structure (not as much or as detailed as the WSEta) and the GFS indicated only a broad area of ascent with little or no structure evident. Figures 3a through 3c show areas of 700 hPa ascent (and descent) for the three models respectively. The following subsections explore some of the findings from WSEta runs using the configuration as specified above.

Frontal Boundary. The WSEta model runs depicted a low-level boundary, which is well portrayed in a plot of surface theta-e and surface wind barbs (Figure 4) from the 00:00 UTC run of the WSEta. This boundary indicated a tight gradient of theta-e across interior southeast Virginia, with north winds blowing parallel to the theta-e gradient along and on the cool side of the boundary and northeast winds on the warm side of the boundary. This setup

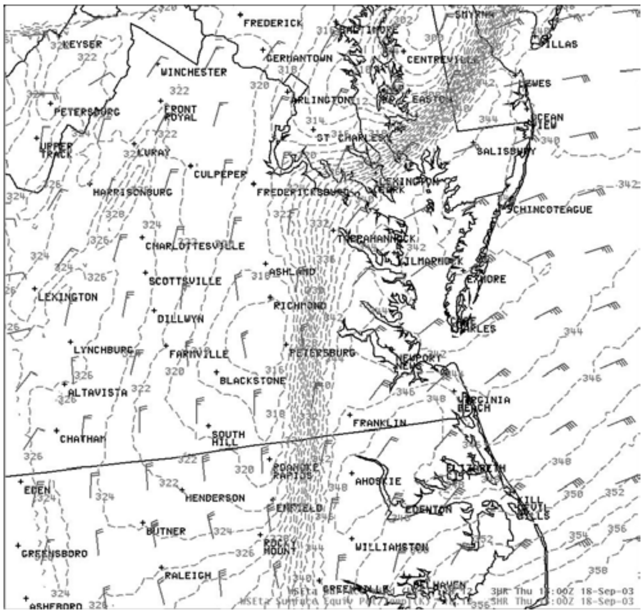


Figure 4. Forecast theta-e at 4K intervals (gray) and surface wind (gray barbs) from the 06:00 UTC WSEta run, valid 15:00 UTC.

is typical of conditions for an inland-moving coastal front over the Mid-Atlantic region. This coastal front delineates a relatively unstable maritime tropical airmass to its south and east and a relatively stable continental polar airmass to its north and west, associated with high pressure area to the north pushing drier air into the Mid-Atlantic states on 17 September 2003. The coastal front moved slowly inland over the coastal plain during the day on 18 September 2003 and was shown by Millet and Billet [9] to substantially affect the timing of stronger winds from Isabel reaching the ground.

WSEta soundings from Roanoke Rapids, North Carolina and Norfolk, Virginia (Figure 5) indicate the depth of this boundary aloft. In Figure 5a, the inversion extends to about 875 hPa, with the inversion preventing the downward mixing of the stronger winds above this layer [9]. Figure 5b indicates a more unstable airmass, however, with the potential to mix down stronger winds from aloft. This stability difference at the two locations is also demonstrated by the CAPE (convective available potential energy) increasing from 50 Jkg^{-1} near Roanoke Rapids to around 500 Jkg^{-1} near Norfolk at 15:00 UTC (not shown). The winds below 950 hPa on the sounding show more northerly winds at Roanoke Rapids, while winds at Norfolk have a more easterly, onshore component. This pattern is typical of a coastal front that has recently moved through one station (Norfolk) and is approaching another (Roanoke Rapids). Wind speeds at 950 hPa are comparable at both locations, providing similar gust potentials, but surface wind gusts are much lower near Roanoke Rapids in the sounding. Real-

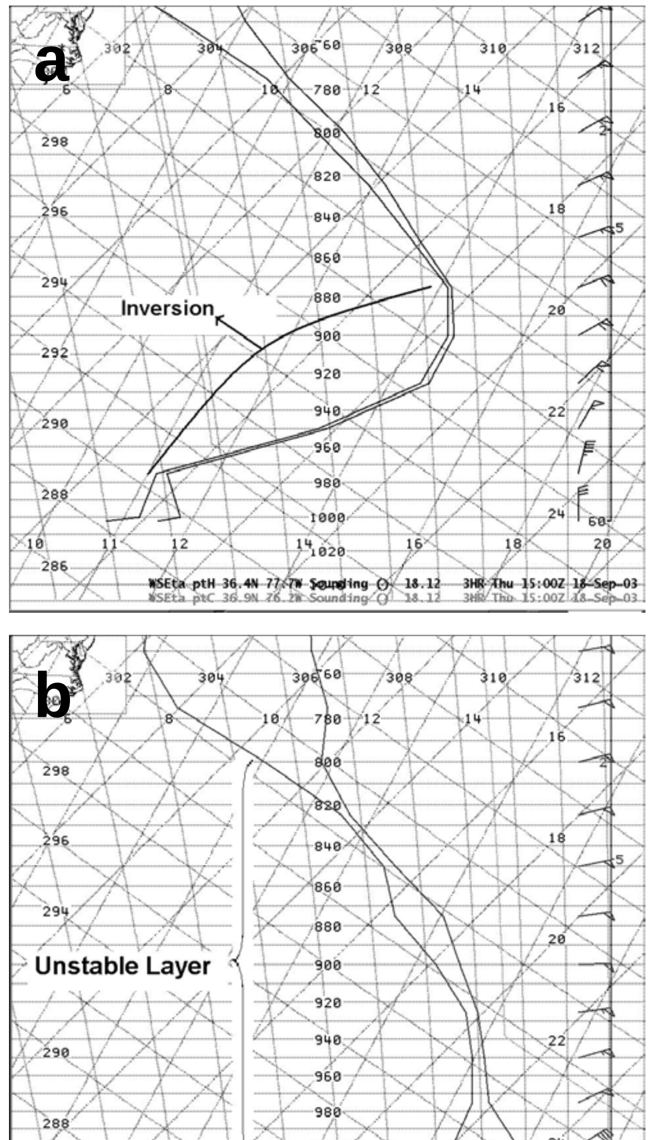


Figure 5a. a) WSEta Sounding at Roanoke Rapids, NC from 12:00 UTC WSEta run valid at 15: 00 UTC 18 September 2003; b) WSEta Sounding at Norfolk, VA from 12:00 UTC WSEta run valid at 15:00 UTC 18 September.

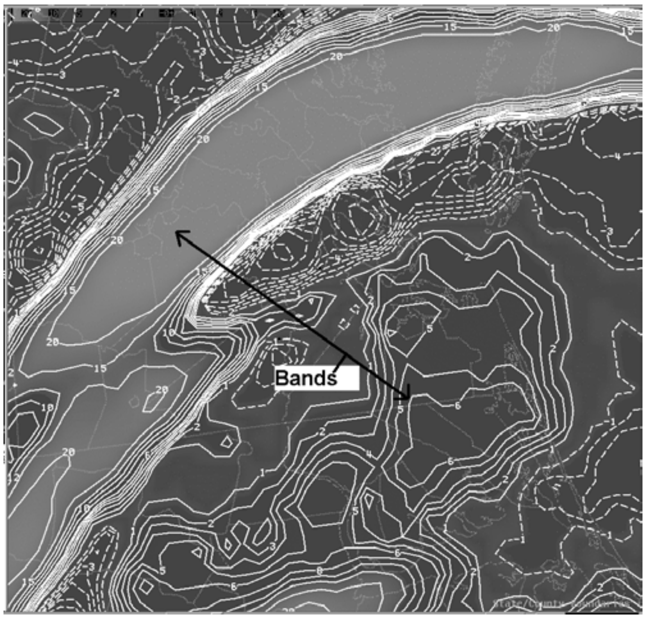


Figure 6. Identical to Figure 2a.

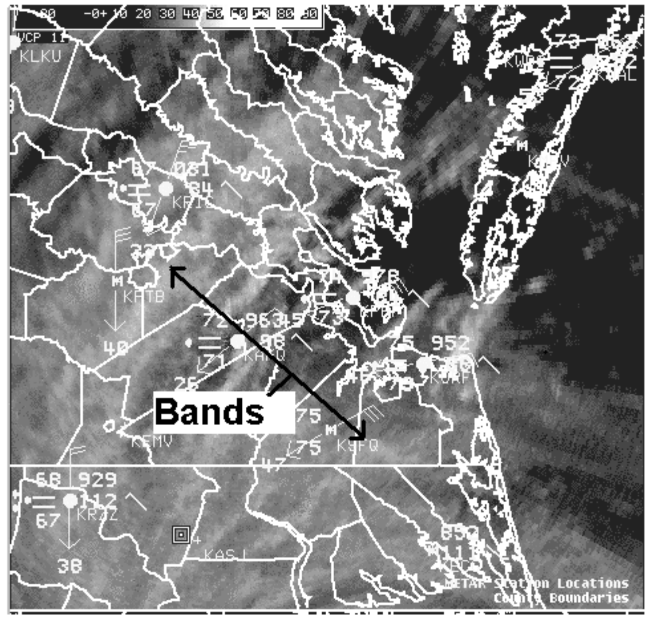


Figure 7. Wakefield, Virginia WSR-88D 0.5-degree, 8-bit reflectivity at 17:57 and 18:00 UTC observations.

time observations show the validity of these model soundings since winds at 2500 ft (762 m) (925 mb) were depicted by radar at approximately 74 kts at both locations near 15:00 UTC, but winds at the surface near 15:00 UTC only peaked at 33 kts at Roanoke Rapids and 52 kts at Norfolk [0].

Banded Structures. Vertical motion at 700 hPa has long been used to diagnose the location of convection from numerical weather prediction models. Examination of the vertical motion forecast from the WSEta valid at 18:00 UTC (Figure 6) indicates a banded structure to the convection (upward vertical motion), with a primary band stretching from the Virginia Eastern Shore, across the Chesapeake Bay, and southwest into south-central Virginia. A second, though weaker, band occurs from southeast Virginia into northeast North Carolina, with a region of sinking air between the two bands. The NWS Wakefield Doppler radar at 17:57 UTC (Figure 7) indicated similar structure and strength to the two bands, with a minimum of activity in between and corresponding to the area of descending vertical motion in Figure 6.

Further comparison of Figure 6 and Figure 7 suggests that the model bands were similar to radar observations, including the shape narrowing with time as the bands propagated further from the center. The behavior of the bands when looping model output was similar to their behavior while looping an extended radar or enhanced IR satellite loop. This ability of the WSEta to replicate the general structure and behavior of the bands shows the validity of using the model to gather meaningful detail about these bands as they move about the storm. In other words, the WSEta produced a detailed and realistic storm-relative picture of Isabel's banded structure.

While the location of the bands in the model corresponded well with the actual location of the bands, this situation was not always the case. The primary reason may be that the WSEta, as a consequence of using Eta boundary conditions, did not always provide accurate motion, and hence instantaneous location, for Isabel. Because the WSEta does capture the storm-relative essence of the structure, strength, and motion of individual bands, however, meaningful information can still be derived from its output—even when the physical location and/or intensity of the storm in the WSEta differed from what actually occurred or was forecast. By translating the model location for Isabel (and all associated detail) to the corresponding location (in space and time) along

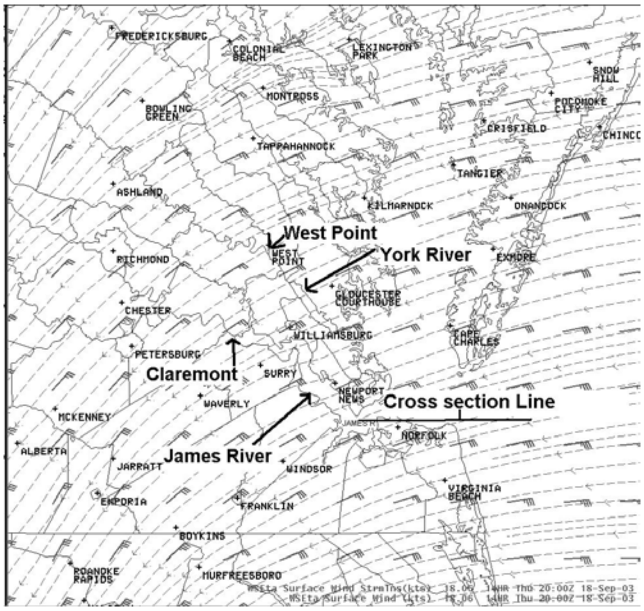


Figure 8. Forecast surface wind barbs and stream-lines from the 12:00 UTC WSEta run valid 18:00 UTC, 18 September 2003.

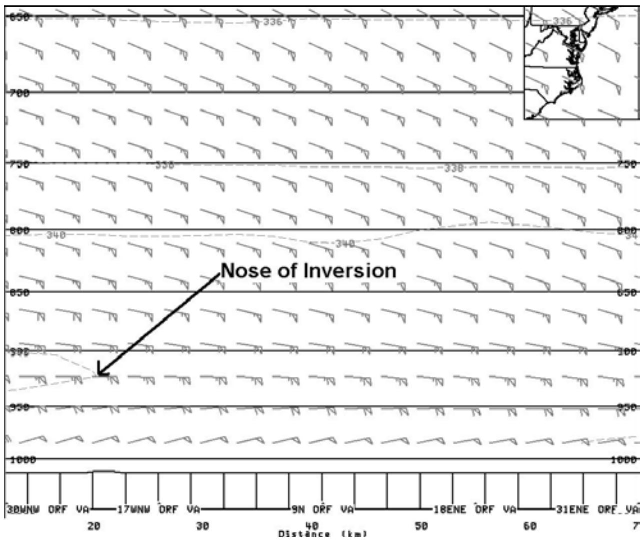


Figure 9. Cross-section of wind and theta-e dashed from 1000 to 650 hPa along an east-west line in Figure 8.

the National Hurricane Center track for the storm, the bands ended up close to where they were observed.

The WSEta forecast of these bands was accurate up to 12 hours ahead of their actual occurrence. In addition, each successive run of the WSEta provided similar details and evolution of these bands, which helps forecaster confidence when providing this information to customers. The timing of these features can help emergency managers determine when particularly severe weather will move across their area. Possessing this specific information should enable them to better manage their short-term resources.

Wind Trajectories with Wave Setup. Some of the more extensive damage associated with Isabel occurred along the York and James rivers, particularly in the towns of West Point and Claremont, with storm surveys indicating the damage came from high storm surge and wave action. Real-time wind trajectories traveled over open water, which played a major role in causing this damage. Initially, winds had a long water trajectory pointing into the mouth of the Bay, which raised water levels and drove water into these rivers. As Isabel moved inland, winds became southeast and pushed water up the rivers, increasing storm surge. In addition, long trajectories over open water built waves to an estimated .37 m (1.2 ft) on the rivers, with waves of this height adding around .09 m (0.3 ft) to the storm surge where it came ashore. The WSEta wind fields provided a means of examining the over-water wind trajectories. Figure 8 shows long over-water wind trajectories forecast by the WSEta, which would support piling of water into the mouth of the Bay. These forecast wind trajectories were accurate in orientation and duration, with the WSEta depicting longer over-water wind trajectories up the James and York rivers, but surface wind speeds were significantly less than observed.

Figure 9 shows a cross-section, from the coastal waters into the mouth of the James River, from east of Norfolk to south of Newport News. The cross-section showed unidirectional winds greater than 50 kts to the east of the low-level inversion through 900 hPa, allowing the wind gusts to enhance the surface winds and resulting in increased wave action up the James River. The WSEta indicated that the winds would veer to the southeast late on 18 September 2003 (not shown), allowing the water piling into the mouth of the James and York rivers to be pushed further upriver. At the same time, high tide was occurring, increasing the amount of water flowing up the rivers on the west side of the Bay. This information could have been given to emergency managers as early as nine hours before the highest tides during Isabel on the evening of 18 September 2003. The advanced knowledge of these long-duration fetches of wind up the rivers on the Bay's west side would have been useful to emergency managers in planning for more water damage in specific areas. Predictions of the onset and duration of local maxima of storm surge and wave flooding and suggestions that storm surge and wave impact projections might be exceeded could have proved particularly useful.

CONCLUSIONS

The WSEta can be used in a real-time operational environment to examine mesoscale features. The best WSEta model configuration for depicting the coastal front, banded precipitation structures, and wind trajectories and wind speed maxima in this case was the use of explicit convection in the nested grid, Kain-Fritsch convective parameterization over the coarse domain, and hydrostatic equations. Several features relative to the impact of Isabel were provided in WSEta runs including coastal front depiction, convective band structure, and over-water wind trajectories. The strong theta-e gradient across the Wakefield CWA indicated a change in the ability to mix higher wind speeds from aloft to the surface. Convective band structure was present by the WSEta depiction of strong vertical velocities and provided a storm-relative frame to suggest when periods of more intense rains and higher wind gusts would occur, especially when combined with information on the coastal front location. Wind trajectories from the WSEta provided details on where the most significant waves might occur and information on where increased storm surges were possible.

Overall, the WSEta did a good job of indicating where increased storm surge and higher waves would combine to cause potentially greater damage once the location of features were translated to the projected NHC track for the storm. When properly interpreted output from the WSEta is relayed to customers, such information can guide planning for worsening conditions and indicate how long these conditions might last. Finally, since this study involves only one storm, its results should be used with care until additional research on other tropical systems is conducted.

REFERENCES

1. NCEP. 2004. *www.emc.ncep.noaa.gov/mmb/wrkstn_eta*
2. T.L. Black. 1994. The new NMC mesoscale Eta Model: Description and forecast examples. *Wea. Forecasting*. 9: 265–278.
3. NCEP. 2004. *www.emc.ncep.noaa.gov/mmb/research/eta.log.html*
4. NCEP. 2004. *www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html*
5. J. Sela. 1980. Spectral modeling at the National Meteorological Center. *Mon. Wea. Rev.* 108: 1279–1292.
6. J.S. Kain and J.M. Fritsch. 1993. Convective parameterization for mesoscale models. *Meteorol. Monogr.* No. 24. American Meteorological Society. pp. 165–170.
7. M.L. Weisman,W. Skamarock, and J. Klemp. 1997. The resolution dependence of explicitly model convective systems. *Mon. Wea. Rev.* 125: 527–548.
8. M.A. Magsig and E.M. Page. 2003. Weather event simulator implementation and future. *Preprints, 19th Conference on IIPS. 83rd AMS Annual Meeting*, Long Beach, CA. American Meteorological Society. CD-ROM 12.9.
9. P.F. Maloit and J. Billet. 2004. Forecasting the impact of a statically stable layer in the lower atmosphere on surface wind conditions during Hurricane Isabel. *26th Conference on Hurricanes and Tropical Meteorology.* Miami, FL. American Meteorological Society. pp. 350–351.

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

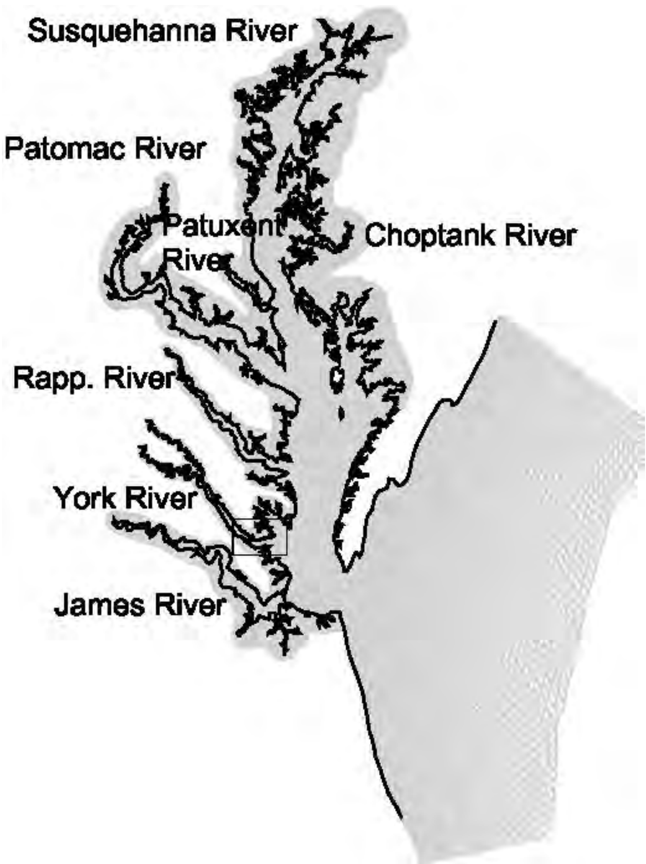

Figure 1. High-resolution model grid.

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

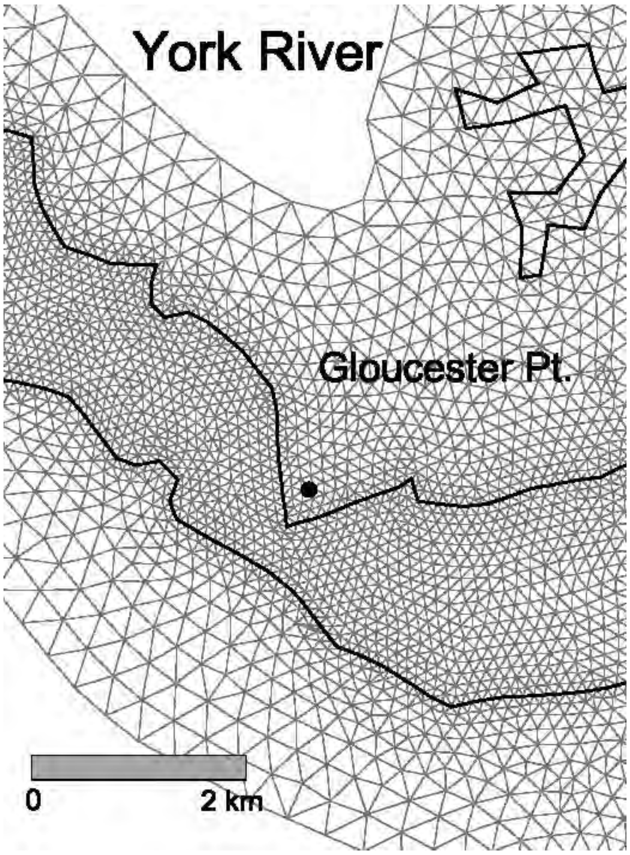

Figure 2. Grid layout at the mouth of York River.

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.

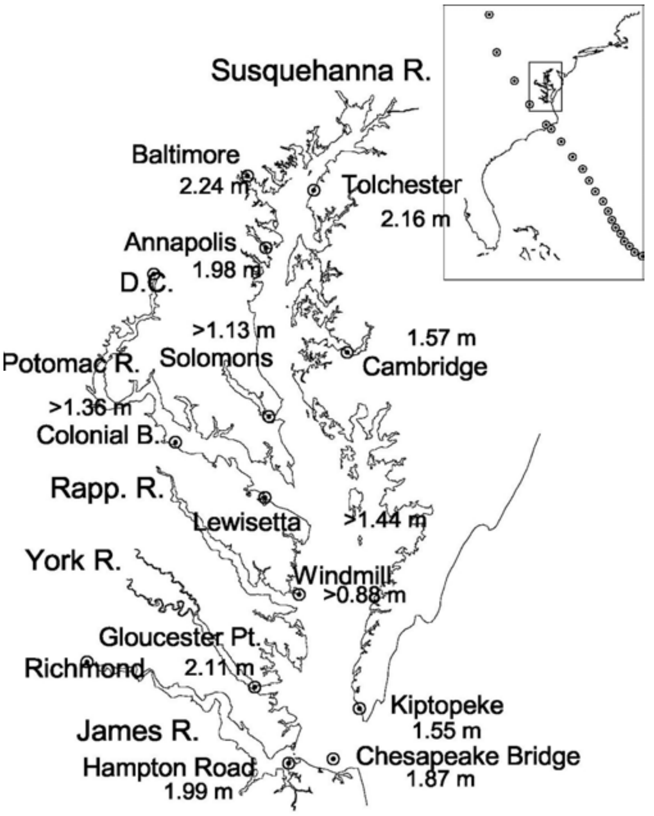

Figure 3. Map of tidal gauge stations and maximum storm tide during Hurricane Isabel.

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

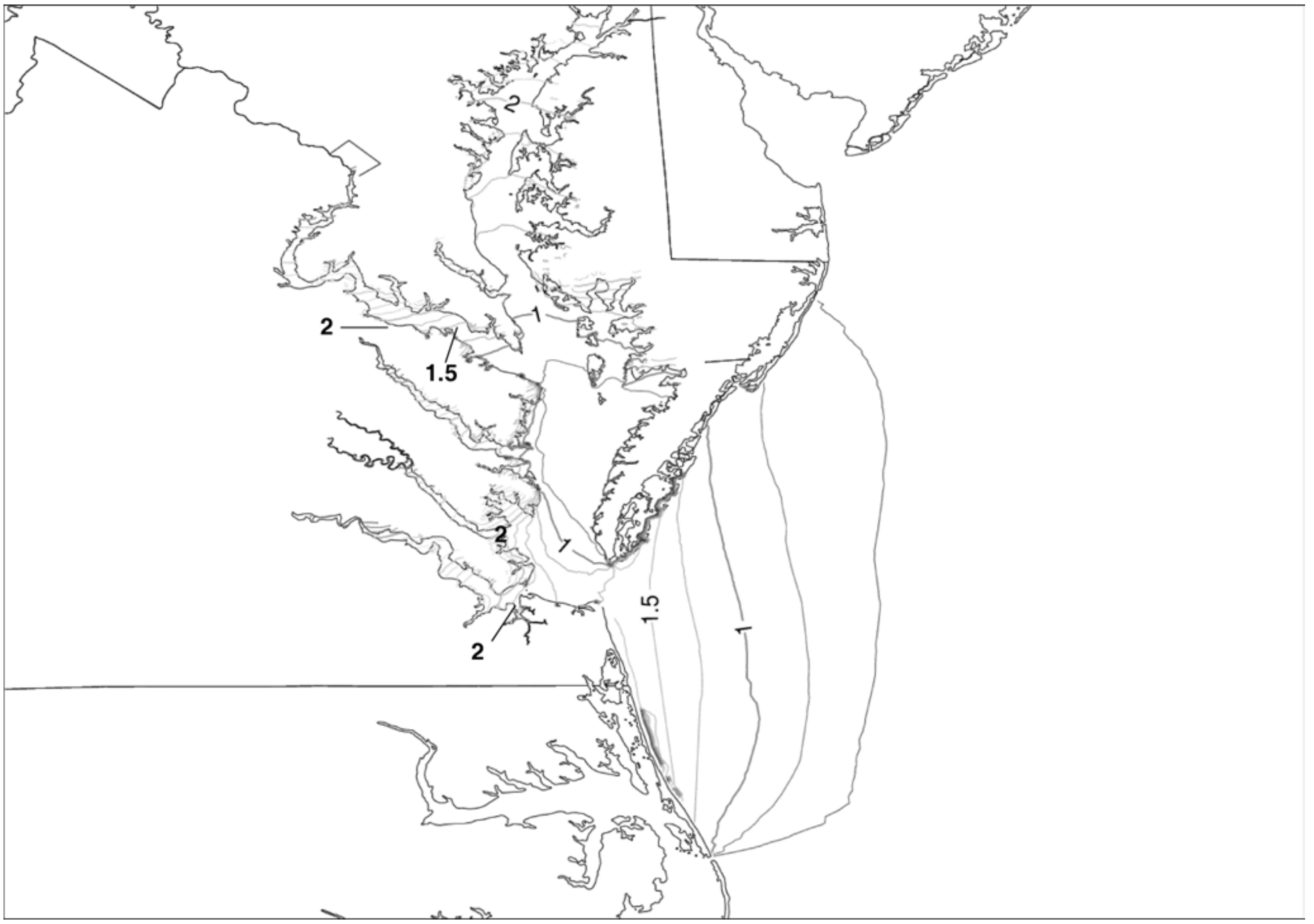

Figure 4. Contours of maximum surge predicted by ADCIRC in Chesapeake Bay (contour interval is 0.25 m).

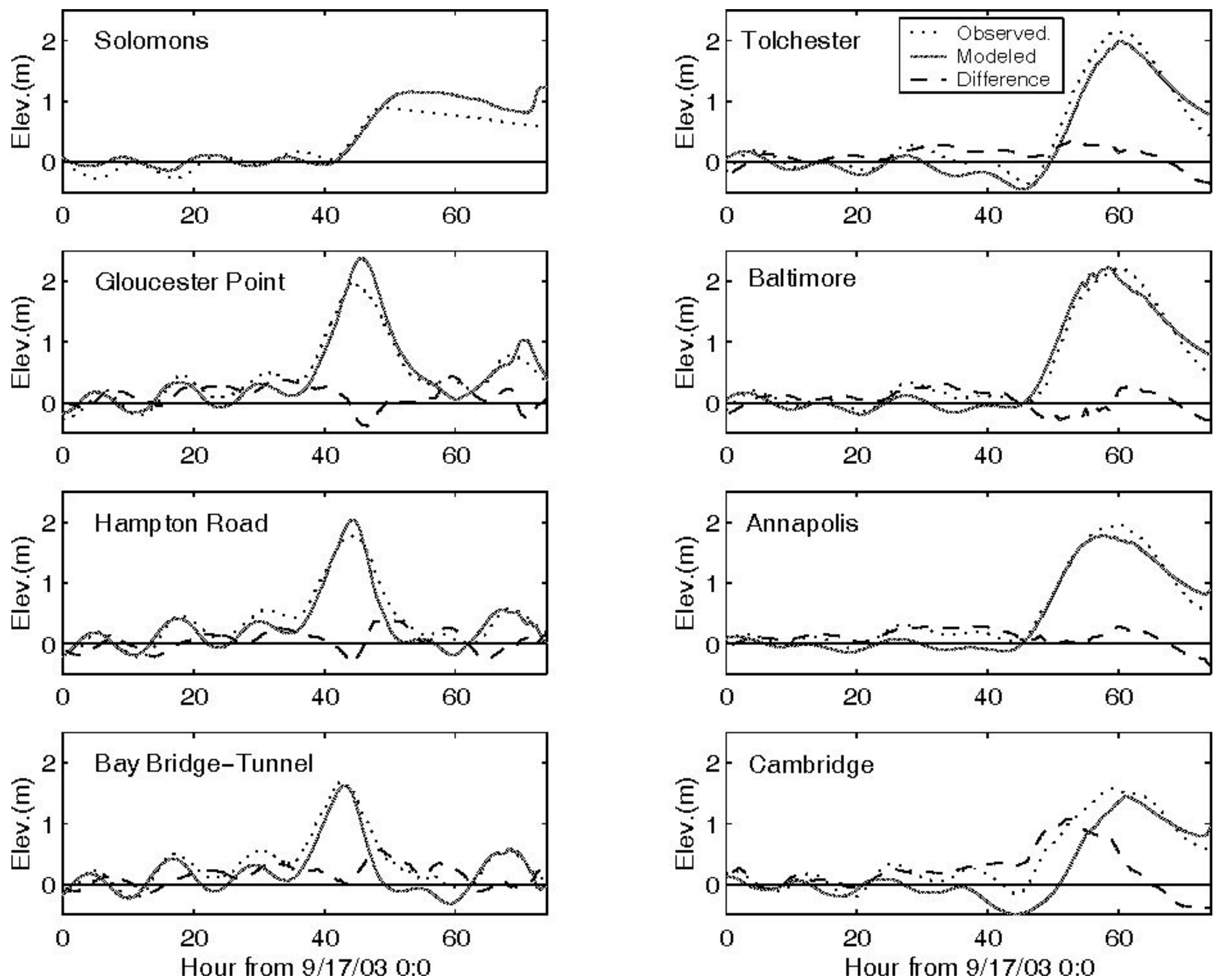

Figure 5. Time series comparison of ADCIRC model simulations with observations at different stations (dotted lines are observations, solid lines are model results, and dashed lines are differences).

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·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

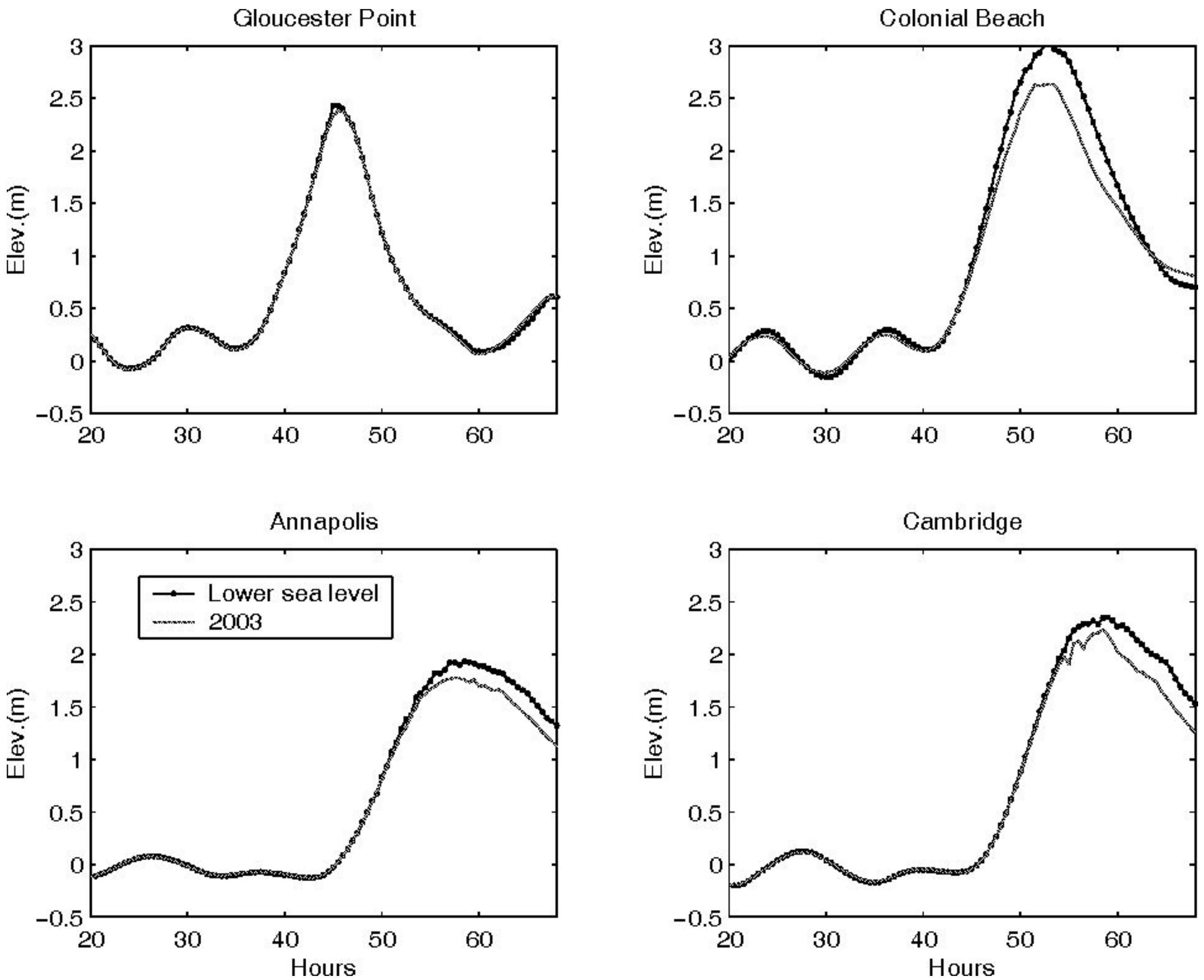

Figure 6. Comparison of model predicted surge under different sea level condition (lines with dots are results for low sea level (40 cm lower) and solid lines are the results under the current sea level).

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.

ACKNOWLEDGMENTS

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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).

Luettich for providing the ADCIRC model to us. The reviewer's constructive suggestions are also appreciated. This paper is Virginia Institute of Marine Science Contribution No. 2646.

REFERENCES

1. C.P. Jelesnianski, J. Chen, and W.A. Shaffer. 1992. SLOSH: Sea, Lake, and Overland Surges from Hurricane. National Weather Service, Silver Springs, MD. 71 pp.
2. J.J. Westerink, C.A. Blain, R.A. Luettich, and N.W. Scheffner. 1992. ADCIRC: An Advanced Three-Dimensional Circulation Model For Shelves, Coasts, and Estuaries, Report I, Theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. Technical Report DRP-92-6, U.S. Army Corps of Engineers. 137 pp.
3. R.A. Luettich, J.J. Westerink, and N.W. Scheffner. 1992. ADCIRC: An Advanced Three-Dimensional Circulation Model For Shelves, Coasts, and Estuaries, Report 2, User's Manual for ADCIRC-2DDI. Technical Report DRP-92-6, U.S. Army Corps of Engineers. 166 pp.
4. C.A. Blain, R.H. Preller, and A.P. Rivera. 2002. Tidal prediction using the Advanced Circulation Model (ADCIRC) and a relocatable PC-based system. *Oceanography*. 15(1): 77–87.
5. C.A. Blain, J.J. Westerink, and R.A. Luettich, Jr. 1998. Grid convergence studies for the prediction of hurricane storm surge. *Int. J. Num. Meth. Fl.* 26: 369–401.
6. C.A. Blain, J.J. Westerink, and R.A. Luettich, Jr., 1994. The influence of domain size on the response characteristics of a hurricane storm surge model. *J. Geophys. Res.* 99: 18,467–18,479.
7. M. Cobb and C.A. Blain. 2002. Simulating wave-tide induced circulation in Bay St. Louis, MS with a coupled hydrodynamic-wave model, *Mar. Technol. Sci.* 3: 1494–1500.
8. J.P. Mathew, R. Mahadevan, B.H. Bharatkumar, and V. Subramanian. 1996. Numerical simulation of open coast surges. Part I: Experiments on offshore boundary conditions. *J. Coast. Res.* 12: 112–122.
9. A.Y. Mukai, J. J. Westerink, and R.A. Luettich. 2002. Guidelines for using the East Coast 2001 database of tidal constituents within western North Atlantic Ocean, Gulf of Mexico and Caribbean. U.S. Army Corps of Engineers, ERDC/CHL CHETN-IV-40. 20 pp.
10. J.J. Westerink, R.A. Luettich, A.M. Baptista, N.W. Scheffner, and P. Farrar. 1991. Tide and storm surge predictions using finite element model. *J. Hydraul. Eng.* 118: 1373–1390.

11. G.K. Verboon, J.G. Ronde and R.P. Van Dijk. 1992. A fine grid tidal flow and storm surge model of the North Sea. *Cont. Shelf Res.* 12(2/3): 213–233.
12. J. Boon. 2005. Isabel's silent partners: seasonal and secular sea level change. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.), Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD. pp. 49–52.
13. J. Beven, and H. Cobb. 2004. Tropical Cyclone Report Hurricane Isabel, National Hurricane Center.

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 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·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

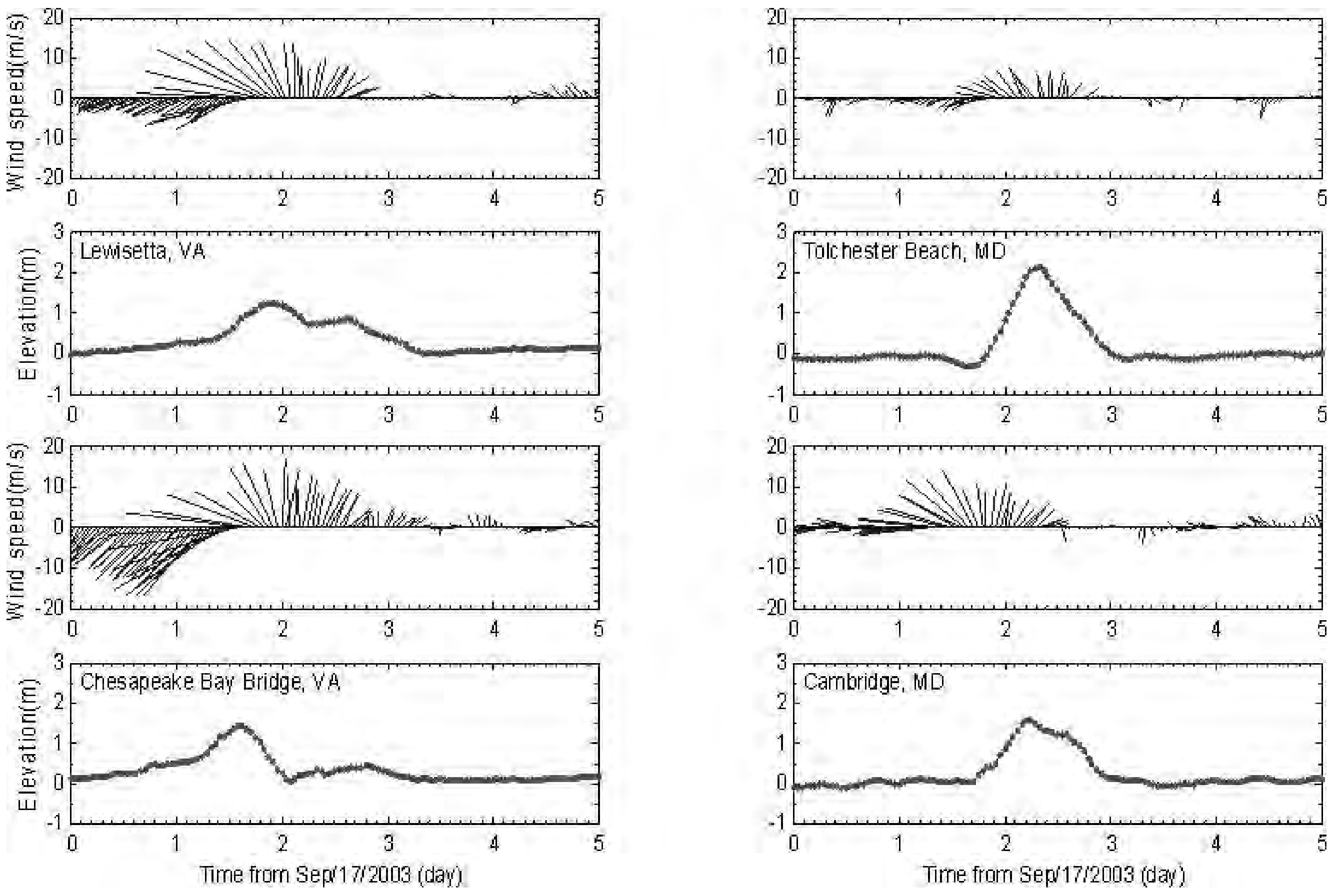


Figure 1. Observed storm surge (excluding astronomical tide) and the corresponding wind vectors in Chesapeake Bay stations during Hurricane Isabel.

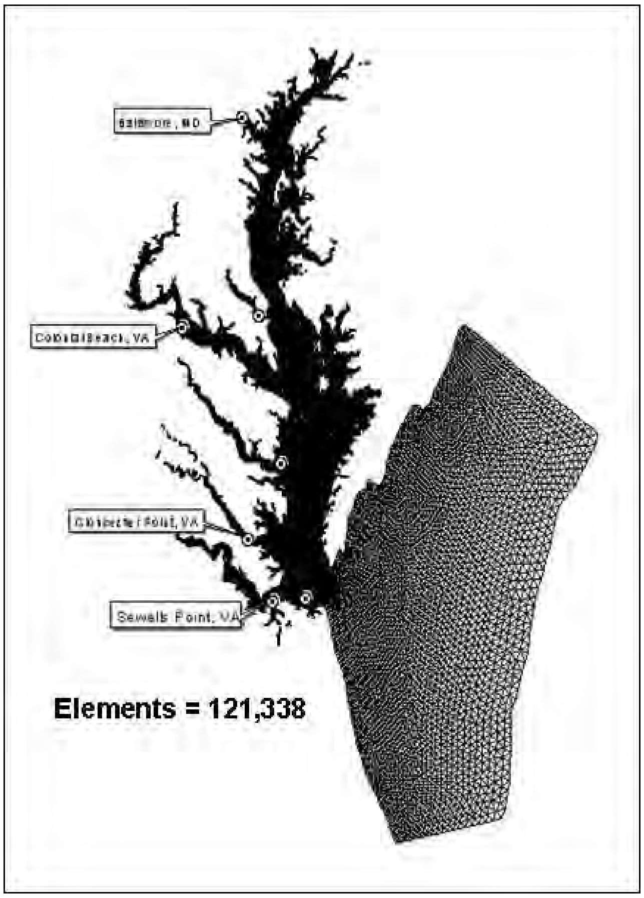


Figure 2. Modeling domain of Chesapeake Bay and the adjacent coastal water using a high-resolution unstructured grid.

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

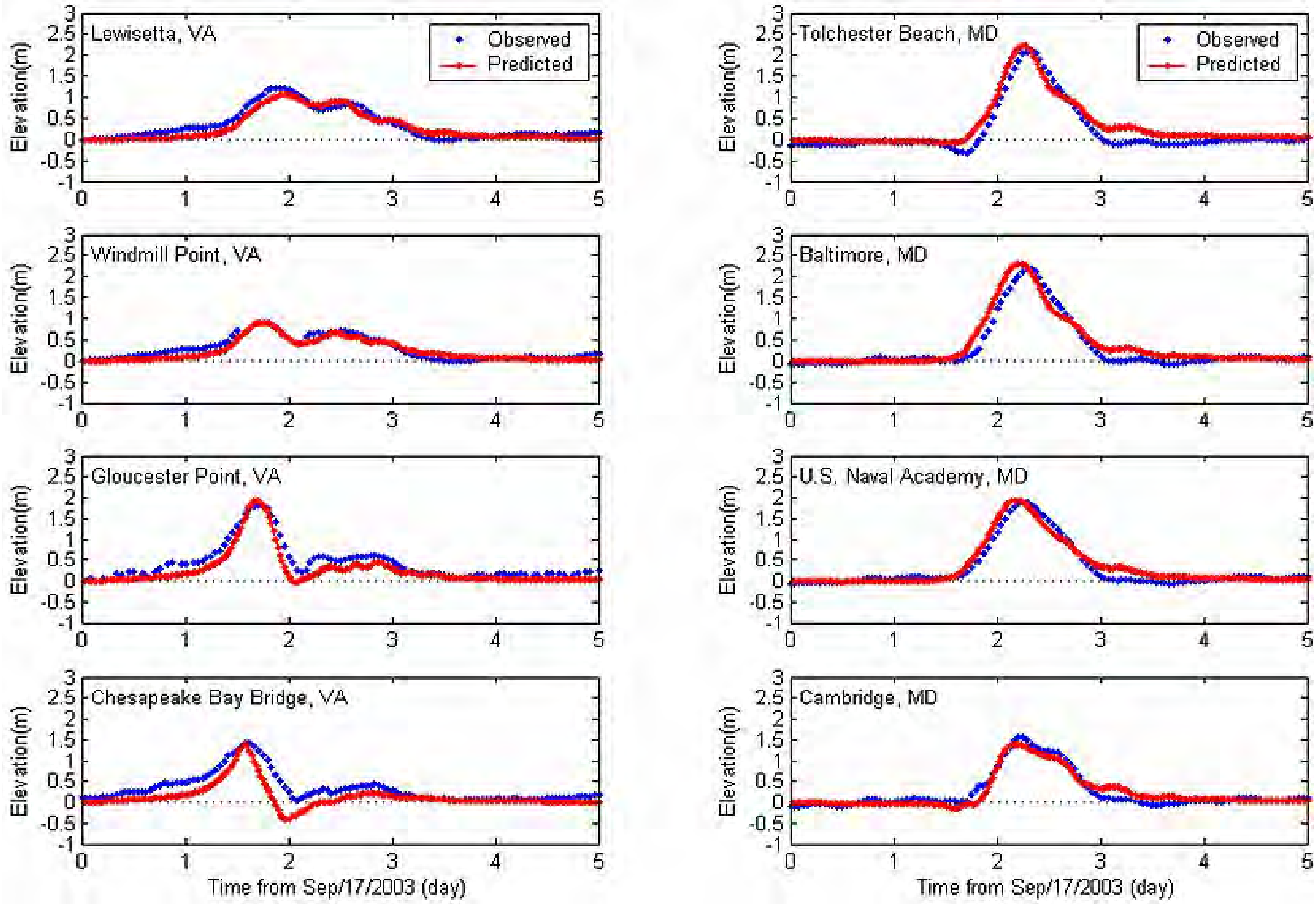


Figure 3. The observed versus modeled storm surge during Hurricane Isabel.

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

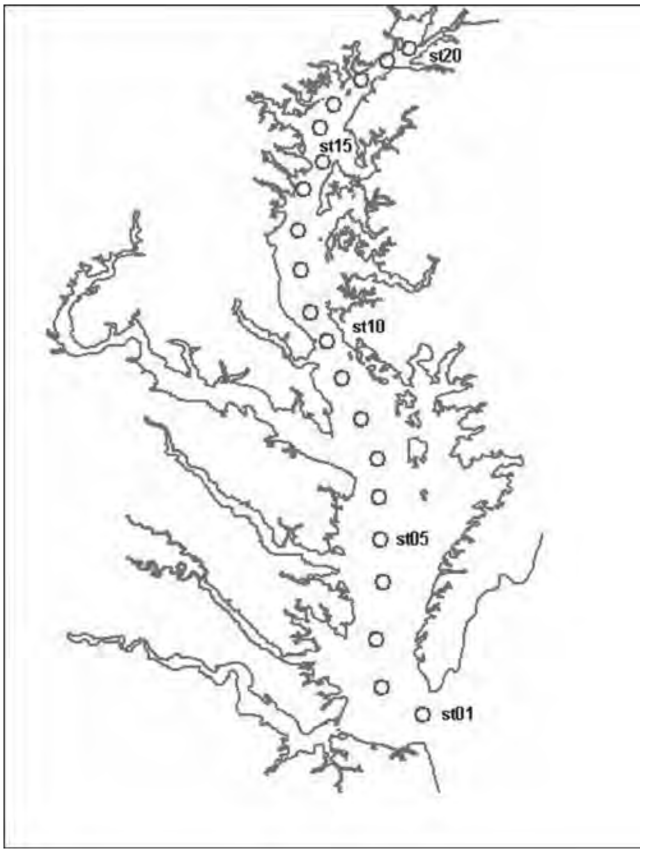


Figure 4. The locations of 20 stations in the Chesapeake Bay model domain selected for storm surge analysis.

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

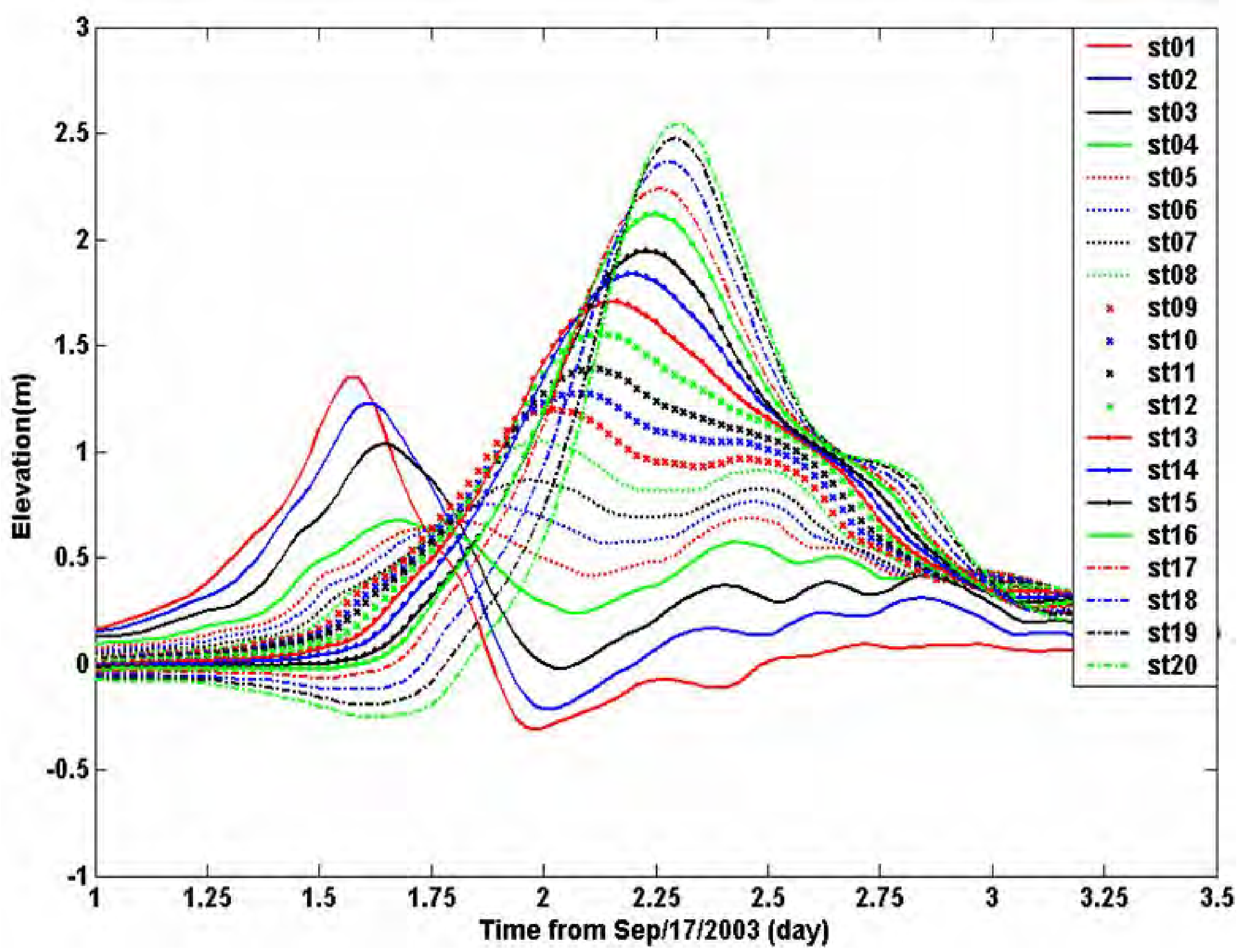


Figure 5. Elevation versus time shown for stations 1 through 20.

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·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·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·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

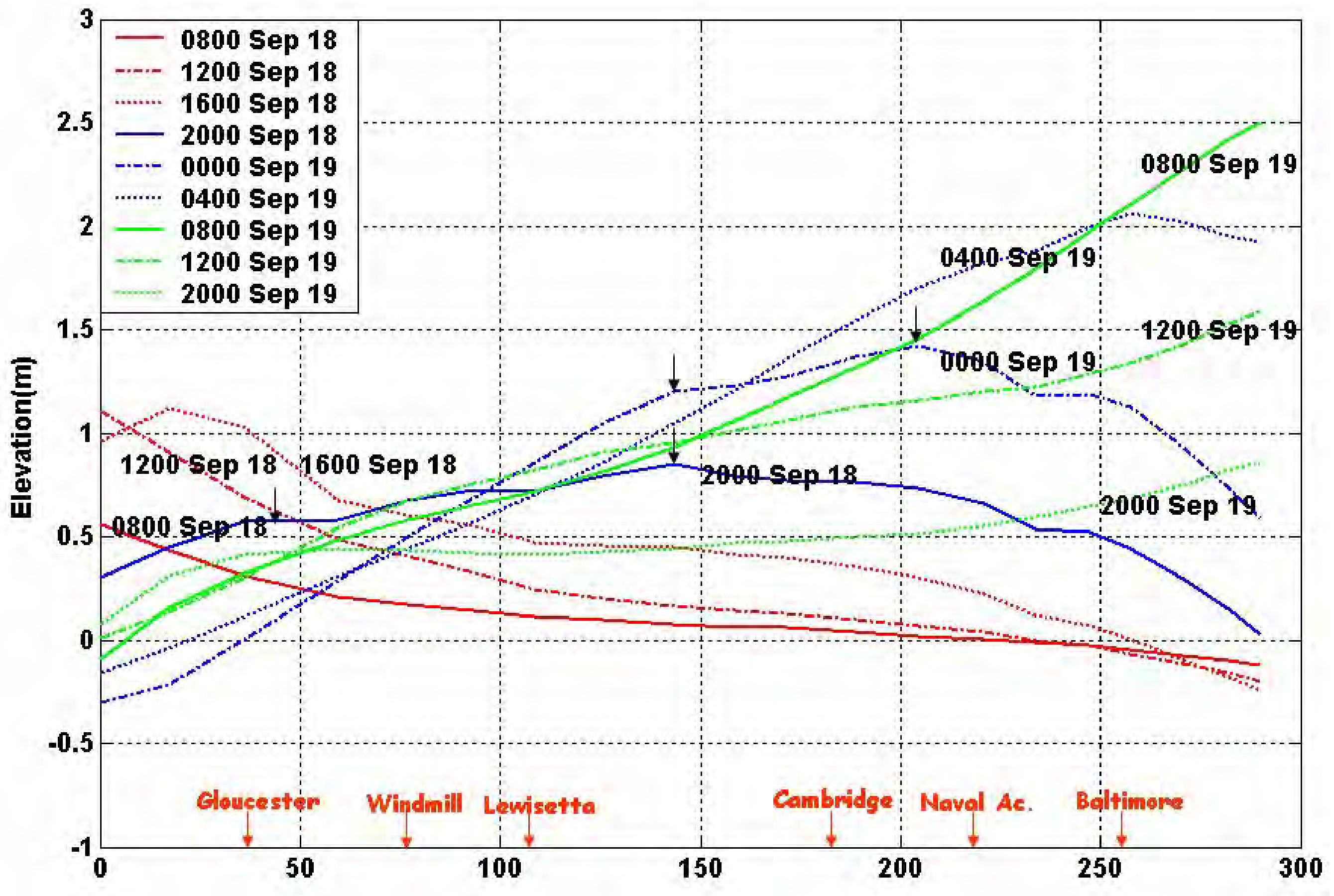


Figure 6. The elevation versus space plot for stations 1 through 20.

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:

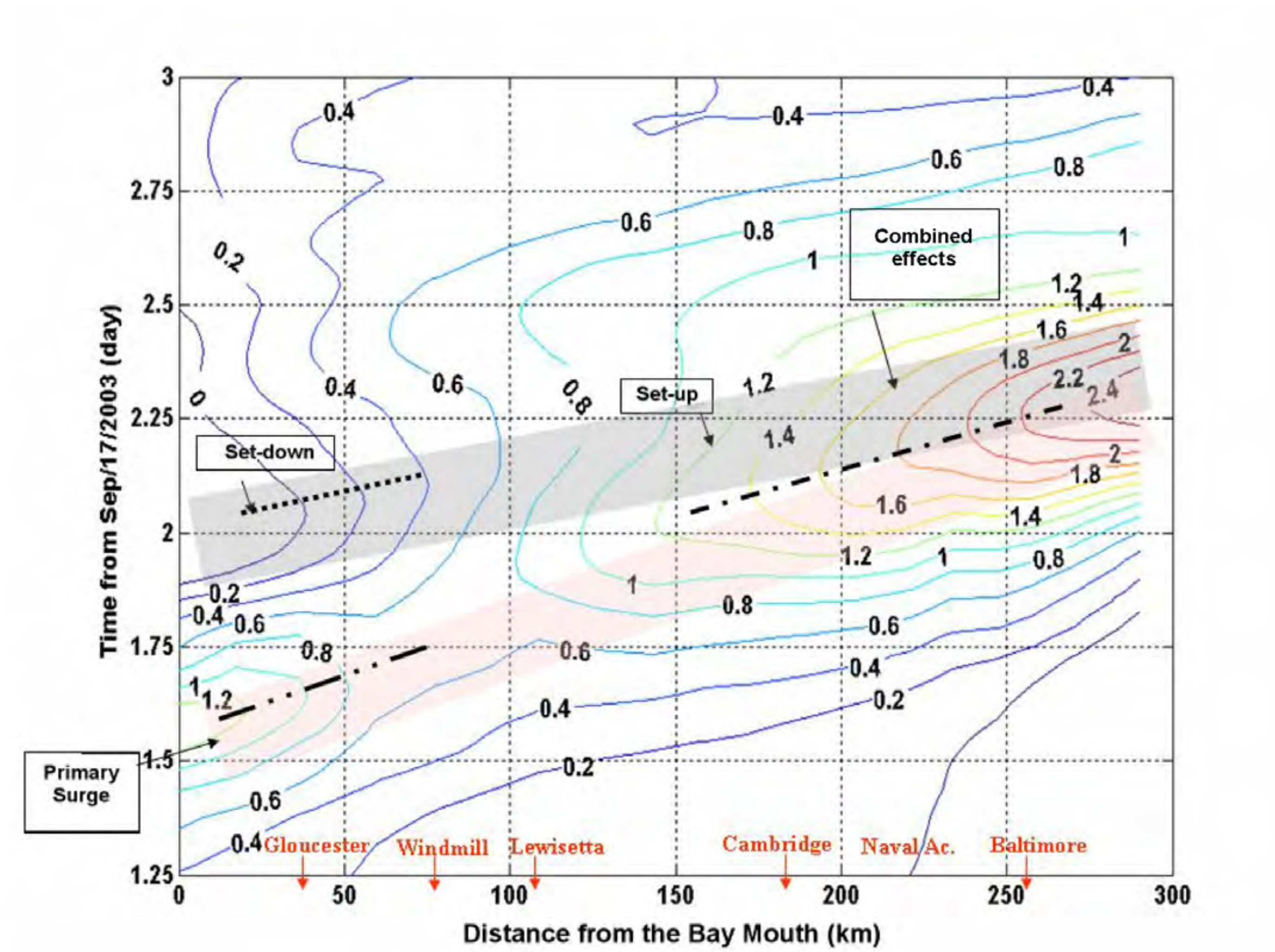


Figure 7. The space versus time plot for stations 1 through 20

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.

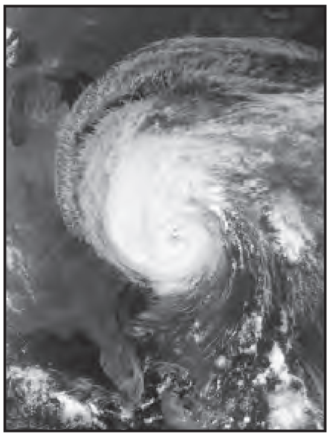
ACKNOWLEDGMENTS

During Hurricane Isabel, the Ferry Pier that housed the tidal gauge for VIMS was completely destroyed. With the foresight of Don Wright and Willy Reay, alternative instruments were put in place before the hurricane struck and the data they provided to reconstruct the water level at Gloucester

Point is appreciated. Further acknowledgments go to Dr. Philip Bogden for his encouragement and advice. NOAA funded the study through SURA (Southeastern Universities Research Association).

REFERENCES

1. C.L. Bretschneider. 1959. Hurricane surge predictions for Chesapeake Bay. Miscellaneous Paper No. 3-59, Beach Erosion Board, Office of the Chief of Engineers, U.S. Army Corps of Engineers.
2. V. Casulli and R.T. Cheng. 1992. Semi-implicit finite difference methods for three-dimensional shallow water flow. *Int. J. Numer. Methods Fluids* 15: 629–648.
3. R.T. Cheng and V. Casulli. 2002. Evaluation of the UnTRIM model for 3-D tidal circulation. Proc. 7th International Conference on Estuarine and Coastal Modeling. M.L. Spaulding (ed.). St. Petersburg, FL. pp. 628-642.
4. Y. Zhang, A.M. Baptista, and E.P. Meyers. In press. A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf system: I. Formulation and skill assessment. *Cont. Shelf. Res.* 25.
5. V.A. Myers and W. Malkin. 1961. Some properties of hurricane wind fields as deduced from trajectories. National Hurricane Research Project Report, No. 49, NOAA, U.S. Department of Commerce, 43 pp.
6. C. Jelesnianski, J. Chen, and W.A. Shaffer. 1992. SLOSH: Sea, Lake, and Overland Surge from Hurricanes. NOAA Tech. Rpt. NWS 48. U.S. National Weather Service. Silver Spring, MD. 71 pp.
7. R.A. Luettich, J.J. Westerlink, and N.W. Scheffner. 1992. ADCIRC: An ADvanced three-dimensional CIRculation model for shelves, coasts, and estuaries. Report I: Theory and methodology of ADCIRC-2ddi and ADCIRC-3di. Tech. Rpt. DRP-9-6, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
8. G.B. Whitham. 1974. *Linear and Nonlinear Waves.* Wiley-Interscience. New York. 636 pp.



Isabel's Impact on Water Quality and Living Resources

IMPACT OF HURRICANE ISABEL ON THE WATER PROPERTIES OF THE CHESAPEAKE BAY AREA

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ABSTRACT

On 18 September 2003, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the NASA satellite Aqua (EOS PM) and Terra (EOS AM) took stunning pictures of Hurricane Isabel's landfall over the U.S. East Coast. Satellite images of the Chesapeake Bay region before and after landfall show important qualitative changes in the water properties due to the huge amount of sediment delivered to the Bay, extending far beyond the coastal region (more than 100 km). The impact on the ecosystem of this rare phenomenon deserves additional analysis.

Remote sensing data from the Terra and Aqua system can be inverted to estimate key water properties (chlorophyll, transparency, sediment loading), which can be validated using the network of measurements taken in the Chesapeake Bay area. Once validated, the remote sensing products can be used to estimate the change in water properties up to twice a day and over the entire area. In particular, comparison of the water properties before and after the landfall of Isabel provides a quantitative estimate of this hurricane's impact on selected water properties.

Using the co-analysis of precipitation measurements from the Tropical Rainfall Measuring Mission (TRMM) sensors, the basic factors responsible for changes in the water properties in the Chesapeake are isolated.

INTRODUCTION

Suspended matter plays an important role in water quality management since it is related to total primary production (e.g., nutrient release) and fluxes of heavy metals and micropollutants. Synoptic information on suspended matter at regular frequencies is difficult to obtain from the routine *in situ* monitoring network, since suspended matter, such as chlorophyll, is a spatially inhomogeneous parameter. Earth-observing satellite systems provide powerful high-technology tools that can monitor these phenomena. NASA's MODIS system (on the Terra and Aqua satellites) yields daily coverage of the study area. It has a visible and near-infrared channel with pixels of 250 x 250 m. These higher-resolution images can provide time-series regional synoptic views of suspended sediments. This information, integrated with "groundtruth" data, may prove useful in understanding and managing the impact of rare phenomena (such as a hurricane) on an ecosystem.

It is well known that water reflectance increases with increasing concentration of suspended matter in the visible spectrum and even some of the near-infrared portion of the spectrum [2] (Figure 1). Several studies have been performed based on this property. Most research with a large range (i.e., 0–200 mg·L^{-1}) of suspended sediment concentration found a curvilinear relationship between suspended sediment and radiance or reflectance [1, 3, 6, 8] because the amount of reflected light tends to saturate as suspended sediment concentration increases. If the suspended sediment values range between 0 and 50 mg·L^{-1}, reflectance from almost any wavelength will be significantly related to suspended sediment concentrations [7].

Gaseous and aerosol scattering and absorption, adjacency effects caused by the presence of land pixels and the inhomogeneous distribution of total suspended sediment, the bidirectional reflectance distribution function (BRDF) and atmospheric coupling effect, and contamination by thin cirrus clouds, all affect the reflectance signal.

An accurate atmospheric correction is the first step in performing further analysis. The MODIS instrument contains several features, which make the atmospheric correction algorithm more accurate than in the past. Most important is the availability of seven channels in the spectral interval 0.41–2.1 μm that enables the derivation of aerosol loading and aerosol optical thickness [4]. Likewise, reducing pixel size from 1 km in the previous satellite generation to 250 m in MODIS increases the ability to detect cloudy pixels and reduces contamination by subpixel clouds.

The objectives of this study were to determine the potential of remote sensing data to estimate sediment concentrations in the Chesapeake Bay and to study temporal variability in the sediment during 2003, particularly after Hurricane Isabel made landfall and affected the region.

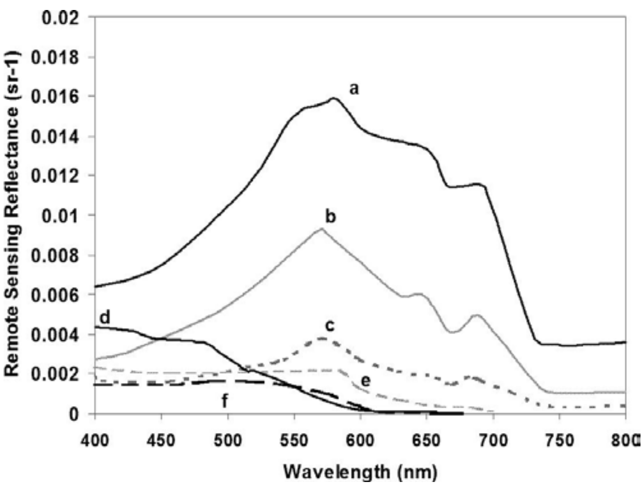


Figure 1. Reflectance from: a) waters with very high sediment; b) high sediment concentrations; c) moderate sediment with some phytoplankton; d) clear water; e) waters with moderate chlorophyll and sediment concentrations; and f) waters with moderate chlorophyll concentration [5].

MATERIALS AND METHODS

The Bay proper is approximately 320 km long, but contains over 7,100 km of shoreline. It ranges in width from about 6.5 km near Annapolis, Maryland to more than 50 km at its widest point, near the mouth of the Potomac.

Tributaries continuously discharge water into the Chesapeake Bay. Almost 85–90 percent of the fresh water entering the Bay comes from the northern and western areas. The Eastern Shore contributes the remaining 10 to 15 percent. Nearly an equal volume of salt water enters the Bay from the ocean. The tributaries supply waters with a broad geochemistry due to the influence of the three different geological provinces of the Chesapeake region. Each tributary contributes a unique mix of minerals, nutrients, and sediments.

Data have been collected from the Chesapeake Bay Program website *www.chesapeakebay.net/data* for the year 2003. The Chesapeake Bay Program, a cooperative effort of federal, state, and local governments, funds the states of Maryland and Virginia for routine monitoring of 19 directly measured water quality parameters at 49 stations in the mainstem Bay. The Water Quality Monitoring Program began in June 1984 with stations sampled once each month during the late fall and winter months and twice each month during the warmer months. Over the years, the number of sampling events has been reduced to 16 per year in Maryland and 14 per year in Virginia.

The collecting organizations coordinate the sampling times at their respective stations, so that data for each sampling event, or “cruise,” represent a synoptic picture of the Bay at a particular time. At each station, a hydrographic profile is made (including water temperature, salinity, and dissolved oxygen) at approximately 1- to 2-m intervals. Water samples for chemical analysis (e.g., nutrients and chlorophyll) are collected at the surface and bottom, as well as at two additional depths that depend on the existence and location of the pycnocline (the region or regions of density discontinuity in the water column). Correlative data on sea state and climate are also collected. Maryland, Virginia, and District of Columbia tributary data are included in this database.

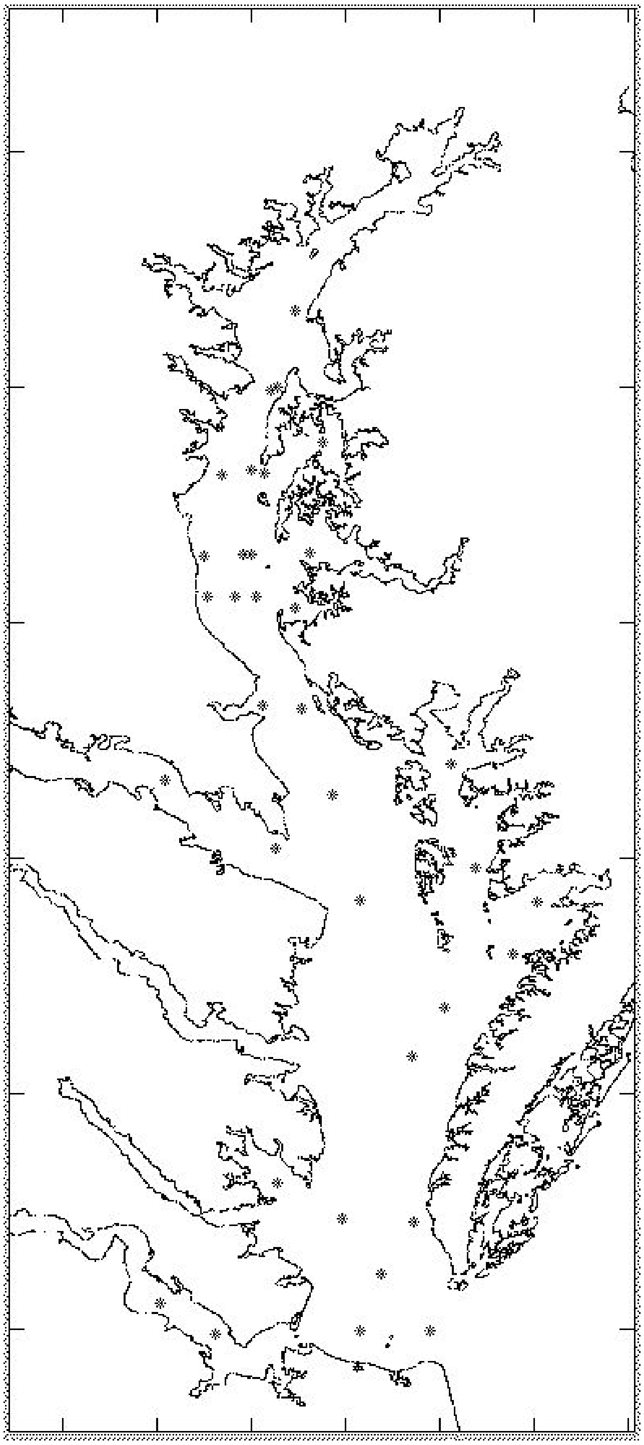


Figure 2. Field stations used for the calibration of the suspended sediment algorithm.

Sediment concentration can be measured using two different quantities: total suspended solids (gravimetric, dried at 103–105º C) and total suspended sediments (gravimetric, filtration, dried at 104º C), Although the total suspended sediments

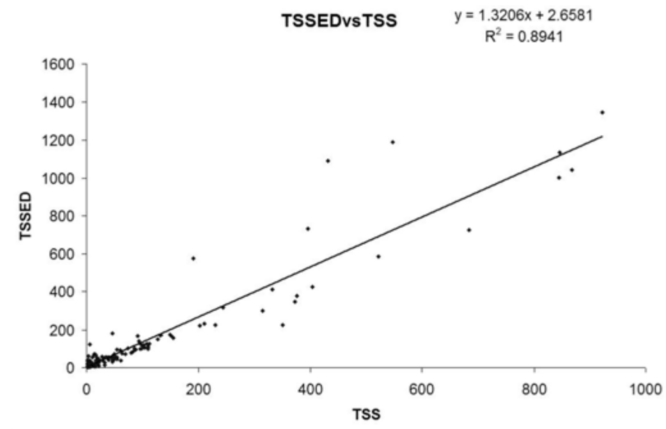


Figure 3. Relationship between TSSED and TSS.(F-statistic: 2189 on 1 and 139 degrees of freedom; p-value is 0)

measurement is preferred, it was not available at the field stations chosen to calibrate the remote sensing algorithm (Figure 2). Stations chosen were sufficiently distant from the shore to avoid contamination of the satellite pixel by a land signal.

Since total suspended sediment (TSSED) differs because of filtration, compared to the measurement of total suspended solids (TSS), the relationship between TSS and TSSED was investigated over another set of stations measuring

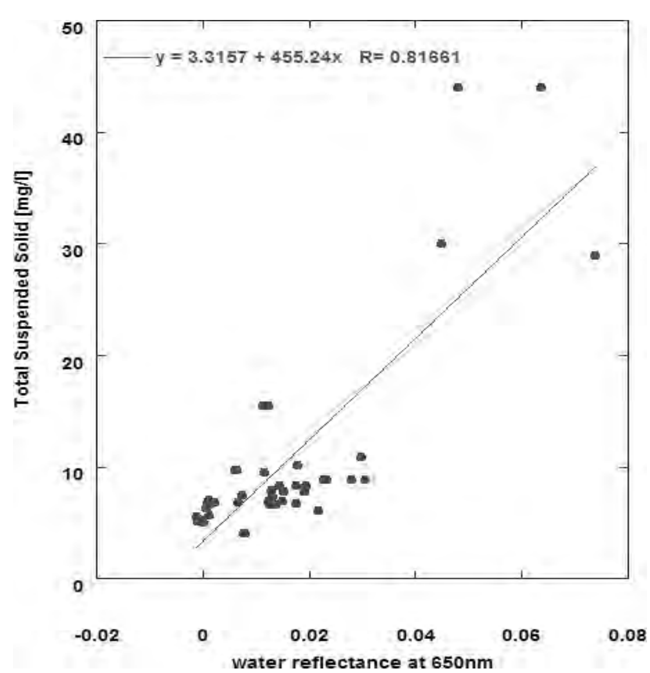


Figure 4a. Total suspended solids versus surface reflectance at 650 nm (F-statistic: 80.06 on 1 and 40 degrees of freedom; p-value is 4.306e-011).

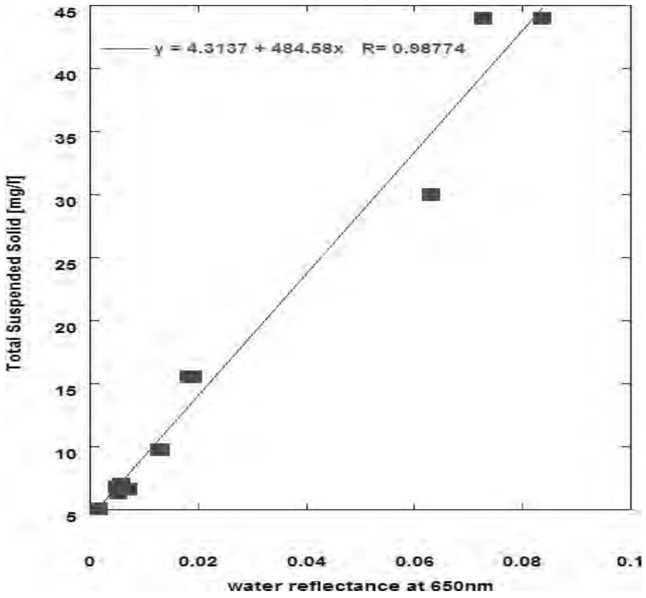


Figure 4b. Total suspended solids versus surface reflectance at 650 nm (for days 105 and 232 of 2003).

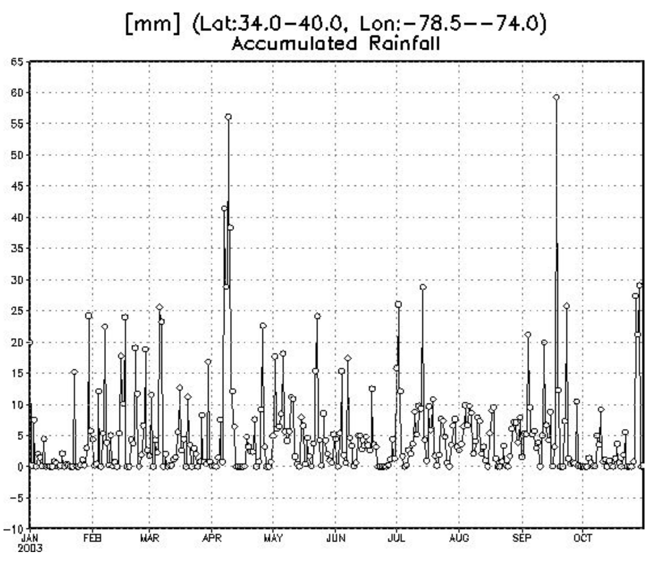


Figure 5. Rainfall (mm) over the Chesapeake Bay in 2003.

both parameters. The agreement between the two parameters is good (Figure 3) and justifies the hypothesis of using TSS values to calibrate the remote sensing algorithm.

The preliminary atmospheric correction performed was the same one used on the MOD09 MODIS product, with an urban model. The correction is obtained using a table that provides transmittance and path radiances for a variety of sun-sensor geometries and aerosol loadings [9]. Aerosol optical thickness has been derived from MODIS using a method similar to that of the atmosphere group [4], but adapted for coastal water (not discussed in this paper).

Once corrected, reflectance values in band one (650 nm) showed a correlation with TSS (Figure 4a). The derived algorithm is:

$$TSS = a*R(b1) + b \quad (1)$$

where a = 455.24 and b = 3.315.

The relationship can be greatly improved if only part of the dataset is considered—for example, the relationship obtained by considering only days 105 and 232, which have similar geometrical conditions (Figure 4b).

RESULTS AND DISCUSSIONS

The Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) is a passive microwave sensor that provides quantitative rainfall information over a wide swath under the TRMM satellite. By carefully measuring the minute amount of microwave energy emitted by the earth and its

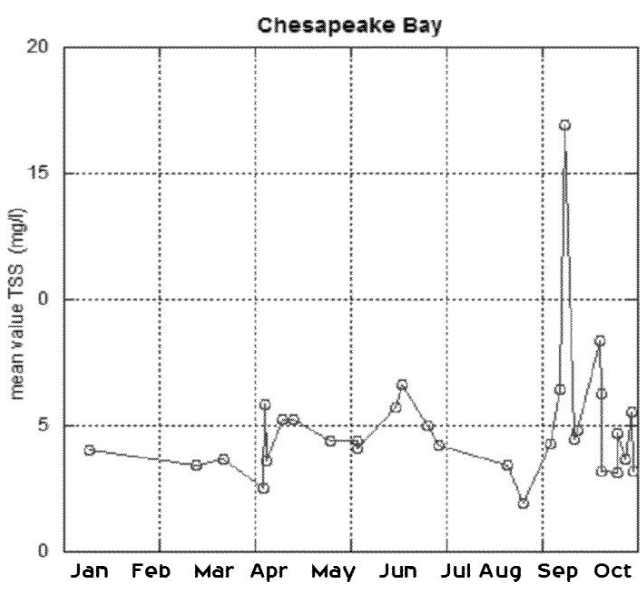
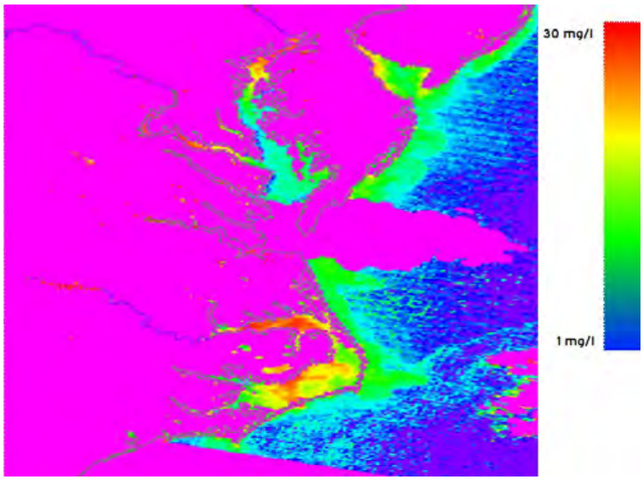
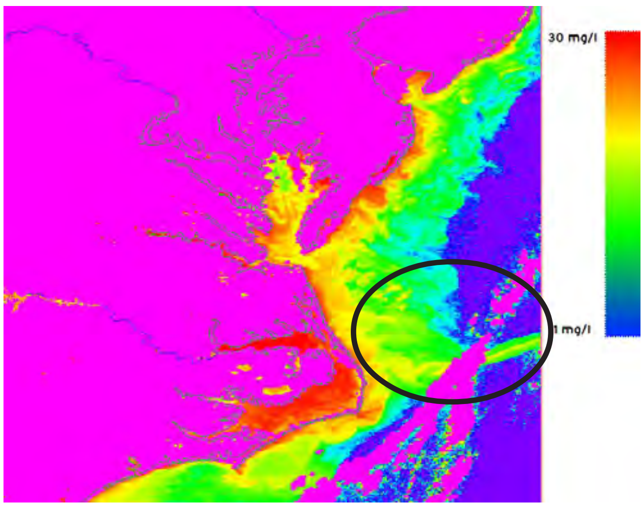


Figure 6. TSS averaged over the Chesapeake Bay (for water pixels between 37.00 N to 39.50 N and -77.0 W to -75.50 W) from maps produced by applying the algorithm for the year 2003.





Figures 7 and 8. Distribution of TSS on 14 April and 19 September 2003. The circled region highlights a narrow plume of sediment moving toward the ocean.

atmosphere, TMI can quantify the water vapor, cloud water, and rainfall intensity in the atmosphere. Daily data of accumulated rainfall are available at *http://lake.nascom.nasa.gov/tovas/*.

The time series of rainfall over the Chesapeake Bay in 2003 shows two main events with more than 55 mm of rain in one day (Figure 5). The first one corresponds to four days of rain (7–10 April); the second corresponds to the passage of Hurricane Isabel (18 September).

By applying the empirical relationship determined in the previous section (Equation 1) on the cloud-free MODIS band 1 (650 nm) surface reflectance data, several maps of TSS during 2003 have been produced and used to extract a time series of TSS averaged over the Chesapeake Bay (Figure 6). The sediment concentration averaged around 5 $mg \cdot L^{-1}$ during the entire year except for a single peak on 19 September (262 Julian Day)—the day after Isabel's landfall when the concentration reached 17 $mg \cdot L^{-1}$.

The distributions of TSS for 14 April and 19 September are very different (Figure 7 and Figure 8, where the same color map has been used and the land and clouds are masked in magenta). Even though the rainfall of the two events was similar (Figure 5), the quantity of suspended solids in the Bay after Isabel considerably increased in value and area, spreading over the ocean, compared to the aftermath of the April storm.

The different sediment distribution can be explained by the distribution of accumulated rainfall from TRMM data (Figure 9). In the April storm, moderate precipitation resulted in runoff and sediment transport in the upper Potomac and northern Bay. In Isabel, however, short duration

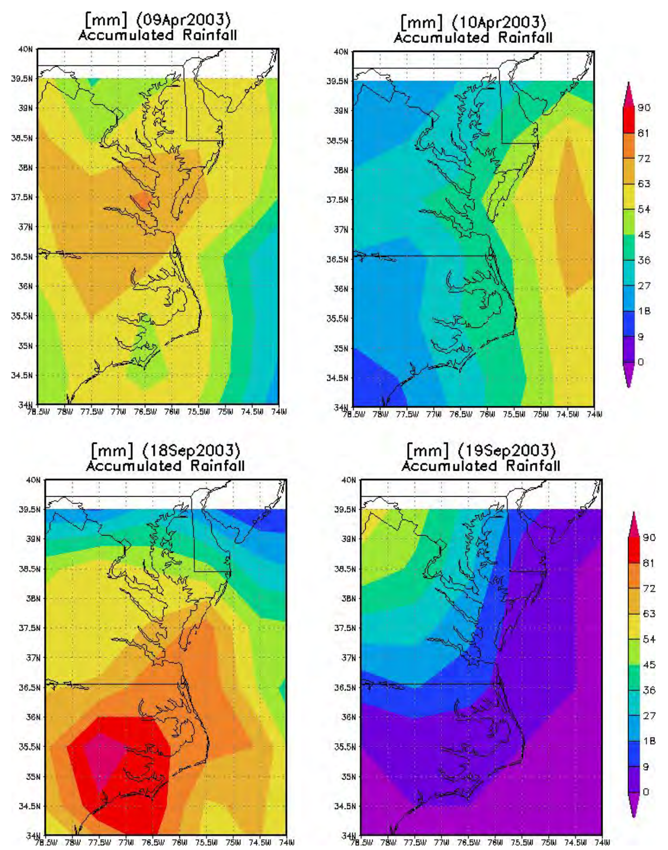


Figure 9. Accumulated rainfall on 9 and 10 April 2003 and on 18 and 19 September 2003.

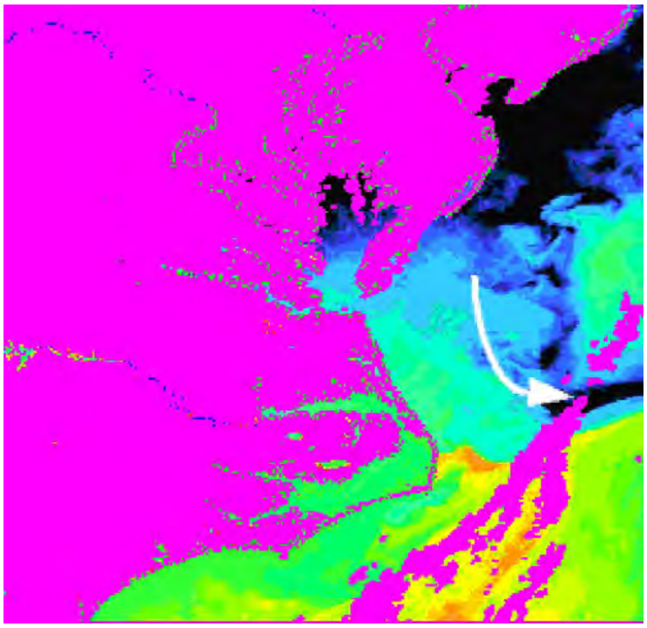


Figure 10. Temperature distribution on 19 September 2003.

precipitation was focused over the southern Bay, leading to modest sediment input in this region. The southern Bay sediments were, in turn, supplemented with surge- and wave-induced resuspended sediment for subsequent transport out of and south of the Chesapeake's mouth.

The distribution of TSS for 19 September also shows a narrow sediment plume (circled region in Figure 8). Measurements on that day (Figure 10) indicate two fronts separating water of different temperatures: one in the northeast region of the ocean and the other in the southern region, generating a cold current moving from the north portion of the image to the east (see arrow) associated with the sediment plume.

CONCLUSION

This paper shows that it is possible to recover sediment concentrations from the MODIS Aqua and Terra data, improving synoptic information of water quality in the Chesapeake Bay with higher temporal frequency. It also demonstrated that the sediment concentrations in the Chesapeake after the landfall of Isabel reached the highest level observed in 2003 and that the main factor responsible for the increase was not the amount of precipitation, but other parameters (wind, storm surge) associated with the storm.

ACKNOWLEDGMENTS

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REFERENCES

1. J.G. Acker, A. Vasilkov, D. Nadeau, and N. Kuring. 2004. Use of SeaWiFS ocean color data to estimate neritic sediment mass transport. *Coral Reefs* 23: 39–47.
2. R.P. Bukata, J.H. Jerome, K.Y. Kondratyey, and D.V. Pozdnyakov. 1995. *Optical Properties and Remote Sensing of Inland and Coastal Waters*. CRC Press Inc., FL. 320 pp.
3. P.J. Curran and E.M.M. Novo. 1988. A review. *J. Coast. Res.*, 4(3): 351–368.
4. Y.J. Kaufman and D. Tanre. 1998. Algorithm Technical Basis Document. NASA.
5. International Ocean-Color Coordinating Group. 2000. IOCCG Report No. 3. p. 140.
6. M.R. Mobasheri and H. Mousavi. 2004. Proc. XXth ISPRS Congress, 12–23 July 2004, Istanbul, Turkey.
7. J.C. Ritchie and F.R. Schiebe. 2000. *Water Quality*. G.A. Schultz and E.T. Engaman (eds.). Springer-Verlag, Berlin, Germany. pp. 287–303. 351–352.
8. J.C. Ritchie, F.R. Schiebe, and J.R. McHenry. 1976. Remote sensing of suspended sediment in surface waters. *Photogram. Eng. Remote Sens.* 42(2): 1539–1545.
9. F.E. Vermote and A. Vermeulen. 1999. Algorithm Technical Basis Document, NASA.

IMPACTS OF TROPICAL CYCLONE ISABEL ON SHALLOW WATER QUALITY OF THE YORK RIVER ESTUARY

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ABSTRACT

Water quality impacts from Tropical Cyclone Isabel on the York River estuary were assessed based on long-term, near-continuous, shallow-water monitoring stations along the York River proper (poly- and mesohaline regimes) and its two tidal tributaries—the Mattaponi and Pamunkey rivers (oligohaline and tidal freshwater regimes). Regional rainfall from 18 to 19 September 2003 ranged from 5.8 to 11.7 cm. Peak mean daily stream flow occurred on 21 September 2003 and represented a 20- and 30-fold increase over pre-storm conditions on the Mattaponi and Pamunkey rivers, respectively. Isabel produced a storm surge of 1.7 m near the mouth of the estuary and 2.0 m in the upper tidal freshwater regions. The tidal surge resulted in a short-term (12- to 36-hour) pulse of high salinity water (approximately 10 ppt greater than pre-storm conditions) within the oligohaline portion of the estuary. In comparison, salinity levels within the upper tidal fresh water and down-river poly-and mesohaline regions remained relatively unchanged. Following the storm surge, salinity levels within lower portions of the estuary declined 1.5 to 4.5 ppt for an extended period in response to freshwater runoff. Elevated turbidity—in some cases extreme—was in direct response to the storm surge and waves associated with Tropical Cyclone Isabel. With the exception of a single station, maximum storm-associated turbidity levels varied between 192 and >1000 NTUs (nephelometric turbidity units). Turbidity levels returned to pre-storm conditions within a 24- to 30-hour period at most stations. Perhaps the most significant environmental impact associated with the passage of Isabel was the persistent low dissolved oxygen (DO) levels (3–4 $mg \cdot L^{-1}$) that occurred at the tidal freshwater stations. Low DO at these stations coincided with increased freshwater inflow to the Mattaponi and Pamunkey rivers, suggesting augmented loadings of readily degradable organic material from the watershed. Mean daily DO levels took approximately two weeks to return to pre-storm levels at these sites. Dissolved oxygen levels at the poly- and mesohaline stations within the York River proper remained at or above 5 $mg \cdot L^{-1}$ prior to, during, and after the storm's passage.

INTRODUCTION

Large-scale tropical cyclones, such as tropical storms and hurricanes, can generate both short- and long-term disturbances in estuarine systems. These disturbances occur in response to the high winds, storm surges, and rainfall generally associated with such storms. Isabel brought hurricane conditions to portions of eastern North Carolina and southeast Virginia and is considered to be one of the most significant storms to have affected the Chesapeake Bay region. It has been compared to the Category 3 Chesapeake-Potomac Hurricane of 23 August 1933, described as the storm of the century for Chesapeake Bay. Effects caused by large storm surges and surface waves include extensive flooding of low-lying areas, shoreline erosion, sediment resuspension and associated pollutant availability, vertical water column mixing, and increased upstream salinities [1]. The consequences of excessive rainfall include elevated freshwater input and associated downstream salinity depression [2, 3], along with elevated sediment [1], carbon

[3, 4, 5], and nutrient [4, 5] loadings from stormwater runoff. Just as each storm has distinct characteristics and hydrologic responses by the impacted watershed and water body, the types and severity of biological responses can also vary. Reported observations have included elevated phytoplankton biomass and changes in community composition stimulated by newly available nutrients [2], depressed oxygen levels and severe hypoxic events [2, 4, 5, 6], and damage to submersed aquatic vegetation [7, 8], wetlands, and coastal upland forest communities [9].

On 18 September 2003, at approximately 01:00 PM (EDT), Hurricane Isabel made landfall near Drum Inlet, North Carolina, approximately 240 km south of the entrance to Chesapeake Bay. Upon landfall, Hurricane Isabel was a Category 2 storm with hurricane force winds extending 185 km from the storm's center and tropical-storm-force winds extending out to 555 km [10]. Rainfall was on the order of 10 to 20 cm. Following landfall, Isabel tracked northwest at a speed of near 30 $km \cdot hr^{-1}$ and began to rapidly weaken. Hurricane Isabel was downgraded to a tropical storm over southern Virginia; at 23:00 (EDT) the storm's center was just west of Richmond, Virginia. Given Isabel's track, the Chesapeake Bay was predominantly impacted by the northeast quadrant of the storm, a region characterized by the maximum effects of wind, surge, and rain.

The main objective of this paper is to describe the temporal and spatial patterns of water quality within the nearshore, shallow water regions of the York River estuary in response to Tropical Cyclone Isabel. Near-continuous data collected prior to, during, and after the passage of the storm are used to assess the response.

STUDY SITE AND METHODS

This study was conducted in the York River estuary, the Chesapeake Bay's fifth-largest tributary in terms of flow and watershed area (6900 km^2). The York River basin is located within Virginia's Coastal Plain and Piedmont physiographic provinces, and includes all of the land draining into the Mattaponi, Pamunkey, and York rivers (Figure 1). Tidal influence occurs as far as 97 km upriver on the Mattaponi and as far as 60 km upriver on the Pamunkey. Mean tidal range near the mouth of the York River is 0.7 m and increases to 0.9 and 1.2 m in the upper tidal freshwater regions of the Mattaponi and Pamunkey rivers, respectively [11]. The York River basin is predominantly rural with forest cover accounting for 61% of the basin's cover, agricultural land for 19%, urban land for 4%, mixed-open land for 14%, and water for the remaining 2%.

The York River estuary continuous water quality monitoring network is operated by the Chesapeake Bay National Estuarine Research Reserve (CBNERR) and supports the NOAA/NERR System-Wide Monitoring Program and Chesapeake Bay Shallow Water Monitoring Program. A total of nine fixed water quality stations are located within the polyhaline (GI, GP, and YT), mesohaline (CB and TC), oligohaline (MP and SH), and tidal freshwater (WH and WK) regions of the system (Figure 1). All stations except TC are located along the tributary proper or in a more open water setting (GI). The TC station is located in a tidal creek immediately adjacent to the York River; forests and tidal wetlands dominate the creek's watershed. Two stations, GI and YT, were damaged and inoperable during portions of the study. All stations were located within shallow water or shoal regions where mean water depths were about 2 m or less. Water quality stations were instrumented with YSI 6600 EDS data sondes that collect information from 25 to 50 cm off the bottom substrate on water depth, temperature, specific conductance, percent dissolved oxygen (DO) saturation, and turbidity. Salinity and DO concentrations are calculated parameters. Water depths were corrected for atmospheric pressure changes during the deployment period. Water quality stations were maintained on either a one- or two-week schedule, depending on salinity regime and season, to minimize biofilm effects.

Daily precipitation and wind speed information was obtained from meteorologic stations maintained by NOAA's National Weather

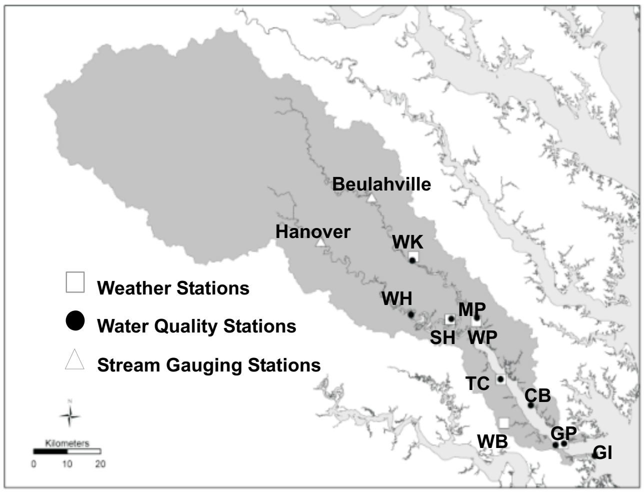

Figure 1. Location map of environmental data collection stations. Continuous water quality stations include: Goodwin Islands (GI), Gloucester Point (GP), and Yorktown (YT) in the polyhaline region; Clay Bank (CB) and Taskinas Creek (TC) in the mesohaline region; Sweet Hall (SH) and Muddy Point (MP) in the oligohaline region; and White House (WH) and Walkerton (WK) in the tidal freshwater region. Meteorologic stations include Gloucester Point (GP), Williamsburg (WB), Taskinas Creek NERR (TC), West Point (WP), Sweet Hall Marsh NERR (SH), and Walkerton (WK). Stream gauging stations were near Hanover and Beulahville, Virginia.

Service (NOAA/NWS; stations: WK, WP and WB), the CBNERR (stations: SH and TC), and the Virginia Institute of Marine Science (VIMS; station: GP) (Figure 1). River stage and calculated stream flow was measured continuously within the Pamunkey and Mattaponi rivers at the U.S. Geological Survey (USGS) gauging stations near Hanover (Station ID: 01673000) and Beulahville (Station ID: 01674500), Virginia, respectively. The Hanover station integrates discharge from 45% of the York River basin as compared to 25% for the Beulahville station.

RESULTS

Physical Conditions, Rainfall and River Flow

A minimum atmospheric barometric pressure of 990 mb was measured along the York River proper (TC) during the passage of Isabel. At Gloucester Point, near the mouth of the York River, strong winds (>20 m·sec^{-1}) persisted for over six hours; maximum measured wind speed was 31.9 m·sec^{-1}. Total rainfall amounts during Isabel's passage on 18 to 19 September 2003 ranged from 5.8 to 11.7 cm within the York River watershed (Figure 2). Peak mean daily stream flow occurred on 21 September 2003 and represented an approximate 20- to 30-fold increase over pre-storm (early September) conditions on the Pamunkey (317.1 vs. 10.5 m^3·sec^{-1}) and Mattaponi (57.5 vs. 3.4 m^3·sec^{-1}) rivers. River discharge exhibited a complex hydrograph thought to result from rainfall associated with post-Isabel storm activity. Figure 3 presents Pamunkey and Mattaponi river mean daily streamflow for water year (WY) 2002 (October 2001 to September 2002), WY 2003, and succeeding months. Results from an acoustic Doppler current profiler showed maximum wave heights of 2 meters and an up-estuary current of 1 m·sec^{-1} [12]. Isabel produced a storm surge, as determined by the difference between storm water levels and predicted tide levels, of 1.7 m near the mouth of the estuary (GP) and 2.0 m in the upper tidal freshwater regions (WH). Water levels remained elevated for the succeeding tide after the storm's passage and returned to near normal

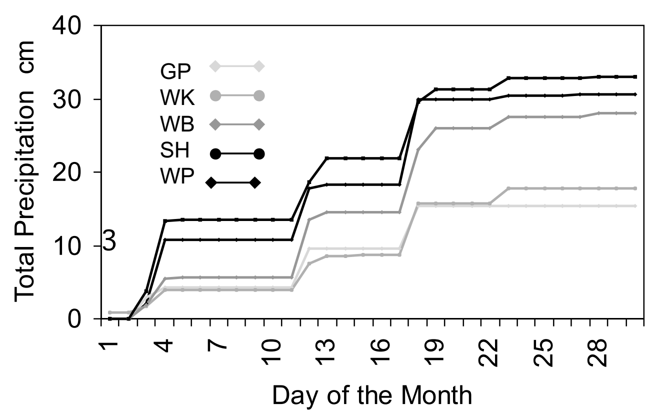

Figure 2. Cumulative total precipitation (cm) within the York River watershed for September 2003. Meteorologic stations include Gloucester Point (GP), Williamsburg (WB), West Point (WP), Sweet Hall Marsh NERR (SH), and Walkerton (WK). Average regional long-term September total precipitation, based on historical data from WK (1932 to 2004), WP (1954 to 2004) and WB (1941 to 2004), is 10.4 cm (denoted by 3).

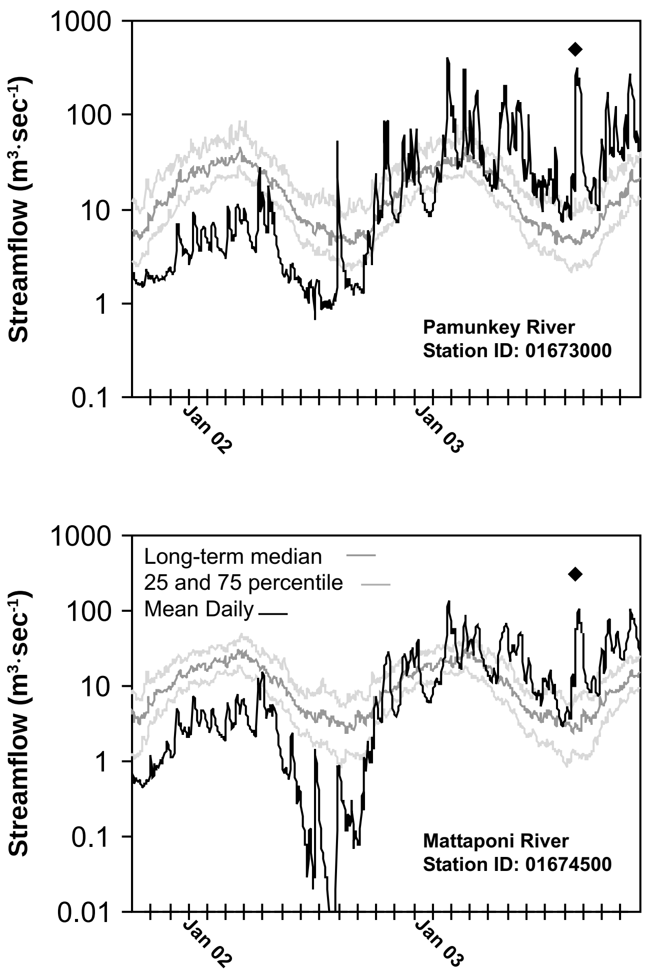

Figure 3. Pamunkey and Mattaponi rivers mean daily streamflow for WY 2002 (October 2001 to September 2002), WY 2003, and succeeding months. The 25th and 75th percentile values represent the normal range of streamflow over the record at USGS stations 01673000 and 01674500. The symbol (♦) represents 18 September 2003, the passage of Isabel.

conditions approximately 30 hours after peak storm tide levels (Figure 4).

Salinity, Turbidity and Dissolved Oxygen

In conjunction with water levels, salinity values within the shallow waters of the York River estuary from 14–22 September 2003 are presented in Figure 4. Little change in salinity was observed at the polyhaline (GI and GP) and mesohaline (CB and TC) stations during the storm tide. In contrast, significant increases in salinity were observed at the oligohaline stations (MP and SH). Peak salinity values were 15.0 ppt at MP and 11.7 ppt at SH,

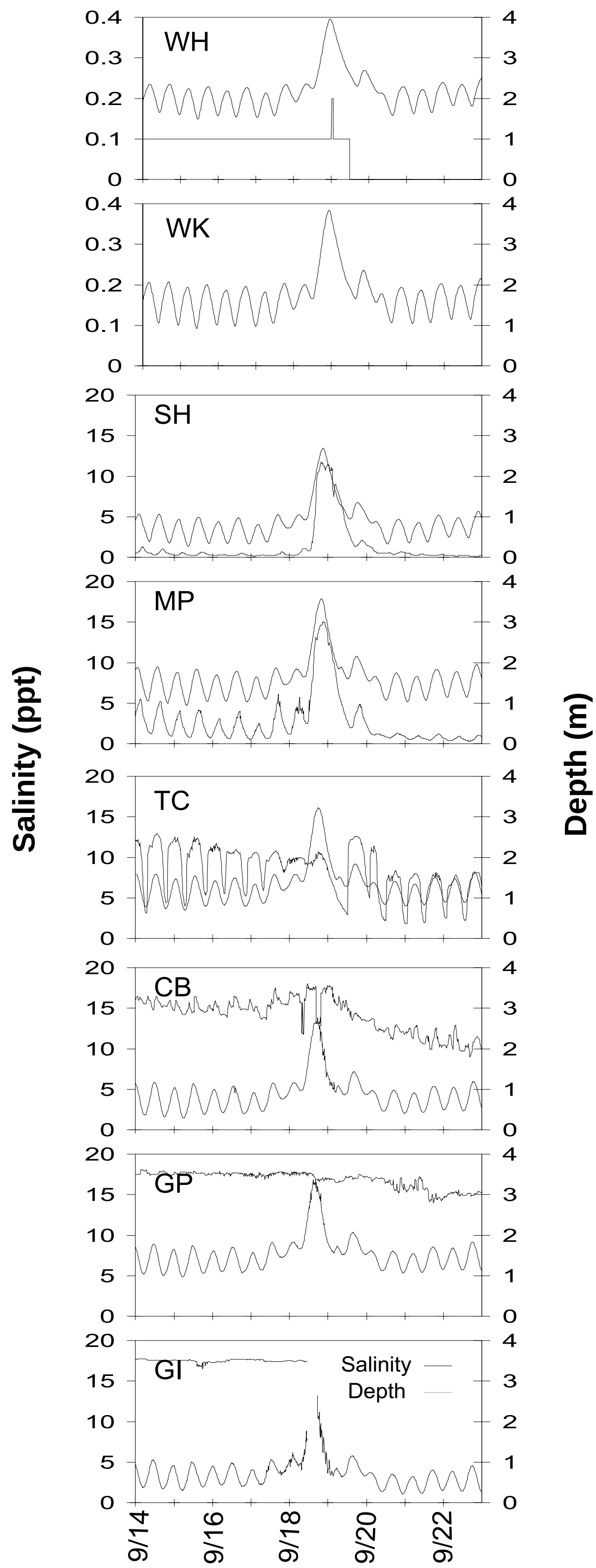

Figure 4. Water and salinity levels within the York River estuary from 14–22 September 2003. Note: Salinity values for WK were 0.0 ppt throughout the measurement period.

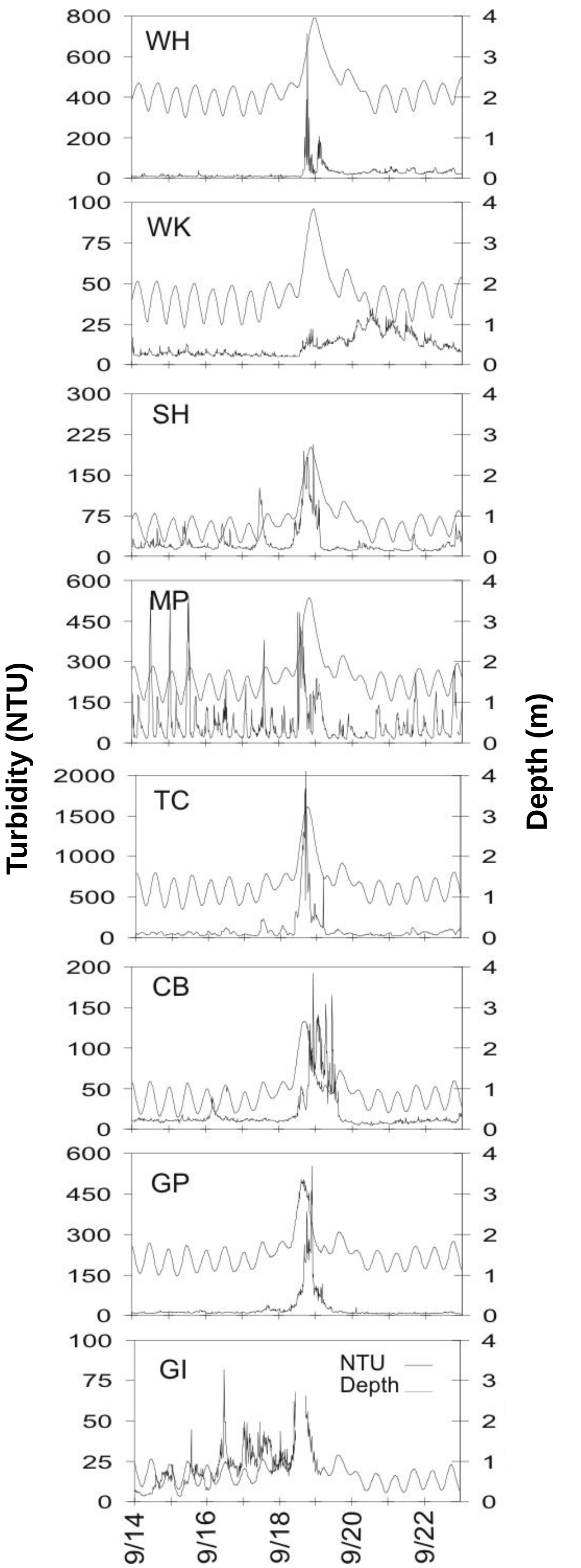

Figure 5. Water and turbidity levels within the York River estuary from 14–22 September 2003.

coinciding with peak storm tide water levels. Pre-storm salinities were 0.8 to 5.7 ppt at MP and <0.5 ppt at SH. The tidal freshwater stations (WH and WK) remained fresh throughout the passage of Isabel. Following the storm surge, freshwater runoff depressed salinities 1.5 to 4.5 ppt in the lower portions of the York River estuary.

Elevated water turbidity, in some cases extreme, occurred in direct response to Tropical Cyclone Isabel. With the exception of station WK, maximum storm surge-associated turbidity levels varied between 192 and >1000 NTUs (Figure 5). Mean daily pre-storm turbidity levels were approximately 10–15 NTUs at the tidal freshwater (WH, WK), polyhaline (GP, GI), CB and SH stations; they ranged from 50–100 NTUs at the TC and MP stations. Timing and patterns of water turbidity peaks varied between stations. Peak turbidity values occurred prior to peak storm water levels at WH, MP, and TC, and following peak storm water levels at SH, CB, and GP. Distinct twin turbidity peaks, occurring on either side of slack high water during the storm surge, were observed at the WH, MP, and SH stations. Turbidity levels at the oligohaline (MP and SH), mesohaline (CB and TC), and polyhaline (GI and GP) stations returned to pre-storm conditions within 24 to 30 hours. The tidal freshwater stations (WH and WK) exhibited moderately elevated turbidity levels (>20 NTUs) for several days following the storm's passage, a time that coincided with increased streamflow.

Figure 6 depicts DO levels from 14–22 September 2003. Prior to Isabel's arrival, DO levels were 60–80% of saturated levels at the tidal freshwater and oligohaline stations and 80–100% of saturation levels at the mesohaline and polyhaline stations. Tidal freshwater regions exhibited a rather dramatic decline in DO immediately following the peak storm tide.

Instantaneous low DO levels, as measured by 15-minute data for stations WH and WK were 2.33 and 3.57 $mg{\cdot}L^{-1}$, respectively. From peak storm tide until recovery of pre-storm conditions—a time period of 16 to 20 days—70% of readings were below 5 $mg{\cdot}L^{-1}$ at WH as were 43% of the readings

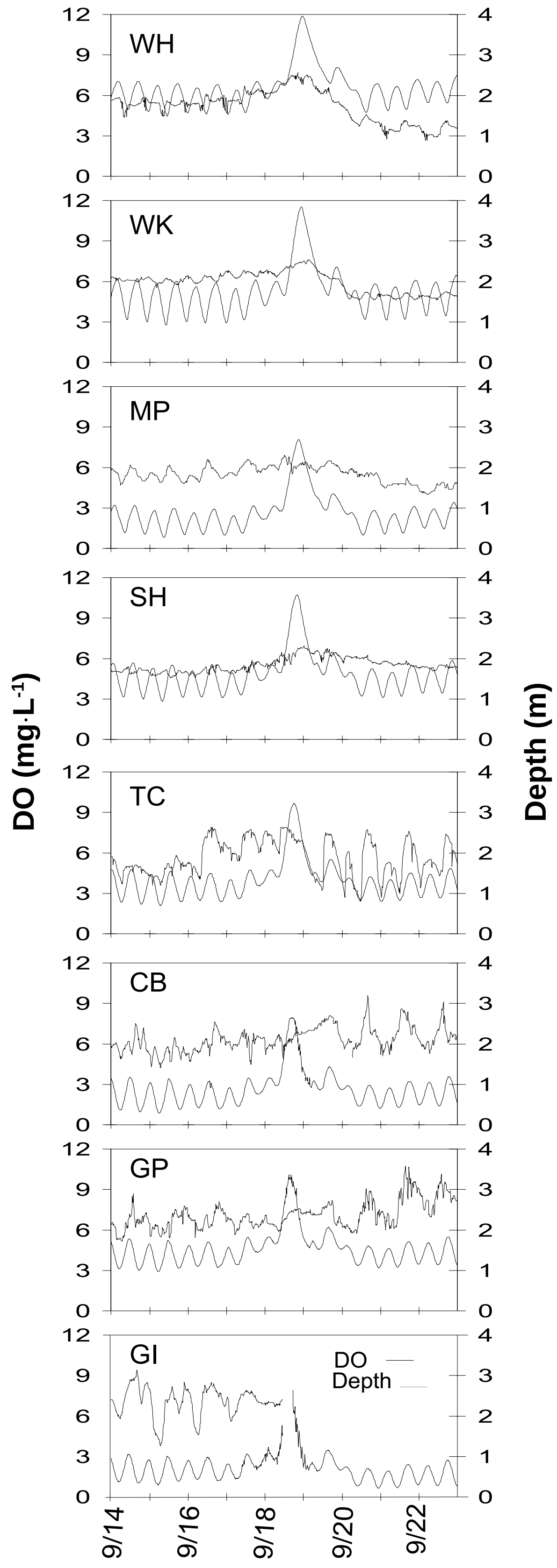

Figure 6. Water and dissolved oxygen levels in the York River estuary from 14 to 22 September 2003.

at WK. Oligohaline stations SH and MP exhibited a similar, but less pronounced pattern. Dissolved oxygen levels at the polyhaline and mesohaline stations within York River proper (GI, GP, and CB) remained above 5 mg·L^{-1} prior to, during, and after the storm's passage.

DISCUSSION

To more fully understand the consequences and potential implications of Tropical Cyclone Isabel on the Chesapeake Bay, and more specifically the York River estuary, it is necessary to describe conditions prior to the storm's arrival. Compared to long-term averages, the 2003 water year (WY) (October 2002 to September 2003) was relatively wet and followed an unusually dry water year. Total precipitation in WY 2003 was approximately 60% greater than the long-term average and 145% greater than WY 2002. Table 1 provides long-term averages for total precipitation and streamflow along with comparisons between WY 2002 and WY 2003. As expected, streamflow in the Pamunkey and the Mattaponi rivers, the principal tributaries of the York River estuary, reflected total precipitation within the watershed. Mean daily stream flows in WY 2003 were 35% and 65% greater in the Pamunkey and Mattaponi rivers, respectively, compared to the long-term average. These WY 2003 values were approximately an order of magnitude greater than those for WY 2002. Due to the wet conditions of 2003, salinity levels throughout the York River estuary were generally depressed compared to prior years. In the Chesapeake Bay system, freshwater inflow during the 2003 WY was 56% above the average, the second highest level since record keeping began in 1937. High freshwater inputs in the WY prior to Isabel caused increased loadings of nutrients and sediments and near-record low DO levels within the Bay [13].

Significant rainfall occurred throughout the York River watershed immediately prior to, during, and (in more isolated portions of the watershed) following the passage of Isabel. Rainfall associated with Isabel ranged from 5.8 to 11.7 cm. For

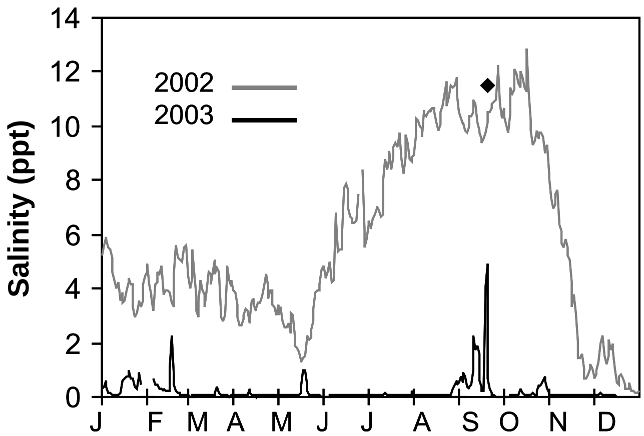

Figure 7. Daily mean salinity values at Sweet Hall Marsh (Station: SH) for CY 2002 and 2003. The symbol (♦) represents the maximum instantaneous salinity value observed during Isabel.

comparative purposes, rainfall amounts of previous tropical cyclones that affected the Bay region were 6.8 to 11.3 cm for Agnes (21–23 June 1972), 0.4 to 6.6 cm for Fran (5–8 September 1996), and 21.7 to 43.1 cm for Floyd (14–16 September 1999). While not excessive, the rainfall immediately prior to, during, and after Isabel did elevate freshwater inflow for several days following the storm's passage. Although daily discharge rates increased approximately 20- (Mattaponi River) to 30-fold (Pamunkey River) over pre-storm conditions, they did not represent the peak mean daily values of the 2003 WY.

The storm surge from Tropical Cyclone Isabel was significant; in some cases, its magnitude was unexpected within some portions of the Chesapeake Bay. Surge values of 1.7 m were observed at the mouth of the York River estuary and increased up to 2.0 m in the upper tidal freshwater regions. When combined with waves up to 2.0 m in height along with persistent high winds and upriver current velocities, the York River estuary experienced extensive shoreline erosion, sediment resuspension, and water and salt transport up the river. The tidal surge significantly increased salinity by about 10 ppt, within the oligohaline portion approximately 70 km upriver from the mouth of the York. In comparison, salinity in downriver poly- and mesohaline regions and upper tidal freshwater regions remained relatively unchanged. The pulse of high salinity water within the oligohaline reaches was short-lived with pre-storm levels restored within 12 (MP) to 36 (SH) hours. Following the storm surge, the effects of freshwater runoff were evident in the lower portions of the York River where salinities remained depressed for an extended period.

Short-term salinity pulses and longer-term seasonal trends in elevated salinity have biological consequences for marsh plant communities. Studies within the York River estuary suggest that plant communities at a lower tidal freshwater/upper oligohaline marsh (SH) are shifting to more salt-tolerant species due to increases in salinity associated with relative sea level rise [14]. More recent work within this marsh indicates that the vegetation community may be more highly variable from year to year, perhaps in response to short-term climatic effects.

To put Isabel's induced salinity pulse in perspective, Figure 7 shows the mean daily salinity pattern at Sweet Hall Marsh for CY 2002 and 2003. Isabel's storm tide resulted in peak instantaneous and mean daily salinity levels of 11.7 and 4.9 ppt, respectively, at this site. During the drought of 2002, salinity levels of 5 ppt or greater occurred during 70% of the growing season (April through October) and mean daily levels of 5 ppt or greater persisted from early June through October. Clearly this marsh system has been exposed to salinity levels observed during Isabel for extended periods, however, the exact impact of such exposure on inter-annual plant community variation is unknown and warrants further investigation.

Decreased water clarity, as measured by increased turbidity, was observed within the shallow-water regions of the York River estuary during and after Isabel's passage. Extensive shoreline erosion and sediment resuspension caused by waves and water currents are primary contributing factors that resulted in elevated and, in some cases extreme, turbidity levels during the storm surge. Several stations within the tidal freshwater and oligohaline portions of the estuary exhibited distinct turbidity peaks on either side of the storm's

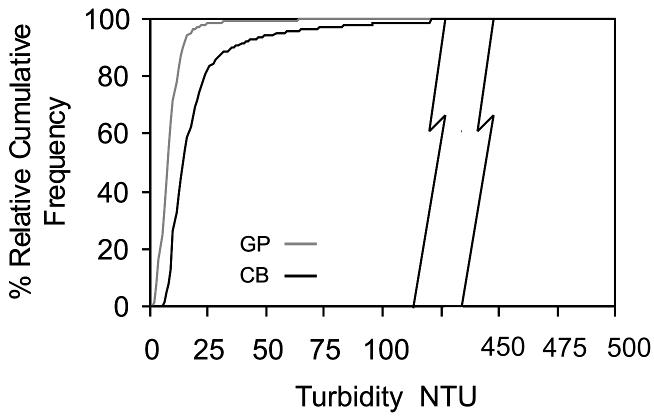

Figure 8. Relative cumulative frequency of turbidity measurements (NTUs) at the GP and CB stations during the 2003 SAV growing season.

peak water level, suggesting reduced sediment resuspension as current velocity decreased near slack high water. The duration of storm-induced, highly turbid water (≥200 NTUs) was relatively short-lived; turbidity levels returned to pre-storm or near pre-storm conditions within 24 to 30 hours at the oligo-, meso-, and polyhaline stations. Subaqueous substrate at several of these stations, particularly those in the York River proper (CB, GP, GI), was dominated by coarse-textured sediments; the rapid settling of such sediments promote quick recovery of water clarity. Moderately elevated turbidity levels persisted for several days following the storm at the tidal freshwater stations (WH and WK). Freshwater inflow, and associated storm runoff from Isabel and post-Isabel events, may have contributed to the turbidity.

Water clarity is a principal water quality criterion by which shallow water habitats, specifically submerged aquatic vegetation (SAV) beds, are assessed. Within the York River estuary, SAV is currently restricted to the lower 10 km (GP and GI); historical distribution of SAV extended approximately 40 km upriver (CB). For higher salinity southern Bay waters, the SAV water clarity criterion is 22% ambient light through water, which translates into turbidity levels of 7 NTUs for 1-m depths and 12 NTUs for .5-m depths. Mean daily average turbidity for the 2003 SAV growing season was 9.7 NTUs at GP (data availability: 28 May to 30 November) and 23.5 NTUs at CB (1 April to 30 October). Based on analysis of relative cumulative frequencies, peak turbidity levels at station GP (460–553 NTUs) during Isabel were representative of the upper 0.1% of turbidity values observed during the 2003 SAV polyhaline growing season (Figure 8). Peak turbidity levels at CB (147–192 NTUs) represented the upper <1% of observed values during the 2003 mesohaline growing season. While storm-induced elevated turbidity levels at both sites occurred with low frequency, levels on the scale of Isabel (both in terms of NTU values and time duration) occurred several times at CB during the 2003 growing season.

Prior to Isabel, DO levels and temporal patterns at the oligohaline and tidal freshwater stations differed from the higher salinity stations in the York River proper. Shallow-water DO levels generally varied from 5–6 mg·L^{-1} (60–80% saturation) at the tidal freshwater and oligohaline stations (WH, WK, SH, MP) and from 5–8 m·L^{-1} (60–100% saturation) at the meso- and polyhaline stations (TC, CB, GP, GI). A gradual increase in DO of 1–2 mg·L^{-1} was observed prior to and during the storm tide at oligohaline and tidal freshwater stations, likely in response to enhanced mixing and agitation from wind, waves, currents, and an influx of higher salinity water at the oligohaline stations. This pattern was not evident at the meso- and polyhaline stations, where daily maximum oxygen concentrations were at or near saturation. As the storm tide ebbed, DO levels returned to pre-storm conditions at the oligohaline stations but continued to recede at the tidal freshwater stations. While hypoxic conditions (<2 mg·L^{-1}) did not occur, relatively long-term recessions resulting in concentrations of 3 (WH) and 4 mg·L^{-1} (WK) were observed at the tidal freshwater stations (Figure 9). It took approximately two weeks for mean daily DO levels to return to pre-storm DO levels at these stations. While not as pronounced or as long in duration, oligohaline stations (SH and MP) exhibited a similar pattern. In contrast, shallow-water DO levels within the higher salinity York River (CB and GP) remained at or above 5 mg·L^{-1} prior to, during, and after the storm's passage. Varying between a low of 2–3 mg· L^{-1} (20–40%

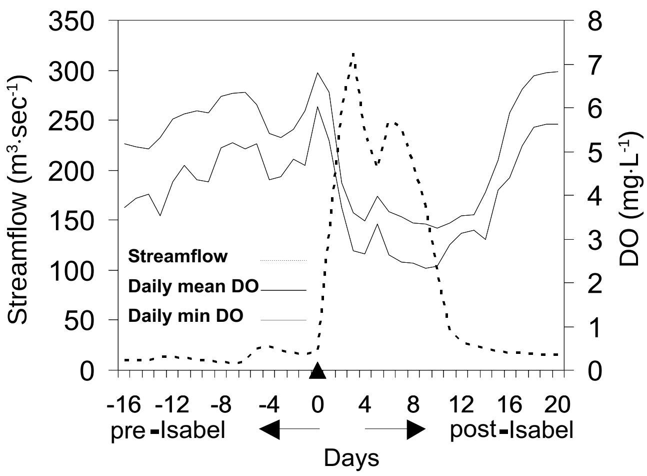

Figure 9. Daily mean and minimum dissolved oxygen concentrations at White House (Station: WH), and mean daily streamflow at Hanover, Virginia prior to, during (day 0 = 18 September 2003), and post-Isabel.

saturation) and a high of 7–8 mg·L^{-1} (100% saturation) on a daily basis, DO dynamics were more complex at the TC station compared to other stations. In addition to diel biological processes, oxygen levels at TC reflected high-salinity and high-DO water inputs at high tide with flushing of low-salinity, low-DO water draining forests and tidal wetlands during low tide.

Several possible explanations may account for the low DO levels at the tidal freshwater (WH and WK) stations following Isabel, including water column stratification from enhanced freshwater inflow, decreased light penetration due to increased turbidity and subsequent reduction in productivity, increased nutrient loading with consequent response by primary producers and decomposers, or increased availability of readily degradable *in situ* or watershed-derived organic material. Since these stations are in shallow, freshwater reaches with moderate tidal currents (0.3–0.8 m·sec^{-1}), stratification of the water column by enhanced freshwater inflow and subsequent oxygen consumption in bottom waters does not seem a satisfactory explanation. Vertical temperature, salinity, and DO profiles taken during instrument deployment and retrieval events support this premise. With respect to stimulation of primary productivity and decomposition by increased nutrient availability, one would anticipate an increase in the amplitude of the diel DO fluctuations. In contrast, a relatively steady decay of oxygen levels was observed, suggesting other dominant controlling factors. Given that post-Isabel low-DO levels at the tidal freshwater stations coincided with increased freshwater inflow to the Mattaponi and Pamunkey rivers (Figure 9), enhanced watershed material loadings (e.g., sediment and degradable organic matter) are implicated as plausible explanations. Organic material loadings from natural habitats (e.g., forests and wetlands), agriculture, and developed areas are a frequent and widespread consequence of large-scale storms within river and estuarine systems [5].

Near-continuous monitoring resulted in an unprecedented ability to measure water quality parameters prior to, during, and after the passage of Tropical Cyclone Isabel within shallow-water regions of the York River estuary. Both spatial and temporal responses to salinity, turbidity, and DO were observed, highlighting the dynamic nature of estuarine systems. Noteworthy changes in salinity caused by short-term saltwater intrusion occurred within oligohaline regions; freshwater inputs caused salinity depression for days in mesohaline areas. Increased turbidity, which decreases water clarity, occurred throughout the York River estuary. While turbidity was exceedingly high in some instances, the impact was short-lived with many sites returning to pre-storm condition within 24 to 30 hours. Perhaps the most significant environmental impact associated with Isabel was the low oxygen levels at selected stations. While hypoxic conditions were not observed, persistent low DO occurred in some tidal freshwater regions. Sustained, near-continuous monitoring of water quality and causative factors (e.g., waves, current, meteorologic variables, and streamflow) will provide greater insight into the system's response to event-based or chronic disturbances.

ACKNOWLEDGMENTS

Continuous, fixed water quality stations, surface water quality mapping, and selected meteorologic stations are operated and maintained by the Chesapeake Bay National Estuarine Research Reserve in Virginia (CBNERRVA). Funding support was provided for the NOAA/NERRS System-Wide Monitoring Program and the USEPA/VaDEQ Chesapeake Bay Shallow Water Quality Monitoring Program. The field and laboratory support of B. Neikirk, J. Austin, E. Wooden, J. Goins, B. Anderson, S. Davies, and F. Parker is gratefully acknowledged along with their dedication to the shallow water quality and meteorologic monitoring programs. This manu-script represents Contribution No. 2661 of the Virginia Institute of Marine Science, College of William and Mary.

REFERENCES

1. N.D. Walker. 2001. Tropical storm and hurricane wind effects on water level, salinity, and sediment transport in the river-influenced Atchafalaya-Vermilion Bay system, Louisiana USA. *Estuaries* 24(4): 498–508.
2. B.L. Peierls, R.R. Christian, and H.W. Paerl. 2003. Water quality and phytoplankton as indicators of hurricane impacts on a large estuarine ecosystem. *Estuaries* 26(5): 1329–1343.
3. J.D. Bales. 2003. Effects of Hurricane Floyd inland flooding, September–October 1999, on tributaries to Pamlico Sound, North Carolina. *Estuaries* 26(5): 1319–1328.
4. J. Burkholder, D. Eggleston, H. Glascow, C. Brownie, R. Reed, G. Janowitz, M. Posey, G. Melia, C. Kinder, R. Corbett, D. Toms, T. Alphin, N. Deamer, and J. Springer. 2004. Comparative impacts of two major hurricane seasons on the Neuse River and Western Pamlico Sound ecosystems. *Proc. Nat. Acad. Sci*. 101(25): 9291–9296.
5. H.W. Paerl, J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, J.M. Fear, M. Go, B.L. Peierls, T.L. Richardson, and J.S. Ramus. 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound, NC. *Proc. Nat. Acad. Sci*. 98(10): 5655–5660.
6. M.A. Mallin, M.H. Posey, M.R. McIver, D.C. Parsons, S.H. Ensign, and T.D. Alphin. 2002. Impacts and recovery from multiple hurricanes in a Piedmont-Coastal Plain river system. *BioScience* 52: 999–1010.
7. J.A. Kerwin, R.E. Munro, and W.A. Peterson. 1976. Distribution and abundance of aquatic vegetation in the upper Chesapeake Bay, 1971–1974. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E. Ruzecki, J.R. Schubel, R.J. Huggett, A.M. Anderson, M.L. Wass, R.J. Marasco, and M.P. Lynch (eds.). Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press. Baltimore, MD. pp. 393–400.
8. R.K. Orth, K. Moore, D. Wilcox, and S. Marion. 2005. Hurricane Isabel impacts on seagrass beds in the Chesapeake Bay. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.
9. I.P. Valiela, P. Peckol, C. D'Avanzo, J. Kremer, D. Hersh, K. Foreman, K. Lajtha, B. Seely, W.R. Geyer, T. Isaji, and R. Crawford. 1998. Ecological effects of major storms on coastal watersheds and coastal waters: Hurricane Bob on Cape Cod. *J. Coast. Res.* 14(1): 218–238.
10. National Weather Service. 2003. Tropical Prediction Center Bulletin. 3 PM EDT, 18 Sept. 2003.
11. Nautical Software Inc. 1993. Tides and Currents. Windows Version 2.0.
12. L.A. Brasseur, A. Trembanis, J. Brubaker, C. Friedrichs, T. Nelson, L.D. Wright, W. Reay, and L. Haas. 2005. Physical response of the York River estuary to Hurricane Isabel. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.
13. USGS. 2004. Nutrient and Sediment Loads of Major Rivers Entering Chesapeake Bay. Information Bulletin. pp. 1–3.
14. J.E. Perry and C. Hershner. 1999. Temporal changes in the vegetation pattern in a tidal freshwater marsh. *Wetlands* 19(1): 90–99.

IMPACTS OF HURRICANE ISABEL ON MARYLAND WATER QUALITY AND LIVING RESOURCES

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ABSTRACT

Spatially intensive, continuous, and fixed-station water quality monitoring data collected by the Maryland Department of Natural Resources provided an unprecedented opportunity to assess the impacts from Hurricane Isabel on Maryland's Chesapeake and Coastal Bays and tidal tributaries. Isabel made landfall on the Outer Banks of North Carolina on 18 September 2003; the storm's center traveled west of the Chesapeake Bay during much of 19 September. Isabel was noted for its extreme storm surge, but average rainfall statewide was only 3 to 4 in (7.6–10.2 cm) with an additional 2 to 3 in (5.1–7.6 cm) several days later. As a result, continuous monitoring data generally revealed short, one-day increases in salinity up to 7 ppt immediately following the storm, and rises in turbidity over 600 NTUs (nephelometric turbidity units). In many areas, salinities remained elevated by 1–2 ppt for weeks compared to pre-Isabel levels, but were not above average due to the extremely wet conditions of 2003. Turbidities in the shallow-water areas quickly returned to slightly above site-specific averages following Isabel's passage. Winds from Isabel mixed the water column and dissipated the Bay's "dead zone" several weeks earlier than normal. Several days after Isabel, continuous monitoring at 13 of 17 functioning shallow-water monitoring sites, along with baywide remote sensing, showed small ($5\ g \cdot L^{-1}$) to large ($>25\ g \cdot L^{-1}$), one- to two-day increases in chlorophyll. Consequently, low dissolved oxygen (DO) resulted with subsequent algal die-offs. Following Isabel, fixed-station nutrient data illustrated that these blooms were most likely fueled by increased nutrient runoff. Hurricane Isabel's impact on living resources in Maryland appeared minimal. Benthic and non-tidal stream reference sites showed little change compared to conditions earlier in the year; impacts to submerged aquatic vegetation were mitigated by the late-summer timing of the storm and increased tidal heights that prevented scouring. Following Isabel, numerous record-low monthly DO levels were recorded for January, February, and March. High nutrient loads (mainly from a wet 2003 but in part due to Isabel), a ubiquitous *Heterocapsa rotundata* bloom, and a winter 2004 ice cover that reduced mixing in the upper Bay are believed to have caused these low DO levels.

INTRODUCTION

For those who study and manage the Chesapeake Bay, no single natural event looms larger in memory than Tropical Storm Agnes in June 1972. Delivering a 10-year or greater average load of sediment in a matter of days, Agnes had a devastating impact upon the Bay's submerged aquatic vegetation (SAV), as well as the oyster and soft shell clam populations—an impact still manifested today. At that time, the Chesapeake research community mounted a large effort, often without assurance of reimbursement or in conjunction with existing projects, to capture the immediate and long-term impacts to the Bay's water quality and living resources. The resulting synopsis, *The Effects of Tropical Storm Agnes on the Chesapeake Bay*, [1] compiled by the Chesapeake Research Consortium, provides a record of these events and a testimony to the great power that natural forces, in combination with anthropogenic influences, have upon ecosystems.

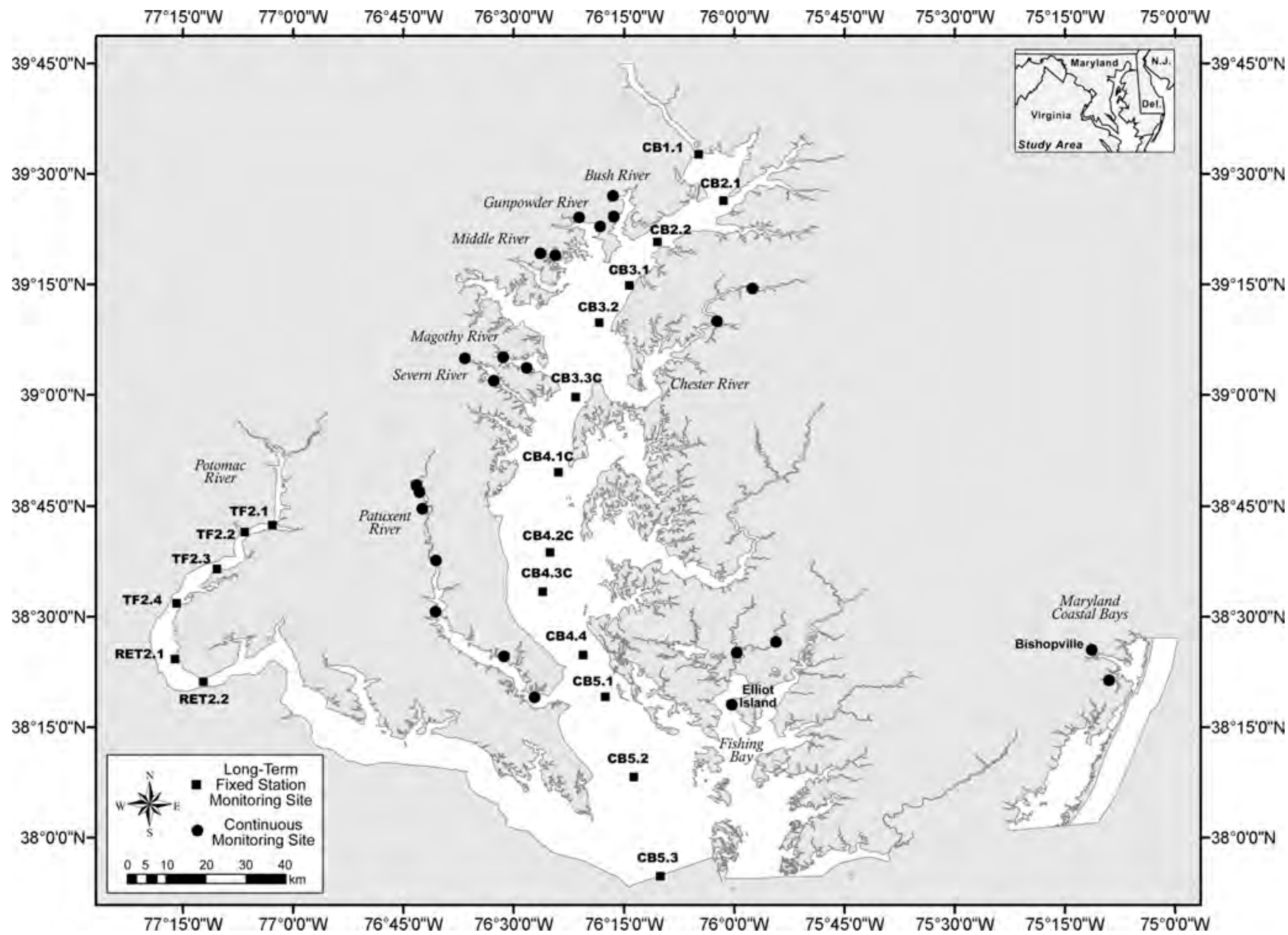

Figure 1. Map of long-term, fixed-station and continuous monitoring sites sampled pre- and post-Isabel.

In the week preceding Isabel, the Maryland Department of Natural Resources (MD DNR) recognized an opportunity to build upon the discoveries made during Agnes. A 20-year data record from fixed stations—many of which were based on locations sampled by the Chesapeake Bay Institute during Agnes—and a network of continuous monitors and spatially intensive sampling allowed an assessment of Isabel's impact on water quality baywide. Continuous monitors sampled ambient water quality at 15-minute intervals throughout the storm. The water quality mapping program provided spatially intensive maps that delineated the extent of water quality degradation.

METHODS

A full suite of ambient physical, chemical, and nutrient samples were collected from fixed stations on the mainstem Maryland Chesapeake Bay and Potomac River (Figure 1). Chesapeake Bay samples were collected on 15–17 September 2003 and 23–24 September 2003. Potomac River samples were collected on 15 and 22 September 2003.

During April through October 2003, 24 YSI-6600 continuous monitoring data sondes were deployed throughout Maryland's shallow tidal waters having depths of 2 m or less (Figure 1). Continuous monitors measured DO, turbidity, chlorophyll, water temperature, salinity, and pH at 15-minute intervals and were usually positioned floating 1 m below the water's surface. To map water quality, a YSI 6600 continuous monitor was also employed, which collected data every 4 seconds at a depth of approximately 0.5 m aboard a moving small boat. The resulting data from throughout each tributary allowed creation of

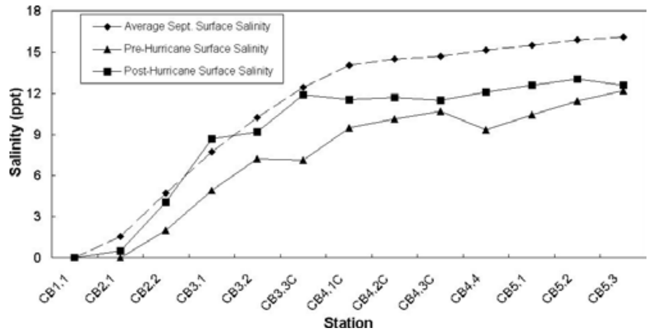

Figure 2. Comparison of long-term, mainstem Chesapeake Bay average September surface salinity (1986–2002) versus surface salinities pre- and post-Isabel. The below-average salinities before and after the storm reflect the extremely wet 2003 season.

spatially detailed maps of surface water quality. From April through October 2003, nine systems were sampled monthly (Severn, Magothy, Patuxent, Middle, Bush, Gunpowder, Chester, Fishing Bay/ Chicamacomico, and Coastal Bays) with special pre- and post-Isabel sampling on the Magothy (4 and 23 September 2003) and Middle (8 and 23 September 2003) rivers.

Complete records of continuous monitoring and water quality mapping data, and select fixed-station data, are available through DNR's Eyes on the Bay website *(www.eyesonthebay.net)*. Full fixed-station datasets are available through the Chesapeake Bay Program's data hub website *(www.chesapeakebay.net)*. Complete collection and analytical methodologies can be referenced in quality assurance project plans for fixed-station monitoring [2] and shallow-water monitoring [3].

RESULTS AND DISCUSSION

Salinity

Salinities along the main stem of the Chesapeake Bay prior to Isabel were well below the long-term (1985–2002) average for September (Figure 2) due to the high amount of precipitation the Bay region received in spring and summer 2003. The tidal surge associated with Isabel increased salinities along the Bay's main stem by up to 5 ppt, but even with this storm-associated increase, salinities remained below the long-term average for September (Figure 2). Water quality mapping of the Middle River pre- and post-Isabel demonstrated a similar slight increase in salinity several days and one month after the storm (Figure 3). Continuous monitors throughout the Bay generally recorded a substantial increase in salinity during and immediately after the storm, followed by a return to pre-storm (or slightly above) levels within approximately 24 hours (Figure 4). In general, salinity increases were more pronounced in tributaries along the Eastern Shore (Figure 5). One notable exception was at Bishopville in Maryland's Coastal Bays, where a large decrease in salinity was attributed to high upstream freshwater input (Figure 5). U.S. Geological Survey stream gauge data from nearby Birch Branch at Showell, Maryland indicated a maximum gauge height on 18 September 2003 exceeding 8 feet (2.4 m)—4 feet (1.2 m) above gauge levels in the days prior to Isabel.

Water Clarity

Hurricane Isabel decreased the water clarity (through increased turbidity) throughout the Chesapeake Bay and the Coastal Bays and their tributaries (Figure 6). This decreased water clarity following the storm was attributed to increased sediment input from upriver sources, shoreline erosion, and re-suspension of bottom sediments. The tidal surge associated with the storm caused extensive damage to waterfront property with localized areas of shore erosion.

The long-term (1985–2002) average September Secchi depths for the upper tidal Potomac River indicated that the wet 2003 spring and summer had resulted in *pre-storm* water clarity that was generally less than long-term averages. Hurricane Isabel further reduced water clarity in the upper tidal Potomac River (Figure 7). Results from 18 statewide continuous water quality monitors revealed water clarity declines in all monitored tributaries (Figure 6). Like the impacts to salinity, continuous monitors generally recorded a substantial decrease in water clarity during the hurricane, followed by a return to pre-storm or slightly poorer than pre-storm conditions within approximately 24 hours (Figure 8). As illustrated by water quality mapping data in the Middle River,

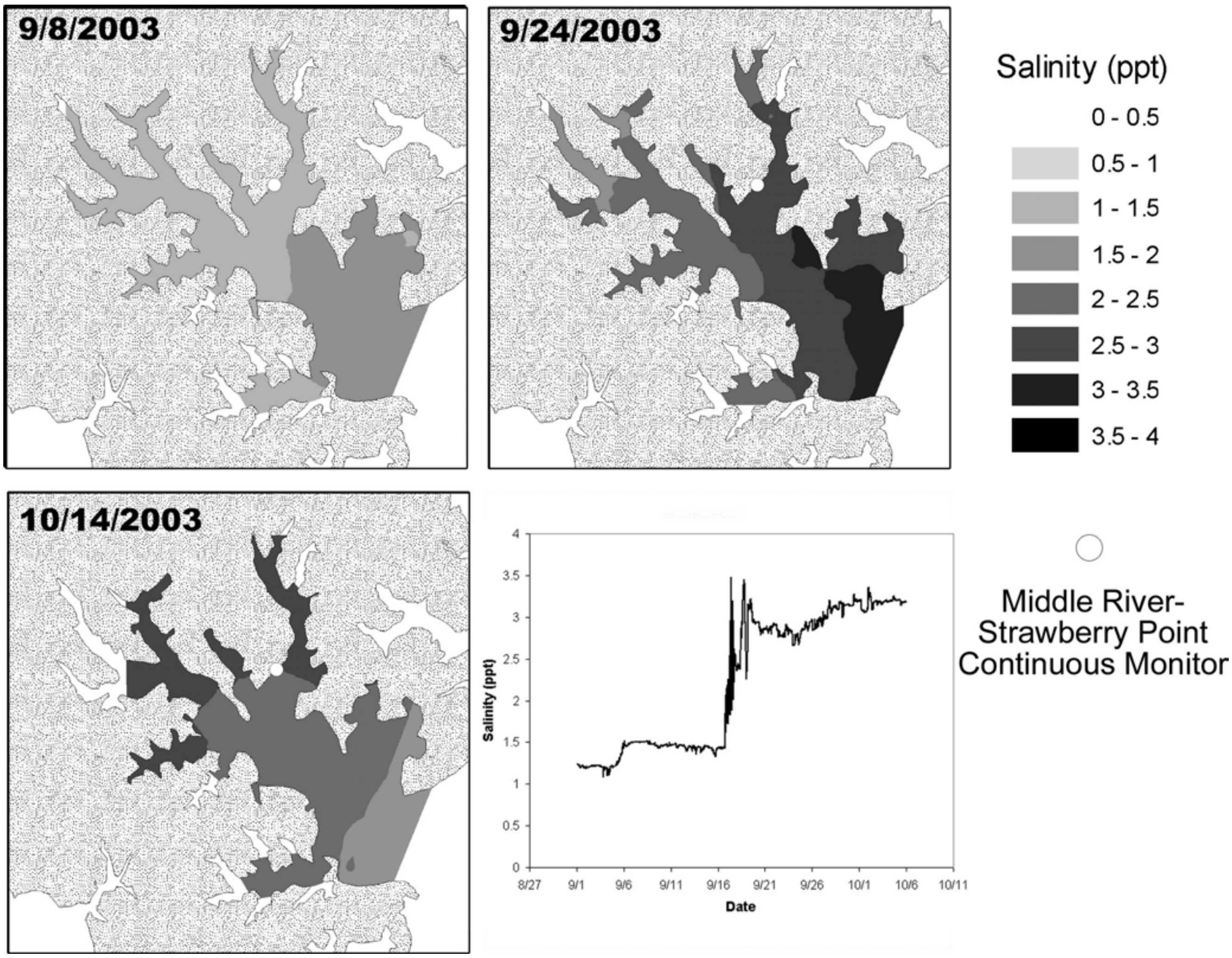

Figure 3. Water quality mapping of surface salinities on Middle River pre- and post-Isabel and continuous monitoring salinity data at Strawberry Point.

upriver locations may have received inputs of sediment after a one-week lag (Figure 9).

Dissolved Oxygen, Chlorophyll, and Nutrients

Post-storm bottom dissolved oxygen in the Bay's main stem increased at most stations over pre-storm and long-term average levels (Figure 10). This effect most likely resulted from water column mixing by winds and waves. Predictably, during the summer months, excessive anthropogenic nutrient additions to a stratified Bay fuel biological consumption of oxygen in unmixed bottom waters [4]. This reduction in dissolved oxygen produces a "dead zone" within which insufficient oxygen remains to support most aquatic life. A mixing of the Bay's waters typically occurs as water temperatures cool in late summer or early fall. The tidal surge and wind mixing from Hurricane Isabel, however, likely hastened this event by several weeks. Spatially interpolated maps of DNR fixed-station dissolved oxygen data, produced by the EPA Chesapeake Bay Program, illustrate the spatial extent of this overturn (Figure 11).

At many shallow-water continuous monitoring stations, higher oxygen levels following the storm were associated with algal production, followed by lower dissolved oxygen as algal blooms died off (Figure 12). The Chesapeake Bay Remote Sensing Program also documented baywide algal blooms following the hurricane (maps are on the website: *www.cbrsp.org*). In early November, a *Prorocentrum minimum* bloom of

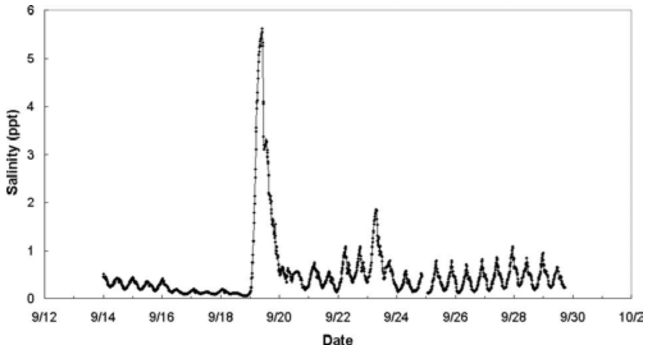

Figure 4. Continuous monitoring salinity data from Deep Landing on the Chester River during Isabel (18–19 September 2003).

over 100,000 cells·ml^{-1} was observed in Breton Bay on the Potomac River.

There was a positive note, however, as pervasive late-summer *Microcystis aeruoginosa* blooms on the Potomac River were dissipated during the hurricane. *Microcystis* is a cyanobacterium that blooms in the fresh and oligohaline, nutrient-enriched portions of the Chesapeake Bay, typically in late spring through fall. *Microcystis* is known to produce cyanotoxins [5]. Human health symptoms related to contact, ingestion, and inhalation of aerosols in bloom regions include itching and watery eyes, skin rashes, gastrointestinal discomfort, vomiting, diarrhea, headache, and fever [6]. Animal deaths have occurred from ingesting bloom-affected waters [6]. In the first week of September, the area near the Potomac River fixed station RET2.1 was the focus of a major *Microcystis* bloom (2 x 10^6 cells·ml^{-1}).

Chesapeake blooms are defined by abundances greater than 1 x 10^4 cells·ml^{-1} [7]. Bloom conditions were observed at lower but significant levels from Indian Head to Morgantown days before Isabel arrived. Initial post-hurricane sampling by the MD DNR and the Department of the Environment indicated that *Microcystis* was still

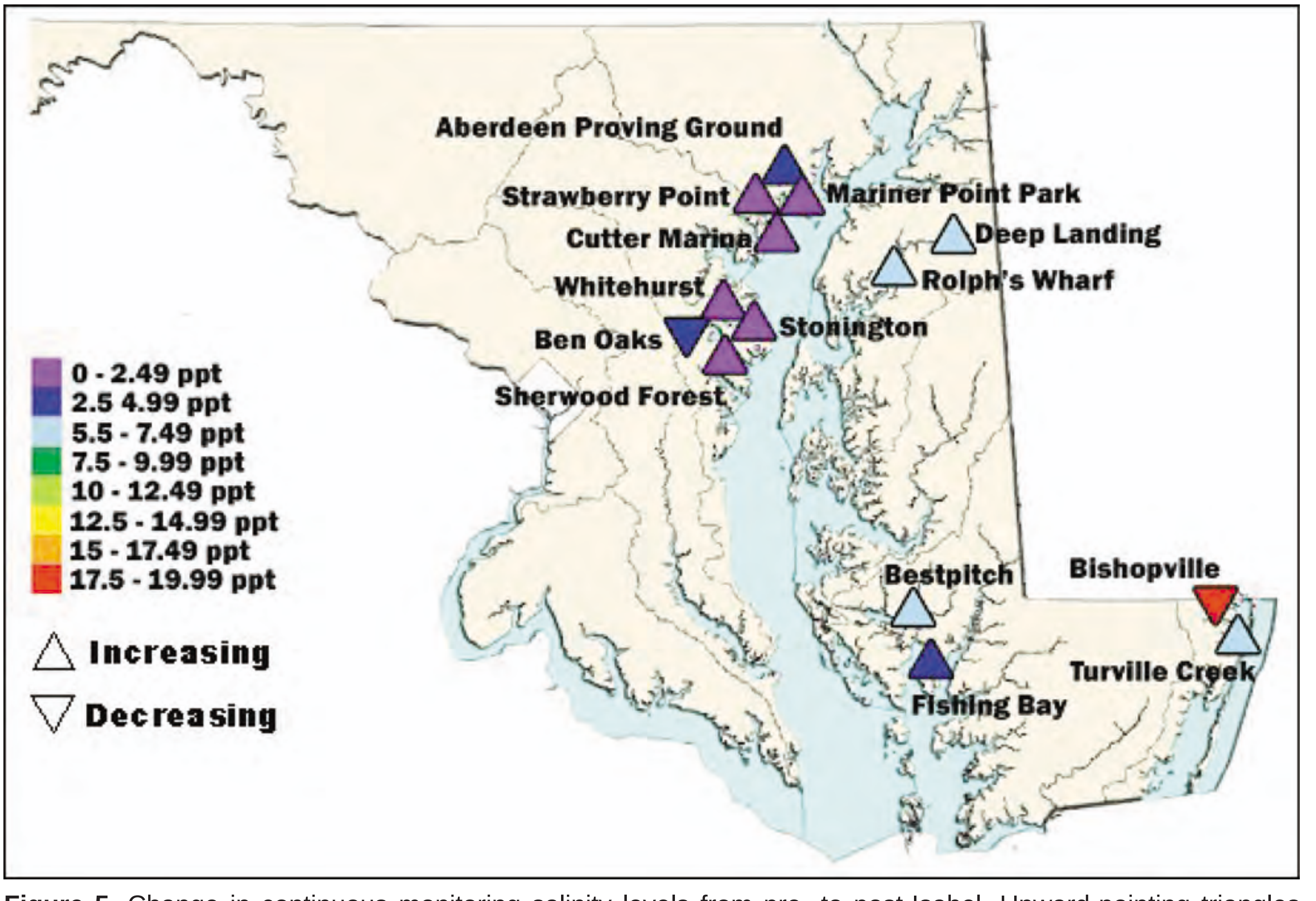

Figure 5. Change in continuous monitoring salinity levels from pre- to post-Isabel. Upward-pointing triangles indicate an increase in salinity; downward-pointing triangles indicate a decrease in salinity.

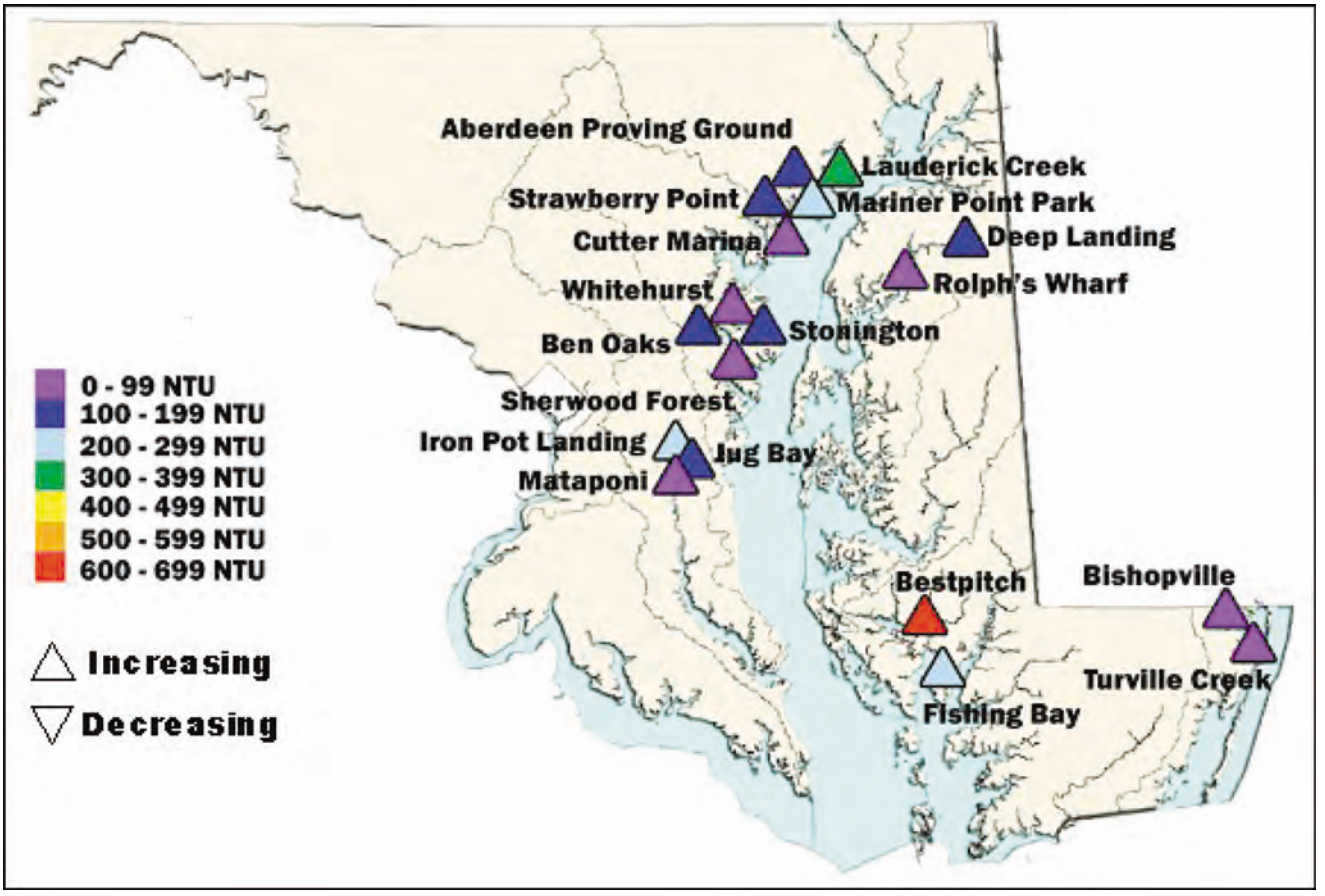

Figure 6. Maximum change in water clarity (turbidity) levels from pre- to post-Isabel from continuous monitoring data. Upward pointing triangles indicate a decrease in water clarity (increase in turbidity).

present on the river, but at significantly reduced levels [8]. *Microcystis* abundances ranging from 53–21,960 cells·ml^{-1}at Station RET2.1 and downstream were well below pre-hurricane levels. Some combination of intensive mixing related to wind effects, storm surge, and high river flows, as well as declines in water temperature to levels below optimal for *Microcystis*, may have caused its lower abundance [8].

In general, nutrient levels were elevated in the wet year of 2003 compared to the drought conditions in 2002, illustrated by average April to

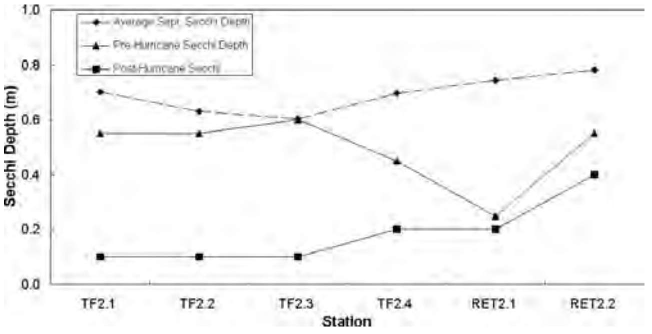

Figure 7. Comparison of long-term, mainstem Potomac River average September Secchi depths (1986–2002) versus Secchi depths pre- and post-Isabel.

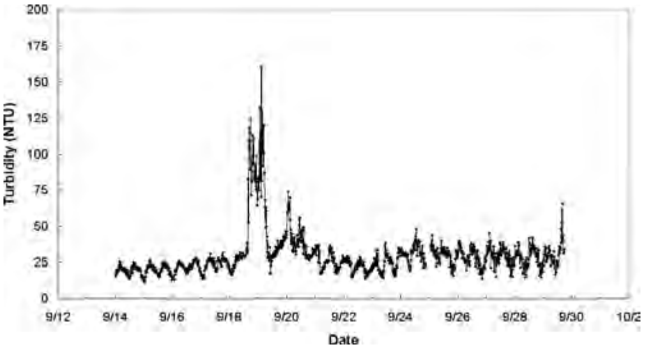

Figure 8. Continuous monitoring turbidity data from Deep Landing on the Chester River during Hurricane Isabel (18–19 September 2003). Higher turbidity values indicate lower water clarity.

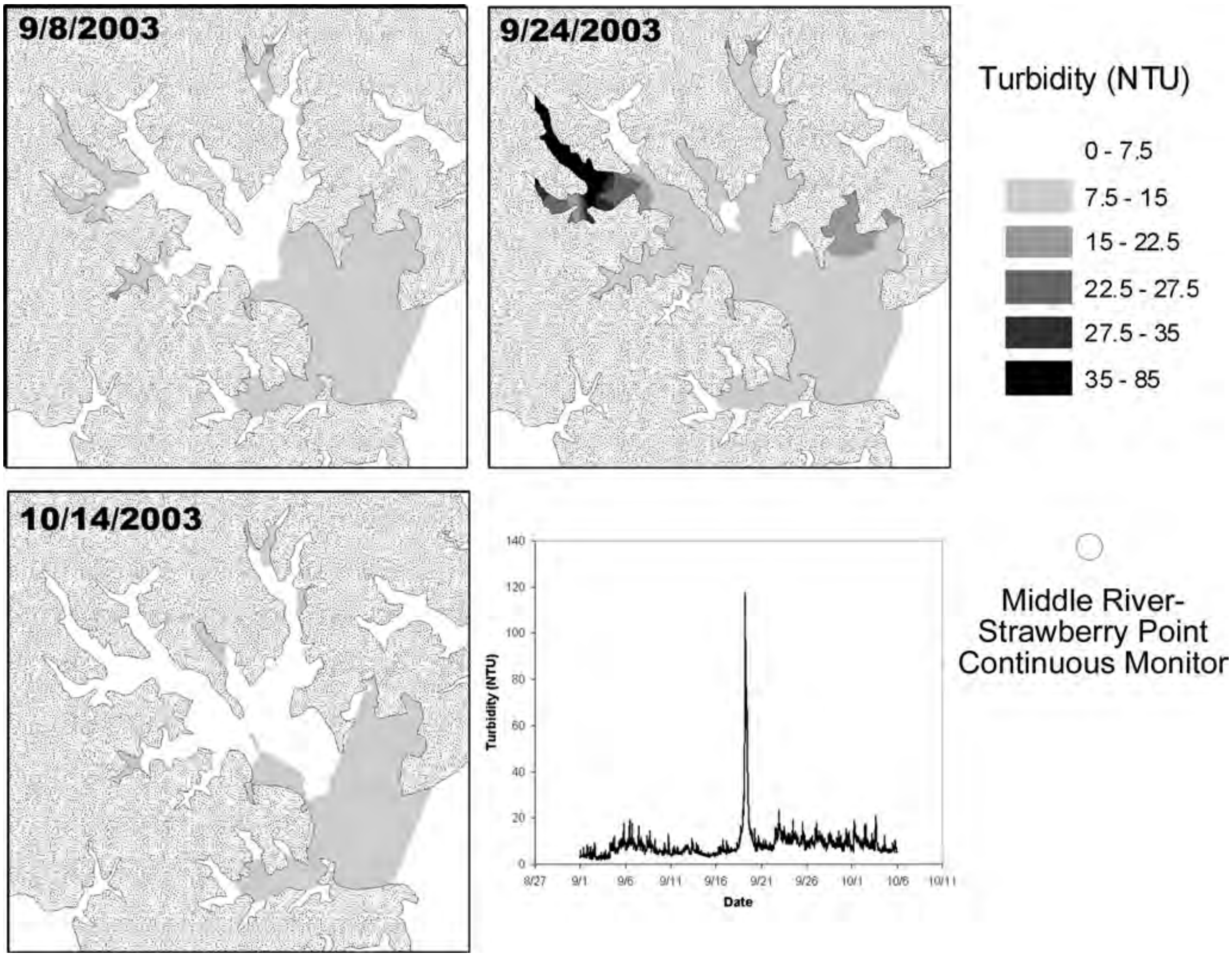

Figure 9. Water quality mapping of surface turbidity on the Middle River pre- and post-Isabel and continuous monitoring turbidity data at Strawberry Point.

October mainstem Bay total nitrogen plots (Figure 13). Pre-Isabel total nitrogen concentrations were already above long-term averages, but were further increased by Isabel in the upper Maryland portion of the Bay (Figure 14). A pulse of phosphate concentrations was also observed post-Isabel in the upper Bay; this pulse correlates well with data from September 2002, when increased rainfall began to alleviate drought conditions (Figure 15).

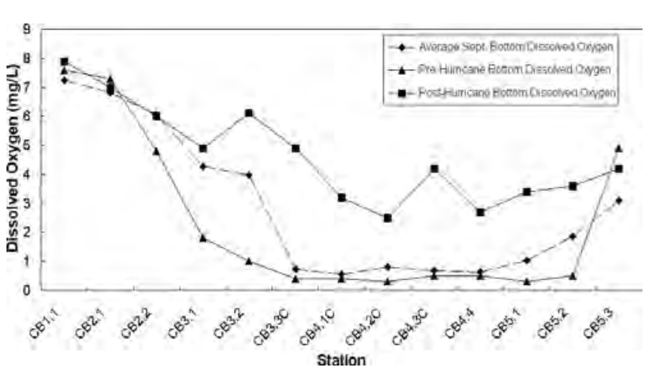

Figure 10. Comparison of long-term, mainstem Chesapeake Bay bottom dissolved oxygen for September with pre- and post-Isabel storm levels.

Ultimately, increased nutrients sent to the Chesapeake during a wet 2003 and during Isabel contributed to relatively low DO levels in the first quarter of 2004. A rather ubiquitous winter bloom of *Heterocapsa rotundata*, perhaps fueled by these nutrients and pervasive ice cover in the upper Bay that inhibited water column mixing, presumably contributed to all-time-low monthly bottom DO observations for January through March 2004 (Figure 16). The most extreme case was a reading of zero for the South River in January.

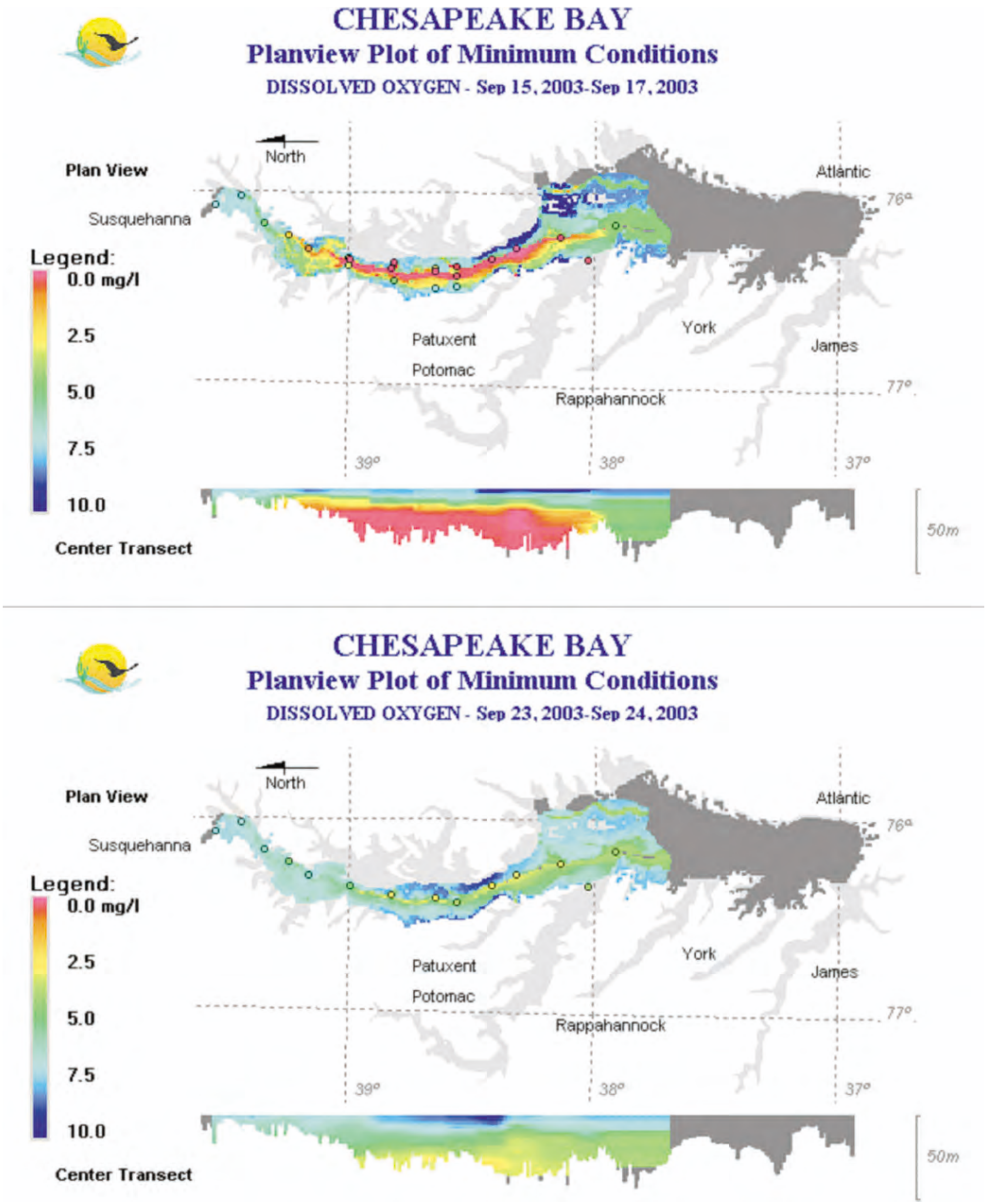

Figure 11. Interpolated plots of minimum dissolved oxygen conditions in the Chesapeake Bay before (top) and after (bottom) Isabel. Provided courtesy of the EPA Chesapeake Bay Program.

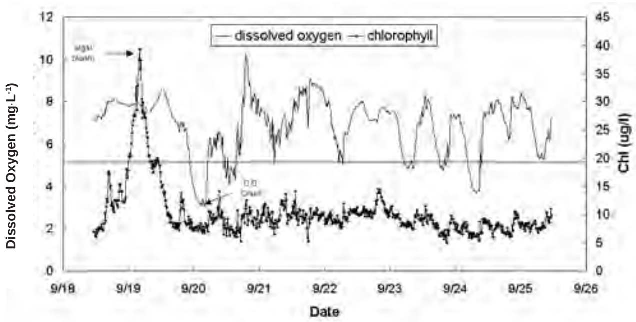

Figure 12. Chlorophyll and dissolved oxygen continuous monitoring data from Elliot Island on Fishing Bay following Hurricane Isabel. Data were collected 1 m below the surface.

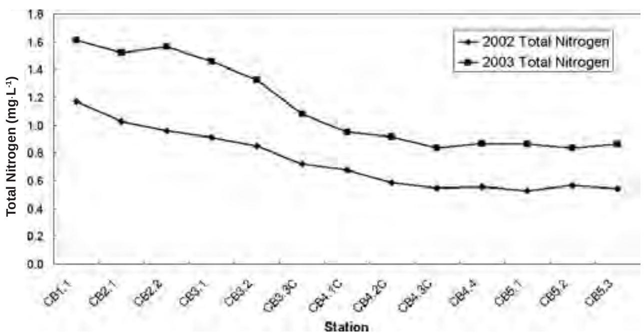

Figure 13. Mean mainstem Bay total nitrogen concentrations (April through October 2002 and 2003).

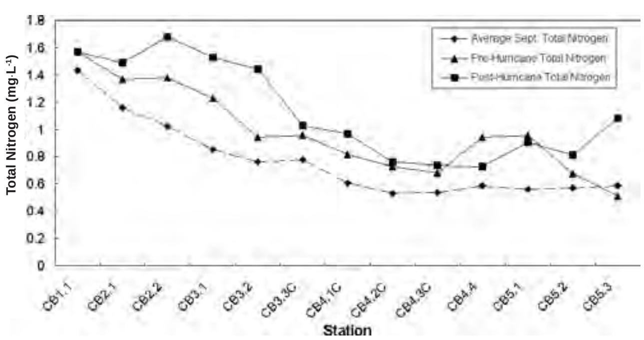

Figure 14. Mainstem Bay total nitrogen concentrations, pre- (15–17 September 2003) and post-Isabel (October) compared to the long-term September mean (1986–2002).

Living Resources

The DNR's Monitoring and Non-tidal Assessment (MANTA) division investigated possible impacts to five representative streams in the Coastal Plain, Piedmont, and Appalachian Plateau. It found no detectable changes in fish community assemblages and minor changes in physical habitat. Greater habitat perturbations occurred during significant rains in spring 2003.

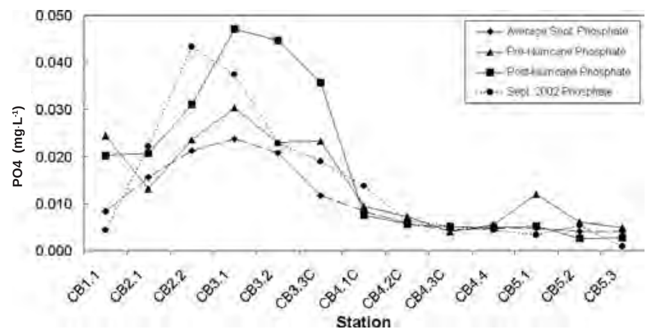

Figure 15. Mainstem Bay phosphate concentrations, pre- (15–17 September 2003) and post-Isabel (23–24 September 2003) compared to September 2002 and the long-term September mean (1986–2002).

Versar, Inc., a DNR consultant, re-examined several benthic reference sites in the Potomac River following Isabel [9]. No significant changes in a Benthic Index of Biotic Integrity (IBI) were observed. Impacts to SAV in Maryland appeared minimal [10]. Turbid conditions in 2003 likely had more impact on SAV than did Isabel. The timing of the storm at the end of the SAV growing season probably prevented the type of extensive damage that occurred during Agnes in June 1972. Also, increased water heights at the time of maximum wave energy prevented extensive scouring of shallow-water SAV beds. Some effects to SAV were observed in Virginia waters from Isabel and are contained in Orth et al. in this volume. Fish and shellfish impacts were not studied for this paper, but are also discussed elsewhere in this volume.

CONCLUSIONS

Advances in monitoring technology have provided the means to assess water quality on increasingly fine temporal and spatial scales. These improved capabilities, coupled with an existing long-term, fixed-station record, provide a greater understanding of the Bay's ecosystem and response to extreme meteorological events and anthropogenic influences. Hurricane Isabel's greatest impacts were the destruction of many human structures; ambient water quality and living resources appeared to escape relatively unscathed. The maintenance and expansion of monitoring technologies and networks in the Bay is, nonetheless,

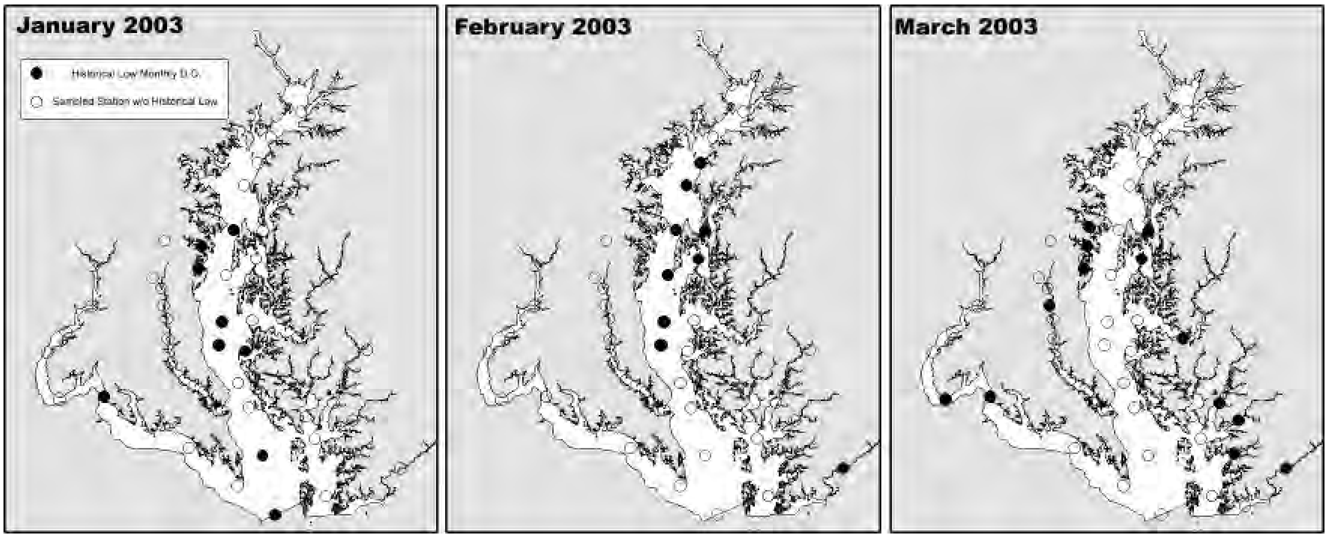

Figure 16. Record-low dissolved oxygen levels in 2003 for January, February, and March compared to monthly data from 1986 to 2002.

of great import and will increase our understanding of the Bay's response to extreme events and guide ecosystem management decisions.

REFERENCES

1. E.P. Ruzecki and others (eds.). 1976. *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System.* Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD.
2. B. Michael and B. Ebersole. 2004. Quality Assurance Project Plan for the Maryland Department of Natural Resources Chesapeake Bay Water Quality Monitoring Program - Chemical and Physical Properties Component for the period July 1, 2004 – June 30, 2005. Tidal Ecosystem Assessment. Maryland Department of Natural Resources. Annapolis, MD.
3. B.M. Michael, B. Ebersole, T.M. Trice, and C. Heyer. 2004. Quality Assurance Project Plan for the Maryland Department of Natural Resources Chesapeake Bay Shallow Water Monitoring Program for the period July 1, 2004 – June 30, 2005. Tidal Ecosystem Assessment, Maryland Department of Natural Resources. Annapolis, MD.
4. W.C. Boicourt. 1992. Influences of Circulation Processes on Dissolved Oxygen in the Chesapeake Bay. In: D.E. Smith, M. Leffler, and G. Mackiernan (eds.). *Oxygen Dynamics in the Chesapeake Bay*. Maryland Sea Grant. College Park, MD.
5. W.W. Carmichael. 1997. The cyanotoxins. *Adr. Bot. Res.* 27: 211–256.
6. I. Chorus and J. Bartram (eds.). 1999. *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*. World Health Organization, London, Routledge E&FN Spon.
7. U.S. Environmental Protection Agency. 2003. Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll *a* for the Chesapeake Bay and its tidal tributaries. U.S. EPA CBPO, WPD, EPA 903-R-03-002. April 2003. 231 pp.
8. P. Tango, W. Butler, M. Trice, and C. Heyer. 2005. Phytoplankton community dynamics in Maryland's tidewaters in response to Hurricane Isabel. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.
9. R. Llanso. 2004. Pers. comm. Versar, Inc.
10. M. Naylor. 2004. Pers. comm. Maryland Department of Natural Resources Resource Assessment Service.

THE INFLUENCE OF HURRICANE ISABEL ON CHESAPEAKE BAY PHYTOPLANKTON DYNAMICS

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ABSTRACT

Phytoplankton biomass in mid- to lower Chesapeake Bay increased significantly following Hurricane Isabel in September 2003. Observations of ocean color from aircraft before (11 September) and after (24 September) Isabel revealed a two-fold increase of chlorophyll *a* (chl-a) in a large area of the Bay encompassing ~3000 km^2. Continuing flights and shipboard sampling indicated that the increase dissipated by early October as chl-a returned to typical fall values. Average fall conditions show decreasing phytoplankton biomass from the head (~11 mg chl-a·m^{-3}) to the mouth (~5 mg chl-a·m^{-3}) of the estuary. Resolving the effect of Isabel on chl-a was complicated by record freshwater flow into the Bay in 2003 that strongly affected phytoplankton dynamics. Measurements of water column structure from before and after Isabel suggest that the Bay was rapidly destratified by the passage of the storm. The increased chl-a was caused by wind mixing and storm surge that introduced nutrients from bottom waters into the photic layer at a time of year when nitrogen is usually the limiting macronutrient for phytoplankton.

INTRODUCTION

Only three storms made landfall as hurricanes in Virginia and Maryland between 1851 and 1996, although numerous tropical storms have influenced the region [1]. Hurricane Isabel reached the coast on 18 September 2003 near Cape Lookout, North Carolina and moved quickly to the northwest, arriving in Canada by mid-day on 19 September. The storm passed to the west of Chesapeake Bay, producing strong and sustained winds from the south. The speed and track of the storm, along with the winds, created a set of physical conditions in the Bay that enhanced the storm surge [2], causing tidal flooding along western shore tributaries. The last major storm to follow that path was an unnamed hurricane in August 1933 that had a similar effect on water level. Winds and storm surge were exceptional during Isabel, although precipitation was not. Only the eastern half of Virginia received more than 5 cm of rain during the storm. The most significant environmental forcing, therefore, came from wind and surge rather than freshwater flow.

The response of estuarine phytoplankton to hurricane or tropical storm passage has been documented for several systems [3, 4, 5]. In all examples, phytoplankton biomass increased in response to storm passage. However, there appear to be two distinct mechanisms underlying storm effects on phytoplankton dynamics. Zubkoff and Warinner [3] and Paerl et al. [5] in Chesapeake Bay and Pamlico Sound, respectively, reported biomass increases in response to record-setting freshwater flow and nutrient delivery associated with tropical storm/hurricane passage, whereas Valiela et al. [4] described a short-lived phytoplankton bloom in response to water column mixing and nutrient release from the sediment in Waquoit Bay.

Aircraft remote sensing of ocean color and sea surface temperature in Chesapeake Bay before and after the passage of Hurricane Isabel was used to quantify the effect of the storm on phytoplankton biomass in the Bay. Supporting data were obtained from an analysis of 15 years (1989–2004) of archived data on fall chl-a from remote sensing to place the phytoplankton response in the context of contemporary conditions. Finally, shipboard data on water column structure and constituents before and after the storm were examined to infer a mechanism for the response observed.

METHODS AND MATERIALS

Phytoplankton biomass as chl-a was obtained as part of the Chesapeake Bay Remote Sensing Program (CBRSP; *www.cbrsp.org*). Ocean color data were collected using a multi-spectral radiometer (SeaWiFS Aircraft Simulator, SAS III, Satlantic, Inc. Halifax, NS, Canada) from light aircraft operating at low altitude (~150 m) and low speed (~50 $m \cdot s^{-1}$), following a defined set of flight lines covering approximately 750 km. The nadir-viewing radiometers sample at 10 Hz with a 3.5^o field of view. At flight parameters given above, this sampling creates a footprint of 5 m x 50 m when averaged to 1 sec, providing approximately 12,000 data points per flight. We used a spectral curvature algorithm [6, 7] to convert water-leaving radiances in the blue-green region of the spectrum [$L_w(443)$, $L_w(490)$, and $L_w(555)$] to chl-a. Empirical relationships have been developed to calibrate the general curvature algorithm to *in situ* observations made in Chesapeake Bay [8, 9, 10, 11, 12]. Flight data were then interpolated to a 1-km^2 grid of the Bay using a two-dimensional, inverse-distance-squared, octant search. Interpolation was performed on $\log_{10}$ chl-a to achieve normality. Flights have been conducted 20 to 30 times per year, concentrating on the productive period (March to October), with tracks that extend into all regions of the mainstem Bay to produce a chl-a climatology for the full period of the study (1989–2004). The long-term average chl-a for September is comprised of data from 35 flights, totaling 245,000 data points. All analyses were performed on interpolated data using SAS version 8.0 (Cary, NC) and mapped in Surfer version 8.0 (Golden, CO).

In situ data were obtained from water quality monitoring cruises of the Chesapeake Bay Program (CBP) that collect information on water column structure and constituent concentrations from approximately 50 stations in the mainstem Bay roughly 14 times per year. Data were drawn from nine stations in the deep central channel of the mid-Bay (CB3.3C, CB4.1C, CB4.2C, CB4.3C, CB4.4, CB5.1, CB5.2, CB5.3, LE2.3) collected during the month of September. This region has an average depth of 25 m and is an area where bottom-water nutrient concentrations tend to be high and dissolved oxygen low, with sub-pycnocline waters becoming hypoxic or anoxic in summer. Information on the collection protocols for parameters used in this study can be obtained from the CBP website (*www.chesapeakebay.net*).

RESULTS AND DISCUSSION

Long-term average chl-a for September is characterized by decreasing concentrations from north to south following the main axis of the Bay (Figure 1a), and gradients of other major constituents, including salinity, nutrients, and light attenuation. Based on long-term data from aircraft remote sensing, September appears to be a rather quiescent period in the annual phytoplankton cycle, with large blooms (magnitude, duration, or areal extent) infrequent for the period of record. Standard deviations of the mean for each grid cell are typically less than 2 $mg \cdot m^{-3}$, suggesting that conditions do not vary appreciably from the long-term average.

Chl-a, prior to Isabel (11 September 2003; Figure 1b), was not very different from the long-term average, with only slightly elevated concentrations in the northern part of the Bay. Six days after the passage of the hurricane (13 days after the last remote sensing image), chl-a greatly increased over a significant part of the mid- to lower Bay. The area of increased chl-a covered approximately 3000 km^2 and represented a rise of 2–3 times the long-term average. Our 15-year remote sensing record shows that biomass levels of this magnitude and areal extent are rare in September in the mid- to lower Chesapeake. Shipboard chl-a in the Bay's Maryland portion on 24 September 2003 was consistent with remotely sensed retrievals. Figure 1d shows the difference

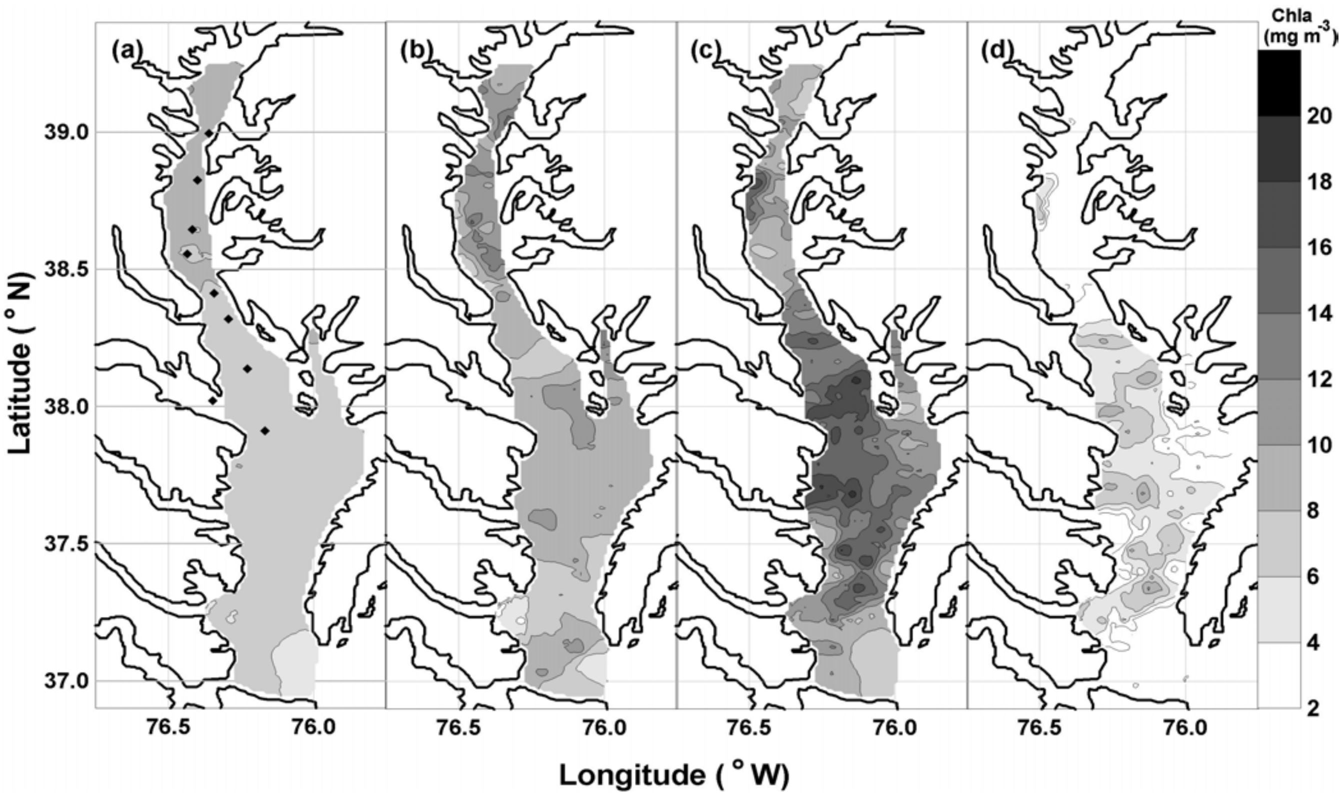

Figure 1. Remotely sensed phytoplankton biomass: a) Long-term September average; b) Pre-Isabel biomass, 11 September 2003; c) Post-Isabel biomass, 24 September 2003; and d) Difference plot, post-Isabel minus pre-Isabel biomass. Diamonds in panel a indicate location of CBP monitoring stations used in these analyses.

in chl-a between pre- and post-Isabel flights, with chl-a increases between 4 and 10 mg·m^{-3} common in the region between the Patuxent and York rivers. The rapid biomass increase was followed by an equally rapid decrease as a remote sensing flight on October 2 (image not shown) and shipboard data collected as part of an NSF biocomplexity project on 2 to 4 October showed that chl-a levels had returned to typical fall values (range = 5.0–12.9 mg chl-a·m^{-3}; mean = 6.65 mg chl-a·m^{-3}).

During fall, the mid- to lower Chesapeake Bay is nitrogen limited [13]. Therefore, increases of phytoplankton biomass in response to the passage of a hurricane likely resulted from an input of nutrients to the photic zone. Nutrient supply from freshwater runoff associated with heavy precipitation from Isabel was not likely a major contributor given the short time lag between storm passage and phytoplankton response. Typically, phytoplankton responses to pulses of freshwater flow occur weeks to months after the passage of a storm [14, 15], rather than days later, so the rapid biomass response observed on 24 September 2003 was probably not related to precipitation in the western portion of the Chesapeake Bay watershed. In addition, surface salinities in the mid-Bay were significantly higher in the post-Isabel sampling (11.96 vs. 10.29; t-test $p = 0.0098$), suggesting mixing of high-salinity bottom water rather than any appreciable input of fresh water.

Whereas freshwater flow is not directly linked to the bloom observed on 24 September, flow during the months prior to Isabel clearly affected Bay phytoplankton dynamics in 2003. Record flow delivered substantial quantities of nutrients to the Bay that were assimilated into phytoplankton biomass that sedimented from the photic layer and were retained in bottom waters of the mid-Bay by two-layer circulation [16]. Nutrients may also have been entrained directly into the sub-pycnocline waters at the onset of summer stratification. Average dissolved inorganic nitrogen (DIN = NO_2

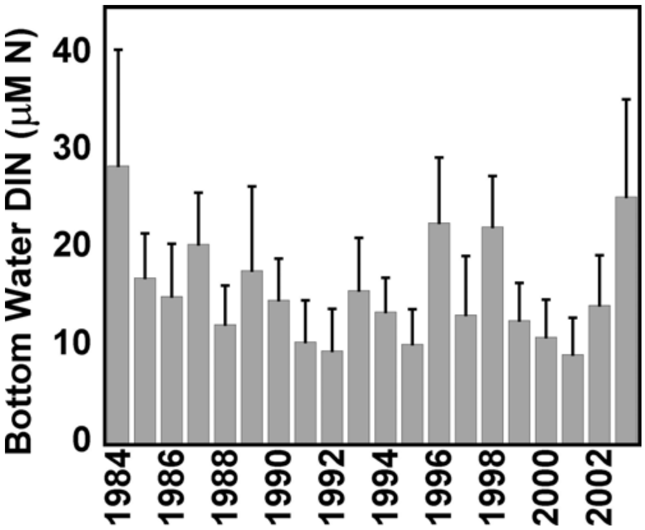

Figure 2. Average September bottom-water DIN concentrations from mid-Bay channel stations from 1984 to 2003. Data from CBP monitoring cruises. Error bars = 1 SD.

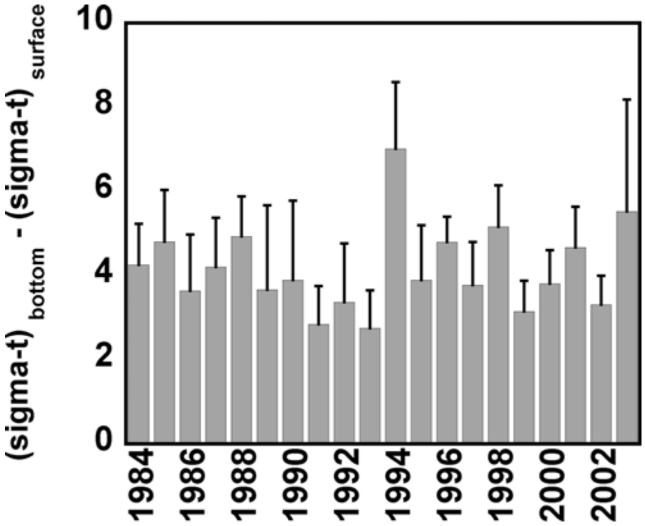

Figure 3. Average September density differences between surface and bottom samples for mid-Bay channel stations from 1984–2003. Data from CBP monitoring cruises. Error bars = 1 SD.

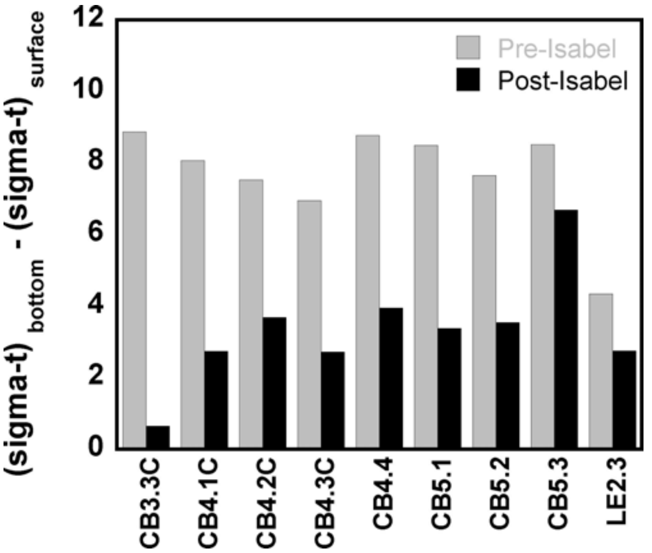

Figure 4. Pre- (9/15) and post-Isabel (9/25) density difference between surface and bottom samples for mid-Bay channel stations (CB3.3C northernmost station). Data from CBP monitoring cruises.

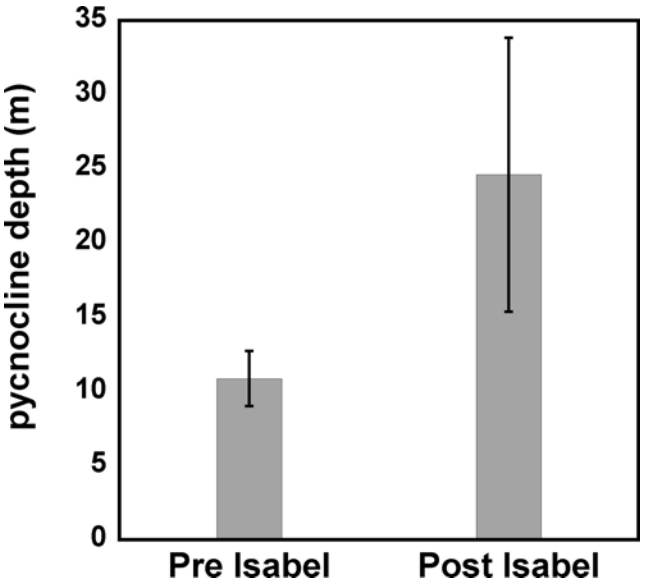

Figure 5. Average pycnocline depth for mid-Bay channel stations, pre- (9/15/03) and post-Isabel (9/25/03). Data from CBP monitoring cruises. Error bars = 1 SD. Note six of nine stations in post-Isabel sampling had no pycnocline and were mixed surface to bottom.

+ NO_3 + NH_4) concentrations in bottom waters for the month of September at mid-Bay stations show that high nutrient concentrations were prevalent (Figure 2). The DIN in 2003 was the highest of any year since 1984, suggesting sufficient nitrogen existed in bottom waters to support a bloom once mixing occurred. Surface DIN concentrations in 2003 were significantly greater than the long-term average condition for September in the mid-Bay (0.177 vs. 0.052; t-test $p < 0.0001$), however, the post-Isabel surface DIN was not statistically different from the pre-Isabel conditions (0.177 vs. 0.143; t-test $p < 0.651$), most likely because excess DIN had already been incorporated into phytoplankton biomass.

Density differences between surface and bottom layers provide a metric for the intensity of stratification. Stratification in the mid-Bay was particularly strong in September 2003 (Figure 3) associated with high freshwater flow in the spring and summer preceding the storm. Strong stratification separates regenerated nutrients in bottom waters from the photic layer except during extreme events.

Sustained strong winds out of the south, together with an ~2-m storm surge, likely broke down the stratification that existed in the mid-Bay prior to the storm [2]. The density gradient, expressed as differences of surface and bottom water densities before and after the storm's passage, showed a large decrease suggesting that mixing had occurred (Figure 4). Other evidence for mixing was the 13-m increase of the average depth of the pycnocline in the mid-Bay following the storm, including six of nine stations where the water column was mixed top to bottom (24.61 vs. 10.88; t-test $p = 0.0005$; Figure 5).

Mixing associated with the passage of Isabel was essential to inject nutrients from below the pycnocline into the photic zone, while the partial re-stratification of the lower Chesapeake was also necessary to retain the nutrients and phytoplankton in well-illuminated surface waters. The turbulent mixing may have also supplied sub-pycnocline and benthic phytoplankton to the surface layer, providing additional biomass and a potential seed population for bloom formation. The rapid formation and cessation of the post-Isabel bloom in the mid- to lower Chesapeake Bay, together with nutrient and water column properties, suggest a phytoplankton response that was fueled by (and quickly exhausted) the nutrients mixed into the photic zone by Isabel.

CONCLUSIONS

The predominant short-term impact of Hurricane Isabel on phytoplankton dynamics in Chesapeake Bay was a ~two to threefold increase in biomass in the mid- to lower Bay, from the Patuxent to York rivers and covering approximately 3,000 km^2. The likely physical mechanism underlying this response was storm surge and wind mixing of bottom-water nutrients into the photic zone during a time of year when surface waters are usually nitrogen-limited. Phytoplankton responses to the passage of Hurricane Isabel were also influenced by the preceding "wet" year and associated high freshwater flow that produced higher-than-normal concentrations of DIN below the pycnocline.

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REFERENCES

1. J.B. Elsner and A.B. Kara. 1999. *Hurricanes of the North Atlantic, Climate and Society.* Oxford University Press, New York. 488 pp.
2. M.R. Roman, J.E. Adolf, J. Bichy, W.C. Boicourt, L.W. Harding, Jr., E.D. Houde, S. Jung, D.G. Kimmel, W.D. Miller, and X. Zhang. In press. Enhancement of plankton and fish abundance in Chesapeake Bay by Hurricane Isabel. *EOS*.
3. P.L. Zubkoff and J.E. Warinner III. 1977. The effect of Tropical Storm Agnes as reflected in chlorophyll *a* and heterotrophic potential of the lower Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD. pp. 368–387.
4. I. Valiela, P. Peckol, C. D'Avanzo, J. Kremer, D. Hersh, K. Foreman, K. Lajtha, B. Seely, W.R. Geyer, T. Isaji, and R. Crawford. 1998. Ecological effects of major storms on coastal watersheds and coastal waters: Hurricane Bob on Cape Cod. *J. Coast. Res.* 14: 218–238.

5. H.W. Paerl, J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, J.M. Fear, M. Go, B.L. Peierls, T.L. Richardson, and J.S. Ramus. 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound, NC. *Proc. Natl. Acad. Sci.* 98: 5655–5660.
6. G.W. Grew. 1981. Real-time test of MOCS algorithm during Superflux. NASA Publication CP-2188, pp. 301–322.
7. J.W. Campbell and W.E. Esaias. 1983. Basis for spectral curvature algorithms in remote sensing of chlorophyll. *Appl. Opt.* 22: 1084–1093.
8. L.W. Harding, Jr. and E.C. Itsweire. 1991. Synoptic measurements of the distribution of chlorophyll in the Chesapeake Bay using aircraft remote sensing. In: New Perspectives in the Chesapeake System: A Research and Management Partnership. J.A. Mihursky and A. Chaney (eds.). Chesapeake Research Consortium Publication No. 137. Baltimore, MD. pp. 147–160.
9. E.C. Itsweire, L.W. Harding, Jr., and L.H. Bahner. 1991. Comparison of phytoplankton biomass estimates for Chesapeake Bay using aircraft remote sensing and *in situ* chlorophyll data. In: New Perspectives in the Chesapeake System: A Research and Management Partnership. J.A. Mihursky and A. Chaney (eds.), Chesapeake Research Consortium. Publication No. 137. Baltimore, MD. pp. 161–168.
10. L.W. Harding, Jr., E.C. Itsweire, and W.E. Esaias. 1992. Determination of phytoplankton chlorophyll concentrations in the Chesapeake Bay with aircraft remote sensing. *Remote Sens. Environ.* 40: 79–100.
11. L.W. Harding, Jr., E.C. Itsweire, and W.E. Esaias. 1994. Estimates of phytoplankton biomass in the Chesapeake Bay from aircraft remote sensing of chlorophyll concentrations. *Remote Sens. Environ.* 49: 41–56.
12. L.W. Harding, Jr., E.C. Itsweire, and W.E. Esaias. 1995. Algorithm development for recovering chlorophyll concentrations in the Chesapeake Bay using aircraft remote sensing. *Photogramm. Eng. Remote Sens.* 61: 177–185.
13. T.R. Fisher, E.R. Peele, J.W. Ammermann, and L.W. Harding, Jr. 1992. Nutrient limitation of phytoplankton in Chesapeake Bay. *Mar. Ecol. Prog. Ser.* 82: 51–63.
14. T.C. Malone, L.H. Crocker, S.E. Pike, and B.W. Wendler. 1988. Influence of river flow on the dynamics of phytoplankton production in a partially stratified estuary. *Mar. Ecol. Prog. Ser.* 48: 235–249.
15. L.W. Harding, Jr. and E.S. Perry. 1997. Long-term increase of phytoplankton biomass in Chesapeake Bay, 1950–1994. *Mar. Ecol. Prog. Ser.* 157: 39–52.
16. W.C. Boicourt. 1992. Influence of circulation processes on dissolved oxygen in the Chesapeake Bay. In: D.E. Smith, M. Leffler, and G.E. Mackiernan. (eds.), *Oxygen Dynamics in the Chesapeake Bay. A Synthesis of Recent Research*. Maryland Sea Grant College, University of Maryland, College Park, MD, pp. 7–59.

PHYTOPLANKTON COMMUNITY DYNAMICS IN MARYLAND'S TIDEWATERS IN RESPONSE TO HURRICANE ISABEL

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ABSTRACT

During the summer of 2003, cyanobacterial blooms were encountered across a broad region of the upper Chesapeake Bay and in the Potomac River. While upper Bay cyanobacterial blooms had declined significantly by early September, the cessation of the 2003 Potomac River bloom coincided with diverse impacts to habitat conditions by Hurricane Isabel. Phytoplankton abundance on the Maryland mainstem Chesapeake Bay showed little evidence for phytoplankton response to the storm effects, however, timing in the transition to diatom dominance in the tidewater region appears linked to storm event effects.

INTRODUCTION

Phytoplankton species composition and abundance are functions of interactions with environmental conditions including salinity, temperature, light, nutrients, turbulence, and water depth [1] in addition to grazing, competition, and disease. In 2003, flows to the Bay increased dramatically over the largely drought years of 1999 to 2002, particularly in the Potomac River basin. Flow conditions influence nutrient loadings to Chesapeake Bay; annual means of phytoplankton production and abundance have been significantly correlated to riverine nutrient inputs [2].

The large-scale seasonal flow effects due to the climatic differences between years significantly impacted the distribution of habitat in the Bay and tributaries well ahead of Tropical Storm Isabel [3]. However, storm events bring wind, storm surge, and runoff effects that can impact habitat conditions for phytoplankton populations. Margalef [4] and Reynolds [5] have shown that changing the physical conditions in surface waters is a major determinant of community change. Pearl [6] has reported that physically stable conditions are necessary for cyanobacterial blooms, but related changes in temperature, wind speed, and wind direction lead to the disappearance of the blooms.

Microcystis blooms are primarily warm-water phenomenon; Kruger and Elhoff [7] cite 28.8–30.5^{o} C as the range for optimum growth. During 2003, upper Chesapeake Bay and Bay tributaries, including the Bush and Sassafras rivers, produced cyanobacteria blooms beginning in July with densities reaching 1.6 x 10^6 cells·ml^{-1} (MD DNR *http://mddnr.chesapeakebay.net/hab/news_7_30_03.cfm*). A late-season cyanobacteria bloom dominated by *Microcystis aeruginosa* (>10^4 cells·ml^{-1}) developed on the middle Potomac River from mid-August to mid-September. *Microcystis* abundance peaked in the surface waters at >1 x 10^6 cells·ml^{-1} from 2–15 September. The upper Bay cyanobacteria bloom declined ahead of the tropical storm, but the cessation of the Potomac River bloom appeared more closely tied to storm-related effects. Post-storm effects on the broader phytoplankton community in the upper Bay were also of interest.

For this study, the time series of the 2001–2004 phytoplankton community composition data were reviewed for three long-term monitoring stations in the upper Bay and the cyanobacteria bloom region in the middle Potomac. River flow conditions were examined from U.S. Geological Survey (USGS) data collected at the Little Falls station on the Potomac River near Washington D.C. (station 01646500). Water quality data were reviewed from the Chesapeake Bay Program long-term monitor-

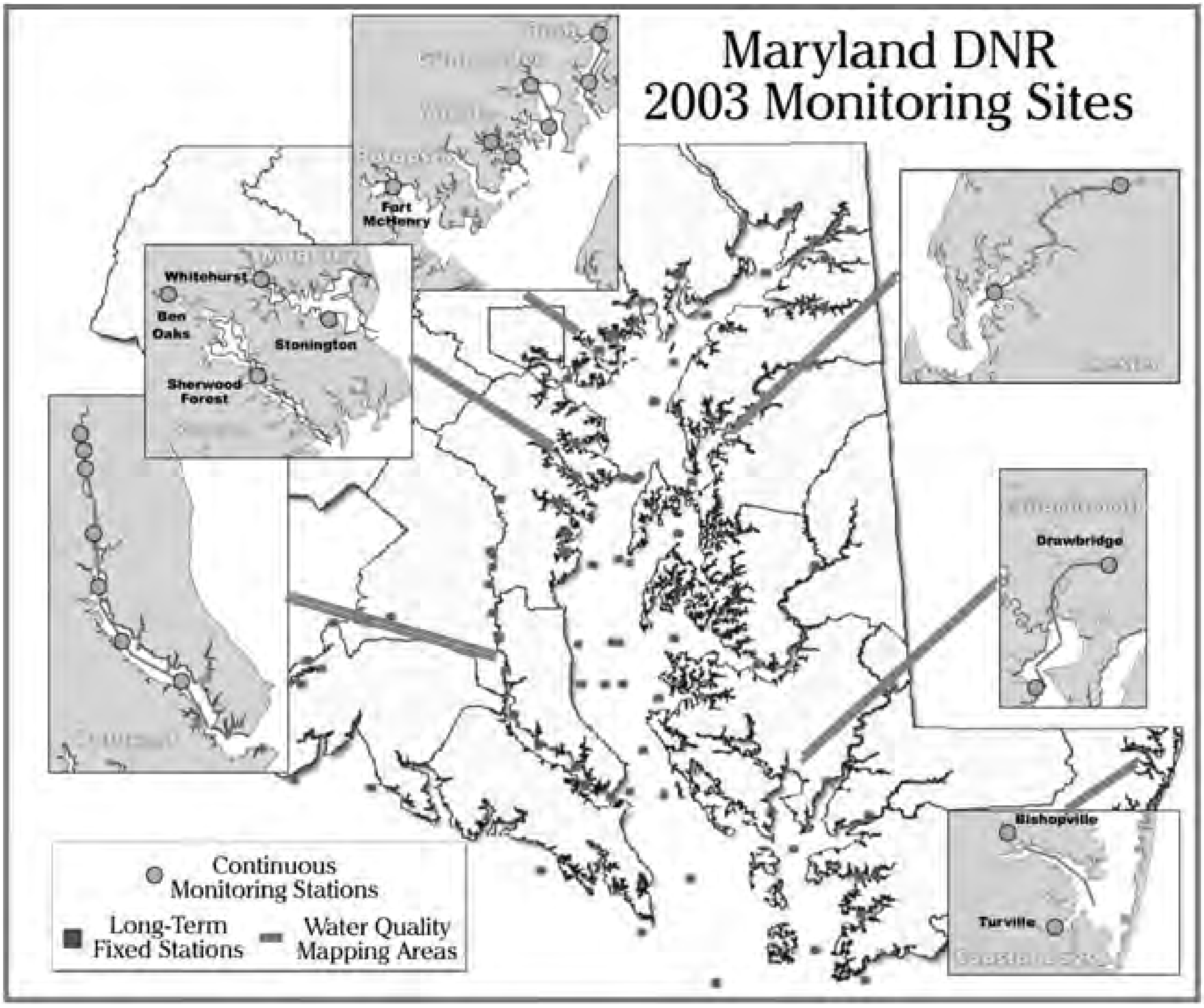

Figure 1. Distribution of relevant Chesapeake Bay Water Quality Monitoring Program station locations for mainstem Chesapeake Bay and the bloom region on the Potomac River (2003).

ing stations. Phytoplankton data were examined for patterns of short-term response to the storm-related effects in flow and water quality parameters. Annual-scale time series of phytoplankton abundance, community composition, and timing of possible storm response were graphically compared to assess community level changes.

METHODS

The Maryland Phytoplankton Monitoring Program samples 20 stations distributed on the mainstem of the Chesapeake Bay (n=3), Potomac River (n=10), Patuxent River (n=4), Choptank River (n=1), Chester River (n=1), and Patapsco River (n=1). A harmful algal bloom response program provides additional samples from other sites in response to human health or living resources events. Phytoplankton samples are collected monthly (fall and winter) to biweekly (spring and summer). Samples analyzed for this paper were grab samples of 500–750 ml of surface water from three mainstem Chesapeake Bay long-term monitoring stations and additional stations on the Potomac River (Figure 1).

Live samples were returned to the laboratory for light microscope analysis. Live samples (1 ml) were used for species identification and counting

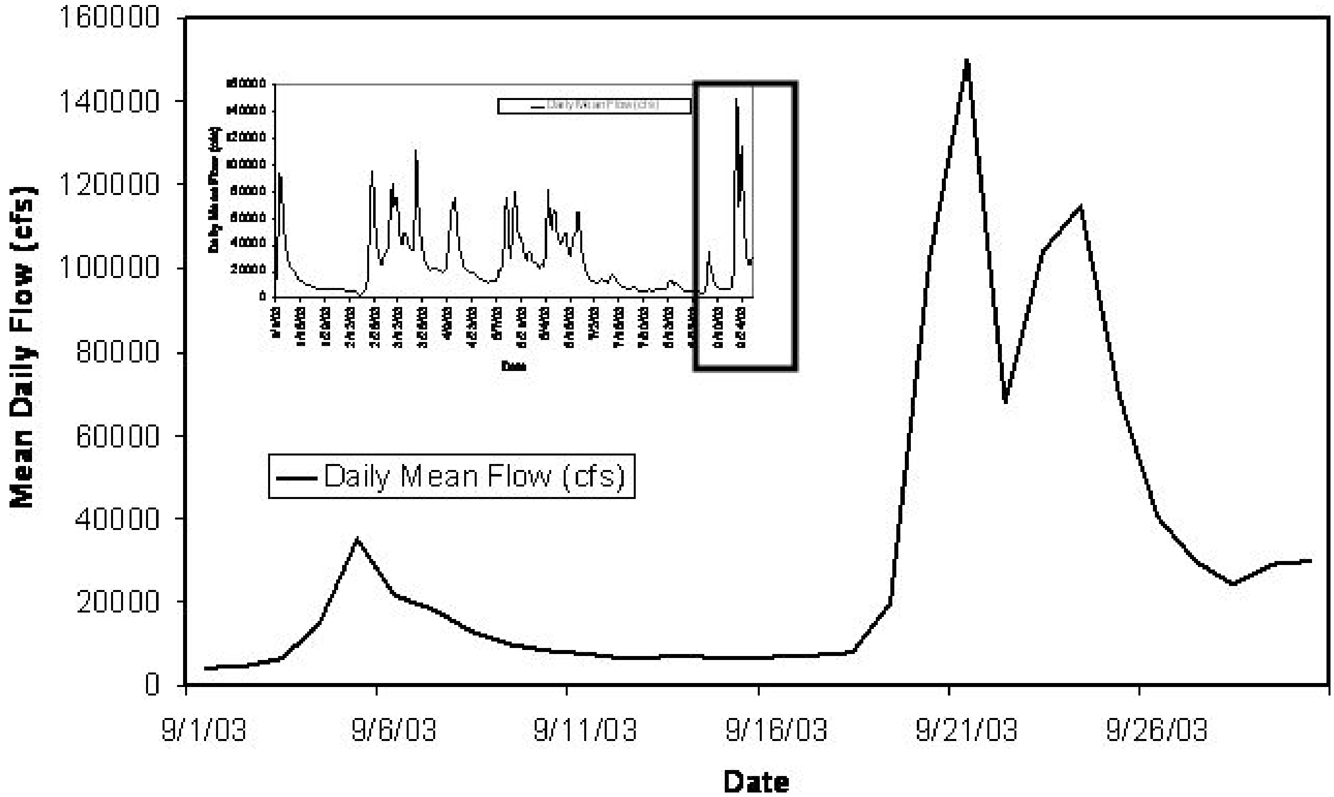

Figure 2. Potomac River flows at Chain Bridge, Maryland showing post-storm flows arriving September 21. The January to October 2003 flow time series is inset for reference.

on a Sedgewick-Rafter cell at 100x and 200x magnification. Preservative fixed high-density samples for counting after species identification. Sample dilutions were conducted on high-density samples and counts multiplied according to the dilution factor to estimate the original density with bloom species. Phytoplankton community composition was summarized by sampling event; water quality data collected coincident with phytoplankton sampling were compared with the plankton data.

RESULTS

Cyanobacteria

During 2003, the upper Bay and Bay tributaries produced cyanobacteria blooms first detected in July with densities reaching 1.6 x 10^6 cells·ml^{-1} in upper Bay tributaries (*http://mddnr.chesapeakebay.net/hab/news_7_30_03.cfm)*. By 4 September, upper Bay blooms had declined with cell counts of 1.2 x 10^4 cells·ml^{-1} measured on the Sassafras River, but visible scum was still accumulating in local areas *(http://mddnr.chesapeakebay.net/hab/news_ 9_16_03. cfm).*

A late-season cyanobacteria bloom dominated by *M. aeruginosa* developed on the Potomac River from mid-August to mid-September. *Microcystis* abundance peaked in the surface waters at >1 x 10^6 cells·ml^{-1} from 2–15 September. The cessation of the bloom concentrations coincided with storm events. Between 18 and 19 September, the Washington D.C. metro area experienced wind gusts of 78 mph at Quantico Air Force Base and 69 mph at Andrews AFB and Patuxent Naval Air Station; National Airport on the Potomac River sustained a two-minute period of 45 mph with a peak gust of 58 mph during the storm (*http://www.weatherbook.com/Isabel_report.htm*). Rainfall was 2–3 in (5.1–7.6 cm) in the D.C. area but 6–12 in (15.2–30.5 cm) fell in the Shenandoah Valley and Blue Ridge Mountains creating localized flash flooding (*www.weatherbook.com/Isabel_ report.htm*). Two days after the storm, on 21 September, the mean daily water flow at Little Falls on the Potomac River near Washington D.C. peaked at 1.5 x 10^5 cfs, the highest level of the year (Figure 2). Coincident with flow effects in the river were: declines in salinity

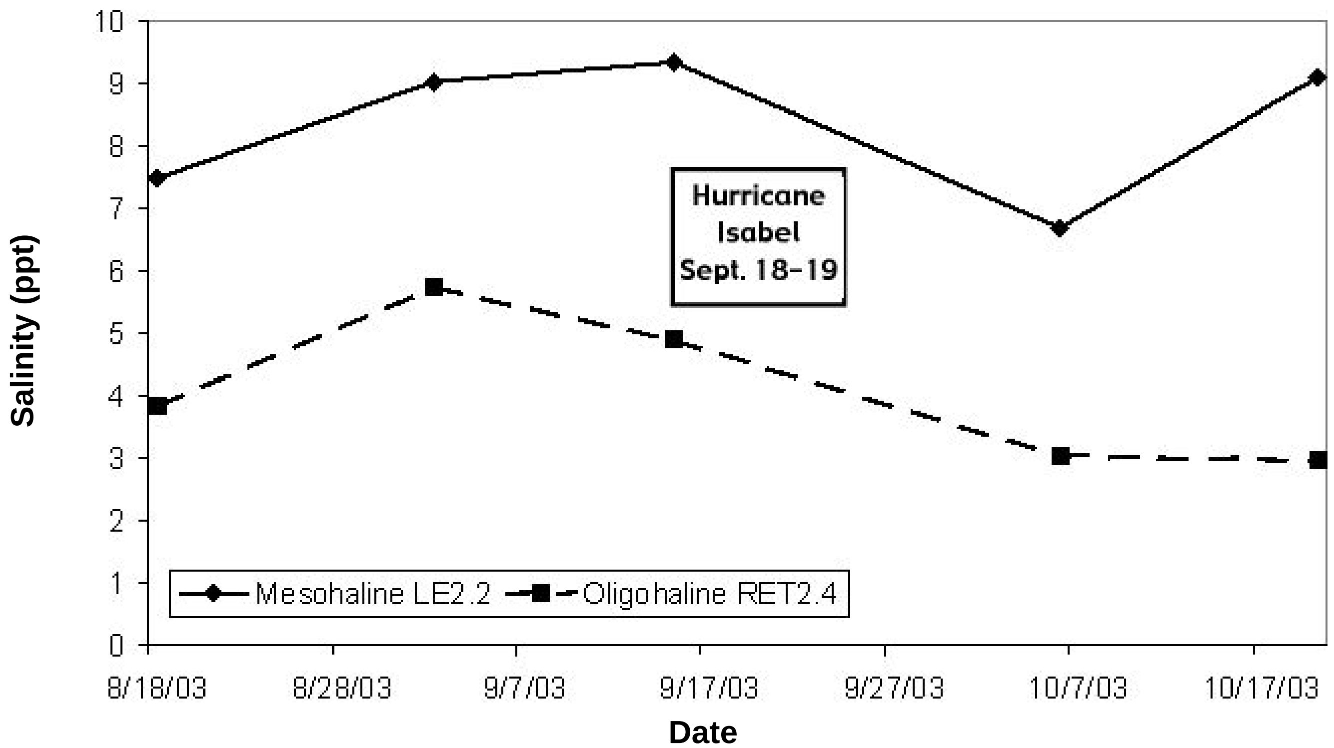

Figure 3. Storm flow impacts on the surface salinity distribution in the Potomac River, 2003.

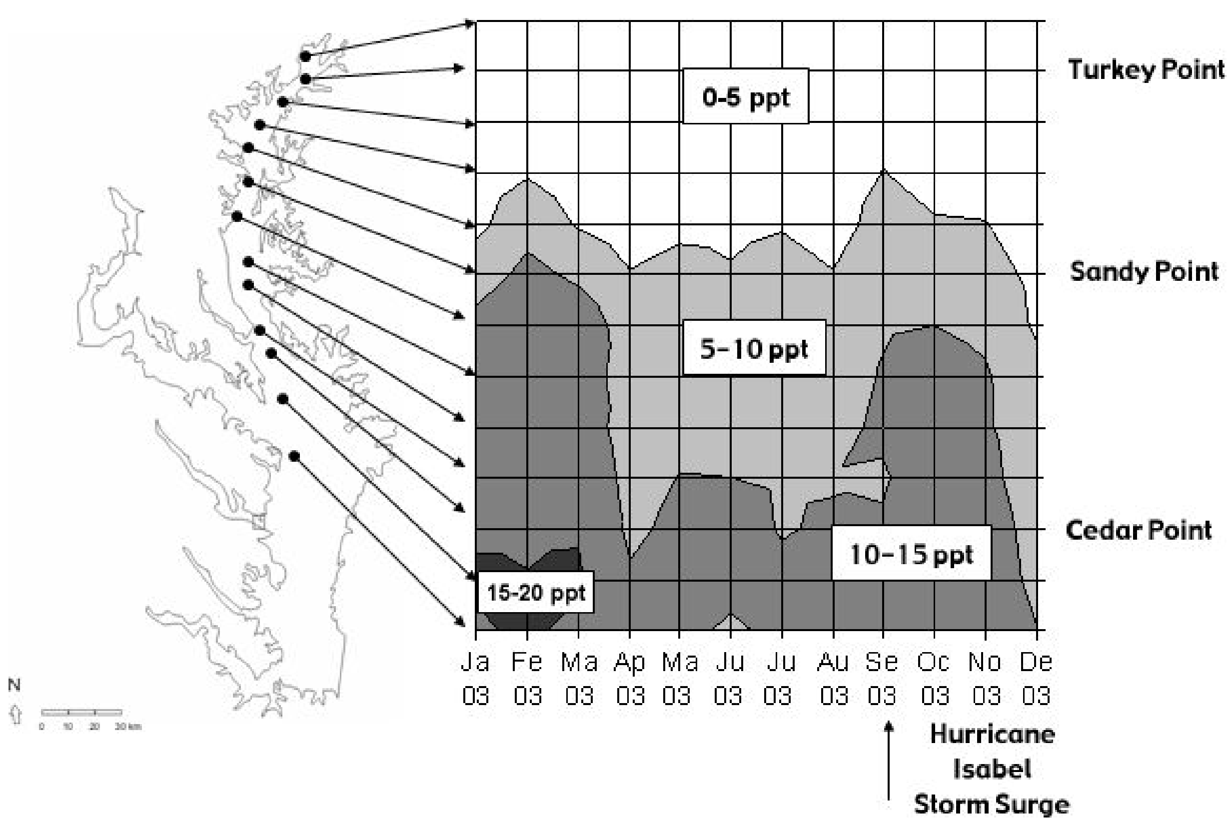

Figure 4. Surface plot of salinity distribution in the main stem of Maryland's tidal Chesapeake Bay in response to storm surge and resulting persistence of elevated salinity into November 2003 in the upper Chesapeake Bay.

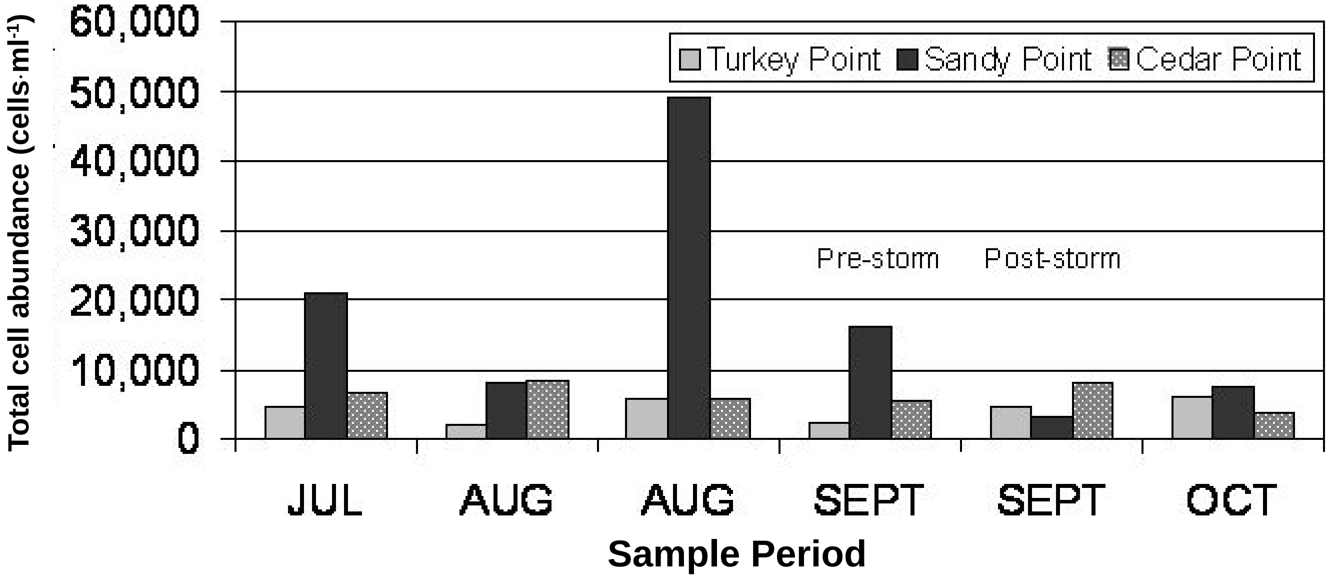

Figure 5. Phytoplankton abundance from July to October 2003 for mainstem Chesapeake Bay stations Turkey Point, Sandy Point, and Cedar Point.

in the oligohaline and mesohaline zones between September 15 and October 6 indicative of downstream shifts in habitat conditions (Figure 3); and surface water temperatures from a tidal-fresh average of 23.3°C on 15 September (n=3 pre-storm) to 19.8°C on 22 September (n=3 post- storm). By 6 October, mean water temperatures in the tidal-fresh zone were 16.2°C, well below favorable *M. aeruginosa* bloom conditions

Maryland's Tidewaters of Chesapeake Bay

In the main Bay, surface salinity effects were most pronounced in the mid-Bay region and persisted into November (Figure 4). Salinity at three phytoplankton monitoring stations (Turkey Point, Sandy Point, and Cedar Point) showed little change in spite of the storm's impacts. Sandy Point experienced an algal bloom in late August and declined by 15 September—the pre-storm sampling date. Across all three stations, phytoplankton abundance showed low variability consistent with summer conditions for Turkey Point and Cedar Point; September pre-storm abundance remained low following the storm at Sandy Point into October (Figure 5). Diatoms showed an increase in their contribution to the community after the storm; however, 2002 and 2004 results also showed increases in diatom representation in the community progressing into the fall season for Turkey Point and Cedar Point (Figure 6).

DISCUSSION AND CONCLUSIONS

Hurricane Isabel produced little short-term impact to the upper Chesapeake Bay phytoplankton community dynamics except in promoting the timing of seasonal changes. Low algal concentrations present before the storm persisted in the upper Bay region after Hurricane Isabel. An increase in the contribution of diatoms to the community after the summer was reflected in drought and wet years compared with 2003. The timing of this shift, however, was closely associated with the period of the storm suggesting a possible event linkage. An algal response was prominent in the lower Bay below the mouth of the Potomac River as measured by increases in chlorophyll *a* subject to wind-mixing effects and storm surge [3]. Isabel was a storm in which winds and runoff were considered comparatively weak but the surge was high, particularly in the upper portions of the estuary. The characteristic effects differed sharply from other hurricanes and tropical storms that affected the region, such as Agnes, which had high precipitation and runoff in the upper watershed, yet weak winds and a minor storm surge [8].

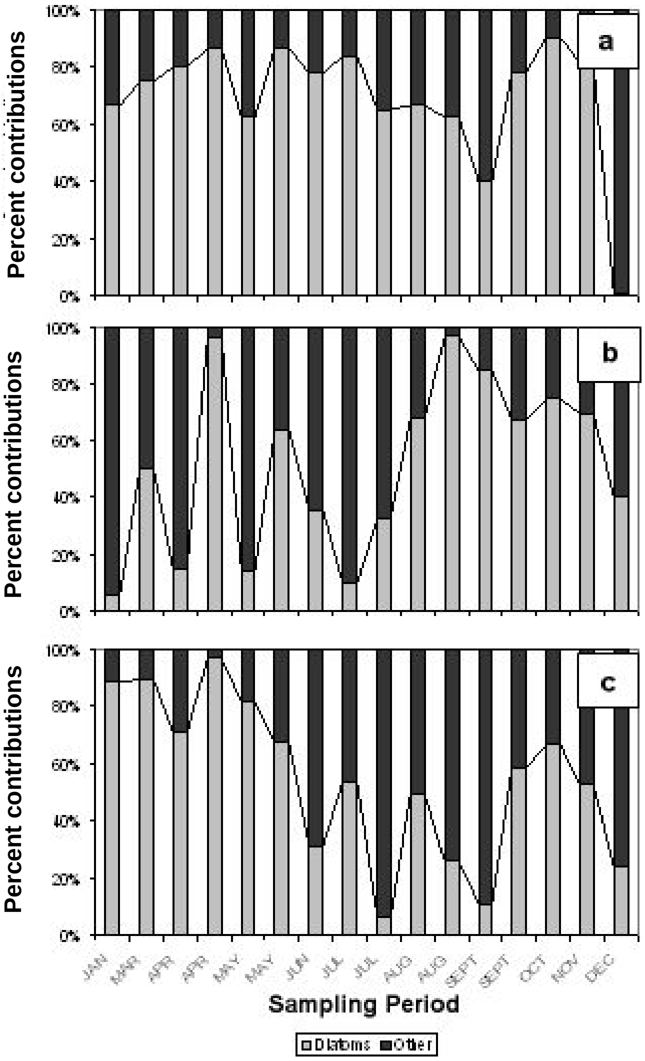

Figure 6. Phytoplankton community shifts during 2003 for mainstem Chesapeake Bay stations Turkey Point (5a), Sandy Point (5b), and Cedar Point (5c).

In contrast to the upper Chesapeake Bay and its tributaries, the cessation of the cyanobacteria blooms on the Potomac River were coincident with storm impacts. Strong winds were measured at National Airport and the surrounding region near the Potomac River, producing a major stress on the bloom. Flows into the region increased dramatically and salinity declines in the oligohaline and mesohaline indicate an advective mechanism to move the remaining bloom downstream. Coincident declines in water temperature below optimal growth conditions, reduced water clarity, and the shorter day lengths of autumn reduced any likelihood for bloom resurgence in the weeks after the storm.

ACKNOWLEDGMENTS

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REFERENCES

1. J.W. Day, Jr., C.A.S. Hall, W.M. Kemp, and A. Yanez-Aranciba. 1989. *Estuarine Ecology*. John Wiley and Sons, New York. 558 pp.
2. W.R. Boynton, W.M. Kemp, and C.W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. In: *Esutarine Comparisons*. V.S. Kennedy (ed.). Academic Press, New York, NY. pp 69–90.
3. W.D. Miller, L.W. Harding Jr., and J.E. Adolf. 2004. Abstract. The influence of Hurricane Isabel on Chesapeake Bay phytoplankton dynamics. Hurricane Isabel in Perspective. Nov. 15–17, 2004. Linthicum Heights, MD.
4. R. Margalef. 1978. Phytoplankton communities in upwelling areas. The example of NW Africa. *Oecol. Aquatica* 3: 97–132.
5. C.S. Reynolds. 1980. Phytoplankton assemblages and their periodicity in stratifying lake systems. *Hol. Ecol.* 3: 141–159.
6. H.W. Pearl. 1988. Growth and reproductive strategies of freshwater blue-green algae (Cyanobacteria). In: *Growth and Reproductive Strategies of Freshwater Phytoplankton*. C.D. Sandgren (ed.). Cambridge University Press, New York, pp. 261–315.
7. G.H. Kruger and J.N. Elhoff. 1978. The effect of temperature on specific growth rate and activation energy of *Microcystis* and *Synnechococcus* isolates relevant to the onset of natural blooms. *J. Limnol. Soc. S. Afr.* 4: 9–20.
8. J.C. Stevenson and M. Kearney. 2004. Abstract. Dissecting and classifying the impacts of hurricanes on estuarine systems. Hurricane Isabel in Perspective. 15–17 Nov., 2004. Linthicum Heights, MD.

DISSECTING AND CLASSIFYING THE IMPACTS OF HISTORIC HURRICANES ON ESTUARINE SYSTEMS

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ABSTRACT

Since the Great Hurricane of 1667 hit Chesapeake Bay, many have tried to describe the impacts caused by these destructive storms. Other than Hurricane/Tropical Storm Agnes in 1972, however, only sporadic efforts have assessed the many changes that can occur during and after these tropical visitors pass. One problem is that hurricanes vary widely in their impact, both temporally and spatially. Not only is wind strength important, but also the path that the winds take over the watershed can prove crucial in their impact. To analyze hurricane impacts more systematically, a simple classification system is proposed that accounts for the three main forcing functions or drivers that can significantly change estuaries.

The first driver emanates from the storm's precipitation and consequent runoff, which can cause massive flushing of the watershed and a freshet in the upper reaches of an estuary. Winds and waves, which can alter shorelines and disrupt normal estuarine stratification processes, constitute the second driver. The third driver is the surge associated with low-pressure systems as these systems move over the Bay, potentially transporting oceanic organisms far up the Bay, overwhelming wetlands, and spilling salt water into normally non-saline uplands. By categorizing each of the drivers into high, medium, and low impacts for hurricanes, three main categories of storms are shown to have affected the Chesapeake Bay in the 20th century with as many as 27 different combinations of wind, storm surge, and precipitation. For example, Isabel is a storm in which winds and runoff remained comparatively weak, but surge was high, particularly in the upper portions of the estuary. This situation differs sharply from hurricanes or tropical storms, such as Agnes, which had high precipitation and runoff in the upper watershed but weak winds and storm surge. Such differences highlight the need for additional analyses of historical storms.

INTRODUCTION

Along with the New World, Christopher Columbus made another startling discovery: hurricanes. He appears to have encountered his first hurricane in 1493, with an additional three during his Caribbean voyages. The Spanish were the first to introduce the Caribbean Indian word for the severe tropical storms to Europe, but it took the English a century to understand fully the fury of these storms.

Hurricanes have captured our imagination and terror at least since 1609 when the wreck of the *Sea Venture* off Bermuda inspired William Shakespeare to write *The Tempest*. In a more scientific context, hurricanes are extreme high-energy events. While such storms are generally rare in a given area, they can obliterate structures in their path and profoundly affect estuarine ecosystems. One of the earliest well-documented hurricanes in Chesapeake Bay occurred in 1667 when a huge storm with 12-ft (3.7-m) surge was noted in a dispatch from Virginia to London [1]:

Sir, having this opportunity, I cannot but acquaint you with the relation of a very strange tempest which hath been in these parts with us called a hurricane which had began August 27th *and continued with such violence, that it overturned* *many houses, burying in the ruines much goods and many people, beating to the ground such as were any wayes employed in the fields, blowing many cattle that were near the sea or rivers, into them, whereby unknown numbers have perished, to the great afflication of all people, few having escaped who have not suffered in their persons or estates, much corn was blown away, and great quantities of tobacco have been lost, to the great damage of many, and utter undoing of others. Neither did it end here, but the trees were torn up by the roots, and in many places whole woods blown down so that they cannot go from plantation to plantation. The sea, by the violence of the wind, swelled twelve feet above its usual height drowning the whole country before it, with many of the inhabitants, their cattle and goods, the rest being forced to save themselves in the mountains nearest adjoining, while they were forced to remain many days together in great want.*

It now appears likely that this was the same hurricane that eight days before passed over Barbados and left most houses standing [2]. The damage was so extensive in Virginia, however, that the Secretary of State of the Colony, Thomas Ludwell, who lived at Rich Neck on Archer's Creek, related the following in a letter to Lord Berkeley of Stratton, a favorite of King Charles II [3]:

this poore country is now reduced to a very miserable condition by a continental course of misfortune. On the 27th of August followed the most dreadful Hurry Cane that ever the Colony groaned under. It lasted 24 hours, began at North East and went around northerly till it came to west and so it came to Southeast where it ceased. It was accompanied with a most violent rain but no thunder. The night of it was the most dismal time I ever knew or heard of, for the wind and rain raised so confused a noise, mixed with the continued cracks of failing houses…The waves were impetuously beaten against the shores and by that violence forced and as it were crowded into all creeks, rivers and bays to that prodigious height that it hazarded the drowning of many people who lived not in sight of the rivers, yet were then forced to climb to the top of their houses to keep themselves above water. The waves carried all the foundations of the Fort at Point Comfort into the river and most of furnished and garrison with it… The nearest computation is at least 10,000 houses blown down, all the Indian grain laid flat on the ground, all the tobacco in the fields torn to pieces and most of that which was in the houses perished with them. The fences about the corn fields were either blown down or beaten to the ground by trees which fell upon them.

The description indicates that the storm could have been a Category 3 or even possibly a 4 on the Saffir-Simpson scale when it hit the lower Chesapeake. Curiously, there appears to be no direct mention of the 1667 event in the official records of colonial Maryland [4]. The only 17th-century reference to a hurricane in Maryland notes another hurricane, which apparently occurred in 1670 [5]. In fact, the 1667 hurricane may have headed inland, missing tidewater Maryland and then recurving sharply eastward, since a severe storm was noted on Manhattan Island shortly thereafter.

Whatever the exact track of the storm, Maryland planters eventually benefited because the storm devastated production in Virginia. Consequently, the price of tobacco, which had been slumping, rose for a brief period. This differential response is due in part to the localized area of high winds that occurs around the inner eye wall, as well as localized surge and rainfall that may differ dramatically over a 200-mile-long ecosystem, such as Chesapeake Bay.

The differences in precipitation, wind, and surge not only vary based on the intensity of hurricanes (now classified by the Saffir-Simpson scale), but also due to the direction that such storms approach the Bay. Obviously, hurricanes that approach an estuarine system from the seaward side have a higher probability of surge than hurricanes that approach from the landward direction. In addition, because of the counter-clockwise circulation patterns of hurricanes in the northern hemisphere, the area on the right side of the approaching storm is more likely to have a higher storm surge.

Table 1. The ten heaviest rains in Virginia from tropical cyclones and their remnants.

Total Rainfall	Dates	Location
27.00" (68.58 cm)	8/19 —20/1969	Nelson County
19.77" (50.22 cm)	11/02 —07/1985	2 NE Montebello
18.13" (46.05 cm)	9/14 —16/1999	Yorktown
16.57" (42.09 cm)	9/14 —16/1999	Newport News
16.00" (40.64 cm)	6/17 —24/1972	Chantilly
14.30" (36.32 cm)	9/14 —16/1999	James City
14.30" (36.32 cm)	9/05 —09/1996	Tom's Branch
14.18" (36.02 cm)	6/17 —24/1972	Centreville
14.17" (35.99 cm)	9/05 —09/1996	Luray 5 SE
13.60" (34.54 cm)	6/17 —24/1972	Big Meadows

Despite the many subtle facets that make each hurricane a distinctive event in a given area, we hypothesize that three primary driving forces—precipitation, wind speed, and storm surge—can be used to construct a storm classification that may prove useful to the environmental community in describing major storm events.

PRECIPITATION

The amount and intensity of rainfall associated with hurricanes is often extraordinary and account for various impacts beyond those associated with wind and wave damage or even surge damage. The classic case of a high-precipitation hurricane/ tropical storm in Chesapeake Bay is Agnes in 1972 in which a deluge occurred not only in the northern Bay watershed, but also in many parts of Virginia. Indeed, three of the highest precipitation amounts of the top ten in Virginia were associated with Agnes from 16–17 June 1972 (Table 1). Table 1 suggests that three classes can be used for the proposed hurricane classification system: P Class A = 0–10 ft (0–25.4 cm), P Class B = 1–20 ft (25.4–50.8 cm), and P Class C >20 ft (>50.8 cm).

WIND

Since the Saffir-Simpson scale is now widely used to describe the potential impacts of hurricanes and tropical storms, the same cut-off points are used for the proposed classification, while condensing them into three classes (Table 2).

Mercifully, the Chesapeake Bay has not yet experienced any recorded hurricanes in the W Class C range. This lack of extremely strong storms is due to the relative protection afforded from the south by the North Carolina landmass and the fact that storms approaching more directly from the east usually have less energy because they have passed over cooler Mid-Atlantic water before moving ashore. Temperatures of the North Atlantic Ocean have been rising faster than any other ocean since the mid-1950's [6], however, increasing the probability that the Bay will experience a W Class C hurricane in the future. Such a hurricane could literally reach catastrophic proportions, particularly if accompanied by high storm-surge levels.

STORM SURGE

The very low atmospheric pressures associated with hurricanes often cause elevated sea states, termed storm surge. Particularly if a hurricane comes ashore at high tide, storm surge

Table 2. The Saffir-Simpson hurricane classification compared to a three-class system.

Tropical Storms Wind <74 mph	**Class A** Wind <95 mph (119 $km \cdot hr^{-1}$)
Category 1 Wind 74 —95 mph	
Category 2 Wind 96 —110 mph	**Class B** Wind 96 —130 mph (154 — 209 $km \cdot hr^{-1}$)
Category 3 Wind 111 —130 mph	
Category 4 Wind 131 —155 mph	**Class C** Wind >130 mph (>209 $km \cdot hr^{-1}$)
Category 5 Wind >155 mph	

can become a significant factor in changing shoreline dynamics. On barrier islands, surge (combined with waves) is capable of cutting new inlets that result in massive changes in estuarine circulation. A classic example of this occurred during the August 1933 storm, which severed Assateague Island south of Ocean City, Maryland. The cutting of that inlet and subsequent stabilization by the U.S. Army Corps of Engineers has led to a more complex altered circulation in Chincoteague Bay and much more saline water in the Maryland Coastal Bays from Sinepuxent northward. A more recent example of inlet creation occurred during Hurricane Isabel; a new inlet was cut in a low point along the Outer Banks south of Cape Hatteras. The maximum surge recorded in Chesapeake Bay was in the range of 2 m during the hurricane of August 1933 [7], but a few hurricanes that have hit the North American coast had surges that exceeded 8 m (e.g., Camille, discussed below). The scale we propose would place surges <2 m into S Class A, 2–4 m in into S Class B, and >4 m into Class C.

STORM CLASSIFICATION

The traditional classification of hurricanes by wind strength typified by the Saffir-Simpson scale has limitations when assessing the impacts of such storms on large and complex estuaries such as Chesapeake Bay due to its unique geography. Given the great length of the Bay and its relative narrowness, storms can have either baywide effects or be restricted in their impact to only part of the system based on the track, intensity, and speed of the storm. By examining the tracks and types of tropical storms that characterized the Chesapeake region during the 20th century (Figure 1), it is possible to delineate as many 27 different combinations of the effects of storm surge, precipitation, and wave processes to classify tropical storms based on their effects in the Bay. When viewed in aggregate, however, two main categories of storms become evident:

1) Backdoor Storms - Backdoor storms either originate in the Gulf of Mexico or are Atlantic hurricanes that make landfall in Georgia or South Carolina and move considerably inland before reaching the middle Atlantic Coast. Their general effects are likely to be high precipitation with large levels of runoff. They can become baywide events if their tracks cross the upper Bay.

2) Outer Banks Landfall - These storms fall into two general groups: *Lower Outer Banks* storms that tend to track along the lower Virginia Eastern Shore with storm surge and waves affecting the lower Bay; and *Upper Outer Banks* storms that generally track northwest, paralleling the main axis of the Bay and producing storm surges and waves that affect the upper and middle Bay (the exception is Hurricane Connie in 1955).

The backdoor storms most often originate as major hurricanes that make landfall adjacent to the Gulf of Mexico, move northeast across the lower Ohio Valley, and then turn east toward the Mid-Atlantic region. Generally, by the time such storms reach the Chesapeake Bay, they have weakened to tropical storm strength in terms of sustained wind speeds, but can pack a considerable punch in terms of precipitation nevertheless. Indeed, two of the most severe floods the Chesapeake region has experienced in the last 35 years were produced by Gulf of Mexico hurricanes—namely hurricanes Camille and Agnes. Because storms of this magnitude are often large and can track over the Appalachian Highlands, catastrophic flooding can occur over a wide area before these storms reach the main Bay. In 1972, Tropical Storm Agnes (born as Hurricane Agnes) produced rainfall amounts in the upper Susquehanna Basin that resulted in unparalleled levels of runoff and discharge into the upper Chesapeake Bay [8]. Three years earlier, remnants of Hurricane Camille, the strongest hurricane to have made landfall in the continental United States in the 20th century, yielded a 27-foot storm surge in Biloxi, Mississippi and produced severe flooding in the lower Bay, especially in the James River.

Backdoor storms, by the very nature of their origin and track as well as their relatively low peak winds and weakening center of circulation, would appear to be unlikely candidates for significant storm surges or winds. Moreover, since most cross

Figure 1. Mid-Atlantic hurricanes in the Chesapeake Bay region during the 20th century. The solid arrow indicates the track of backdoor storms; the dotted arrow shows the general track of lower Outer Banks storms; the dashed arrow gives the general track of upper Outer Banks storms. Modified figure of the Coastal Services Center of NOAA (*www.noaa.gov*).

the Bay's main stem at right angles (i.e., the least favorable direction for significant fetch in this long and relatively narrow estuary), substantial wave activity across the Bay is likely restricted to the storm's vicinity.

The same cannot be said for hurricanes and even strong tropical storms making landfall on the Outer Banks. The storms coming ashore just south of the Chesapeake Bay have constituted some of the strongest and most damaging storms (many Category 2 and some Category 3 on the Saffir-Simpson scale and Category 2 on the simplified scale presented here) affecting the estuary in the last century. The relative impact of the Outer Banks depends on where these storms make landfall since this influences their track across the Bay. Storms that make landfall on the lower Outer Banks tend to follow tracks that lead over the Tidewater area of Virginia and the lower Virginia Eastern Shore. Apart from storm surges (depending on the central pressure in the eye), waves generated by these winds from the southwest quadrant generally produce flooding in the peninsula down through Virginia Beach. If the storm tracks along the Virginia Eastern Shore, close to the Bay stem, the York and Rappahannock rivers could also come under the influence of storm tides (i.e., waves). Hurricane Brenda (1960) and Hurricane Doria (1971) typify this category of storm.

Perhaps the most dangerous storms in terms of baywide effects are those that make landfall on the upper Outer Banks, just south of the Virginia state line. These storms drive waves into the Bay from the northeast quadrant that flood Tidewater Virginia (in addition to the storm surge), and then track north-northwest paralleling the Bay. This situation contrasts with the lower Outer Banks storms, which tend to drive winds (and waves) to the southwest (Figure 2). By the time these storms reach the latitude of the mid-Bay, they have often moved as far west as West Virginia, but by this point, their effects can reach well into the upper Bay.

With winds coming from the south-southeast across the main axis of the Bay for several hours as they move north, these storms can produce substantial "wind tides," piling up water in the middle and upper Bay. Although the phenomenon is often associated with open coast nor'easters and hurricanes, it is possible that such storms create the conditions for significant wave setup. This phenomenon occurs when waves break on a beach, with the surf progressively increasing the nearshore water level. The longer the waves break at the shoreline, with wave crests parallel or sub-parallel to the trend of the shoreline, the greater the setup. Field measurements taken during storms indicate that a setup of 1 m is possible [9], with the potential for shifting the effective shoreline considerably inland depending on the coastal profile. On the lowlying Eastern Shore, such a setup would translate to extensive flooding.

Like the catastrophic flooding during the Great New England Hurricane of 1938, which could be accounted for by storm surge elevations alone, wave setup probably explains a good deal of the flooding that occurred in the middle and upper Bay from Hurricane Isabel and the notorious "Storm King" Hurricane of 1933. Both storms followed very similar tracks, staying close to the western

Figure 2. Directions of winds from lower Outer Banks storms that track to the northeast across the lower Delmarva Peninsula and upper Outer Banks storms that track to the north-northwest, paralleling the western shore of the Bay.

shore of the Bay until reaching the latitude of Maryland. With hurricane-force winds for almost 4 to 5 hours pushing up the axis of the Bay, the situation in each case was ripe for wave setup. In a highly irregular coast like that of the Chesapeake, however, not all areas in the upper and middle Bay receive waves approaching directly onshore—the most ideal condition for wave setup.

Though analysis of storms over the last 150 years indicates that the occurrence of storms such as Isabel is comparatively infrequent, two trends are converging to make the future impact of large tropical storms in the Chesapeake Bay greater than ever before. Development around the Bay's shore has burgeoned in the last two decades, far beyond any expectations of a few generations ago. Even though shoreline development has probably reached saturation in some areas (such as Annapolis), with approximately 6,000 miles (9654 km) of tidal shoreline many areas remain that can reasonably be considered undeveloped. Estimates for the growth of county populations in some of these areas predict figures anywhere from 50% to 100% higher by the year 2020 [10]. Upper Bay tributaries, such as the Sassafras, could look substantially different in terms of shoreline development within a generation.

Concurrently, sea level rise is projected to increase significantly over this century [11] and will heighten the flood risk. Moreover, as the waters of the Chesapeake Bay deepen with increasing sea level, the capacity of waves to produce greater damage will be significantly enhanced. Because most of the Bay is relatively shallow (generally averaging between 4.5 and 6 m), any increase in its average water depth will disproportionately influence wave power. Figure 3 shows how much the increase in the average depth of the Bay over approximately the past 60 years (~0.3 m) has affected wave power from the same, very moderate storm with winds of 40 $km \cdot hr^{-1}$. For a 4-sec wave, wave power increases by 40% (Figure 3) with a substantial increase in the likelihood of higher rates of shore erosion, wave damage to shore structures, and coastal flooding.

ECOLOGICAL EFFECTS OF HURRICANE TYPES

The ecological effects of tropical storms on mid-latitude complex estuaries such as the Chesapeake Bay have mostly been examined from the standpoint of flooding impacts. Wave and wind effects are less well understood. In the Chesapeake Bay, there are good reasons for this relative lack of information on wave and wind impacts from tropical storms. Foremost among them is the passage of 50 years without a significant hurricane traversing the main stem of the Bay. Unfortunately, when the eye of Hurricane Connie crossed the Bay in 1955, the quality of the instrumentation was primitive compared to current devices. More importantly, the spatial distribution of monitoring stations at the time was quite limited. Though

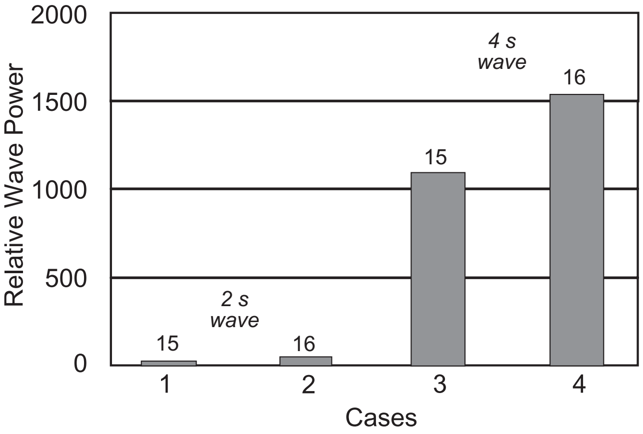

Figure 3. The increase in wave power associated with increasing average water depth in Chesapeake Bay from 4.5–4.8 m, with winds of 40 km·hr^{-1} and a fetch of 15 km.

Connie may have generated waves with heights of perhaps 6 m off Tangier Island [16], little evidence is extant in the literature concerning the effects of waves on the Bay ecosystem.

The other principal reason for the information gap, still true today, is the lack of an adequate baywide wave model, especially for areas such Tangier Sound where an archipelago of islands creates the potential for complex wave refraction patterns. Tangier Sound, coincidentally, is an area of extensive seagrass beds, fringed by some of the largest coastal marshes in the Bay. Both ecosystems would presumably be severely affected by large waves causing subtidal and shore erosion as well as by littoral transport of large volumes of sand (sand makes up most of the shallow shoreface of the sound).

Certainly, a major hurricane making landfall in the Chesapeake Bay and following a track similar to Hurricane Connie (i.e., an upper Outer Banks storm) could be expected to cause locally substantial erosion, both subtidally and at the shore (Figure 4). Moreover, in areas where annual longshore transport is high (such as Calvert Cliffs [17]), severe disruption of benthic communities by unprecedented sand transport could occur.

The impact of backdoor storms, which are mainly precipitation/flooding events, rests on more solid evidence. The existing literature on the ecological effects of hurricanes in Chesapeake Bay has been largely influenced by Tropical Storm Agnes in 1972. This storm, in the classification proposed here, clearly belongs to the backdoor category though its track across the upper reaches of the Susquehanna River was different from more classic backdoor storms, such as Camille. In addition, Tropical Storm Agnes occurred in June, as opposed to August or July. Nonetheless, this storm serves as an example of how an extreme precipitation event can affect the ecology of the Bay.

Peak flooding from Tropical Storm Agnes in the Chesapeake Bay occurred from 21–24 June 1972. The initial effects of the storm were a dramatic reduction in salinity (especially in the upper and middle Bay) along with tremendous flushing of the Bay system overall [18]. Due to the exceptional runoff, suspended concentrations reached unprecedented levels [19].

Tropical Storm Agnes was also associated with high sediment concentrations and high nutrient loads. The precipitous drop in salinities and high flushing rates particularly affected the plankton communities. In the Virginia portion of the mainstem Chesapeake Bay, Grant et al. [20] reported much lower than normal zooplankton biomass (89 mg·m^{-3} in August of 1972 compared to 269 mg·m^{-3} the previous August). This difference is largely reflected the decimation of Cladocerans following the flood. However, sampling at seven

Figure 4. Shore and subtidal erosion from the 1933 "Storm King" hurricane at the Chesapeake Biological Laboratory. Photo courtesy of the Calvert Marine Museum.

stations by Heinle et al. [21] off of Calvert Cliffs revealed little change in the usually dominant euryhaline copepod *Acartia tonsa* population, compared to *Oithona brevicornis*, which disappeared after Agnes. The latter species does not tolerate low salinity (which was ~1.0 psu in the surface layer there on 28 June 1972).

Agnes also disrupted benthic communities, particularly clam and oyster populations, for which mortality varied greatly depending on location [22]. Generally, clam and oyster beds in the upper parts of the tributaries were hardest hit; there was also a marked decline in the occurrence of submersed aquatic vegetation (SAV) baywide by about two-thirds. Later interpretations attributed the seagrass decline to elevated nutrients introduced by high runoff [23].

Overall, the impacts of Tropical Storm Agnes—especially those resulting from the massive sediment accumulation and excessive nutrient loading including the increase in phytoplankton and the decline of SAV—persisted into subsequent years [23, 24]. Arguably, Agnes can be viewed as the turning point at which the Chesapeake Bay shifted from a benthic to planktonic system, in terms of productivity.

Tropical storms in the Chesapeake Bay can also affect the coastal wetlands. Studies [25] indicate that much of the loss in the extensive marshes on the lower Eastern Shore resulted from storm waves eroding the edges of large interior ponds. It follows that hurricanes (or large nor'easters) with peak winds of 180 km·hr^{-1} would cause massive edge erosion in interior ponds; even winds of 40 km·hr^{-1} can cause substantial erosion [15]. Such potentially massive marsh erosion in some areas of the Eastern Shore brings enormous concentrations of suspended solids, much of it organic carbon [26], into the estuary in amounts that easily dwarf the quantity of suspended sediments contributed by river runoff. In this respect, the impacts of a hurricane or large tropical storm could spread far beyond the marshes and associated loss of habitat for wading birds and invertebrates, ultimately influencing estuarine turbidity.

SUMMARY

More detailed classifications of hurricane characteristics, tracks, and wave generation, as attempted in this paper, could prove helpful to the scientific and management communities in assessing the impacts of past storms and providing a better understanding for planning. The public is keenly aware of the destructive power of hurricanes in terms of societal impact. Hurricanes and other tropical storms are not totally without benefit, however, and this or other classification schemes might help identify when and where such storms could yield positive changes in the natural system. For example, cleaner ocean water brought in to estuaries may dilute the normally high nutrient waters now present in U.S. coastal environments. In addition, studies of hurricanes on marsh accretion in Louisiana [12], as well as extratropical storms in Florida [13] and Delaware [14], indicate that high accretion rates result from storms and suggests that they play an important role in the long-term maintenance of marsh systems, which need to keep up with rising sea levels. Others have argued that while some events may help subsidize the sediment budget of some tidal marshes, other events can be quite erosive [15]. Clearly, more study of key processes in estuaries in relation to various types of hurricanes should be undertaken. A fully developed hurricane classification system could potentially aid such research.

REFERENCES

1. R.V. Truit. 1968. *High Winds and Waves: A Chronicle of Maryland's Coastal Hurricanes*. Natural Resources Institute. Educational Series No. 77. University of Maryland Press. College Park, MD. 35 pp.
2. R.H. Schomburgk. 1848. *The History of Barbados*. Frank Cass Publishers Reprint Edition (1971), London, U.K. 722 pp.
3. W.N. Sainsbury (ed.). 1880. *Calendar of State Papers: Colonial Series, American and West Indies, 1661-1668*. Longman & Co. London. 32 pp.

4. A.P. Middleton. 1984. *Tobacco Coast: A Maritime History of Chesapeake Bay in the Colonial Era*. Johns Hopkins University Press. Baltimore MD, 508 pp.
5. P.G. Clemens. 1980. *The Atlantic Economy and Colonial Maryland's Eastern Shore: From Tobacco to Grain*. Cornell University Press. Ithaca, NY. 249 pp.
6. S. Levitus, J.I. Antonov, T.P. Boyer and C. Stevens. 2000. Warming of the world ocean. *Science* 287: 2225–2229.
7. U.S. Army Corps of Engineers. 1959. *Hurricane Survey: Norfolk, Virginia*. Engineer District. Norfolk, VA.
8. J. Davis and B. Laird (eds.). 1976. *The Effects of Tropical Storm Agnes on Chesapeake Bay Estuarine Systems*. Chesapeake Research Consortium Publication No. 54. Johns Hopkins University Press. Baltimore, MD. 639 pp.
9. R.A. Holman and A.H. Sallenger. 1985. Set-up and swash on a natural beach. *J. Geophys. Res.* 90(C1): 945–953.
10. J.C. Stevenson and M.S. Kearney. 1996. Shoreline dynamics on the windward and leeward shores of a large temperate estuary. In: *Estuarine Shores: Hydrological, Geomorphological and Ecological Interactions*. K.F. Nordstrom and C.T. Roman (eds.). John Wiley & Sons. New York. pp. 233–259.
11. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Makell, and C.A. Johnson. 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press. Cambridge, U.K. 881 pp.
12. R.H. Baumann, J.W. Day, Jr., and C.A. Miller. 1984. Mississippi deltaic wetland survival: sedimentation versus coastal submergence. *Science* 224: 1093–1095.
13. L.A. Leonard, A.C. Hine, M.E. Luther, R.P. Stumpf, and E.E. Wright. 1995. Sediment transport processes in a west-central Florida open marine marsh tidal creek: the role of tides and extra-tropical storms. *Est. Coast. Shelf Sci.* 41: 225–248.
14. R.P. Stumpf. 1983. The process of sedimentation on the surface of a salt marsh. *Est. Coast. Shelf Sci.* 17: 495–508.
15. J.C. Stevenson, L.G. Ward, and M.S. Kearney. 1988. Sediment transport and trapping in marsh systems: implications of tidal flux studies. *Mar. Geol.* 80: 37–59.
16. D.G. Shomette. 1982. *Shipwrecks of the Chesapeake: Maritime Disasters on Chesapeake Bay and its Tributaries, 1608–1978*. Tidewater Publishers, Centreville, MD, p. 324.
17. L.L. Downs. 1993. Historical Shoreline Analysis and Determination of Littoral Cells, Rockhold Creek to Solomons Island, Chesapeake Bay. Thesis, University of Maryland. College Park, MD.
18. M. Dahlberg. 1978. Tropical Storm Agnes and estuaries. *Ecology* 59(2): 423.
19. J.R. Schubel. 1974. Effects of Tropical Storm Agnes on the suspended solids of the Northern Chesapeake Bay. In: *Suspended Solids in Water*. R. Gibbs (ed.). Plenum Press, New York. pp. 113–132.
20. G.C. Grant, B.B. Bryan, F. Jacobs, and J.E. Olney. 1977. Effects of Tropical Storm Agnes on zooplankton in the lower Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Bay Research Consortium Publication No. 54. Johns Hopkins University Press. Baltimore, MD. pp. 425–442.
21. D.R. Heinle, H.S. Millsaps, and C.V. Millsaps. 1977. Effects of Tropical Storm Agnes on standing crops and age structure of zooplankton in middle Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. Johns Hopkins University Press, Baltimore, MD. pp. 443–447.
22. D.S. Haven, W.J.Hargis, J.G. Loesch, and J.P.Whitcomb. 1977. The effect of tropical storm Agnes on oysters, hard clams, soft clams, and oyster drills in Virginia. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium

Publication No. 54. Johns Hopkins University Press, Baltimore, MD. pp. 488–508.

23. J.C. Stevenson and N.M. Confer. 1978. Summary of Available Information on Chesapeake Bay Submerged Vegetation. U.S. Fish and Wildlife Service, Biological Services Program (FWS/OBS-78/66) NTIS, 335 pp.
24. M.E. Loftus and H.H. Seliger. 1977. A comparative study of primary production and standing crops of phytoplankton in a portion of the upper Chesapeake Bay subsequent to tropical storm Agnes. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System.* E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. Johns Hopkins University Press. Baltimore, MD. pp. 509–521.
25. M.S. Kearney, R.E. Grace, and J.C. Stevenson. 1988. Marsh loss in the Nanticoke Estuary, Chesapeake Bay. *Geogr. Rev.* 78: 205–220.
26. M.S. Kearney, A.S. Rogers, J.R.G. Townshend, J.C. Stevenson, J. Stevens, E. Rizzo, and K. Sundberg. 2002. Landsat imagery shows decline of coastal marshes in Chesapeake and Delaware Bays. *EOS* 83(16): 173, 177–78.

EFFECT OF TIMING OF EXTREME STORMS ON CHESAPEAKE BAY SUBMERGED AQUATIC VEGETATION

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ABSTRACT

The Chesapeake Bay Estuarine Water Quality Model was used to assess the effect of extreme storm events (≥100-year storms) in different seasons on submerged aquatic vegetation (SAV). For this analysis, a three-year portion (1985–1987) of the ten-year (1985–1994) calibration period was simulated, including the November 1985 Hurricane Juan storm. Hurricane Juan was a 100-year storm in the basins of the Potomac and James rivers. The simulated November 100-year storm event was compared with other scenarios, in which an equivalent 100-year storm is simulated in the spring, summer, or autumn. These scenarios indicated that the severity of extreme-storm SAV damage depends on storm timing relative to the SAV growing season. Model estimates showed that an extreme storm can cause significant damage if it occurs in months of high SAV shoot biomass, but has no significant impact on SAV if the storm takes place in the winter or in other periods outside of the SAV growing season.

INTRODUCTION

Submerged aquatic vegetation (SAV) is important for crab, fish, and other aquatic habitats in the Chesapeake estuary [1]. Sufficient light at an appropriate depth is essential for the growth of these plants. Suspended sediment blocks light to SAV, as does excessive nutrient input that causes phytoplankton and epiphytic algae light attenuation sufficient to impair SAV growth. Suspended sediment is a major component of light attenuation and is the major impairment to SAV restoration in many regions of the Chesapeake Bay [1, 2]. Upland loads and erosion of shoreline are two major sources of suspended sediment in the Chesapeake estuary.

Sediment loads delivered to the Bay by extreme storms in just a few days are comparable to annual average sediment loads. In the last several decades, the Bay has experienced extreme storms or events that have influenced water quality and SAV to a greater or lesser extent [3, 4, 5]. An example of a high level of persistent negative influence on water quality and SAV is the June 1972 event of Hurricane Agnes [5]. Thought to be a key event in the long-term degradation of the Chesapeake SAV resource ". . . all [SAV] decreased significantly through 1973. . . eelgrass decreased the most (89%). . . For all species combined the decrease was 67%." [5].

In contrast, a January 1996 event on the Susquehanna led to flooding on the same scale as Agnes due to a period of warmer weather and extensive rain on snowpack, as well as the formation and subsequent breaching of an ice dam. This extreme storm had little discernible influence on Chesapeake water quality and SAV beyond the immediate event, though the storm had flows and sediment loads comparable to Agnes [3]. The June 1972 Agnes event delivered an estimated 30 million MT (metric tons) and the January 1996 event brought in 10 million MT of silts and clays, each over a period of days compared to an annual average fine-grain sediment load of about 1 million MT for the Susquehanna. This work uses the Chesapeake Bay Estuarine Model to assess the differential impacts of extreme storms that occur in different seasons on SAV.

METHODS

The year 2002 version of the Chesapeake Bay Estuarine Model (CBEM) [6] is used to model the response of SAV to nutrient and sediment loads. The CBEM is a coupled three-dimensional Hydrodynamic Model and Water Quality Model [6, 7]. The Water Quality Model is simulated in a 15-minute time step, driven by hydrodynamic forcing in a two-hour interval, with daily inputs of nonpoint sources and other loads. The model was calibrated over a ten-year period (1985–1994) [6].

Water quality and SAV responses to flow and loads were successfully simulated by both the Chesapeake Bay Watershed Model [8] and the Water Quality Model [6] for the calibration period of 1985–1994, including Hurricane Juan, a 100-year storm occurring in November 1985. The following points describe three important components of the model in this work.

1) The Water Quality Model simulates light extinction (K_e) due to water, dissolved organic matter (DOM) also know as "color," volatile suspended sediment (VSS), and inorganic suspended sediment (ISS) [6, 9]:

$$K_e = a^1 + a^2 * ISS + a^3 * VSS \quad (1)$$

where:

a_1 = background attenuation from water and DOM

a_2 = attenuation from inorganic solids

a_3 = attenuation from organic suspended solids

2) The simulated SAV production is light, temperature, and nutrient dependent. The SAV submodel simulates three major components: shoots, roots, and epiphytes. Production transformation between shoots and roots is considered. The simulated shoot reflects the above-ground abundance of SAV. The following equation is shoot simulation in the SAV submodel in the CBEM [9]:

$$\frac{d\,SH}{d\,t} = [P - (1\text{-}Fpsr) - R - SL]\,SH + TrsRT \quad (2)$$

where:

SH = SAV shoot biomass; (g C m^{-2});

t = time (d);

Fpsr = fraction of gross production routed from shoot to root;

P = production (d^{-1});

R = shoot respiration (d^{-1});

SL = sloughing (d^{-1});

Trs = rate at which carbon is transported from root to shoot (d^{-1}).

RT = root biomass (g C m^{-2}),

3) The setup of scenarios with a 100-year storm in different seasons is as follows:

The November storm scenario simulates the actual November, 1985 Hurricane Juan event. Although only a Category 1 hurricane, Juan ranks as the eighth costliest hurricane to strike the U.S. mainland. In the Chesapeake, Hurricane Juan constituted a 100-year storm that caused flooding primarily in the Potomac and James watersheds. The other scenarios simulate an extreme storm occurring in other months, including May, July, and September in 1985, or a simulation of no storm in the year 1985.

Hurricane Juan hit the Chesapeake region on 3 November in 1985, and lasted for 3 days as a high rainfall event centered in the upper watersheds of the Potomac and James rivers. The high river flows from this rainfall event persisted for about 2 weeks (Figure 1). The hydrology and nonpoint load of one spring-neap tide cycle (about 14 and a half days) during 1–15 November in 1985 were used as the "storm input" for other scenarios. For example, the May Storm Scenario uses the equivalent "storm input" in May. In the meantime, the September low-flow condition in one spring-neap tide cycle was used as the "no-storm condition" input during 1–15 November for the May Storm Scenario (Figure 2). The 14-and-a-half-day storm substitution matches the cycles of the spring-neap tides (from the 1985 tide record) [10]. Since point source load input for the Water Quality Model input is monthly and varies only a trivial amount during among the 1985 months, point source load is not adjusted for these scenarios.

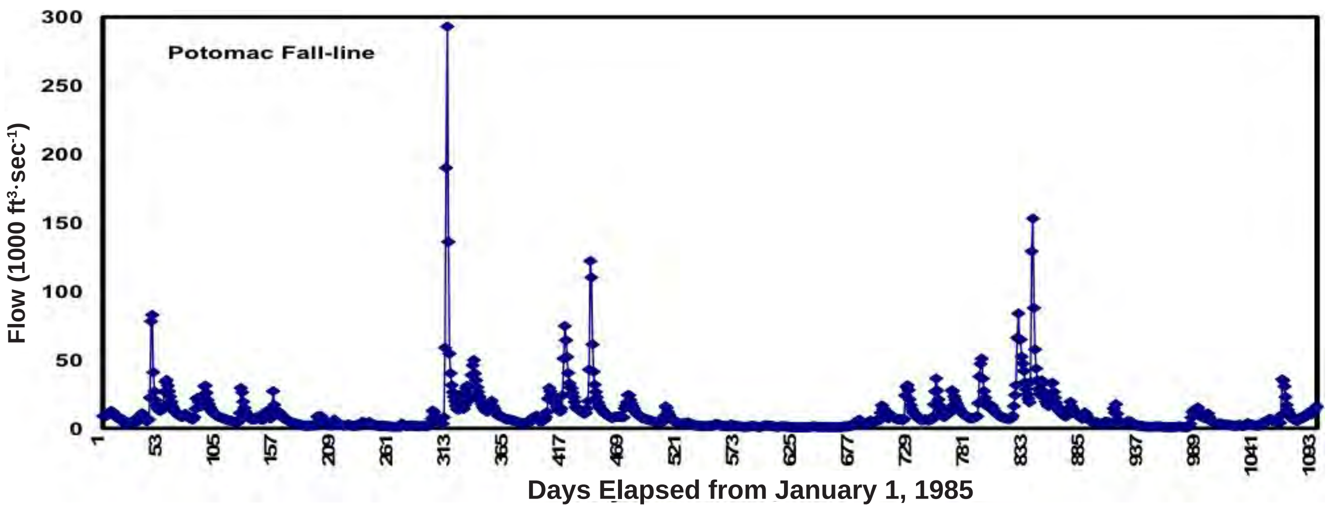

Figure 1. Daily flow at the fall-line of the Potomac River (1985–1987).

The CBEM is simulated for 3 years from 1985 to 1987. All of these scenarios use the same hydrology and loading inputs in the simulation during 1986 and 1987.

RESULTS AND DISCUSSION

Effect on Water Clarity by Hurricanes

In the tidal-fresh Potomac region, light attenuation (K_e) increases abruptly due to the simulated 100-year storm event (Figure 3). Four light attenuation peaks (K_e near 100 m^{-1}) correspond to the simulated May, July, September, and November storms. The light attenuation remains high (K_e >4 m^{-1}) for weeks after the storm, most significantly (e.g., K_e >8 m^{-1}) in the first week after the storm. The graph's open circle symbol denotes the No-Storm Scenario, which has no extreme high peaks in light attenuation. However, K_e in many days is higher than the optimal level to SAV communities (tidal-fresh SAV, K_e <2.0 m^{-1} at 1-m depth). The fluctuation of K_e, 2–8 m^{-1}, in the No-Storm scenario is due to minor storms in 1985–1987. After day 320, all five scenarios have almost the same K_e levels. The simulated long-term effects, other than the storm event, are essentially the same in all five scenarios. Figure 4 shows the TSS concentration peaks, which are almost entirely

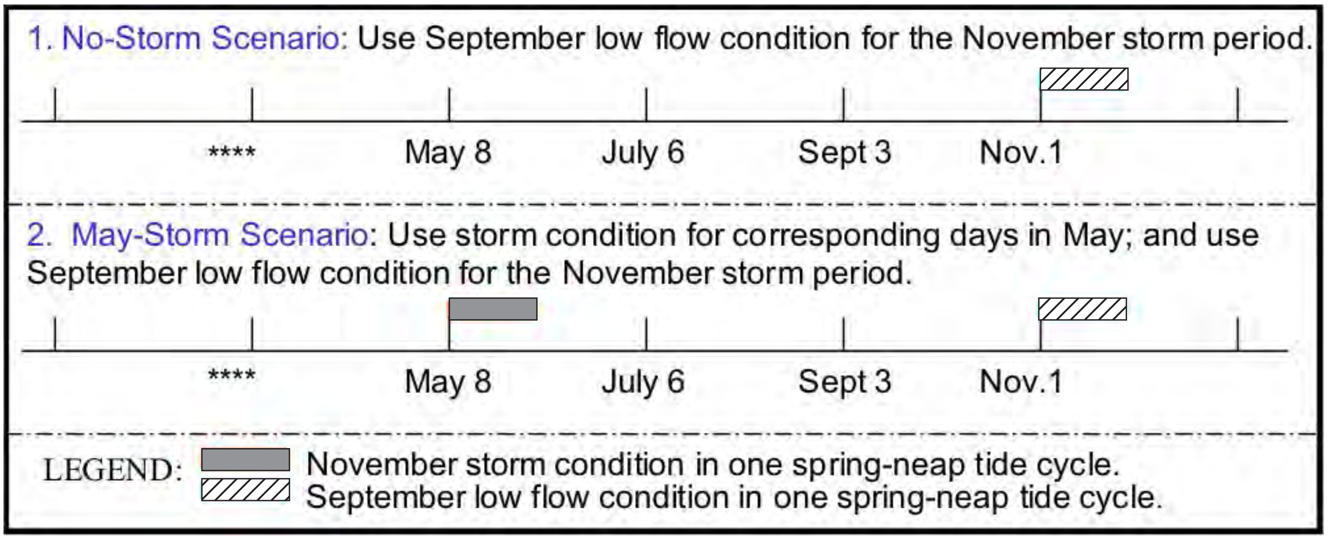

Figure 2. Example of the method used to simulate the Hurricane Juan event in May.

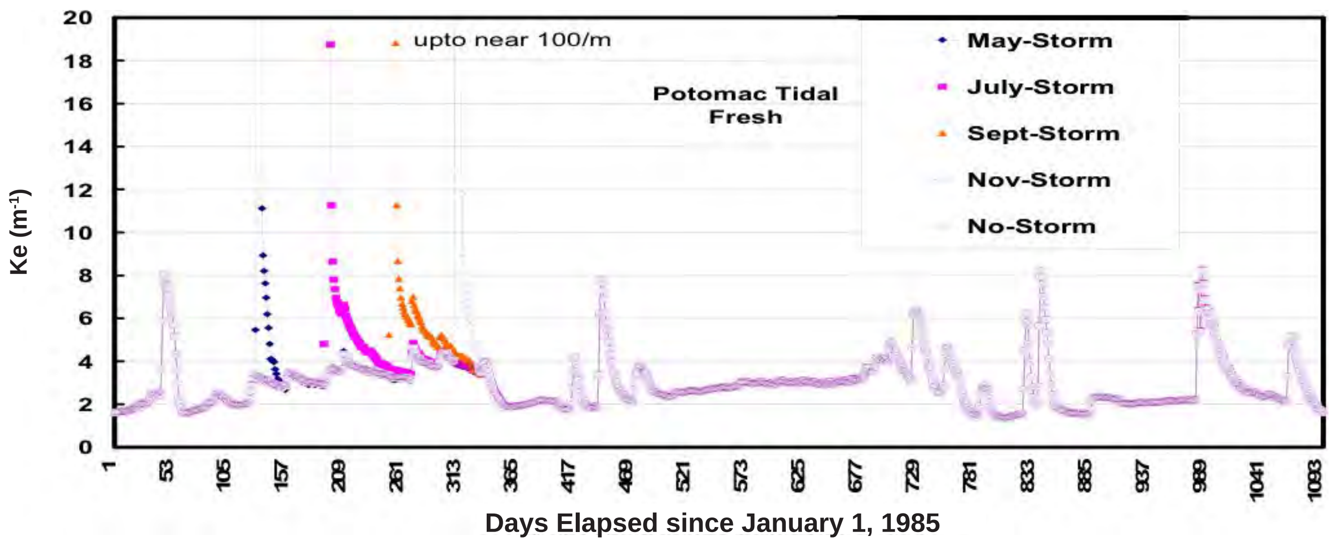

Figure 3. Ke in the Potomac tidal fresh region for five scenarios.

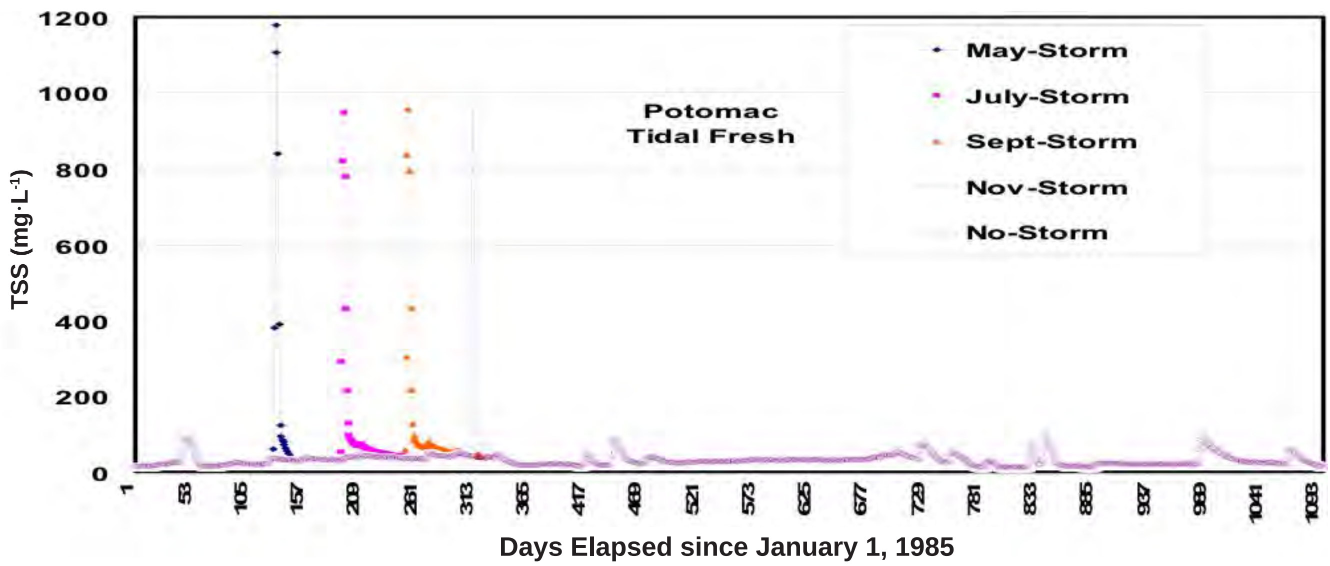

Figure 4. TSS in the Potomac tidal fresh region for five scenarios.

due to inorganic suspended solids, for the different scenarios.

Effect of Extreme Storms in Different Seasons on SAV

Tidal-Fresh Regions

Figure 5 and Figure 6 are simulated monthly SAV biomass from 1985 to 1987 in the Potomac and James rivers' tidal-fresh regions. Generally, the shoot biomass of the tidal-fresh SAV community peaks during September and October with a prominent growing season of shoot biomass from May to November (Figure 7) [9, 11]. The tidal-fresh SAV community is simulated in both the Potomac and James tidal-fresh regions (Figures 5 and 6).

The Potomac and James tidal-fresh (Figures 5 and 6), SAV biomass was decremented in the first year by the simulated May, July, and September extreme storm. The November extreme storm has no more effect than the No-Storm Scenario. After the peak in September, SAV growth follows the natural decline of shoots toward winter; therefore, the response of SAV to a post-peak storm is less than the response of SAV to a storm during or before the peak.

SAV biomass was also affected in the second year in the May, July, and September scenarios and again the effects of the November storm were indiscernible from the No-Storm Scenario (Figures 5 and 6). The second-year influence of the May, July, and September scenarios probably results from decreases in simulated overwintering SAV root due to the Fpsr and Tsr terms in Equation 2.

This decrease suggests that lower shoot survival during the winter due to the effect of storm before winter results in the apparent lower biomass in the following year for the corresponding storm scenario.

Polyhaline Region

Figure 8 shows simulated monthly SAV biomass from 1985 to 1987 in the lower estuary polyhaline James River. The polyhaline SAV community peaks in July and again in October, with a prominent growing season of shoot biomass occurring from April to November [9, 11], as shown in Figure 9.

In the James lower estuary polyhaline region, simulated SAV shoot biomass is decreased by the May, July, and September simulated extreme-storm events but not by the November simulated extreme storm (Figure 8). In this storm, the simulation of

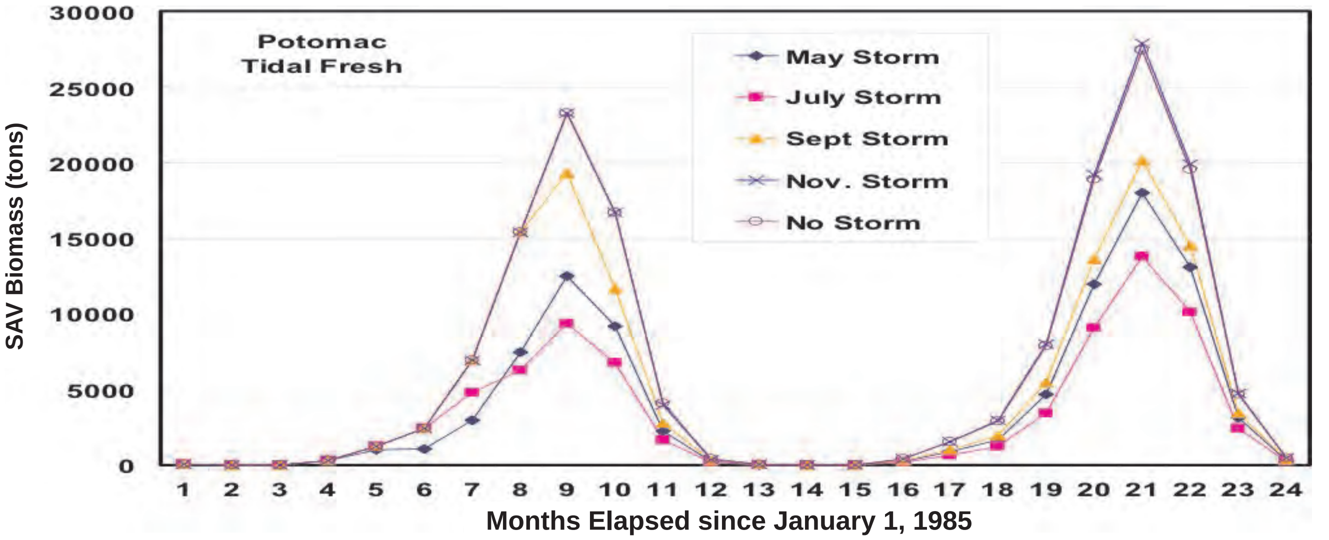

Figure 5. SAV biomass in the Potomac tidal fresh region for five scenarios.

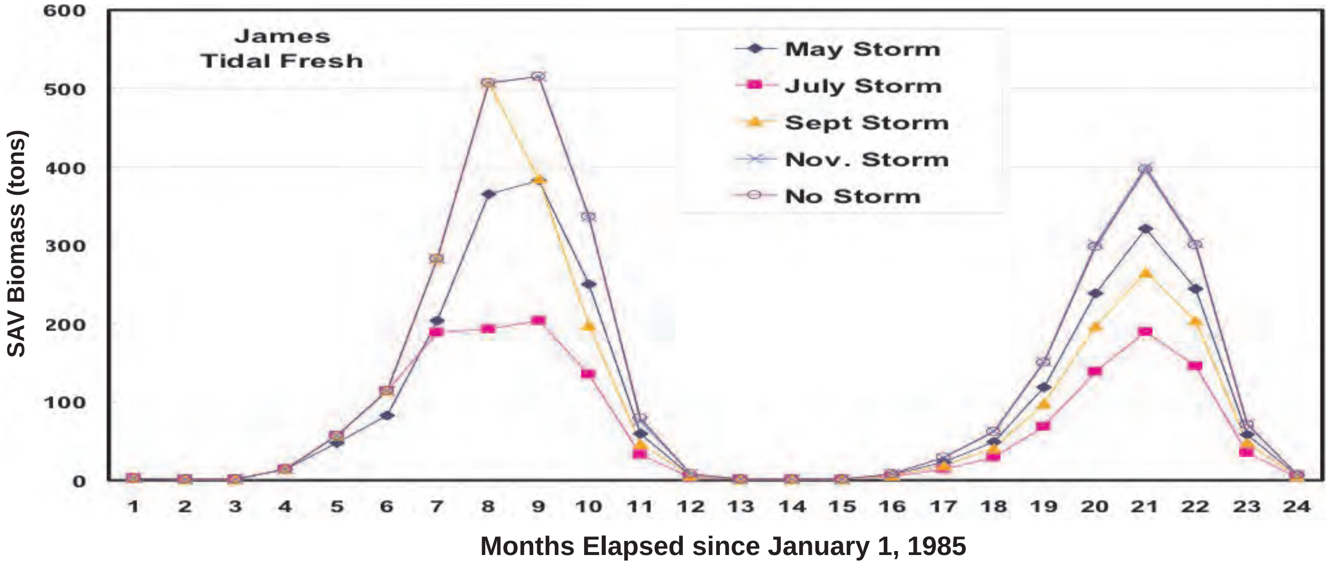

Figure 6. SAV biomass in the James tidal fresh region for five scenarios.

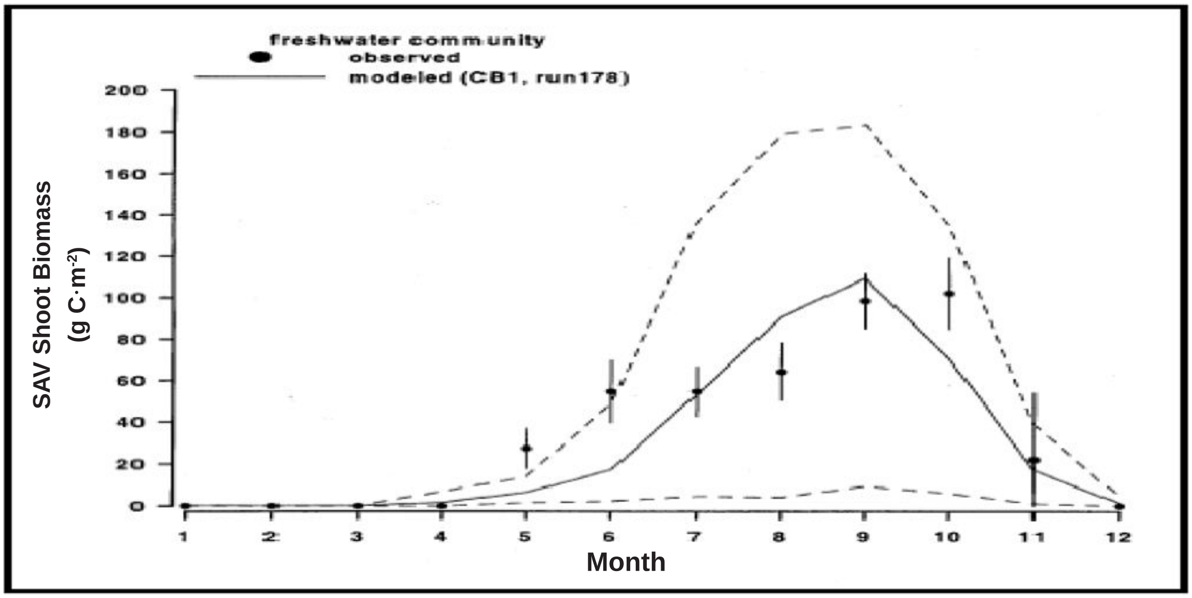

Figure 7. Simulated and observed SAV shoot biomass for a tidal fresh SAV community. Modeled (mean [solid line] and interval encompassing 95% of computations [dashed line]) and observed (mean [dot] and 95% confidence interval [vertical line through dot]) freshwater SAV community (above-ground shoot biomass only). Observations from Moore et al. [11]. Model simulation from the Susquehanna Flats (Segment CB1TF) using the 10,000-cell 1998 version of the Water Quality Model. Source: Cerco et al. [9].

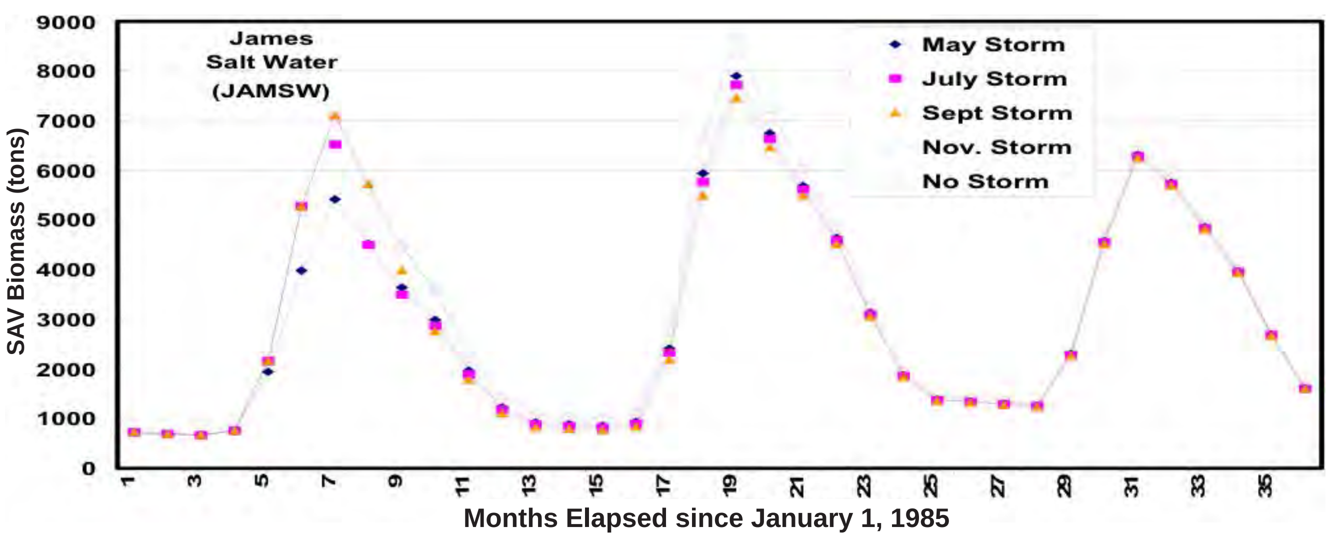

Figure 8. SAV biomass in the James lower estuary region for five scenarios.

the first year's effects is the same in the tidal-fresh and polyhaline SAV communities. A difference occurs in the second year when the simulated polyhaline SAV shoot biomass is influenced by the November extreme storm.

In all cases, by the third year the effect of simulated extreme storm events on SAV shoot biomass is unobserved.

CONCLUSIONS

Based on the model scenarios, the following conclusions were reached:

- Extreme events, such as hurricanes, deliver high sediment loads and reduce clarity below that level required to support SAV, often over a period of weeks.

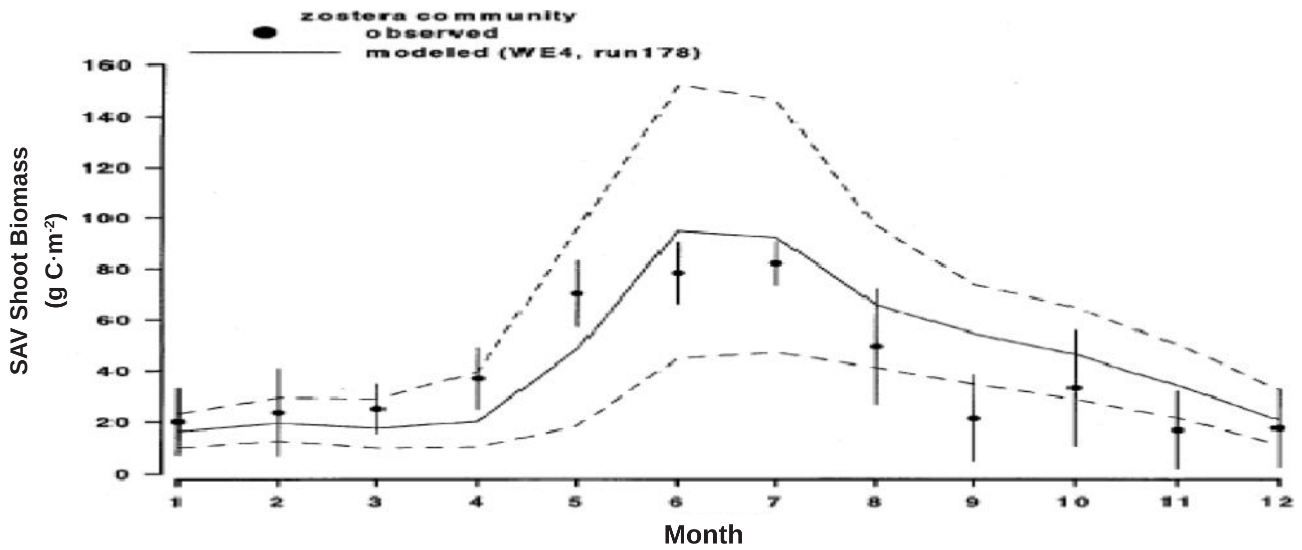

Figure 9. Simulated and observed SAV shoot biomass for a polyhaline SAV community. Modeled (mean [solid line] and interval encompassing 95% of computations [dashed line]) and observed (mean [dot] and 95% confidence interval [vertical line through dot]) polyhaline SAV community (*Zostera* above-ground shoot biomass only). Observations from Moore et al. [11]. Model simulation from Mobjack Bay (segment MOBPH, formerly WE4) using the 10,000-cell 1998 version of the Chesapeake Bay Water Quality Model. Source: Cerco et al. [9].

- Extreme storm events during the SAV growing season are detrimental, particularly during periods before peak shoot biomass.
- Extreme storms during the SAV growing season, but after the shoot biomass peak, are estimated to be less detrimental. In the simulated tidal-fresh SAV community, the November extreme event has no effect on SAV shoot biomass as the shoot biomass during this time is already in a normal, natural decline leading to an absence of SAV shoot biomass by December.
- In tidal-fresh SAV communities, the degree of diminution of SAV shoot biomass carries over as an "echo" of decreased SAV biomass in the second year. This effect is due to the decrease in simulated shoot biomass carried forward by a decrease in simulated shoot biomass. By the third simulated year of SAV response, the effect of extreme storms on SAV biomass is generally unobserved.
- In the simulated polyhaline James SAV community, the SAV response to extreme storms was similar to that of the tidal fresh with the exception of the November storm. In this case, the simulated November storm is close to the secondary October peak in the polyhaline SAV community shoot biomass. The resulting decreased SAV shoot biomass in November carried over to a noticeable SAV decrease during the second year.
- Timing of storms relative to SAV growing seasons causes different effects on SAV, consistent with the observations noted in the introduction [3, 4, 5], though the model does not directly simulate some of these storms.

REFERENCES

1. R.A. Batiuk, P. Bergstrom, M. Kemp, and others. 2000. In: Chesapeake Bay Submerged Aquatic Vegetation Water Quality, Habitat-Based Requirements, and Restoration Targets: A Second Technical Synthesis. USEPA Chesapeake Bay Program, Annapolis, MD. 217 pp.
2. L.C. Gallegos. 2001. Calculating optical water quality targets to restore and protect submersed aquatic vegetation: Overcoming problems in partitioning the diffuse attenuation coefficient for photosynthetically active radiation. *Estuaries* 24: 381–397.

3. Virginia Institute of Marine Science. 2004. SAV areas in Chesapeake Bay by CBP segments (1971–2001). *www.vims.edu.*
4. Virginia Institute of Marine Science. 2004. 2003 field observations and a first look at the aerial photography. *www.vims.edu.*
5. E.P. Ruzecki and others (eds.). 1976. *The Effect of Tropical Storm Agnes on the Chesapeake Bay Estuarine System.* Chesapeake Bay Research Consortium Publication No. 54. Johns Hopkins University Press. Baltimore, MD.
6. C.F. Cerco and M.R. Noel. 2004. The 2002 Chesapeake Bay eutrophication model, Prepared for Chesapeake Bay Program Office, Annapolis, MD. EPA 903-R-04-004. p. 349.
7. C.F. Cerco and T.M. Cole. 1993. Three-dimensional eutrophication model of the Chesapeake Bay. *J. Envir. Eng.* 119(6): 1006–1025.
8. L.C. Linker, G.W. Shenk, P. Wang, and J.M. Storrick. 1998. Chesapeake Bay Watershed Model Application & Calculation of Nutrient & Sediment Loading, Appendix B. EPA903-R-98-003, CBP/TRS 196/98. p. 641.
9. C.F. Cerco, B.H. Johnson, and H.W. Wang. 2002. Tributary Refinements to the Chesapeake Bay Model. Report ERDC TR-02-4. U.S. Army Corps of Engineers, Washington, D.C.
10. Virginia Institute of Marine Science. 2004. Historical tide data. *www.vims.edu./resources/databases.html#tide*
11. K.A. Moore, D.J. Wilcox, and R.J. Orth. 2000. Analysis of abundance of submersed aquatic vegetation communities in the Chesapeake Bay. *Estuaries* 23(1): 115–127.

EFFECTS OF HURRICANES ON ATLANTIC CROAKER (*MICROPOGONIAS UNDULATUS*) RECRUITMENT TO CHESAPEAKE BAY

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ABSTRACT

Few studies have focused on the effects of climatic perturbations, such as hurricanes, on finfish recruitment and behavior. The Virginia Institute of Marine Science (VIMS) Trawl Survey has sampled continuously throughout the Virginia portion of Chesapeake Bay for 50 years. While hurricanes have impacted Chesapeake Bay during this time, three periods of hurricane activity—September and November 1985 (hurricanes Gloria and Juan), September 1989 (Hurricane Hugo), and September 2003 (Hurricane Isabel)—coincided with the largest spikes in juvenile recruitment of Atlantic croaker (*Micropogonias undulatus*) for half a century. The fall (October–December) croaker young-of-year indices for 1985, 1989, and 2003 were seven, five, and eight times greater, respectively, than the 50-year average. Typically Atlantic croaker display great interannual variability in Chesapeake Bay, with these fluctuations shown to be weather related. The timing of Atlantic croaker recruitment to Chesapeake Bay is such that late summer/fall hurricanes are most likely to affect them, as opposed to other shelf spawners. Understanding the effects of hurricanes on species, such as croaker, that have enormous ecological, commercial, and recreational importance is essential for prudent fisheries management.

INTRODUCTION

The Chesapeake Bay and its tributaries form the largest estuary in the continental United States, providing food and shelter to more than 260 fish species [1] and countless crustaceans and other invertebrates. Estuarine organisms, such as molluscs, crustaceans, and fishes, support important commercial and recreational fisheries [2]. Their temporal distributions and recruitment are often dependent on annual climatic conditions and water currents [2]. Additionally, species not supporting fisheries are ecologically important, serving as key predators or prey items within the Bay [3]. The recent occurrence of a forceful hurricane (Hurricane Isabel) in the Bay, as well as the prediction of high levels of hurricane activity in this region for the next 10–40 years [4], warrant an investigation into whether recruitment of important marine species might be impacted. The objective of this study was to examine the effects of hurricanes on Atlantic croaker recruitment to Chesapeake Bay.

Three types of spawning activity occur in the Chesapeake Bay [5]: spring anadromous spawning (striped bass - *Morone saxatalis* and Alosidae), summer Bay spawning (bay anchovy - *Anchoa mitchelli*; blue crab - *Callinectes sapidus;* weakfish - *Cynoscion regalis*; and American oyster - *Crassostrea virginica*) and fall-winter shelf spawning (Atlantic menhaden - *Brevoortia tyrannus*; spot - *Leiostomus xanthurus*; Atlantic croaker; and summer flounder - *Paralichthys dentatus*). The majority of northwest Atlantic hurricanes occur in the late summer/fall and, therefore, are most likely to affect the fall/winter shelf spawners, particularly those that recruit heavily to Chesapeake Bay for only a few short months during this time (e.g., Atlantic croaker).

Atlantic croaker is one of the most abundant inshore demersal fishes along the southeastern coast of the United States [1, 6]. Croaker first spawn at age 2–3 from July through December in estuarine [7] and continental shelf waters between Delaware Bay and Cape Hatteras [8], with peak spawning August through October off Chesapeake Bay [1, 9]. Pelagic young of year (YOY) of 8–20 mm total length (TL) leave shelf waters and enter larger estuaries, eventually moving into nursery habitats associated with low-salinity tidal creeks [8]. The YOY (20 mm TL) first enter the Chesapeake Bay in August and move into freshwater creeks and low-salinity nursery habitat [1]. Croaker larvae generally enter the Bay in the deeper inward flowing water with greatest concentrations below 3 m [10]. Initial fall recruit-ment of croaker depends on fall continental shelf winds to provide transport into the Bay, with shelf winds and winter temperature explaining 89% of the variance in subsequent summer year-class strength [11]. If wind relaxation occurs prior to the autumn migration of croaker out of the estuaries, spawning occurs in the middle portion of the Mid-Atlantic Bight [12]. Prolonged summer winds keep nearshore waters cool and force the croaker further south to spawn, potentially shifting distribution of juvenile recruitment to southern Pamlico Sound [12]. In autumn, the young croaker move into the deeper portions of tidal rivers, where they overwinter and leave the Bay as adults the following fall [1].

Interannual variability in croaker abundance may be climate related, with colder winters causing increased mortality in overwintering YOY [6, 13]. During cold winters, the spawning population may be pushed farther south along the coast, reducing the number of postlarval fish capable of reaching nursery areas of the Bay [1, 14]. When average January–February water temperatures remain above 4.0º C, juvenile croaker recruited into the Bay survive in greater numbers [11]. Cold tolerance in juvenile croaker is size and salinity dependent; smaller individuals survive longer than larger ones and their cold tolerance increases with increasing salinity [13].

Recruitment of fall/winter shelf spawners may be impacted by hurricanes, but appears to be initially dependent on the timing of the seasonal wind shift in the Mid-Atlantic Bight (and its resultant effect on bottom-water temperatures), including variations in strength, duration, and direction of wind-driven transport [11]. For example, a late wind shift would result in croaker spawning south of Cape Hatteras [12] and introduction of a hurricane may have negligible effects on recruitment to Chesapeake Bay as the croaker larvae have already been displaced. Conversely, an early seasonal wind shift may enhance croaker recruitment to the Bay. Thus a hurricane occurring in mid- to late August may preempt the usual shift to northeast winds which occurs in early September and accelerate the warming of nearshore waters, thereby stimulating the croaker to spawn weeks earlier close to Chesapeake Bay.

MATERIALS AND METHODS

The annual presence (or absence) of hurricanes in Virginia was determined through examination of the NOAA National Weather Service Hydrometeorological Prediction Center website detailing late 20th-century hurricanes in Virginia [15]. Wind at Norfolk International Airport [16] was deemed to be a proxy for offshore winds (Godshall as reported by [11]) and plotted with MATLAB [17]. Both daily and weekly resultant direction and speed were examined. A two-week moving average was applied to weekly data to filter out storm effects and ascertain when the late summer/early fall offshore wind shift or cessation of summer winds may have occurred (see [12] for details). Wind stress was examined through calculation of monthly meridional wind values.

The VIMS Juvenile Finfish and Blue Crab Trawl Survey (1955 to present) was used for this study because of its long duration and spatial coverage, which includes major Virginia tributaries (James, York, and Rappahannock rivers) and the lower portion of Chesapeake Bay [18]. A lined 30-ft (9.14 m) semi-balloon otter trawl, 1.5-in (38.1 mm) stretched mesh, and 0.25-in (6.35 mm) cod liner was towed along the bottom for 5 minutes during daylight hours. Water quality was measured at each station with a YSI 650 hydrographic meter. Both Bay and major tributaries were sampled with a random stratified design. Stratification was based on depth and latitudinal regions in the Bay (random stations only), or depth and longitudinal regions in the rivers (random and fixed stations; see [18] for further sampling details). The survey random stratified converted index (RSCI) incorporated gear and vessel changes [19] to provide an uninterrupted time series for five decades [18]. Individual species indices were derived based on modal analyses and aging studies as well as monthly catch rates [20].

The Fall Atlantic Croaker YOY Index (fall YOY) is composed of the following months and respective individual fish total lengths (TL): October (0–80 mm); November (0–100 mm); and December (0–100 mm). The following Spring Atlantic Croaker Recruit Index (spring recruit) is composed of the following months and respective TL: May (0–135 mm); June (0–160 mm); July (0–180 mm); and August (0–220 mm). Numbers of individuals caught were log transformed (ln (n+1)) prior to abundance calculations. Resultant average catch rates (and the 95% confidence intervals as estimated by $\pm$ 2 standard errors) were then back-transformed to the geometric means.

A one-way analysis of variance was performed with fall YOY as the response variable and annual presence of hurricanes (non-hurricane vs. hurricane years in Virginia) as the factor for the years 1956–2004. A multiple regression was performed with fall YOY as the response variable and time of cessation of summer winds and monthly meridional wind stress (July through December) as the predictor variables. A linear regression was performed with the spring recruits (yr^{-1}) as the response variable and the fall YOY as the predictor variable for the same time period.

RESULTS AND DISCUSSION

Hurricane Isabel struck Chesapeake Bay from 18–19 September 2003 and produced prolonged onshore winds and sustained wind stress up-estuary for many days prior [21]. Beginning 5 September, there were 8 consecutive days of strong NE winds, 2 days of S and SE winds, and 5 additional consecutive days of NE winds. The cessation of summer winds and resultant wind shift occurred during late August 2002, middle September 2003, and late September 2004—roughly two weeks later each year. Post-storm mean surface salinities at fixed stations in the James, York, and Rappahannock rivers dropped 3.5, 3.2, and 3.0 psu while bottom salinities decreased 3.6, 0.5, and 2.2 psu, respectively. Only stations furthest upriver (nearly freshwater) were unaffected.

The 2003 fall YOY index was 15 times greater than the 2002 index, eight times the survey average, and the highest for the duration of the survey for almost half a decade (Figure 1). Major peaks in 1985, 1989, and 2003, coincided with hurricanes Gloria and Juan (27 September and 2–7 November, 1985), Hugo (21–22 September 1989), and Isabel (18–19 September), resulting in indices seven, five, and eight times greater than the 50-year average (mean = 13.0, s.e. = 3.1).

Minor peaks were evident during 1969 (Camille), 1996 (Fran), and 1998 (Bonnie). One year not associated with hurricanes with a high fall YOY index (1984) may have resulted from prolonged winds associated with normal hurricane activity. Meridional wind stress during August and September 1984 was fairly strong. The fall YOY index was significantly greater (by a factor of three) during hurricane years than non-hurricane years

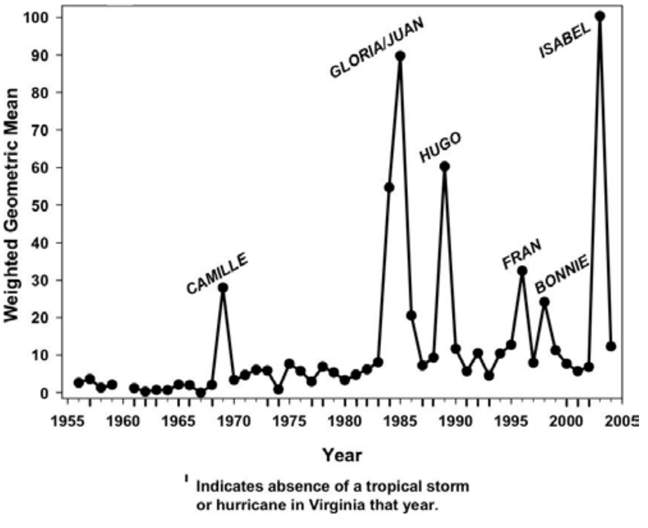

Figure 1. VIMS fall young-of-year croaker index.

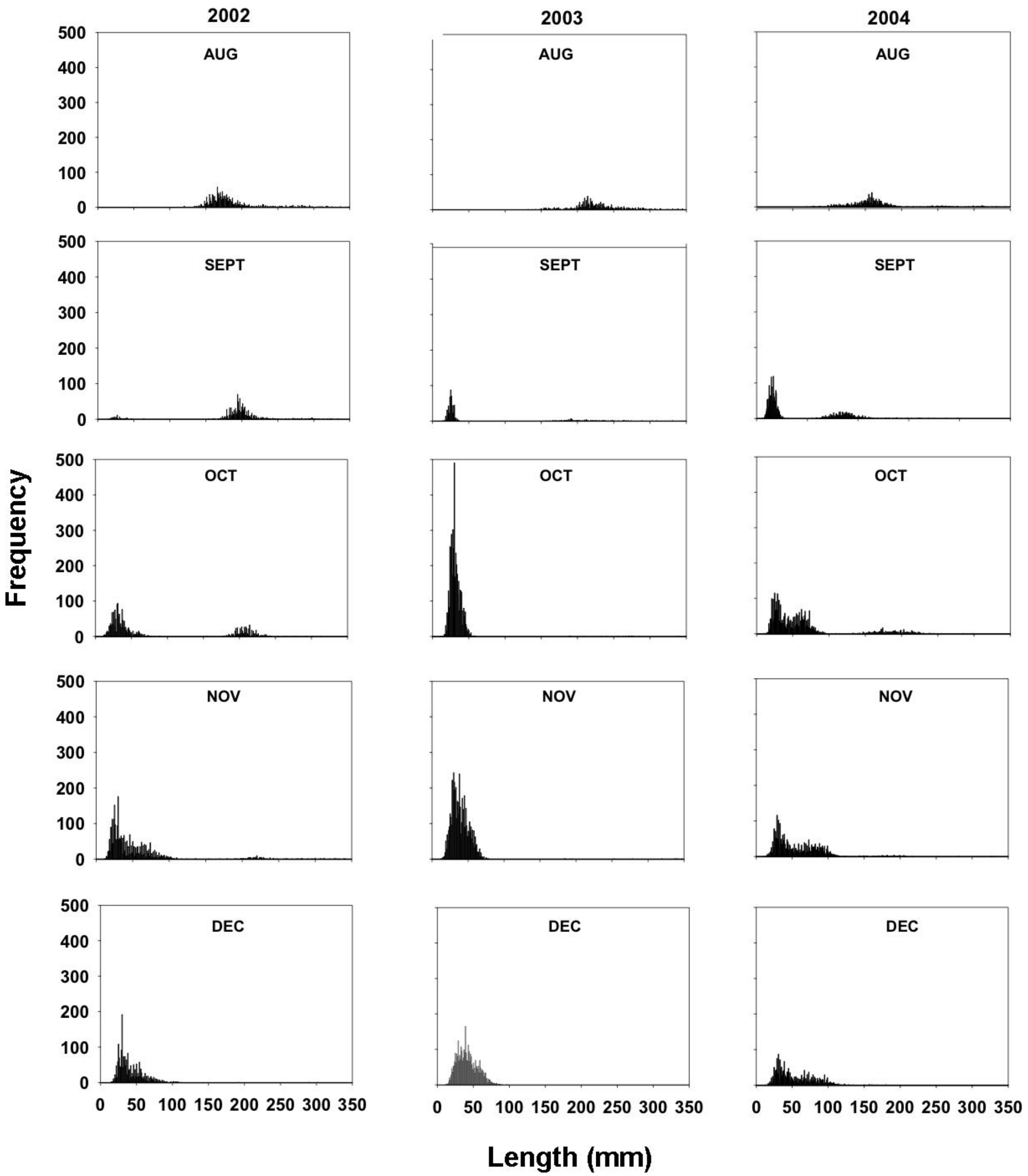

Figure 2. Atlantic croaker size frequencies for August through December 2002 (left), 2003 (center), and 2004 (right).

($F_{0.05, 1, 46}$; P = 0.041). Only August meridional wind stress was a significant predictor of the fall YOY index (P= 0.044). When cessation of summer winds occurred during September, the fall YOY index was highest. This situation was true for both 1985 and 2003.

A comparison of monthly size frequencies from August through December 2002, 2003, and

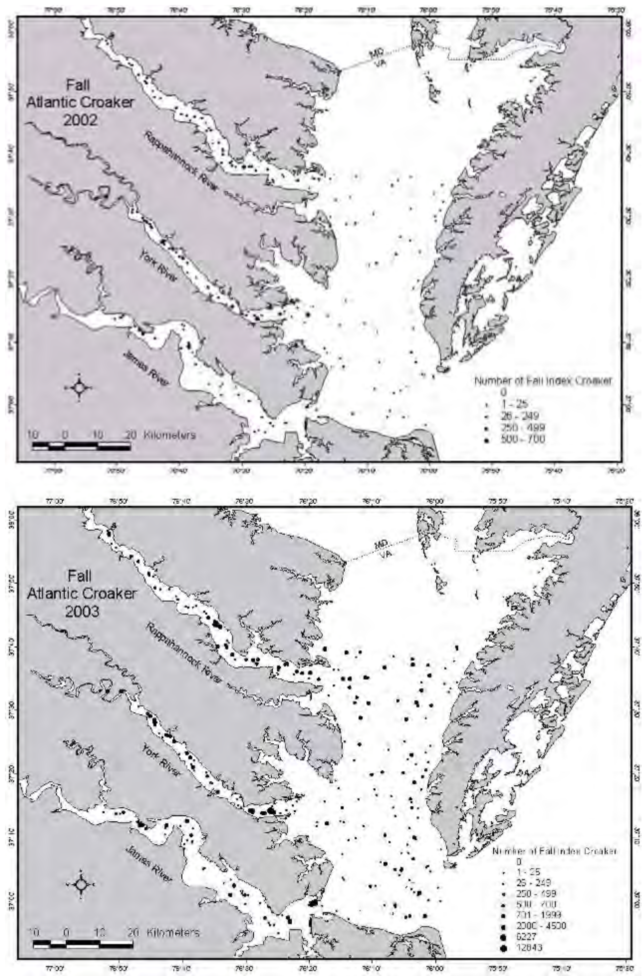

Figure 3. Abundance and distribution of Atlantic croaker during fall 2002 (top) and fall 2003 (bottom).

2004 reveals the enormous increase of YOY croaker less than 50 mm TL present in October 2003 compared to the same months in 2002 and 2004 (Figure 2). Note also that 150–225 mm TL croaker were conspicuously absent during September and October 2003. There was also a notable difference between the abundance and distribution of croaker collected during fall 2002 and fall 2003 (Figure 3, top and bottom). Densities of YOY croaker were elevated in the main stem and lower portions of rivers during fall 2003 (Figure 3, bottom) compared to the previous year (Figure 3, top)—probably due to a combination of downriver displacement of the croaker resulting from decreased salinities and wind-driven transport of YOY into the Bay. The mean YOY croaker catch per station was an order of magnitude higher in fall 2003 compared to fall 2002 (means of 448.5, s.e.= 53.2; and 45.0, s.e.=5.41, respectively).

The very successful year classes in the fall of 1984, 1985, 1989, and 2003 often did not result in comparably successful recruitment the following spring (Figure 4). There was no significant linear relationship between the fall YOY and following spring recruit indices (P=0.62).

Significant weather events, such as tropical storms may impact fish and crustacean populations in Chesapeake Bay directly by changing the salinity of the water, preventing or enhancing larval entrance into the Bay due to wind events or indirectly by causing habitat declines (see Houde et al., this volume). Drastic changes in environmental variables (i.e., changes in salinity, dissolved oxygen) may directly affect the mortality rates of pre-recruits or indirectly exert influence by altering the abundance of forage predators [21]. Some species, such as newly settled juvenile blue crabs, may actually benefit from storms as the increased turbidity may favor chemotactic (blue crab) search modes, but have negative impacts on visual predators (e.g., Atlantic croaker and other finfish) [22].

The spike in the 2003 fall YOY croaker index was related to persistent onshore winds associated with Isabel. The next highest fall YOY index occurred in 1985, coincident with Gloria (27 September) and Juan (2-7 November), followed by Hugo (September 1989). Winds in 2003 shifted from southwest to northeast about two weeks later than 2002, suggesting that croaker spawned later in 2003 and larval croaker may have been displaced farther south. However, strong northeast winds from Isabel and the resultant Ekman transport enhanced transfer of croaker larvae back into the Bay, resulting in the spike of croaker less than 50 mm TL in October 2003. Due to the shape and orientation of the Bay coastline, larval transport models have shown that larvae can only recruit back to the Bay from the south under a wind stress with a large north-northwesterly component [23]. Larval transport to the Bay can be enhanced through large-scale advection from wind-forced inflow events that bring large volumes of water into the Chesapeake as described above. Hurricane Juan moved 8 km^3

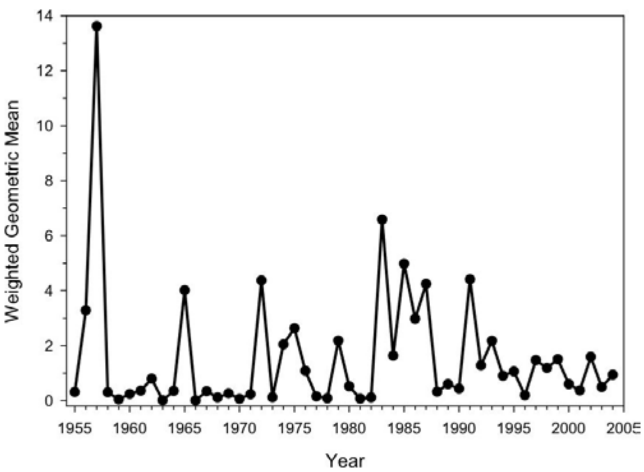

Figure 4. VIMS spring recruit Atlantic croaker index.

of shelf water into the Bay resulting in a large blue crab megalopal settlement event during early November 1985 [24]. Incidentally, nearly a three-fold increase occurred in the VIMS Trawl Survey fall (September through November) blue crab YOY index in 2003, compared to 2002. An increase is not always the result, however, as hurricanes in North Carolina during 1996 and 1999 resulted in blue crab recruitment failure with significant declines in YOY and postlarval abundance [25].

Storms and hurricanes may be beneficial to species. For example, menhaden may have evolved to reproduce under physical conditions (similar to hurricanes) optimal for the survival and shoreward transport of its eggs and larvae [26]. These physical conditions include storms (during which upwelling and spawning occur) and persistent heat loss and stratification (during which rapid development and shoreward transport occur). In addition, species such as spot, croaker, flounder, striped mullet (*Mugil cephalus*), and pinfish (*Lagodon rhomboides*) spawn south of Cape Hatteras and west of Gulf Stream fronts, using estuaries as nursery habitats [11, 26, 27, 28, 29]. All of these species have evolved to spawn during winter, shoreward of a warm boundary current, allowing rapid development and drift of their eggs and larvae and ultimately resulting in enhanced recruitment and fitness [26]. In Chesapeake Bay, hurricanes do not appear to enhance recruitment of spot and flounder, as indicated by our trawl indices for these species.

Large variations in annual fisheries landings in Chesapeake Bay are common and most often attributed to natural phenomena [30]. Interannual variability in croaker and blue crab abundance may be climate related, with colder winters causing increased mortality in overwintering YOY in Chesapeake Bay [6, 31] and along the Mid-Atlantic Bight [13]. During these same winters, the spawning population may be pushed farther south along the coast, reducing the number of postlarval fish capable of reaching nursery areas of the Bay [1, 14]. When average January–February water temperatures are above 4.0º C, juvenile croaker recruited into the Bay survive in greater numbers [11]. Additionally, striped bass are known to prey heavily on overwintering YOY croaker in Chesapeake Bay (Dovel, 1968 as reported in [7]). Even though hurricanes may aid recruitment of species such as Atlantic croaker to Chesapeake Bay, cold winters and predation (as discussed above) may result in only average abundances of the recruits the following spring and summer [18].

Recent climate conditions (winter/spring patterns) affecting Chesapeake Bay (rather than hurricanes) appear to have reduced annual recruitment in species such as spot and Atlantic menhaden [29]. However, the effect of hurricanes (which are predicted to be more frequent in the future) on recruitment of important ecological, commercial, and recreational species should be taken into consideration by fisheries managers, as different species may be impacted in various ways by different storms.

ACKNOWLEDGMENTS

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REFERENCES

1. E.O. Murdy, R.S. Birdsong, and J.A. Musick. 1997. *Fishes of Chesapeake Bay*. Smithsonian Institution Press. 324 pp.
2. S.L. Stone, T.A. Lowery, J.D. Field, C.D. Williams, D.M. Nelson, S.H. Jury, M.E. Monaco, and L. Andreasen. 1994. Distribution and abundance of fishes and invertebrates in Mid-Atlantic estuaries. ELMR Rep. No. 12. NOAA/NOS Strategic Environmental Assessments Div., Silver Spring, MD. 280 pp.
3. R.J. Wood, E.D. Houde, and S. Jung. 2003. Variability in the dynamics of forage fish abundances in Chesapeake Bay: Retrospective analysis, models and synthesis. Chesapeake Bay Fisheries Research Program Symp. Report, NOAA-CBO. pp. 97–107.
4. S.B. Goldenberg, C.W. Landsea, A.M. Mestas-Nunez, and W.M. Gray. 2001. The recent increase in Atlantic Hurricane activity: causes and implications. *Science* 293: 474–479.
5. H.M. Austin. 2002. Decadal oscillations and regime shifts, a characterization of the Chesapeake Bay marine climate. *Amer. Fish. Soc. Symp.* 32: 155–170.
6. E.B. Joseph. 1972. The status of the sciaenid stocks of the Middle Atlantic Coast. *Chesap. Sci*. 13(2): 87–100.
7. L.R. Barbieri, M.E. Chittenden, Jr., and S.K. Lowerre-Barbieri. 1994. Maturity, spawning, and ovarian cycle of Atlantic croaker, *Micropogonias undulatus*, in the Chesapeake Bay and adjacent coastal waters. *Fish. Bull.* 92: 671–685.
8. K.W. Able and M.P. Fahay. 1998. *The First Year in the Life of Estuarine Fishes in the Middle Atlantic Bight*. Rutgers University Press, New Jersey. 342 pp.
9. W.W. Morse. 1980. Maturity, spawning and fecundity of Atlantic croaker, *Micropogonias undulatus*, occurring north of Cape Hatteras, North Carolina. *Fish. Bull.* 78: 190–195.
10. B.L. Norcross. 1991. Estuarine recruitment mechanisms of larval Atlantic croakers. *Trans. Amer. Fish. Soc.* 120: 673–683.
11. B.L. Norcross. 1983. Climate scale environmental factors affecting year-class fluctuations of Atlantic croaker (*Micropogonias undulatus*) in the Chesapeake Bay. Ph.D. Dissertation. College of William & Mary. 388 pp.
12. B.L. Norcross and H.M. Austin. 1988. Middle Atlantic Bight meridional wind component effect on bottom water temperatures and spawning distribution of Atlantic croaker. *Cont. Shelf Res.* 8: 69–88.
13. T.E. Lankford, Jr. and T.E. Targett. 2001. Low-temperature tolerance of Age-0 Atlantic croakers: Recruitment implications for U. S. Mid-Atlantic Estuaries. *Trans. Amer. Fish. Soc.* 130: 236–249.
14. E.D. Houde. 2002. The unique contributions of early life stages. In: *Fishery Science*. L.A. Fuiman and R.G. Werner (eds.). Blackwell Publishing, pp. 64–87.
15. NOAA National Weather Service. *2004*. Virginia Hurricane History: late Twentieth Century. *www.hpc.ncep. noaa.gov/research/ roth/valate20hur.htm*
16. NOAA National Weather Service. 2004. *www.erh.noaa.gov/er/akq/climate/climate.htm*
17. MATLAB. 2004. Version 7.0. The MathWorks, Inc.
18. M.M. Montane, W.A. Lowery, and H.M. Austin. 2004. Estimating relative juvenile abundance of ecologically important finfish and invertebrates in the Virginia portion of Chesapeake Bay. Annual Report to NOAA-CBO, Project No. NA03NMF4570378. VIMS, Gloucester Pt., VA. 106 pp.
19. D.N. Hata. 1997. Comparisons of gears and vessels used in the VIMS juvenile finfish trawl survey. SRAMSOE No. 343. VIMS, Gloucester Pt. VA. 244 pp.
20. J.A. Colvocoresses and P.J. Geer. 1991. Estimation of relative juvenile abundance of recreationally important finfish in the Virginia portion of Chesapeake Bay. Annual Report to VMRC/USFWS Sportfish Restor-ation Project F104R1. July 1990 to June 1991. VIMS, Gloucester Pt. VA. 64 pp.

22. R.E. Ulanowicz, M.L. Ali, A. Vivian, D.R. Heinle, W.A. Richkus, and J.K. Summers. 1982. Identifying climatic factors influencing commercial fish and shellfish landings in Maryland. *Fish. Bull.* 80(3): 611–619.
23. A.J. Pile, R.N. Lipcius, J. van Montfrans, and R.J. Orth. 1996. Density-dependent settler-recruit-juvenile relationships in blue crabs. *Ecol. Monogr.* 66(3): 277–300.
24. J.A. Quinlan, B.O. Blanton, T.J. Miller, and F.E. Werner. 1999. From spawning grounds to the estuary: Using linked individual-based and hydrodynamic models to interpret patterns and processes in the oceanic phase of Atlantic menhaden *Brevoortia tyrannus* life history. *Fish. Oceanogr.* 8 (Suppl. 2): 224–246.
25. D.M. Goodrich, J. van Montfrans, and R.J. Orth. 1989. Blue crab megalopal influx to Chesapeake Bay: Evidence for a wind-driven mechanism. *Est. Coast. Shelf Sci.* 29: 247–260.
26. J. Burkholder, D. Eggleston, H. Glasgow, C. Brownie, R. Reed, G. Janowitz, M. Posey, G. Melia, C. Kinder, R. Corbett, D. Toms, T. Alphin, N. Deamer, and J. Springer. 2004. Comparative impacts of two major hurricane seasons on the Neuse River and western Pamlico Sound ecosystems. *Proc. Nat. Acad. Sci.* 101(25): 9291–9296.
27. D.M. Checkley, Jr., S. Raman, G.L. Maillet, and K.M. Mason. 1988. Winter storm effects on the spawning and larval drift of a pelagic fish. *Nature* 335: 346–348.
28. D. Bodolus. 1994. Mechanisms of larval spot transport and recruitment to the Chesapeake Bay. Ph.D. Dissertation. College of William & Mary. 350 pp.
29. M.P. Weinstein. 1981. Plankton productivity and the distribution of fishes on the southeastern U. S. Continental Shelf. *Science* 214: 351–352.
30. R.J. Wood. 2000. Synoptic scale climatic forcing of multispecies recruitment patterns in Chesapeake Bay. Ph.D. Dissertation. College of William and Mary. 146 pp.
31. Rothschild, B.J. 1984. Trends in Chesapeake Bay Fisheries. *Trans. 46th N. Amer. Wildl. Nat. Res. Conf.* 46: 284–298.
32. A.F. Sharov, J.H. Volstad, G.R. Davis, B.K. Davis, R.N. Lipcius, and M.M. Montane. 2003. Abundance and exploitation rate of the blue crab (*Callinectes sapidus*) in Chesapeake Bay. *Bull. Mar. Sci.* 72(2): 543–565.

EFFECTS OF HURRICANE ISABEL ON FISH POPULATIONS AND COMMUNITIES IN CHESAPEAKE BAY

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ABSTRACT

Trawl surveys throughout Chesapeake Bay documented abundances and distributions of pelagic and bentho-pelagic fishes after Hurricane Isabel. Species richness increased, primarily from occurrences of previously uncommon freshwater species that possibly were transported to the Bay's main stem by high freshwater flow from the Susquehanna River. Abundances of young-of-the-year (YOY) anadromous fishes (e.g., striped bass and white perch) were above the decadal mean for fall trawl surveys, probably more in response to the prevailing "wet" conditions of spring 2003 that favored successful reproduction of anadromous fishes than as a consequence of Isabel. In the lower Bay, a large post-Isabel increase in abundance of adult bay anchovy occurred, likely resulting from post-Isabel migration into the Bay or downriver displacement from tidal tributaries. Young-of-the-year (YOY) Atlantic croaker were remarkably abundant in the post-Isabel survey. Their peak abundance, centered in the lower Bay, was more than 30 times higher than mean abundance for the previous decade, suggesting a large entrainment of croaker larvae from coastal ocean spawning sites in the aftermath of Isabel. The apparent near-term effects of Isabel mostly indicated enhanced abundances and shifts in distributions; no obvious negative effects on fish populations, recruitment of YOY fishes, or fish communities were observed.

INTRODUCTION

Documented effects of hurricanes and tropical storms on fish communities are limited, in part due to the lack of pre-storm data required to conduct before- and after-storm comparisons. Under some circumstances, hurricanes can cause massive mortalities of fish and destruction of their habitats in coastal and estuarine ecosystems [1]. Under other circumstances, the effects may be small [2]. However, storm effects on fish communities typically are described as short term [3, 4, 5]. Observed effects include high mortality, shifts in species composition and biomass, social/reproductive abnormalities, export and loss of egg and larval stages, and a rise in the incidence of fish disease [6, 7, 8, 9, 10, 11].

The Chesapeake Bay has experienced impacts from hurricanes and tropical storm systems in the past. Most notable was Tropical Storm Agnes in June 1972, which resulted in a 100- to 200-year flood [12]. Although Agnes' effects on finfish proved temporary, the storm's impact on shellfish (oyster - *Crassostrea virginica* and soft-shelled clam - *Mya arenaria*) was devastating, with an estimated loss in Virginia of 7.9 million dollars [12].

On 18 September 2003, Hurricane Isabel made landfall east of Cape Lookout, North Carolina as a Category 2 hurricane. The storm center approached from south of the Chesapeake Bay during the afternoon of 18 September and passed to the west of the Bay in the early morning of 19 September as a sub-Category 1 storm. Isabel brought the highest storm surge and wind to the region since Hurricane Hazel in 1954 and the Chesapeake-Potomac Hurricane of 1933 (*www.erh.noaa.gov/er/akq/wx_events/hur/isabel_2003*).

A baywide trawl survey was conducted to evaluate the effects of Hurricane Isabel on fish community structure in the Chesapeake Bay. The objectives were to measure and map species distributions and abundances within the Chesapeake's main stem. The results were compared with distribution and abundance data collected 2 to 9 days prior to Hurricane Isabel in a CHESFIMS[1] survey (9–16 September 2003). In addition, results were compared with data from previous fall baywide fish surveys in TIES[2] and CHESFIMS (1995–2002).

MATERIALS AND METHODS

Two post-Isabel trawl surveys were conducted. The first was a BITMAX[3] survey in the upper Bay on RV *Aquarius* from 21–23 October 2003; the second was a survey on RV *Cape Henlopen* from 6–10 November 2003. Together, these surveys sampled the entire Chesapeake Bay main stem (30 trawling stations). Fish were collected at night in an 18-m^2 mouth-opening, midwater trawl (MWT) with 3-mm cod-end mesh. The MWT was fished for 20 minutes in stepwise fashion from surface to bottom. The post-Isabel abundances and distributions were compared with pre-Isabel data from CHESFIMS (September 2003) and earlier years' data from TIES[2] and CHESFIMS[1]

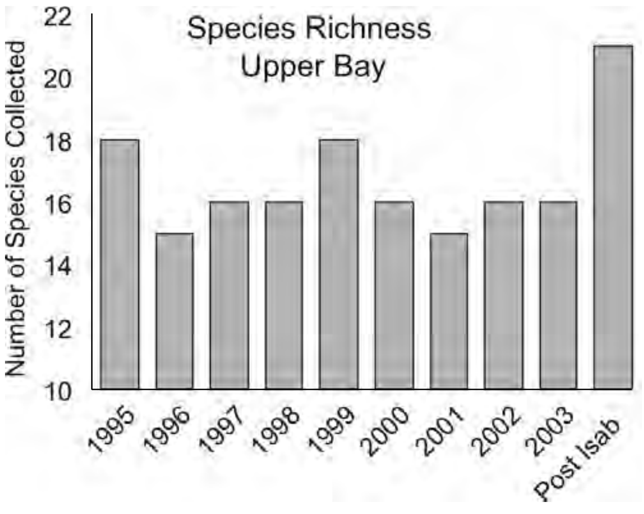

Figure 1. Number of fish species collected in the upper Chesapeake Bay (up-Bay of latitude 39º N) during fall (mid September to early November) surveys, by year. All fish were collected in an 18-m^2 mouth-opening, midwater trawl with 3-mm cod-end meshes.

fall surveys of fishes collected using the same midwater trawl. The six TIES cruises were conducted in October/November (1995–2000) [13]; the CHESFIMS cruises were conducted in September (2001–2003). In addition, ichthyoplankton and jellyfish were collected in a 1-m^2 Tucker trawl (280-µm meshes) during the post-Isabel cruises (16 stations) and data were compared with similar data from previous TIES collections.

The number of fish species (diversity) in each trawl sample, relative abundances (numbers per 20-min tow), and sizes were recorded and contoured abundance maps produced. Diversity and abundances of key taxa were compared to the decadal means for previous fall cruises and to abundances and distributions found on the CHESFIMS pre-Isabel cruise (9–16 September 2003).

RESULTS AND DISCUSSION

Environmental Data

Substantial declines in salinity and water temperature in the Bay main stem occurred between pre- and post-Isabel cruises, reflecting the normal seasonal pattern from September to early November. Bottom water temperatures ranged from 14º C to 19º C during the post-Isabel survey, increasing from the head down the Bay, a typical early November pattern. The post-Isabel water temperatures were similar to those measured in fall cruises during the TIES years. Baywide, post-Isabel bottom salinities were lower in October and November than in all years since 1995, except for

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[1] *CHESFIMS, Chesapeake Bay Fishery-Independent Multispecies Survey, a project funded by the NOAA Chesapeake Bay Office (Grant NA07FU0534) to survey fish throughout the Bay from 2001 to 2004.*

[2] *TIES, Trophic Interactions in Estuarine Systems, a NSF-funded, multidisciplinary research program (Grant DEB 9412113) that sampled and surveyed the Bay from 1995 to 2000.*

[3] *BITMAX, Biophysical Interactions in the Estuarine Turbidity Maximum, a NSF-funded multidisciplinary research program (Grant OCE 0002543) to sample and survey the upper Bay region near the salt front and estuarine turbidity maximum zone from 2001 to 2003.*

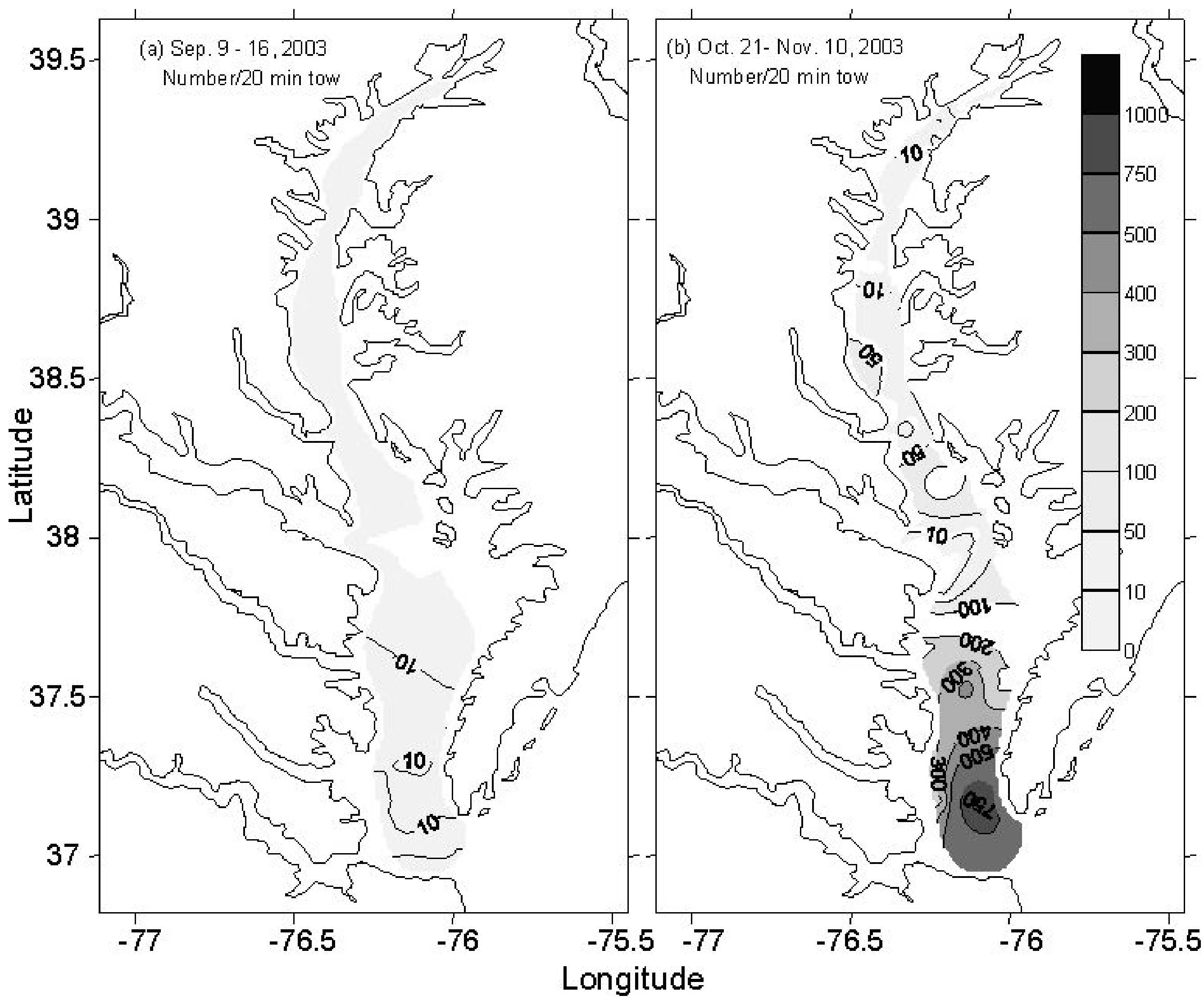

Figure 2. Maps of adult bay anchovy (age 1+) distribution (numbers per tow) from mid-water trawl collections in fall baywide surveys in Chesapeake Bay. Left panel: 9 to16 September 2003 (pre-Isabel); Right panel: 21 October to 10 November 2003 (post-Isabel).

the "wet" year 1996 (TIES[2] and CHESFIMS[1] CTD data). Salinities near the western shore of the Bay were lower than those near the Eastern Shore during the post-Isabel survey, attributable in part to the heavier rainfall and higher tributary flows on the western shore. Bottom salinities in the uppermost Bay increased slightly in the immediate aftermath of the hurricane, but declined substantially in the following weeks (Chesapeake Bay Program monitoring data).

Fishes

A total of 103,392 fish was collected during the post-Isabel survey. Young-of-the-year (YOY) bay anchovy (*Anchoa mitchilli)* dominated catches, contributing 83% to the total number and 32% to the biomass. Relative abundance and biomass (catch-per-tow (CPUE)) of all fish species combined were similar to CPUE levels in previous years, but significantly higher than CPUE for the pre-Isabel cruise in September 2003. Baywide, a total of 35 species was collected in the post-Isabel surveys, three more than the long-term average of 32+ species in previous fall collections (1995–2003).

In the upper Bay's estuarine transition zone, three more species were collected during the post-Isabel cruise than in any previous fall cruise and the mean number of post-Isabel species was five more than the long-term fall survey mean (Figure 1). Unusual or uncommon species in the post-Isabel cruise included the brown bullhead (*Ameiurus nebulosus)*, a sunfish (*Lepomis* sp.*)*, a darter (*Etheostoma olmstedi*), and the yellow perch (*Perca flavescens)*, all sampled from the upper Bay. Yellow perch had not been collected in previous fall TIES or CHESFIMS surveys in the mainstem Bay.

Abundances of YOY anadromous fishes in fall 2003 were well above the decadal average for the upper Bay, probably due to the high rainfall and stream discharge in spring 2003, which favor recruitment of these fishes [14]. There were no obvious negative effects of Isabel on YOY anadromous fishes. Comparing distributions in the pre- and post-Isabel cruises, the centers of YOY striped bass (*Morone saxatilis)* and white perch (*M. americana)* abundances shifted slightly down-estuary after the hurricane, apparently in response to a similar down-estuary shift in the salt front. Similar responses were observed after Tropical Storm Agnes [4, 15]. Notably, the post-Isabel distributions of YOY blueback herring, alewife, and shads (*Alosa* spp.) extended into the mid-Bay, a pattern similar to that observed previously only during fall of the wet year 1996.

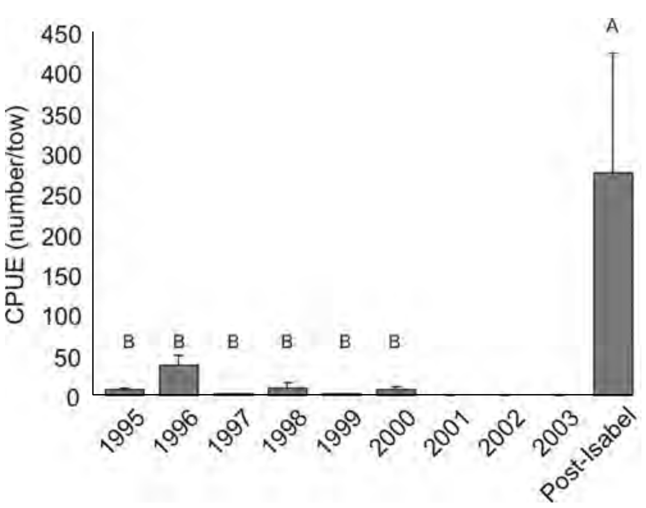

Figure 3. Atlantic croaker young-of-the-year relative abundance (number/tow) in Chesapeake Bay (+/- standard error) from mid-water trawl tows in fall surveys. Means were tested using one-way ANOVA, followed by Duncan's multiple range test. Different letters over a bar indicate significant difference (p <0.05).

A sharp increase in the abundance of adult (age 1+) bay anchovy occurred after passage of Hurricane Isabel (Figure 2), mostly in the lower Chesapeake (pre-Isabel CPUE = 6.2 ±2.0 per tow; post-Isabel CPUE = 192.3 ±44.0 per tow). The apparent influx of adult anchovy may have resulted from entrainment with shelf waters into the lower Bay or possibly flushing from western shore tributaries after Isabel. The YOY bay anchovy were more abundant throughout the Bay following Hurricane Isabel and their center of abundance shifted down-estuary after the hurricane. The elevated abundance and down-estuary shift followed the normal seasonal recruitment pattern in this species [16], however, and probably was not due to the hurricane.

Other key species in fall surveys included Atlantic croaker (*Micropogonias undulatus)*, Atlantic menhaden (*Brevoortia tyrannus)*, and weakfish (*Cynoscion regalis)*. Of these, only YOY Atlantic croaker apparently had a major response to hurricane effects (Figures 3 and 4). Baywide, post-Isabel YOY croaker abundance was more than 30 times higher than in any previous TIES or CHESFIMS fall survey except for 1996 (the abundance was seven times higher after Isabel than in fall 1996). In most years, YOY croaker October/November abundance peaked in the upper Bay, suggesting transport of larvae from spawning grounds on the continental shelf to the Bay mouth and then a rapid, up-estuary transport.

The post-Isabel, YOY croaker abundance was centered in the lower Bay. Mean length of measured YOY croaker was significantly smaller (ANOVA, p<0.0001) in the post-Isabel survey (33.0±0.4 mm) than the overall mean length for 1995–2000 fall surveys (43.0±1.4 mm). Field notes taken during the post-Isabel survey indicated unprecedented numbers of croaker <20 mm long (not fully vulnerable to the trawl) that escaped cod-end meshes, spilled onto the deck when the trawl was brought on board, and were not counted or measured. The high abundance and small size in the lower Bay indicated a massive and recent import

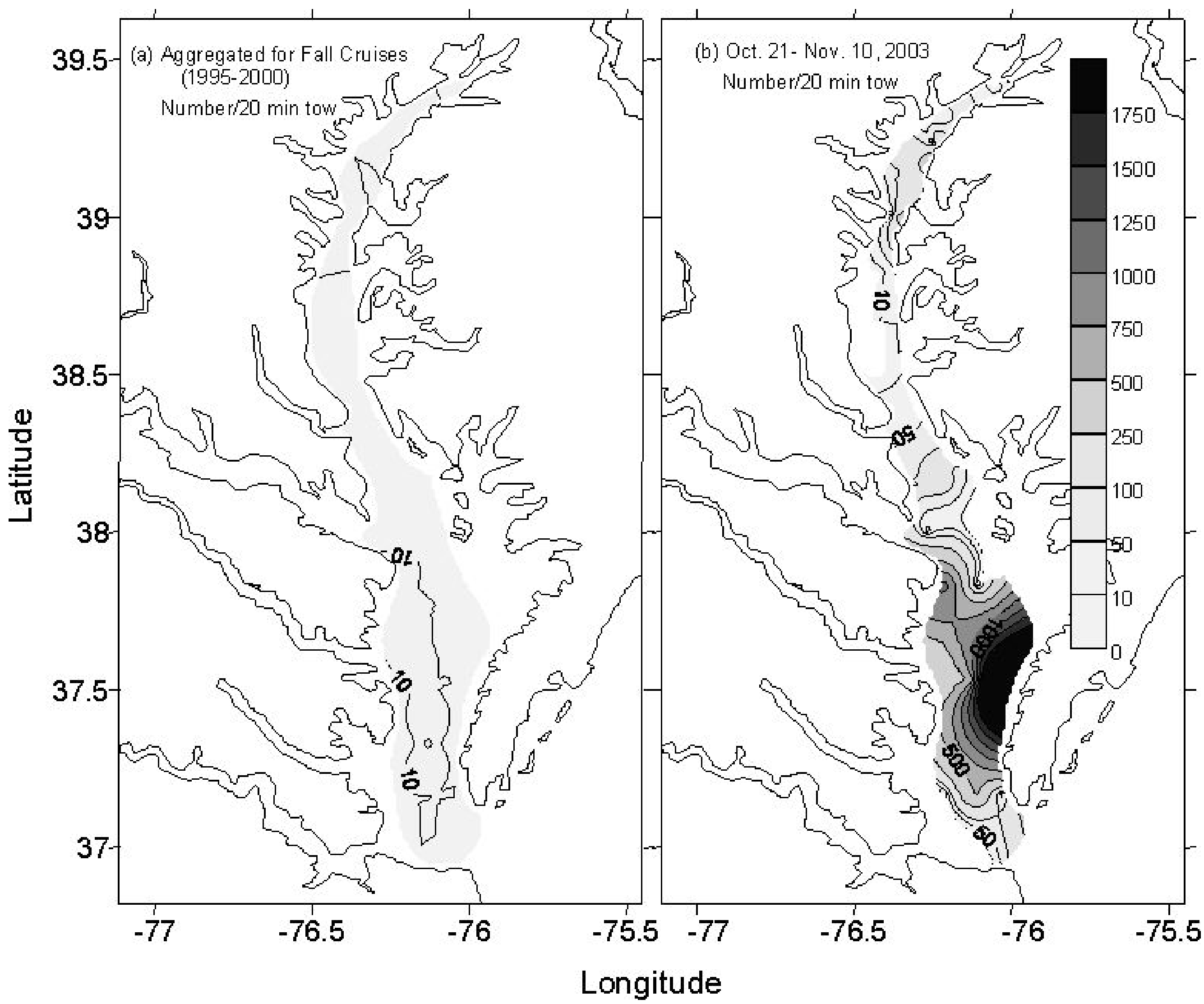

Figure 4. Distribution and abundance (number/tow) of young-of-the-year Atlantic croaker in Chesapeake Bay in the post-Isabel survey (21 October to 10 November 2003) compared to the mean for fall surveys from previous TIES[1] years (1995 to 2000).

of croaker larvae from offshore, possibly from above-average, cross-shelf transport after Isabel and subsequent up-estuary advection in bottom waters with enhanced estuarine circulation. Monthly trawl-survey results in the Virginia portion of Chesapeake Bay also indicated unprecedented numbers of YOY croaker in the October to December 2003 period attributed to the effects of Hurricane Isabel [17, 18].

Hurricane Isabel crossed the Bay region during the summer/fall transition season after most estuarine-spawning fishes had completed spawning; consequently, YOY juveniles were abundant but eggs and larvae were uncommon. In contrast, Tropical Storm Agnes hit the Bay region in late June 1972 during the peak spawning season of bay anchovy, naked goby (*Gobiosoma bosc)*, weakfish, and other species. Their eggs and larvae were absent or rare in the post-Agnes surveys [6], suggesting disruption of spawning, mortality, or export from tidal tributaries and perhaps from the Bay itself. Hoagman and Merriner [7] estimated losses of >10^8 eggs and larvae from the Rappahannock and James rivers in the two weeks following Agnes. In our post-Isabel surveys, there was no evidence of catastrophic displacement or mortality of YOY juveniles of anadromous and estuarine-spawning fishes. Larvae of the ocean-spawning Atlantic croaker also apparently experienced a massive import into the Bay.

Jellyfishes

In comparing distributions and abundances of two common jellyfishes—the lobate ctenophore (*Mnemiopsis leidyi)* and the sea nettle medusa (*Chrysaora quinqecirrha)*—from TIES fall surveys in 1995–2000 and the post-Isabel surveys in October–November 2003, no evidence was seen of a hurricane effect. Distributions, abundances, and biovolumes of these jellyfishes were highly variable among years and regions in fall cruises; the post-Isabel distributions and abundances were not anomalous.

SUMMARY

In summary, based on comparison of pre- and post-Isabel survey data, the Bay's fish community apparently responded to hurricane effects although the high freshwater flow to the Bay throughout 2003 adds uncertainty to the results. The increase in species richness observed post-Isabel in the upper Bay included many freshwater species previously uncommon or unobserved in mid-water trawl surveys in the Bay's main stem. These species possibly were flushed into the Bay from the Susquehanna River after Isabel. A pulse of freshwater from Isabel and the overall high freshwater flow to the Bay in 2003 also could explain the post-Isabel, down-estuary shift in YOY *Alosa* species distributions, a pattern only observed previously in the wet year of 1996. Results from fish surveys on the James, York, and Rappahannock rivers in July 1972, following Tropical Storm Agnes, support the finding that downstream displacement of juvenile fishes occurs following the passage of strong storm systems [4, 15]. A surge of ocean water into the lower Bay associated with Hurricane Isabel may have promoted immigration of adult bay anchovy into the Bay. The same mechanism could explain the extraordinary abundance of YOY Atlantic croaker in Isabel's aftermath.

Our post-Isabel sampling was conducted 5 to 7 weeks after Hurricane Isabel passed through the Bay region, which limited our ability to observe or interpret the immediate impacts of the hurricane on the Bay's fish community. Despite this constraint, it was possible to document shifts in distributions and abundances of fishes apparently attributable to the hurricane. Observed near-term effects were mostly indicative of enhanced abundances (e.g., YOY Atlantic croaker and adult bay anchovy) [18]. No observed, obviously negative effects of Isabel on fish populations or communities in the Bay were noted.

ACKNOWLEDGMENTS

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REFERENCES

1. D.C. Tabb and A.C. Jones. 1962. Effect of Hurricane Donna on the aquatic fauna of north Florida Bay. *Trans. Amer. Fish. Soc*. 91: 375–378.
2. J.T. Tilmant, R.W. Curry, R. Jones, A. Szmant, J.C. Zieman, M. Flora, M.B. Roblee, D. Smith, R.W. Snow, and H. Wanless. 1994. Hurricane Andrew's effect on marine resources. *Bioscience* 44: 230–237.
3. S.A. Bortone. 1976. Effects of a hurricane on the fish fauna at Destin, Florida. *Fla. Sci.* 39: 245–248.
4. D.E. Ritchie, Jr. 1977. Short-term response of fish to Tropical Storm Agnes in mid-Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD. pp. 460–462.

5. M. Bell and J.W. Hall. 1994. Effects of Hurricane Hugo on South Carolina's marine artificial reefs. *Bull. Mar. Sci.* 55: 836–847.
6. G.C. Grant, B.B. Bryan, F. Jacobs and J.E. Olney. 1977. Effects of Tropical Storm Agnes on zooplankton in the lower Chesapeake Bay. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The Johns Hopkins Press, Baltimore, MD. pp. 425–442.
7. W.J. Hoagman and J.V. Merriner. 1977. The displacement and loss of larval fishes from the Rappahannock and James rivers, Virginia following a major tropical storm. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The Johns Hopkins University Press, Baltimore, MD. pp. 591–593.
8. C. Bouchon, Y. Bouchon-Navaro, and M. Louis. 1994. Changes in the coastal fish communities following Hurricane Hugo in Guadeloupe Island (French West Indies). *Atoll Res. Bull.* 425: various pages.
9. J.M. Fitzsimons and R.T. Nishimoto. 1995. Use of fish behaviour in assessing the effects of Hurricane Iniki on the Hawaiian island of Kaua'i. *Environ. Biol. Fish*. 43: 39–50.
10. M.A. Mallin, M.H. Posey, G.C. Shank, M.R. McIver, S.H. Ensign, and T.D. Alphin. 1999. Hurricane effects on water quality and benthos in the Cape Fear River watershed: Natural and anthropogenic impacts. *Ecol. Appl*. 9: 350–362.
11. H.W. Paerl, J.D. Bales, L.W. Nusley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, J.M. Fear, M. Go, B.L. Peierls, T.L. Richardson, and J.S. Ramus. 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary. *Proc. Natl. Acad. Sci. U.S.A.* 98: 5655–5660.
12. J. Davis and B. Laird. 1977. The effects of Tropical Storm Agnes on the Chesapeake Bay estuarine ecosystem. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The John Hopkins University Press, Baltimore, MD. pp. 1–29.
13. S. Jung and E.D. Houde. 2003. Spatial and temporal variabilities of pelagic fish community structure and distribution in Chesapeake Bay, USA. *Est. Coast. Shelf Sci.* 58: 335–351.
14. E.W. North and E.D. Houde. 2003. Linking ETM physics, zooplankton prey, and fish early-life histories to striped bass *Morone saxatilis* and white perch *M. americana* recruitment. *Mar. Ecol. Prog. Ser.* 260: 219–236.
15. W.J. Hoagman and W.L. Wilson. 1977. The effects of Tropical Storm Agnes on fishes in the James, York, and Rappahannock rivers of Virginia. In: *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*. E.P. Ruzecki and others (eds.). Chesapeake Research Consortium Publication No. 54. The John Hopkins University Press, Baltimore, MD. pp. 464–477.
16. S. Jung and E.D. Houde. 2004. Recruitment and spawning-stock biomass distribution of bay anchovy (*Anchoa mitchilli*) in Chesapeake Bay. *Fish. Bull.* 102: 63–77.
17. M.M. Montane, W.A. Lowery, and H.M. Austin. Estimating relative juvenile abundance of ecologically important finfish and invertebrates in the Virginia portion of Chesapeake Bay. Annual Report to NOAA Chesapeake Bay Office, Project NA03 NMF4570378. Virginia Institute of Marine Sciences, Gloucester Pt., VA. 106 pp.
18. M.M. Montane and H. M. Austin. 2005. Effects of hurricanes on Atlantic croaker (*Micropogonias undulatus*) recruitment to Chesapeake Bay. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium, CRC publication 05-160. Edgewater, MD. pp. 185-192.

HURRICANE ISABEL AND THE FORESTS OF THE MID-ATLANTIC PIEDMONT AND BLUE RIDGE: SHORT-TERM IMPACTS AND LONG-TERM IMPLICATIONS

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ABSTRACT

Hurricane Isabel caused large forest blowdowns over a wide area of the Mid-Atlantic, including the Piedmont and Blue Ridge in Maryland, Virginia, and West Virginia. This damage occurred despite these regions being well inland from the coast and maximum wind gust speeds of only about 50 mph (23 $m \cdot s^{-1}$). Forest damage was intensively sampled in a 1-ha plot in the Piedmont of Maryland that had been delimited and tagged five years prior to Hurricane Isabel, and thus can be considered a random sample with respect to storm impact. Additionally, blowdown and control transects were compared at six other locations in the region.

The intensive study site (West Woods Permanent Plot) had 23.5% of its trees showing "severe damage" (uprooting or snapping of the trunk) and destruction of the canopy over 21% of its area. Damage was patchy, with some large gaps of up to 1500 m^2, but with other parts of the plot showing little or no damage. Tree fall was overwhelmingly toward the west. Uprooting—total or partial—was the predominant form of damage (over 19% of trees). The storm contributed an estimated 78 $Mg \cdot ha^{-1}$ of coarse woody debris to the forest floor, over five times the amount previously present and comparable to levels typically found in old-growth forests.

At the intensive study site and in all six blowdown-control pairs, areas of forest with larger trees had the highest probabilities of uprooting. Tuliptree and black cherry were especially likely to be uprooted. These patterns imply that as the secondary forests of the inland Mid-Atlantic grow older and their trees become larger, they will be increasingly vulnerable to damage, even from relatively weak storms. This prediction has implications for a variety of policy questions, including suburban sprawl, land use planning, risk estimation, burial of utility lines, and forest management, as well as for greenhouse warming, nitrogen inputs to the Chesapeake Bay, and the ecology of disturbance.

INTRODUCTION

Most of the articles in this volume concern estuarine ecosystems, particularly those of the Chesapeake Bay. Here the focus shifts to terrestrial, upland ecosystems, in particular, the forests of the Piedmont and Blue Ridge in the Mid-Atlantic region. In this landscape, the predominant impact of Hurricane Isabel resulted from wind damage.

At first glance, one would not have expected Hurricane Isabel to have had much impact on the forests of this region. Its intensity at landfall was only Category 2. By the time it reached the Piedmont of central Maryland, it had traveled across several hundred kilometers of Coastal Plain and the storm had diminished to tropical storm intensity with wind speeds comparable to those of thunderstorms, winter nor'easters, and other storms typical of the region that may occur annually or more frequently.

Several of the initial descriptions of Isabel's impact on the Piedmont matched the expectation of little impact on the inland areas. Some officials did describe the storm's impact in dire terms, but other coverage emphasized that damage appeared to be less than expected—at least in inland areas.

The headline in the Frederick News-Post on the day after the storm was “Isabel Not So Bad,” and climatologist Patrick Michaels, in an op-ed a week later, said simply: “As windbags go, Isabel was a weenie” [1, 2].

In this paper, the authors show that although such statements accurately describe wind speeds, the damage to inland forests was considerably greater than expected. Furthermore, the factors that led to the forests’ vulnerability, such as large tree size, particularly in species such as *Liriodendron tulipifera* (tuliptree or yellow-poplar), are likely to become more important in coming decades. This prediction has implications for several issues of ecology and policy.

METHODS

Wind Gust Estimation

Standard NOAA estimates of sustained winds associated with Hurricane Isabel in our region were used. However, since damage to trees may be more closely associated with wind gusts than with sustained wind speeds, estimates of maximum wind gust intensities at a finer resolution than is possible with official weather station data were also sought.

For this purpose, the authors used the records of maximum wind gusts recorded at the stations of the NBC-4 WeatherNet, affiliated with television station WRC-TV in Washington, D.C. [3]. These stations are located at schools, colleges, federal agencies, and other institutions, and provide daily measurements of basic weather data (including maximum wind gust) available through the television station’s website.

On 29 September 2003, the data for all WeatherNet stations between Manassas, Virginia in the south and Ijamsville, Maryland in the north and from Washington, D.C. in the east to Martinsburg, West Virginia in the west were downloaded. After discarding stations lacking data for 18 and 19 September and excluding one station with anomalously low values as an outlier (NIST, Gaithersburg, Maryland; maximum gusts recorded as 27.8 mph (km·hr^{-1}) or 18 September and 4.6 mph (km·hr^{-1}) for 19 September), 25 stations contained valid data. The larger of the 18 September and the 19 September “maximum wind gust” values was taken as the estimate. To check for latitudinal and longitudinal trends, the maximum wind gust estimates were regressed against each station’s latitude and longitude.

Study Sites: West Woods Permanent Plot

Site Description

In studies of forest damage by storms, study sites are usually chosen and plots laid out only after storm damage has occurred. This situation creates problems in estimating forest damage, since the exact location of the plot boundaries can have major effects on estimates. Thus, the subjectivity involved in locating study plots makes it difficult to assess whether the forest damage measured is truly representative of the overall landscape.

Serendipitously, a study site in the Piedmont of Maryland had been established 5 years before Isabel with all trees in a 1-ha forest plot at this site identified, tagged, and annually measured from summer 1998 through 2003. Thus, this site provides both long-term background data in addition to detailed estimates of forest damage due to Isabel at a location independent of damage by the hurricane. These estimates can, therefore, be considered as a random sample of the damage to the forests in this region.

The West Woods study site is located in Dickerson, Maryland (39.21º N, 77.42º W) at 100 m elevation in the Piedmont of Maryland, about 50 km northwest of Washington, D.C., 5 km from Sugarloaf Mountain and well inland from the Atlantic coast (220 km). It is located on Penn sandy loam soils over bedrock of New Oxford Triassic sandstone. The site slopes gently to the west (1–5%) down to the floodplain of the Little Monocacy River. The approximately 4 ha of forest is estimated to be 80–100 years old.

A 100 x 100 m Permanent Plot was established within the 4 ha of forest in the summer of 1998; all trees 10 cm DBH (diameter at breast height) and up were tagged, identified, measured, and mapped on a 10 x 10 m grid. As of September

2003, the Permanent Plot had 23 tree species and was dominated by tuliptree (*Liriodendron tulipifera*) and black cherry (*Prunus serotina*). Other important trees were: oaks (*Quercus*, 4 spp.), hickories (*Carya*, 4 spp.), ashes (*Fraxinus*, 2 spp.), maples (*Acer*, 2 spp.), beech (*Fagus grandifolia*), and elm (*Ulmus rubra*). No conifers were present. Tree density was 425 trees$\cdot$ha^{-1} and the total basal area was 36.32 m$^2\cdot$ha^{-1} Canopy height, estimated with an electronic clinometer, averaged 33.8 m (SD = 0.6 m, range = 29.4–42.7 m), and was less than 5 m at only 1.7% of the 121 grid points.

Damage Estimation

The annual measurements of the Permanent Plot for summer 2003 had been taken from 22–24 June. These data were updated on the morning of 18 September, just before the hurricane passed over the region. All trees in the plot were checked to see whether they had died since June with their damage status classified on a 7-point scale: 1 = Standing erect (“OK”), 2 = Leaning by 1–15 º, 3 = Leaning 16–30 º, 4 = Leaning 31–45 º, 5 = Leaning more than 45º, 6 = Trunk snapped, and 7 = Uprooted. The direction of leaning or fall was also noted.

Immediately after the hurricane’s passage (19–21 September), this damage assessment was repeated for all trees. Trees in category 5 (Leaning by more than 45º) were kept from falling because their crowns were ensnared in neighboring trees and would otherwise have been classified as Uprooted.

Coarse Woody Debris

Coarse Woody Debris (CWD) input to the forest floor of the Permanent Plot by Isabel was estimated using the line transect method [4]. Since the direction of fall was clearly non-random, perpendicular transects in cardinal directions (N-S, E-W) [5] were used. Each piece of CWD was measured, identified, and assigned a decay class using a modified Adams and Owens’ classification [6]. Total CWD volume was determined using the standard formula for line-transect sampling; biomass was calculated by multiplying volume by density separately for each species and decay class [5, 6].

Study Sites: Blowdown and Control Paired Transects

To verify conclusions from the West Woods site with replicates at other sites in the region, paired transects were established at six other forest sites in September and October 2003. Each pair consisted of a 0.2-ha transect through a blowdown caused by Isabel and a 0.2-ha transect through adjacent forest that had suffered little or no damage, as a control.

The transect pairs were located at sites in the Piedmont and Blue Ridge within 60 km of the West Woods. From east to west, their locations were: Schaeffer Farms area, Seneca Creek State Park, Maryland (2 sites), Sugarloaf Mountain, Maryland (1 site), Turner’s Gap, Maryland (2 sites), and Keyes’ Gap, on the Virginia/West Virginia border (1 site). At three sites, the forest is dominated by oaks and hickories, while tuliptree is the dominant at the other three (Table 1). Stand density does not vary greatly among these sites.

Locating these transects involved a certain amount of subjectivity, as discussed above. To minimize this, pre-existing trails were used as the centers of 20-m-wide (10 m on each side of the trail) x 100-m-long transects for both blowdowns and control. After locating the blowdown transect so that its center was within the heavily damaged area, the control transect was placed along the nearest part of the trail that matched the blowdown transect in slope and aspect. In three of the six cases, the control was immediately adjacent to the blowdown; the largest distance between the two transects in a pair was less than 100 m.

In each blowdown and control transect, the DBH of all trees were identified and measured and assigned to damage categories using the same scale as the West Woods site.

Growth Trends of Mid-Atlantic Forests

The findings at the West Woods site and the six blowdown-control transect pairs (see Results) indicated that future growth trends of the region’s forests will have a major influence on their vulnerability to damage by storms. To evaluate growth trends, data from the U.S. Forest Service’s

Table 1. Mean DBH (mm) of trees in paired 0.2-ha transects in blowdowns caused by Hurricane Isabel and in nearby less-damaged control forest and percent of trees with severe damage (Leaning > 45º, Snapped, or Uprooted) at six sites in the Piedmont and Blue Ridge of Maryland, Virginia, and West Virginia. For paired t-test of difference in mean DBH between blowdowns and controls: Mean difference = 60 mm, t = 5.89, n = 6, P (two-tailed) = 0.002.

Site	Forest type	Blowdown mean DBH (mm; trees·ha^{-1} in parentheses)	Control mean DBH (mm; trees·ha^{-1} in parentheses)	Percent of trees w/ severe damage in blowdown
Sugarloaf E, MD	Tuliptree	380 (305)	284 (405)	28.7
Keyes' Gap, WV-VA	Oak-hickory	312 (330)	248 (570)	9.2
Turner's Gap N1, MD	Tuliptree	355 (260)	283 (355)	13.5
Turner's Gap N2, MD	Oak-hickory	270 (385)	249 (450)	15.6
Schaeffer Farms S Seneca Creek State Park, MD	Tuliptree	395 (390)	349 (435)	14.1
Schaeffer Farms N Seneca Creek State Park, MD	Oak-hickory	332 (415)	268 (500)	6.0

Forest Inventory and Analysis (FIA) project were used. These data are part of a standardized nationwide inventory of forest growth and composition available in tabulated form on the Internet [7] and also summarized in various forms [8, 9]. The data for the state of Maryland, where most of the study sites are located, were used in the study. The most recent FIA data for Maryland are from 1999.

RESULTS

Storm Track and Wind Speeds

Hurricane Isabel's center passed approximately 110 km to the west of the West Woods site between 02:00 and 05:00 on 19 September 2003. The maximum sustained 1-min wind speed in the vicinity of the West Woods Permanent Plot, based on the NOAA Tropical Storm Surface Wind Field Analysis contour map [10], was about 37 mph (16.5 m·s^{-1}). The maximum wind gust for the 25 NBC-4 WeatherNet stations in the study region averaged 50.5 mph (22.6 m·s^{-1}) with a standard deviation of 6.9 mph (3.1 m·s^{-1}). The maximum value recorded among the 25 stations was 62.9 mph (28.1 m·s^{-1}) at Reston, Virginia while the minimum was 36.0 mph (16.1 m·s^{-1}) at Leesburg, Virginia. There was no significant trend in either direction in the regression of maximum wind gust versus latitude and longitude.

Forest Damage: Permanent Plot

Despite these relatively low wind speeds, damage to the Permanent Plot was high (Figure 1). Overall, 15.5% of the trees were uprooted, 4.2% were snapped, and 3.8% were left leaning by more than 45º. These results compare to none uprooted, 0.2% snapped, and 0.7% leaning by more than 45º just before Isabel. Combining these three highest damage categories as "Severe Damage" gives a value of 23.5% after the storm versus just 0.7% beforehand.

Other measures of forest damage yield similar values. Using basal area instead of density to calculate the percentages gives a Severe Damage value of 25.1%. Canopy gap area (points where the canopy height was less than 5 m) was 21.5% of the plot post-Isabel compared to 1.7% prior to the storm.

The direction of fall of the severely damaged trees was overwhelmingly toward the west (mode = 270º), with the large majority falling between 225º and 315º. The spatial pattern of tree fall was quite clumped, with large gaps in some parts of the plot and practically no damage in others. The largest gap was about 1500 m^2, extending from the central part of the plot to the southeast corner; a second gap along the south border of the plot covered about 600 m^2 within the plot and about an equal area outside of it.

Logistic regressions of the probability of severe damage versus DBH and tree species showed significant effects of both. Larger DBH trees were considerably more likely to suffer severe damage ($P < 0.001$). A separate analysis showed that for a given DBH, trees with greater heights were more likely to be severely damaged. While levels of severe damage varied considerably among species, only black cherry was significantly more likely to suffer severe damage after controlling for DBH ($P = 0.004$).

Coarse woody debris input to the forest floor in the Permanent Plot was very large, with an estimated 78 $Mg \cdot ha^{-1}$ being added by the hurricane. This compares to 15 $Mg \cdot ha^{-1}$ present before Isabel. The CWD input was about equally divided between trunks (53%) and branches (47%). An estimated 77.5% of the CWD biomass was from tuliptree, the site's dominant species.

Forest Damage: Blowdown-Control Pairs

The relationship between tree size and severe damage was reinforced by the comparison of the blowdown and control transects at the six other sites. In every case, trees in the blowdown area had a larger mean DBH than trees in the control transects (Table 1), a difference that is highly significant (mean difference = 60 mm, $t = 5.89$, $n = 6$, P (two-tailed) = 0.002). Forest stands dominated by tuliptree had consistently greater levels of severe damage in their blowdown transects (mean of 18.8%), than did forests dominated by oak and hickory (10.3%).

Logistic regression of the probability of severe damage versus DBH and species, taking the trees from the six blowdown-control transect pairs as a

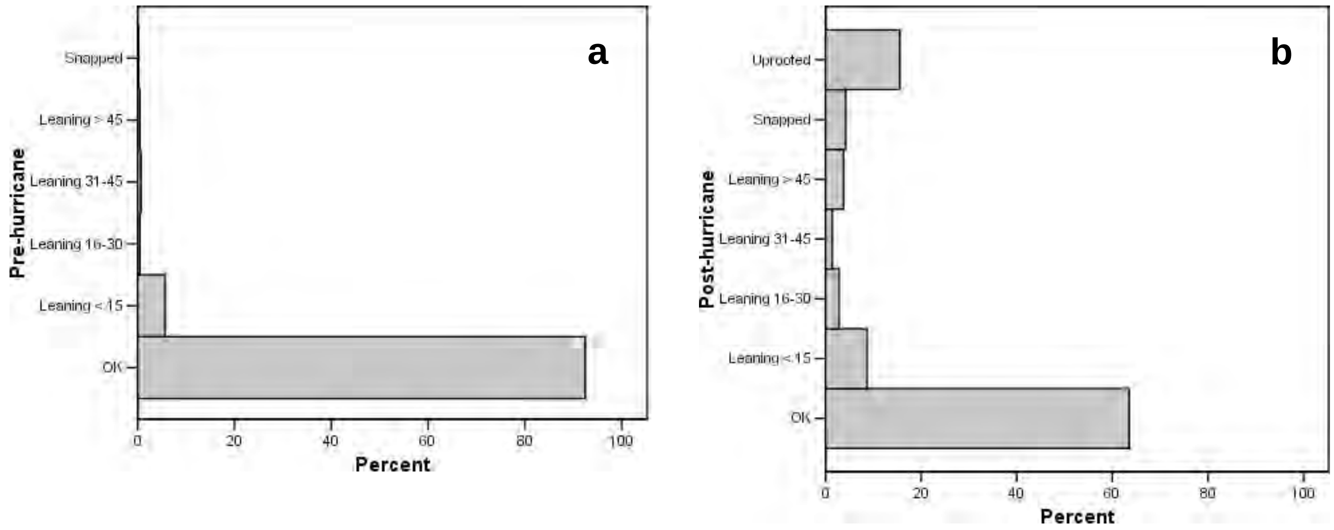

Figure 1. Damage status of trees before (a) and after (b) the passage of Hurricane Isabel at the West Woods Permanent Plot, Dickerson, Maryland. Damage categories were: Standing erect ("OK"); Leaning by 1–15º; Leaning by 16–30º; Leaning by 31–45º; Leaning by more than 45º; and Trunk snapped and uprooted.

whole, shows the same patterns as the paired comparisons. Probability of severe damage is significantly increased by increasing DBH (P = 0.001) and controlling for DBH if the species is tuliptree (P = 0.012) or black cherry (P = 0.016).

Forest Growth Trends in the Mid-Atlantic

The FIA inventories indicate clearly that tree DBHs and timber volumes in Maryland forests have increased substantially in recent decades, and that this trend is continuing. Average timber volume per acre in Maryland forests has grown from 2274 bd-ft·acre^{-1} in 1950 to 6814 bd-ft·acre^{-1} in 1999 [8]. The diameter distribution of tree sizes shifted towards larger trees between 1986 and 1999, with more individuals having diameters above 400 mm (16 in) and fewer with diameters below that size [9].

Tuliptree was already the most abundant tree in the state in 1999 [8]. In coming decades, its relative abundance should increase even more, based on the annual rates of change calculated from the 1999 inventory. That inventory showed that annual net change in sawtimber volume on Maryland timberlands was 155,901 Mbd-ft·yr^{-1}, of which 125,707 Mbd-ft·yr^{-1} was tuliptree (80.6%). The percentage is even higher for growing-stock volume (21,082 M cu-ft·yr^{-1} out of a total 24,137 M cu-ft·yr^{-1}, or 87.3%) [7].

DISCUSSION

Vulnerability of the Region's Forests to Damage by Weak Storms

Taken together, our results indicate that the forests of the Mid-Atlantic Piedmont and Blue Ridge are vulnerable to substantial damage, even from weak storms. Hurricane Isabel had diminished substantially in intensity by the time it reached this region, with maximum wind gusts estimated at only 50.5 mph (22.6 m·s^{-1}). Nevertheless, it severely damaged high percentages of trees at seven forest sites, ranging up to 28.6%. The percentage for the Permanent Plot (23.5%) is especially notable, since this plot was established five years before the hurricane and thus was located without the possible subjective bias in the other samples.

This plot had no true pioneer species, in the sense of species that dominate the early years of succession and then disappear as the canopy closes (e.g., red cedar - *Juniperus virginiana* or Virginia pine - *Pinus virginiana*). Like many century-old forest stands in the Mid-Atlantic, however, it was dominated by fast-growing, shade-intolerant species (tuliptree and black cherry) that persist for centuries during succession, but do not successfully reproduce in their own shade. Such species appear to be particularly vulnerable to damage from wind storms such as Isabel.

Vulnerability to wind damage was clearly related to tree DBH in both the Permanent Plot dataset and the six blowdown-control transects. Furthermore, dominance of forest stands by tuliptree and black cherry further increased vulnerability, compared with oak-hickory stands. Since trends in the region indicate that future forests will have larger DBH trees and will be more and more dominated by tuliptree, vulnerability to windstorms will only increase in decades to come. This prediction is independent of the still-debated idea that hurricane frequency and intensity will increase with global warming [11]

These results reinforce the findings of other researchers studying hurricane impacts in the North Carolina mountains [12, 13, 14, 15]. It is becoming increasingly evident that temperate forest landscapes, as well as tropical ones, can be significantly impacted by disturbances such as hurricanes [16].

Long-term Implications

Over the long term, these results raise questions about our current patterns of land use in the Mid-Atlantic. A major concern in this region is the issue of suburban sprawl, particularly the tendency to develop subdivisions in areas of older forest. This pattern of land use can be expected to produce increasingly severe problems as windstorms occur in coming decades, even if wind velocities are low. If the frequency and/or intensity of future hurricanes increase due to global warming, as has been predicted [11], it will further accentuate these difficulties.

Rather than look upon hurricanes such as Isabel as unforeseeable "acts of God," it is reasonable to take their expected impacts into account in land use planning. These impacts are relevant to such concerns as:

- The debate about the burial of utility lines, which reduces the danger of outages due to trees falling on above-ground lines.
- Calculations of insurance risk based on past history of storm damage, without accounting for the effects of changing size and composition of forests.
- Trends in forest management, including harvest and land-use policies, which have tended to decrease the proportion of oaks.
- The growing threat of invasive exotic species, perhaps further aggravated by high white-tailed deer densities [17].

These findings also have implications for important ecological questions. McNulty [18] has made the case that because of their substantial CWD input, "hurricanes are a significant factor in reducing short-term carbon storage in U.S. forests." His regional analysis showed that hurricanes can be expected to lower the amount of carbon sequestered by eastern forests by about 10%. This study complements McNulty's findings: CWD levels after a single weak hurricane that were comparable to those typical of old-growth forests [4]. Lowered estimates of carbon sequestration by forests imply that greenhouse warming may be a more serious problem than previously thought.

Such major impacts on biomass also affect the forest's role in storing other elements, such as nitrogen. This storage role is an important link between the terrestrial ecosystems of the Chesapeake watershed and the dynamics of the Bay's aquatic ecosystems. While the data necessary to estimate release of N or other nutrients from forests due to Isabel are not currently available, this link between land and water deserves increased scrutiny from both terrestrial and aquatic scientists.

Finally, these findings can alter our view of the role of disturbance in structuring ecological communities. They indicate that disturbance impact is a function not only of the physical characteristics of the disturbance but also of the community's composition, which depends on its land use history. Land use decisions being made today, interacting with future disturbances similar to Isabel, will produce the forest landscape of the Mid-Atlantic in the 21st century.

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REFERENCES

1. E. Slagle and T.E. Buck. 2003. Isabel not so bad. *Frederick News-Post*, Sept. 20, p. 1.
2. P.J. Michaels. 2003. A passion that leaves us powerless. *The Washington Post*, Sept. 28, p. B1.
3. NBC-4 WeatherNet. 2003. Instaweather. *http://instaweather.com/WRC/default.asp?cid=0.*
4. M.E. Harmon, J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.Q. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr., and K.W. Cummins. 1986. Ecology of coarse woody

debris in temperate ecosystems. *Adv. Ecol. Res.* 15: 133–302.
5. D.C. Lutes. 2002. Assessment of the line transect method: an examination of the spatial patterns of down and standing dead wood. U.S. Forest Service Gen. Tech. Rept. PSW-GTR-181: 665–674.
6. M.B. Adams and D.R. Owens. 2001. Specific gravity of coarse woody debris for some central Appalachian hardwood forest species. U.S. Forest Service Northeastern Research Station. Res. Paper NE-716.
7. U.S. Forest Service Northeastern Research Station. 2002. Northeastern Forestry Inventory and Analysis – USDA Forest Service. FIA unit. U.S. Forest Service Northeastern Research Station. Pub. NE-INF-152-02. *www.fs.fed.us/ne/fia/8*
9. S.W. Koehn. 2001. The Future of Forestry in Maryland. Powerpoint Presentation, Maryland State Forester.
10. NOAA Hurricane Research Division. Atlantic Oceanography Lab. 2003. Hurricane Isabel. *http://20www.aoml.noaa.gov/hrd/Storm_pages/isabel2003/Isabel_swath-3.png.*
11. T.R. Knutson and R.E. Tuleya. 2004. Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *J. Climate.* 17: 3477–3495.
12. H. McNab, C.H. Greenberg, and E.C. Berg. 2004. Landscape distribution and characteristics of large hurricane-related canopy gaps in a southern Appalachian watershed. *For. Ecol. Mgmt.* 196: 435–447.
13. C.H. Greenberg and W.H. McNab. 1998. Forest disturbance in hurricane-related downbursts in the Appalachian Mountains of North Carolina. *For. Ecol. Mgmt.* 104: 179–191.
14. B.D. Clinton and C.R. Baker. 2000. Catastrophic windthrow in the southern Appalachians: Characteristics of pits and mounds and initial vegetation responses. *For. Ecol. Mgmt.* 126: 51–60.
15. K.J. Elliott, S.L. Hitchcock, and L. Krueger. Vegetation response to large-scale disturbance in a southern Appalachian forest: Hurricane Opal and salvage logging. *J. Torrey Bot. Soc.* 129: 48–59.
16. E.R. Boose, D.R. Foster, and M. Fluet. 1994. Hurricane impacts to temperate and tropical forest landscapes. *Ecol. Monogr.* 64: 369–400.
17. J. Snitzer, D.H. Boucher, and K.L. Kyde. 2005. Response of exotic invasive plant species to forest damage caused by Hurricane Isabel. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD. pp. 209–214.
18. S.G. McNulty. 2001. Hurricane impacts on U.S. forest carbon sequestration. *Environ. Pollution* 116: S17–S24.

RESPONSE OF EXOTIC INVASIVE PLANT SPECIES TO FOREST DAMAGE CAUSED BY HURRICANE ISABEL

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ABSTRACT

In September 2003, Hurricane Isabel caused unexpectedly high levels of wind damage to an 80- to 100-year-old forest in the Piedmont of Maryland. The storm had decreased in intensity from landfall by the time it reached the study site—sustained winds were moderate and maximum gusts recorded in the area were only 62.7 mph (28.1 $m \cdot s^{-1}$). Mid-sized gaps (up to 1 ha) were created in forest that historically had only small or single-tree gaps.

Isabel created the opportunity to determine whether natural disturbance facilitates the spread of exotic invasive plant species. Exotic invasive species populations were sampled in 400 5 x 5 m quadrats in a heavily damaged 1-ha, long-term forest study plot and in 160 5 x 5 m quadrats in 0.4 ha of a nearby, less-damaged forest between mid-October and mid-December 2003. Light levels (quantum flux density of photosynthetically active radiation) in the heavily disturbed Permanent Plot and the Less Damaged control plot were surveyed in October 2003 and 2004. The fall 2004 resurvey for exotic plants has also been completed.

Based on a random sample of the fall 2004 exotics data, exotic invasive plant species responded strongly to the increased light levels in patches of forest damaged by Isabel. Collectively, the mean increase in percentage cover of exotic plants was 47.8% in high-light canopy gaps versus only 4.8 % in low-light non-gaps and 4.2% in the less-damaged forest. Several individual exotic species—*Polygonum perfoliatum*, *Polygonum caespitosum*, and *Lonicera japonica* had significant positive responses to higher light levels. The shade-loving biennial, *Alliaria petiolata*, changed significantly in the opposite direction, decreasing in the high-light areas and increasing in the low-light areas.

The authors are also investigating the interaction of exotic plants with native plants, forest regeneration, and white-tailed deer (*Odocoileus virginianus*) in damaged areas. Study areas and exclosures for these projects were set up in 2004 and will be resurveyed beginning in 2005.

INTRODUCTION

Remnants of Hurricane Isabel passed across the Maryland Piedmont the night of 18–19 September 2003. The storm had decreased considerably in intensity by the time it reached central Maryland. It produced about 5 cm of rain locally (Dickerson, MD, author's rain gauge). Winds were moderate. Maximum sustained winds in Dickerson were 37.2 mph (16.7 $m \cdot sec^{-1}$ [1]). Maximum gusts recorded within a 50-km radius were 62.7 mph (28.1 $m \cdot sec^{-1}$) [2]. This was a moderate-level storm, not a severe hurricane, yet it created unexpectedly large amounts of damage to forests [3].

Based on patterns of tree fall from Hurricane Isabel, the susceptibility to wind damage for canopy trees has been found to increase with tree size [3]. As forests age and trees grow larger, moderate winds are likely to cause more damage, both by uprooting trees and by snapping them off. As the probability of wind damage for individual trees increases, the pattern of damage shifts from small, or single-tree gaps to larger patches of disturbance. Therefore, it is predicted that in the future, forests in the Mid-Atlantic states will be increasingly subject to medium- and large-scale damage from moderate winds [3].

Hurricane Isabel provided an unexpected opportunity to study the response of exotic invasive plants to natural disturbance. These plants often respond positively to disturbance [4]. Disturbed ecosystems typically have more resources available to colonizing or invading plants than undisturbed ecosystems. This situation is well documented for anthropogenic disturbances, such as timber harvest, road building, and utility right-of-way construction [5]. Natural disturbances (such as flooding, high winds, and fire) perturb forests and make light, space, and disturbed soil available to invading plants, increasing establishment, survival, and growth [6]. The high winds and flooding of a hurricane, which typically occur near the end of the growing season when plants have already set seed, can also increase the dispersal of exotic plants. The spread of exotic organisms has been linked to hurricanes in the past. Forest damage from Hurricane Gilbert in 1988 facilitated the spread of exotic *Pittosporum undulatum* (Cheesewood) in the Blue Mountains in Jamaica [7]. Forest damage from Hurricane Eva in 1982 was linked to the spread of *Schefflera actinophylla* (Octopus tree) in a preserve in the Limahuli Valley on Kauai, Hawaii [8, 9]. Recently, Hurricane Ivan in 2004 was suspected of bringing the spores of Asian soybean rust (*Phakopsora pachyrhizi*) to Louisiana from South America [11]. A strong positive response by exotic plants to predicted and increasingly frequent natural disturbances in eastern deciduous forest would have serious implications for natural resource management and the conservation of rare forest plant species.

METHODS

Work on exotic plant invasion following Hurricane Isabel has focused on the West Woods site, a pre-existing forest plot in Dickerson, Montgomery County, Maryland (39.21º N, 77.42º W). The 1-ha Permanent Plot (PP) was set up in 1998 to study forest growth and succession. The 100 x 100 m plot was subdivided on a 10-m grid into 100 10 x 10 m quadrats. The size, growth, and mortality of trees in the forest had been surveyed for five years before Isabel. The forest was heavily damaged by the storm, with 23.5% of the canopy trees severely damaged, comprising 25.1% of the basal area [3]. The damage was patchy, with both undisturbed areas and canopy gaps up to roughly 1500 m^2. Following the hurricane, the plot was subdivided into 400 5 x 5 m quadrats. A 0.4-ha control plot was set up in comparable but less-damaged forest south of the Permanent Plot called the Less Damaged Plot (LDP). Both plots were surveyed for the presence and cover of exotic plant species between mid-October and mid-December 2003. Since Isabel arrived near the end of the growing season, negligible new growth of herbaceous vegetation had occurred between the storm's passage and the fall 2003 survey. In addition, the plants being surveyed were woody, evergreen, or had persistent dried plant parts after senescence. Thus, the fall 2003 survey provided an unbiased sample of the exotic plant population before significant effects or disturbances occurred due to the passage of Hurricane Isabel.

Removal of the forest canopy increases light levels at the forest floor, but in an irregular and continuously varying fashion. The storm did not leave discrete patches of severely damaged trees in a matrix of undisturbed forest; there are no unambiguous "gap edges" around the blowdowns. In other words, damaged forests are not Swiss cheese [11]. Light levels at the forest floor were used as a measure of the disturbance to the tree canopy by Isabel rather than through definition of "gaps" and "non-gaps." Measuring light allows direct use of a resource made available by Isabel, rather than an arbitrary classification of gap status, to evaluate plant response to the hurricane. Furthermore, light levels in the gaps are not fixed; the amount of light in a gap is roughly proportional to the size of the damaged area. Using light levels differentiates between small, one- or two-tree gaps, and more extensive blowdowns in evaluating plant response. Finally, additional light from canopy gaps penetrates into surrounding undamaged forest. Light effects from hurricane damage may be present tens of meters into still-closed canopy forest. Measuring actual light levels captures this spillover effect. Other effects of hurricane damage may influence the growth of exotic invasive plants, particularly soil disturbance, changes in soil nutrients, and changes in soil moisture. Others have found that soil resources change little following a simulation of hurricane damage [12]. If such effects do occur, they would tend to be spatially correlated with canopy damage. Changes in light levels may not be the entire reason for changes in the herbaceous layer, but these changes should be good markers for storm effects.

Light levels were measured for the PP and LDP plots in October 2003 and 2004 with two paired light meters (LICOR LI-250). Quantum flux density of photosynthetically active radiation was measured simultaneously at the 10-m intersection points of the 1999 plot grids and in a nearby, open field. Readings were taken at 55 points in the LDP and 121 points in the PP. Measurements were taken of diffuse, indirect light in early morning and late evening with continuous 15-sec readings. Timing of readings was coordinated to the nearest second with handheld radios.

The "end-of-year-one post-Isabel" fall survey of exotic plants began on 17 October 2004. The same order of survey was followed as in the fall of 2003 to minimize the effects of any seasonal differences in vegetation. Thus, each quadrat was being surveyed within a week of the date of survey in 2003. As of 12 November 2004, 360 of 560 quadrats had been resurveyed.

Hurricane Isabel left behind a less-than-optimal experimental design. While the control plot is in all measurable ways similar to the Permanent Plot (surrounding land use, forest age, land use history, forest cover, soil, slope, aspect, initial herbaceous cover, percentage in floodplain), completely randomizing disturbance effects throughout the less damaged, low-light, and high-light quadrats was not possible. There is minor clumping of the high- and low-light quadrats due to the patchy distribution of storm damage, but the quadrats are well dispersed across the plot. Quadrats were selected randomly but are not entirely independent, again due to the nature of natural disturbance. Given that the West Woods plot was set up years before the hurricane and was thus random with respect to storm damage, it is suggested that the problems related to independence of samples are acceptable.

RESULTS AND DISCUSSION

The light surveys have demonstrated the extent of damage to forest canopy. Mature forest is dark. After Isabel, light increased almost an order of magnitude in heavily damaged areas. The mean light level in the selected quadrats in the LDP was 3.2 % of ambient light (n = 15). Mean light levels in the high-light and low-light quadrats in the PP were 24.7 % and 3.9% respectively (n = 15 each). Clearly, the storm increased a limited resource on the forest floor.

Eight species of exotic plants were located in the PP and LDP in fall 2003, with frequency of occurrence ranging from 0.18% for English ivy, (*Hedera helix*, 1 of 560 quadrats) to 87.8 % for Japanese honeysuckle (*Lonicera japonica*). The biennial garlic mustard (*Alliaria petiolata*) was also common, occurring in 79.6% of the quadrats. These common plants tended to be sparse, typically covering less than 1% in quadrats. Multiflora rose (*Rosa multiflora*) was less common, occurring in 55.5% of the 560 quadrats, but individual plants covered large areas, exceeding 50% of some quadrats.

In the first year following the hurricane, exotic invasive plants have responded vigorously to the change in light levels. Percentage cover for random samples of 15 quadrats each from the three light environments were compared: closed canopy forest in the LDP; high-light areas in heavily damaged sections of the PP; and low-light areas in the relatively undamaged sections of the PP. Mean percentage cover by exotic plants responded strongly to growing in high-light areas (Figure 1). The mean changes in percentage cover of exotic invasive plants in LDP, high-light PP, and low-light PP quadrats between 2003 and 2004 were 4.2%,

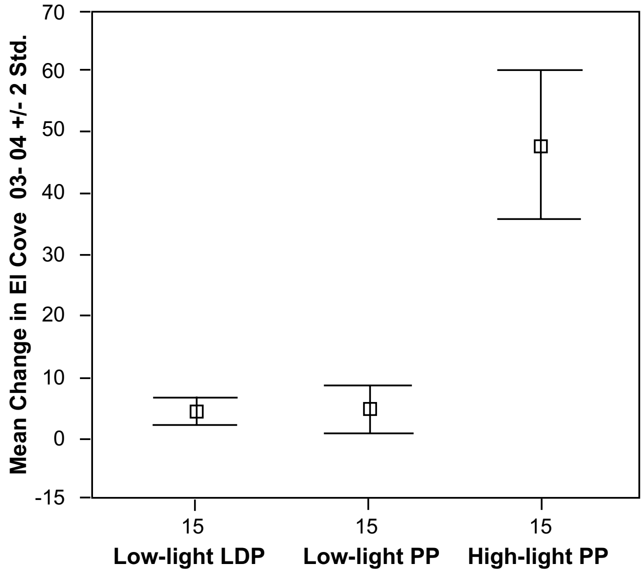

Figure 1. Change in percent cover of exotic invasive plants in plots with differing canopy disturbance levels between fall 2003 and fall 2004. LDP and low-light PP are not significantly different. High-light PP and the other two treatments are significantly different ($P < 0.05$).

4.8%, and 47.8% respectively (significantly different by a Kruskal-Wallis test, $P < 0.001$). The frequency of occurrence of exotic plants also changed between 2003 and 2004 (Table 1).

Broken down by species, exotic plant cover has changed significantly for four out of fifteen species since the hurricane. This response is strongly related to the three different light environments. Increased percentage cover for mile-a-minute (*Polygonum perfoliatum*), long-bristled smartweed (*Polygonum caespitosum*), and Japanese honeysuckle (*Lonicera japonica*) is in each case significantly greater in the high-light than in the low-light and LDP areas (Table 1). Garlic mustard (*Alliaria petiolata*) also changed significantly, but with increased coverage in the shady quadrats and decreased coverage in the high-light quadrats. The cause of this decrease is not known. Garlic mustard may be decreasing due to competition from other invasive plants. But since garlic mustard is a biennial, the observed decrease in cover may be due to a difference in distribution of the alternate-year cohorts.

The species with a significant increase in the light-rich blowdowns are two annuals that did not exist in the plots before Isabel (mile-a-minute and long-bristled smartweed) and a widely dispersed perennial (Japanese honeysuckle) that was already in place in the disturbed patches. Less widely dispersed perennials also increased in frequency and cover in the high-light areas, but not significantly.

These results are important because a change in the herbaceous layer influences forest succession [13]. Dense herbaceous vegetation can increase seed predation on large-seeded trees such as oaks. Exotic plants growing in high-light field edges near this research site form dense mats of vegetation and overwhelm less aggressive plants. Native vegetation is suppressed or replaced by exotic invasives [14]. High densities of exotic plants also alter ecosystem function. Nutrient cycling, hydrology, and food webs are altered when exotic plants replace native ones [4, 15, 16, 17]. High populations of exotic plants reduce populations of native plants and threaten local extinction for uncommon plants. The forest that regenerates in the 21st century, responding to increasingly frequent wind damage [3] and an herbaceous layer dominated by exotic plants, will differ from the forest that would have regenerated hundreds of years ago.

This exotic survey is part of a long-term assessment of the interactions between exotic invasive plants, the native plants in the herbaceous layer, forest regeneration, and elevated populations of white-tailed deer in natural areas in the Mid-Atlantic region. Both exotic and native plants in the herbaceous layer were surveyed in May 2004 and again in May 2005 (and later) to evaluate the effect of disturbance and exotic spread on native plant populations. Tree seedlings are also being monitored to assess the interaction of exotic plants and canopy tree regeneration.

Deer could be influencing the spread of exotic plants and regeneration of the forest. Exotic plants leave behind most of their co-evolved herbivores [18]. If deer are avoiding exotics and browsing preferentially on native plants, deer browsing pressure could increase the growth, survival, and spread of exotic plant species. While working on this and other projects at the same site, deer browse on garlic mustard, Japanese stiltgrass

Table 1. Change of percent cover in 5 x 5-m quadrats between fall 2003 and fall 2004, by species and type of plot. P values are from Kruskal-Wallis tests for significant differences between plots with Bonferroni correction. Significant changes in percent cover are in boldface.

Species	Change in % cover '03-'04, LDP	Change in freq., low-light LDP	Change in % cover '03-'04, low-light PP	Change in freq., low-light PP	Change in % cover, 03-'04, high-light PP	Change in freq., high-light PP	Change in % cover
Polygonum perfoliatum (Mile-a-minute)	0.0	0	0.0	0	2.00	46.7	**<0.001**
Rosa multiflora (Multiflora rose)	-0.50	13.3	0.17	6.7	2.17	20.0	0.137
Alliaria petiolata (Garlic mustard)	1.33	53.3	0.33	13.3	-0.17	-6.7	**0.001**
Lonicera japonica (Japanese honeysuckle)	0.17	6.7	-1.00	-6.7	3.67	13.3	**0.005**
Rubus phoenicolasius (Wineberry)	0.33	13.3	0.33	13.3	4.17	40.0	0.160
Glechoma hederacea (Gill-over-the-ground)	0.17	6.7	0.33	13.3	0.67	26.7	0.540
Duchesnea indica (False strawberry)	0.17	6.7	1.00	6.7	11.17	0	0.081
Polygonum caespitosum (Long-bristled smartweed)	2.50	100.0	3.33	100.0	24.00	86.7	**0.002**
Total	4.17	25.0	4.83	18.3	47.83	28.3	**<.001**

(*Microstegium vimineum*), or mile-a-minute has not been observed. Deer also serve as dispersal vectors for exotic plants. Deer eat fruit and pass viable seeds from exotic plants [19]. The weed seeds that stick to clothes evolved to take advantage of animals for dispersal, not wool socks and cotton sweatshirts. Deer exclosures have been set up in damaged and less-damaged forest to evaluate the impact of deer on exotic plant spread.

If natural disturbance triggers the interactions suggested here, forest regeneration could be altered or suppressed. Populations of native wildflowers will be reduced or replaced. Forests in the future could end up quite different from the historic forests of the Mid-Atlantic states.

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REFERENCES

1. NOAA Hurricane Research Division. 2003. *www.aoml.noaa.gov/hrd/Storm_pages/isabel2003/Isabel_swath-3.png*
2. NBC-4 WeatherNet. 2003. *http://instaweather.com/WRC/default.asp?cid=0*
3. D.H. Boucher, C.L. Rodick, J.N. Bailey, J.L. Snitzer, K.L. Kyde, and B. Prudden. 2005. Hurricane Isabel and the forests of the mid-Atlantic Piedmont and Blue Ridge: Short-term impacts and long-term implications. In: Hurricane Isabel in Perspective. K.G. Sellner (ed.). Chesapeake Research Consortium, CRC Publication 05-160. Edgewater, MD. pp. 201–208.
4. P.M. Vitousek, C.M. D'Antonio, L.L. Loope, and R. Westbrooks. 1997. Introduced species: A significant component of human-caused global change. *NZ J. Ecol.* 21: 1–16.
5. M.A. Davis, J.P. Grime and K. Thompson. 2000. Fluctuating resources in plant communities: A general theory of invasibility. *J. Ecol.* 88: 528–534.
6. R.J. Hobbs and L.F. Huenneke. 1992. Disturbance, diversity, and invasion: implications for conservation. *Cons. Biol.* 6: 324–337.
7. T. Goodland and J.R. Healy. 1996. The Invasion of Jamaican Montane Rainforests by the Australian Tree, *Pittosporum undulatum*. School of Agriculture and Forestry, University of Wales, Bangor, U.K. 56 pp.
8. C. Wichman and M. Shuford. *www.plant-talk.org/stories/32limah.html*
9. D. Tennenbaum. *http://whyfiles.org/112trop_plant/3.html*
10. E. Stokstad. 2004. Plant pathologists gear up for battle with dread fungus. *Science* 306: 1672–1673.
11. M. Lieberman, D. Lieberman, and R. Peralta. 1989. Forests are not just Swiss cheese: Canopy stereogeometry of non-gaps in tropical forests. *Ecology* 70: 550–552.
12. G.C. Carlton and F.A. Bazzaz. 1998. Resource congruence and forest regeneration following an experimental hurricane blowdown. *Ecology* 79: 1305–1319.
13. L.O. George and F.A. Bazzaz. 2003. The herbaceous layer as a filter determining spatial pattern in forest tree regeneration. In: F.S. Gilliam, and M.R. Roberts (eds.). *The Herbaceous Layer in Forests of Eastern North America*, Oxford University Press, Oxford, U.K. pp. 265–282.
14. K.E. Miller and D.L. Gorchov. 2004. The invasive shrub, *Lonicera maackii*, reduces growth and fecundity of perennial forest herbs. *Oecologia* 139: 359–375.
15. J.G. Ehrenfeld, P. Kourtev, and W. Huang. 2001. Changes in soil functions following invasions of exotic understory plants in deciduous forests. *Ecol. Apps.* 11: 1287–130.
16. D.R. Gordon. 1998. Effects of invasive, non-indigenous plant species on ecosystem processes: Lessons from Florida. *Ecol. Apps.* 8: 975–989.
17. R.N. Mack, D. Simberloff, W.M. Lonsdale, H. Evans, M. Clout, and F. Bazzaz. 2000. Biotic invasions: Causes, epidemiology, global consequences, and control. *Issues Ecol.* 5: 1–20.
18. R.M. Keane and M.J. Crawley. 2002. Exotic plant invasions and the enemy release hypothesis. *Trends Ecol. Evol.* 17: 164–170.
19. J.A. Meyers, M. Vellend, S. Gardescu, and P.L. Marks. 2004. Seed dispersal by white-tailed deer: implications for long-distance dispersal, invasion, and migration of plants in eastern North America. *Oecologia* 139: 35–44.

Management, Preparedness, and Response: Isabel and Future Storms

INTEGRATING SCIENCE AND MANAGEMENT FOR STORMS AND HURRICANES: A PANEL DISCUSSION

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ABSTRACT

At the conclusion of the "Hurricane Isabel in Perspective" conference, a panel of scientists and managers discussed lessons learned. Some responses of the Chesapeake Bay to the hurricane (e.g., storm surge) were predictable, while others (e.g., restratification of water masses after passage of the storm) were surprises. The large storm surge and shoreline erosion provided a significant scientific opportunity to understand processes and verify models. Large perturbations such as this, however, must be viewed as interacting with, and frequently exacerbating, the other human and natural stressors of the ecosystem that diminish its resilience. Risks to people and property could be reduced through better communication of forecasts and warnings, public education, and efforts to make the infrastructure and shorelines less vulnerable in an era of accelerated sea level rise.

CONFERENCE OVERVIEW

The conference on "Hurricane Isabel in Perspective" was a success on several fronts. First, it provided an impetus for scientists to pull together a rich array of information concerning the physical, ecological, and human responses within the Chesapeake Bay ecosystem to this unusual event. While the effects of Isabel on the estuary itself were not as dramatic as those of Tropical Storm Agnes with its heavy rains and overwhelming floods, the impacts were certainly felt by waterfront property owners. In the estuary itself, the responses were simultaneously both reassuringly predictable (e.g., the propagation of storm surge) and quite surprising (e.g., the biophysical processes associated with destratification and restratification of the Chesapeake). In either case, Hurricane Isabel provided a remarkable opportunity to learn how the Bay works.

Second, the conference provided a rare occasion for individuals working at the local government level—those responsible for emergency preparedness and response, planning and zoning, and infrastructure management—to interact with Bay scientists and those at the leading edge of weather and storm forecasting. Much learning took place in both directions.

Third, energy and enthusiasm was developed among the participants to improve planning, dissemination of information, and incorporation of a more dynamic view of the Chesapeake Bay in its restoration. In particular, calls echoed throughout the conference to take advantage of the freshness of the storm experience to improve public understanding and response to avoid personal tragedies, economic losses, and unsustainable investments.

PANEL DISCUSSION

The conference closed with a discussion among six very experienced panel members. The essence of the panelists' viewpoints has been captured below. No doubt, some important points have been inadvertently omitted. Also, the reader should remember that the following sections are summarizations of the discussion by the author, not a verbatim representation of panelist comments. Thus, any credit goes to the panelists, but blame stops with me.

K.G. Sellner (ed.). 2005. Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.

Dr. Hans Paerl, a highly regarded ecologist from the University of North Carolina, has had unsolicited, first-hand experience regarding the effects of hurricanes on coastal ecosystems. Working at the Institute of Marine Sciences in Morehead City, the epicenter of one of the most hurricane-prone regions on the coast of the United States, Paerl has experienced six major hurricanes that made landfall on the North Carolina coast between 1996 and 1999, as well as Isabel in 2003 [1]. In 1999 the assault seemed unrelenting, with Dennis and Floyd hitting the North Carolina coast in September and Irene passing just offshore in October. These storms led to unprecedented rainfall and prolonged flooding in the eastern part of the state.

Dr. Paerl observed that the effects of northeast storms should be considered as well as hurricanes because they can have very similar effects. But he also cautioned that storms can be very different in their impacts, largely depending upon landfall location and its influence on wind direction and speed along with rainfall patterns. The three successive storms in 1999, for example, had very different impacts.

Dr. Paerl also stressed that both science and management need to consider the context of multiple stressors and management challenges within the coastal ecosystem and associated watershed. Many of these systems are already under a high level of anthropogenic pressure, so a storm represents an additional rather than an isolated pressure. In Pamlico Sound, for example, there is a very high level of fishing pressure, including shrimp trawling. Storm-induced floods resulted in a dislocation of some fishery resources, causing increased pressure on the stocks due to concentrated harvesting. Such a scenario suggests that a need exists for more sophisticated models that can adjust predictions of storm impact as an ecosystem becomes more or less stressed by other factors over time. Paerl commented that, sadly, memories of storm effects often fade quickly. Despite the ravages of its floods, Hurricane Floyd is largely forgotten and people are once again building in the flood-plains of eastern North Carolina.

Mr. David Lyons, Chief of the Enforcement Division in the Water Management Administration of the Maryland Department of the Environment, noted that a principal lesson from Hurricane Isabel is the need to focus on how to make people better prepared. In addition to individual preparedness, Lyons stressed the need for local government to take storms into account when building, updating, and managing infrastructure. For example, wastewater treatment plants and sewerage pumping facilities need to be carefully designed and have emergency plans in place. The region is already struggling to reduce overflows from sewerage systems that receive storm waters; planning for tidal flooding from hurricanes adds yet another requirement.

Although Isabel was a relatively dry storm (i.e., modest rainfall), it re-enforces the need to limit the proliferation of impervious surfaces and enhance stormwater management capabilities. Mr. Lyons stressed the importance of conserving and protecting natural systems that will buffer against storm damage, including the use of non-structural shoreline erosion controls. He was encouraged by presentations at the conference on improved knowledge of elevations of low-lying lands though LIDAR surveys [2, 3]. These efforts are producing very useful information in planning for both storm surge and stormwater flooding.

As suggested by Paerl, Mr. Lyons also reminded the audience that the public's memory is short and people will rapidly forget about the impacts of Hurricane Isabel. Consequently, it is important to communicate to the public now what happened and why the storm surge was so high. He further noted that many of the best management practices used for Chesapeake Bay conservation are not currently designed to cope with hurricanes and other extreme storm events. These practices range from agricultural management practices to fisheries management. An example for the latter indicates this concern: how should harvest quotas be adjusted following such storm events?

Dr. Wilson Shaffer, a storm-surge modeler with NOAA's National Weather Service, picked up on the theme of the public's short memory. He emphasized that tropical storms are relatively rare events in the Chesapeake Bay region, with 70 years between the 1933 storm and Hurricane Isabel [4, 5]; both produced similar storm surges. Very few people had thought such flooding possible and most are unaware of the general axiom, "run from the water, hide from the wind." Some hid when they should have run. Overall, better education of the public is required to ensure that people respond appropriately to warnings. Also, it is important to improve public understanding of storms. For example, people should be aware that the greatest danger lies in the northwest quadrant of an approaching hurricane. Perhaps there is a need for an ensemble of models that project the worst and best case scenarios for each storm so that appropriate warnings can be provided.

Mr. Richard Batiuk, Associate Director for Science of EPA's Chesapeake Bay Program Office, observed that Hurricane Isabel provided an opportunity to assess what worked and what did not. For example, in many places significant erosion occurred behind bulkhead walls, whereas nearby natural shorelines with no engineered protection did not suffer serious erosion. Further, it appears that the physical processes in the Bay are of major consequence in ways not previously understood, and thus improving our understanding of these processes remains important. Hurricanes also magnify the dynamics normally occurring within the Bay, making them more obvious and amenable to quantification. The continuing assessment of the observed responses of the estuarine ecosystem to Hurricane Isabel, therefore, provides a real opportunity to substantially improve our knowledge and our ability to predict responses to phenomena—both natural and anthropogenic.

Ms. Ann Swanson, Executive Director of the Chesapeake Bay Commission, asked: What have science and management taught us? There is a division in perception between the scientific community (which increasingly recognizes ecosystems such as the Chesapeake Bay as highly dynamic) and most of the public (which expects stability). How can we reconcile the ecological tendency for variability with a human desire for predictable structure? While much is known, large gaps in knowledge still exist, yet management decisions need to be made every day. Should management decisions be made only when something is well known or, in fact, because not as much is known as desired? In Swanson's experience, three elements are required to effect change: knowledge (among scientists and in the broader community); political interest; and public concern. She suggested that Hurricane Isabel has provided a window of opportunity for progress because it created public concern and, thus, political interest.

Ms. Swanson noted that an environmental agenda can be moved forward, driven by quite different interests. For example, impervious surface can be reduced in a development due to both environmental (reducing runoff) and financial (less expensive) requirements. Both arguments can have credibility with different audiences, but both yield the same result. It is crucial to consider the responses to Hurricane Isabel in this context: when dealing with a socioeconomic concern, environmental improvements could result as well. In this regard, there is a need to consider locations for future development, runoff management, shoreline stabilization and the use of living shorelines, and abatement of sediment loads to the Bay's tidal waters. She asked, based on the lessons of Hurricane Isabel, if the scientific community could identify a short list of things that should be carried out differently from both ecological and social perspectives? Isabel has provided a window of opportunity with the public for dramatic change, but it will soon close.

Dr. Carl Hershner, Director of the Center for Coastal Resources Management at the Virginia Institute of Marine Science, observed that Boicourt [4] mentioned integrated models of the continental shelf, estuary, and watershed as the holy grail of physical scientists who study estuaries. He pointed out that, while it is important not to underestimate the significance of physical processes, the behavior of the ecosystem may be much more complex. Much recent information indicate that such ecosystems are dynamic over the long term as well as the short term, requiring consideration of ecosystem resilience not just in terms of how quickly it returns to "normal" after an extreme event such as a hurricane, but also the potential that it may shift to another state due to the combined pressures of chronic human alteration and acute natural events.

CONCLUSION

The panel's discussion was lively and seemingly well appreciated by the audience. Those who attended both the conference and concluding panel discussion are now likely committed to remembering the lessons of Hurricane Isabel as captured in these proceedings and to helping citizens understand better the risks, changes, and options confronting them in the world in which we live.

REFERENCES

1. H.W. Paerl, B.L. Peierls, L.M. Valdes, R.S. Weaver, T. Gallo, and J.S. Ramus. 2005. Ecological effects of a recent rise in Atlantic hurricane activity on North Carolina's Pamlico Sound system. In: Hurricane Isabel in Perspective. 2005. K.G. Sellner (ed.). Chesapeake Research Consortium. CRC Publication 05-160. Edgewater, MD. pp. 3–18.
2. Z.P. Johnson and A. Luscher. 2005. Management, planning, and policy conference sessions. In: Hurricane Isabel in Perspective. 2005. K.G. Sellner (ed.). Chesapeake Research Consortium. CRC Publication 05-160. Edgewater, MD. pp. 221–232.
3. A.E. Luscher. 2005. Improving utilization of geospatial information in coastal hazard planning in Maryland. In: Hurricane Isabel in Perspective. 2005. K.G. Sellner (ed.). Chesapeake Research Consortium. CRC Publication 05-160. Edgewater, MD. pp. 233–242.
4. W.C. Boicourt. 2005. Physical response of Chesapeake Bay to hurricanes moving to the wrong side: Refining the forecasts. In: Hurricane Isabel in Perspective. 2005. K.G. Sellner (ed.). Chesapeake Research Consortium. CRC Publication 05-160. Edgewater, MD. pp. 39–48.
5. L.H. Brasseur, A.C. Trembanis, J.M. Brubaker, C.T. Friedrichs, T. Nelson, L.D. Wright, W. Reay, and L.W. Haas. 2005. Physical response of the York River estuary to Hurricane Isabel. In: Hurricane Isabel in Perspective. 2005. K.G. Sellner (ed.). Chesapeake Research Consortium. CRC Publication 05-160. Edgewater, MD. pp. 57–64.

MANAGEMENT, PLANNING, AND POLICY CONFERENCE SESSIONS

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ABSTRACT

Hurricane Isabel's impact on the Chesapeake and its local citizens was devastating, but could have been worse but for the highly developed and effective management, planning, and policy programs in Maryland. Four panel presentations—Hazard Mitigation: Tools, Technologies, and Opportunities; Regulatory and Permitting Issues; Advances in Hazard Mapping; and Promoting Soft Approaches to Shoreline Management—provided an excellent opportunity for open discussion of successes and options for better preparedness in the future. As hurricanes and other natural disasters are certainly likely over the coming decades in Maryland waters, training opportunities identified by the group provide substantial capacities for educating and informing our local managers and responders, assuring potential within-state disaster preparedness for the coming years.

INTRODUCTION

Hurricane Isabel, a Category 2 hurricane, made landfall between Cape Lookout and Cape Hatteras on North Carolina's Outer Banks on Thursday, 18 September 2003. As the hurricane approached the Chesapeake Bay, it weakened to a tropical storm and tracked west of the Bay's main stem, causing the event to evolve into a watershed, rather than a coastal, event. Although the measured wind speed suggested low to moderate infrastructure damage, the wave setup from Hurricane Isabel's path concluded in one of the largest surge events recorded in the Chesapeake Bay.

Throughout the next several days, Isabel's destructive effects were felt throughout the Chesapeake Bay and the entire Mid-Atlantic region. A tally by the Maryland Department of Planning showed: 2,000 Maryland residents were evacuated; the agricultural industry sustained extensive damage; 2,550 businesses applied for aid; 18,000 Maryland residents applied for individual FEMA assistance; 3,250 homes received tax abatements; approximately 70 miles of shoreline experienced erosion damage; and approximately 50,000 gallons of fuel was recovered [1]. Hurricane Isabel was one of the most devastating natural events to affect the Chesapeake region in more than a century. This damage occurred in response to coastal flooding from the storm surge (the water height from the combined normal high tide and storm tide) as opposed to wind damage, which is most often associated with hurricanes.

The "Hurricane Isabel In Perspective" conference was organized to discuss the many factors that exacerbated Isabel's impact on the Chesapeake Bay ecosystem and its coastal communities. The conference agenda was developed through a solicitation of papers, as well as invited speakers and panelists. A primary goal of the conference was to create an open dialog between the scientific and management communities. To achieve this goal, conference organizers balanced the sessions with presentations and panel discussions of interest to both the academic and the scientific communities, as well as representatives of federal, state, and local agencies involved in management, planning, and emergency response. Additionally, sponsor funding was used to reduce or eliminate conference fees for the local planners and emergency managers to encourage participation. The plenary sessions focused on broad-scale issues crossing all disciplines and were followed with paper presentations and panel discussions of planning, impact, and modeling issues.

This section of the proceedings document presents an overview of the Management, Planning, and Policy conference track. This conference track encompassed four panel presentations: Hazard Mitigation: Tools, Technologies, and Opportunities; Regulatory and Permitting Issues: Lessons Learned; Advances in Hazard Mapping; and Promoting Soft Approaches to Shoreline Management. Panelists within each session provided unique perspectives related to the hurricane and its impacts, as did audience participants encouraged to engage in panel discussions. Overviews of the four sessions are provided below, along with a list of panel participants and generalized findings.

HAZARD MITIGATION: TOOLS, TECHNOLOGIES, AND OPPORTUNITIES

Hazard mitigation is defined as sustained action taken to reduce or eliminate long-term risk to people and property from hazards and their effects. Numerous federal, state, and local hazard mitigation plans and programs exist in the Chesapeake Bay region. Panelists in this session discussed the development, adoption, and implementation of some of these programs, including Local Hazard Mitigation Planning, the Hazard Mitigation Grant Program (HMGP), the National Flood Insurance Program (NFIP), the Community Rating System (CRS), and hazard preparedness planning for federal facilities and the agricultural industry.

Session Chair: Zoe Johnson - Maryland Department of Natural Resources

Panelists:

David Thomas - Baltimore County Public Works
John Govoni - NOAA's National Centers for Coastal Ocean Science
Kimberly Golden Brandt - Maryland Emergency Management Agency
John Joyce - Maryland Department of the Environment
Pamela King - University of Maryland Cooperative Extension
Richard Sobota - Federal Emergency Management Agency

In the year after the storm, many of the agencies involved in hazard mitigation and response evaluated the effectiveness of the mitigation tools and technologies they use on a day-to-day basis in light of damage incurred by the storm. Drawing on lessons learned during and after the storm, panelists presented an overview of their independent evaluations; in doing so, they identified opportunities for improved preparedness, response, and recovery.

Planning Does Pay Off

One of the most important lessons learned from Hurricane Isabel is that elevating structures above the 100-year base flood elevation (BFE) helps prevent flood damage. Most structures elevated at the time of construction experienced less structural damage than similar structures in the same geographic area built lower to the ground. The current minimum standard under the NFIP for elevating structures is the BFE. To participate in the NFIP, communities must adopt and enforce a floodplain management ordinance containing minimum NFIP requirements. As the state coordinating office for the NFIP and the Community Assistance Program in Maryland, however, the Maryland Department of the Environment (MDE) recommends that all tidal communities adopt additional elevation requirements into their floodplain ordinances for new buildings. In light of sea level rise and storms such as Hurricane Isabel, the MDE is advocating that structures be elevated at least 0.61 m (2 ft) above the BFE. This measure will not only protect property and life from future flooding, but will pay for itself in a few years in reduced flood insurance premiums under the CRS.

Non-structural mitigation measures include land use regulations and policies, building codes, open space preservation, dune and beach maintenance, and public education/outreach. Structural mitigation techniques include activities such as relocating homes or structures, constructing flood control devices, elevating ductwork, and anchoring residential oil and propane tanks. The Maryland Emergency Management Agency (MEMA) is the state agency charged with protecting the lives and property of Maryland citizens. It accomplishes this charge through an integrated and coordinated effort to mitigate, prepare for, respond to, and recover from emergencies and disasters. The MEMA oversees and/or administers several of the state's mitigation programs, including the HMGP, which received 5.5 million dollars in federal funds after Hurricane Isabel. These funds are being matched with monies from Maryland's Comprehensive Flood Management Grant Program (CFMGP) to finance structural elevation projects in eight jurisdictions and acquisition/demolition projects in three jurisdictions. In the event of another major storm, planning and mitigation efforts such as these will undoubtedly pay off.

Use of Forecasts and Models in Planning

Panelists provided multiple examples of how first responders and planners used forecasts and models to prepare and respond to the event. The National Centers for Coastal Ocean Science of NOAA have established detailed emergency response plans for their Beaufort, North Carolina and Oxford, Maryland laboratories in the event of either a hurricane watch or hurricane warning [2]. In addition to the National Weather Service (NWS) hurricane warnings, NOAA used the NWS National Digital Forecast Database and the SLOSH model to determine the level of necessary preparedness for Hurricane Isabel. Damage to NOAA's federal facilities was lessened because of adequate preparation in response to their surveillance of the NWS's forecasts and storm surge predictions. Several panelists, however, noted concern over the interpretation of models and forecasts and voiced the need to understand and recognize limitations of forecasts and projections, particularly at the local level and by popular media. Several panelists testified that the classified category of the storm did not represent the actual storm surge as it equated to a Category 4 hurricane. Many planners, as well and public citizens, were caught off-guard.

Local and Resource-based Planning

Local and resource-based planning form a critical component of hazard planning. Local governments are often the first and last responders to natural disasters: they must deal with the immediate impacts as well as the logistical red tape associated with cleanup and recovery for months to years after. Resource-based planning agencies, such as the Maryland Department of Agriculture (MDA), are also critically and closely involved in all phases of hazard planning and response [3]. Press releases, such as those issued by the MDA prior to the storm, urged farmers to prepare farms and livestock for Hurricane Isabel and provided invaluable and case-specific information to affected communities in a way unlike any other popular media source. The intimate knowledge that local and resource planners hold of the landscape, history, and resources at the local and regional levels proved invaluable in the response to Hurricane Isabel.

Need for Increased Education and Outreach

Despite accurate tracking of Isabel's landfall by the NWS, impacts still occurred that could have been avoided. Significant numbers of vehicles and private property were destroyed from floodwaters created by the surge of 1.2 to 2.4 m (4 to 8 ft) predicted in the Bay. The announcement of the surge forecasts was provided in sufficient time to evacuate automobiles and move personal items to higher ground. On the whole, the communication of this risk to the public proved ineffective. Many citizens were left stunned as they had little understanding of how to apply the forecasts to their own property. The public was more concerned about rainfall than storm surge, as the area had fairly recent experience with high-rainfall hurricanes (e.g., Floyd, Agnes). For instance, Baltimore City emergency response personnel were posted along the Jones Falls in anticipation of high rains and flooding, but those impacts never materialized.

What did materialize was extensive coastal flooding throughout the Inner Harbor of Baltimore, but no staff was posted in this area to report the surge as it came ashore. The last memorable and comparable storm surge event in the Bay region occurred in 1933, when an unnamed hurricane also tracked onto the Bay's western shore. Session panelists commented that Hurricane Isabel has given the region a benchmark from which to measure and gauge the impact of future storms. This gauge will hopefully help alert the public and improve communication.

REGULATORY AND PERMITTING ISSUES: LESSONS LEARNED

Drawing from lessons learned from Isabel, panelists in this session presented an overview of the permitting and regulatory issues they faced during and after the hurricane, covering regulatory and permit compliance, emergency permitting, tree and vegetation removal, post-storm reconstruction, and public health. The panel's goal was to provide a forum to discuss these topics, while exploring methods and exchanging ideas for enhanced planning and preparedness for future natural events.

Session Chair: Julie LaBranche - Maryland Critical Area Commission

Panelists:

Tracy Keefer - U.S. Army Corps of Engineers
Doldon Moore - Maryland Board of Public Works
Patricia Farr - Baltimore County
Michael Galvin - Maryland Department of Natural Resources
Alan Williams - Maryland Department of the Environment

Panelists in this session conducted an informed dialogue on permitting and regulatory issues before, during, and after Hurricane Isabel. The exchange of information on what worked and what failed will both guide and further streamline future response efforts.

Streamlined Permitting and Review Made Recovery Effort Faster and Smoother

A major theme running throughout the session's presentations was the overwhelming effort federal, state, and local governments made to expedite permit processes. The U.S. Army Corps of Engineers (USACE) implemented expedited permit guidance through Special Public Notice #03-20, which established emergency permitting regulations for a two-year period. Immediately after the storm hit, the Maryland Board of Public Works (BPW) and the Critical Area Commission for the Chesapeake and Atlantic Coastal Bays (CAC) also realized the need to implement streamlined permit processes.

The BPW moved quickly to provide guidance on repairing damage while recognizing the significant volume of requests that would be forthcoming and the limited staff resources to assist with application reviews. It issued an Expedited Tidal Wetlands License to repair/replace structures damaged by Hurricane Isabel. The BPW also set out the authority; defined a timeline; established authorized activities, license conditions, and penalties for violations; and issued a consumer advisory.

The CAC's guidance on emergency permit procedures provided authority to local jurisdictions to implement a streamlined permit application process to allow property owners to: remove damaged structures and rebuild them on the original footprint or foundation; and remove damaged trees and other damaged vegetation, restore previously vegetated areas, and restore areas disturbed through compliance with emergency procedures.

Baltimore County also provided expeditious service to its communities by staffing the county's Disaster Recovery Center with personnel from Environmental Impact Review and Permitting departments. Building permit applications and approvals could be made at the center. The county used 2002 geographic information system (GIS) information to verify the existence and size of structures and sent staff into the field only when structures could not be verified on aerial photos. Personnel also tracked the number of permits reviewed per hour to determine day-to-day staffing needs and developed categories of permits that could be finalized without delay. In the two months following the storm, Baltimore County processed over 300 permits per month, far exceeding the average 35 permits per month processed during the same time in the year after the storm.

Needed Improvements

Despite the large-scale efforts outlined above, panelists noted that some improvements could be made based on the lessons learned from their response to Hurricane Isabel. Most of the panelists agreed that federal, state, and local permitting processes should be amended to allow for minor enhancements or improvements to the design of rebuilt structures instead of replacing “like” structures in the same footprint. The BPW noted that it would have preferred to issue an Expedited Tidal Wetlands License to replace structures damaged by Hurricane Isabel with structures that would provide “greater environmental benefit,” such as substituting damaged hard-shoreline structures with environmentally friendly methods of protection. Revetments to marsh creations, beach nourishment, and/or beach platform grading and bulkheads to revetments or marsh creations are all examples of projects that would provide “greater environmental benefit.” Unfortunately, the state and federal permit processes could not be aligned to accomplish this process in expedited fashion.

“I Have No Idea How This Happened”

Another theme running through the panel presentations and audience discussions was the lack of understanding the general public has concerning the impact of natural hazards in local communities. Slides and visuals that showed extensive structural, physical, and natural resource damage that could have been avoided with proper planning appeared time and time again in the conference presentations.

Conversely, on a more positive note, panelists provided some sound guidance on how to improve the situation. Proper vegetation management—particularly within utility corridors—would prevent some undue electrical power outages. Elevating electrical meters and placing utility lines underground would lessen impact, as would educating public agencies and citizens not to store valuables or irreplaceable items in basements. Another recommendation, perhaps key to the “lessons learned” concept of the conference, was to use damage and permit application statistics along with demographic information to target planning and mitigation enhancements in preparation for the next major storm. As suggested, this step can be accomplished by mapping out structures within local communities that require repair/replacement permits to visually determine where to pursue flood mitigation efforts, including participation in the NFIP.

ADVANCES IN HAZARD MAPPING

Maryland is limited in its experience with storm disaster events compared to hot spots such as south Florida, North Carolina, and the Gulf Coast. Hurricane Isabel tested Maryland’s response capabilities and planning activities. In particular, the events surrounding the preparation and response provided many success stories for which advancing technical capabilities proved invaluable. Since Hurricane Agnes in 1972, the evolution of GIS and information technology has greatly improved the ability to identify vulnerable areas. In turn, this advancement in technology has increased the sophistication of pre-disaster hazard planning and mitigation activities.

Within hours of the storm’s passage over the Bay area, metropolitan regions rapidly generated incident reports and tracked these occurrences spatially through GIS databases. These products greatly assisted local staff in informing the commissioning bodies and allowing political appointees to illustrate the magnitude of the impacts to federal and state disaster relief and recovery organizations. Ultimately, these products rapidly facilitated the declaration of Maryland as a State of Emergency and allowing it to become immediately eligible for federal disaster relief assistance.

The session highlighted advances in data and mapping technologies and demonstrated enhancements in identifying and mapping hazard areas more accurately. In particular, GIS provides an unprecedented opportunity to integrate multiple datasets to derive and visualize solutions to complex emergency management issues and identify hazard mitigation opportunities. Panel members included representatives of federal and state government and private and academic institutions working on various aspects of hazard mapping. Specific mapping applications discussed in these sessions included: LIDAR based-surge inundation modeling; modernization of floodplain studies; the HAZUS loss estimation tool; and statewide all-hazard mapping.

Session Chair: Ken Miller - Maryland Department of Natural Resources

Panelists:

Audra Luscher - Maryland Department of Natural Resources
Joseph Gavin - U.S. Army Corps of Engineers
Carrie Capuco - Capuco Consulting
David Sides - Towson University
Peter Conrad - City of Baltimore
Dave Guignet - Maryland Department of the Environment

Efforts and Opportunities in Hazard Mapping

Hazard mitigation mapping in Maryland is conducted mainly by two lead agencies: MDE and MEMA. Both agencies comply with federal mandates and programs established through the Federal Emergency Management Agency (FEMA). The MDE has responsibility for floodplain studies and mapping, repetitive loss GIS, and the CFMGP while MEMA is the first responder to any disaster in the state and prepares the State Hazard Mitigation Plan (SHMP) and vulnerability mapping, administers the HMGP, the Flood Mitigation Assistance Program (FMAP), and the Pre-Disaster Mitigation Program (PDM). MEMA is the primary contact agency for FEMA funding.

The MDE recently completed “A Business Plan for Map Modernization” for floodplain mapping and management. This report outlines the state’s vision for floodplain management over the next five years (2004–2008) [4]. Maryland’s vision for floodplain management is closely coupled with its vision for map modernization. The MDE seeks to reduce costs associated with traditional detailed studies by developing a new set of “live” studies (digital verses paper product), which can be modified as watershed conditions change. Any proposed changes can be modeled to keep the maps current as permits are issued. Another key to the modernization process is the acquisition of additional partnerships and funding to accomplish value-added improvements to support the study process.

With the advent of better elevation data and motivation from the storm to improve flood hazard mitigation, great momentum exists to update and increase the accuracy of floodplain maps in Maryland. These improvements incorporate updated elevation information generated from new data from LIDAR (LIght Detection And Ranging), using automated hydrology and hydraulic techniques to improve riverine floodplain analysis, and adding bridge and culvert data.

The MDE is currently working with FEMA and local governments to update all of the paper Flood Insurance Rate Maps (FIRMs) in Maryland and to develop Digital FIRMs for every county to allow different layers to be overlain in GIS. Each county will have continuous coverage (towns will be part of the county coverage), eliminating problems associated with annexations. The agency has received $2 million to complete flood studies and develop D-FIRMs for Anne Arundel and Howard counties and the lower half of the Eastern Shore, where LIDAR data are available. Once procedures are developed, the remaining counties will be completed as LIDAR becomes more accessible.

An important aspect of map modernization for state citizens will be better estimation of the risk of flooding and more accurate determination of who needs flood insurance from the NFIP. In Maryland, 116 communities participate in the NFIP—virtually all communities with land use authority with the exception of a few small towns. Whenever maps are revised based on better floodplain determinations, some properties will move into the floodplain, while other properties will be moved out. The ultimate objective, however, is to estimate the risk to all property more accurately.

In November 2004, MEMA completed the SHMP and associated mapping pursuant to regulations established by the Disaster Mitigation Act (DMA) of 2000. The goal of the SHMP is to reduce the loss of life and property damage associated with hazard events in Maryland. The agency complied with this priority as considerable effort has been expended to map state-owned and critical facilities, as well as impact areas for eleven other hazards.

The most important aspect of this mapping effort was the identification of facilities, total populations at risk, and vulnerable populations at risk within hazard areas. The data sets and mapping effort will continue to evolve and improve as new data and technologies become available. The FEMA has emphasized the importance of using the best available data when delineating hazardous areas, identifying facilities and populations at risk, and developing mitigation strategies.

Local governments are also required to develop multi-hazard mitigation plans and generate map products on vulnerable populations. These plans must be revised on a five-year schedule; however, annual reviews—particularly map updates—are encouraged. With the passing of the DMA, the PDM was created and is intended to fund mitigation measures before a disaster occurs to counties with hazard mitigation plans in place. Prior to the creation of this program, the only significant source of funding for hazard mitigation to county governments and citizens was the HMGP—grants only available after a presidential disaster declaration.

Another ongoing mapping effort involves HAZUS-Multi Hazard (MH), a risk assessment software program for analyzing potential losses from floods, hurricane winds, and earthquakes. This software estimates damage before or after a disaster and accounts for various impacts of a hazard event such as: physical damage to residential and commercial buildings, critical facilities, etc.; economic loss from lost jobs, business interruptions, and repair and reconstruction costs; and social impacts to people including requirements for shelters and medical aid.

The FEMA is sponsoring Anne Arundel County, Maryland as a national pilot for a coastal community. However, MDE is furthering these efforts and has partnered with Salisbury University to complete a statewide analysis of flood vulnerability estimated through the HAZUS-MH flood module. A Level One analysis estimating projected flood damage from a 100-year flood for each county, using national datasets, was released in spring 2005. The local jurisdictions can then decide to refine the analysis further by incorporating more precise local data.

New Data Advance Hazard Mapping

In Maryland, federal, state, and local partners have worked cooperatively using considerable resources to improve digital ortho-based mapping capabilities by acquiring high-resolution digital LIDAR imagery. This imagery provides elevation information at a scale never before offered and is improving the study and identification of flood and surge hazards. The use of LIDAR has multiple research and management benefits, with application to a range of tools and analyses including floodplain and hydrologic modeling, sea level rise studies, nonpoint source identification and resolution, and siting storm water restoration and "best management practices."

Acquisition of LIDAR was initiated in the low-lying counties of Maryland's Eastern Shore due to their vulnerability to coastal flooding and sea level rise. To date, over 1.5 million dollars have been provided through the Maryland's Coastal Zone Management Program (CZMP) and county funds to acquire the bare earth or gridded digital elevation model (DEM) data. Ten coastal counties have been mapped, with partial coverage in two additional counties. Further funding from the CZMP has been allocated to delineate 2-ft (0.61-m) contours for portions of Dorchester, St. Mary's, and Anne Arundel counties and throughout Worcester County.

Panel discussions identified LIDAR as the most important data/tool available. Second to LIDAR was availability of good demographic and social data—essential for determining a region's vulnerability and potential impacts. With the exception of the HAZUS loss estimation model, all of the mapping products discussed used the newly acquired high-resolution elevation information.

Accessibility and Availability of Various Data Formats is Key Issue for Local Governments

The use of GIS and technical assessments to identify and develop strategies to mitigate storm impacts provided significant advantages in planning for and recovering from a disaster. The capacity to utilize these technical products, however, was not equal across all levels of government. In the days after the storm, differences in the capacity to use GIS-based information were highlighted, particularly at the county level. Metropolitan counties with numerous staff and advanced GIS facilities were more capable of using advanced technologies in the recovery process by spatially tracking damages, using GIS-based products to identify damage trends, and supporting decision-making. Such GIS tools and technologies are not as useful during the event, as emergency response decisions and activities are facilitated through more traditional means, such as radio announcements, word of mouth, and experience of residents and long-time emergency management staff to guide citizens out of harm's way. To merge technical capabilities into emergency management and planning activities of rural counties, however, an executive commitment to build facilities is needed from all levels of governments. Addressing the development of consistent data formats and mechanisms to transfer information to users of variable skill levels is also needed to increase the utility of many of these technical tools [5]. A concerted effort to make information available online through Internet mapping applications and data servers is a feasible option. Academia should also investigate its role in these efforts and seek opportunities to augment training and partnerships with state and local governments.

SOFT APPROACHES TO SHORELINE MANAGEMENT: ARE THEY EFFECTIVE?

Maryland's coastal zone comprises 66 percent of the total land area of the state. Bordering this coastal area is over 7,700 miles of shoreline, a disproportionate amount given the overall size of the state. A study by Maryland Geological Survey before Isabel determined approximately 69 percent of the shoreline has a measurable rate of shoreline change. A majority of this change, however, is less than $0.6\ m \cdot yr^{-1}$ ($2\ ft \cdot yr^{-1}$) [6].

Immediately after Hurricane Isabel, Governor Robert L. Ehrlich tasked the Maryland Department of Planning (MDP) to oversee identification of the economic and environmental impacts and gather insights from the event to improve emergency response and recovery efforts. In June 2004, MDP issued "Lessons Learned from Tropical Storm Isabel" [1]. One of the single largest impacts of the event identified in the report was the economic impact of shore erosion on the citizens of the Chesapeake Bay. Much of the erosion occurred on properties along the open Bay, many with structural erosion control measures in place. Anecdotal information related to the success and performance of softer approaches in tidal creeks and embayments began to circulate in the months following the event.

The panel's objective was to discuss example projects that represent alternative approaches to traditional structural control in the Maryland Bay. These approaches are "softer," more natural shoreline treatments that incorporate living landscapes and minimize the structural components of erosion control. Although acceptance of these practices is growing, homeowners often hesitate to rely on “softer” methods, as they are unsure of their effectiveness. The panel discussed the alternative approaches and identified approaches that performed well during the storm surge.

Session Chair: Audra Luscher, Maryland Department of Natural Resources

Panelists:

David Burke - David Burke & Associates
Kevin Smith - Maryland Department of Natural Resources
Bruce Young - St. Mary’s County Soil Conservation District
David Wilson - Eastern Shore Resource, Conservation & Development Council
Marguerite Whilden - Terrapin Institute

Structural Control not Fail-safe

The surge generated from Hurricane Isabel piled up on the western shore of Maryland’s Chesapeake Bay. The western side of the Bay has shorelines that are higher in elevation than those on the Eastern Shore. Along banks and bluffs, the surge elevated the line of wave attack higher on the banks. Any protection—manmade or natural (e.g., a narrow beach or marsh strand at the base of bluff)—was topped with the waves reaching farther inland. Upland areas not usually subject to wave attack were eroded during Isabel, while the shoreline itself did not appear to change position significantly. The main effect of the storm surge was the translation of the zone of wave influence vertically, removing the energy of wave attack from the toe of the bank or bluff [7].

After the surge peaked, floodwaters began to drain to the Bay. Most damage to erosion control structures occurred from hydraulic loading of the floodwaters on the backside of structures. Receding floodwaters scoured fastland sediment behind the structures and appeared to cause selective failure in the lowest or weakest point in a line of structural control. Once a structure was breached, water funneled to the Bay through that position, consolidating the energy and significantly scouring individual land parcels.

The need for maintenance of non-structural/ hybrid approaches was minimal compared to the cost of reconstructing erosion control structures. In many cases, the greatest cost for reconstruction was replacing the tremendous volume of fill to re-establish the pre-storm profile above the height of the existing erosion control structure. To avoid any storm impact on these shorelines from a 100-year surge event, the structures would need to be considerably higher in profile or the bank would require a grade that accommodates wave run-up from the surge. To create a structure of that magnitude is economically prohibitive for most property owners and would lead to considerable impact on public bottom, access, and shoreline habitat. For many homeowners and coastal managers, the trade-off of greater protection is not worth sacrificing the connection to the Bay. Therefore, the concept of designing with nature instead of total defense against storm and wave processes was a major theme in the session.

Design with Nature

The panelists discussed a wide array of non-structural/hybrid approaches that were in place before the storm. These approaches included shore-perpendicular groins (rock and biologs) with marsh plantings, low-profile sills, marsh toe revetments, and offshore breakwaters (unattached and shore-parallel). For the structures highlighted in the session, post-construction photos and “as built” drawings were used to determine if changes in profile, sediment distribution, and plant abundance and health occurred. A structure’s success depended greatly on site-specific characteristics, including energy environment, sun exposure, and boat traffic. In low-energy environments, low-profile sills with backside vegetative plantings appeared to have greater stability and success than groin systems. The low-profile sills appeared to diminish day-to-day wave attack and allowed the surge to roll up and over the structure with the vegetation baffling surge energy. Changes in profile of the shoreline due to sediment redistribution and loss of vegetation occurred more often with the groin projects. Groin projects had the most success in areas with sediment sources and longshore transport that built the shoreline outward. Adjustments in profile and plant density can often be dealt with through routine maintenance, including re-grading the profile and vegetation plantings. Routine maintenance is not usually associated with structural approaches.

Monitoring Can Guide Site-selection Criteria

As soft approaches are not appropriate in all locations, better targeting of suitable shoreline settings can help assure project success. In particular, long-term monitoring of projects is needed throughout the Bay, as most are not evaluated after installation. Several recent efforts and studies are addressing how these projects perform over time. The Eastern Shore Resource Conservation and Development Council is in the process of assessing and photographing many of the more than 500 non-structural projects implemented over the last 15 years. Furthermore, the University of Maryland Center for Environmental Studies was supported to conduct science-based monitoring and assessment of five non-structural approaches in summer 2004 [8].

On-site and pre-construction analysis of site-specific conditions are the best approaches to ensure the success of an individual project. However, regional and eco-based assessments to assist in targeting areas for alternative approaches do not exist for most shorelines along the Bay. The CZMP, in cooperation with Towson University, is developing a data-intensive and spatial approach for regional targeting and shoreline management. An Internet-based resource portal, Shorelines Online, will provide data distribution capabilities, Internet mapping tools, and information about shore erosion and innovative methods for shoreline protection and restoration. The portal will provide a framework for centralizing access to technical and financial resources and data as a mechanism to improve shoreline planning and assist in decision-making/visualization of potential options. As shoreline management must balance infrastructure/property risk with the need to maintain shoreline habitat, a mapping tool hosted on this site will display spatial data and targeting tools to help stakeholders identify where alternative approaches are appropriate. The project seeks involvement of a wider array of stakeholder participation, particularly the public, in decision-making and data utilization by having the product available through the Internet.

TRAINING OPPORTUNITIES

Drawing from lessons learned, conference participants engaged in a dynamic forum to understand large storm events more fully and to enhance planning and preparedness for future natural events. The conference offered an excellent opportunity for information gathering and exchange for local planners and resource managers. One of the conference's major lessons learned was the need to increase our knowledge of hurricane dynamics and resultant impacts, and to translate this information from scientists to planners and emergency responders, and ultimately, to the general public. Opportunities to continue the education process are provided below.

Severe Storms Conference. This annual conference is hosted by the MEMA in the spring of each year. The conference provides valuable information on hurricane preparedness for Maryland's local governments and state agencies. The agenda for the conference includes a variety of breakout groups and presentations by the NWS and the National Hurricane Center (NHC). For more information, contact Robert Ward at (410) 517-3600 or by e-mail at *rward@mema.state.md.us*.

Maryland Association of Floodplain and Stormwater Managers. Formed in 2004, the association is comprised of local, state, and corporate floodplain managers. Anyone interested in floodplain or stormwater management can become a member and/or attend its annual meetings and training opportunities. For more information, contact Mike Sheffer at (301) 210-6800 or by e-mail at *msheffer@pbsj.com.*

Certified Floodplain Manager Program. This program was established by the Association of State Floodplain Managers to enhance the training and professional status of floodplain managers. Training courses are offered throughout the year. More information about the program and training opportunities can be found on the website at *www.floods.org.*

Introduction To Hurricane Preparedness. This course is held annually at the NHC. For more information, contact Robert Ward at (410) 517-3600 or by e-mail *rward@mema.state.md.us.*

Emergency Management Institute (EMI). This institute offers several useful floodplain management and hurricane planning courses online and at its training facility in Emmitsburg, Maryland. For more information on courses or to download an admission application, go to *http://training.fema.gov/EMIWeb/*. All applications must first be forwarded to the state training officer at MEMA.

Hurricane Planning. This two-day course is held annually by EMI. The course covers proven methods and techniques for planning response operations before and after a hurricane. Topics include hurricane hazards forecasting and decision aids, evacuation, shelter, refuges of last resort, and initial post-storm response. Planners responsible for developing or revising hurricane operations plans and procedures should attend. For more information, visit EMI's website at *http://training.fema.gov/EMIWeb/* or contact Sam Isenberger, EMI Training Division, at (301) 447-1071.

HURREVAC/SLOSH Training. This one-day training is held annually by EMI. It is a new FEMA developed standardized course of the FEMA-US Army Corps of Engineers hurricane decision-making software program known as HURREVAC. The training provides instruction with hands-on (interactive) experience and includes an exercise. The course briefly covers all aspects of HURREVAC and is for beginners as well as users seeking a refresher. For more information, visit EMI's website at *http://training.fema.gov/EMIWeb/* or contact Sam Isenberger, EMI Training Division, at (301) 447-1071.

Community Hurricane Preparedness. This EMI computer-based course provides those involved in the decision-making process for hurricanes with basic information about how hurricanes form and their hazards, how the NWS forecasts future hurricane behavior, and what tools and guiding principles can help emergency managers prepare their communities. For more information, visit EMI's website at *http://training.fema.gov/EMIWeb/* or contact Sam Isenberger, EMI Training Division, at (301) 447-1071.

Hurricane: Preparedness and Response. This EMI exercise-based course addresses preparedness and response in emergency situations due to a hurricane. The course places public officials and other key community leaders in a disaster simulation. Methodologies of classroom instruction, planning sessions, and exercises allow structured decision-making in an educational, yet realistic, environment. A key outcome is that additional planning needs are identified, providing the opportunity to enhance overall preparedness. The exercise scenario focuses on evacuation issues prior to the simulated hurricane making landfall and response activities after. For more information, visit EMI's website at *http://training.fema.gov/EMIWeb/* or contact Sam Isenberger, EMI Training Division, at (301) 447-1071.

Hurricane: Recovery and Mitigation. This EMI exercise-based course emphasizes recovery and mitigation issues. The course places public officials and other key community leaders in a simulation that begins after a disaster has affected a community. The course methodologies of classroom instruction, planning sessions, and exercises allow structured decision-making in a realistic learning environment. A key outcome is to provide participants with the ability to carry out their respective functions related to disaster recovery, both in the short and long term. The exercise scenario focuses on community recovery from a hurricane disaster. Mitigation activities to prevent or reduce the future impact of a hurricane are also identified through course exercises. For more information, visit EMI's website at *http://training.fema.gov/EMIWeb/* or contact Sam Isenberger, EMI Training Division, at (301) 447-1071.

FEMA/NFIP website. This website is a great resource for multiple audiences, including consumers, insurance professionals, and state and local officials. The site provides links to computer-based training, classroom training, and "Ask the Expert" training. Visit *www.fema.gov/nfip* or for more information, contact Richard J. Sobota at (856) 489-4003 or by e-mail at *rsobota@csc.com.*

REFERENCES

1. Maryland Department of Planning. 2004. Lessons Learned from Tropical Storm Isabel: Improving Disaster Management in Maryland. Maryland Department of Planning, Baltimore, MD. 28 pp.
2. J.J. Govoni and F.G. Kern. 2005. Using forecasts to protect federal facilities in the path of Hurricane Isabel. In: K.G. Sellner (ed.). Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD. pp. 255–258.
3. R. Halman, P. King, and G. Bowling. 2005. Hurricane Isabel: An Agricultural Perspective. In: K.G. Sellner (ed.). Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD. pp. 243–248.
4. Maryland Department of the Environment. 2004. A Business Plan for Map Modernization. Maryland Department of the Environment, Baltimore, MD, 11 pp.
5. A. Luscher. 2005. Improving utilization of geospatial information in coastal hazard planning in Maryland. In: K.G. Sellner (ed.). Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD. pp. 233–242.
6. L. Hennessee, M.J. Valentino, and A.M. Lesh. 2003. Updating shore erosion rates in Maryland: Maryland Geological Survey, Baltimore, MD. Coastal & Estuarine Geology File Report No. 03-05, 26 pp.
7. E.L. Hennessee and J.P. Halka. 2005. Hurricane Isabel and erosion of Chesapeake Bay shorelines, Maryland. In: K.G. Sellner (ed.). Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD. pp. 81–88.
8. D. Burke, E.W. Koch, and J.C. Stevenson. 2004. Assessment of Hybrid Type Shore Erosion Control Projects in Maryland's Chesapeake Bay. Maryland Department of Natural Resources, Annapolis, MD. 36 pp.

IMPROVING UTILIZATION OF GEOSPATIAL INFORMATION IN COASTAL HAZARD PLANNING IN MARYLAND

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ABSTRACT

Through an open forum and panel discussion, the importance of geographic information systems (GIS) and information technology (IT) in state and local government responses to Hurricane Isabel's passage across Maryland was recognized and lauded. More notably, discussion identified additional capacities and processes that could be implemented to prepare the state and its responders for future events more fully. Specific recommendations for expanding state preparedness include: increasing statewide standards, protocols, and centralized access for geospatial information including better capabilities to transfer and use information at the county/local level; identifying and implementing better coordinated communication from state to county/local level *and* the public; increasing capacities for more data-rich products, such as light detection and ranging (LIDAR) elevation information as well as georeferenced addresses for vulnerable buildings, structures, etc.; securing fiscal resources (e.g., reserves) permitting continuous, across-budget-year upgrades of GIS and IT capacities at the county/local level; and expanding government-academic partnerships to increase training opportunities and science-based emergency response planning.

INTRODUCTION

Advances in data gathering, geographic information systems (GIS), and information technology (IT) have greatly improved the ability to identify vulnerable areas and improve the sophistication of planning for hazard response and mitigation. The events surrounding the preparation and recovery from Hurricane Isabel provided many examples for which the benefits of advancing technologies and planning became obvious. The use of GIS and forecasting assessments in hazard planning and mitigation has significant advantages. Although many examples exist in which GIS and modeling assisted in forecasting the potential impacts from Hurricane Isabel, the sophistication and capacity to use GIS-based information are not equal across all levels of government. Issues impeding the incorporation of geospatial information into coastal hazard planning and decision-making, particularly at the local level, will be discussed in this paper. Recommendations are also provided to enhance local technical capabilities and to address specific issues associated with the accessibility and utility of geospatial products.

GIS tools and technologies are not as useful during the event itself, as emergency response decisions and activities are facilitated through more traditional means, such as radio announcements, word of mouth, and the first-hand experience of residents and long-time emergency management staff to guide citizens out of harm's way. Institutional and experiential knowledge are powerful tools; at times they provide the best information in emergency situations. For instance, the decision to evacuate an area may depend more on emergency responder or citizen awareness of areas that regularly flood versus use of a floodplain or inundation map to guide such decisions.

Issues covering utilization of geospatial technologies in pre-disaster planning depend on the user group and whether analysis results were provided in a format appropriate for the specific target audience. Many counties are capable of receiving raw spatial information (point data, etc.) and incorporating it into ongoing GIS activities. In an emergency response situation, however, critical information may need to be provided in a map layout format available for immediate printing to allow comparisons with other maps at the local emergency operation center (EOC) to assist in decision-making. Therefore, the ability to transition GIS for use in emergency response and information transfer depends on whether the information is provided in an array of formats that accommodate users of variable skill levels.

In the days after the storm hit the Chesapeake Bay, differences in the capacity to use GIS-based information were highlighted at the county level. Metropolitan counties with numerous staff and more advanced GIS facilities were more capable of using advanced technologies in the recovery process. Examples of map products surfaced at the Maryland State Geographic Information Committee (MSGIC) meeting just after the storm, showcasing how some counties used GIS to track damages spatially, identify damage trends, and support decision-making.

To achieve the efficiency that mapping technologies offer at all levels, issues and outstanding needs concerning formatting, housing, and distribution of data technology and modeling products should be addressed. Advanced modeling and mapping tools prove especially useful to local governments in land use decisions and comprehensive planning before a disaster. These mapping and modeling products, however, are often not in a useful or accessible format, particularly for local planning and response agencies.

ISSUES

The transfer of geospatial information and mapping tools at the local level faces a suite of technological and capacity hurdles. This section highlights transfer issues, pointing to specific examples where the utility and accessibility of geospatial information is being impeded. These obstacles relate to five broad issues: 1) statewide institutional structure and technical framework for sharing information; 2) communication and coordination; 3) outstanding data and information needs; 4) technical assistance and capacity building opportunities; and 5) funding needs and resources.

1) Statewide institutional structure and technical framework

The MSGIC represents the main coordinating body for the development of protocols and standards related to geospatial information. This volunteer organization seeks consensus-building to coordinate data acquisition, standards development, and other activities [1]. Despite important contributions made by MSGIC to information standards and management, data needs are often fulfilled through a piecemeal approach scattered among agencies and academic institutions. No single state agency focused on GIS and information technology exists that oversees data-gathering activities and also has the authority to contract for data and services in Maryland.

Improving county capacity to use technical information is contingent on enhancing the overall institutional and organizational structure and technical framework on data acquisition and handling. Issues concerning the use and accessibility of new technologies go beyond data acquisition and deal with the gathering, sharing, housing, and maintenance of the data. The housing of geospatial information represents a significant issue for many local governments as file sizes grow with increasingly detailed information and higher-resolution imagery. Furthermore, modification to land use and zoning occurs daily and these changes must be represented in the spatial applications, challenging local governments to maintain the data sets on a continuous basis. Such data management issues significantly affect the use and applicability of GIS tools.

Issues of scale, lack of consistent datums, formats, and projections also affect the capability to transfer and use information. Lack of consistency decreases the ease and ability to share digital files and information. Some of the issues could be partially resolved by complying with existing MSGIC standards across all levels of government.

Some county information technology operations are at a disadvantage with respect to available technical and financial resources. At the federal and state levels, the transition from hard copy mapping and assessment to digital capabilities has taken place relatively quickly. This process has not been fully achieved at the county level, however, particularly in rural communities. County technical and hazard response systems require assistance in transitioning from "small-town" operations to networked structures that are more technical in both approach and scale. Effective use of new information technologies often requires an executive-level commitment to build and maintain the required technological and organizational infrastructure. For example, managers at the local level should develop a structure to institutionalize their GIS capabilities (develop metadata, create permanent technical positions, etc.) that maintains their technical capacities even with turnover of staff.

2) Communication and coordination

Federal, state, and county agency participation in coastal hazard mitigation and planning varies in the scope of responsibilities due to specific agency mandates, jurisdictional boundaries, and level of involvement. These differences are especially apparent between land use planning and emergency response agencies. Although activities and communication styles vary, coordination between planning and response remains essential. Feedback from emergency response agents to the planning staff on experiential accounts of disasters assists in future delineation of regional vulnerabilities and risks to specific demographics (non-English-speaking, disabled, etc.). Communicating these risks affects comprehensive planning and land use decisions, which play a considerable role in mitigating coastal hazard impacts. The connection and level of communication between these groups varies on a county-by-county basis, however, with some agencies coordinating frequently and others having little contact.

The public is also an important component in the hazard mitigation process, but communicating risk and vulnerability to these stakeholders has proven difficult. Mitigation is a localized process, with homeowners often making choices that directly influence the extent of impact to private property and infrastructure. A need exists to involve the public in the mitigation process more closely by improving access to the products and results of vulnerability mapping.

The public is often not kept in mind when developing mapping applications and management tools. Such communication gaps were exemplified by the passage of Hurricane Isabel. Although the track and magnitude of the storm were forecast quite accurately through spatial models, damage occurred that could have been avoided. Significant numbers of vehicles and private property were destroyed from floodwaters created by the 1.2–2.4 m (4–8 ft) surge in the Chesapeake Bay. The surge forecasts were provided with sufficient time to evacuate automobiles and move personal items to higher ground. Communicating this risk to the public proved ineffective.

3) Outstanding data and information needs

The availability of pertinent data at a scale relevant to local governments is essential to the development of specific strategies and the identification of activities to mitigate coastal hazards vulnerability. Significant progress in gathering more refined imagery and LIDAR-based (LIght Detection And Ranging) elevation information has occurred. Digital layers with specific georeferenced positions of infrastructure and special-need populations are still lacking, however. Capturing these vulnerabilities at a more-detailed resolution will make them compatible with the high-resolution imagery and elevation data being gathered.

Most vulnerable populations and critical facilities are housed in databases described by a physical (mailing) address. As no geographical coordinate is assigned to these residences, this information cannot be used in geospatial applications. Therefore, a significant effort is underway at the local level to relate addresses to geographical coordinates—a process known as geocoding. This effort is a resource-intensive process particularly with respect to staff time; however, such an effort is essential for fully merging GIS technologies into planning and response activities.

4) Technical assistance and capacity building

At times, technical resources and assistance are difficult to locate since information and assistance are not centralized. File size and data management/storage have become an issue of concern, especially when using LIDAR-based products. Currently, LIDAR data files are stored at two federal agencies: mass points (elevation points of the earth with objects (e.g., trees, buildings) removed) are housed at the National Oceanic and Atmospheric Administration (NOAA) and the digital elevation model at the U.S. Geological Survey (USGS) [2]. As LIDAR data can be analyzed and applied to multiple geospatial applications, needs should be prioritized and processing issues identified.

Most counties are at a crucial, transitional juncture with information technology (IT). A significant IT solution (updated hardware/software, increased networking, staffing, etc.) in any agency is often required to change its ability to house data, update data as needed, and disseminate the data to target groups and users as necessary. Currently, most local governments are in the process of improving their technical capabilities by both increasing their IT hardware and networking capabilities while also gaining staff trained to work with geospatial technologies and software.

Multifaceted approaches to deal with technical issues at the local level, rather than piecemeal changes, have a better chance of improving local capacities to use data and technology. The acquisition of better hardware and software forms an important step in the process of building local government technical capabilities. These activities alone, however, will most likely not facilitate the change necessary to maximize the utility of the technology and justify the investment. The tools must be developed in a manner that assists those in decision-making roles.

5) Funding needs and resources

Funding is a key issue and a major limiting factor when considering any new tools or technologies and their maintenance. A financial strategy is needed that not only considers the cost of acquiring data, but also addresses how information is shared and maintained. Essential to this process is identification of mechanisms to make information accessible to a broader audience, particularly the public. Distribution plans to employ data tools and technologies should also be developed before the acquisition of information. The allocation of resources in the initial stages of acquiring the data and information should also be considered for the distribution and accessibility of the product as well.

Existing funding mechanisms are often slow to react given the speed at which the technical marketplace operates. For example, state agencies find it difficult to establish financial partnerships with counties to leverage funding in acquiring data cooperatively. This issue has been highlighted in the acquisition of LIDAR data. The state procurement process is often not sufficiently responsive to allocate funds in a timely manner to achieve data acquisition objectives during the appropriate season (e.g., with leaves off trees in the autumn).

Until long-range and predictable fiscal acquisition strategies are implemented, funding partnerships need to be flexible and have the ability to respond quickly. Identifying overall funding needs and potential resources may prove advantageous in developing a financial strategy to implement and improve technical capabilities. As funds become available, projects can be considered among the suite of potential needs.

RECOMMENDATIONS

The following recommendations represent potential ideas to enhance the current effort to make technical information accessible to an array of target audiences. Along with the effort to build GIS and information technology capacities, improving cooperative relationships and increasing coordination and communication are also essential. These recommendations are targeted examples; they will not resolve all issues, but could greatly improve the utility of technical services to county and public stakeholders if applied strategically.

Recommendation 1: Build local capacities to use spatial information through the support and use of regional GIS councils.

Gaining technical assistance from emerging GIS councils in Maryland is a practical option to further build the capacity of local government agencies to use geospatial information. The GIS councils align policies, identify local and regional GIS needs, and operate as a focal point for partnerships to build Maryland's geographic information infrastructure. Only recently has technical assistance with GIS for rural lower Eastern Shore counties become available. The Eastern Shore Regional GIS Cooperative (ESRGC) is lending support by providing access to GIS technology, data, technical support, and training to the local governments of Maryland's Eastern Shore [3]. The ESRGC is a joint effort among the Mid-Shore Regional Council (Dorchester, Caroline, and Talbot counties), the Tri-County Council of the lower Eastern Shore of Maryland (Worcester, Wicomico, and Somerset counties), and Salisbury University.

The goal of the ESRGC is to improve the GIS technology capabilities of the county and municipal governments of the six counties of the middle and lower Eastern Shore of Maryland. The services provided by the councils to assist in capacity building include: 1) advice on GIS implementation; 2) technical support; 3) equipment loans; 4) data collection; 5) data analysis exercises; 6) cartographic services; and 7) GIS training. These services are provided at either no cost to the county or municipality or at a very reduced cost.

With counties cooperatively working as a group through the councils, resources can be compiled and the technical and financial disadvantages are reduced for counties with smaller population bases. For example, counties partnering to acquire expensive data, such as aerial photography, benefit from economy of scale since the cost of acquisition is reduced when larger areas are flown. File size and data management/storage of LIDAR-based products can also overwhelm the technical capacity of a local government. Therefore, the council can also assist in storing information on Salisbury University's data servers, centralizing access to assorted projects for a single region. In the near future, ESRGC also intends to make data available publicly via an online data server.

Potential Actions:

- Identify a process to institutionalize GIS councils (formalize activities, allow eligibility for state support and resources) and expand efforts to other regions statewide as these councils currently exist only on the lower Eastern Shore.
- Target resources and support to councils to fill technical gaps on a regional scale rather than dealing with recurring technical capacity issues on a project-by-project basis.
- Promote economies of scale when acquiring large data sets (e.g., a MSGIC implementation team strategy) or for large data acquisition projects (e.g., LIDAR or floodplain mapping) to reduce cost and improve coordination through a cooperative effort to unite public organizations and private contractors.
- Consider working with independent contractors/specialists to review local government IT capabilities in order to develop recommendations and a plan that can be followed incrementally to improve capabilities over time. Periodically conduct a needs assessment to determine if enhancements or upgrades to software and hardware are needed.

Recommendation 2: Increase web-based distribution options and Internet mapping applications to improve access and utility of the information.

The identification of mechanisms to make data accessible to a broader audience, particularly the public, is essential to the utility of data tools and technologies. A concerted effort in making information available over the web through Internet mapping applications and online data servers is a sensible option. The web is quickly becoming a universal tool that all demographic and skill levels can use to retrieve information. If data servers are made accessible online, data become available directly to the desktop of any potential user. This alternative significantly reduces the cost of traditional distribution though printing materials or CDs/DVDs.

When considering new data opportunities, funding strategies are needed that not only consider the cost of creating data, but also how information is shared and maintained. The development of web-based Internet mapping tools and data servers may appear financially burdensome due to up-front costs. However, their use can save future staff time and redistribution costs for information as digital data sets are continually updated. Web-based options—particularly Internet mapping applications that provide a mapping software interface—may also prevent data from being unavailable to members of the public without access to mapping software. These products would provide visualization of vulnerability and risk in an interactive format never before offered.

A specific application implemented and distributed through the web to improve response capacities at the local level is the Emergency Management Mapping Application (EMMA) [4]. Developed by Towson University, EMMA is an incident response tool for the emergency management community. The application is capable of displaying relevant information before, during, and after an incident and enables the emergency responders to identify incident locations from the field, generate location-specific reports, visualize incident locations via a map, perform site-specific analysis, and coordinate response efforts. Using a simple web browser, such as Internet Explorer, EMMA provides basic and advanced tools for map visualization, location analysis, and report generation. This system will be deployed at state and local emergency operation centers to provide improved response capabilities statewide and at the county level.

Maryland's Coastal Zone Management Division, in cooperation with Towson University, is also developing another web-based tool for coastal hazard and shoreline management, "Shorelines Online." The product is a one-stop portal for information and tools for coastal managers and decision makers, educators, and the public on coastal hazards and shoreline management. The portal will enhance shoreline activities by centralizing access to information and involving a wider array of stakeholders—particularly the public—in viewing and using shoreline data and assessments. More specifically, the site will house an Internet mapping application that allows users to identify their shoreline erosion risk and determine appropriate shoreline protection and restoration options to mitigate hazards and enhance natural shoreline habitat.

Potential Actions:

- Develop a web-accessible "clearinghouse" to centralize data and information, handle requests for information and distribution of data to decrease hardships on individual data creators, and resolve proprietary issues associated with data distribution.
- Continue to promote adoption and implementation of open and interoperable standards. These standards provide the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those standards.

Recommendation 3: Build upon existing relationships.

One of the most important means of enhancing the application of geospatial technology is the relationship between governmental and academic institutions. Academic institutions often act as a keystone to fill technical assistance gaps that cannot be addressed by governmental organizations alone. Support of these relationships and strengthening linkages between the two sets of institutions foster innovation in the use of geospatial application at the local level. The existing cooperative relationship between academia and government established through development of geospatial hazard applications would improve the ability to apply scientific principles to policy decisions.

Towson University's Center for Geographic Information Sciences (CGIS) fills technical gaps for state GIS and management activities. The center often serves as a "geospatial hub" for Maryland's geospatial information and it supports many of the state's activities through data and application development, training, and hosting of applications such as the Maryland Metadata Resource Guide (MMRG) [5]. The MMRG website is a convenient one-stop source for: 1) maps and geographic data relating to Maryland; 2) information on GIS and mapping projects; 3) contact information for Maryland State Geographic Information Committee (MSGIC) members; and 4) other resources related to mapping. The MMRG is coordinating many of the geospatial activities in Maryland. If widely supported and utilized, this application could help to coordinate and improve statewide geospatial activities.

Potential Actions:

- Identify mechanisms to formalize partnerships between governmental and academic institutions by developing memoranda of understanding (MOU) to define roles in capacity building and data sharing/storage activities to address local government needs. For example, universities could expand their role as training centers for local and state managers and planners.
- Involve all levels of government and academia in existing steering committees (e.g., MSGIC, ESRGC) that periodically review agency roles in data collection and responsibilities for storage and maintenance, and provide a means to coordinate potential modifications of these processes.
- Seek competitive grant fund opportunities through academia to conduct studies on hazards in a manner that stresses the importance of developing and communicating a message for local governments and the public. The University of Maryland Integration and Application Network is one example of academia developing management and public-friendly products from science-based monitoring and assessments.
- Report regionally significant academic studies and findings routinely to county commissions to effect change at the local level.
- Identify relationships to streamline multi-year contracts for improving the efficiency of existing funding processes and mechanisms such as: developing an account that local and state governments can pay into when they have available funds, which could be maintained across budget cycles; or designating a contract manager outside the state system (such as a university) and developing an MOU.

Recommendation 4: Capitalize on emerging issues.

One of the biggest emerging issues facing our nation and state is homeland security. Establishment of the Department of Homeland Security constituted one of the most comprehensive reorganizations of the federal government in a half-century. The department consolidated 22 agencies and 180,000 employees, unifying once-fragmented federal functions in a single agency dedicated to protecting America from terrorism [6].

Although addressing terrorism is the department's main objective, many of the tools to track, analyze, and assess risk can also be used in natural hazard assessment and disaster response. Populated areas such as Baltimore have already benefited from Homeland Security funds as high-resolution aerial photography was flown for the largest American cities. Capturing high-resolution photography before a disaster is quite useful for comparison with post-disaster imagery to assist in assessing structural and economic impacts.

The Maryland Emergency Management Agency (MEMA) receives most of the federal financial assistance from Homeland Security. This agency is the first-line responder in emergencies and houses the state EOC [7]. It is also responsible for providing awards and grants to support local and county emergency management activities and planning. One of the most significant provisions from Homeland Security funds has been the placement of an additional staff member and technical instruments (e.g., radios, GPS, computers) at each county emergency management office [8]. The funds have assisted local government in initiating the process to geocode addresses and gather crucial socioeconomic information. This information is being housed in spatial databases and is facilitating the identification of vulnerable populations and places, whether from the impact of an explosion or inundation from flooding.

Potential Actions:

- Identify linkages and merge hazard mitigation with Homeland Security objectives to optimize limited financial and technical resources. For example, continue using Homeland Security funds from the State Hazard Mitigation Office to purchase equipment and communication devices, and support staff positions in a manner that addresses both terrorism and hazard vulnerability mapping.
- Communicate across jurisdictional boundaries, including state borders. Encourage participation of local and state agencies in interjurisdictional groups, such as the Delmarva Emergency Management Task Force.

SUMMARY

Hurricane Isabel provided a "learning moment" for many people in the Chesapeake Bay region, but especially for coastal managers and planners. The event put comprehensive planning and associated land use decision/mitigation activities to the test. In many cases, the planning worked; however, examples still exist that illustrate where our current process and activities can be improved to assist in better pre-disaster planning.

Hurdles facing the capacity to use GIS and modeling tools/technologies in pre-disaster planning are not limited to our ability to acquire data. The issue is much greater in scope and also relates to statewide institutional and organizational structures and how information is shared, stored, and maintained. Modifying institutional structures or formalizing processes to increase awareness and participation may be needed. Support and buy-in by executive levels build the institutional capacity and organizational structure to utilize new tools and technologies effectively. Such actions could include formalizing GIS councils and expanding their efforts statewide; only the lower Eastern Shore currently has these resources. Centralizing access to data and information through a state clearinghouse represents another potential organizational change that could facilitate use of information and reduce duplication of effort. Furthermore, program managers at the local level should address their IT structure and consider options to institutionalize their GIS capabilities (e.g., develop metadata, create permanent technical positions) to maintain their technical capacity even with staff turnover.

When considering new data opportunities, funding strategies are needed that not only consider the cost of acquiring data, but also address how information is shared and maintained. A potential mechanism is to establish relationships that streamline multi-year contracts. Such processes include developing an account that local and state governments can pay into when they have available funds, which could be maintained across budget cycles. Essential to any data-funding plan is a strategy to develop the information into a useful management tool with a comprehensible public message. These tools should be provided in a format readily available to local decision-makers and the public. A concerted effort to make information available over the web through Internet mapping application and online data servers is a feasible option. Academia could also develop a larger role in these efforts and seek opportunities to augment training and partnerships with state and local governments.

REFERENCES

1. Maryland State Geographic Information Committee. 21 June 2004. *www.msgic.state.md.us/*.
2. K. Miller. Pers. comm. Maryland Department of Natural Resources.
3. Eastern Shore Regional GIS Council. 31 December 2004. *www.esrgc.org*.
4. Towson University Center for Geographic Information Sciences. *EMMA: Emergency Management Mapping Application*. 12 January 2005. *http://cgis.towson.edu/downloads/EMMA_whitepaper.pdf*.
5. Maryland Metadata Resource Guide. 15 January 2005. *www.MarylandGIS.net*.
6. Department of Homeland Security. 17 January 2005. *www.whitehouse.gov/homeland/*.
7. Maryland Emergency Management Agency. 12 January 2005. *www.mema.state.md.us/.8.K* . Golden-Brandt. Pers. comm. August 2004. Maryland Emergency Management Agency.

HURRICANE ISABEL: AN AGRICULTURAL PERSPECTIVE

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ABSTRACT

The University of Maryland College of Agriculture and Natural Resources (AGNR)-Maryland Cooperative Extension (MCE), working in cooperation with the Maryland Department of Agriculture (MDA), was intimately involved in the events surrounding Hurricane Isabel. Along with other Maryland governmental agencies, MCE and MDA were activated to 24-hour readiness on 16 September 2003 at the Maryland Emergency Management Agency (MEMA) facilities, in preparation for the hurricane's arrival. The MCE/MDA county field faculty and staff were instrumental in providing initial damage assessments from agricultural producers and the agricultural industry. They were also actively involved locally in their county emergency operations centers. The MCE developed a dedicated web page and information resource site on hurricane preparation and recovery. The MCE/MDA also participated on the MEMA Disaster Recovery state team and assisted in the planning, design, and implementation of the county-based Maryland Disaster Recovery Centers (DRCs) established throughout the state. Extension faculty and MDA staff assisted in manning 11 DRCs statewide, providing resource information on animal care, food safety, debris removal, and other storm-related topics. Although Isabel destroyed much personal property and seriously affected many businesses within the state, the agricultural community reported relatively minor effects. The hurricane was, however, the first real test of MCE/MDA's developing agricultural emergency management network and infrastructure.

INTRODUCTION

In September 2003, Hurricane Isabel caused large-scale power disruptions, flooding, and tremendous economic, psychological, and personal damage in the state of Maryland. This storm followed a devastating F4 tornado in Charles, Calvert, and Dorchester counties in April 2002. Loss of equipment and facilities, coupled with lack of insurance coverage, illustrated how unprepared most of the agricultural community was for these types of events. It also demonstrated the need for participation of the University of Maryland College of Agriculture and Natural Resources' outreach component—the Maryland Cooperative Extension (UM-AGNR-MCE) and the Maryland Department of Agriculture (MDA)—in the reporting and public education process before, during, and after emergencies.

In the past, each agency's response to a disaster was primarily reactive and was often independent of other agencies' response**.** During emergencies, a lack of information and disjointed communication made it difficult to assess what was actually happening in the agricultural community. No real network for information existed and few resources were made available before, during, or after an event.

MATERIALS AND METHODS

Infrastructure

The urbanization of Maryland has resulted in a disconnect between the urban and suburban communities and their rural agricultural neighbors. When emergencies occur, much of the attention and resources immediately go to the most populated areas. Rural communities are often left to solve their own problems. Following the tornado that blew through Charles County in April 2002, calling it the "La Plata tornado" became a sore point in the community, since much of the damage to agricultural equipment, barns, fields, forests, and homes had occurred in more rural areas not publicly recognized. Only a limited system existed to report and evaluate the damage in agricultural areas through the USDA Farm Service Agency (FSA) and only limited assistance was available. County government eventually held community meetings to learn more about what was happening and MDA assigned a special evaluator to investigate and take reports. The agricultural agencies and organizations provide assistance after an incident, including assessments through the FSA, but there is duplication of effort and no comprehensive plan. Planning has been limited primarily to specific responses to serious animal diseases, insurance, and low-interest loans for crop damage.

After the tornado and the September 11, 2001 terrorist attacks in New York and Pennsylvania, UM-AGNR-MCE and MDA recognized the need to cooperate more effectively and to become more proactive in assisting the agricultural community in preparing and responding to emergencies. They began to facilitate, enhance, and coordinate their organizational infrastructures for emergency preparedness and antiterrorism, developing a series of internal emergency standard operating procedures (SOPs), and improving communication coordination and outreach capacity for emergency preparation, response, and recovery operations. Efforts included:

- Development of UM-AGNR-MCE policy and educational programming by the UM-AGNR–MCE Disaster Focus Team. This team includes members from the College of Agriculture and Natural Resources as well as the Virginia-Maryland Regional College of Veterinary Medicine (VMRCVM), University of Maryland Eastern Shore (UMES), the Institute for Applied Agriculture (IAA), and the College of Life Sciences.
- Development of UM-AGNR-MCE SOP for emergency preparedness and disaster response.
- Creation of an MDA animal health and biosecurity response team that has been reviewing the capabilities of the animal health diagnostic laboratories, especially regarding personnel and equipment needs. The program has intensified its efforts on animal surveillance, safety, and food regulatory issues.
- Revision of the MDA SOP for emergency preparedness and disaster response.

Outreach

Outreach is a major component of the missions of UM-AGNR-MCE and MDA. Each agency began to improve its capacity to disseminate information on terrorist awareness, food security, and emergency preparedness to the agricultural community and state citizens, to enable these citizens to respond proactively, appropriately, and effectively in the event of a major food security emergency, whether natural or intentional. Situation analysis and actions include:

- Determine:
  - What do we need to do? Determine programs to be developed.
  - What training is needed? For whom? Establish faculty and staff roles and develop procedures and protocols (communications, etc.). Provide training for faculty and staff.
  - What resources and equipment are needed?
- Identify available expertise and resources in:
  - Plant science
  - Animal Science
  - Extension: Agriculture; Family & Consumer Science; 4-H and Youth
- Determine expertise that needs to be developed.
- Identify and develop educational resources needed.
- Identify funding sources.

Collaboration

It became clear that effective collaborations between agricultural organizations and agencies in Maryland were critical. Efforts to foster working relationships with state and county governmental partners, the university community, and agricultural industry began to provide a seamless proactive response before, during, and after an emergency.

- Through collaborative efforts between the UM-AGNR-MCE and MDA, a joint Center for Agrosecurity and Emergency Management (the Center**)** is being developed to coordinate communication and education efforts in the agricultural community to ensure agricultural and food security within the state.
- The Center will capitalize on university research, including the federal Homeland Security Centers of Excellence, as well as other resources. The UM-AGNR-MCE teaching and extension activities along with MDA plant and animal surveillance and regulatory and laboratory activities place these organizations in a unique position to enhance the agricultural community's preparation, response, and recovery.
- Agricultural Local Emergency Response Teams (ALERT) made up of MDA and UM-AGNR-MCE faculty and staff in Maryland counties will be responsible for community outreach and education. They will also provide real-time reporting of the effects upon and needs of the agricultural community during an event to the Center and their local emergency operations center (EOC), as appropriate.
- The Center will significantly augment its capabilities through linkages to both government and the agricultural industry. Strong relationships will be maintained with many agencies and organizations including:
  - USDA Farm Service Agency (FSA)
  - Maryland Department of the Environment (MDE)
  - USDA Natural Resources Conservation Service (NRCS)
  - Maryland Emergency Management Agency (MEMA)
  - Maryland Fire and Rescue Institute (MFRI)
  - University of Maryland, Eastern Shore
  - Maryland Department of Business and Economic Development (DBED)
  - Virginia Maryland Regional College of Veterinary Medicine (VMRCVM)
  - Maryland Department of Health and Mental Hygiene (DHMH)
  - Maryland Department of Natural Resources (DNR)
  - Maryland Farm Bureau
  - Maryland Association of Soil Conservation Districts (MASCD)
  - Forum for Rural Maryland
  - Maryland county governments
- Participation will be renewed by both UM-AGNR-MCE and MDA in MEMA-sponsored exercises and events.

RESULTS

Hurricane Isabel provided the first real test of UM-AGNR-MCE and MDA's developing processes to assist the agricultural community in responding to and recovering from emergencies in a coordinated fashion, and reporting agricultural damage and issues within the emergency management community.

On Tuesday, 16 September 2003, MDA and UM-AGNR-MCE were activated to 24-hour readiness at MEMA facilities in anticipation of Hurricane Isabel. The UM-AGNR-MCE and MDA worked with MEMA and FEMA personnel to monitor Isabel's northeasterly path and arrival in Maryland. This presence allowed information sharing and updates on agricultural issues throughout the emergency management system.

County field faculty and staff from MDA and UM-AGNR-MCE were instrumental in providing an initial damage inventory of agricultural producers and industry, and assisted the USDA Farm Service Agency in assessing agricultural damage after the hurricane. The UM-AGNR-MCE provided educational resource assistance prior to, during, and after the hurricane. County field faculty were actively involved locally in their county emergency operations centers (EOCs) and were invited to be a part of the hurricane performance response.

The UM-AGNR-MCE developed a dedicated web page and information resource site via the UM-AGNR-MCE website that focused on hurricane preparation and recovery. This site highlighted UM-AGNR-MCE specialists' areas of expertise and included disaster preparedness and recovery articles and fact sheets, and provided timely links to other universities, governmental resources, and EDEN (Extension Disaster Education Network). Also, an "expert" list of university specialists from the College of Agriculture and Natural Resources was developed for use by the media to locate useful and credible information.

The MDA responded to assistance needs by funding requests for best management practices (BMPs), including repairs to fences and lagoons as well as other animal and crop practices, through the county Soil Conservation Districts (SCDs). The state chemist's laboratory at MDA provided feed testing and analysis of agricultural animal and pet feed. The MDA's five animal health diagnostics laboratories, located in each region of the state, provided animal disease diagnostics services.

In most years, late September is the end of surveillance and adult mosquito spray operations for MDA's mosquito control program. However, floodwaters from the hurricane increased late-season breeding potential. Mosquito control staff initiated adult mosquito control in areas affected by the hurricane. Insecticides to control adult mosquitoes were applied by air and from trucks and other ground equipment to 98,566 acres between 22 September and 6 October 2003.

The State Emergency Management Operations Center requested that MDA and UM-AGNR-MCE participate as members of the MEMA disaster recovery state team. This team assisted in the planning, design, and implementation of the county-based Maryland Disaster Recovery Centers (DRCs) established throughout the state. MDA and UM-AGNR-MCE personnel staffed 11 DRCs statewide, providing resource information on animal care, food and drinking water safety, debris removal, and other storm-related topics. In addition, a field resource notebook was created for all recovery centers, containing information on agricultural assistance and contact persons, as well as fact sheets on appropriate topics. Individual county faculty and staff developed county-specific exhibits, flyers, and other resource materials for their county-based DRC. The UM-AGNR-MCE Home and Garden Information Center's toll-free telephone line fielded more than 200 storm-related calls before, during, and after the hurricane. Callers requested information on controlling mold and mildew, handling floating oil tanks, handling oil pollution of the soil, removing tree debris, and dealing with the effects of submersion on lawns.

Agricultural Impacts from Hurricane Isabel

Although Isabel destroyed a great deal of personal property and seriously affected many businesses within the state, the agricultural community reported relatively minor effects. Much damage was probably left unreported, however, as UM-AGNR-MCE and MDA recognized that the agricultural agencies did not have the capacity to do an effective, real-time survey. Most of the information is anecdotal. In addition, the agricultural community tends to view most storm damage to their property (such as trees down) as minor due to an attitude of self-reliance, which complicates reporting.

There were no reported serious effects from the storm on livestock. Minor damage occurred to livestock buildings, outbuildings, and sheds, disrupting feed cycles and production schedules. However, these schedules were re-established within a reasonable amount of time. One Frederick County dairy farmer reported to the USDA Farm Service Agency that he lost a hay barn and a dairy barn during the storm.

The USDA FSA estimated state crop losses at 15–30% of the field corn and 10–15% of the soybean crop. Sections of the corn crop were blown down by high storm winds. This type of damage makes harvest difficult. Soybeans suffered damage from windblown plants and saltwater saturation. Mid-September was a critical time in soybean development and the storm damage had a direct effect on the quality at harvest—and subsequently on yields and crop prices. Some Eastern Shore counties also reported debris damage to the soybean crop.

Multiple incidences of trees downed on cropland edges and within forests on agricultural property were reported, requiring cleanup and affecting timber values. Reports also came in of some perishable fruits and vegetables lost due to power outages in cold-storage facilities.

In Kent County, two aquaculture production ponds were overwhelmed with the increased water inflows from Isabel. Most of Maryland's seafood processing facilities lost 1 to 2 weeks of production in addition to plant damage.

When the stormwaters finally receded, many crab processing plants and crab house restaurants were closed due to flooding. Watermen suffered at least 2 weeks of unemployment; many had to pull their pots and nets and reposition them after the storm. The shellfish harvest was closed until 29 September because post-storm water quality in the Bay made the shellfish unsafe to consume. The MDA specialists consulted with these operators to assess damage costs and other recovery issues.

DISCUSSION

Further development and funding of the Center for Agrosecurity and Emergency Management and its ALERT network is a priority to enable UM-AGNR-MCE and MDA to respond in emergencies. The Center will work on the federal ESF-11 (Food and Food Security) issues that integrate the missions of homeland security—as well as education and training—into the rural community.

The experience with Hurricane Isabel illustrated the challenges of communicating with personnel in 23 counties, especially when utilities are down in a substantial portion of the state. It also demonstrated the need to further engage personnel in the network and its mission, as well as provide adequate training to empower them. In the past, members were not been expected to provide emergency status reports beyond the local level, and so are learning a new role. ALERT members will receive emergency management training following a train-the-trainer model and agrosecurity exercises will be instituted. Members will be equipped with disaster kits and communication equipment that allow a proactive approach to county emergencies. Both agencies will enhance communications equipment and resources to ensure and provide local and statewide communication capabilities when the need arises. Response team individuals will be equipped with the appropriate phones, computers, e-mail devices, and other communications equipment along with the resource numbers and contact information needed to provide timely interagency communication for threat identification and diagnostics procedures. A more efficient use of Global Information Systems (GIS) networking will be investigated and enhanced by the agencies, allowing more direct and accurate information gathering and effective response to an emergency event.

Outreach activities will provide educational programs for Maryland citizens that will enable them to protect the food supply (animal and plant) and public health, including an updated website that will link to educational information and resources, a series of Maryland-specific agrosecurity tip sheets, agricultural industry education programs, citizen workshops and demonstrations, and other activities that focus on food security issues and awareness. Following the hurricane, ALERT members identified the need for readily available educational materials on specific topics for members of the network. As a result, tip sheets were produced on "Water Purification for Commercial Food Processing Facilities," "Repairing Storm Damaged Trees," and "Petroleum Storage Tanks on the Farm."

Collaborations will be expanded to include practicing veterinarians and other stakeholders. The Center and ALERT will integrate with the Maryland Department of Health and Mental Hygiene

(DHMH) public health response teams to provide more interagency training and outreach.

Working in conjunction with MEMA and other state and national agencies, the Center will assist in the cross-section coordination and/or facilitation of communication, information distribution, and training for Maryland citizens. For UM-AGNR-MCE and MDA, the Center will provide harmonized leadership for local educational programs on agrosecurity and educational materials directed at internal, private, and public audiences, allowing these agencies to better assist the agricultural community in preparation, response, and recovery from disasters.

Although agricultural entities in other states have had to work together when disasters occurred, no permanent networks of collaboration had formed. It is hoped that the Center and ALERT network, working with other agricultural organizations and the emergency management community in Maryland, will serve as a model to other states. Efforts have begun to expand this network concept into the Mid-Atlantic states and discussions are being held with Delaware to start the process. The UM-AGNR-MCE has also joined the EDEN—a national association of university professionals from throughout the country working in emergency management education programs. All Center forms, reports, and literature will be shared with other participating EDEN states to advance the nationwide system of preparedness and response by educational institutions and their partners.

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TREES AND THEIR IMPACT ON ELECTRIC RELIABILITY DURING AND FOLLOWING TROPICAL STORM ISABEL

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ABSTRACT

With Isabel, rainfall was less than expected and wind speeds were below those normally associated with significant tree failure. Despite this situation, tree failures and associated utility outages were massive and five days after the storm more than 2 million people in the Mid-Atlantic region remained without electricity. The Maryland Public Service Commission's (PSC) inquiry into electrical service interruptions related to the storm considered what impact, if any, certain tree protection laws administered by the Department of Natural Resources (DNR) had on utility outages.

The storm was an act of God and the impacts were not accounted for by existing utility vegetation management practices. A preponderance of dead or damaged roadside trees in the Baltimore-Washington corridor coincided with the area having the majority of utility outages. The DNR laws regulating tree care require adherence to the industry-consensus standards for tree care operations. Adherence to proper tree care practice has been demonstrated to improve electric reliability. A new treatment paradigm—one that addresses trees outside of the traditional treatment envelope and focuses on amelioration of mechanical defects and storm forces on tree crowns using tree pruning, removal, and replacement—may reduce the severity of tree-related utility outages during storms.

INTRODUCTION

Isabel was declared a hurricane on 7 September 2003. By the time it reached landfall on 18 September 2003, it had been downgraded to a tropical storm [1]. Upon arrival in Maryland, the storm had maximum sustained winds of approximately 45 mph (72 $km \cdot hr^{-1)}$) and peak gusts of approximately 58 mph (93 $km \cdot hr^{-1)}$) [2, 3]. Rainfall was less than expected and winds were at speeds below those normally associated with significant tree failure. Despite this situation, tree failures and utility outages were widespread; five days after the storm, more than 2 million people in the Mid-Atlantic region remained without electricity [4], primarily in the Baltimore-Washington corridor.

The Maryland Public Service Commission (PSC) regulates public utilities per the Annotated Code of Maryland Public Utilities Article. The Maryland Department of Natural Resources (DNR) administers numerous laws regulating the treatment of trees under this same article. Since trees can fail and cause electric utility outages, some entities have sought certain exemptions from, or repeal of, certain tree protection laws administered by DNR following major storms.

PSC Case Number 8826, "Investigation into the Preparedness of Maryland Utilities for Responding to Major Outages," was initiated following Tropical Storm Floyd in 1999. In that case, the PSC directed "electric utilities and telephone companies, PSC Staff, the Office of People's Counsel, and other interested parties to work with the Maryland Department of Natural Resources (DNR) to develop recommended modifications to the State's policies and regulations to improve utility tree trimming and maintenance programs within utility rights-of-way, and to evaluate the need for appropriate legislation or regulations with regard to tree trimming on private property [5]."

The former clause of the PSC's charge (regarding utility tree trimming and maintenance programs within utility rights-of-way) developed into a discussion of the validity and applicability of the Maryland Roadside Tree law; the latter clause (regarding tree trimming on private property) led to a similar discussion regarding the Maryland Licensed Tree Expert law.

Natural Resources: Title 5. Forests and Parks: Subtitle 4. Trees and Forest Nurseries: Part I. Roadside Trees ßß 5-401 – ßß 5-411 was passed in 1914. It was developed to protect our roadside trees by ensuring their proper care and protection and to ensure their compatibility with an efficient and dependable public utility system. It provides that any treatment of a roadside tree (a plant that has a woody stem or trunk that grows all, or in part, within the right-of-way of a public road) be subject to approval and regulation by the DNR [6]. Parties wishing to treat (prune, remove, etc.) roadside trees must obtain a permit to do so and must perform the treatments according to regulations promulgated by the department. Because many electric utility distribution lines run along public roads above or adjacent to roadside trees, electric utilities are the primary user group of the permitting process.

Natural Resources: Title 5. Forests and Parks: Subtitle 4. Trees and Forest Nurseries: Part III. Tree Experts ßß 5-415 – ßß 5-423 was enacted in 1945. It provides criminal penalties for those that operate or advertise as a tree expert without a license issued by the department, and also allows the department to permanently revoke or temporarily suspend the license of any licensed tree expert who is found guilty of any fraud or deceit in obtaining the license or is guilty of negligence or wrongful conduct in the practice of tree culture or care [7]. Contractors providing tree care services for utilities are subject to this law; multiple contractors for one electric utility have been subject to sanction by the department under it.

The PSC's order 77132 regarding Case 8826 concluded that certain non-regulatory steps identified by the working group "will enhance the reliability of circuits along the public rights-of-way yet leave Maryland with healthy and properly pruned trees without revising any existing laws or regulations [5]." Primary among these was formation of the Maryland Electric Reliability Tree Trimming (MERTT) Council, made up of the parties named to the initial working group created during the case, which has met quarterly since initiation of that order to coordinate issues relating to trees and electric reliability.

PSC Case 8977, "In the Matter of the Electric Service Interruptions due to Hurricane/Tropical Storm Isabel and the Thunderstorms of August 26–28, 2003," brought another review of whether DNR's administration of these laws caused a significant hindrance to electric reliability, utility preparedness, and post-storm response.

MATERIALS AND METHODS

Documents on file with the Public Service Commission relative to the noted storms were reviewed [5, 8]. Data collected by the Maryland Department of Agriculture under the USDA Forest Service Urban Forest Health Monitoring – Stage 2: State-wide Street Tree Assessments protocol [9] were analyzed for comparisons of the number and percentage of total trees, dead trees, damaged trees, and trees with overhead wire conflicts in various areas of the state. The data are scheduled for publication in mid- to late 2005. The USDA Forest Service had stratified the data by aligning county data into regions. To better align the data with DNR's regions and Maryland utility territories, DNR requested that the Forest Service perform additional analysis with the counties aligned by region as shown in Table 1. The Forest Service performed this analysis.

Weather data for Baltimore and Washington on the day Isabel reached Maryland were reviewed and related to information associated with other storms [1, 2, 3, 10, 11, 12].

Published literature and industry standards for tree care were also reviewed for applicable information regarding the effect of storms and tree treatment methods on tree structure and health as well as electric reliability [9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21].

Table 1. Grouping of jurisdictions.

Baltimore-Washington	Eastern	Western
Anne Arundel	Caroline	Allegany
Baltimore	Cecil	Frederick
Baltimore City	Dorchester	Garrett
Carroll	Kent	Washington
Harford	Queen Anne	
Howard	Somerset	
Montgomery	Talbot	
Prince George's	Wicomico	
	Worcester	

RESULTS AND DISCUSSION

Environmental conditions

Isabel hit the Baltimore-Washington area with maximum sustained winds equaling F0 on the Fujita tornado scale and 8 on the Beaufort scale. The Fujita scale lists no tree effects associated with winds of this speed. The Beaufort scale associates twigs breaking with winds of this speed. According to both scales, shallow-rooted trees are pushed over, and trees are broken or uprooted when wind speeds reach 55–63 mph (89–101 $km \cdot hr^{-1)}$) [13].

Trees adapt mechanically to brace against prevailing winds [14], which in this area normally travel west to east. The counterclockwise motion of the storm brought winds from the opposite direction. Maximum sustained winds and peak gusts recorded at Washington National and BWI airports during the storm came from the east [2, 3].

Prior to the storm, soils around the state were already at or near saturation due to above-average rainfall for most of the year [10]. The USGS average streamflow index for Maryland was above average and increased consistently from October 2002 through the date of the event, resulting in the highest September groundwater levels in 40 years, high streamflow levels, and flooding [11].

According to the PSC Office of Staff Counsel [8], the majority of tree failures during Isabel came as uprooted trees. This situation contrasts with the devastating tornado (Fujita category F4) that hit La Plata, Maryland in April 2002, where the majority of tree damage was to crowns (defoliation, broken branches, loss of apical dominance) rather than to roots or stems (uprooting, broken boles, cracks and seams) [12]. In contrast to Isabel, the La Plata storm was preceded by approximately 8 months of below-average soil moisture.

Roadside trees

The collected data were post-stratified as shown in Table 1. Table 2 shows the results. A preponderance of dead or damaged roadside trees in the Baltimore-Washington corridor coincided with the area of the majority of utility outages [8]. Tree cover in road rights-of-way in the Baltimore-Washington corridor is 13%. This number is more than twice as high as on the Eastern Shore (6%) and more than 6 times as much as in western Maryland (2%). More than three times as many roadside trees ≥2.54 cm (≥1 in) in diameter per road mile occur in the Baltimore-Washington area than in other parts of the state. When counting only trees 25.4 cm (≥10 in) in diameter, the ratio of roadside trees Baltimore-Washington compared to other parts of the state changes to 2:1 in comparison with the Eastern Shore and 5:1 in comparison with western Maryland.

Conflicts between roadside trees and overhead wires are much more prevalent in Baltimore-Washington and on the Eastern Shore. The number of roadside trees per mile in conflict with overhead wires is similar in Baltimore-Washington and the Eastern Shore, but the percentage of miles of right-of-way in conflict is much lower in the Baltimore-Washington area since many more road miles occur there compared to the shore.

The average number of dead or damaged roadside trees per road mile is significantly higher in Baltimore-Washington than in the rest of the state. The percentages of roadside trees that are dead, damaged, severely damaged, and/or have damage to the root or trunk area are also much higher in Baltimore-Washington than in the rest of the state. Structurally compromised trees or tree

Table 2. Roadside tree data by region.

Size	Item	Baltimore-Washington	Eastern	Western
	% tree cover in right-of-way	13.0	6.0	2.0
	Wire conflicts per mile	8.2	8.2	0.0
	% right-of-way w/ tree/wire conflict	9.0	16.4	0.0
	Sidewalk conflicts per mile	7.5	2.7	14.6
	Plantable spaces per mile	24	41	32
‡ 1"	Mean trees per mile	50.7	16.6	13.0
‡ 1"	Mean dead trees per mile	0.8	0	0
‡ 1"	Mean damaged tree per mile	6.8	0.7	0
‡ 5"	Mean trees per mile	39.1	13.9	13.0
‡ 5"	% dead	1.5	0	0
‡ 5"	% damaged	13.2	4	0
‡ 5"	% no damage	52.5	95.2	87.5
‡ 5"	% damaged: conks	7.9	4.8	0
‡ 5"	% damaged: open wounds	12.6	0	12.5
‡ 5"	% damaged: other lower bole	12.6	0	0
‡ 10"	Mean trees per mile	24.5	12.6	4.9

parts are more likely to fail, particularly during storms [16].

Treatment Standards Specified in the Roadside Tree law and Licensed Tree Expert Law

The noted tree laws require, through Incorporation by Reference, by direct inclusion, or by paraphrase, adherence to the American National Standards Institute (ANSI) standards for tree care operations [22]. The American National Standards Institute (ANSI) is a private, non-profit organization (501(c)3) that administers and coordinates the U.S. voluntary standardization and conformity assessment system. The ANSI standards for tree care operations are industry-consensus standards [23].

Federal government agencies use voluntary standards such as ANSI standards for regulatory purposes when appropriate [24]. Many state and local governments also use ANSI to assess standards of goods or services, as is the case regarding the noted laws.

Effects of Treatment Methods on Reliability

Because most utilities, due to monetary considerations, easement limitations, and risk management best management practices (BMPs), focus management on the most likely risk scenarios (crown growth into the lines, crown failure onto lines), the impacts from Isabel were outside of their risk management schemes, although they were similar to those of Tropical Storm Floyd. Following analysis of utility treatment methods and storm impacts related to Isabel, the PSC Office of Staff Counsel reported that it "... does not recommend any changes to utility tree-trimming practices [8]," and the PSC concluded that "Generally, the utilities commented that tree-trimming practices would not have prevented the outages. . . .Even the most aggressive trimming methods can not avoid damage caused by the collapse of an entire tree [5]."

It has been demonstrated that implementation of certain practices during utility tree trimming can result in reliable service and quality tree care. Directional pruning of mature trees under utility lines in a manner that correlates to ANSI standards has been found cost effective and increases electric reliability [16]. Several sources [17, 18, 19] suggest that topping—a technique not endorsed by ANSI—is unethical and malpractice by practitioners. "Topping or heading . . . is cutting branches to stubs or laterals (internodal cuts) that are not large enough to assume the terminal role [18]."

During a storm, generated forces are centered at a point that is approximately 40% of the living-crown height below the crown top in open-grown trees. The effect of such forces on tree crowns can be ameliorated in three ways: crown raising (removing lower limbs); crown reduction (reducing the uppermost and side branches to sufficient lateral branches closer to the main stem); and thinning (reducing the density of branches within the crown) [20]. Such pruning should be performed according to ANSI standards.

Most utilities' tree-trimming programs are based on clearing all vegetation within a specified distance of the wires or clearance envelope, based on the voltage carried in the lines, with the clearance distance superseding considerations of ANSI [8]. In both Floyd and Isabel, however, widespread utility outages were caused by trees or tree parts failing into the lines from outside of the customary treatment envelope [5, 8]. A new treatment paradigm that addresses trees outside of the traditional treatment envelope and focuses on amelioration of mechanical defects and storm forces on tree crowns would likely reduce the severity of tree-related utility outages during storms such as Isabel. Simpson and Van Bossuyt [21] demonstrated that identification and treatment of trees with structural defects adjacent to three-phase portions of distribution circuits resulted in 4% of trees in the utility corridor being treated with a resulting 20–30% increase in reliability. As many defective trees could be outside of easements held by a Maryland utility, however, some form of mitigation program (provision of full or cost-shared tree replacement) would likely be necessary. Some Maryland utilities currently have such programs in place to induce property owner compliance with utility vegetation management objectives. Simpson and Van Bossuyt also reported that mitigation was a component of their successful program [21]. Mitigation programs provide the additional benefit of populating a space with utility-compatible vegetation, reducing the likelihood of colonization of the area by undesirable vegetation.

In its order related to the Isabel investigation, the PSC "ordered that the Commission's Engineering Division Staff and the electric utilities work through the Maryland Electric Reliability Tree Trimming Council to develop a detailed recommendation for specific actions that utilities can take to best manage privately owned trees near utility rights-of-way, and that the utilities shall commence public education efforts in conjunction with local governments within their respective service areas to increase awareness of the potential risk to their power supply that property owners incur in planting trees too close to power lines [5]." The DNR will submit this report to the MERTT Council as a contribution towards development of recommendations as charged by the PSC.

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REFERENCES

1. National Weather Service. 2003. Monthly Tropical Weather Summary. *http://www.nhc.noaa.gov/archive/2003/tws/MIATWSAT_sep.shtml?*
2. National Weather Service. 2003. Preliminary Local Climatological Data (Ws Form: F-6) Baltimore, Sept. 2003. *http://www.erh.noaa.gov/lwx/climate/bwi/bwi0903.txt*
3. National Weather Service. 2003. Preliminary Local Climatological Data (Ws Form: F-6) Washington National, Sept. 2003. *http://www.erh.noaa.gov/lwx/climate/dca/dca0903.txt*
4. P.J. Michaels. 2003. A Passion that Leaves Us Powerless. *Washington Post*. 28 Sept. 2003; p. B1
5. Maryland Public Service Commission. 2001. Order No. 77132. In: The Matter of the Investigation into the Preparedness of Maryland

Utilities for Responding to Major Outages Before the Public Service Commission of Maryland. Case No. 8826. Baltimore, MD. 31 pp.

6. State of Maryland. Annotated Code of Maryland. *Title 5. Forests and Parks. Subtitle 4. Part 1. Roadside Trees.* ßß 5-401–ßß 5-408. Office of State Documents. Annapolis, MD.
7. State of Maryland. Annotated Code of Maryland. *Title 5. Forests and Parks. Subtitle 4. Trees and Nurseries. Part 111. Tree Experts.* ßß 5-417–ßß 5-423. Office of State Documents. Annapolis, MD.
8. Maryland Public Service Commission, Office of Staff Counsel. 2003. Initial Comments – Case No. 8977. *www.psc.state.md.us/psc/home.htm.*
9. D. Twardus, B. Smith, R. Rabaglia, A. Cumming, M. Mielke, D. Nowak, M. Galvin, R. Rideout, and K. Gooch. 2002. Urban Forest Health Monitoring – Stage 2 State-Wide Street Tree Assessments Protocol. USDA Forest Service. 60 pp.
10. J.F. Kelly 2003. Soaked East Coast is In for More; No Room Left in Saturated Soil, Swollen Streams. *Washington Post*. 18 Sept. 2003; p. A1
11. United States Geological Survey. 2003. Flow to Chesapeake Bay in Water Year 2003 Highest Since 1937. Press release. *http://md.water.usgs.gov/publications/press_release/2003/2003-10/index.html*
12. D. Gailey, M. Muir, H. Henry, and R. Hartlove. 2002. *Tornado Damage Assessment Report*. Maryland Department of Natural Resources. Annapolis, MD. 21 pp.
13. S. Cullen 2002. Trees and wind: Wind scales and speeds. *J. Arb.* 28(5): 237–242.
14. C. Mattheck and H. Breloer. 2003. The Body Language of Trees: A Handbook for Failure Analysis. Research for Amenity Trees No. 4. The Stationary Office. Norwich, UK. 240 pp
15. R.J. Hauer and G.R. Johnson. 2003. Tree Risk Management. USDA Forest Service. NA-TP-03-03. *http://www.na.fs.fed.us/spfo/pubs/uf/utrmm/*.
16. R.W. Harris, J.R. Clark, and N.P. Matheny. 1999. *Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines.* 3rd ed. Prentice-Hall, Inc., Upper Saddle River, NJ. 687 pp.
17. N. Polanin and M. Vodak. 2002. Trees & Utilities: Cooperative Management Strategies for Success. Fact Sheet FS1006. Rutgers Cooperative Extension Service. New Brunswick, NJ. 4 pp.
18. D.P. O'Callaghan and D.L. Ham. 2003. Utility Specialist Certification Study Guide. International Society of Arboriculture. Champaign, IL. 84 pp.
19. E.F. Gilman and S.J. Lilly. 2002. Best Management Practice. Tree Pruning. Companion publication to the ANSI A300 Part 1: Tree, Shrub, and Other Woody Plant Maintenance-Standard Practices, Pruning. International Society of Arboriculture. Savoy, IL. 35 pp.
20. K.D. Coder 2000. Pruning Guide for Storm Force Reduction in Tree Crowns. University of Georgia Warnell School of Forest Resources Extension Publication For 00-27. *www.forestry.uga.edu/WARNELL/SERVICE/LIBRARY/index.php3?docID=41&docHistory%5B%5D=2&docHistory%5B%5D=413.*
21. P. Simpson and R. Van Bossuyt. 1996. Tree-caused electric outages. *J. Arb*. 22(3): 117–121.
22. Tree Care Industry Association, Inc. 2001. *American National Standard for Tree Care* Operations – Tree, Shrub, and other Woody Plant Maintenance – Standard Practices, *ANSI A300 (Part1)-2001 Pruning*. Manchester, NH. 9 pp.
23. American National Standards Institute. 2004. *http://www.ansi.org/*
24. Office of Management and Budget. 1998. Circular No. A-119. Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities. *http://www.whitehouse.gov/omb/circulars/a119/a119.html*

USING FORECASTS TO PROTECT FEDERAL FACILITIES IN THE PATH OF HURRICANE ISABEL

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ABSTRACT

Hurricane Isabel made landfall as a Category 2 Hurricane on 18 September 2003, on the North Carolina Outer Banks between Cape Lookout and Cape Hatteras, then coursed northwestward through Pamlico Sound and west of Chesapeake Bay where it downgraded to a tropical storm. Wind damage on the west and southwest shores of Pamlico Sound and the western shore of Chesapeake Bay was moderate, but major damage resulted from the storm tide. The NOAA, National Ocean Service, National Centers for Coastal Ocean Sciences, Center for Coastal Fisheries and Habitat Research at Beaufort, North Carolina and the Center for Coastal Environmental Health and Biomedical Research Branch at Oxford, Maryland have hurricane preparedness plans in place. These plans call for tropical storms and hurricanes to be tracked carefully through NOAA National Weather Service (NWS) watches, warnings, and advisories. When a hurricane watch changes to a hurricane warning for the areas of Beaufort or Oxford, documented hurricane preparation plans are activated. Isabel exacted some wind damage at both Beaufort and Oxford. Storm tide caused damage at Oxford, where area-wide flooding isolated the laboratory for many hours. Storm tide also caused damage at Beaufort. Because of their geographic locations on or near the open ocean (Beaufort) or on or near large estuaries (Beaufort and Oxford), storm tide poses a major threat to these NOAA facilities and the safety of federal employees. Damage from storm surge and windblown water depends on the track and intensity of a storm. One tool used to predict storm surge is the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model of the NWS, which provides valuable surge forecasts that aid in hurricane preparation.

INTRODUCTION

Hurricane Isabel made landfall on 18 September 2003 between Cape Lookout and Cape Hatteras, North Carolina as a Category 2 hurricane, moved across Pamlico Sound, then traveled northwestward passing to the west of Chesapeake Bay where it downgraded to a tropical storm (Figure 1). This storm track brought the storm into close proximity to the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), National Centers for Coastal Ocean Sciences Center for Coastal Fisheries and Habitat Research (CCFHR) at Beaufort, North Carolina, and the Center for Coastal Environmental Health and Biomedical Research (CCEHBR) Branch at

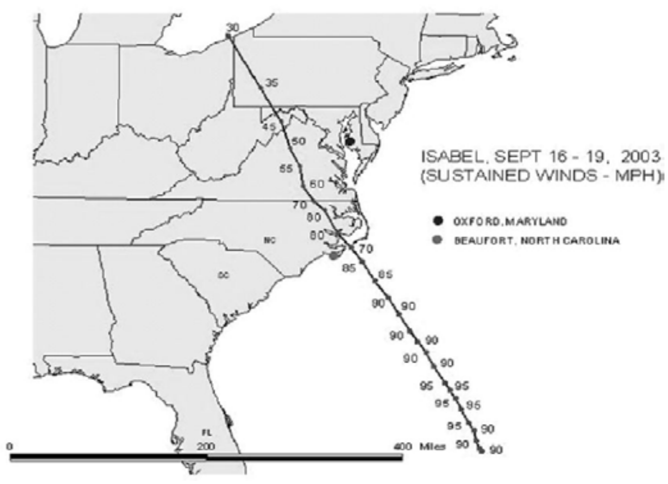

Figure 1. The storm track of Hurricane Isabel.

Oxford, Maryland. Because of this storm track, both Beaufort and Oxford were subject to high winds and storm tide (Figure 2).

NOAA ACTIVITIES

Each NOAA office is charged with the responsibility of protecting federal property at its facilities as well as ensuring the safety of personnel. Preparatory procedures for the NOAA facilities at Beaufort and Oxford are documented in hurricane preparation plans. When a hurricane watch is posted for the areas encompassing these facilities, regular surveillance through the NOAA National Weather Service (NWS) National Hurricane Center begins. When a hurricane warning is posted for the surrounding areas of these facilities, documented hurricane preparation plans are activated with personnel pre-assigned to prescribed responsibilities and tasks. Generally, these plans call for securing these facilities by:

- Securing all computers and analytical equipment on second floors or elevating these instruments to desktops or elevated shelves or benches;
- Securing all government or leased vehicles by moving them to high ground in wind-protected areas;
- Securing vessels by moving the small boats to high ground in central, wind-protected areas;
- Securing research vessels by moving to secure dockage or hauling-out;
- Securing inside of buildings with plastic sheeting over bookshelves, desks, computers, and analytical instruments; and
- Securing buildings by boarding windows (those not protected by impact- resistant glass or film) and sandbagging doorways and entryways.

When the center director in Beaufort or the branch chief in Oxford deems that the facilities are secure, staff personnel are released to tend to personal property.

Because of Hurricane Isabel, CCFHR suffered wind (windows blown out, roof and siding damage, and damage to scaffolding) and storm-tide flood damage (loss of docks, seawall erosion, and undermining of support structures). The CCEHBR at Oxford received minor wind damage, but survived the highest storm tide in 40 years. The laboratory was isolated by water for many hours and one building was damaged. Area communities situated on the southwestern shore of Pamlico Sound, 20 miles east of Beaufort, received extensive storm-tide flooding. Flood damage to communities on the western shore of the Chesapeake Bay was extensive. The tide gage at Cambridge, Maryland, about 10 miles from Oxford, recorded an all-time-record-high level of 6.18 ft (1.88 m) above mean lower low water.

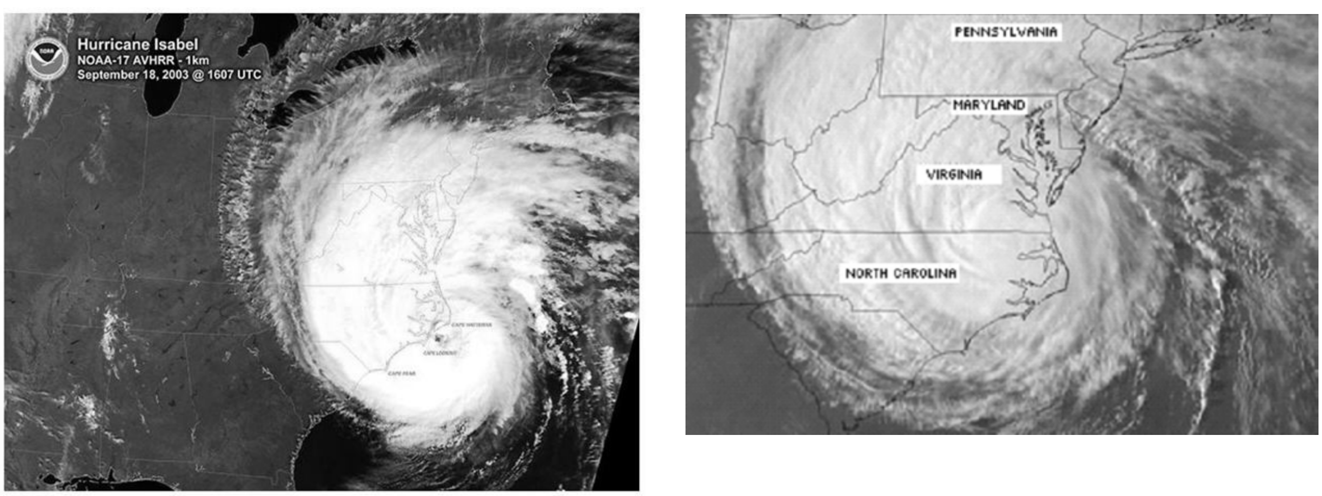

Figure 2. Hurricane Isabel's landfall on North Carolina (left) and her path past the Chesapeake Bay (right).

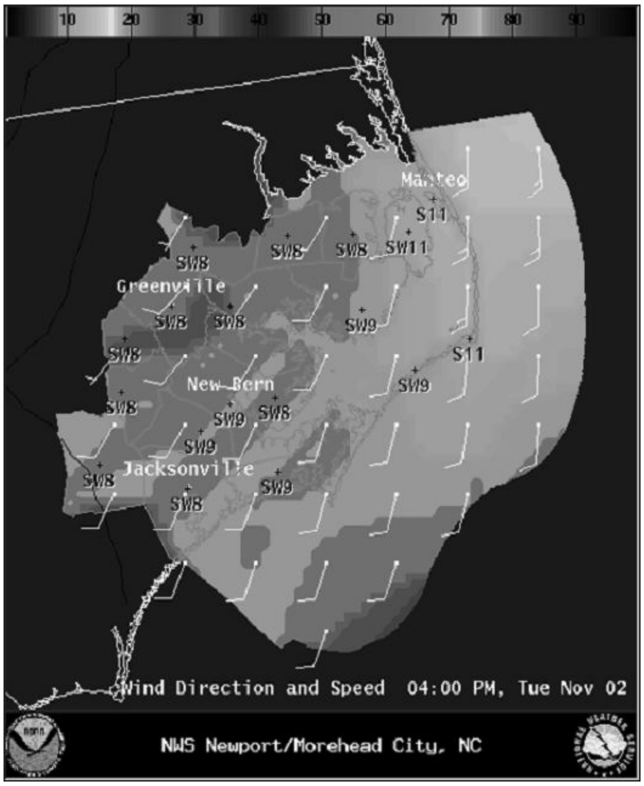

Figure 3. National Weather Service, National Digital Forecast Database prediction of wind direction and speed for 2 November 2003.

In addition to monitoring NWS National Hurricane Center's hurricane watches, warnings, and advisories, CCFHR also uses wind speed predictions from the National Digital Forecast database (Figure 3). The digital forecast data are available at *http://weather.gov.* The CCFHR also uses the NWS SLOSH (Sea, Lake, and Overland Surge from Hurricanes) model, which uses storm track, intensity, and size along with bathymetry and emergent terrain to predict storm surge.

The SLOSH model is generally accurate within plus or minus 20 percent. For example, if the model calculates a peak 10-foot storm surge for the event, one can expect the observed peak to range from 8 to 12 feet. The model accounts for astronomical tides (which can add significantly to the water height) by specifying an initial tide level, but does not include rainfall, riverflow, or wind-driven waves (*www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml*).

The location of a hurricane's landfall is crucial for determining which areas will be inundated by the storm surge. In cases when the hurricane

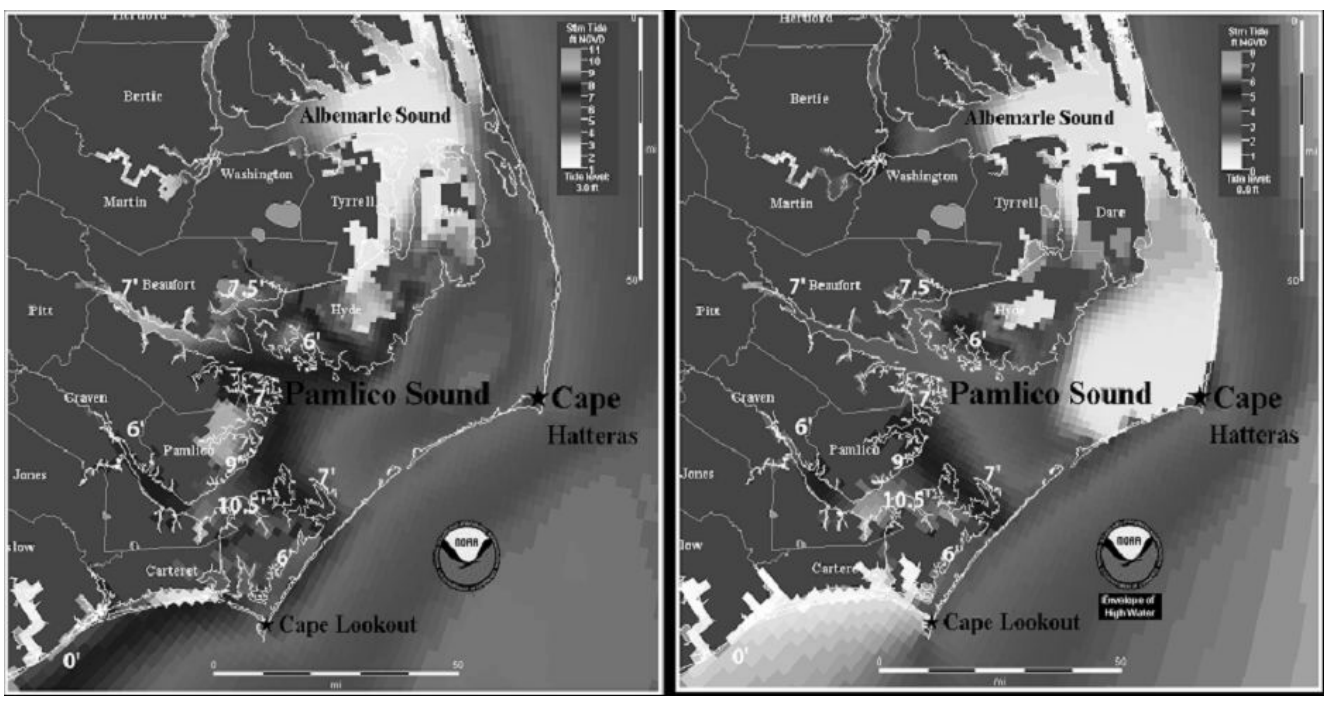

Figure 4. SLOSH model predictions of storm surge in central North Carolina given a worst case scenario, i.e., a Category 2 hurricane moving at 15 miles per hour over Cape Lookout (left); and operational prediction of storm surge given observed input parameters (right).

forecast track is inaccurate, SLOSH model results will also be inaccurate. The SLOSH model, therefore, is best used in defining the potential maximum surge for a location. Figure 4 shows the SLOSH output for a generic Category 2 storm and for Hurricane Isabel.

Isabel caused extensive flooding on the southwestern shore of Pamlico Sound because the storm made landfall over Core Banks at or near high tide and because water was blown across Pamlico Sound and piled on the southwestern shore. The storm's circulation drove water up the Chesapeake Bay, piling on the western shore. The CCFHR has the SLOSH installed at its facility, made available through the NWS Weather Field Office (WFO) in Newport, North Carolina. The SLOSH model, with a refined grid and updated database, is available for Chesapeake Bay through the NWS Wakefield, Virginia office.

SUMMARY

The CCFHR at Beaufort, North Carolina and the CCEHBR at Oxford, Maryland are able to protect federal property to the extent possible by closely monitoring information made available through the NWS, by using model predictions from the NWS, and by activating documented hurricane preparation plans well in advance of hurricane landfall. The hurricane preparation plans employed by CCFHR at Beaufort and CCEHBR at Oxford, outlined here, are not intended to serve as a model for municipal or state facilities, but as suggestions for hurricane preparedness.

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