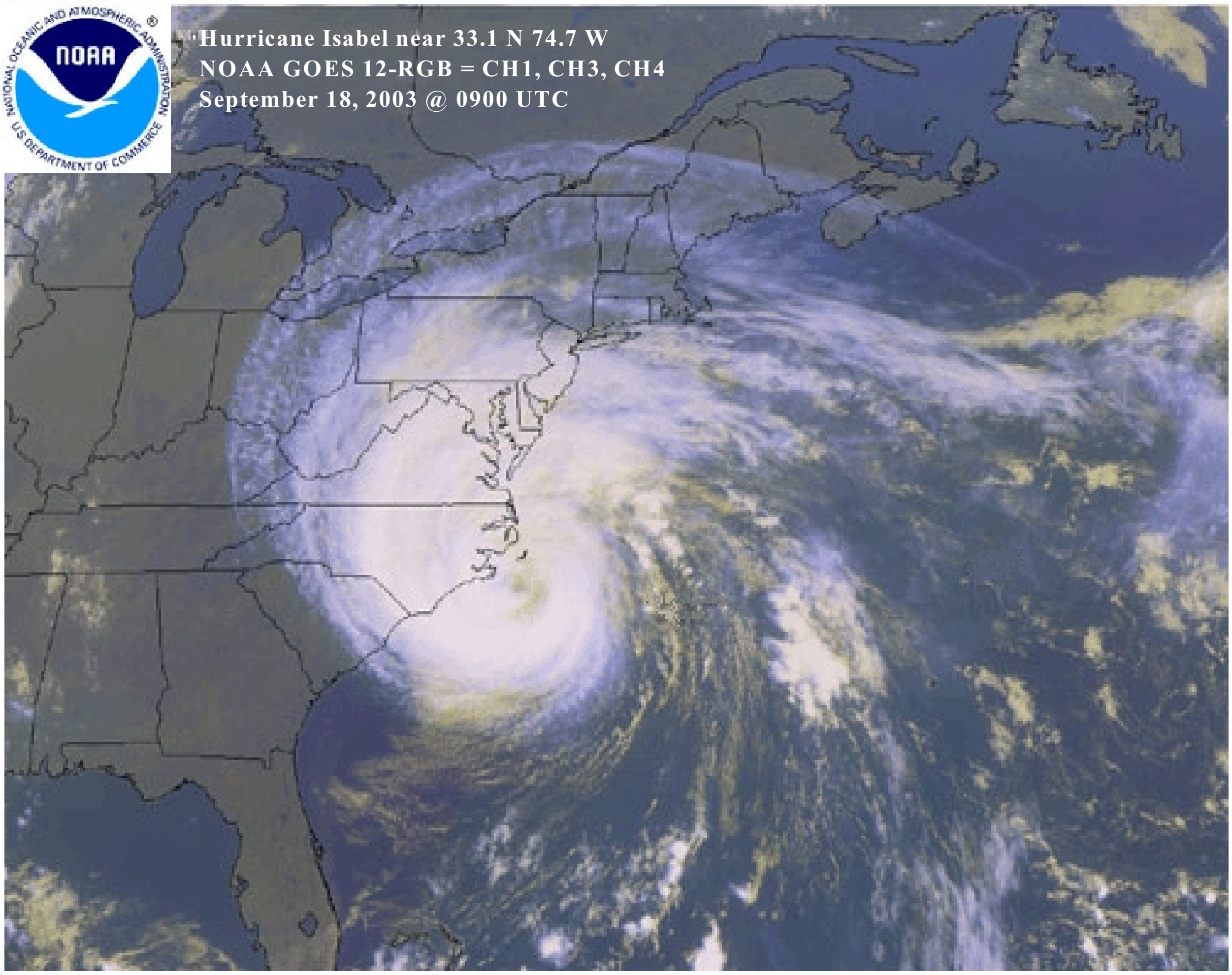
NOAA Technical Report NOS CO-OPS 040

EFFECTS OF HURRICANE ISABEL ON WATER LEVELS DATA REPORT



Hurricane Isabel near 33.1 N 74.7 W
NOAA GOES 12-RGB = CH1, CH3, CH4
September 18, 2003 @ 0900 UTC

Silver Spring, Maryland
April 2004

noaa National Oceanic and Atmospheric Administration
U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) collects and distributes observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and coastal current products required to support NOS' Strategic Plan mission requirements, and assists in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), and a national network of Physical Oceanographic Real-Time Systems (PORTS) in major U.S. harbors. The Center establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

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Jerry Hovis, William Popovich, Chris Zervas, James Hubbard, H. H. Shih, Peter Stone

April, 2004

noaa National Oceanic and Atmospheric Administration

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List of Acronyms and Abbreviations

ADCP	**Acoustic Doppler Current Profiler**
AWIPS	**Advanced Weather Interactive Processing System**
CBBT	**Chesapeake Bay Bridge Tunnel**
CO-OPS	**Center for Operational Oceanographic Products and Services**
CORMS	**Continuous Operational Real-Time Monitoring System**
DCP	**Data Collection Platform**
EDT	**Eastern Daylight Time**
EST	**Eastern Standard Time**
GOES	**Geostationary Operational Environmental Satellite**
GMT	**Greenwich Mean Time**
GT	**Great Diurnal Range**
MODIS	**Moderate Resolution Imaging Spectroradiometer**
MHHW	**Mean Higher High Water**
MHW	**Mean High Water**
MLLW	**Mean Lower Low Water**
MLW	**Mean Low Water**
MSL	**Mean Sea Level**
NASA	**National Aeronautics and Space Administration**
NAVD 88	**North American Vertical Datum of 1988**
NESDIS	**National Environmental Satellite, Data, and Information Service**
NGS	**National Geodetic Survey**
NGVD 29	**National Geodetic Vertical Datum of 1929**
NGWLMS	**Next Generation Water Level Measurement System**
NHC	**National Hurricane Center**
NOAA	**National Oceanic and Atmospheric Administration**
NOS	**National Ocean Service**
NTDE	**National Tidal Datum Epoch**
NWLON	**National Water Level Observation Network**
NWLP	**National Water Level Program**
NWS	**National Weather Service**
PORTS	**Physical Oceanographic Real-Time System**
UTC	**Universal Time Coordinate**

Abstract

Hurricane Isabel was the most powerful hurricane of the 2003 season and the first hurricane to make landfall on the east coast of the United States since 1999. After coming ashore on the Outer Banks of North Carolina on 18 September as a Category 2 hurricane, Isabel took a northward track through Virginia, causing high winds, storm surge flooding, and extensive property damage, especially to the electric power delivery network, throughout the Chesapeake Bay region. Isabel also had a significant impact on the Delaware River and Bay. The remnants of Isabel crossed Lake Erie late on 19 September setting up a wind-driven oscillation on the lake.

The water level stations of the Center for Operational Oceanographic Products and Services (CO-OPS) recorded varying responses along the coastal ocean, bays, estuaries, and rivers of the U.S. east coast and the Great Lakes caused by the passage of Hurricane Isabel. Thirty coastal stations from Wilmington, NC to Sandy Hook, NJ were strongly affected by the storm and produced water level data from the primary or the backup sensor. Five stations were destroyed by storm surge and two stations experienced an unrecoverable loss of data during the storm. Many of the CO-OPS water level stations collected meteorological data (air temperature, barometric pressure, wind speed and direction) and water temperature during the storm. CO-OPS also had a current meter deployed at a site in mid-Chesapeake Bay during this period which recorded wave and current data throughout the water column, echo amplitudes from backscattering particles in the water column, pressures, and bottom water temperatures.

This data report begins with a description of the water level network in place as Hurricane Isabel approached the U.S. east coast and the subsequent response of CO-OPS' stations, equipment, data monitoring systems, staff, and internet websites during the events of 18-19 September. This is followed by a description of the inception, development, and dissipation of the storm system. A major part of the report is an analysis of the coastal water level response to Hurricane Isabel, giving the maximum observed water level recorded at each station. Historical maximum water level records were exceeded at eight stations in the Chesapeake Bay, five stations in the Delaware River and Bay, and at one station in North Carolina on the Atlantic Ocean . Storm surge, defined as the difference between the observed water level and the predicted tide curve, is calculated for each station and the peak storm surges are compared. A subsequent chapter puts the maximum observed water level elevations from Isabel in a geodetic reference frame. The data recorded at the site in mid-Chesapeake Bay are used to sequence the response of the winds, air pressure, currents, waves, and water levels at one location during the progression of the storm. Finally, the maximum observed water level elevations caused by Isabel at four long term stations, with records extending back to at least 70 years, are compared with previous high water levels, after correction for the rates of sea level rise in the region.

Chapter 1: CO-OPS National Water Level Program Response to Hurricane Isabel

NWLON and PORTS®

Nearly forty water level stations belonging to NOAA Center for Operational Oceanographic Products and Services (CO-OPS) programs were profoundly affected by storm surge from Hurricane Isabel. Stations in the National Water Level Observation Network (NWLON), the Physical Oceanography Real-Time System (PORTS®), and several special projects acquired water level data throughout Hurricane Isabel's landfall on the United States east coast. Both equipment and personnel responded successfully to the challenging Hurricane Isabel storm surge environment of 16-20 September 2003.

Coastal coverage of the approach area of Hurricane Isabel was afforded by a combination of NWLON and PORTS® water level stations in mid-Atlantic tidal areas of the United States east coast. The coverage was sufficiently dense to characterize the water level response to the storm.

NWLON, a component of the National Water Level Program (NWLP), is comprised of 175 stations on the United States coastline from Maine to Alaska, plus Pacific, Atlantic and Caribbean islands. NWLON had eighteen stations in operation on the U.S. east coast that were significantly affected by storm surge from Hurricane Isabel. Eight NWLON stations on Lake Erie were moderately affected by the passage of the remnants of Isabel a day after the storm activity in the Chesapeake Bay area. This event, briefly discussed later in the report, was due to the setup of a wind-driven oscillation on the lake as recorded by NWLON stations.

PORTS®, operational in ten major ports in the United States, had 22 stations that were significantly affected by Hurricane Isabel: ten stations in the Chesapeake Bay PORTS® subsystem, eleven in Delaware Bay PORTS®, and one in New York - New Jersey PORTS®.

Personnel from the Continuous Operational Real-Time Monitoring System (CORMS) provided round-the-clock monitoring and quality control of PORTS® and NWLON water level data throughout the Hurricane Isabel event. Real-time plots and data listing of all CO-OPS water level data from the area affected by Hurricane Isabel were available around-the-clock on the internet through the CO-OPS Tides Online web site. A technical description of NWLON, PORTS®, CORMS, and Tides Online is included at the end of this chapter.

Stations in both the NWLON and PORTS® networks were designed for long-term continuous water level measurement, with sufficient hardening to withstand most heavy-weather events. Several stations in the path of Isabel were nevertheless overwhelmed by extraordinary storm surge, wind, and wave energy during the storm. Water level stations at Cape Hatteras, NC; Gloucester Point, VA; Windmill Point, VA and Colonial Beach, VA sustained serious damage or complete destruction. The Solomons Island, MD gauge experienced an unrecoverable transmission failure during the peak surge event. Two special project water level gauges, Kingsmill, VA and Scotland, VA on the James

River, were completely destroyed by flood waters from Isabel. These gauges were part of a partnership with the U.S. Army Corps of Engineers.

Table 1-1 shows CO-OPS water level stations which experienced significant storm surge from Isabel. **Table 1-2** shows CO-OPS water level stations damaged or destroyed by the storm. **Figure 1-1** shows all east coast NWLON and PORTS® stations with the Isabel track displayed. **Figure 1-2** shows CO-OPS Great Lakes water level stations with the Isabel track. Photographs of damage to CO-OPS water level gauges are shown in **Figures 1-3, 1-4, and 1-5.**

The primary water level sensor used in the NWLON and PORTS® networks is an acoustic water level measurement system which recorded six-minute water level readings throughout the critical period of Hurricane Isabel.

The primary period of interest for water level measurement during Hurricane Isabel was 16-20 September 2003. The critical period starts with the initial landfall of Isabel on the Outer Banks of North Carolina on 18 September and concludes with the passage of the storm into the upper middle Atlantic states and eastern Great Lakes on 19 and 20 September.

In several locations the primary acoustic water level sensor was completely submerged in floodwater during the peak storm surge event, invalidating the water level reading. At each of these locations, the "backup" pressure gauge accurately recorded the main storm surge event, and was able to provide a "fill" where acoustic gauge data were unavailable. These stations were Lewisetta, VA; Washington DC, Chesapeake City, MD; and Duck NC.

The data used in this report were 6-minute water level observations and hourly meteorological measurements, rigorously quality-controlled using National Ocean Service (NOS) approved standard operating procedures.

CO-OPS Technical Personnel

Technical personnel in CO-OPS connected with NWLON, PORTS®, CORMS, and the CO-OPS internet website were prepared and aware of the approach of Isabel two weeks before landfall. CO-OPS scientific personnel continued to monitor the storm throughout its approach phase. The expectation of imminent heavy weather and power outages to the Washington DC area led to closing of U.S. government activities at the end of the Wednesday, 17 September business day. The NOAA Silver Spring campus was officially closed 18 and 19 September, including CO-OPS. The CORMS realtime monitoring system was manned and continued to operate around the clock throughout the period of Isabel's landfall and progression through the middle Atlantic states. Several CO-OPS scientific personnel continued to monitor the storm from their homes. Several assisted local emergency agencies by telephone. The CO-OPS internet website, especially Tides Online, operated throughout the storm without interruption, and was able to provide for all internet "hits" requesting water level data and plots. CO-OPS and the rest of NOS reopened on the Monday morning following the storm, 22 September 2003. Extensive post-storm analysis and reporting began immediately.

Dissemination of Water Level and Storm Surge data from the CO-OPS internet website

CO-OPS internet water level websites experienced extraordinary volumes during Hurricane Isabel. Internet volume on the Tides Online website surged from a normal volume of about 60,000 hits per day to nearly 460,000, or an increase of approximately 660%. Customer volume on the general CO-OPS internet website increased from a normal volume of approximately 300,000 to nearly 880,000 or an increase of approximately 190%. **Figure 1-6** graphically depicts internet volume on the general CO-OPS website during the month of September 2003. **Figure 1-7** shows the same information for the Tides Online website.

Table 1-1. CO-OPS water level stations impacted by storm surge from Hurricane Isabel

STATION	NWLON	PORTS	STATION	NWLON	PORTS
Sandy Hook, NJ	X	X	Chesapeake City, MD		X
Atlantic City, NJ	X		Baltimore, MD	X	X
Newbold, PA		X	Tolchester, MD		X
Burlington, NJ		X	Annapolis, MD	X	X
Tacony-Palmyra, NJ		X	Cambridge, MD	X	
Philadelphia, PA	X	X	Washington, DC	X	X
Marcus Hook, PA		X	Lewisetta, VA	X	X
Delaware City, DE		X	Kiptopeke, VA	X	X
Reedy Point, DE	X	X	Chesapeake, BBT VA	X	X
Ship John Shoal, NJ		X	Sewells Point, VA	X	X
Brandywine Shoal ,DE		X	Money Point, VA		X
Cape May, NJ	X	X	Duck, NC	X	
Lewes, DE	X	X	Oregon Inlet, NC	Special Project	
Ocean City Inlet, MD	Special Project		Beaufort ,NC	X	
Wachapreague, VA	X		Wilmington, NC	X	

Table 1-2. CO-OPS water level stations damaged or destroyed by Hurricane Isabel

STATION	CONTINGENCY	NWLON	PORTS
Cape Hatteras, NC	Destroyed by Isabel	X	
Gloucester Point, VA	Destroyed by Isabel	X	X
Windmill Point, VA	Major data loss		X
Colonial Beach, VA	Destroyed by Isabel	X	
Solomons Island, MD	Major data loss	X	X
Kingsmill, VA	Destroyed by Isabel	Special Project	
Scotland, VA	Destroyed by Isabel	Special Project	

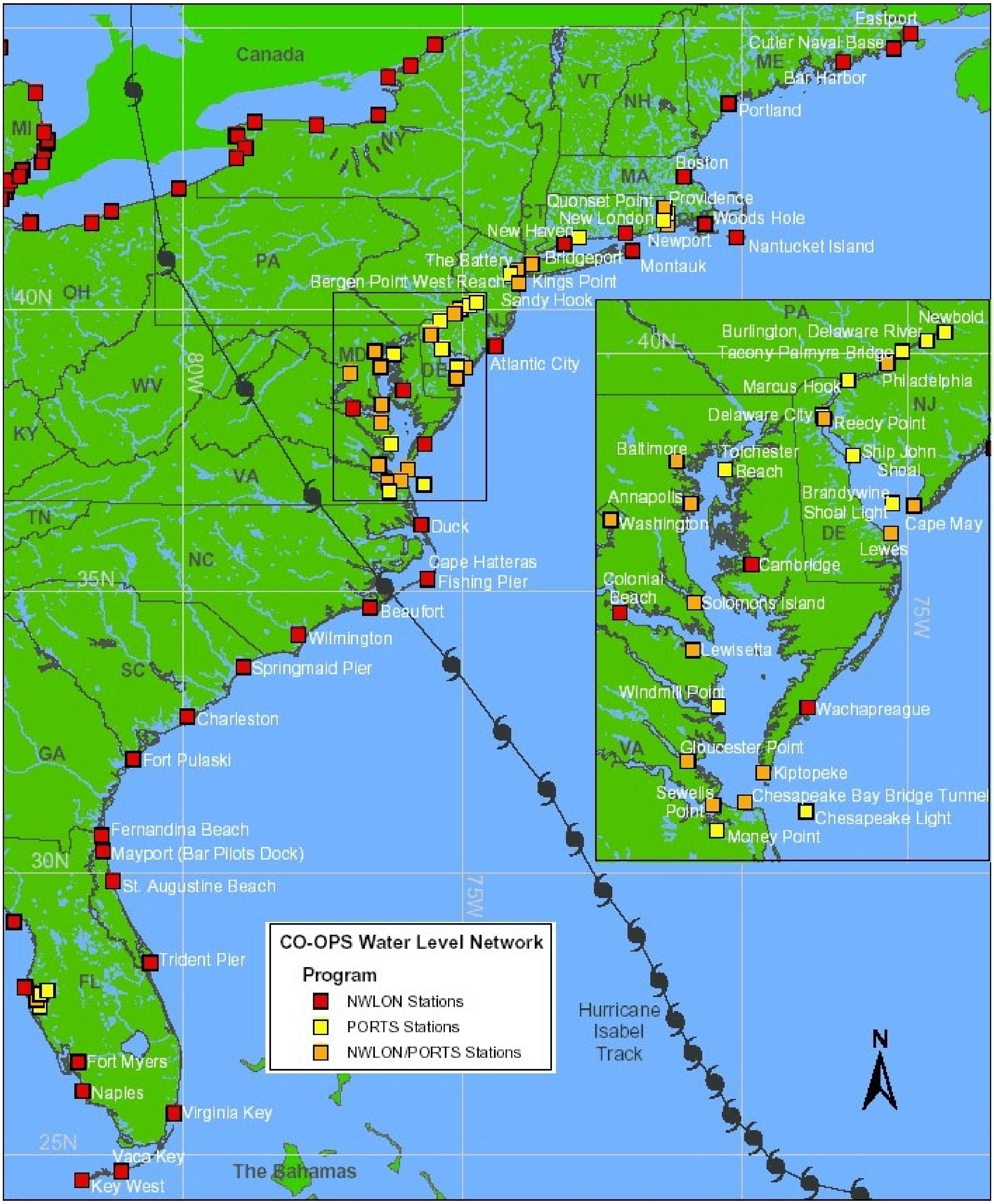


Figure 1-1. CO-OPS Water Level Networks in the area of Hurricane Isabel's track.

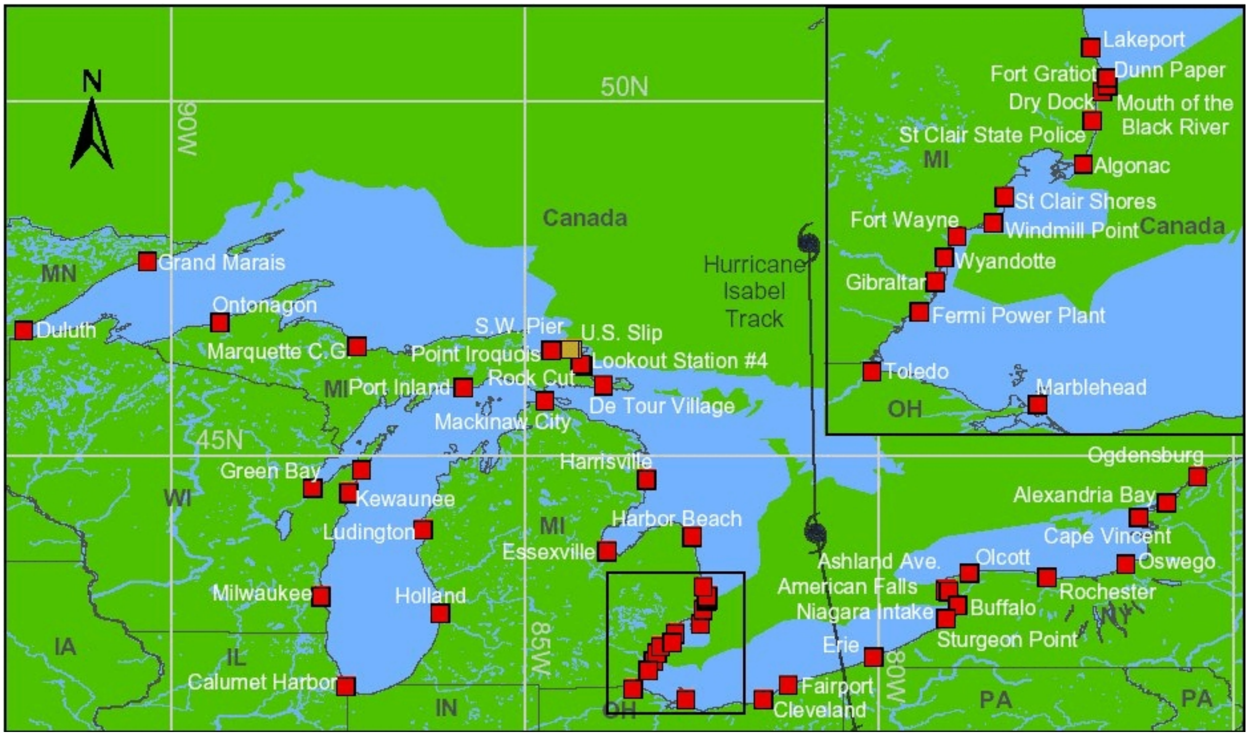


Figure 1-2. Track of the remnants of Isabel across Lake Erie, 19 September 2003.

Figure 1-3. Damage to Lewisetta, VA water level station.

Figure 1-4. Damage to Gloucester Point, VA water level station.

Figure 1-5. Damage to Colonial Beach, VA water level station.

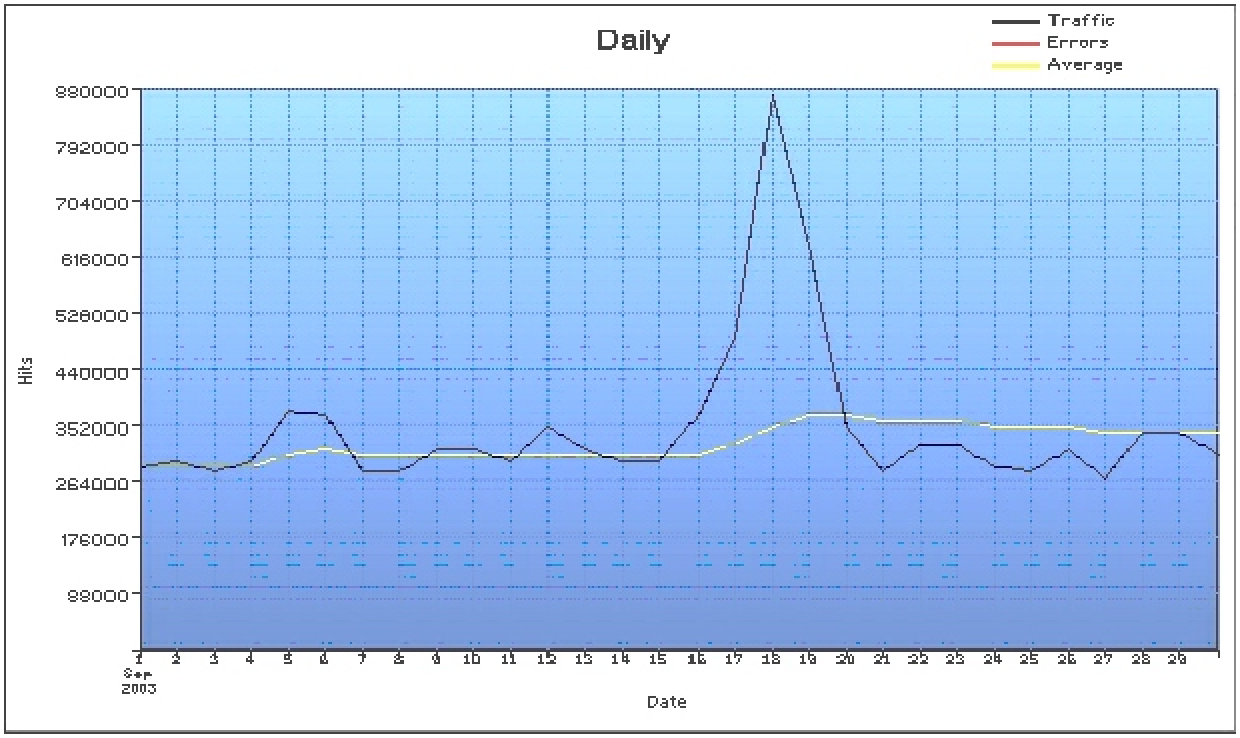


Figure 1-6. Internet volume on the CO-OPS website www.tidesandcurrents.noaa.gov.

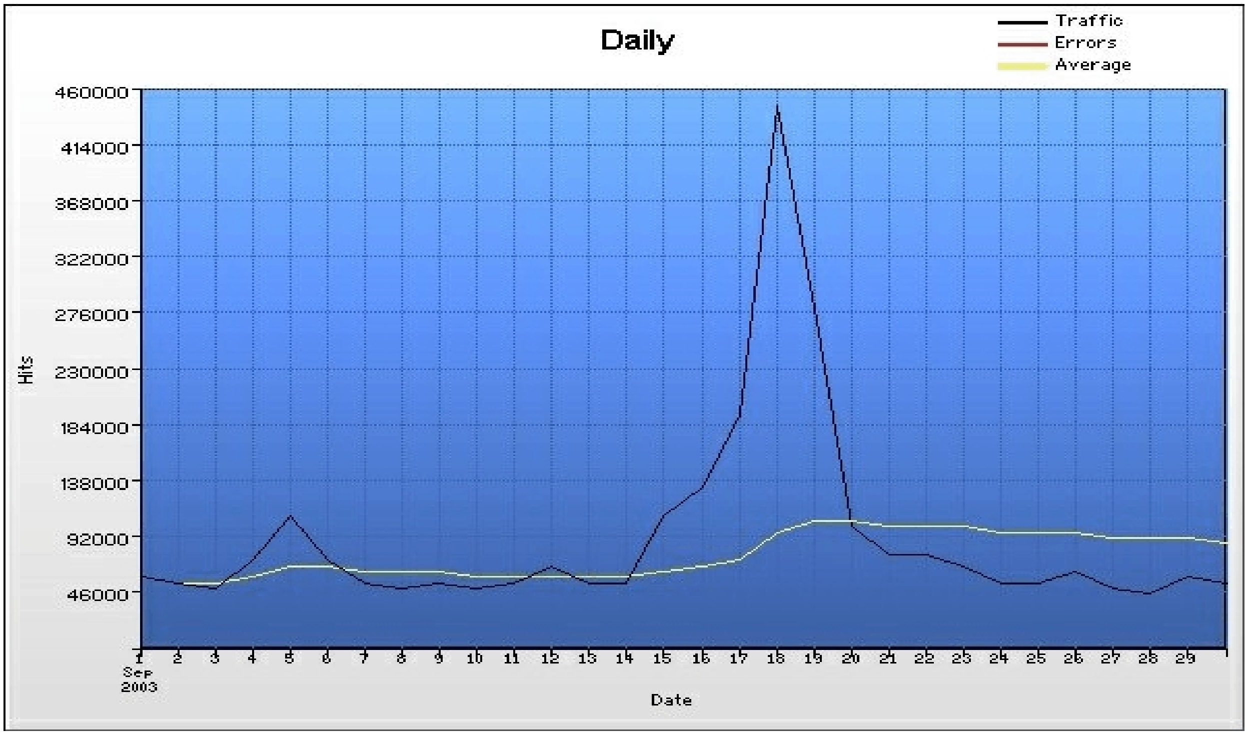


Figure 1-7. Internet volume on the Tides Online website www.tidesonline.nos.noaa.gov.

Technical Description of NWLON and PORTS® water level networks

CO-OPS, operates the NWLON which is composed of approximately 175 long term, continuously-operating stations distributed along the U.S. coast (including the Great Lakes) and on islands in the Atlantic and Pacific Oceans. Data from NWLON stations are used in a wide variety of applications, including: navigational safety, coastal forecasting, surveying and mapping, coastal engineering, marine boundary determination, and monitoring of seasonal and long-term sea levels. Data from these stations are increasingly being required by users in real time. Coastal forecast applications include dissemination of data to the NWS Advanced Weather Interactive Processing System (AWIPS) network, and the development of coastal forecast models.

CO-OPS also operates PORTS®, which currently has systems active in ten U.S. ports. The primary mission of PORTS® is to provide realtime water level data to users to ensure safe navigation. PORTS® stations contain enhanced and redundant communications capabilities to ensure continuous delivery of water level data.

The Next Generation Water Level Measurement System (NGWLMS) installed at most NWLON and PORTS® stations is a stand-alone system that acquires, stores, and transmits water level, meteorological, and other environmental data. The main requirement for the unit is to accurately measure water levels with low power consumption, high reliability, and defined accuracy. NGWLMS water level sensors have a mean accuracy of about 2 centimeters for individual 6-minute water level measurements and 5 millimeters for mean monthly averages. A single 6-minute water level value is derived from the arithmetic mean of 181 consecutive one-second measurements.

The NGWLMS field unit is a fully automated data acquisition and transmission system. The data collection platform (DCP) consists of a power supply, communications controller, GOES satellite transmitter, central processing unit, memory expansion module, telephone modem, general purpose I/O module, and controller. The unit's telemetry capability includes satellite, radio, telephone, and direct access for the dissemination of near-real time data.

The instruments typically installed at NWLON and PORTS® stations are a primary acoustic water level sensor and a pressure transducer for back-up water level measurements. The primary acoustic instrument is a non-contact device. The water level data that can be directly referenced to the station datum at the site as an arbitrary zero. Ancillary sensors may include an anemometer for measuring wind speed, direction, and maximum hourly gusts, air and water temperature thermistors, and a barometer for measuring atmospheric pressure.

Technical Description of the CORMS realtime water level monitoring system

CO-OPS is responsible for the operation and maintenance of ten PORTS®. To monitor the PORTS® sensors and the data quality, CORMS was developed. The objective of CORMS is to provide quality control and decision support on a 24-hour a day, 7-day a week basis. CORMS combines the use of real-time communications and data analysis with a graphical user interface for monitoring and notification. CORMS is monitored by a team of qualified technicians who perform designated actions based on standard operating procedures. It is co-located with the NWS Telecommunications Gateway office in Silver Spring, MD.

In addition to PORTS®, some specific portions of the NWLON are monitored for operations and data quality. DCPs transmit hourly data to headquarters via NOAA's GOES satellite. During times of severe storms, these gauges operate in a special mode to provide data every 20 minutes for distribution to the NWS AWIPS network. Since CORMS is co-located with the 24-hour monitoring systems of the NWS, it is convenient to receive weather bulletins, early designations of tropical depressions, and storm warnings.

CORMS monitors the National Hurricane Center (NHC) reports on tropical formation of hurricanes and utilizes the NHC Landfall product to determine when, and for which, stations to trigger the special reporting mode capability. Gauges in a particular coastal area are triggered when the NHC Landfall product indicates that, based on the current track of a storm, landfall is predicted with a 10% confidence level. To assist state and federal emergency management teams with evacuation strategies, observed data are compared to the predicted tide to show storm surge elevations. In addition, the CO-OPS Tides Online, developed to provide real-time water level data via the internet, provides the public with access to time series plots of the data.

CORMS operations staff closely monitored Hurricane Isabel throughout its existence. They were continuously updated by the NWS during the storm. They monitored gauge performance, providing information regarding gauge failure and data problems during the hurricane. CORMS continuously maintained gauges in a reporting mode except for those gauges damaged or destroyed by the storm.

Technical Description of Tides Online

Tides Online is a CO-OPS web-based product which provides users with the latest graphical and tabular water level and meteorological data for all NOS water level stations. For those stations activated, manually or automatically, for storm surge transmission rates, the Tides Online product also isolates their selection for convenient interactive display. These activated stations are typically located along the projected path of severe storms such as hurricanes. Tides Online can be accessed through the CO-OPS web page or by connecting to **tidesonline.nos.noaa.gov**.

Chapter 2: Brief Meteorological Description of Hurricane Isabel

Hurricane Isabel was the most memorable tropical cyclone of a very active 2003 North Atlantic and Gulf of Mexico hurricane season. Isabel produced a devastating combination of wave and wind energy plus storm surge to the North Carolina Outer Banks and Virginia coastline. Its strong, sustained drive inland with high winds and record-breaking storm surge into the Chesapeake Bay, made Isabel the water level event of record for numerous locations in the middle Atlantic states. Significant wave, wind and surge energy from Isabel was also experienced along the coasts of Maryland, Delaware, and New Jersey, and the Delaware Bay estuary. Lake Erie also experienced a wind-driven oscillation event from the remnants of Isabel.

Isabel was one of the most watched and chronicled North American storms in history. Meteorological and human interest coverage of Isabel dominated American print and broadcast news media for over a week before landfall and many days after dissipation. Weather forecasting media and the National Weather Service provided round-the-clock coverage of Isabel throughout its life as a tropical cyclone. A complete record of water level and storm surge was collected at over thirty water level gauges in tidal areas operated by NOAA's NOS, except for several gauges severely damaged or destroyed by the storm.

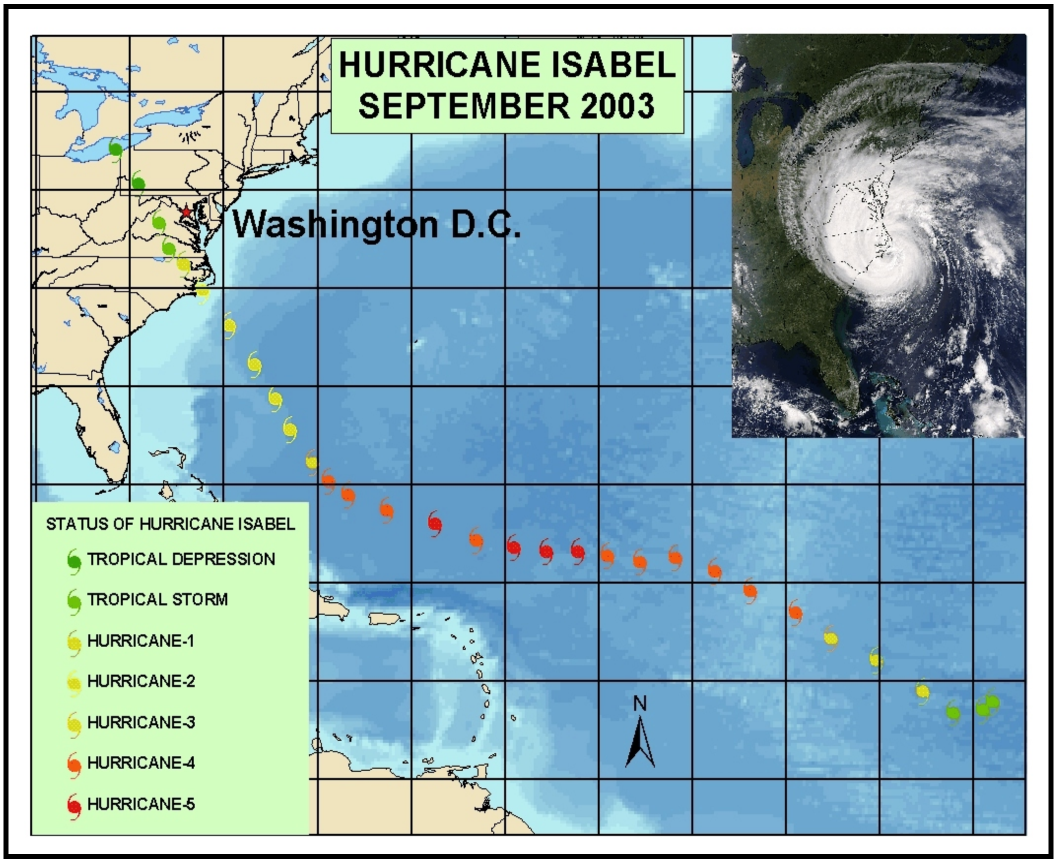


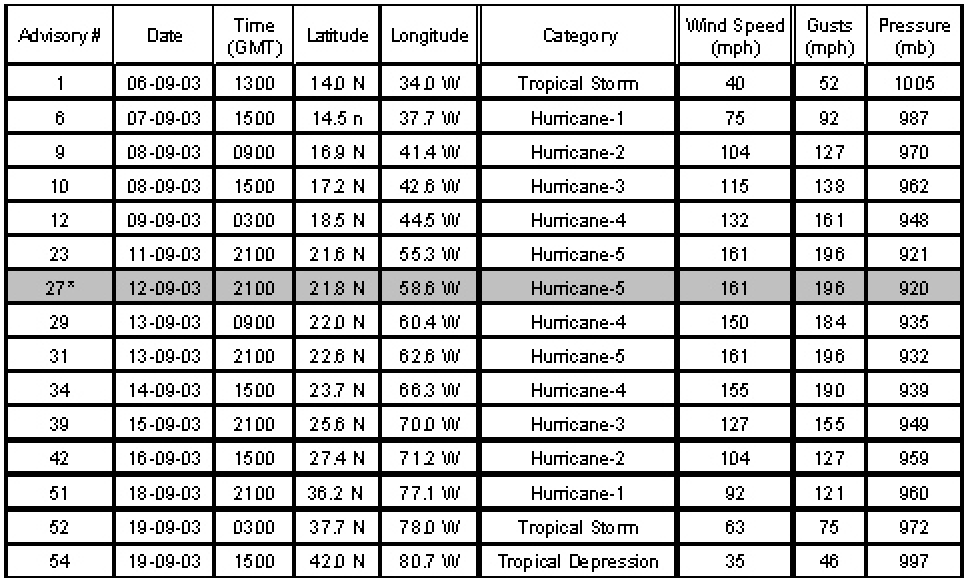
Figure 2-1. Track of Hurricane Isabel from 6-19 September 2003.

Isabel blossomed into a major hurricane only a few days after its formation in the central Atlantic Ocean, about Sunday 7 September 2003. By Thursday 11 September, almost a week before its landfall on the middle Atlantic seaboard, the various hurricane models were predicting a threatening trajectory towards populated U.S. east coast areas. Its brief but spectacular life as a Category 4 and 5 hurricane while approaching the mid-Atlantic coastline (9-15 September) gave pause to storm watchers nationwide, heightening awareness of Isabel's destructive potential.

About two days before landfall (16 September) Isabel weakened to Category 2 intensity and became less organized, drawing some dry air into its circulation. After a northward turn on 15 and 16 September, Isabel began a practically straight-line trajectory towards the middle Atlantic seaboard area. It was forecast as such by NWS with tight agreement among the several hurricane prediction models. Approaching its landfall beginning 17 September, Isabel was still a formidably strong and large hurricane. By afternoon on 17 September, Isabel's wind and surge was affecting the Outer Banks of North Carolina.

Table 2-1 shows Hurricane Isabel advisories from the NHC. For a complete listing of NHC Hurricane Isabel weather advisories see Appendix I. **Figure 2-1** shows the storm track from inception to dissipation. **Figure 2-2** shows the NHC Forecast Advisory 41 graphic and an accompanying GOES satellite image. **Figure 2-3** is an Isabel satellite shot from NASA showing the storms entire footprint at the time of landfall on the U.S. east coast. **Figure 2-4** shows physical damage at Cape Hatteras from Isabel. **Figure 2-5** is a location map of all United States landfalling hurricanes between 1950-2002.

Table 2-1. Hurricane Isabel weather advisories from the NHC
("*" denotes highest wind speed and lowest barometric pressure)



Advisory #	Date	Time (GMT)	Latitude	Longitude	Category	Wind Speed (mph)	Gusts (mph)	Pressure (mb)
1	06-09-03	1300	14.0 N	34.0 W	Tropical Storm	40	52	1005
6	07-09-03	1500	14.5 n	37.7 W	Hurricane-1	75	92	987
9	08-09-03	0900	16.9 N	41.4 W	Hurricane-2	104	127	970
10	08-09-03	1500	17.2 N	42.6 W	Hurricane-3	115	138	962
12	09-09-03	0300	18.5 N	44.5 W	Hurricane-4	132	161	948
23	11-09-03	2100	21.6 N	55.3 W	Hurricane-5	161	196	921
27*	12-09-03	2100	21.8 N	58.6 W	Hurricane-5	161	196	920
29	13-09-03	0900	22.0 N	60.4 W	Hurricane-4	150	184	935
31	13-09-03	2100	22.6 N	62.6 W	Hurricane-5	161	196	932
34	14-09-03	1500	23.7 N	66.3 W	Hurricane-4	155	190	939
39	15-09-03	2100	25.6 N	70.0 W	Hurricane-3	127	155	949
42	16-09-03	1500	27.4 N	71.2 W	Hurricane-2	104	127	959
51	18-09-03	2100	36.2 N	77.1 W	Hurricane-1	92	121	960
52	19-09-03	0300	37.7 N	78.0 W	Tropical Storm	63	75	972
54	19-09-03	1500	42.0 N	80.7 W	Tropical Depression	35	46	997

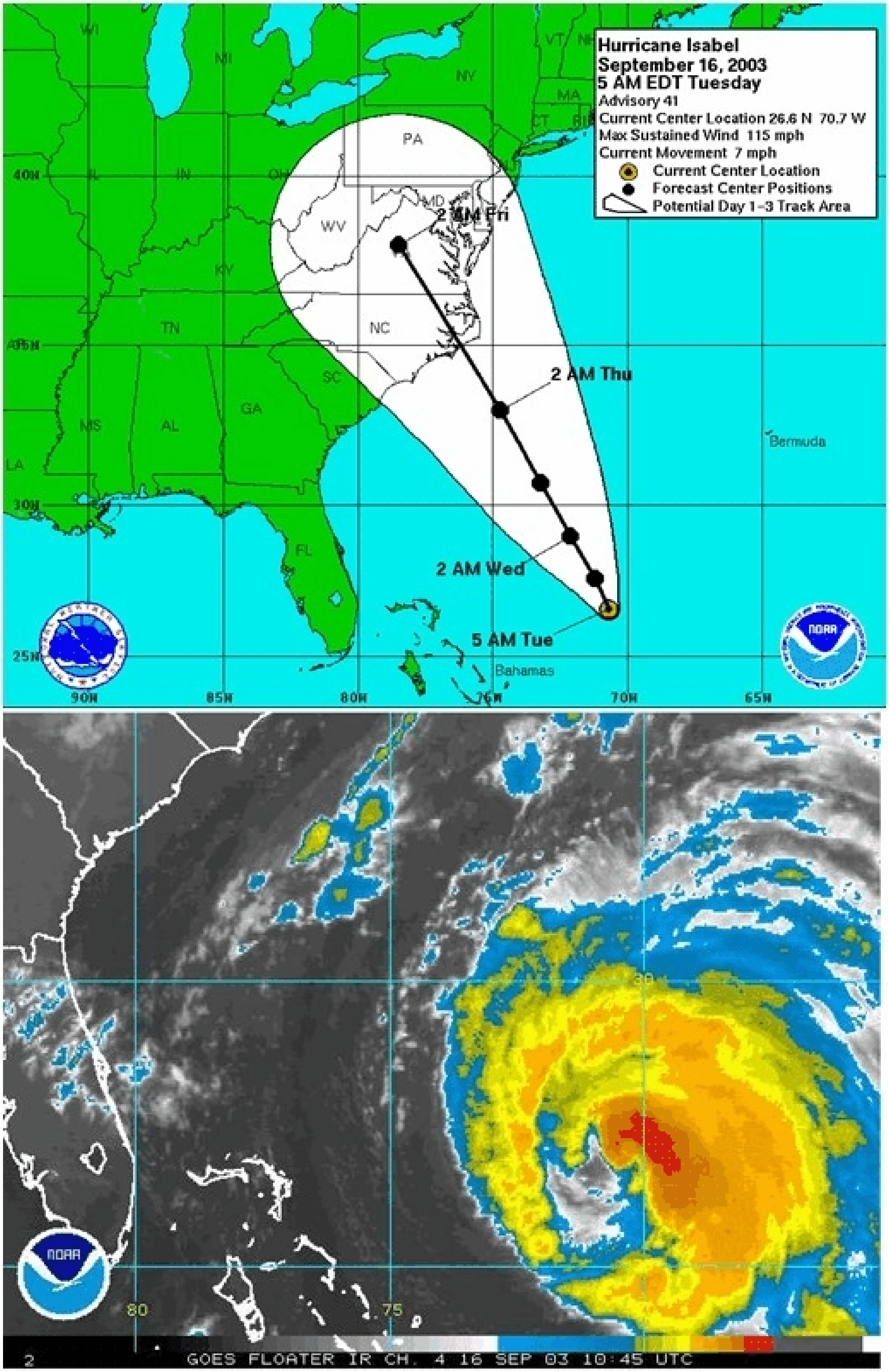


Figure 2-2. NHC Forecast Advisory 41 graphic and accompanying IR GOES image. Courtesy: NHC and NESDIS.

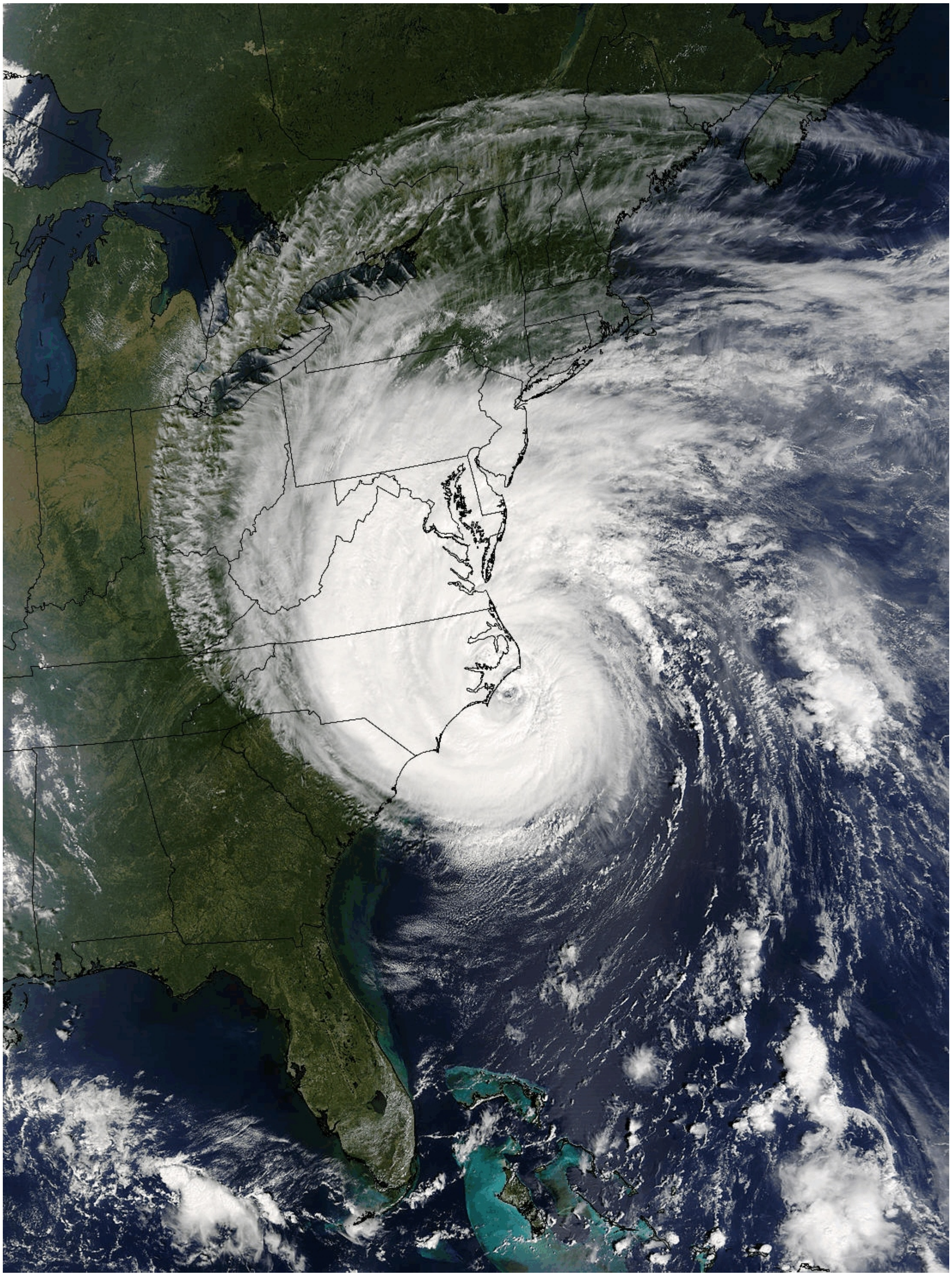


Figure 2-3. Hurricane Isabel over the US East Coast, 18 September @ 1555 UTC. Satellite: Terra. Courtesy: MODIS Rapid Response Team, NASA.

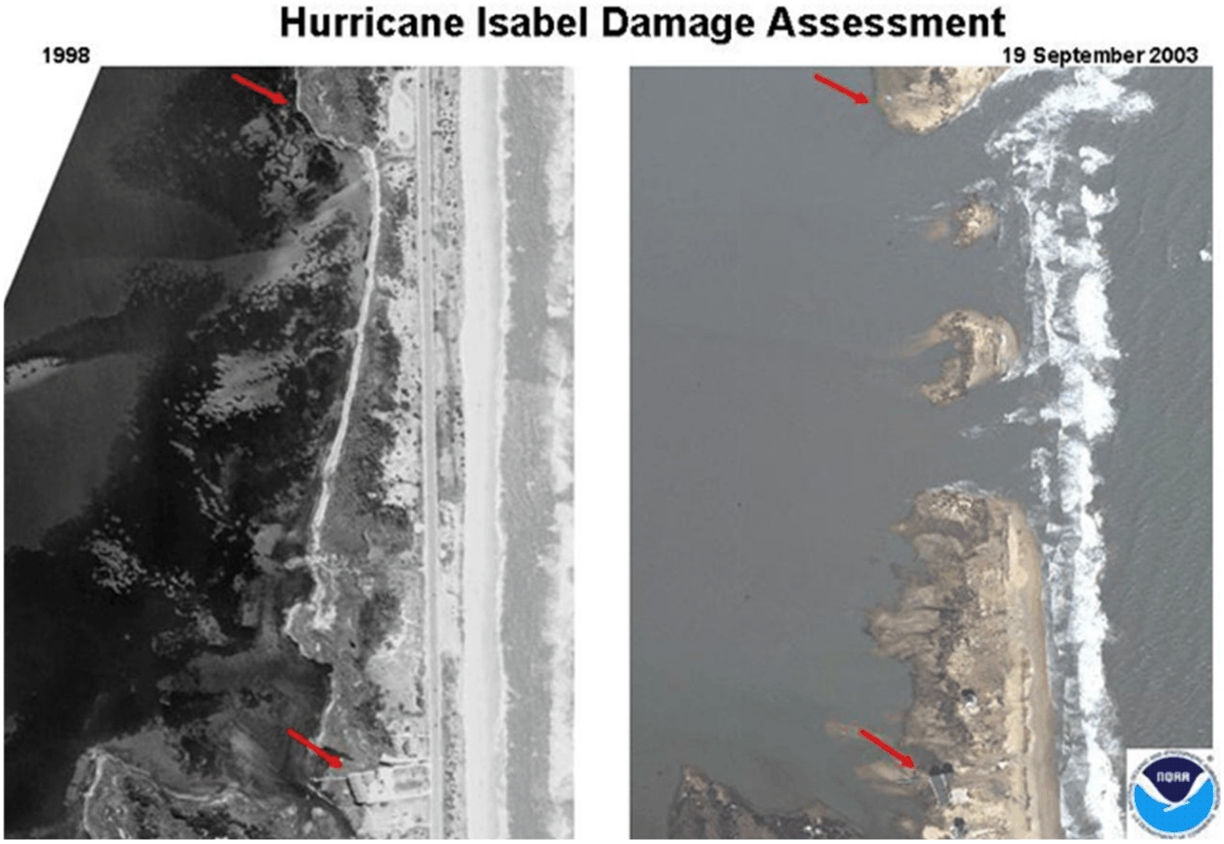


Figure 2-4. Before and After: Cape Hatteras National Seashore, north of Hatteras Village NC. The cuts through the barrier island are nicknamed "Isabel Inlet".

Hurricane Warnings were first issued for the Atlantic Coast late on the evening of Tuesday 16 September 2003:

> "HURRICANE ISABEL ADVISORY NUMBER 44 CORRECTION NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL 11 PM EDT TUE SEP 16 2003. AT 11 PM EDT...0300Z...A HURRICANE WARNING IS IN EFFECT FROM CAPE FEAR NORTH CAROLINA NORTHWARD TO THE NORTH CAROLINA/VIRGINIA STATE LINE INCLUDING PAMLICO AND ALBEMARLE SOUNDS. A HURRICANE WATCH IS IN EFFECT FROM THE NORTH CAROLINA/VIRGINIA STATE LINE NORTHWARD TO CHINCOTEAGUE VIRGINIA INCLUDING CHESAPEAKE BAY AND THE TIDAL POTOMAC."

Official NWS and NHC forecasts accurately predicted and warned of major storm surges and wind events in the mid-Atlantic states, including the Chesapeake and Delaware Bays.

Isabel was still a borderline Category 2 hurricane when it made landfall along the North Carolina coast on 18 September.

Storm surges produced by Isabel in the mid-Atlantic region, especially Chesapeake Bay, were the highest on record for several locations, and resembled the August 1933 hurricane that struck the same geographical area. A chapter of this report is dedicated to a comparison of storm surge and maximum water levels measured during the two storms.

The primary period of interest for storm surge resulting from Isabel was 16-20 September 2003. This period starts with the initial landfall of Isabel on the Outer Banks of North Carolina and concludes with the passage of the storm into the upper middle Atlantic states. The passage of the remnants of Isabel over Lake Erie is briefly discussed due to the occurrence of an oscillation and storm surge event as recorded by CO-OPS water level stations. The timeline of significant water level events for Hurricane Isabel is as follows:

- ***Tuesday 16 September 2003*****:** The 2300 EDT NHC Advisory #44 posts a Hurricane Warning from Cape Fear NC northward to the NC/VA state line including Pamlico and Albemarle Sounds. A Hurricane Watch is posted from the NC/VA state line northward to Chincoteague VA including Chesapeake Bay and the tidal Potomac River. All NWLON and PORTS® water level stations in the mid-Atlantic region are operational and prepared for the landfall of Isabel. About fifty stations, from Beaufort NC to Sandy Hook NJ, and including eight stations in Lake Erie, eventually record significant surge from Isabel

- ***Wednesday 17 September 2003:*** Water level stations on the Outer Banks of NC begin to show storm surge and major wave energy after about 1800 EDT

- ***Thursday 18 September 2003 (0000 to 1200 EDT)****:* Throughout the morning and afternoon water level stations on the Outer Banks of North Carolina experience major storm surge and dramatic wind and wave activity. Several are severely damaged. After about 0900 EDT, water level stations in the Hampton Roads VA area and the lower Chesapeake Bay (Chesapeake Bay-Bridge Tunnel, Sewells Point, and Money Point in the Norfolk- Hampton Roads area) begin to show a quick and dramatic storm surge

- ***Thursday 18 September 2003 (1200 to 1800 EDT)*****:** The swift, dramatic surge in the lower Chesapeake Bay continues and peaks about 1700 EDT in the Hampton Roads, VA area, then begins to quickly recede

- ***Thursday 18 September 2003 (1800 EDT to midnight)*****:** Storm surge continues up the Chesapeake Bay, producing a swift, dramatic rise at many stations from Cambridge, MD to Chesapeake City, MD, and the populations centers at Washington, DC; Annapolis; MD and Baltimore, MD. The historic rises at these locations continue into the next morning

- ***Friday 19 September 2003:*** The dramatic storm surge at upper Chesapeake Bay locations peaks at about 0600 EDT at Washington DC and 0800 EDT at Annapolis and Baltimore. About three-fourths of the dramatic storm surge in the upper Chesapeake Bay recedes by 2200 EDT

- ***Saturday 20 September 2003:*** Water levels return to normal at most locations in the middle Atlantic seaboard area, but levels at Washington DC remain several feet above normal for the next few days

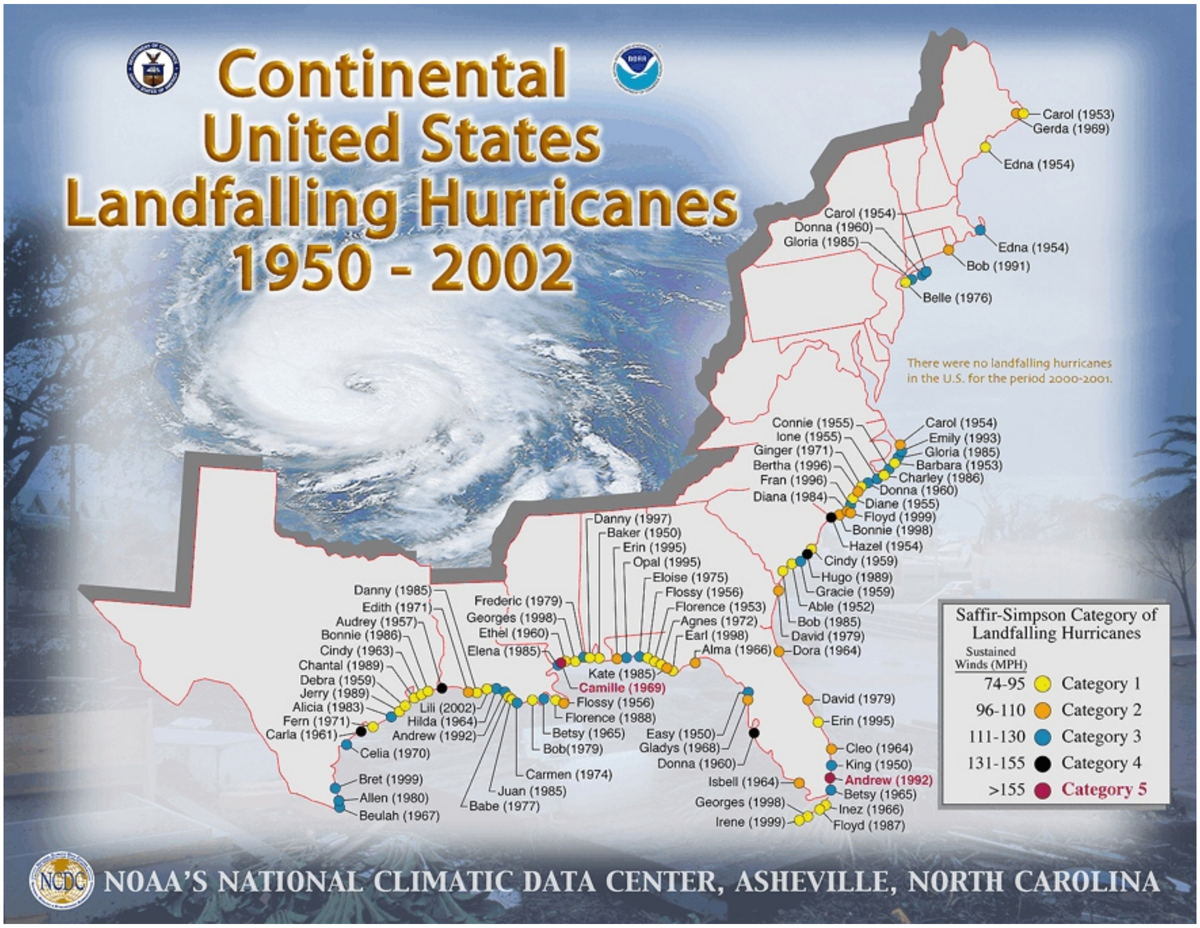


Figure 2-5. Continental U.S. Landfalling Hurricanes 1950-2002. Courtesy: NOAA National Climatic Data Center

Chapter 3: Water Level Heights and Storm Surge Analysis

Maximum Observed Heights

A major concern during a storm such as Hurricane Isabel is the maximum water level reached, which can have a significant effect on the storm's potential for damage. This is a sum of the effect of high wind speed and low atmospheric pressure, in addition to the timing and strength of the tide when the storm reaches its peak strength. If a storm occurs during a low tide and/or during a period of neap tides, the maximum observed water level can be significantly less than when a storm occurs at high tide and/or during a period of spring tides. The landfall time period of Hurricane Isabel (18-19 September, 2003) fell between a full moon on 10 September and a new moon on 26 September. Had the storm coincided with either a new moon or a full moon, higher maximum water levels could have occurred. **Figure 3-1** shows the track of Hurricane Isabel and the CO-OPS stations that measured water level data during the storm.

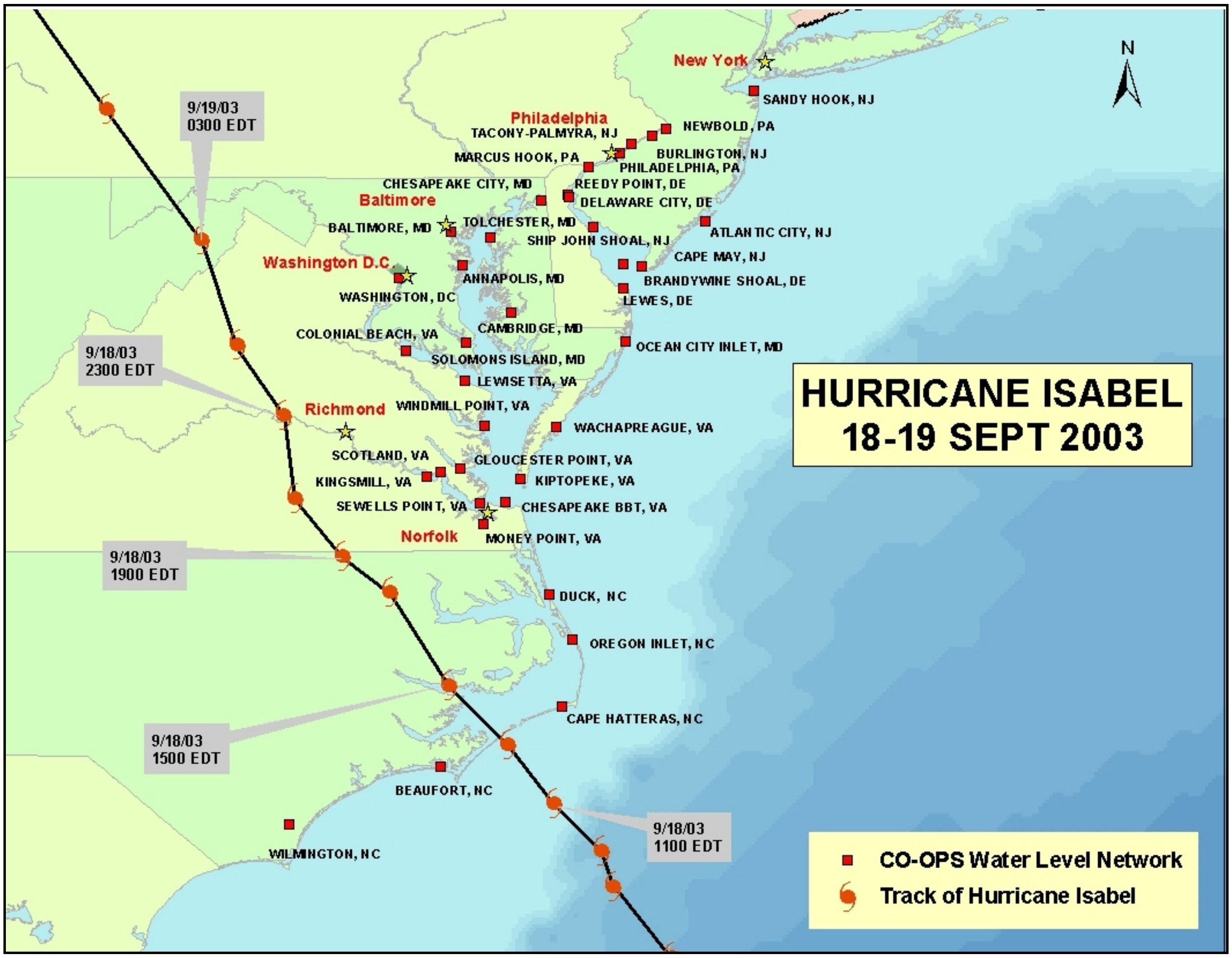


Figure 3-1. CO-OPS water level stations and track of Hurricane Isabel 18-19 September, 2003.

The potential for storm damage to a shoreline is related to both the height and period of time that the water level exceeds MHHW. A comparison of the maximum observed elevation to the maximum historical elevation is shown in **Figure 3-2.** The historical maxima are labeled with the name and date of the hurricane that caused them or with dates for unnamed hurricanes or winter storms.

The heights in **Tables 3-1** and **3-2** are relative to the MLLW and MHHW datums at each location. These datums are based on the 1983-2001 National Tidal Datum Epoch (NTDE) which superceded the 1960-1978 NTDE in April 2003. MLLW is the reference datum for NOAA nautical charts and NOS tide prediction tables. The MHHW datum is the mean elevation of the higher high water observed each tidal day over the entire epoch. The GT is the difference in elevation between MHHW and MLLW and can be considered the average maximum daily vertical excursion of the water level at a given location. Tidal ranges decrease from lower to upper Chesapeake Bay and increase from lower Delaware Bay up the Delaware River. Elevation comparisons to MHHW and the GT of tide put the effects of this particular storm in context with the normal elevation of a tidal high water at each location.

Hurricane Isabel approached or exceeded historical maxima at five locations along the Delaware River near Philadelphia, eight locations in the Chesapeake Bay, and at Duck, NC. However, it should be noted that the majority of stations on the Delaware River were recently established and have limited time series. The Cape Hatteras water level station was destroyed during the storm and did not record a maximum elevation. South of Cape Hatteras, the water levels were less than the historical maxima as Isabel made landfall northeast of Beaufort, NC and moved inland.

Station time series plots of the observed water levels and predicted tides (referenced to MLLW) for the period 16-21 September are located in Appendix II. Information on the maximum observed water levels during the period of 18-19 September are found in **Tables 3-1** (meters) and **3-2** (feet) which includes the following: the date, time, and heights of the maximum observed water level above Mean Lower Low Water (MLLW) and Mean Higher High Water (MHHW), the Great Diurnal Range (GT), and the date and heights of the maximum historical water level. Elevations relative to the North American Vertical Datum of 1988 (NAVD 88) and the National Geodetic Vertical Datum of 1929 (NGVD 29) can be found in Chapter 4.

Stations of the upper Chesapeake Bay region recorded the highest maximum observed elevations relative to MHHW (**Table 3-1**) with the highest being 2.169 meters at Washington, DC on 19 September at 0842 GMT (0442 EDT). This elevation did not exceed the 2.402 meter historical maximum for Washington, DC set during October 1942 when flooding occurred after a tropical storm moved through the region. Fourteen other stations, however, did have maximum observed elevations which exceeded historical observations. Most notable were Baltimore at 1.976 meters, Tolchester Beach at 1.884 meters, Annapolis at 1.757 meters and Chesapeake City at 1.665 meters.

Table 3-1. Maximum observed water levels for Hurricane Isabel compared with historical high water events (meters)

Station	Hurricane Isabel 2003			Great Diurnal Range (GT) m	Historical Maximum		
	Date & Time (GMT)	Above			Date (mo-day-yr)	Above	
		MLLW (m)	MHHW (m)			MLLW (m)	MHHW (m)
SANDY HOOK, NJ	09-18 18:06	1.719	0.126	1.593	09-12-60	3.074	1.482
ATLANTIC CITY, NJ	09-18 17:36	1.724	0.321	1.403	12-11-92	2.738	1.335
NEWBOLD, PA	09-19 12:30	3.402	0.830	2.572	03-21-03	3.231	0.659
BURLINGTON, NJ	09-19 12:06	3.216	0.834	2.382	03-21-03	3.065	0.683
TACONY-PALMYRA, NJ	09-19 12:06	3.007	0.822	2.146	01-03-03	2.817	0.670
PHILADELPHIA, PA	09-19 11:36	2.887	0.872	2.015	11-25-50	3.119	1.184
MARCUS HOOK, PA	09-19 09:54	2.756	0.920	1.836	01-03-03	2.451	0.615
DELAWARE CITY, DE	09-19 09:06	2.628	0.842	1.786	01-03-03	2.417	0.631
REEDY POINT, DE	09-19 09:12	2.640	0.860	1.779	10-25-80	2.707	0.927
SHIP JOHN SHOAL, NJ	09-19 07:48	2.447	0.568	1.880	01-03-03	2.620	0.741
BRANDYWINE SHOAL, DE	09-18 18:54	2.058	0.425	1.633	02-17-03	2.406	0.773
CAPE MAY, NJ	09-18 18:54	1.965	0.305	1.659	09-27-85	2.686	1.026
LEWES, DE	09-18 19:24	1.985	0.567	1.418	03-06-62	2.810	1.392
OCEAN CITY INLET, MD	09-18 19:36	1.338	0.562	0.775	02-05-98	1.865	1.089
WACHAPREAGUE, VA	09-18 20:42	2.559	1.184	1.376	02-05-98	2.720	1.345
CHESAPEAKE CITY, MD	09-19 13:12	2.670	1.665	1.005	09-06-79	2.036	1.031
BALTIMORE, MD	09-19 12:06	2.483	1.976	0.506	08-23-33	2.346	1.840
TOLCHESTER, MD	09-19 12:42	2.411	1.884	0.527	09-07-96	1.486	0.959
ANNAPOLIS, MD	09-19 11:42	2.195	1.757	0.438	08-23-33	1.884	1.446
CAMBRIDGE, MD	09-19 10:48	1.884	1.262	0.622	09-06-96	1.478	0.856
WASHINGTON, DC	09-19 08:42	3.135	2.169	0.965	10-17-42	3.368	2.402
LEWISETTA, VA	09-19 00:36	1.668	1.209	0.458	02-05-98	1.170	0.712
KIPTOPEKE, VA	09-18 19:54	1.986	1.089	0.896	03-08-62	2.156	1.260
CHESAPEAKE BBT, VA	09-18 18:18	2.297	1.413	0.885	02-05-98	2.006	1.122
SEWELLS POINT, VA	09-18 21:00	2.404	1.564	0.841	08-23-33	2.444	1.603
MONEY POINT, VA	09-18 19:54	2.539	1.560	0.979	02-05-98	2.194	1.215
DUCK, NC	09-18 16:06	2.383	1.259	1.124	08-30-99	2.110	0.986
OREGON INLET, NC	09-19 04:00	1.652	1.296	0.356	09-16-99	1.725	1.369
BEAUFORT, NC	09-18 18:42	1.754	0.676	1.079	09-16-99	1.915	0.836
WILMINGTON, NC	09-18 21:24	1.422	0.000	1.427	10-15-54	2.484	1.147

Table 3-2. Maximum observed water levels for Hurricane Isabel compared with historical high water events (feet)

Station	Hurricane Isabel 2003			Great Diurnal Range (GT) ft	Historical Maximum		
	Date & Time (GMT)	Above			Date (mo-day-yr)	Above	
		MLLW (ft)	MHHW (ft)			MLLW (ft)	MHHW (ft)
SANDY HOOK, NJ	09-18 18:06	5.64	0.41	5.23	09-12-60	10.08	4.86
ATLANTIC CITY, NJ	09-18 17:36	5.65	1.05	4.60	12-11-92	8.98	4.38
NEWBOLD, PA	09-19 12:30	11.16	2.72	8.44	03-21-03	10.60	2.16
BURLINGTON, NJ	09-19 12:06	10.55	2.74	7.81	03-21-03	10.05	2.24
TACONY-PALMYRA, NJ	09-19 12:06	9.86	2.70	7.04	01-03-03	9.24	2.20
PHILADELPHIA, PA	09-19 11:36	9.47	2.86	6.61	11-25-50	10.23	3.88
MARCUS HOOK, PA	09-19 09:54	9.04	3.02	6.02	01-03-03	8.04	2.02
DELAWARE CITY, DE	09-19 09:06	8.62	2.76	5.86	01-03-03	7.93	2.07
REEDY POINT, DE	09-19 09:12	10.01	2.82	5.84	10-25-80	8.88	3.04
SHIP JOHN SHOAL, NJ	09-19 07:48	8.03	1.86	6.17	01-03-03	8.59	2.43
BRANDYWINE SHOAL,	09-18 18:54	6.75	1.39	5.36	02-17-03	7.89	2.54
CAPE MAY, NJ	09-18 18:54	6.45	1.00	5.44	09-27-85	8.81	3.37
LEWES, DE	09-18 19:24	6.51	1.86	4.65	03-06-62	9.22	4.57
OCEAN CITY INLET, MD	09-18 19:36	4.39	1.84	2.54	02-05-98	6.12	3.57
WACHAPREAGUE, VA	09-18 20:42	8.39	3.88	4.51	02-05-98	8.92	4.41
CHESAPEAKE CITY, MD	09-19 13:12	8.76	5.46	3.30	09-06-79	6.68	3.38
BALTIMORE, MD	09-19 12:06	8.14	6.48	1.66	08-23-33	7.69	6.04
TOLCHESTER, MD	09-19 12:42	7.91	6.18	1.73	09-07-96	4.87	3.15
ANNAPOLIS, MD	09-19 11:42	7.20	5.76	1.44	08-23-33	6.18	4.74
CAMBRIDGE, MD	09-19 10:48	6.18	4.14	2.04	09-06-96	4.85	2.81
WASHINGTON, DC	09-19 08:42	10.28	7.11	3.17	10-17-42	11.05	7.88
LEWISETTA, VA	09-19 00:36	5.47	3.97	1.50	02-05-98	3.84	2.34
KIPTOPEKE, VA	09-18 19:54	6.51	3.57	2.94	03-08-62	7.07	4.13
CHESAPEAKE BBT, VA	09-18 18:18	7.53	4.63	2.90	02-05-98	6.58	3.68
SEWELLS POINT, VA	09-18 21:00	7.89	5.13	2.76	08-23-33	8.02	5.26
MONEY POINT, VA	09-18 19:54	8.33	5.12	3.21	02-05-98	7.20	3.99
DUCK, NC	09-18 16:06	7.82	4.13	3.69	08-30-99	6.92	3.23
OREGON INLET, NC	09-19 04:00	5.42	4.25	1.17	09-16-99	5.66	4.49
BEAUFORT, NC	09-18 18:42	5.75	2.22	3.54	09-16-99	6.28	2.74
WILMINGTON, NC	09-18 21:24	4.66	-0.02	4.68	10-15-54	8.15	3.47

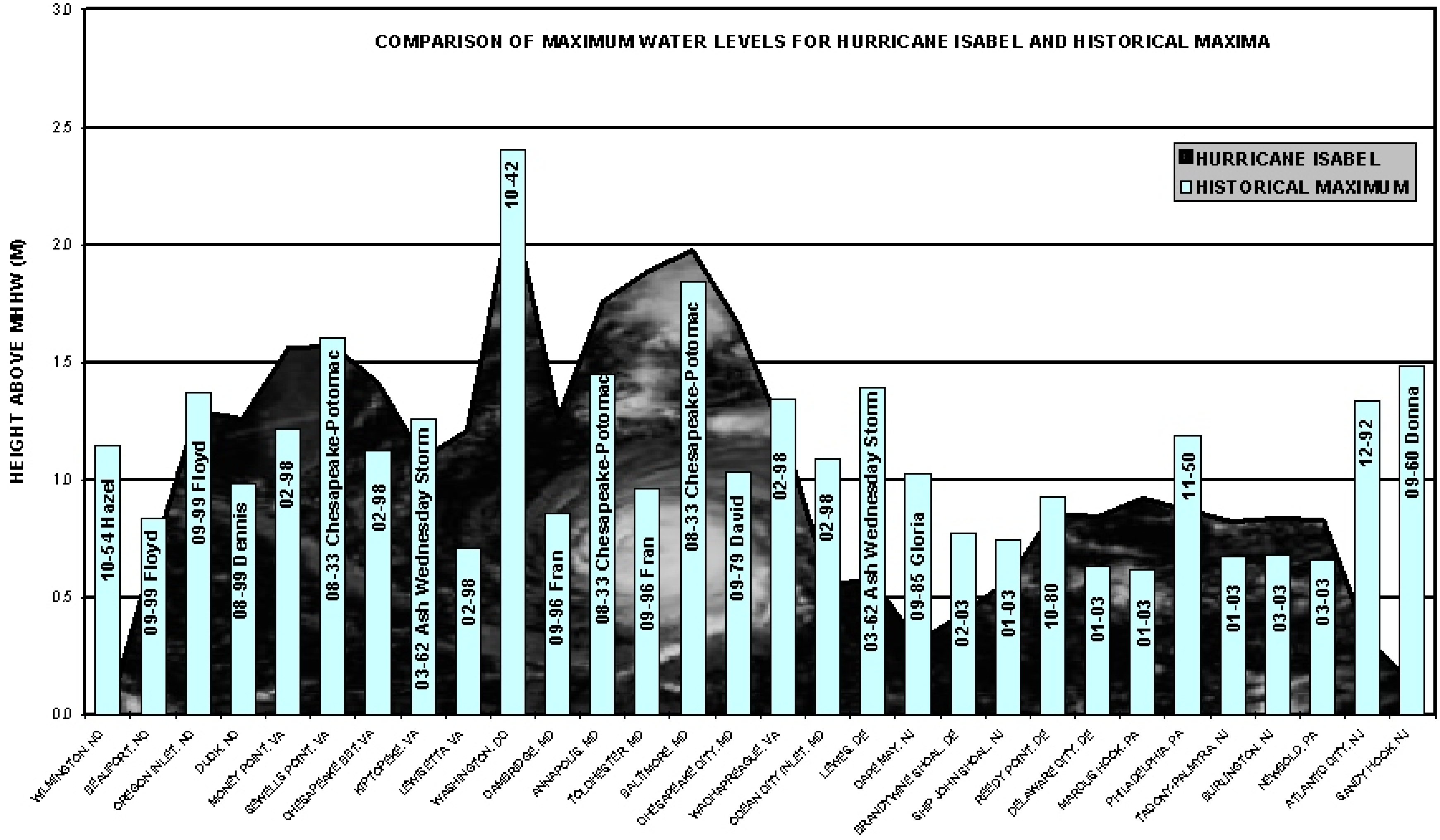


Figure 3-2. Comparison of historical maximum elevations relative to MHHW to the maximum observed elevations during Hurricane Isabel - 18-19 September, 2003. Month and year of historical maximum elevations are indicated.

Table 3-3 lists the six NWLON stations, which have longer data records than PORTS® stations, that produced a maximum observed elevation greater than the historical record at the station. At Baltimore and Annapolis, MD the historical records from the Chesapeake-Potomac hurricane in August 1933 were exceeded by 0.137 meters and 0.311 meters respectively. At Cambridge, MD the previous record from Hurricane Fran in September 1996 was exceeded by 0.406 meters. At Lewisetta, VA and CBBT, the previous records from a February 1998 storm were exceeded by 0.498 meters and 0.291 meters respectively. Finally, at Duck, NC the previous record from Hurricane Dennis in August 1999 was exceeded by 0.273 meters.

Table 3-3. NWLON stations with new maximum observed water levels

Station	Date of historical maximum	Years of data	Period of data	Increase in maximum (meters)
Baltimore, MD	08/33	101+	1902-present	0.137
Annapolis, MD	08/33	74+	1929-present	0.311
Cambridge, MD	09/96	39+	1943-1950 1971-present	0.406
Lewisetta, VA	02/98	29+	1974-present	0.498
Chesapeake BBT, VA	02/98	27+	1976-present	0.291
Duck, NC	08/99	24+	1979-present	0.273

The maximum elevations caused by Isabel approached within 0.3 meters of the maximum historical elevations at eight other locations within the Delaware Bay, Chesapeake Bay, or slightly south of Chesapeake Bay. At Beaufort, NC the NWLON station closest to Isabel's landfall (with the exception of Cape Hatteras which was destroyed), failed to exceed the historical maximum by 0.161 meters. This was set by Hurricane Floyd in September 1999, as it made landfall near Wilmington as a Category 2 hurricane (**Figure 3-2**). However, Isabel did surpass, by 0.273 meters, the level reached in August 1999 when Hurricane / Tropical Storm Dennis made landfall near Beaufort, NC.

The time series presented in Appendix II illustrate a variety of localized responses to the storm. First, it is interesting to note that although Hurricane Isabel made landfall on the Outer Banks region of North Carolina it had its greatest impacts on water levels in the upper Chesapeake Bay. Isabel's track after landfall took it inland towards Richmond, VA. However, with hurricane force winds extending up to 115 miles and tropical storm force winds extending up to 315 miles, Isabel's counter-clockwise rotation increased water flow into the more northerly and westerly tributaries of the Chesapeake Bay. Second, while Hurricane Isabel passed well inland from stations in the upper Delaware River, eight stations recorded elevated water levels as the storm was passing to the west of Washington, DC. Five of those stations exceeded historical maximum observed elevations. The Philadelphia, PA station, which has a much longer period of record than the other stations in the area, has a historical maximum observed water level of 1.184 meters above MHHW set during a November 1950 storm.

Storm Surge

Storm surge is defined by NOS as follows:

> The local change in the elevation of the ocean along a shore due to a storm. The storm surge is measured by subtracting the astronomic tidal elevation from the total elevation. It typically has a duration of a few hours. Since wind generated waves ride on top of the storm surge (and are not included in the definition), the total instantaneous elevation may greatly exceed the predicted storm surge plus astronomical tide. It is potentially catastrophic, especially on low lying coasts with gently sloping offshore topography. [Tide and Current Glossary, NOAA Center for Operational Oceanographic Products and Services 1999, seventh revision, p.24]

The primary physical components of storm surge are 1) water level elevation due to wind stress produced by a storm, mainly manifested as water pushed toward the shore, and 2) water level elevation due to diminished atmospheric pressure within the storm. Complex hydrodynamic phenomena such as tidal current interaction with bathymetry and topography, wave action, and seiche may also be present during a major coastal storm, and can be additional components of storm surge. The height of storm surge, for CO-OPS mission purposes, is computed simply as *the difference between the observed water level and the predicted tide level.*

The predicted tide is computed using standard NOS harmonic analysis and prediction algorithms. The timing of the maximum observed water level (discussed in the previous section) is dependent upon the interaction of the tide and the storm. The timing of the maximum storm surge does not necessarily coincide with the occurrence of the maximum observed water level. Information on the maximum storm surge calculated at each station is found in **Table 3-4** (meters) and **Table 3-5** (feet) which provide the following: the date and time of the maximum storm surge; the observed elevation of the water above MLLW; the predicted elevation of the water above MLLW; and the storm surge value (observed minus predicted elevations). Time series plots of the storm surge were constructed without any smoothing of the observed data prior to subtracting the predicted time series. Individual plots of the storm surge at each station are found in Appendix IV. Maximum storm surge values for all stations are displayed in **Figure 3-3.**

Table 3-4. Maximum storm surge for Hurricane Isabel 18-19 September, 2003 (meters)

Station	Date & Time (GMT)	Elevation Above MLLW(m)		Max.Storm Surge (m)
		Observed	Predicted	
SANDY HOOK, NJ	09-19-03 0230	1.273	0.604	0.669
ATLANTIC CITY, NJ	09-19-03 0012	1.161	0.406	0.755
NEWBOLD, PA	09-19-03 0936	2.602	0.741	1.861
BURLINGTON, NJ	09-19-03 0906	2.332	0.382	1.950
TACONY-PALMYRA, NJ	09-19-03 0830	2.180	0.428	1.752
PHILADELPHIA, PA	09-19-03 0806	2.172	0.519	1.653
MARCUS HOOK, PA	09-19-03 0630	2.035	0.322	1.713
DELAWARE CITY, DE	09-19-03 0512	1.996	0.344	1.652
REEDY POINT, DE	09-19-03 0512	1.929	0.405	1.524
SHIP JOHN SHOAL, NJ	09-19-03 0342	1.843	0.421	1.422
BRANDYWINE SHOAL, DE	09-19-03 0154	1.317	0.237	1.080
CAPE MAY, NJ	09-18-03 2348	1.422	0.471	0.951
LEWES, DE	09-18-03 2348	1.400	0.464	0.936
OCEAN CITY INLET, MD	09-19-03 0218	1.170	0.363	0.807
WACHAPREAGUE, VA	09-18-03 2124	2.450	0.915	1.535
CHESAPEAKE CITY, MD	09-19-03 1448	2.630	0.143	2.487
BALTIMORE, MD	09-19-03 1212	2.481	0.267	2.214
TOLCHESTER BEACH, MD	09-19-03 1248	2.410	0.295	2.115
ANNAPOLIS, MD	09-19-03 1142	2.195	0.264	1.931
CAMBRIDGE, MD	09-19-03 1018	1.874	0.297	1.577
WASHINGTON, DC	09-19-03 0930	3.090	0.620	2.470
LEWISETTA, VA	09-19-03 0324	1.544	0.333	1.211
KIPTOPEKE, VA	09-18-03 1954	1.986	0.791	1.195
CHESAPEAKE BBT, VA	09-18-03 1818	2.297	0.840	1.457
MONEY POINT, VA	09-18-03 2148	2.473	0.740	1.733
SEWELLS POINT, VA	09-18-03 2100	2.404	0.692	1.712
DUCK, NC	09-18-03 1606	2.383	0.952	1.431
OREGON INLET, NC	09-19-03 0236	1.606	0.167	1.439
BEAUFORT, NC	09-18-03 2042	1.606	0.740	0.866
WILMINGTON, NC	09-18-03 2330	1.153	0.680	0.473

Table 3-5. Maximum storm surge for Hurricane Isabel 18-19 September, 2003 (feet)

Station	Date & Time (GMT)	Elevation Above MLLW(ft)		Max. Storm Surge (ft)
		Observed	Predicted	
SANDY HOOK, NJ	09-19-03 0230	4.18	1.98	2.19
ATLANTIC CITY, NJ	09-19-03 0012	3.81	1.33	2.48
NEWBOLD, PA	09-19-03 0936	8.54	2.43	6.10
BURLINGTON, NJ	09-19-03 0906	7.65	1.25	6.40
TACONY-PALMYRA, NJ	09-19-03 0830	7.15	1.40	5.75
PHILADELPHIA, PA	09-19-03 0806	7.12	1.70	5.42
MARCUS HOOK, PA	09-19-03 0630	6.68	1.06	5.62
DELAWARE CITY, DE	09-19-03 0512	6.55	1.13	5.42
REEDY POINT, DE	09-19-03 0512	6.33	1.33	5.00
SHIP JOHN SHOAL, NJ	09-19-03 0342	6.05	1.38	4.66
BRANDYWINE SHOAL, DE	09-19-03 0154	4.32	0.78	3.54
CAPE MAY, NJ	09-18-03 2348	4.66	1.55	3.12
LEWES, DE	09-18-03 2348	4.59	1.52	3.07
OCEAN CITY INLET, MD	09-19-03 0218	3.84	1.19	2.65
WACHAPREAGUE, VA	09-18-03 2124	8.04	3.00	5.04
CHESAPEAKE CITY, MD	09-19-03 1448	8.63	0.47	8.16
BALTIMORE, MD	09-19-03 1212	8.14	0.88	7.26
TOLCHESTER BEACH, MD	09-19-03 1248	7.91	0.97	6.94
ANNAPOLIS, MD	09-19-03 1142	7.20	0.87	6.33
CAMBRIDGE, MD	09-19-03 1018	6.15	0.97	5.17
WASHINGTON, DC	09-19-03 0930	10.14	2.03	8.10
LEWISETTA, VA	09-19-03 0324	5.06	1.09	3.97
KIPTOPEKE, VA	09-18-03 1954	6.51	2.59	3.92
CHESAPEAKE BBT, VA	09-18-03 1818	7.53	2.76	4.78
MONEY POINT, VA	09-18-03 2148	8.11	2.43	5.68
DUCK, NC	09-18-03 16:06	7.82	3.12	4.70
SEWELLS POINT, VA	09-18-03 2100	7.89	2.27	5.62
OREGON INLET, NC	09-19-03 0236	5.27	0.55	4.72
BEAUFORT, NC	09-18-03 2042	5.27	2.43	2.84
WILMINGTON, NC	09-18-03 2330	3.78	2.23	1.55

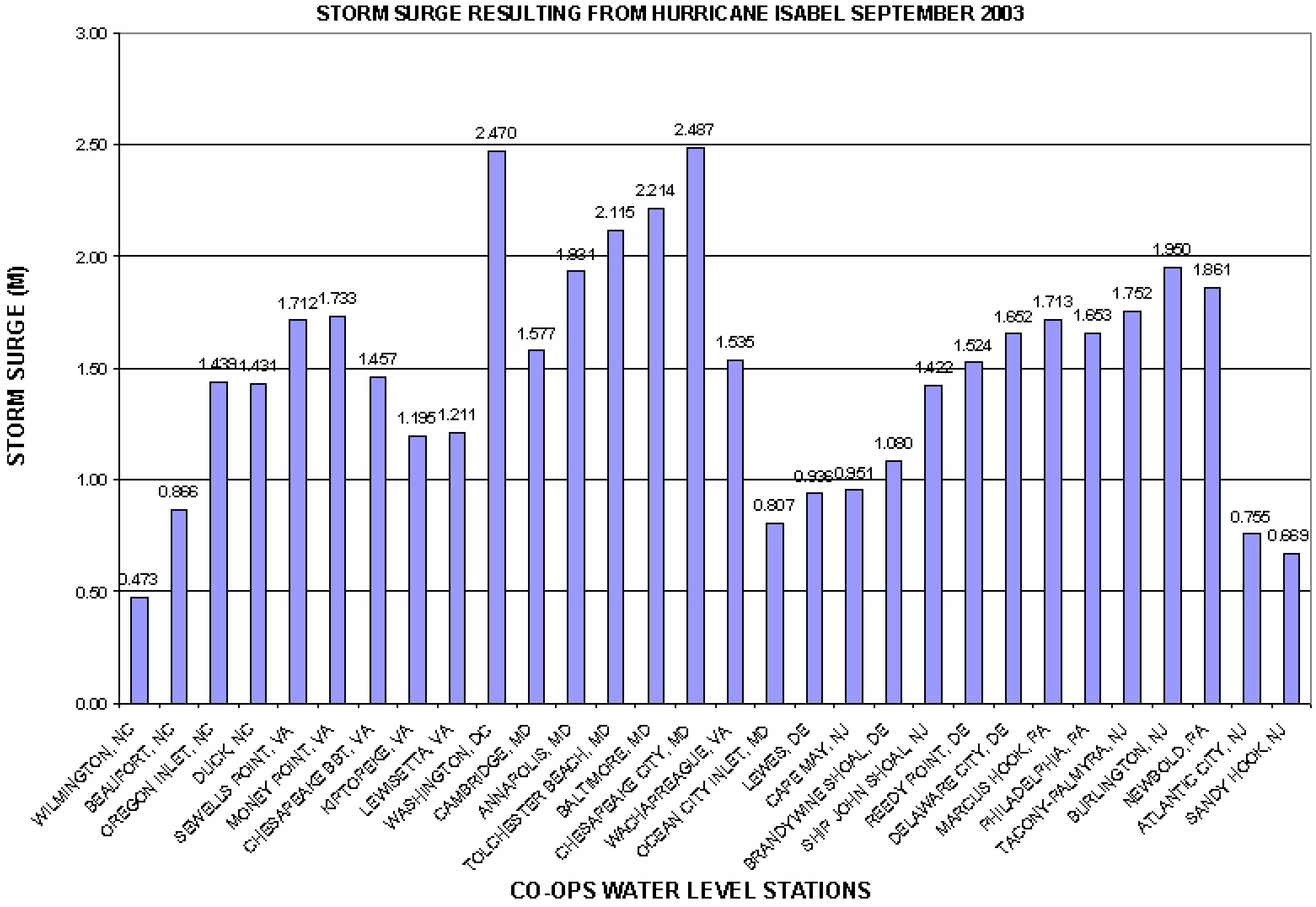


Figure 3-3. Maximum storm surge at CO-OPS water level stations during Hurricane Isabel, 18-19 September, 2003.

The largest storm surge occurred at Chesapeake City, MD (**Figure 3-3**). The calculated surge was 2.487 meters on 19 September at 1448 GMT (1048 EDT). Storm surge values greater than two meters were also calculated for Washington, DC (2.470 m), Baltimore, MD (2.214 m) and Tolchester Beach, MD (2.115 m). Due to the magnitude of the storm, surge values greater than one meter were also calculated for stations in the Delaware River. The greatest storm surge in that location was at Burlington, NJ with a surge of 1.950 meters on 19 September at 0906 GMT (0506 EDT). Eight other Delaware River / Bay water level stations had surge values greater than one meter decreasing from 1.861 meters at Newbold, PA north of Philadelphia, PA to 1.080 meters at Brandywine Shoal Light near the entrance of the Delaware Bay.

Storm surge values near the entrance of the Chesapeake Bay and farther south at Isabel's landfall ,between Cape Hatteras, NC and Beaufort, NC were generally less than those in the upper Chesapeake Bay. The exception to this was seen at Money Point, VA and Sewells Point, VA, which had storm surge values of 1.733 meters and 1.712, meters respectively. The remaining surge elevations ranged from 1.457 meters at CBBT, VA to 0.473 meters at Wilmington, NC. The storm surge values north of Isabel's landfall were similar at Duck, NC (1.431 m), and Oregon Inlet, NC (1.439 m). Surge values were under one meter south of Isabel's landfall at both Beaufort, NC and Wilmington, NC.

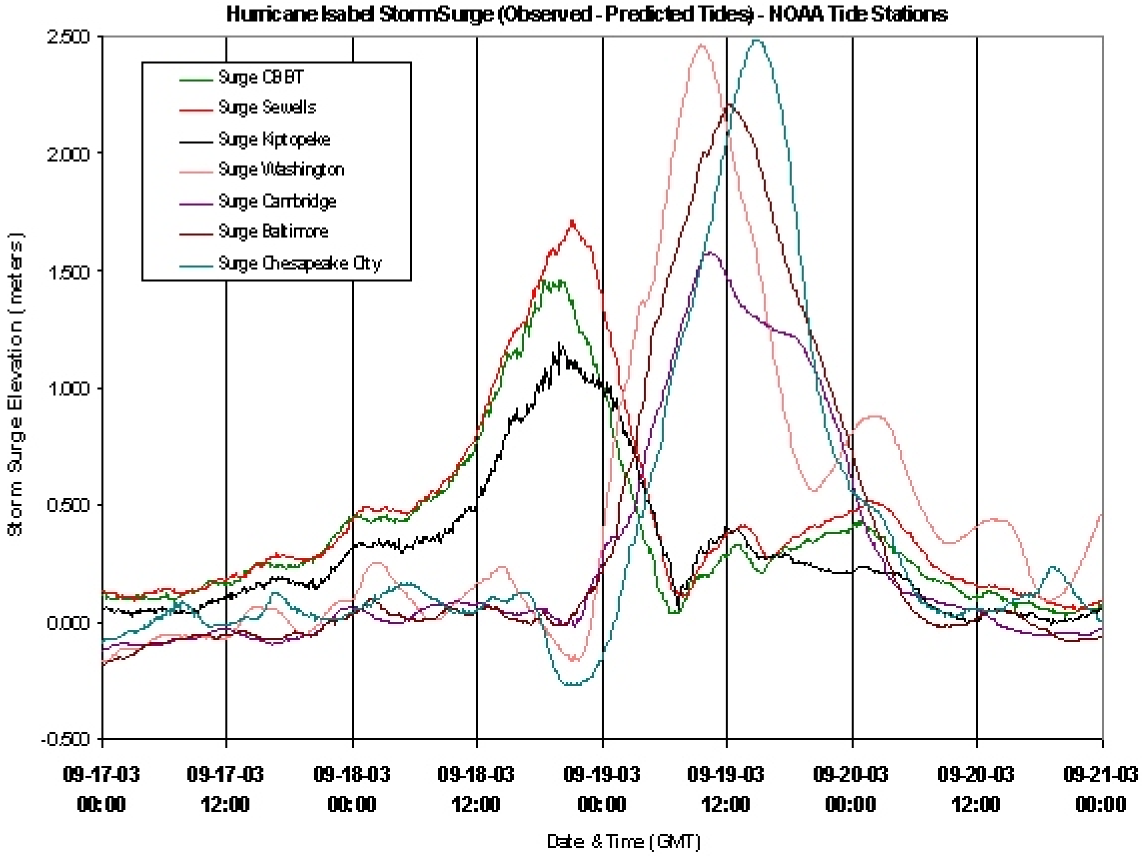


Figure 3-4. Storm surge comparison for selected CO-OPS water level stations during Hurricane Isabel, 17-21 September, 2003.

Storm surge from Hurricane Isabel began significantly impacting CO-OPS water level stations early on 18 September. The selected stations shown in **Figure 3-4** demonstrate that surge levels were reaching the maximum in the lower Chesapeake Bay just before 2400 GMT and rapidly dropped in the morning hours of 19 September. Surge levels had largely returned to normal in the lower Chesapeake Bay as surge levels in the upper Chesapeake Bay were beginning to elevate. Washington, DC reached its peak surge 2 hours 45 minutes before Baltimore, MD and 5 hours 18 minutes before the peak surge at Chesapeake City, MD. The individual curves also show that the maximum heights were less, however, the durations of elevated water were greater in the lower Chesapeake Bay, mid Chesapeake Bay (as indicated by Cambridge) and at Baltimore, MD. However, the maximum heights were greater and the durations of elevated water were shorter at Washington, DC and Chesapeake City, MD, which are located near the upper reaches of the Potomac River and Chesapeake Bay, respectively.

Figures 3-5 through **3-8** are simultaneous plots of the storm surge for various geographical regions over a six-day time period centered around the time of the storm. All of the storm surge figures use the same vertical scale (in meters) so that the magnitude of the surge can be put into perspective between stations and regions.

The storm surge values associated with the lower Chesapeake Bay and Outer Banks tended to be variable and generally lower than those calculated for the upper Chesapeake Bay (**Figure 3-5)**. The storm surges in the lower bay were generally coincident with predicted high tides. Surges at Kiptopeke, VA and CBBT, VA at the entrance to the bay, were lower than surges at Sewells Point,VA and Money Point, VA located in the more restricted James and Elizabeth Rivers. The peak storm surge at Oregon Inlet, NC occurred about 10½ hours after the peak surge at Duck, NC, which can be attributed to the fact that the Duck station is located on the Atlantic Ocean and the Oregon Inlet station is located on Pamlico Sound. The Cape Hatteras water level station just north of Isabel's landfall was damaged and did not record water levels after 18 September, at 1430 GMT (1030 EDT).

The greatest storm surge values occurred in the upper Chesapeake Bay (**Figure 3-6.)** These stations were typically located at the headwaters of larger rivers or bays where persistent winds from the storm pushed water into enclosed areas and held it there through a complete tidal cycle. Therefore, the water level remained unusually high during the time of the predicted low tide. Most notable was Chesapeake City, MD, which had the greatest storm surge value of any station during the storm. Washington, DC also recorded a near-record high surge that resulted from a combination of the storm center proximity and water being pushed up the narrowing Potomac River from counter-clockwise storm winds.

The seven storm surge plots from Sandy Hook, NJ to Ocean City Inlet, MD represent the area with the lowest surge values (**Figure 3-7).**The stations located in this region did record a brief elevation in water level lasting the duration of one tidal cycle. However, their distance northeast from the hurricane's center and the short duration of elevated water resulted in lower storm surge values. The exception to this was seen at Ship John Shoal. This station is sufficiently near the back of the Delaware Bay that the slightly higher surge at this station was in part due to the effect of water piling up in the narrowing Delaware Bay.

Storm surge plots covering the area along the Delaware River are shown in **Figure 3-8.** Although these stations are also located north and east of the track of the storm, surge values tended to be high in this region. This is representative of water piling up in the Delaware Bay and River and being held there through a complete tidal cycle. This combination of factors resulted in surge values that were higher than those on the coast or near the entrance to the Delaware Bay.

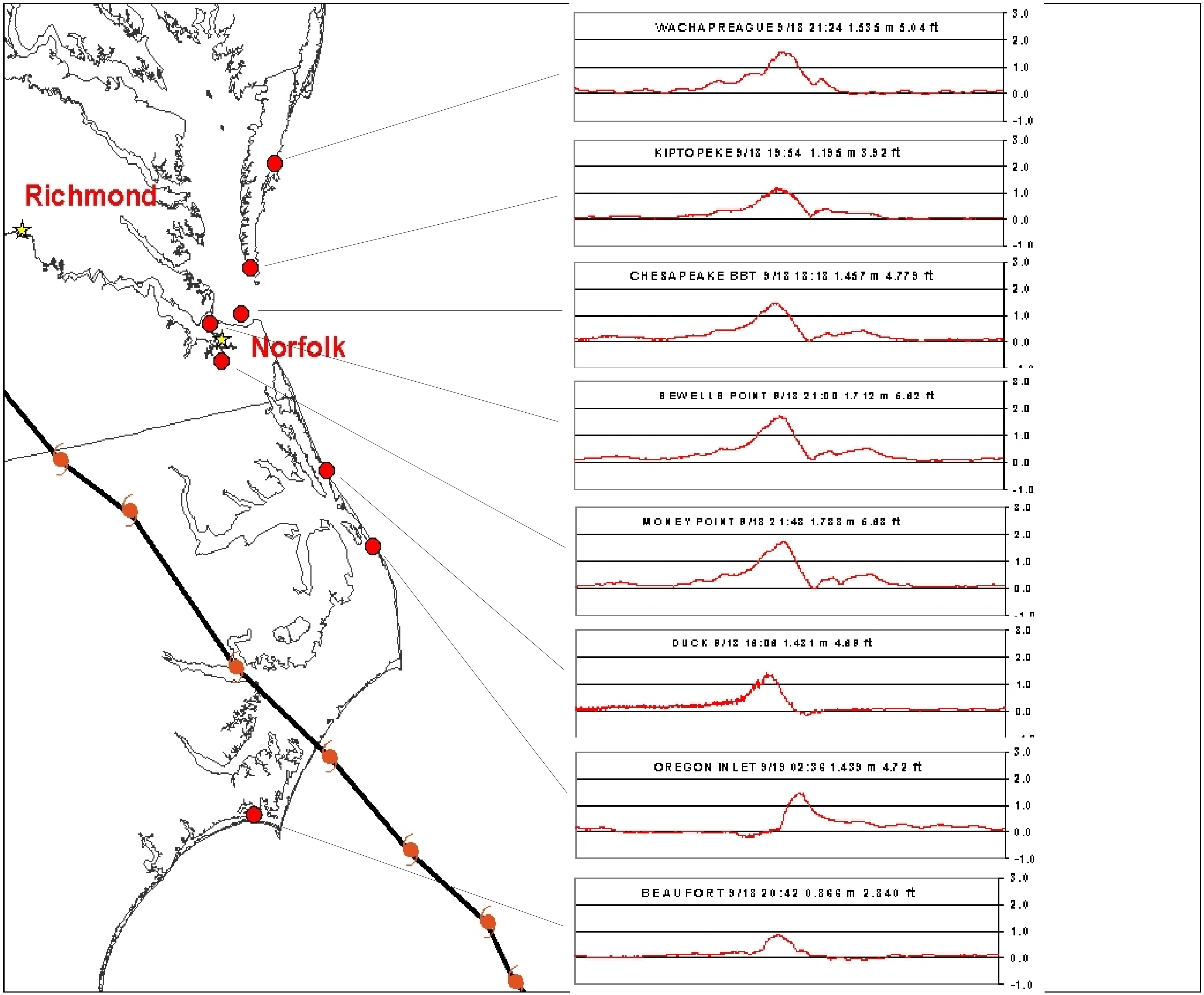


Figure 3-5. Hurricane Isabel storm surge comparison for stations in North Carolina and Virginia.

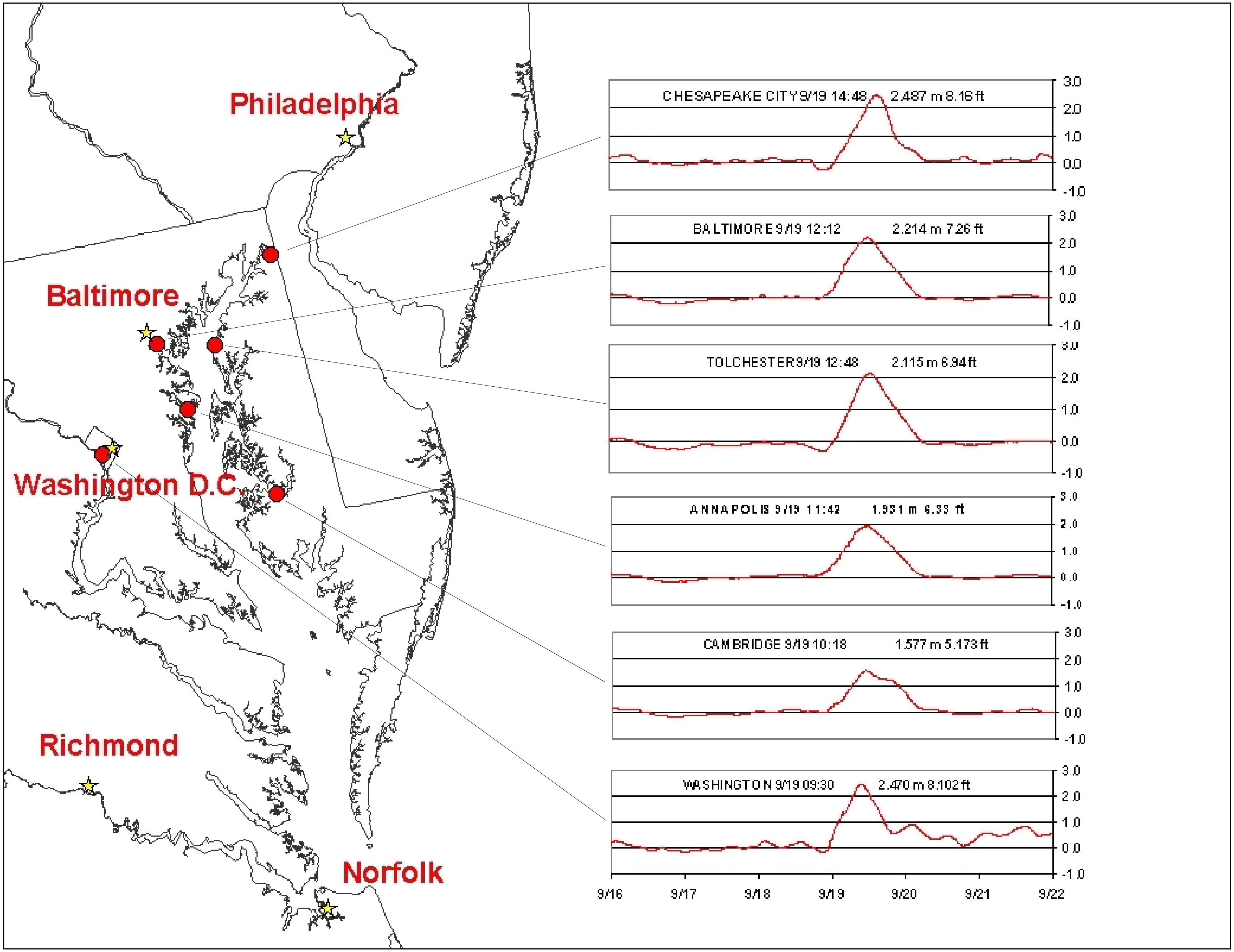


Figure 3-6. Hurricane Isabel storm surge comparison for stations in the upper Chesapeake Bay and the Potomac River.

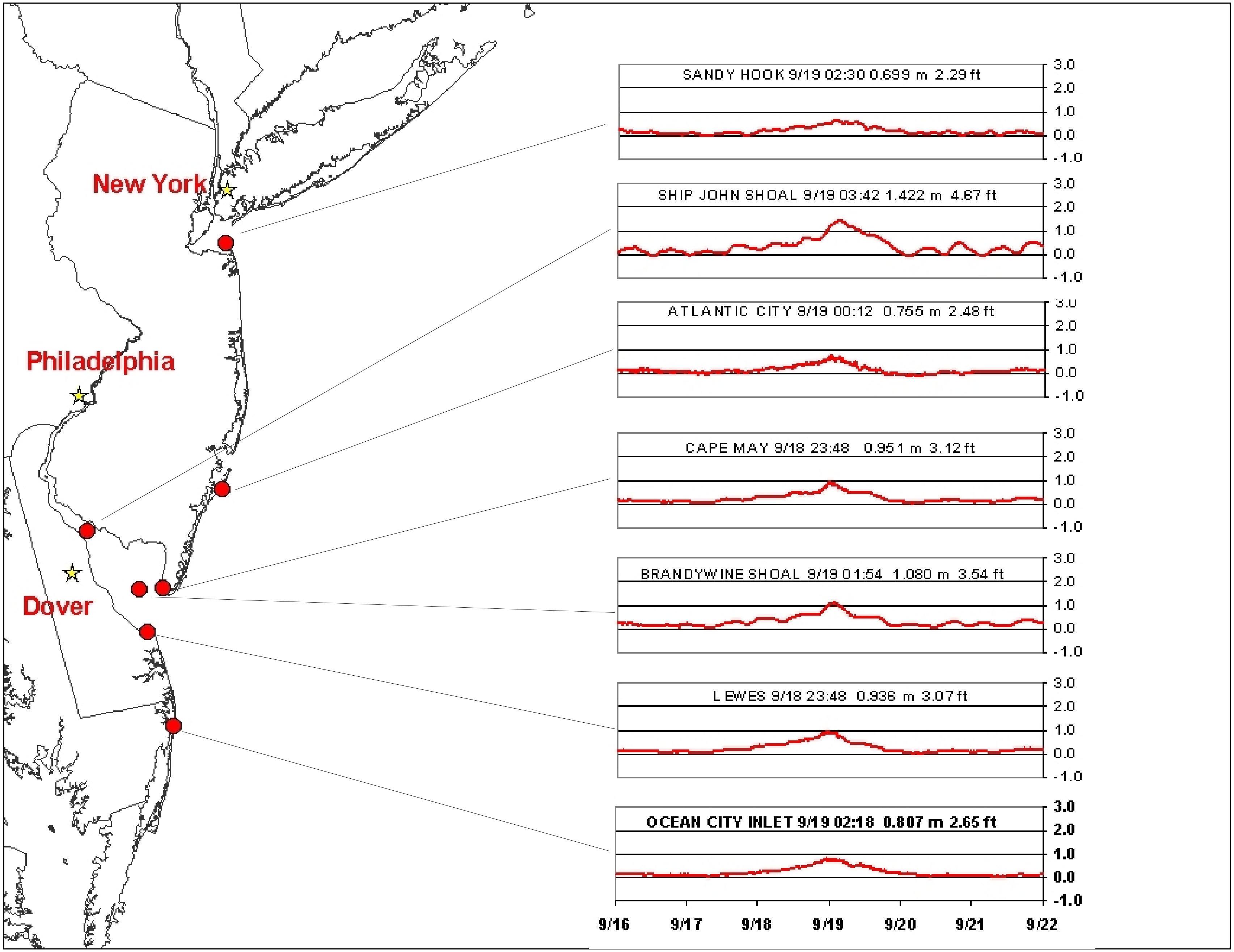


Figure 3-7. Hurricane Isabel storm surge comparison for stations on the Atlantic coast and the Delaware Bay.

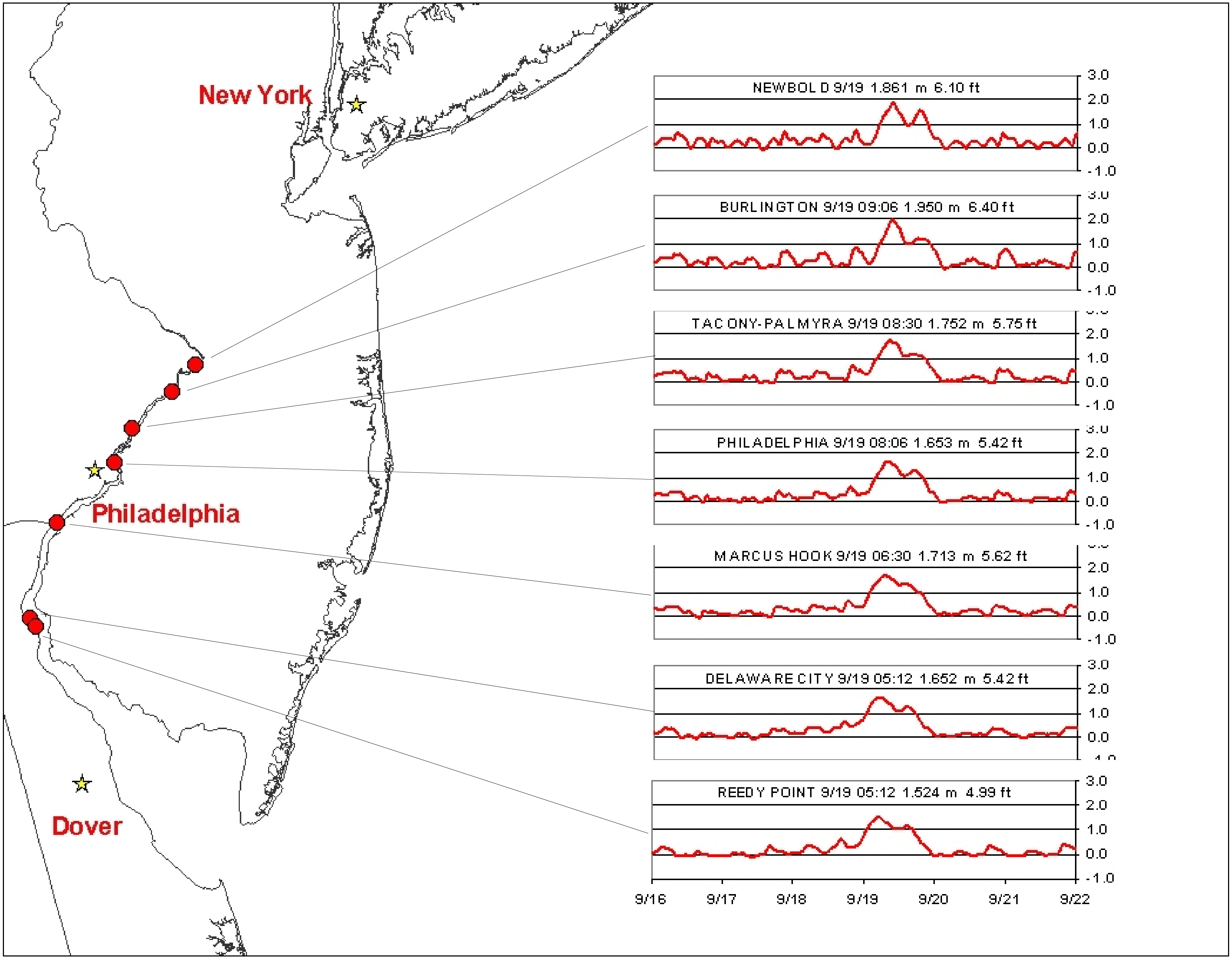


Figure 3-8. Hurricane Isabel storm surge comparison for stations in the Delaware River.

Effect of the timing of storm surge on maximum observed water level

Although there is a general correlation between the time of the maximum storm surge and the time of the hurricane's passage, many factors influence the time, height and duration of the surge. The location of the station with respect to the track of the storm, the local orientation of the coastline with respect to the direction of prevailing winds, and the storm's strength and speed at the time of passage all contribute to the height and timing of the storm surge. The storm surge also interacts with the predicted tide to produce a maximum observed water level which may or may not coincide with the peak storm surge.

Figure 3-9 shows the timing of the maximum observed water levels and the maximum storm surges for the water level stations. The figure shows the progression of the effects of the hurricane over the 23-hour period between the earliest peak storm surge at Duck, NC and the latest peak storm surge at Chesapeake City, MD. The peak storm surge reached CBBT, VA at the entrance to the Chesapeake Bay, about 2 hours after it peaked at Duck, NC and it reached Lewes, DE at the entrance to the Delaware Bay, about 7½ hours after peaking at Duck, NC. The peak storm surges reached stations in the bays and rivers much later. The peak surge hit Oregon Inlet, NC 10½ hours after it peaked at Duck, NC. The peak storm surge reached Washington, DC about 15 hours after it peaked at CBBT, VA and reached Chesapeake City, MD 20½ hours after peaking at CBBT, VA. In the upper Delaware River, the peak storm surge reached Newbold, PA about 10 hours after peaking at Lewes, DE but about 5 hours before the peak at Chesapeake City, MD.

Figure 3-9 also indicates how closely the highest observed water level coincided with the peak storm surge. For all points south of Wachapreage on the Atlantic coast and all points in Chesapeake Bay, the highest observed water level was nearly coincident with the peak storm surge. At five locations (Annapolis, MD; Kiptopeke, VA; CBBT, VA; Sewells Point, VA and Duck, NC), the timing of the maximum observed water levels and the maximum storm surge was identical. For all points north of Wachapreage, VA including the Delaware Bay and River, the highest observed water levels occurred more than 3 hours before or after the peak storm surge.

Differences in the timing of the highest observed water level and the peak storm surge are the result of the interaction of the storm surge with the tide. **Table 3-6** gives the time lag of the peak storm surge relative to the higher high tide of 18-19 September. If the peak storm surge occurs 3.1 hours (one quarter of a tidal cycle) before or after a predicted high tide, the tide was adding on to the surge; otherwise, the tide was working against the surge.

Table 3-6 shows that at only six stations the peak storm surge arrived near high tide. These stations were located along the North Carolina coast or at the entrance to the Chesapeake Bay (Beaufort, Duck, Sewells Point, Money Point, CBBT, and Kiptopeake). At the other stations, the peak storm surge was arriving closer to low tide. At stations with a great tide range, such as those on the Delaware Bay and River and along the coast north of Wachapreage, resulted in large timing differences between the peak storm surge and the highest observed water level (**Figure 3-9**). In the upper Chesapeake Bay, the storm surge overwhelmed the weak tides, resulting in very small timing differences between peak storm surge and highest observed water level.

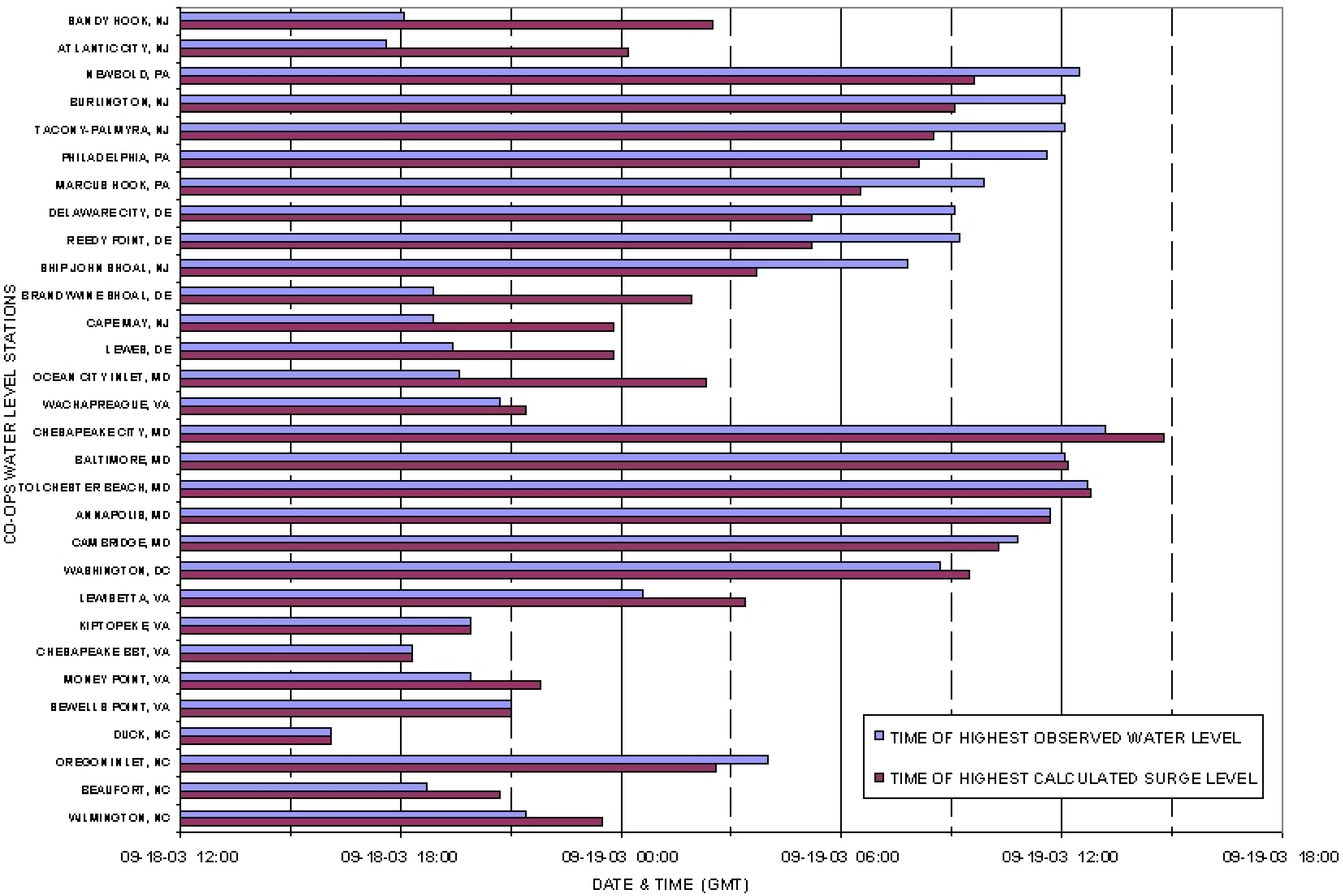


Figure 3-9. Comparison of the timing of the highest observed water levels with the highest calculated storm surge during Hurricane Isabel 18-19 September, 2003.

Table 3-6. Time lag of the peak storm surge relative to predicted high tide during Hurricane Isabel September 2003

STATION	TIME OF PEAK OBSERVED SURGE (GMT)	TIME OF PREDICTED HIGH TIDE (GMT)	TIME LAG
SANDY HOOK, NJ	09-19 02:30	09-18 17:52	8 hours 38 minutes after
ATLANTIC CITY, NJ	09-19 00:12	09-18 17:31	6 hours 41 minutes after
NEWBOLD, PA	09-19 09:36	09-19 01:32	8 hours 4 minutes after
BURLINGTON, NJ	09-19 09:06	09-19 01:12	7 hours 54 minutes after
TACONY-PALMYRA, NJ	09-19 08:30	09-19 01:20	7 hours 10 minutes after
PHILADELPHIA, PA	09-19 08:06	09-19 00:31	7 hours 35 minutes after
MARCUS HOOK, PA	09-19 06:30	09-18 23:02	7 hours 28 minutes after
DELAWARE CITY, DE	09-19 05:12	09-18 21:31	7 hours 41 minutes after
REEDY POINT, DE	09-19 05:12	09-18 21:28	7 hours 44 minutes after
SHIP JOHN SHOAL, NJ	09-19 03:42	09-18 19:59	7 hours 43 minutes after
BRANDYWINE SHOAL, DE	09-19 01:54	09-18 18:44	7 hours 10 minutes after
CAPE MAY, NJ	09-18 23:48	09-18 18:35	5 hours 13 minutes after
LEWES, DE	09-18 23:48	09-18 18:44	5 hours 4 minutes after
OCEAN CITY INLET, MD	09-19 02:18	09-18 17:39	8 hours 39 minutes after
WACHAPREAGUE, VA	09-18 21:24	09-18 18:09	3 hours 15 minutes after
CHESAPEAKE CITY, MD	09-19 14:48	09-19 09:35	5 hours 13 minutes after
BALTIMORE, MD	09-19 12:12	09-19 05:27	6 hours 45 minutes after
TOLCHESTER BEACH, MD	09-19 12:48	09-19 05:55	6 hours 53 minutes after
ANNAPOLIS, MD	09-19 11:42	09-19 03:49	7 hours 53 minutes after
CAMBRIDGE, MD	09-19 10:18	09-19 02:43	7 hours 35 minutes after
WASHINGTON, DC	09-19 09:30	09-19 06:18	3 hours 12 minutes after
LEWISETTA, VA	09-19 03:24	09-18 23:56	3 hours 28 minutes after
KIPTOPEKE, VA	09-18 19:54	09-18 18:25	1 hour 29 minutes after
CHESAPEAKE BBT, VA	09-18 18:18	09-18 18:08	10 minutes after
MONEY POINT, VA	09-18 21:48	09-18 19:17	2 hours 31 minutes after
SEWELLS POINT, VA	09-18 21:00	09-18 19:10	1 hour 50 minutes after
DUCK, NC	09-18 16:06	09-18 17:27	1 hour 21 minutes before
OREGON INLET, NC	09-19 02:36	09-18 17:58	8 hours 38 minutes after
BEAUFORT, NC	09-18 20:42	09-18 18:13	2 hours 29 minutes after
WILMINGTON, NC	09-18 23:30	09-18 19:55	3 hours 35 minutes after

Shading indicates that peak storm surge occurred within 3.1 hours (a quarter of a tidal cycle) of predicted high tide.

Great Lakes Observations

A complex oscillation and surge event occurred on Lake Erie driven by winds associated with the Hurricane Isabel system. The rise was uneven across the lake, and a wind-driven oscillation formed between Toledo, OH and Buffalo, NY. A water level plot of the Lake Erie oscillation and surge event is shown in **Figure 3-10**. Wind speed, gust, and direction plots from MET-instrumented water level stations at Buffalo, NY (Lake Erie) and Oswego, NY (Lake Ontario) are shown in **Figures 3-11** and **3-12.**

Major oscillations occurred between noon on 17 September and about 2300 EST (18 UTC) on 19 September. As the storm approached Lake Erie, the water levels rose at stations near the west end of the lake (Toledo), and fell at stations near the east end of the lake (Buffalo). After the storm center crossed the lake around 1200 EST on 19 September, the wind-driven tilt of the lake surface reversed, with water levels near the east end (Buffalo) reaching their peaks and water level near the west end (Toledo) reaching their lowest points. The maximum water level difference between Buffalo and Toledo was about 1.6 meters (5.3 feet) at about 1700 EST on 19 September. Water levels on the lake abruptly returned to near normal on 20 September, as seiche components seemed to cancel each other out. The usual period of a single-node seiche on Lake Erie is approximately 14 hours.

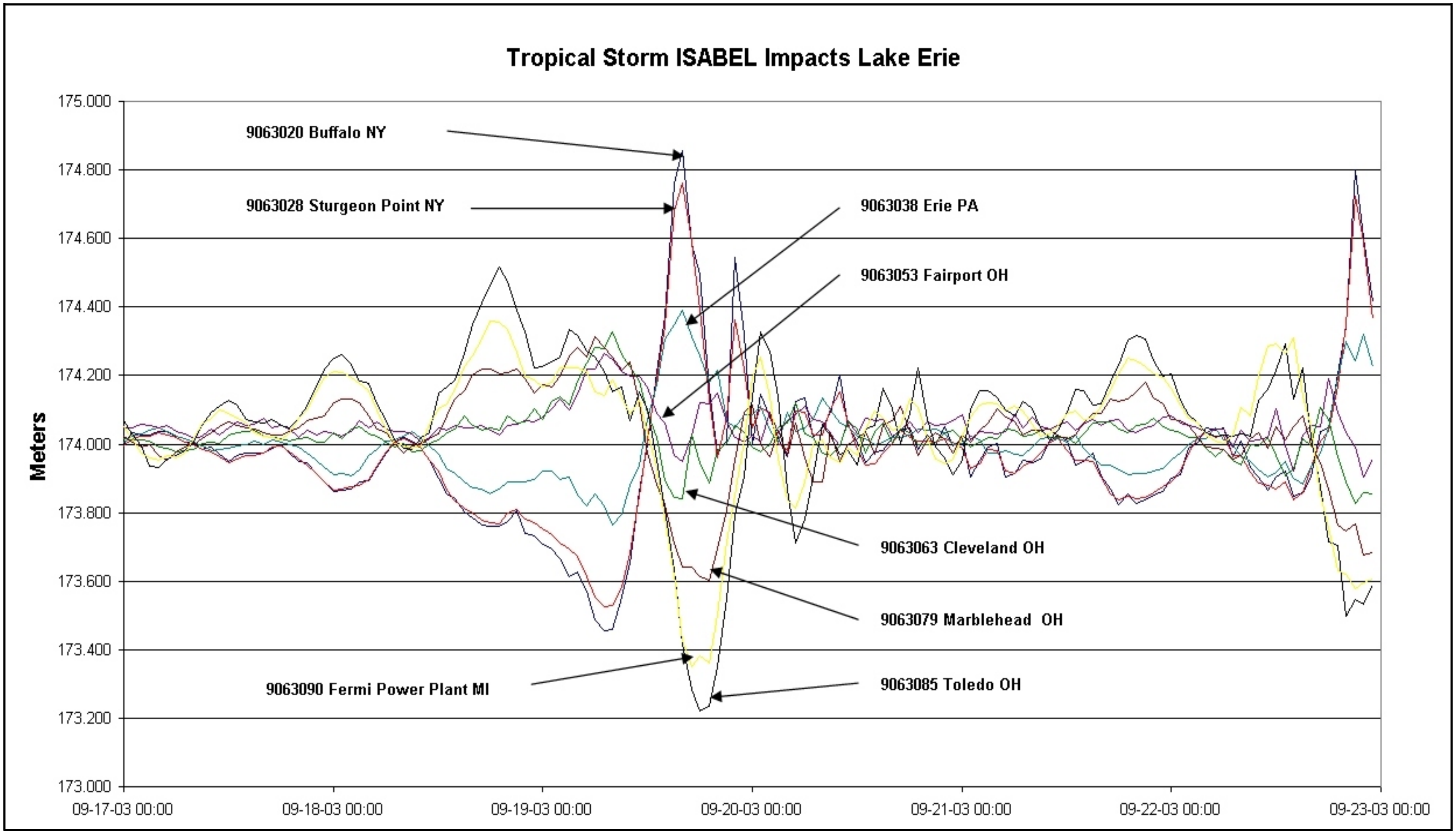


Figure 3-10. Oscillation and storm surge on Lake Erie 17-22 September 2003 (Times in EST).

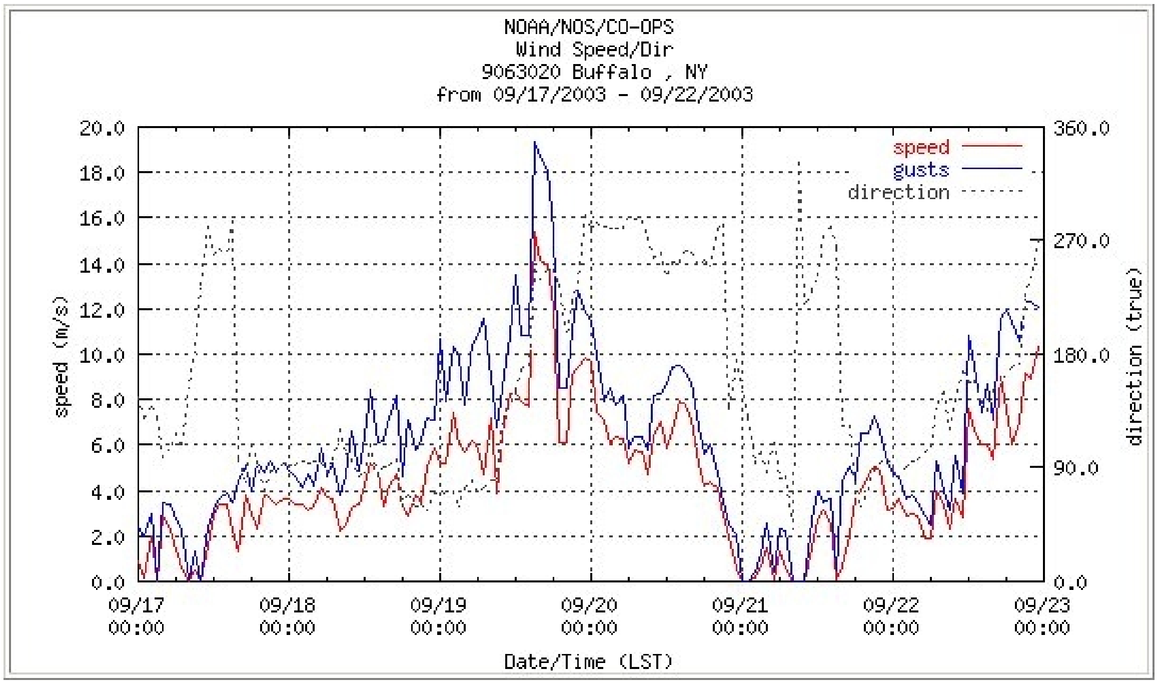


Figure 3-11 Wind speed, gust, and direction at Buffalo NY, Lake Erie, 17-22 Sept 2003

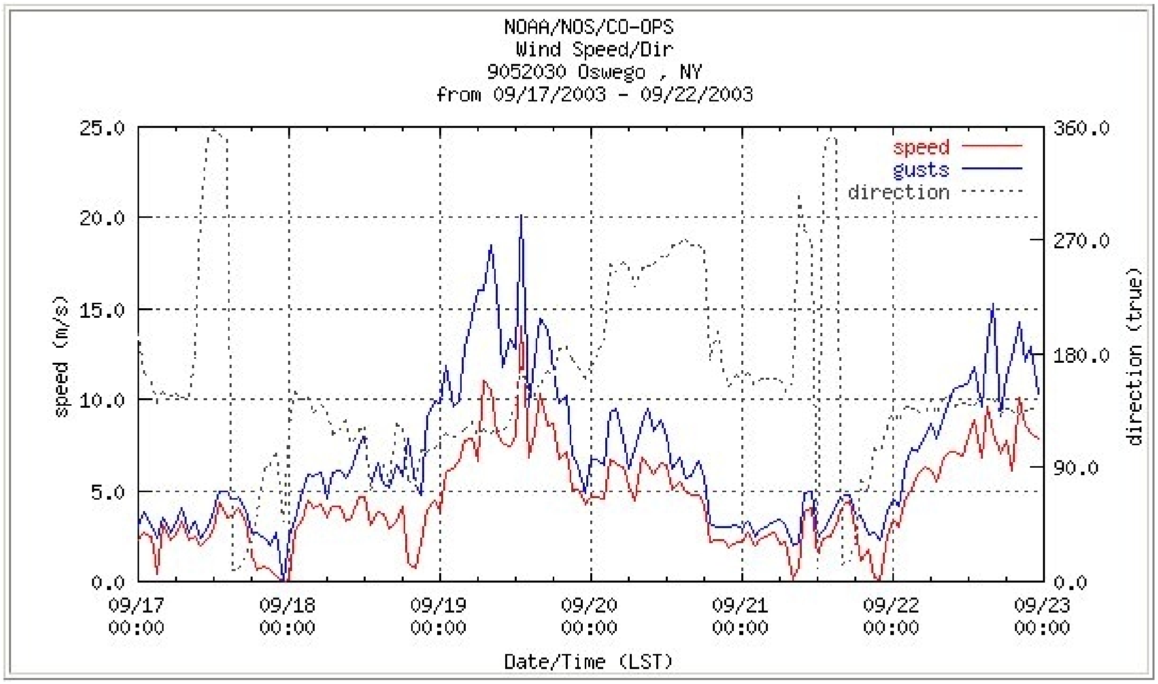


Figure 3-12. Wind speed, gust, and direction at Oswego NY, Lake Ontario, 17-22 Sept 2003

Chapter 4: Geodetic Observations and Relationships

Vertical Datums: Geodetic and Tidal

Geodetic datums define the reference systems that describe the size and shape of the Earth and the orientation of the coordinate systems used to map the Earth. The vertical datums discussed in this section define the height of surfaces and are the North American Vertical Datum of 1988 (NAVD 88) and the National Geodetic Vertical Datum of 1929 (NGVD 29). NAVD 88 is the vertical control datum established in 1991 by US - Canadian - Mexican leveling observations. It held fixed the height of the primary tidal bench mark, referenced to the new International Great Lakes Datum of 1985 local mean sea level at Father Point/Rimouski, Quebec, Canada. NGVD 29 originated from the 1973 renaming of the Sea Level Datum of 1929. The datum was defined by the observed heights of mean sea level at 26 tide stations and by the set of elevations of all bench marks totaling 106,724 km of leveling. Another major distinction between these two vertical geodetic datums is that NAVD 88 is decoupled from local Mean Sea Level (MSL) whereas NGVD 29 is based on the local MSL elevations However, since 1929 MSL has since changed considerably at these locations.

Vertical datums defined in terms of the phase of the tide are tidal datums. Tidal datums published by NOS / CO-OPS are used for determining mapping boundaries and estimating heights or depths for coastal and marine applications. They utilize a base elevation reference from which to reckon heights or depths. Tidal datums are local datums and should not be extended into areas that have differing hydrographic features without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks. A chart datum is the datum to which soundings on a NOAA hydrographic chart are referred. It corresponds to MLLW and is calculated from the arithmetic mean of the lower low water tidal heights observed over a 19-year National Tidal Datum Epoch (NTDE). Other datums similarly calculated and published by NOS / CO-OPS are MHHW, Mean High Water (MHW), and Mean Low Water (MLW).

The National Geodetic Survey (NGS) maintains the current national geodetic vertical datum, NAVD 88. CO-OPS publishes tidal bench mark information and the relationship between NAVD 88 and various water level/tidal datums. The relationships to NGVD 29 are not published due to the fact that NGS no longer supports this superseded datum. However, it may be estimated independently from specified tidal bench mark sheet links to the NGS data base. Tidal bench mark information, water level/tidal datums, and their relationship to geodetic vertical datums are available at the CO-OPS web site (http://www.tidesandcurrents.noaa.gov).

Information on the relationship between highest observed water levels during Hurricane Isabel, MHHW, NAVD 88 and NGVD 29 is presented in **Table 4-1** (meters) and **Table 4-2** (feet). The tables include the date and time of highest observed water levels above NAVD 88 and NGVD 29 and the tidal datum MHHW above NAVD 88 and NGVD 29 as a point of reference. NAVD 88 is above NGVD 29 throughout the area of consideration. Therefore, heights relative to NAVD 88 are always lower than heights relative to NGVD 29. These elevation differences are significant because

NAVD 88 and NGVD 29 are utilized as reference datums by the Federal Emergency Management Agency (FEMA) and scientists developing storm surge models.

Stations of the upper Chesapeake Bay recorded the highest maximum observed elevations relative to NAVD 88 and NGVD 29 (**Figure 4-1)**. The highest maximum observed elevation above NAVD 88 and NGVD 29 due to Hurricane Isabel was 2.710 meters and 2.947 meters respectively, occurring at Washington on 19 September at 0842 GMT (0442 EDT). Three other water level stations had observed water levels exceeding two meters above both NAVD 88 and NGVD 29. These stations were Baltimore (2.229 and 2.469 meters), Chesapeake City (2.170 and 2.408 meters), and Tolchester (2.138 and 2.381 meters). Three other stations, Annapolis, Sewells Point, and Money Point had elevations just under two meters above NAVD 88 and over two meters above NGVD 29. All of the Chesapeake Bay stations recorded elevations over one meter above MHHW which is generally two tenths to seven tenths of a meter above NAVD 88 and NGVD 29.

Figures 4-2 and **4-3** show geodetic relationships at CO-OPS water level stations located in Delaware Bay and coastal stations from Wilmington to Sandy Hook. **Figure 4-2** shows that there was a general increase in the elevations above NAVD 88 and NGVD29 from the mouth of the bay to Philadelphia. Although Lewes and Cape May only recorded elevations ranging from one to one and a half meters, Philadelphia recorded elevations of 1.927 and 2.243 meters above NAVD 88 and NGVD 29, respectively. None of the Delaware River / Bay stations recorded elevations over one meter above MHHW, which typically runs one meter above NAVD 88 and NGVD 29 in this region**.**

Along the coast from Wilmington to Sandy Hook (**Figure 4-3**), elevations tended to increase from Wilmington (0.689 and 0.993 meters) to the location of Hurricane Isabel's landfall south of the Cape Hatteras station which was destroyed by the storm. Oregon Inlet and Duck recorded elevations of (1.450 and 1.758 meters), and (1.716 and 2.010 meters) above NAVD 88 and NGVD 29, respectively. Farther north along the coast the elevations decreased as Isabel moved inland rapidly. Near Wilmington, where MHHW is close to one meter above NAVD 88 and NGVD 29, water levels did not exceed MHHW.

Table 4-1. Maximum observed water levels and MHHW relative to NGVD 29 and NAVD 88 during Hurricane Isabel September 2003 (meters)

STATION	DATE & TIME (GMT)	HIGHEST OBSERVED WATER LEVEL ABOVE NAVD 88 (m)	HIGHEST OBSERVED WATER LEVEL ABOVE NGVD 29 (m)	MHHW ABOVE NAVD 88 (m)	MHHW ABOVE NGVD 29 (m)
SANDY HOOK, NJ	09-18-03 1806	0.861	1.190	0.735	1.064
ATLANTIC CITY, NJ	09-18-03 1736	0.927	1.332	0.606	1.011
PHILADELPHIA, PA	09-19-03 1136	1.927	2.243	1.055	1.371
REEDY POINT, DE	09-19-03 0912	1.735	1.967	0.875	1.107
CAPE MAY, NJ	09-18-03 1854	1.045	1.449	0.740	1.144
LEWES, DE	09-18-03 1924	1.184	1.427	0.617	0.860
OCEAN CITY INLET, MD	09-18-03 1936	0.823	1.069	0.261	0.507
CHESAPEAKE CITY, MD	09-19-03 1312	2.170	2.408	0.505	0.743
BALTIMORE, MD	09-19-03 1206	2.229	2.469	0.252	0.492
TOLCHESTER, MD	09-19-03 1242	2.138	2.381	0.254	0.497
ANNAPOLIS, MD	09-19-03 1142	1.960	2.212	0.203	0.455
CAMBRIDGE, MD	09-19-03 1048	1.535	1.776	0.273	0.514
WASHINGTON, DC	09-19-03 0842	2.710	2.947	0.541	0.778
LEWISETTA, VA	09-19-03 0036	1.415	1.661	0.206	0.452
KIPTOPEKE, VA	09-18-03 1954	1.406	1.657	0.316	0.567
SEWELLS POINT, VA	09-18-03 2100	1.903	2.151	0.339	0.587
MONEY POINT, VA	09-18-03 1954	1.982	2.229	0.422	0.669
DUCK, NC	09-18-03 1606	1.716	2.010	0.457	0.751
OREGON INLET, NC	09-19-03 0400	1.450	1.758	0.154	0.462
BEAUFORT, NC	09-18-03 1842	1.121	1.414	0.445	0.738
WILMINGTON, NC	09-18-03 2124	0.689	0.993	0.694	0.998

Table 4-2.Maximum observed water levels and MHHW relative to NGVD 29 and NAVD 88 during Hurricane Isabel September 2003 (feet)

STATION	DATE & TIME (GMT)	HIGHEST OBSERVED WATER LEVEL ABOVE NAVD 88 (ft)	HIGHEST OBSERVED WATER LEVEL ABOVE NGVD 29 (ft)	MHHW ABOVE NAVD 88 (ft)	MHHW ABOVE NGVD 29 (ft)
SANDY HOOK, NJ	09-18-03 1806	2.82	3.90	2.41	3.49
ATLANTIC CITY, NJ	09-18-03 1736	3.04	4.37	1.99	3.32
PHILADELPHIA, PA	09-19-03 1136	6.32	7.36	3.46	4.50
REEDY POINT, DE	09-19-03 0912	5.69	6.45	2.87	3.63
CAPE MAY, NJ	09-18-03 1854	3.43	4.75	2.43	3.75
LEWES, DE	09-18-03 1924	3.88	4.68	2.02	2.82
OCEAN CITY INLET, MD	09-18-03 1936	2.70	3.51	0.86	1.66
CHESAPEAKE CITY, MD	09-19-03 1312	7.12	7.90	1.66	2.44
BALTIMORE, MD	09-19-03 1206	7.31	8.10	0.83	1.61
TOLCHESTER, MD	09-19-03 1242	7.01	7.81	0.83	1.63
ANNAPOLIS, MD	09-19-03 1142	6.43	7.26	0.67	1.49
CAMBRIDGE, MD	09-19-03 1048	5.03	5.82	0.90	1.69
WASHINGTON, DC	09-19-03 0842	8.89	9.67	1.77	2.55
LEWISETTA, VA	09-19-03 0036	4.64	5.45	0.68	1.48
KIPTOPEKE, VA	09-18-03 1954	4.61	5.43	1.04	1.86
SEWELLS POINT, VA	09-18-03 2100	6.24	7.06	1.11	1.93
MONEY POINT, VA	09-18-03 1954	6.50	7.31	1.38	2.19
DUCK, NC	09-18-03 1606	5.63	6.59	1.50	2.46
OREGON INLET, NC	09-19-03 0400	4.76	5.77	0.51	1.52
BEAUFORT, NC	09-18-03 1842	3.68	4.64	1.46	2.42
WILMINGTON, NC	09-18-03 2124	2.26	3.26	2.28	3.27

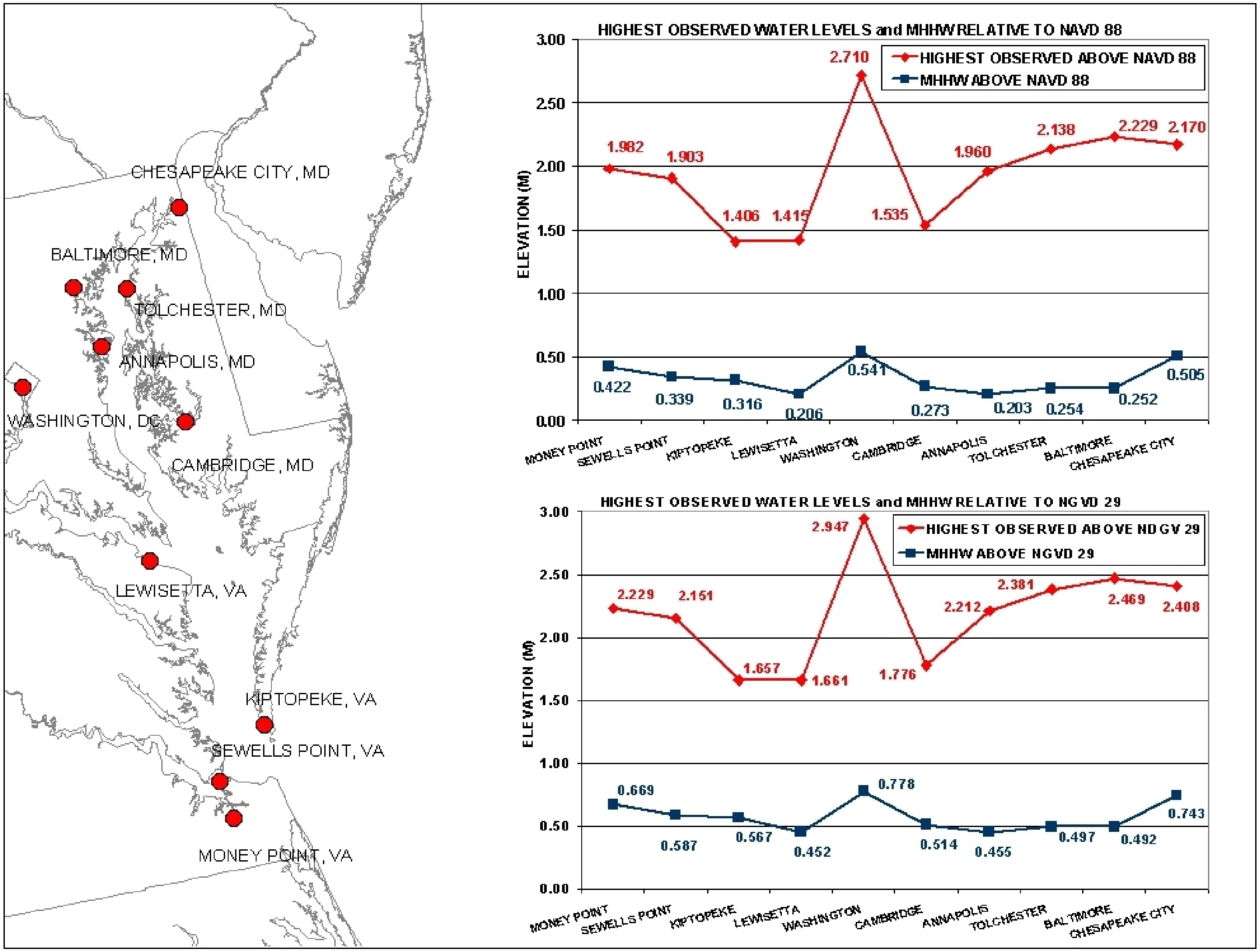


Figure 4-1. Highest observed water levels and MHHW relative to NAVD 88 and NGVD 29 for the Chesapeake Bay during Hurricane Isabel 18-19 September, 2003.

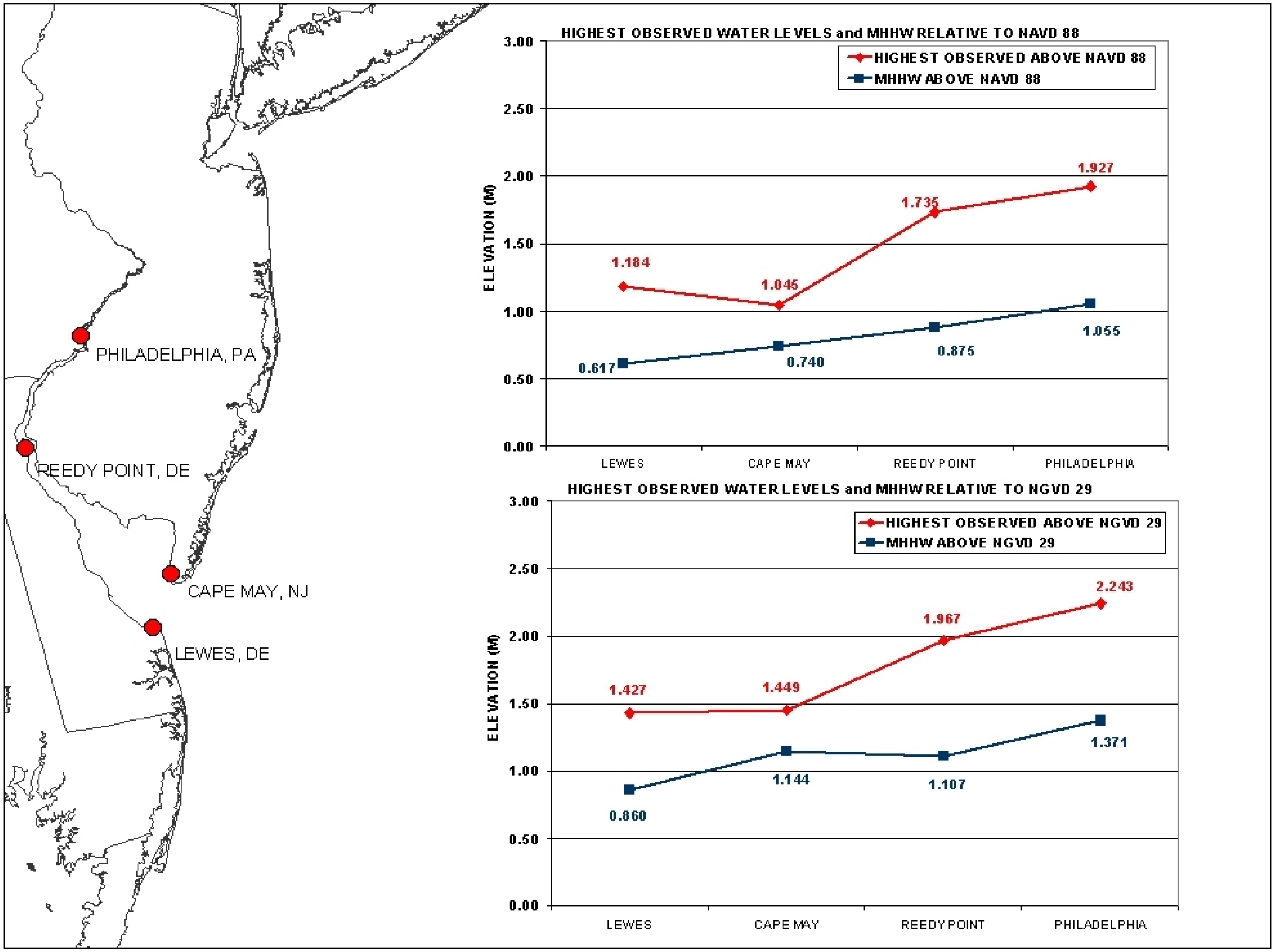


Figure 4-2. Highest observed water levels and MHHW relative to NAVD 88 and NGVD 29 for the Delaware Bay during Hurricane Isabel 18-19 September, 2003.

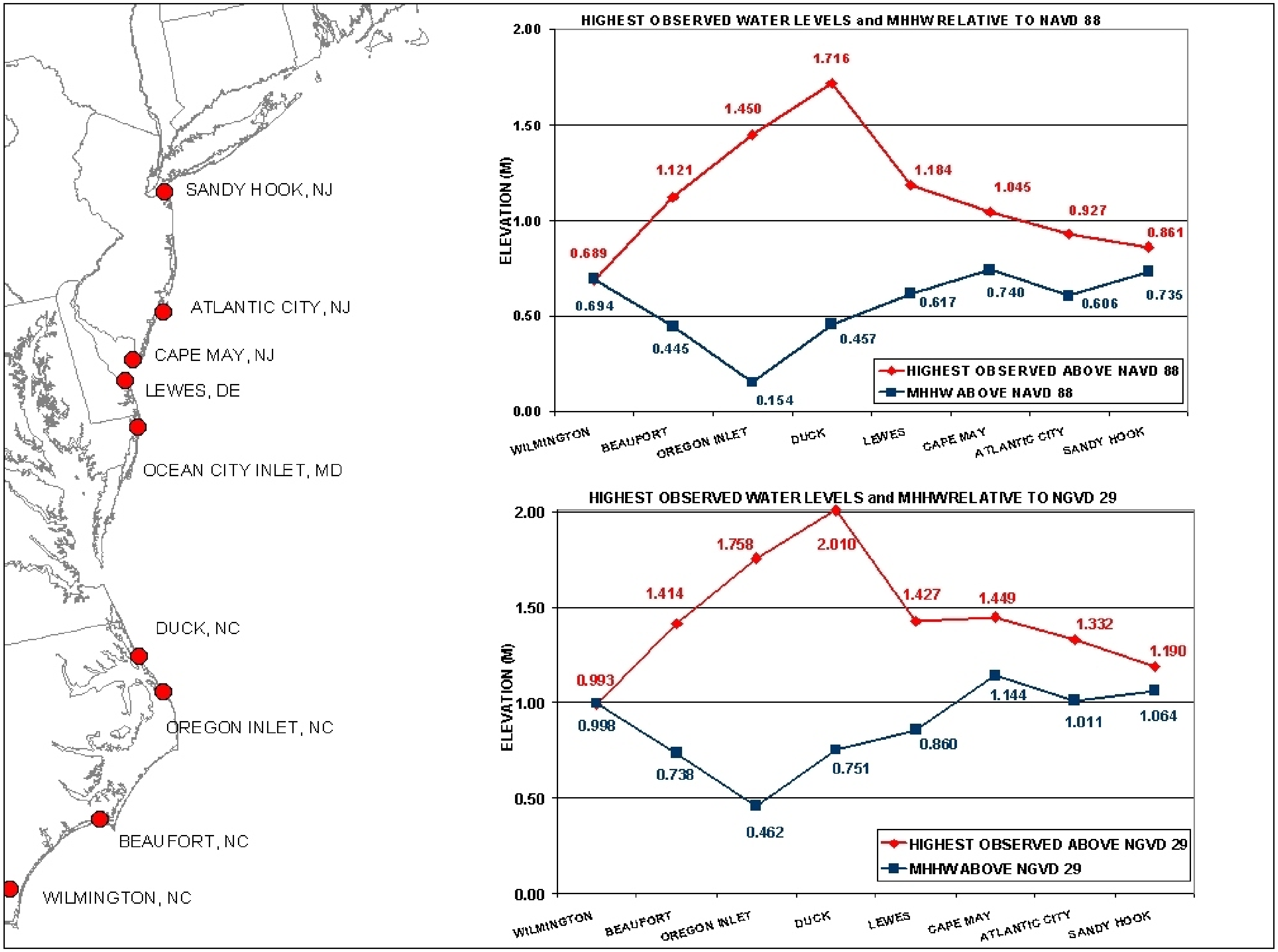


Figure 4-3. Highest observed water levels and MHHW relative to NAVD 88 and NGVD 29 for the Atlantic coast during Hurricane Isabel 18-19 September, 2003 .

Chapter 5: Currents and Waves in the Chesapeake Bay

In the summer of 2003, CO-OPS deployed an Acoustic Doppler Current Profiler (ADCP) just west of Taylors Island, MD on the eastern edge of the Chesapeake Bay's main stem (**Figure 5-1**). The location is about halfway between the NWLON stations at Cambridge and Solomons Island. The instrument was a RD Instruments 1200 kHz Workhorse Sentinel ADCP mounted on a bottom platform in approximately 7.4 meters (below MLLW). This installation was designed to test the ADCP's wave measurement and underwater acoustic modem data telemetry capabilities. In addition it collected current, pressure, and near bottom temperature data throughout the event. The system stopped due to low battery voltage on the morning of 21 September as the bay was returning to normal conditions. The system was back in operation on 10 October.

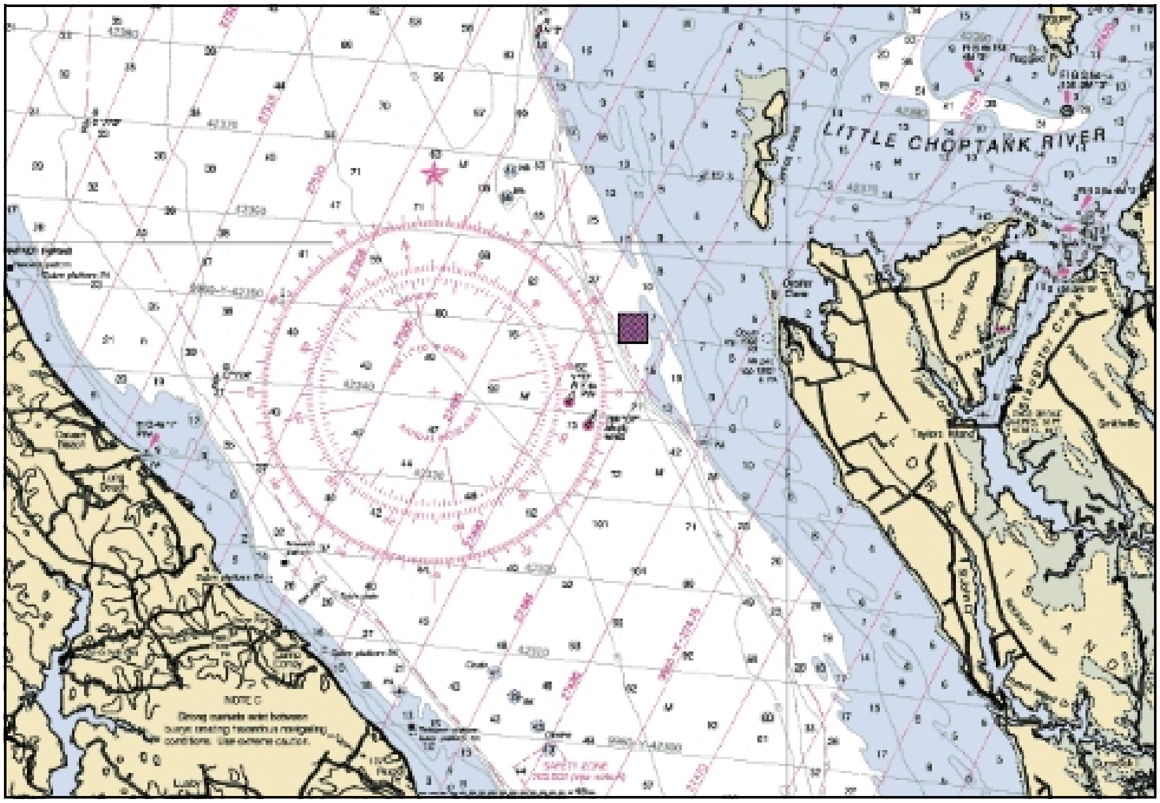


Figure 5-1. Location of ADCP in Chesapeake Bay at 38° 29.144'N, 76° 21.874'W.

A 5-day time series of the ADCP data set during the storm periodis shown in **Figure 5-2.** Vertical current profiles were collected at 0.35 m depth intervals (bins) from the ADCP transducer face about 0.68 m above the bottom. The top two panels show the current speeds and directions every 6 minutes at depth bin 15, approximately 0.5 meters below the surface. The significant wave heights in the third panel represent the mean of the 1/3 highest wave heights in a 20-minute interval each hour. Wave directions shown in the fourth panel are noisy and not quite meaningful when the waves are small. The water levels in the fifth panel are 6-minute averages and are measured from the bottom by a pressure sensor. The near bottom water temperatures in the sixth panel are measured near the ADCP transducer level.

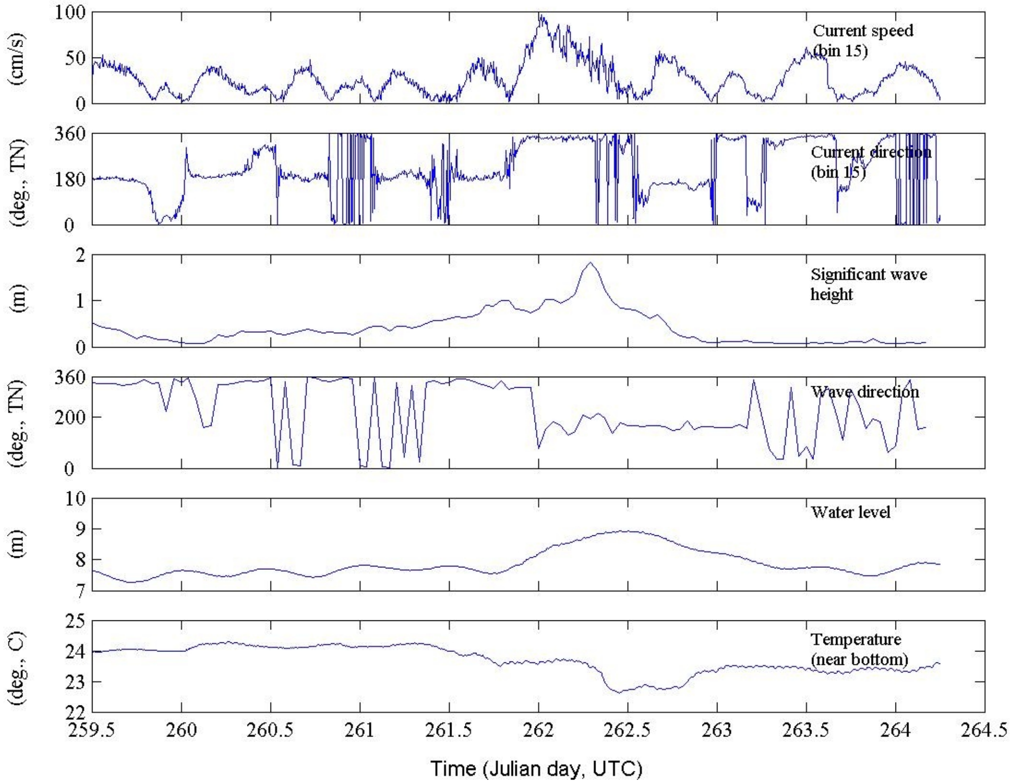


Figure 5-2. Five day time series of ADCP data during Hurricane Isabel (from noon 16 September to noon 21 September). Note the relative timing of the peak current, significant wave height, and water level.

Figure 5-2 shows the significant changes in currents, waves, water levels, and bottom water temperature during the Hurricane Isabel storm period. High winds and low barometric pressures affecting the mid-bay site (see the wind and barometric pressure plot at Cambridge MD in Appendix III) began on 18 September (Julian day 261) and ended by 20 September (Julian day 263). The highest wind speed at Cambridge (19.3 m/s) occurred at 2054 GMT, 18 September and was from east to west across the bay (from an azimuth of 106°). Subsequently, the center of the storm moved closer, however, since it was weakening, the result was decreasing wind speeds as the wind direction was shifting clockwise to the south. Barometric pressure at Cambridge, MD reached a minimum at 0300 GMT, 19 September. Wind speeds were about half their previous peak, and were now aligned along the length of the bay. As the storm center moved away to the northwest, the wind direction at Cambridge shifted clockwise from south to west and the wind speed continued to decrease.

Currents

The Chesapeake Bay is often heavily influenced by nontidal forcing due to the relative weakness of the tides and shallow depth. **Figure 5-3** shows the storm period in the current data record for depth bin 15. In this figure, the along-channel current (flood current being positive along the principal current axis of 347°) is compared with a predicted time series, obtained by a 15-day harmonic analysis carried out on the data for 25 August to 8 September using standard NOS tidal analysis routines. Predicted tidal currents at this location have alternating peak floods of about 10 and 20 cm/s (0.2 and 0.4 kts) and peak ebbs of about 30 cm/s (0.6 kts). The nontidal component (residual difference) is also shown.

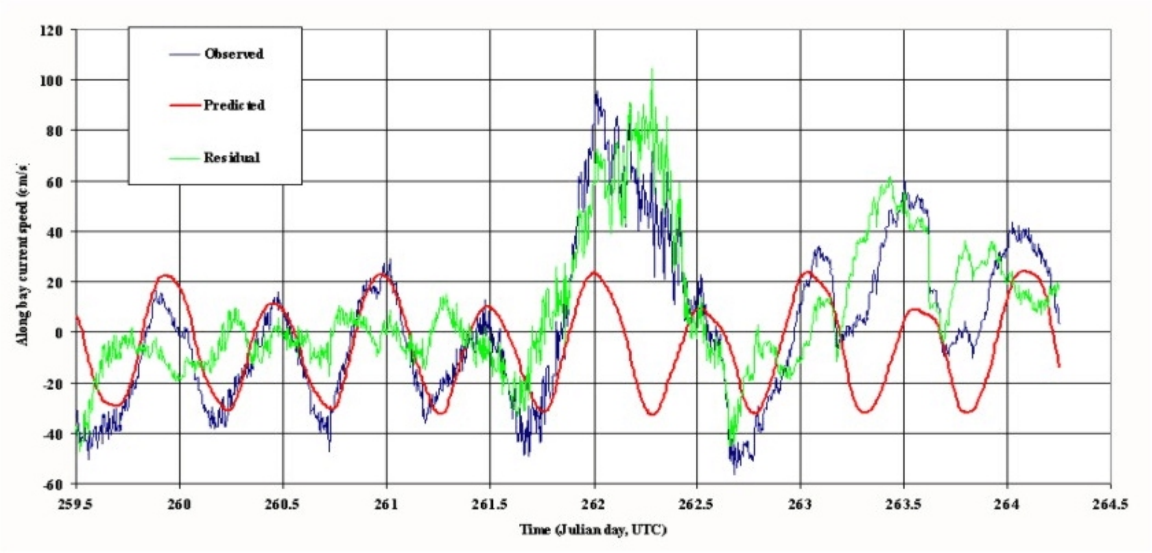


Figure 5-3. Observed, predicted, and residual currents in cm/s for bin 15 along 347° from noon 16 September to noon 21 September.

On 17 September, the tidal current observations closely matched predictions, but late on 18 September a stronger than predicted ebb current was observed. As the storm traveled to the north, west of the bay, the current turned from ebb to flood approximately one hour earlier than predicted (at 2015 GMT 18 September) and then greatly increased until 0026 GMT 19 September, when it reached its maximum of 95 cm/s (1.9 kts). This happened to coincide with a predicted flood current. At this time, the current was approximately 70 cm/s (1.4 kts) greater than the predicted current. The upper bay rapidly filled with the incoming storm surge. The nontidal flood current peaked at 105 cm/s (2 kts) at 0657 GMT 19 September, around the time of a predicted ebb current. The flood current turned to ebb throughout the water column at approximately the same time (1325 GMT 19 September). The ebb current was stronger than the predicted current, reaching 57 cm/s (1.1 kts) at 1620 GMT, 19 September. The current at this site did not ebb significantly for the rest of the record.

Since there was no significant wind on 20 September (Julian day 263) and water levels in the bay had returned to normal, the three post-storm flood flows were likely caused by unsymmetric along-channel flow up the bay during the flood tide phase. It was known (from U.S. Geological Survey stream flow data) that a significant volume of fresh water was discharged into the bay from the western shore during this period. These and other hydrodynamic conditions in the bay may have disrupted the pre-existing nontidal flow patterns resulting in stronger than normal flood currents along the eastern side of the bay at the ADCP site and stronger than normal ebb currents on the western side of the bay.

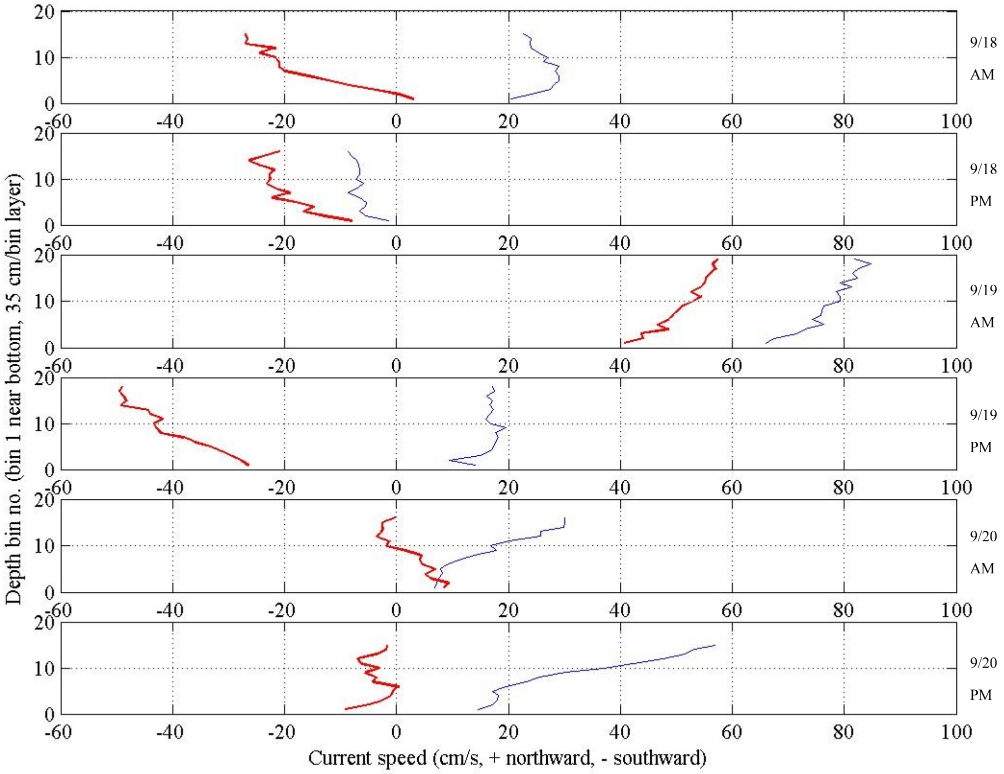


Figure 5-4. Evolution of vertical current profiles during Hurricane Isabel (blue - near predicted flood tide phase, red - near predicted ebb tide phase). Panels from top: 9/18 at 0000 and 0600; 9/18 at 1200 and 1800; 9/19 at 0000 and 0600; 9/19 at 1200 and 1700; 9/20 at 0300 and 0500; 9/20 at 1200 and 1800 (Times in GMT).

Figure 5-4 shows the changes in vertical along-channel current profiles near the times of normal flood/ebb tidal phases, as the storm developed. At times, there are large vertical gradients in current speeds in the water column. Strong flow toward the upper bay is evident in all tidal phases during the storm's peak on 19 September (third panel) when a predicted ebb phase did not occur, which was followed by a strong ebb flow later on 19 September (fourth panel). Flood currents the following day (20 September) were much stronger at the top of the water column.

Water levels and waves

The surge in water level is clearly evident from the pressure sensor data shown in the fourth panel of **Figure 5-2.** An enlarged view of the water level data is shown in **Figure 5-5.** The water level above bottom exceeded 8.0 m at 2226 GMT 18 September and remained above that level for approximately 30 hours. The greatest water level above bottom (8.93 m) occurred at 1103 GMT, 19 September. (At Cambridge, the maximum water level occurred at 1048 GMT 19 September). Also shown in **Figure 5-6** are the significant wave height and the transient water level, which is a superposition of half the significant wave height and the water level above bottom. A maximum magnitude of 1.83 m for significant wave height was recorded at 0700 GMT 19 September. The waves comprised a significant portion of the transient water level during the storm surge. The highest transient water levels occurred at the time of the maximum significant wave height, not at the time of the peak storm surge about four hours later. The corresponding peak spectrum wave period was about 4 to 6 seconds during the storm.

Bottom water temperature

There was a change of about 1° C in bottom water temperature during the passage of Isabel as shown in the sixth panel of **Figure 5-2.** The water temperature at NWLON stations in the bay also dropped by approximately this magnitude. Previous NOS measurements in this area (October - November 2002 near Barren Island about 20 km south of the ADCP) showed that the differences between surface and bottom temperature are normally insignificant.

Water turbidity

An ADCP obtains current measurements by sending acoustic signals through the water column. These signals are reflected off suspended sediment and bubbles moving at the same speed as the currents and the returning signals, with the resulting Doppler frequency shift, are measured at the instrument's transducers. Higher concentrations of suspended particles create a higher echo amplitude value. However, the instrument is unable to determine the exact nature of these particles given the size (approximately 1 mm). Particles in this size range include plankton, suspended sediments and detritus. Density gradients of the water are also weak scatterers. **Figure 5-6** shows the beam-averaged echo amplitude from the ADCP during Hurricane Isabel. There is a significant increase in backscatter associated with the storm surge. A likely source of the increased backscatter is re-suspension of fine bottom sediment caused by the strong velocity shear and the wave action. The re-suspension and subsequent transport of bottom sediments could affect the water clarity (high turbidity lasted for about 2 days) and shore erosion (long term impact). Shoreline erosion was a major problem as a consequence of this storm.

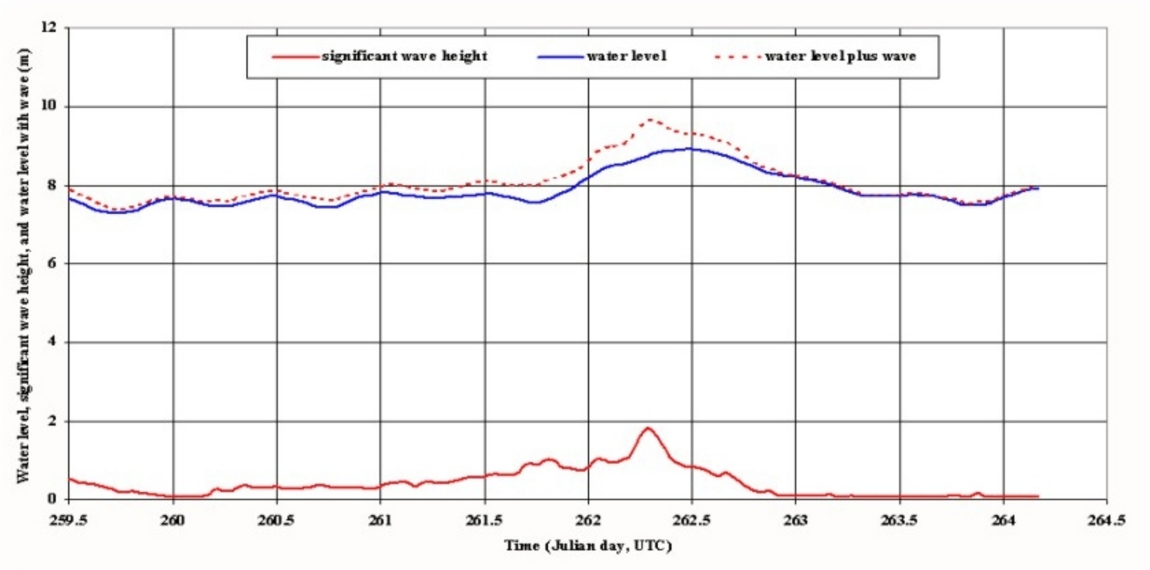


Figure 5-5. Time series plot of significant wave height, water level above bottom, and transient water level above bottom in meters from 16 September (1200) to 21 September (1200). The transient water level (dotted line) is the sum of the water level above bottom and half the significant wave height.

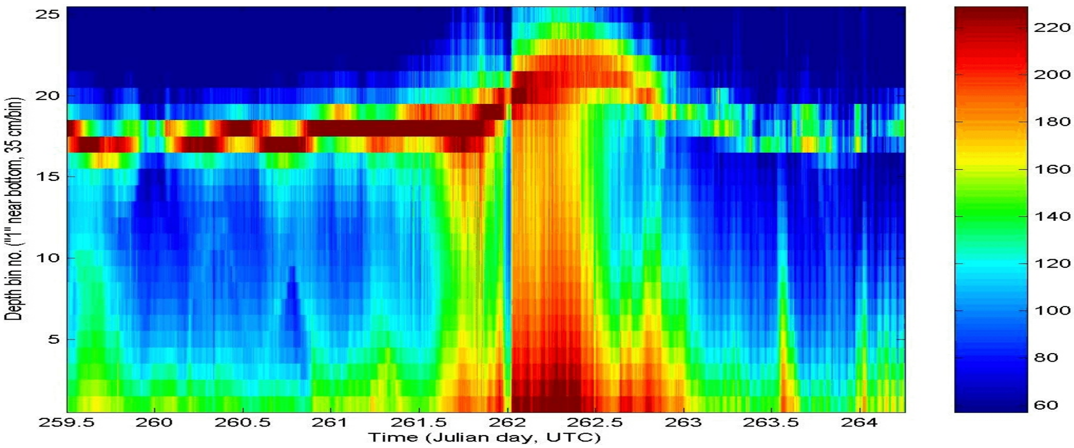


Figure 5-6. Echo amplitudes showing degree of concentration of suspended particles in the vertical water column for each 0.35 m depth bin versus time. Units are counts (0.45 decibels per count, red - highest). Water surface is shown by the sharp color change on the top (bins 17 to 22). Highest turbidity occurred during period of rising storm surge.

Timing of peak events

It is evident that the effects of the hurricane on Chesapeake Bay changed rapidly as the storm moved first towards and then away from the mid-bay ADCP. The timing of the extremes of various measured parameters at the ADCP site or nearby at Cambridge, MD can explain the sequence of events affecting the upper bay. **Figure 5-7** depicts the location of the storm center along its trackline, as various measurements at the ADCP and Cambridge, MD reached their extreme values.

The highest wind speed at Cambridge was measured at about 2100 GMT (1700 EDT) 18 September , before Isabel had crossed the North Carolina-Virginia border. However, the direction of the wind across the width of the bay prevented it from having a great effect on the currents, waves or water levels in the upper bay. About three hours later, after Isabel had crossed into Virginia, the highest currents were recorded at the mid-bay ADCP. The wind, although diminished, had rotated so that

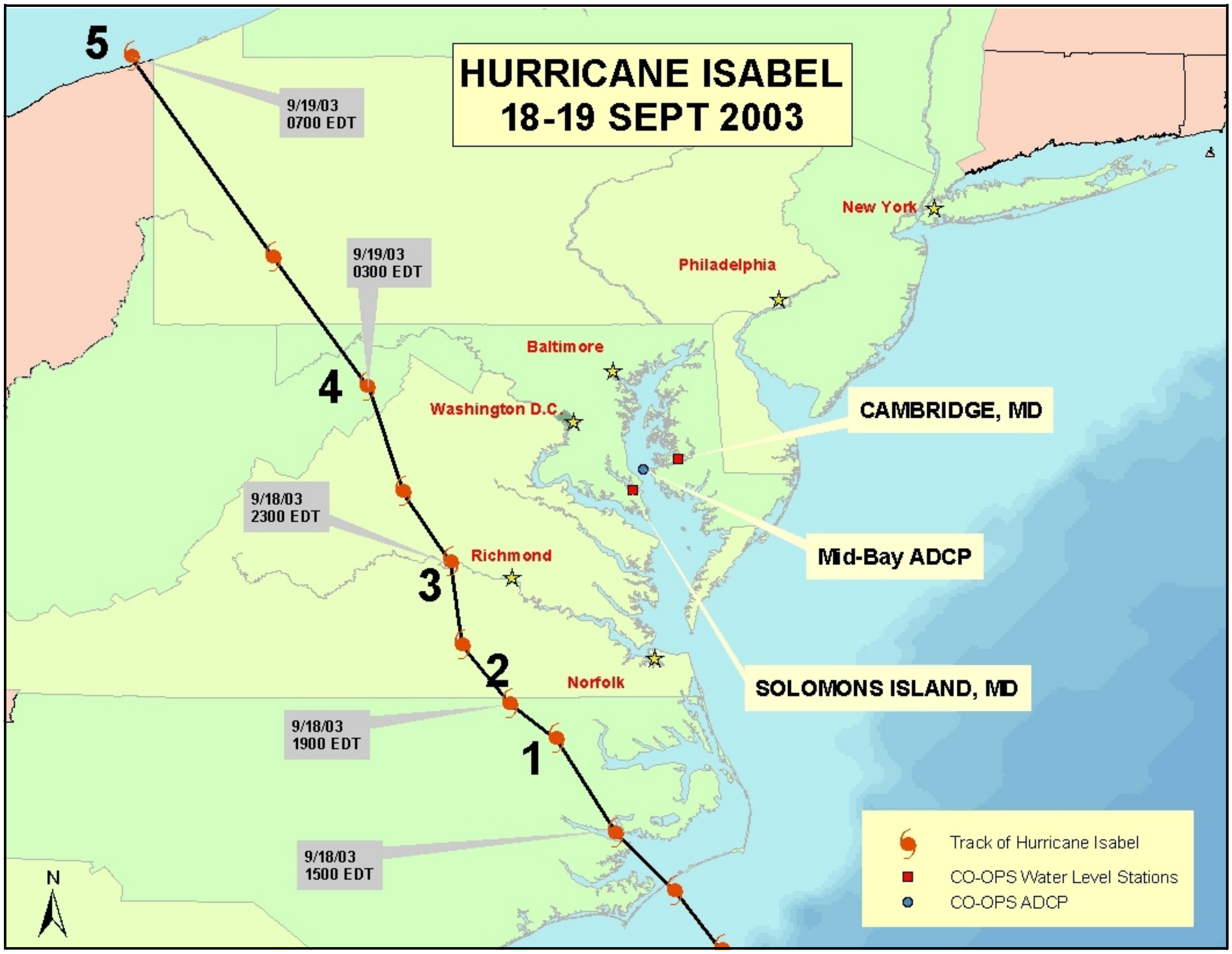


Figure 5-7. Location of mid-bay ADCP and track of Hurricane Isabel 18-19 September, 2003. Numerals indicate positions of storm center as various measured parameters reached their extreme values: 1 - highest wind speed at Cambridge, 2 - highest mid-bay current, 3 - lowest air pressure at Cambridge, 4 - highest mid-bay nontidal current and greatest significant wave height, 5 - highest water level and peak storm surge.

it now had a component along the length of the bay. The highest speed of the current was partially due to the contribution of a predicted tidal flood.

Around three hours later (0300 GMT 19 September or 2300 EDT 18 September), the storm center passed west of Richmond VA, reaching its closest distance to the ADCP. Cambridge recorded its minimum air pressure. Four hours later at 0700 GMT (0300 EDT) 19 September, the storm center was over the West Virginia panhandle. At this time, the ADCP recorded its strongest nontidal flow (at the time of a predicted tidal ebb) and the greatest significant wave height. The highest water levels at the ADCP and at Cambridge were not recorded until four hours later (about 1100 GMT or 0700 EDT 19 September), after the storm center had crossed Pennsylvania and reached Lake Erie.

Chapter 6: Comparison with Previous Maximum Water Levels and Storm Surges

Four NWLON stations in the Chesapeake Bay region have been in operation for over 70 years. These stations are Baltimore MD, Annapolis, MD; Washington, DC; and Sewells Point, VA, which have records beginning in 1902, 1928, 1931, and 1927, respectively. **Figure 6-1** shows the monthly highest water levels with dates of the four previous highest levels at each station. Prior to Hurricane Isabel, the highest water levels reached at Baltimore, MD; Annapolis,MD and Sewells Point, VA occurred during the passage of a major hurricane in August 1933. At Washington, DC the 1933 hurricane caused the third highest recorded water level, surpassed only by river floods in October 1942 and March 1936. Hurricane Isabel caused water levels to exceed the August 1933 levels at Baltimore, MD; Annapolis, MD and Washington, DC by 0.137 m, 0.310 m, and 0.041 m, respectively. At Sewells Point, VA the highest water level from Hurricane Isabel was only 0.041 m below the level reached in 1933.

The Chesapeake Bay region has relatively high rates of sea level rise [Sea Level Variations of the United States, 1854-1999, NOAA Technical Report NOS-CO-OPS 36, Zervas, 2001]. This is due to a combination of global sea level rise (between 1 and 2.4 mm/yr) and regional subsidence caused by the ongoing glacial isostatic adjustment due to melting of the ice sheets of the North American lithosphere. Using all monthly water level data up to 1999, sea level trends for Baltimore, MD; Annapolis, MD; Washington, DC and Sewells Point,VA were 3.12, 3.53, 3.13, and 4.42 mm/yr, respectively. The effect of sea level rise can be seen in **Figure 6-1** as the gradual rise in the monthly highest water levels.

In order to determine whether the rising sea levels of the Chesapeake Bay region are responsible for the levels reached by Hurricane Isabel exceeding the levels reached by the August 1933 hurricane, sea level change must be taken into account. This can be done by adjusting each monthly highest water level in **Figure 6-1** for the subsequent sea level rise up to the year 2003. The resulting time series indicates the highest level reached by each storm as if it had taken place in 2003, thus allowing an unbiased comparison of storms.

The five highest water levels at each of the four stations are shown in **Tables 6-1** to **6-4**, both before and after correction for sea level trends. It can be seen that the 1933 hurricane would have exceeded the levels reached by Isabel at Baltimore, MD; Washington, DC and Sewells Point, VA by 0.080 m, 0.176 m, and 0.347 m, respectively, if it had occurred in 2003. At Annapolis, the 1933 hurricane would have fallen 0.065 m short of the level reached by Isabel. Therefore, it can be concluded that the 1933 hurricane was the cause of the century's highest water levels to affect the lower Chesapeake Bay (Sewells Point) and the Potomac River (Washington). Furthermore, the 1933 hurricane and Isabel were roughly equivalent in their effect on water levels of the upper Chesapeake Bay (Baltimore and Annapolis).

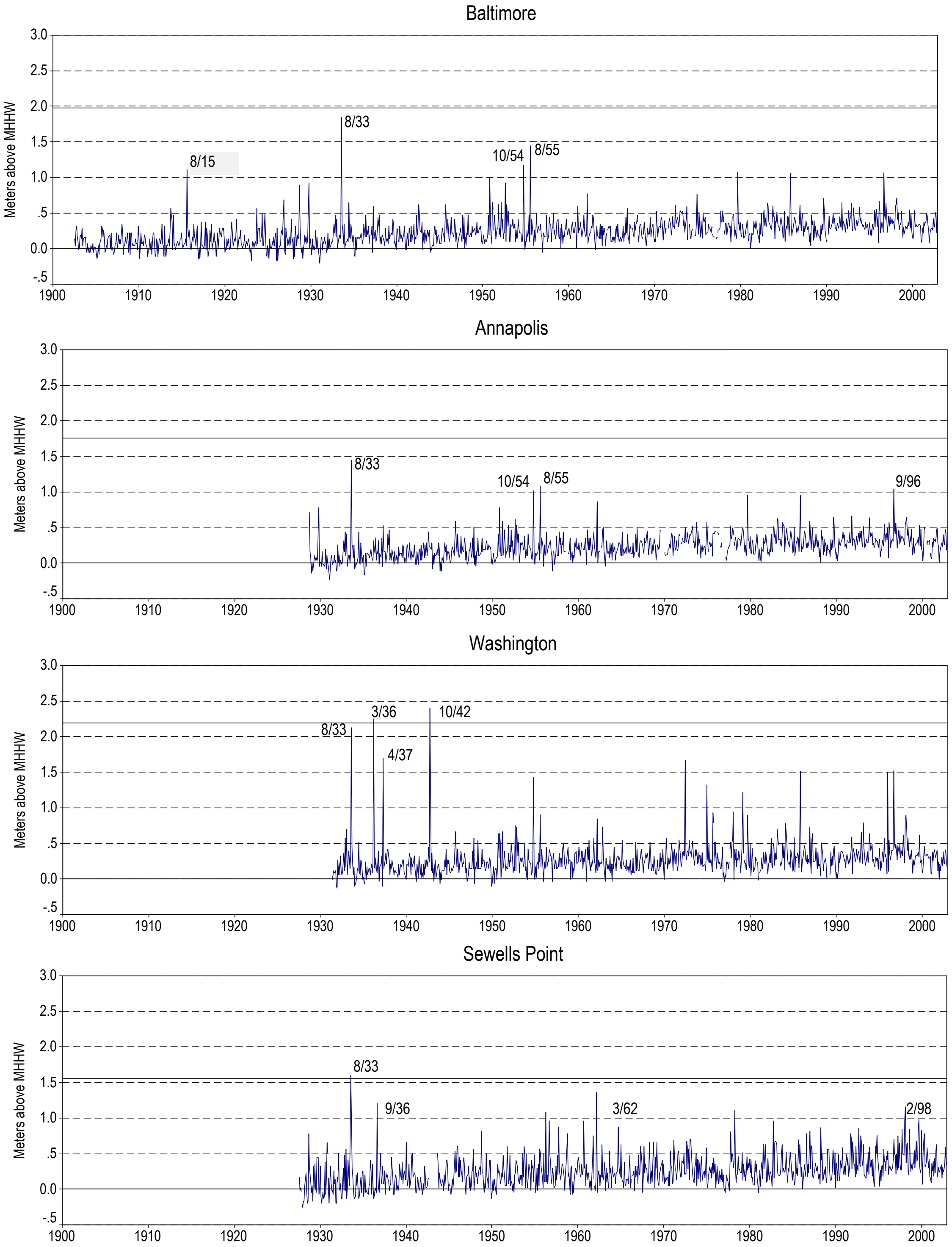


Figure 6-1. Highest monthly water levels in meters above MHHW up to December 2002 with the four highest months labeled. Heavy horizontal line indicates level reached by Hurricane Isabel in September 2003. Note the effect of rising sea levels.

Table 6-1. Five highest water levels for Baltimore, MD in meters above MHHW

Absolute water level			Corrected for sea level rise to 2003		
Hurricane Isabel	Sep 2003	1.976	Hurricane	Aug 1933	2.056
Hurricane	Aug 1933	1.839	Hurricane Isabel	Sep 2003	1.976
Hurricane Connie	Aug 1955	1.443	Hurricane Connie	Aug 1955	1.591
Hurricane Hazel	Oct 1954	1.169	Hurricane	Aug 1915	1.381
Hurricane	Aug 1915	1.108	Hurricane Hazel	Oct 1954	1.319

Table 6-2. Five highest water levels for Annapolis, MD in meters above MHHW

Absolute water level			Corrected for sea level rise to 2003		
Hurricane Isabel	Sep 2003	1.756	Hurricane Isabel	Sep 2003	1.756
Hurricane	Aug 1933	1.446	Hurricane	Aug 1933	1.691
Hurricane Connie	Aug 1955	1.081	Hurricane Connie	Aug 1955	1.248
Hurricane Fran	Sep 1996	1.038	Hurricane Hazel	Oct 1954	1.190
Hurricane Hazel	Oct 1954	1.020	Hurricane Fran	Sep 1996	1.060

Table 6-3. Five highest water levels for Washington, DC in meters above MHHW

Absolute water level			Corrected for sea level rise to 2003		
Flood	Oct 1942	2.402	Flood	Oct 1942	2.590
Flood	Mar 1936	2.249	Flood	Mar 1936	2.458
Hurricane Isabel	Sep 2003	2.169	Hurricane	Aug 1933	2.345
Hurricane	Aug 1933	2.128	Hurricane Isabel	Sep 2003	2.169
Flood	Apr 1937	1.701	Flood	Apr 1937	1.907

Table 6-4. Five highest water levels for Sewells Point, VA in meters above MHHW

Absolute water level			Corrected for sea level rise to 2003		
Hurricane	Aug 1933	1.604	Hurricane	Aug 1933	1.910
Hurricane Isabel	Sep 2003	1.563	Hurricane Isabel	Sep 2003	1.563
Winter Storm	Mar 1962	1.360	Winter Storm	Mar 1962	1.540
Hurricane	Sep 1936	1.207	Hurricane	Sep 1936	1.500
Winter Storm	Feb 1998	1.164	Hurricane	Sep 1933	1.330

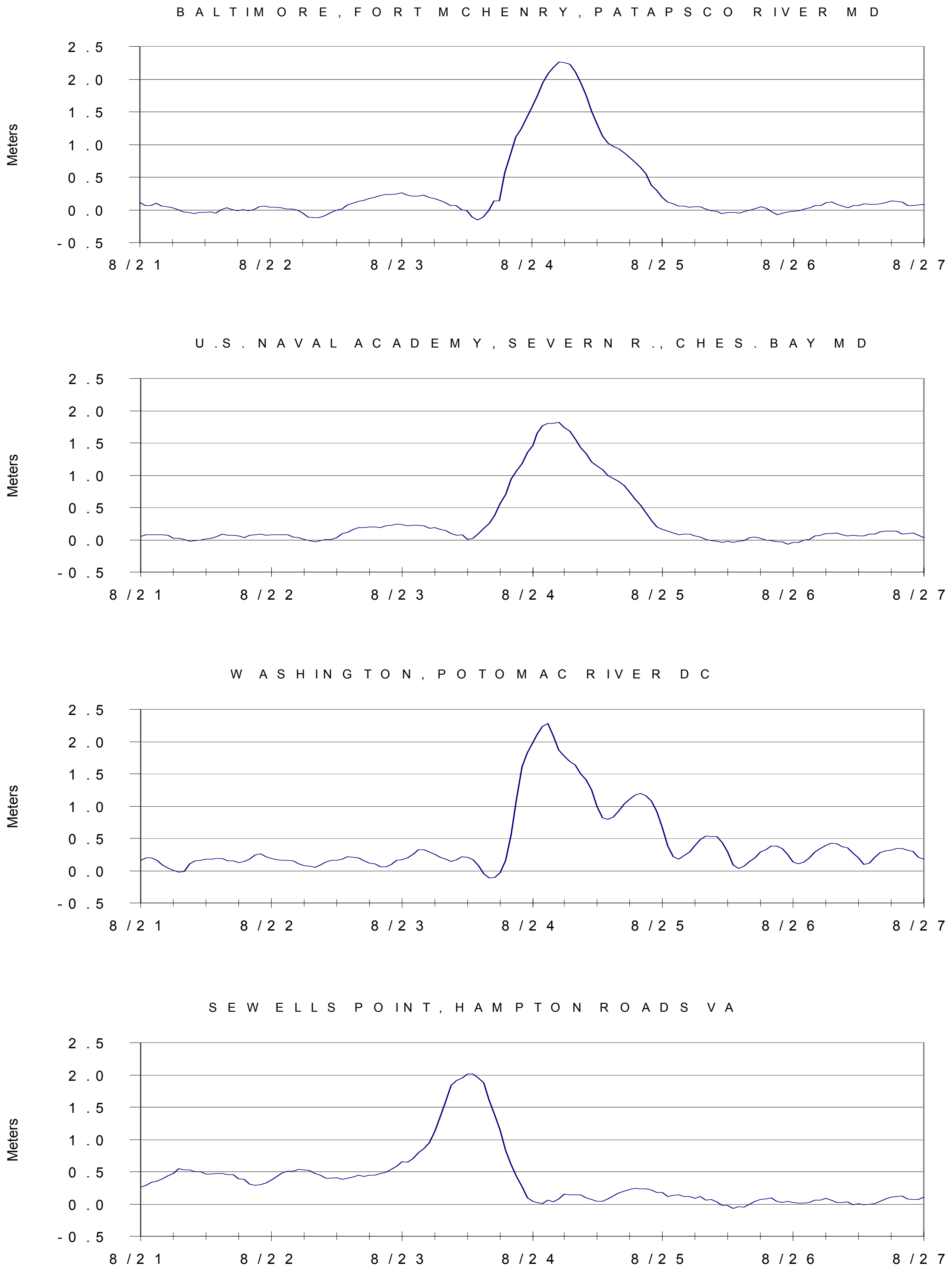


Figure 6-2. Storm surges at Baltimore, MD; Annapolis, MD; Washington, DC and Sewells Point, VA for August 1933 hurricane. Hourly data with time in GMT.

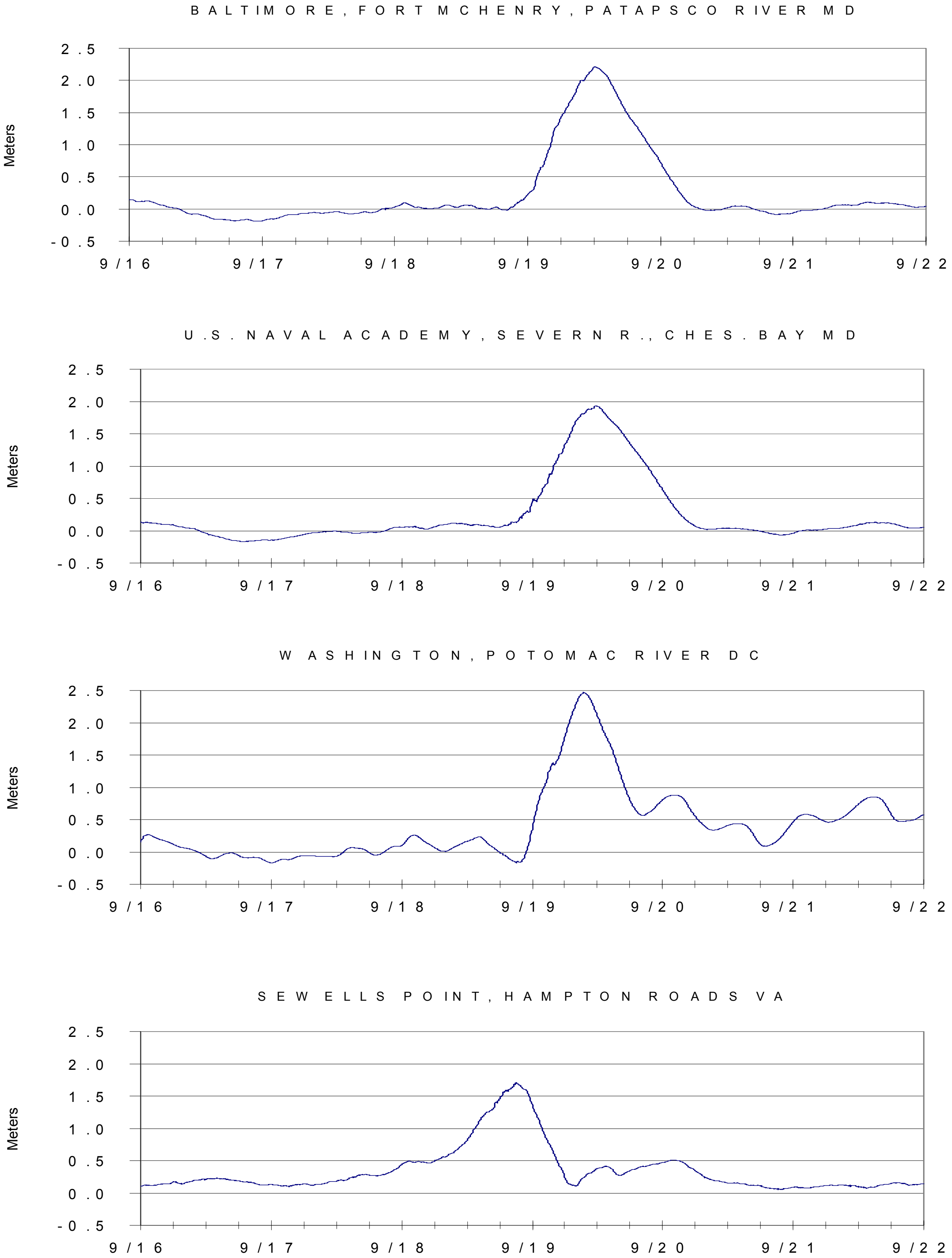


Figure 6-3. Storm surges at Baltimore, MD; Annapolis, MD; Washington, DC and Sewells Point,VA for Hurricane Isabel, September 2003. Six-minute data with time in GMT.

The highest water levels reached during a storm are not simply due to the strength of the storm but are also dependent on the timing of the surge relative to the tide. Therefore, the storm surges for the 1933 hurricane have been calculated for comparison with the storm surges for Hurricane Isabel. After the predicted tide is subtracted from the 21-26 August 1933 hourly data, the resulting time series is raised to account for 70 years of sea level rise using the calculated trends. This provides a direct comparison of the strength of the two storms after removing tidal and sea level rise factors.

The storm surges for the August 1933 hurricane and for Isabel are shown in **Figures 6-2** and **6-3**. They are remarkably similar. The maximum storm surges and their timing with respect to the predicted time of high tide are given in **Table 6-5.** The main difference of the storm surge timing with respect to the peak of the tidal cycle was at Washington, DC where the 1933 hurricane surge peaked near high tide and Isabel's surge peaked halfway between high tide and low tide.

The storm surges at Baltimore, MD and Annapolis, MD are essentially equivalent for the two storms. The 1933 hurricane storm surge was only 0.043 m higher at Baltimore, MD and only 0.110 m lower at Annapolis, MD than Isabel's peak storm surge. At Sewells Point, VA the 1933 hurricane storm surge was substantially higher (0.305 m) than Isabel's peak storm surge. At Washington, DC the 1933 hurricane storm surge was 0.194 m lower than Isabel's storm surge. The reason that the 1933 hurricane would have exceeded Isabel's maximum water level at Washington, DC (see **Table 6-3**), is because it occurred only 36 minutes after high tide. Isabel's peak storm surge at Washington, DC occurred 3 hours and 12 minutes after high tide. Therefore, it can be concluded that the 1933 hurricane caused the strongest storm surge of the past century for the lower Chesapeake Bay (Sewells Point), hurricane Isabel caused the strongest storm surge of the past century in the Potomac River (Washington), and the two hurricanes caused roughly equivalent storm surges in the upper Chesapeake Bay (Baltimore and Annapolis).

Table 6-5. Comparison of maximum storm surges after correction for sea level rise

Location	August 1933 Hurricane		Hurricane Isabel	
	Height (m)	Time relative to predicted high tide	Height (meters)	Time relative to predicted high tide
Baltimore, MD	2.257	3 hours 48 minutes after	2.214	6 hours 45 minutes after
Annapolis, MD	1.821	5 hours 21 minutes after	1.931	7 hours 53 minutes after
Washington, DC	2.276	36 minutes after	2.470	3 hours 12 minutes after
Sewells Point, VA	2.017	2 hours 15 minutes before	1.712	1 hour 50 minutes after

Summary

Hurricane Isabel will be remembered as one of the strongest hurricanes to impact the mid-Atlantic region of the Unites States in the historical record. After landfall at the Outer Banks of North Carolina as a Category 2 hurricane on the 18 September 2003, it continued to move northwest through Virginia, West Virginia and Pennsylvania, before crossing Lake Erie. As Isabel traveled up the western shore of Chesapeake Bay, its strong, damaging winds caused record-breaking storm surges in the bay and in rivers flowing into the bay. Significant storm surges were also recorded along the Outer Banks, NC and in the Delaware Bay and River.

The CO-OPS water level network stations and ADCP profiler in the mid-Atlantic states and on Lake Erie recorded the effects of Isabel at many different coastal locations. During the course of the storm, five stations were destroyed and two stations experienced an unrecoverable loss of data. At four stations, the water levels were only available from the backup pressure sensor, as the primary acoustic sensor could not record the maximum water level. Throughout the storm period the water level network was monitored by CO-OPS personnel on a 24-hour basis. Water level and meteorological data were continuously available to the public in real time on the CO-OPS websites.

The maximum observed water levels reached during Hurricane Isabel are tabulated in this report and compared to the previous historical maximum at each station. Isabel was responsible for new maximum observed water levels at eight stations in the Chesapeake Bay, five stations in the Delaware Bay and one station on the Outer Banks. The highest observed water levels were 2.169 meters above MHHW at Washington and 1.976 meters above MHHW at Baltimore, MD. It is likely that Isabel caused record levels at the stations it destroyed. Isabel also set up a water level oscillation and seiche as it crossed Lake Erie. The maximum observed water levels are also tabulated relative to the geodetic datums of NGVD 29 and NAVD 88 for the coastal water level stations.

Storm surge time series were calculated for the coastal stations by subtracting the predicted tides from the water levels. The times and heights of the peak storm surge were tabulated and compared. The highest peak storm surges were 2.487 meters at Chesapeake City, MD and 2.470 meters at Washington, DC. The timing of the peak storm surge relative to predicted high tide was calculated for each station. Peak storm surges were nearly coincident with the high tide along the Atlantic coast of North Carolina and Virginia and at locations in lower Chesapeake Bay. Peak storm surges were closer to the following low tide at the stations in upper Chesapeake Bay, the Atlantic coast of Maryland, Delaware and New Jersey, and in the Delaware Bay and River.

During the period of the storm, CO-OPS had an ADCP deployed at a mid-Chesapeake Bay location to measure currents and significant wave heights. Observations at this site and meteorological measurements at the nearby water level station at Cambridge, MD were used to put together the sequence of the storm's effects on upper Chesapeake Bay. The maximum observed water level and peak storm surge in upper Chesapeake Bay did not occur until the storm center had already reached Lake Erie.

The monthly maximum observed water levels at four stations with over 70 years of data (Baltimore, MD; Annapolis, MD; Washington, DC and Sewells Point, VA) were used to compare the effect of Hurricane Isabel with the effects of previous storms. The previous storm of record for the Chesapeake Bay was a hurricane that struck the region in August 1933. A comparison of the two storms required a correction be made for the relative sea level rise that took place over the intervening years. The maximum observed water levels for Hurricane Isabel and the August 1933 hurricane were roughly comparable for upper Chesapeake Bay (Baltimore, MD and Annapolis, MD). The August 1933 hurricane would have resulted in higher maximum observed water levels for lower Chesapeake Bay (Sewells Point, VA) and the Potomac River (Washington, DC) had it occurred in 2003.

Acknowledgments

This report represents the cumulative efforts of personnel of the Center for Operational Oceanographic Products and Services. We would like to acknowledge the support of the Field Operations Division personnel who are responsible for the operation and maintenance of the water level stations and the Products and Services Division personnel who are responsible for the processing and analysis of the data incorporated into this report. Zhong Li produced the wind plots and Kelly Huennekens produced geographic plots of station locations and Isabel's track. John Herron provided the Great Lakes plots. Brenda Via and Gina Stoney prepared and reviewed the final document for publication. We would also like to thank Stephen Gill, William Stoney, Leonard Hickman, Scott Duncan and Tom Landon, Laura Rear and Lori Fenstermacher for their suggestions and reviews which helped to improve this report.

Appendix I

Preliminary and Verified Hurricane Isabel weather advisories from the NOAA National Hurricane Center

Preliminary NHC Advisories

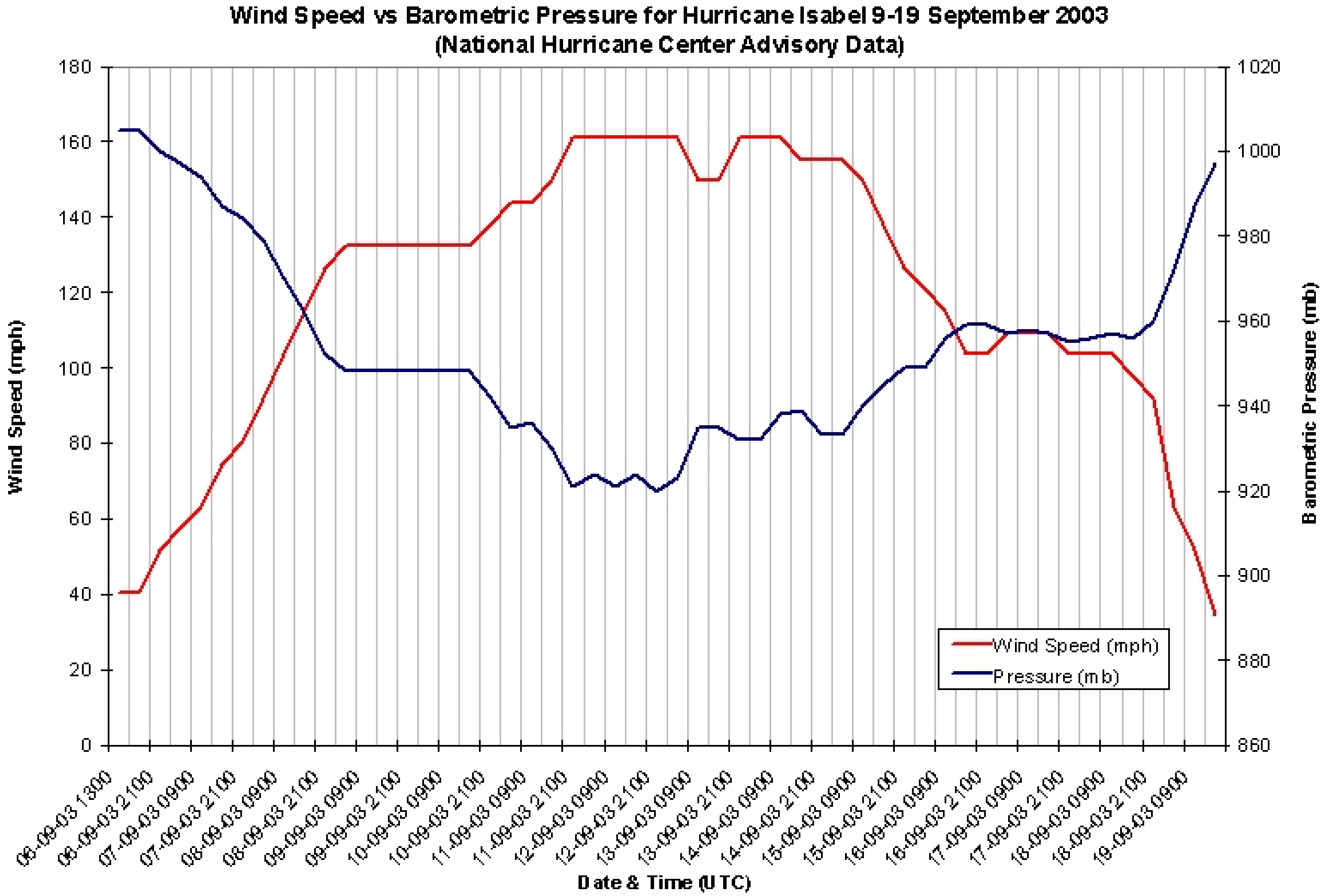
NHC Advisory	Date	Time (UTC)	Lat (N)	Long(W)	Saffir/Simpson Hurricane Scale	Wind Speed	Gusts (mph)	Pressure (mb)
1	06-09-03	1300	14.0 N	34.0 W	Tropical Storm	40	52	1005
2	06-09-03	1500	13.6 N	34.5 W	Tropical Storm	40	52	1005
3	06-09-03	2100	13.4 N	35.4 W	Tropical Storm	52	63	1000
4	07-09-03	0300	13.4 N	36.1 W	Tropical Storm	58	69	997
5	07-09-03	0900	13.7 N	37.1 W	Tropical Storm	63	75	994
6	07-09-03	1500	14.5 N	37.7 W	Hurricane-1	75	92	987
7	07-09-03	2100	15.2 N	39.1 W	Hurricane-1	81	98	984
8	08-09-03	0300	16.1 N	40.2 W	Hurricane-1	92	115	979
9	08-09-03	0900	16.9 N	41.4 W	Hurricane-2	104	127	970
10	08-09-03	1500	17.2 N	42.6 W	Hurricane-3	115	138	962
11	08-09-03	2100	17.9 N	43.7 W	Hurricane-3	127	155	952
12	09-09-03	0300	18.5 N	44.5 W	Hurricane-4	132	161	948
13	09-09-03	0900	19.1 N	45.7 W	Hurricane-4	132	161	948
14	09-09-03	1500	19.6 N	46.9 W	Hurricane-4	132	161	948
15	09-09-03	2100	20.3 N	47.8 W	Hurricane-4	132	161	948
16	10-09-03	0300	20.6 N	48.8 W	Hurricane-4	132	161	948
17	10-09-03	0900	20.9 N	50.2 W	Hurricane-4	132	161	948
18	10-09-03	1500	21.3 N	50.9 W	Hurricane-4	132	161	948
19	10-09-03	2100	21.2 N	51.9 W	Hurricane-4	138	167	942
20	11-09-03	0300	21.1 N	52.8 W	Hurricane-4	144	178	935
21	11-09-03	0900	21.3 N	53.7 W	Hurricane-4	144	178	936
22	11-09-03	1500	21.4 N	54.5 W	Hurricane-4	150	184	930
23	11-09-03	2100	21.6 N	55.3 W	Hurricane-5	161	196	921
24	12-09-03	0300	21.6 N	56.1 W	Hurricane-5	161	196	924
25	12-09-03	0900	21.7 N	57.0 W	Hurricane-5	161	196	921
26	12-09-03	1500	21.6 N	57.8 W	Hurricane-5	161	196	924
27	12-09-03	2100	21.8 N	58.6 W	Hurricane-5	161	196	920
28	13-09-03	0300	21.8 N	59.5 W	Hurricane-5	161	196	92

NHC Advisory	Date	Time (UTC)	Lat (N)	Long(W)	Saffir/Simpson Hurricane Scale	Wind Speed	Gusts (mph)	Pressure (mb)
29	13-09-03	0900	22.0 N	60.4 W	Hurricane-4	150	184	935
30	13-09-03	1500	22.2 N	61.5 W	Hurricane-4	150	184	935
31	13-09-03	2100	22.6 N	62.6 W	Hurricane-5	161	196	932
32	14-09-03	0300	23.0 N	63.7 W	Hurricane-5	161	196	932
33	14-09-03	0900	23.3 N	65.2 W	Hurricane-5	161	196	938
34	14-09-03	1500	23.7 N	66.3 W	Hurricane-4	155	190	939
35	14-09-03	2100	24.1 N	67.4 W	Hurricane-4	155	190	933
36	15-09-03	0300	24.5 N	68.3 W	Hurricane-4	155	190	933
37	15-09-03	0900	24.8 N	69.0 W	Hurricane-4	150	184	940
38	15-09-03	1500	25.2 N	69.4 W	Hurricane-4	138	167	945
39	15-09-03	2100	25.6 N	70.0 W	Hurricane-3	127	155	949
40	16-09-03	0300	26.1 N	70.2 W	Hurricane-3	121	150	949
41	16-09-03	0900	26.6 N	70.7 W	Hurricane-3	115	138	956
42	16-09-03	1500	27.4 N	71.2 W	Hurricane-2	104	127	959
43	16-09-03	2100	27.8 N	71.4 W	Hurricane-2	104	127	959
44	17-09-03	0300	28.5 N	71.7 W	Hurricane-2	109	132	957
45	17-09-03	0900	29.4 N	72.2 W	Hurricane-2	109	132	958
46	17-09-03	1500	30.0 N	72.6 W	Hurricane-2	109	132	957
47	17-09-03	2100	31.1 N	73.3 W	Hurricane-2	104	132	955
48	18-09-03	0300	31.9 N	73.9 W	Hurricane-2	104	132	956
49	18-09-03	0900	33.1 N	74.7 W	Hurricane-2	104	127	957
50	18-09-03	1500	34.4 N	75.7 W	Hurricane-2	98	121	956
51	18-09-03	2100	36.2 N	77.1 W	Hurricane-1	92	121	960
52	19-09-03	0300	37.7 N	78.0 W	Tropical Storm	63	75	972
53	19-09-03	0900	39.3 N	78.7 W	Tropical Storm	52	63	987
54	19-09-03	1500	42.0 N	80.7 W	Tropical Depression	35	46	997

Verified NHC Advisories

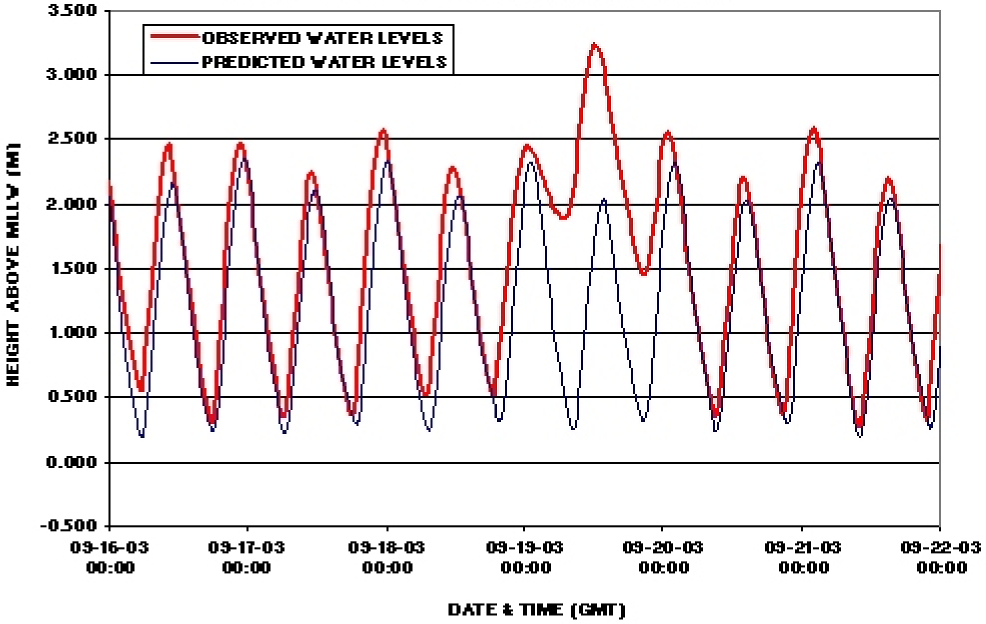
Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
06 / 0000	13.8	31.4	1009	30	tropical depression
06 / 0600	13.9	32.7	1005	35	tropical storm
06 / 1200	13.6	33.9	1003	40	"
06 / 1800	13.4	34.9	1000	45	"
07 / 0000	13.5	35.8	994	55	"
07 / 0600	13.9	36.5	991	60	"
07 / 1200	14.4	37.3	987	65	hurricane
07 / 1800	15.2	38.5	984	70	"
08 / 0000	15.8	39.7	976	80	"
08 / 0600	16.5	40.9	966	95	"
08 / 1200	17.1	42.0	952	110	"
08 / 1800	17.6	43.1	952	110	"
09 / 0000	18.2	44.1	948	115	"
09 / 0600	18.9	45.2	948	115	"
09 / 1200	19.4	46.3	948	115	"
09 / 1800	20.0	47.3	948	115	"
10 / 0000	20.5	48.3	952	110	"
10 / 0600	20.9	49.4	952	110	"
10 / 1200	21.1	50.4	948	115	"
10 / 1800	21.1	51.4	942	120	"
11 / 0000	21.2	52.3	935	125	"
11 / 0600	21.3	53.2	935	125	"
11 / 1200	21.4	54.0	925	135	"
11 / 1800	21.5	54.8	915	145	"
12 / 0000	21.6	55.7	920	140	"
12 / 0600	21.7	56.6	920	140	"
12 / 1200	21.6	57.4	920	140	"
12 / 1800	21.7	58.2	920	140	"
13 / 0000	21.8	59.1	925	135	"
13 / 0600	21.9	60.1	935	130	"

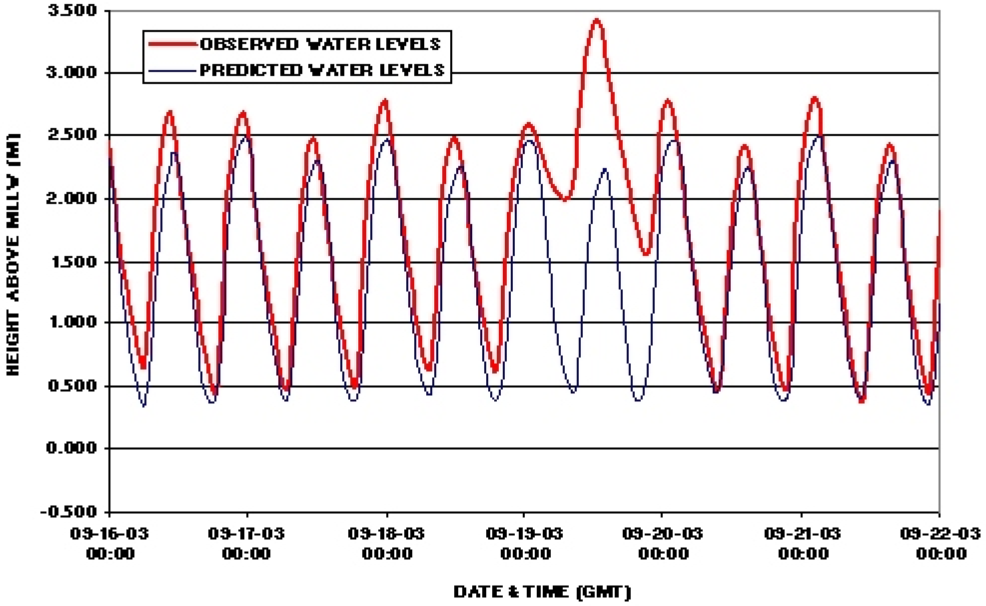
Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
13 / 1200	22.1	61.0	935	135	"
13 / 1800	22.5	62.1	932	140	"
14 / 0000	22.9	63.3	935	135	"
14 / 0600	23.2	64.6	939	135	"
14 / 1200	23.5	65.8	935	135	"
14 / 1800	23.9	67.0	933	140	"
15 / 0000	24.3	67.9	937	130	"
15 / 0600	24.5	68.8	940	125	"
15 / 1200	24.8	69.4	946	120	"
15 / 1800	25.3	69.8	949	115	"
16 / 0000	25.7	70.2	952	105	"
16 / 0600	26.3	70.5	955	100	"
16 / 1200	26.8	70.9	959	95	"
16 / 1800	27.4	71.2	959	95	"
17 / 0000	28.1	71.5	957	95	"
17 / 0600	28.9	71.9	957	95	"
17 / 1200	29.7	72.5	957	90	"
17 / 1800	30.6	73.0	955	90	"
18 / 0000	31.5	73.5	953	90	"
18 / 0600	32.5	74.3	956	90	"
18 / 1200	33.7	75.2	956	90	"
18 / 1800	35.1	76.4	958	85	"
19 / 0000	36.7	77.7	969	65	"
19 / 0600	38.6	78.9	988	50	tropical storm
19 / 1200	40.9	80.3	997	35	extratropical
19 / 1800	43.9	80.9	1000	30	"
20 / 0000	48.0	81.0	1000	25	"
20 / 0600					absorbed by extratropical low
11 / 1800	21.5	54.8	915	145	minimum pressure
18 / 1700	34.9	76.2	957	90	landfall at Drum Inlet, North Carolina

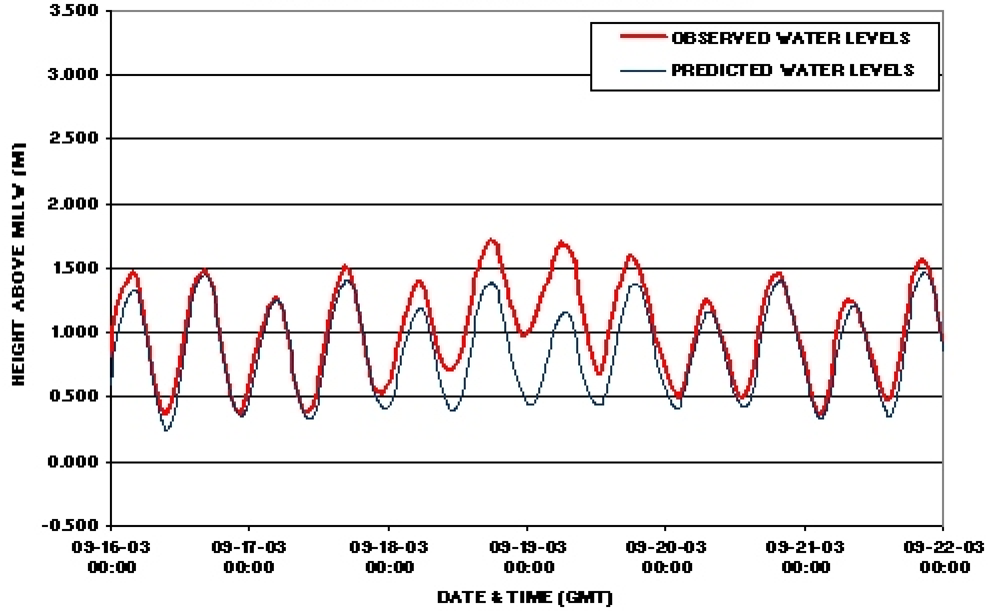

Wind Speed vs Barometric Pressure for Hurricane Isabel 9-19 September 2003
(National Hurricane Center Advisory Data)
Wind Speed (mph)
180
160
140
120
100
80
60
40
20
0
Barometric Pressure (mb)
1020
1000
980
960
940
920
900
880
860
Wind Speed (mph)
Pressure (mb)
06-09-03 1300
06-09-03 2100
07-09-03 0900
07-09-03 2100
08-09-03 0900
08-09-03 2100
09-09-03 0900
09-09-03 2100
10-09-03 0900
10-09-03 2100
11-09-03 0900
11-09-03 2100
12-09-03 0900
12-09-03 2100
13-09-03 0900
13-09-03 2100
14-09-03 0900
14-09-03 2100
15-09-03 0900
15-09-03 2100
16-09-03 0900
16-09-03 2100
17-09-03 0900
17-09-03 2100
18-09-03 0900
18-09-03 2100
19-09-03 0900
Date & Time (UTC)

Appendix II

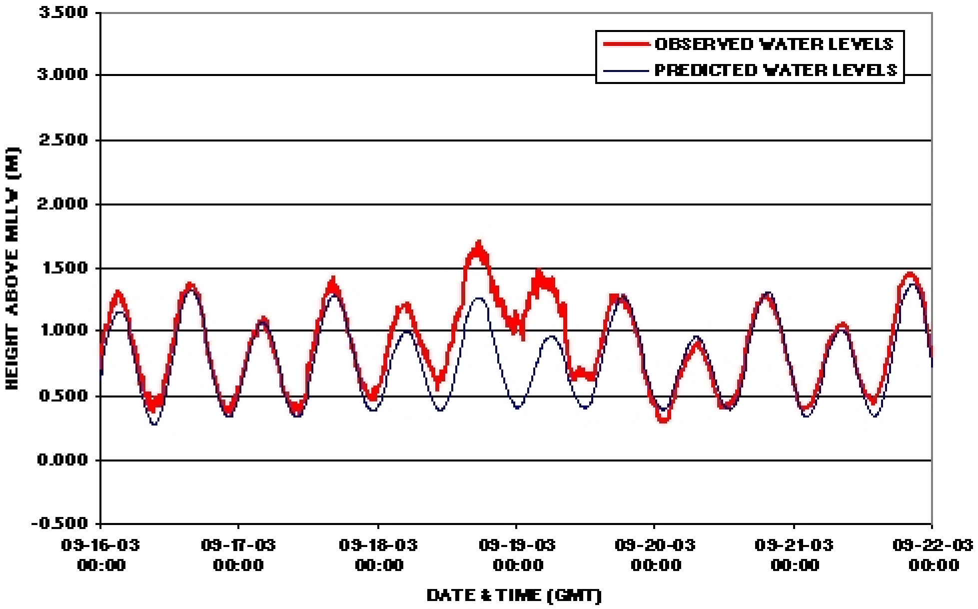
Time series of observed water level and predicted tide at CO-OPS water level stations


OBSERVED VS PREDICTED WATER LEVELS
8539094 BURLINGTON, DELAWARE RIVER NJ
PEAK ELEVATION 09-19-03 12:06 3.216 (M) 10.55 (FT)


OBSERVED VS PREDICTED WATER LEVELS
8548989 NEWBOLD, DELAWARE RIVER PA
PEAK ELEVATION 09-19-03 12:30 3.402 (M) 11.16 (FT)

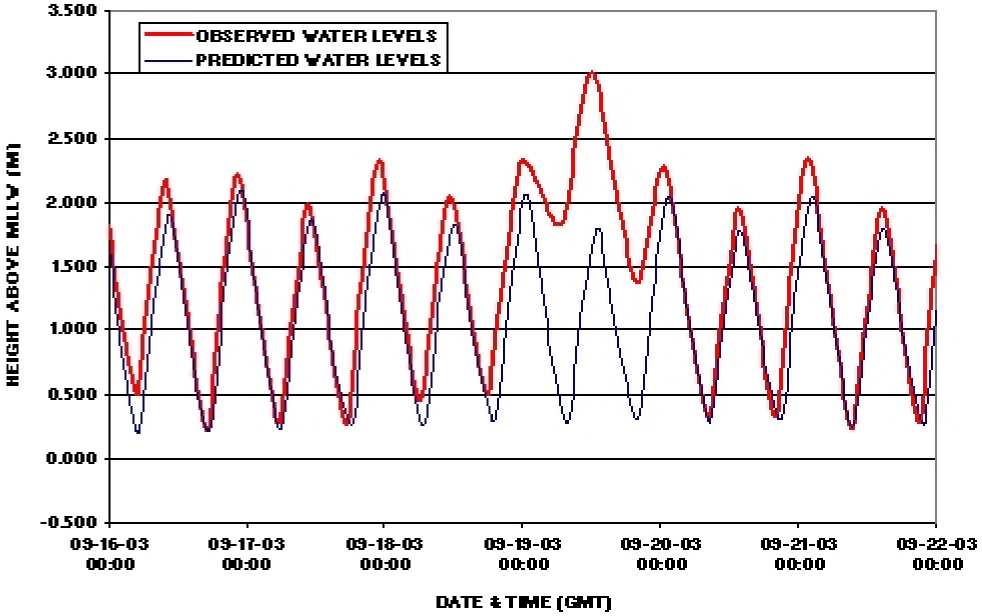


OBSERVED VS PREDICTED WATER LEVELS
8531680 SANDY HOOK NJ
PEAK ELEVATION 09-18-03 18:06 1.719 (M) 5.64 (FT)

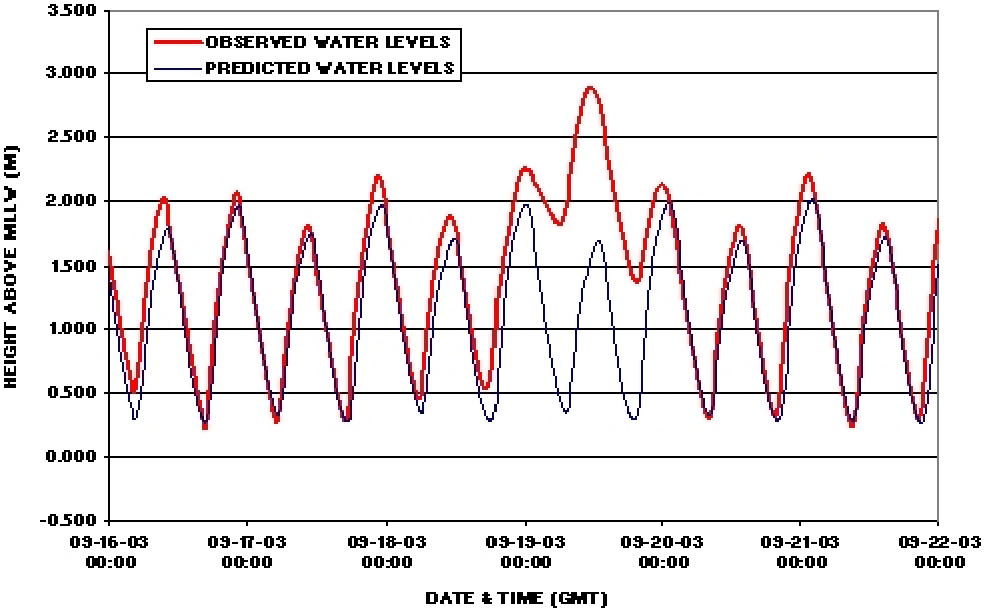


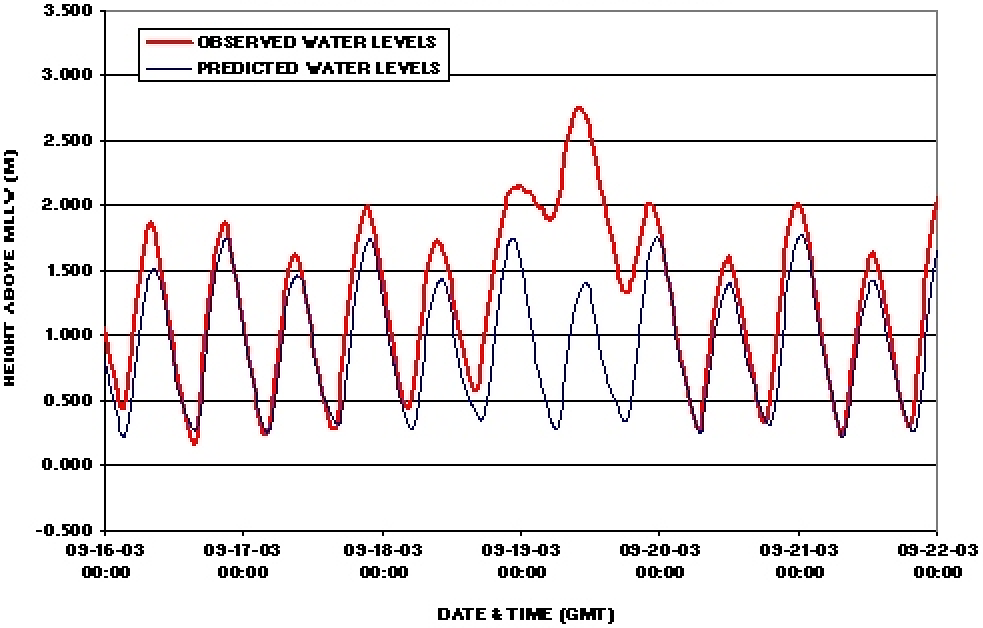
OBSERVED VS PREDICTED WATER LEVELS
8534720 ATLANTIC CITY, NJ
PEAK ELEVATION 09-18-03 17:36 1.724 (M) 5.65 (FT)

OBSERVED VS PREDICTED WATER LEVELS
8538886 TACONY-PALMYRA BRIDGE NJ
PEAK ELEVATION 09-19-03 12:06 3.007 (M) 9.86 (FT)

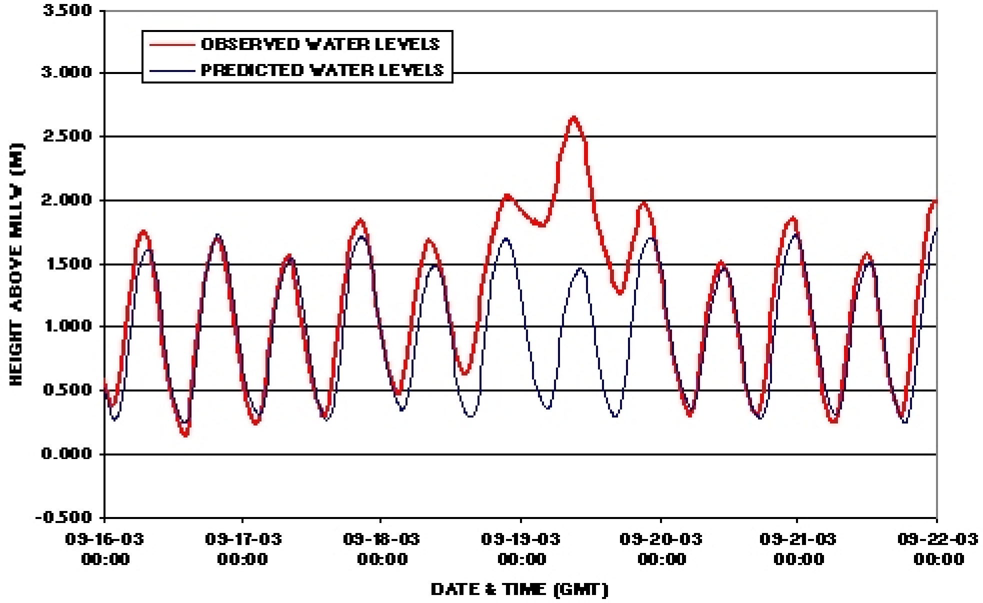


OBSERVED VS PREDICTED WATER LEVELS
8545240 PHILADELPHIA, DELAWARE RIVER PA
PEAK ELEVATION 09-19-03 11:36 2.887 (M) 9.47 (FT)



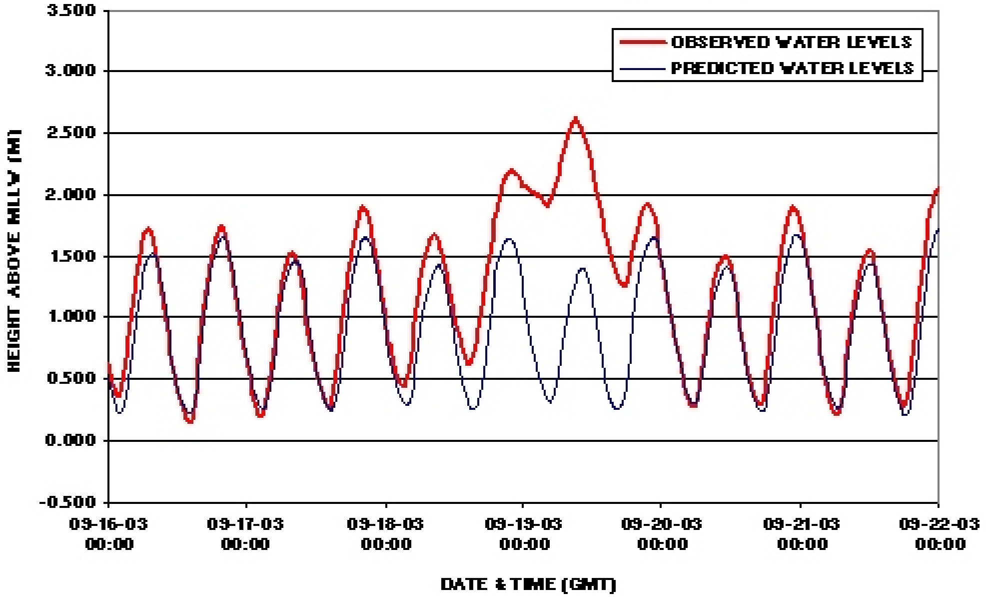


OBSERVED VS PREDICTED WATER LEVELS
8540433 MARCUS HOOK PA
PEAK ELEVATION 9-19-03 9:54 2.756 (M) 9.02 (FT)

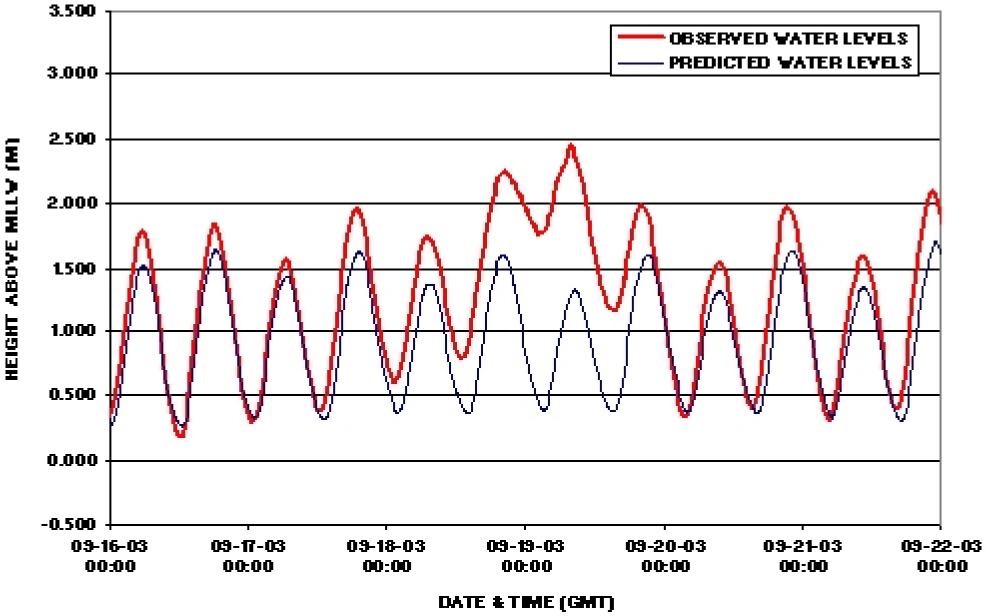


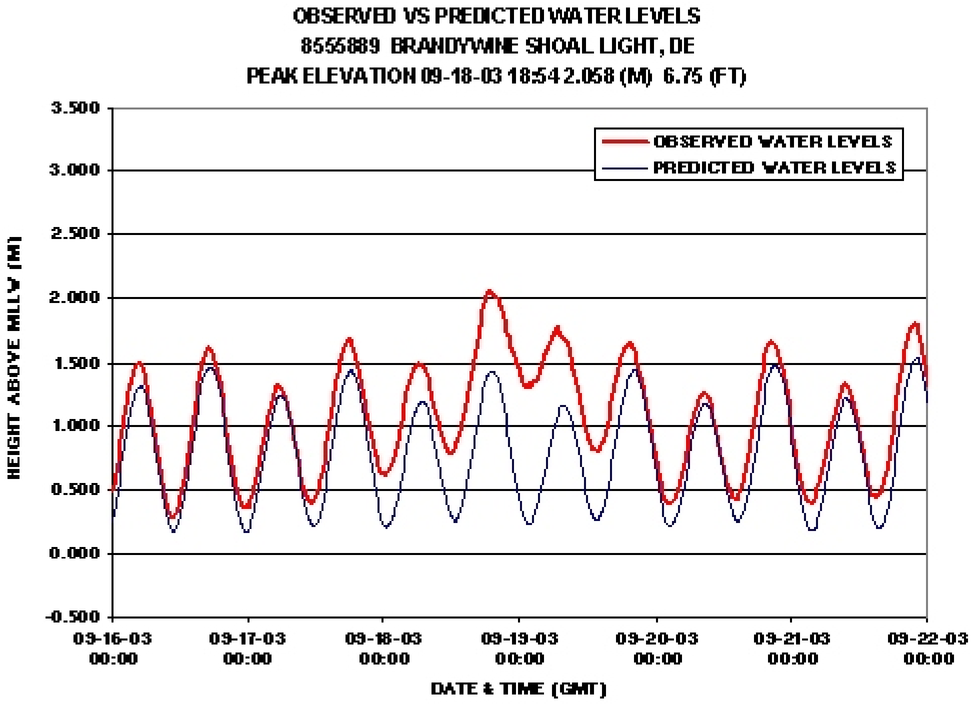
OBSERVED VS PREDICTED WATER LEVELS
8551910 REEDY POINT, C&D Canal DE
PEAK ELEVATION 09-19-03 09:12 2.640 (M) 8.66 (FT)

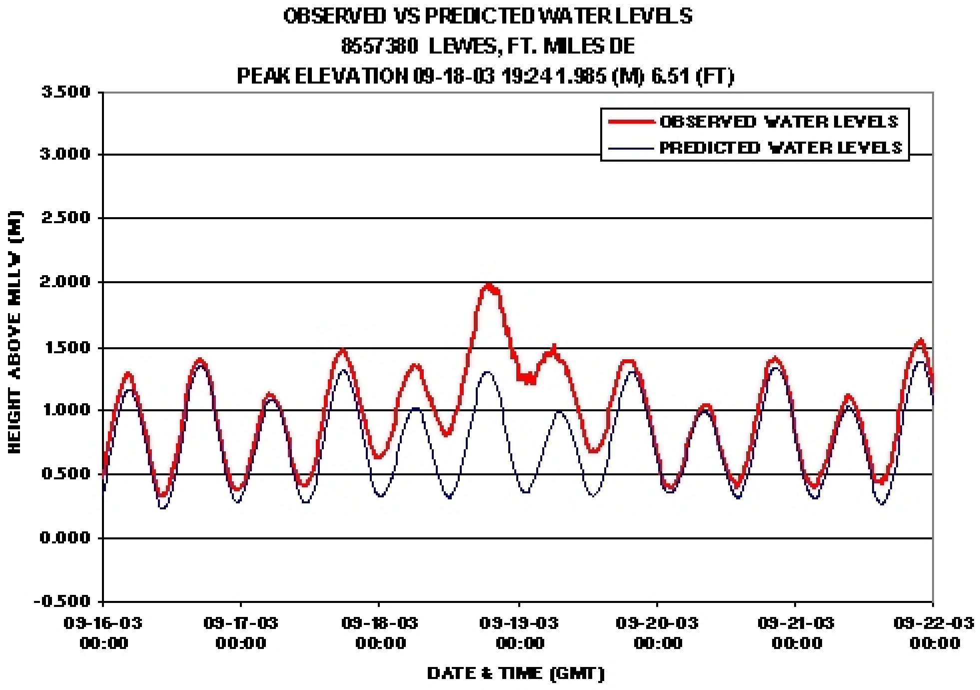
OBSERVED VS PREDICTED WATER LEVELS
8551762 DELAWARE CITY, DELAWARE RIVER DE
PEAK ELEVATION 09-19-03 09:06 2.628 (M) 8.62 (FT)



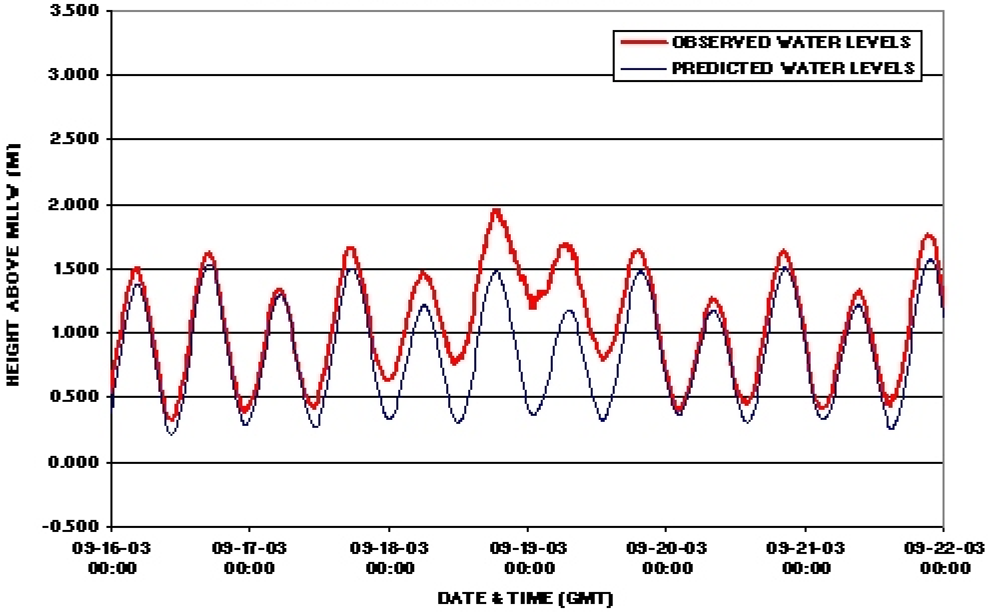
OBSERVED VS PREDICTED WATER LEVELS
8537121 SHIP JOHN SHOAL, NJ
PEAK ELEVATION 09-19-03 07:48 2.447 (M) 8.03 (FT)



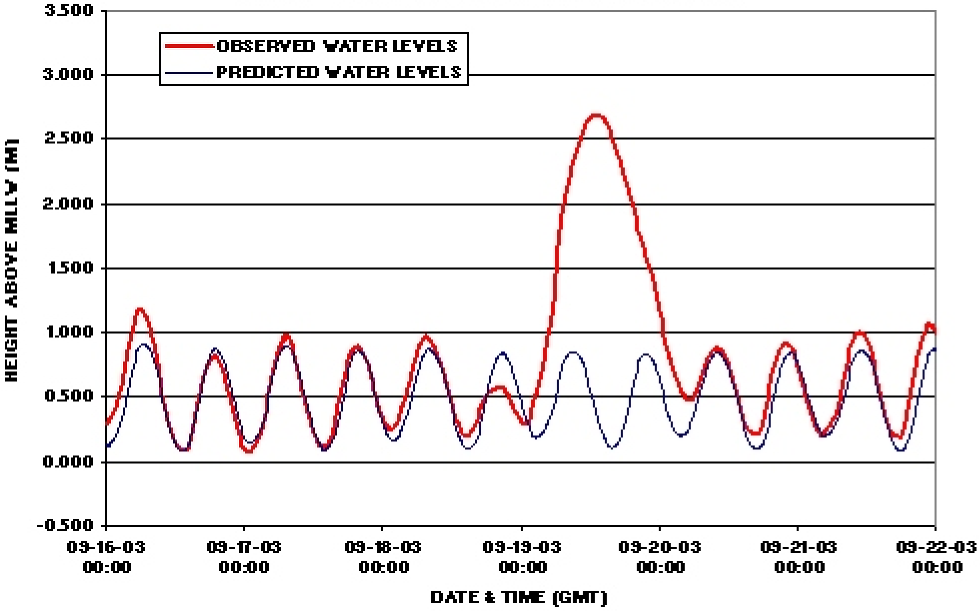

OBSERVED VS PREDICTED WATER LEVELS
8555889 BRANDYWINE SHOAL LIGHT, DE
PEAK ELEVATION 09-18-03 18:54 2.058 (M) 6.75 (FT)

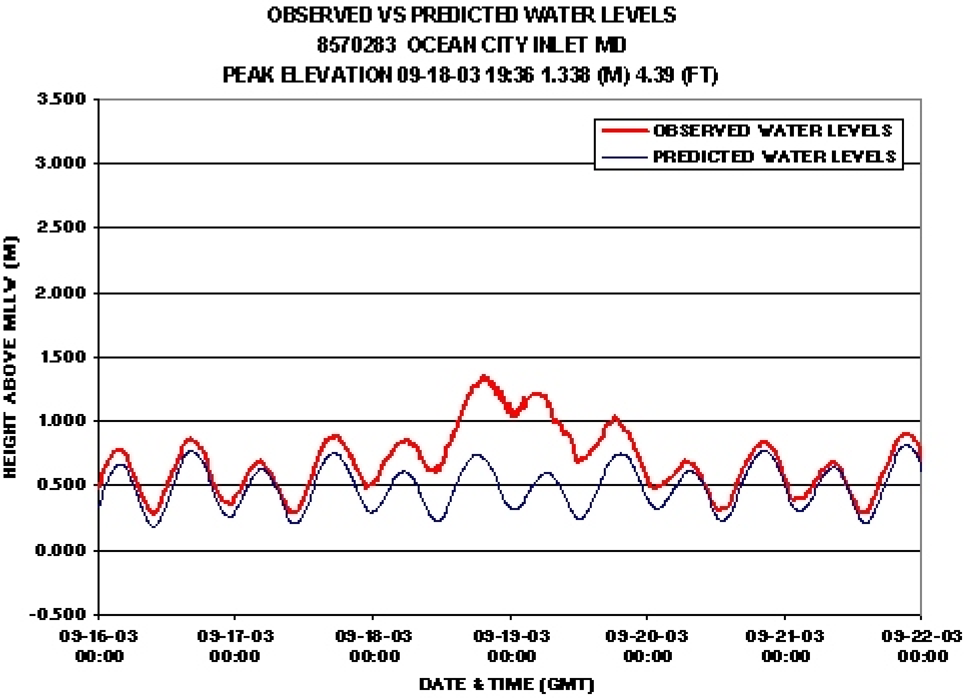

OBSERVED VS PREDICTED WATER LEVELS
8557380 LEWES, FT. MILES DE
PEAK ELEVATION 09-18-03 19:24 1.985 (M) 6.51 (FT)

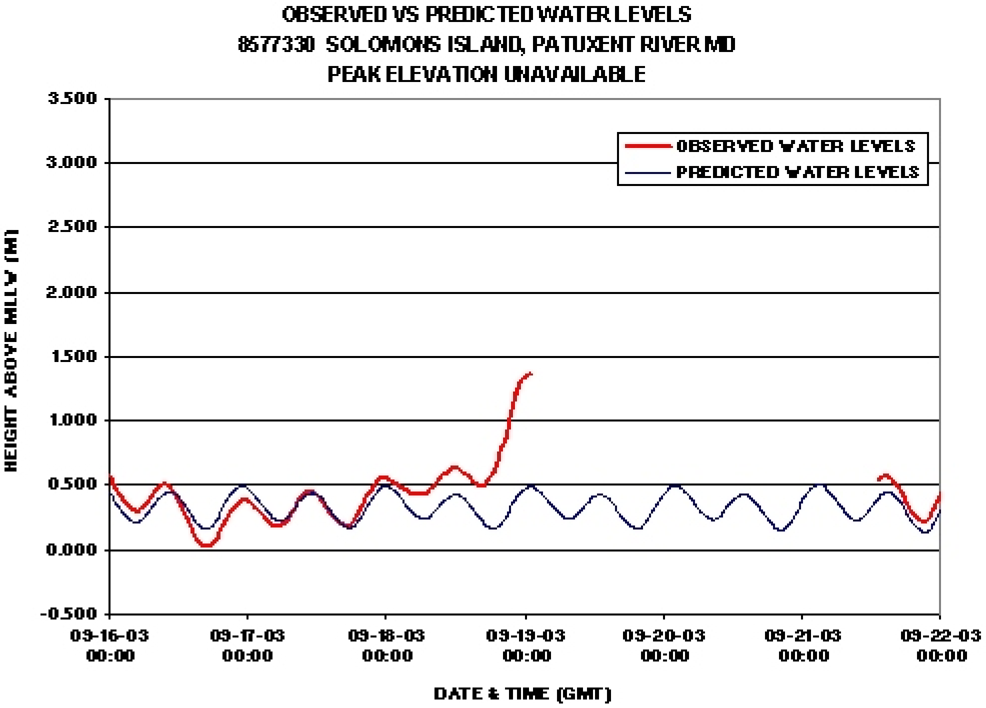
OBSERVED VS PREDICTED WATER LEVELS
8536110 CAPE MAY, NJ
PEAK ELEVATION 09-18-03 18:54 1.965 (M) 6.45 (FT)



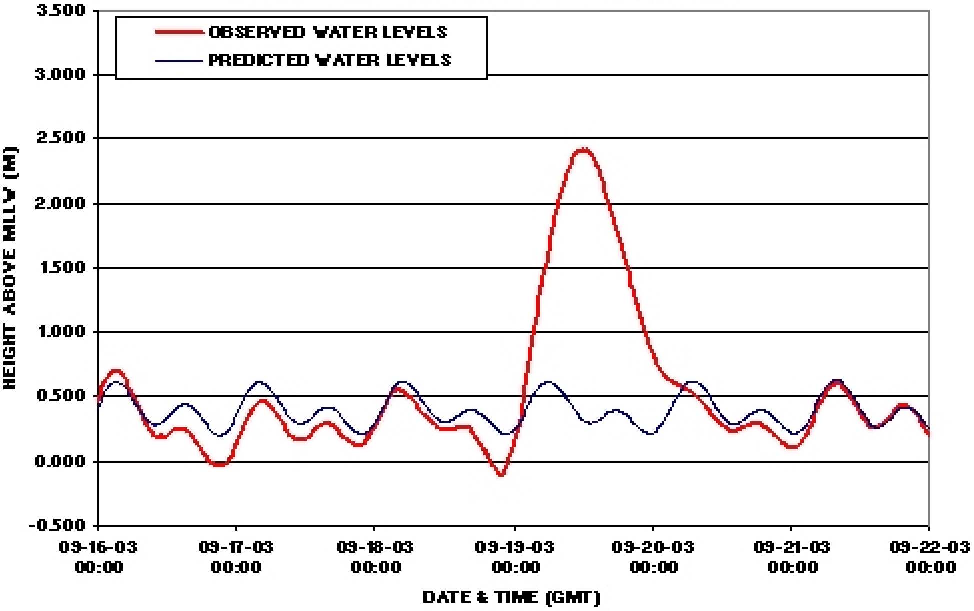
OBSERVED VS PREDICTED WATER LEVELS
8573927 CHESAPEAKE CITY MD
PEAK ELEVATION 09-19-03 13:12 2.670 (M) 8.76 (FT)



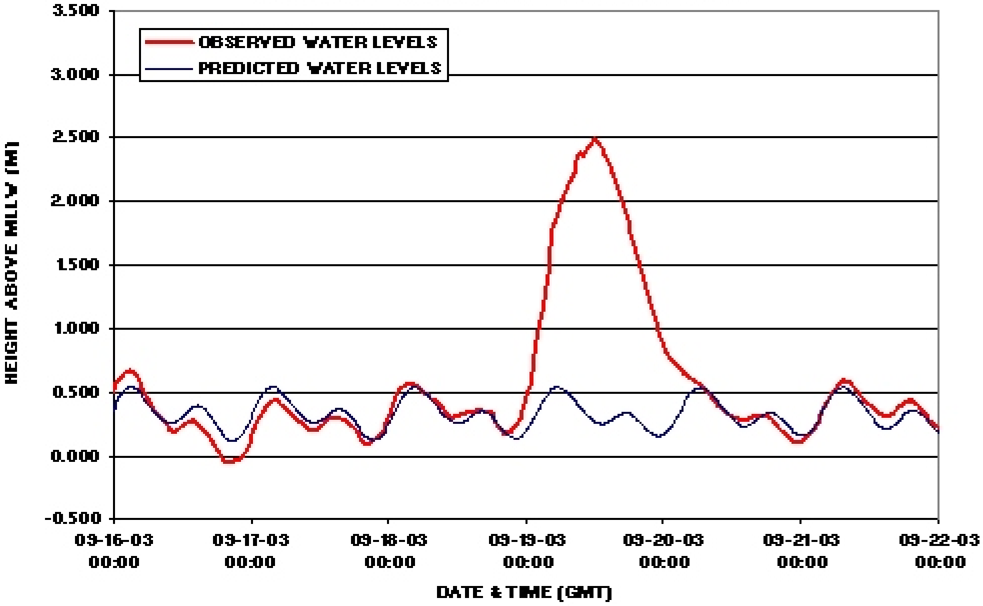

OBSERVED VS PREDICTED WATER LEVELS
8570283 OCEAN CITY INLET MD
PEAK ELEVATION 09-18-03 19:36 1.338 (M) 4.39 (FT)


OBSERVED VS PREDICTED WATER LEVELS
8577330 SOLOMONS ISLAND, PATUXENT RIVER MD
PEAK ELEVATION UNAVAILABLE

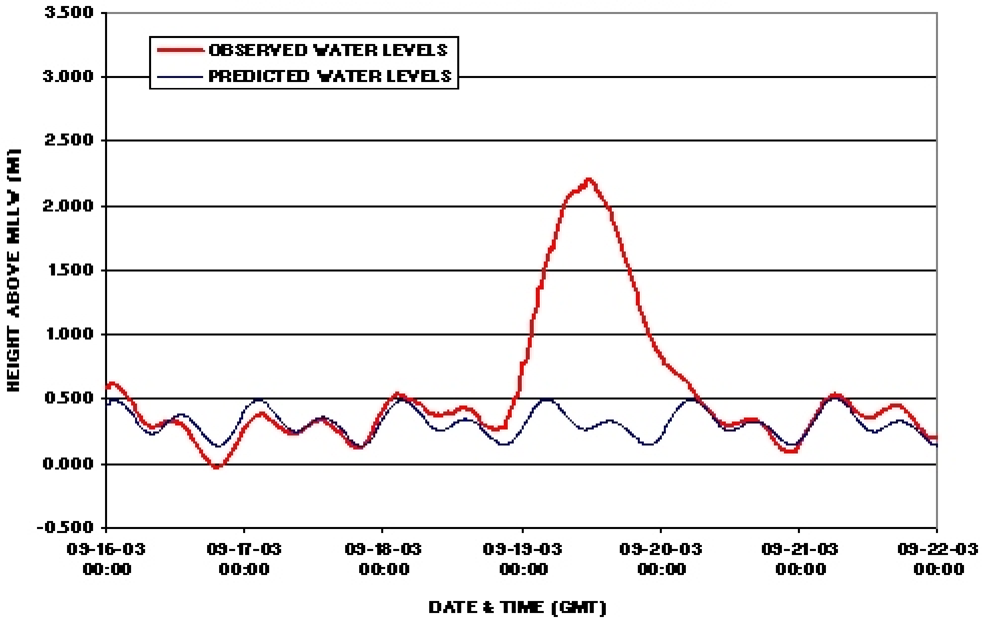
OBSERVED VS PREDICTED WATER LEVELS
8573364 TOLCHESTER BEACH, MD
PEAK ELEVATION 09-19-03 12:42 2.411 (M) 7.91 (FT)



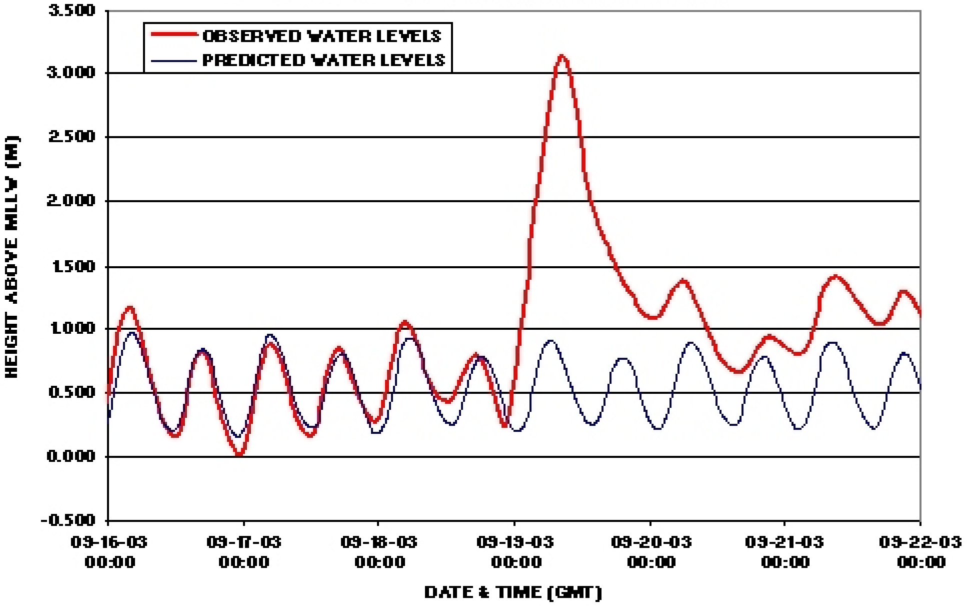
OBSERVED VS PREDICTED WATER LEVELS
8574680 BALTIMORE, FORT MCHENRY, MD
PEAK ELEVATION 09-19-03 12:06 2.483 (M) 8.14 (FT)



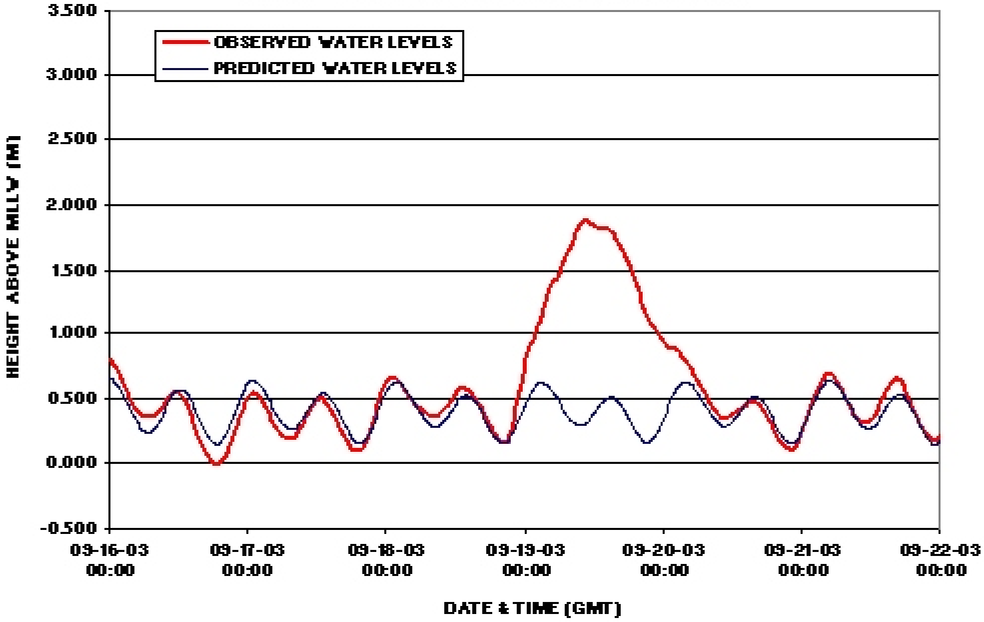
OBSERVED VS PREDICTED WATER LEVELS
8575512 ANNAPOLIS, MD
PEAK ELEVATION 09-19-03 11:42 2.195 (M) 7.20 (FT)



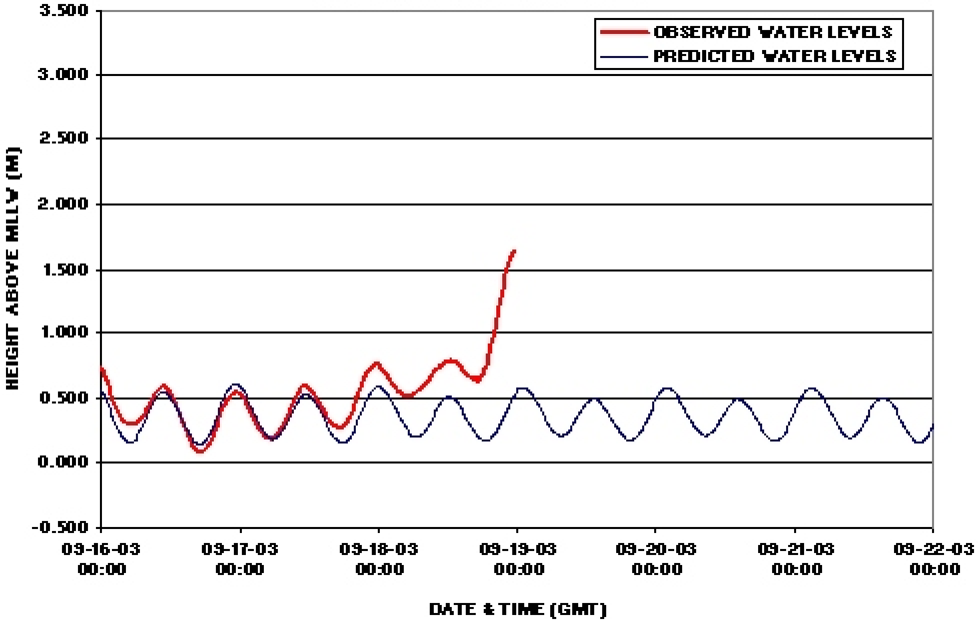
OBSERVED AND BACKUP VS PREDICTED WATER LEVELS
8594900 WASHINGTON, POTOMAC RIVER DC
PEAK ELEVATION 09-19-03 08:42 3.135 (M) 10.28 (FT)

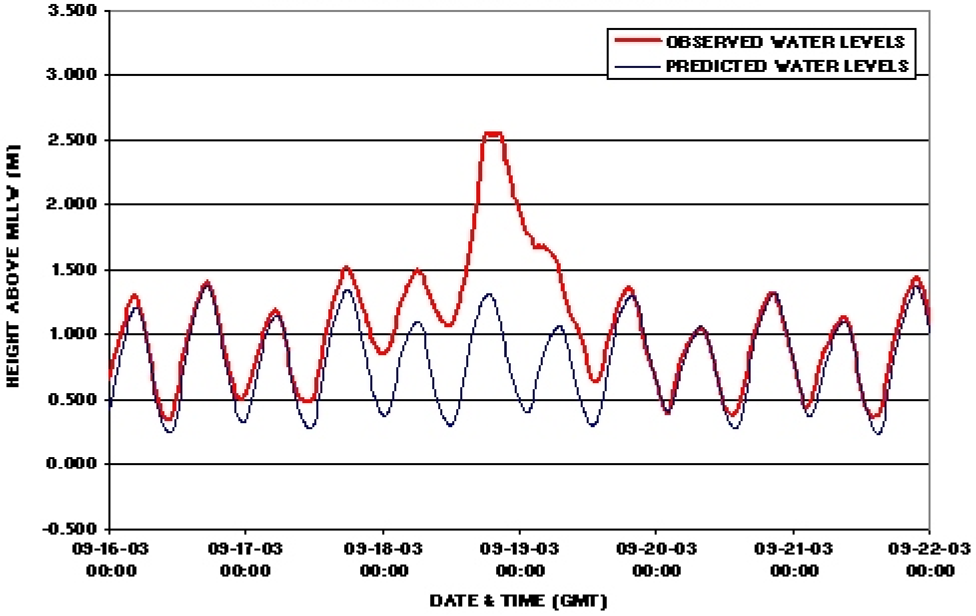


OBSERVED VS PREDICTED WATER LEVELS
8571892 CAMBRIDGE, CHOPTANK RIVER MD
PEAK ELEVATION 09-19-03 10:48 1.884 (M) 6.18 (FT)

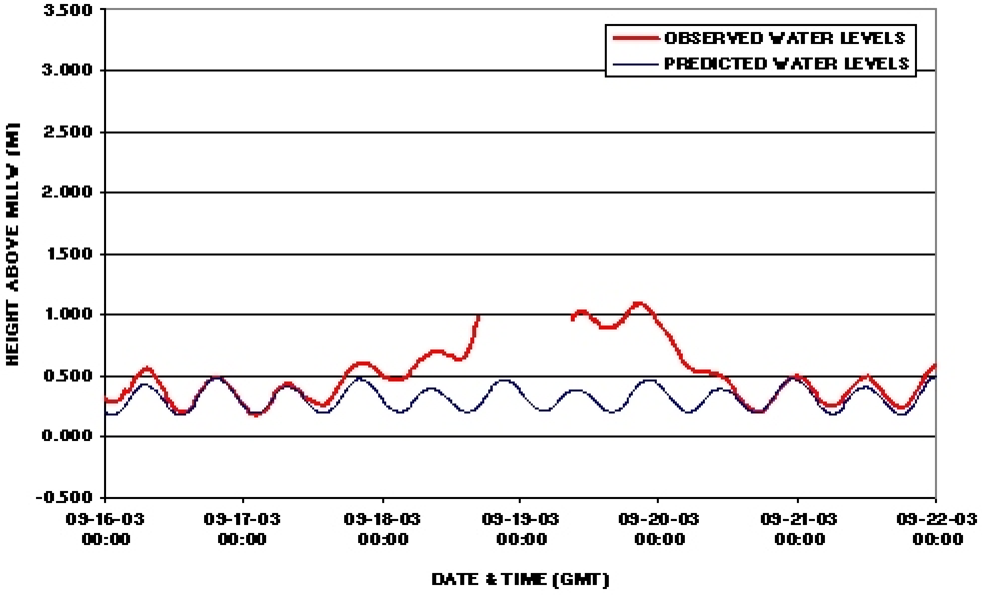


OBSERVED VS PREDICTED WATER LEVELS
8635150 COLONIAL BEACH, VA
PEAK ELEVATION UNAVAILABLE

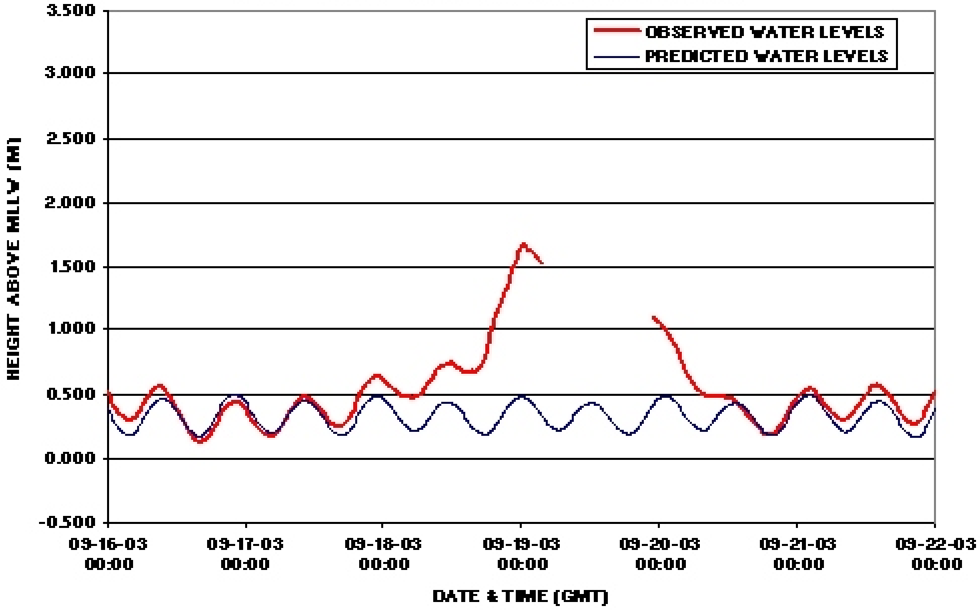




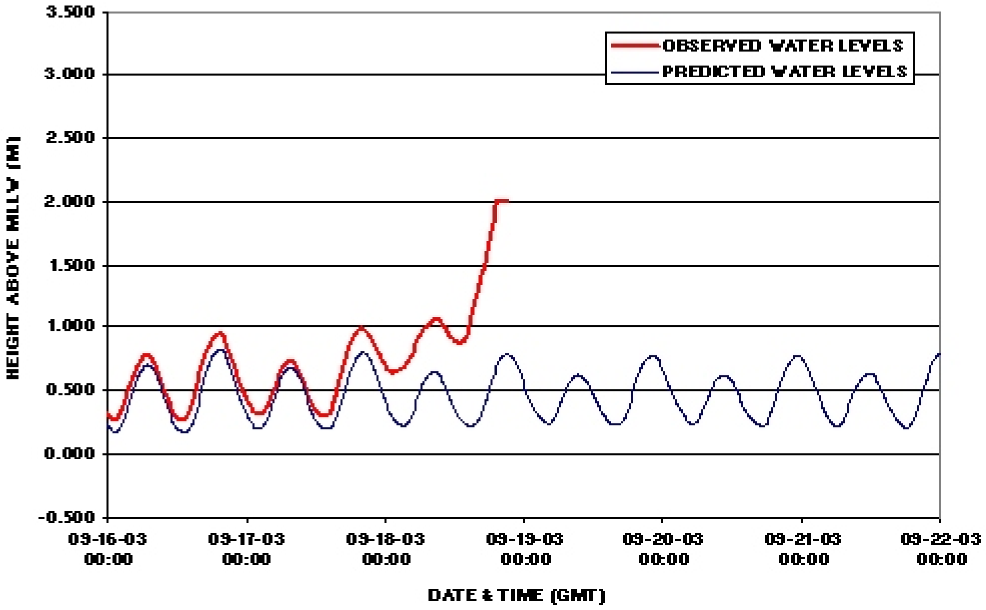
OBSERVED VS PREDICTED WATER LEVELS
8631044 WACHAPREAGUE, VA
PEAK ELEVATION 09-18-03 20:42 2.559 (M) 8.39 (FT)



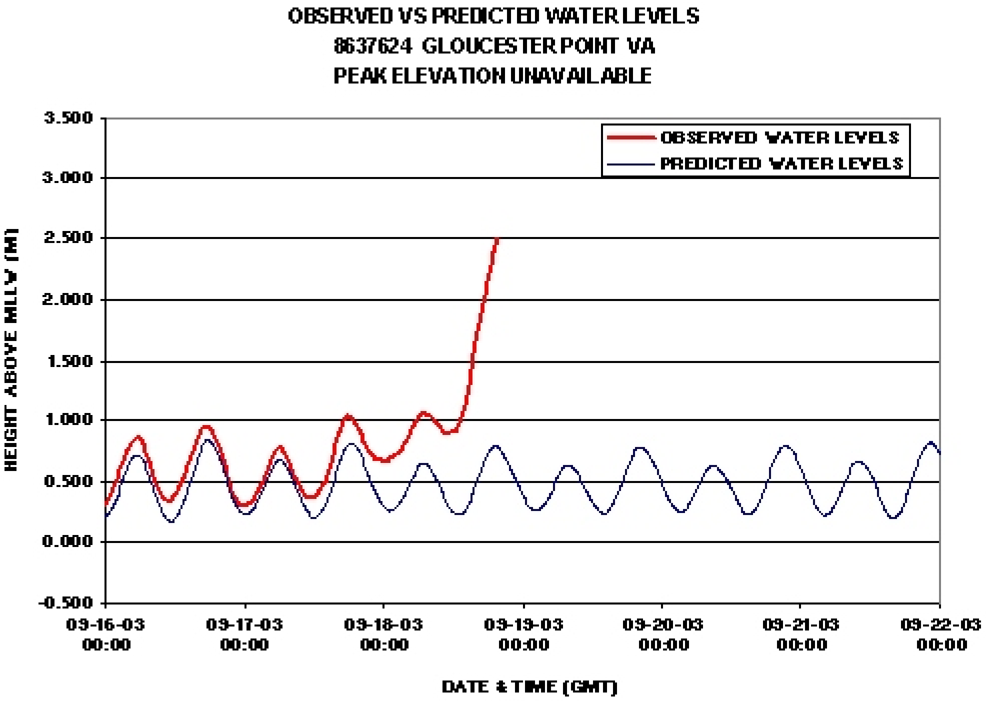
OBSERVED VS PREDICTED WATER LEVELS
8636580 WINDMILL POINT, VA
PEAK ELEVATION UNAVAILABLE

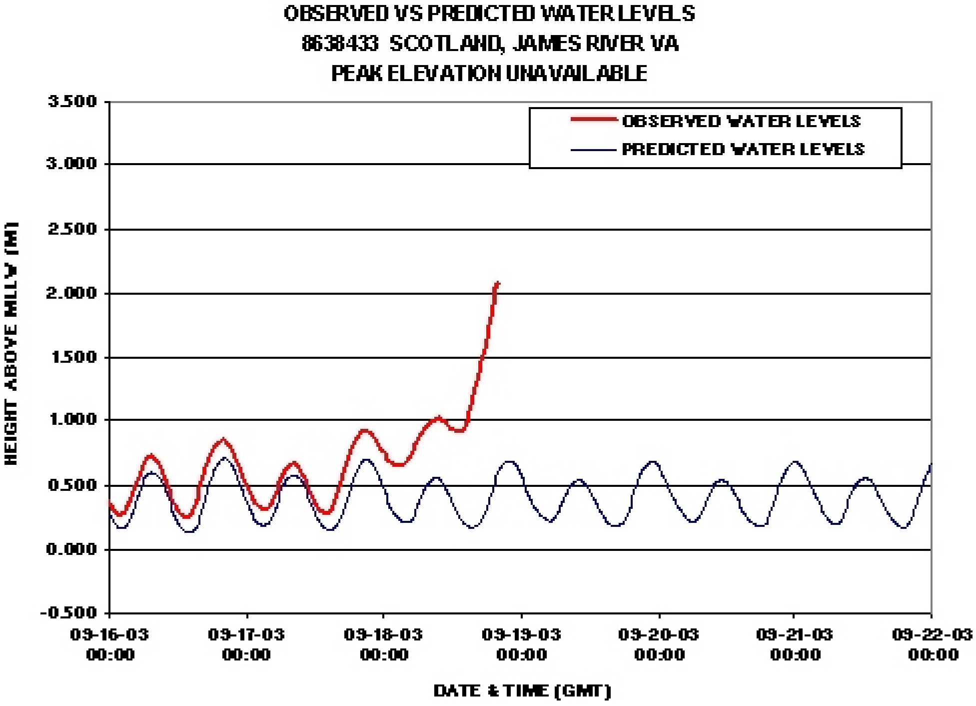


OBSERVED VS PREDICTED WATER LEVELS
8635750 LEWISETTA, POTOMAC RIVER VA
PEAK ELEVATION 09-19-03 00:36 1.668 (M) 5.47 (FT)

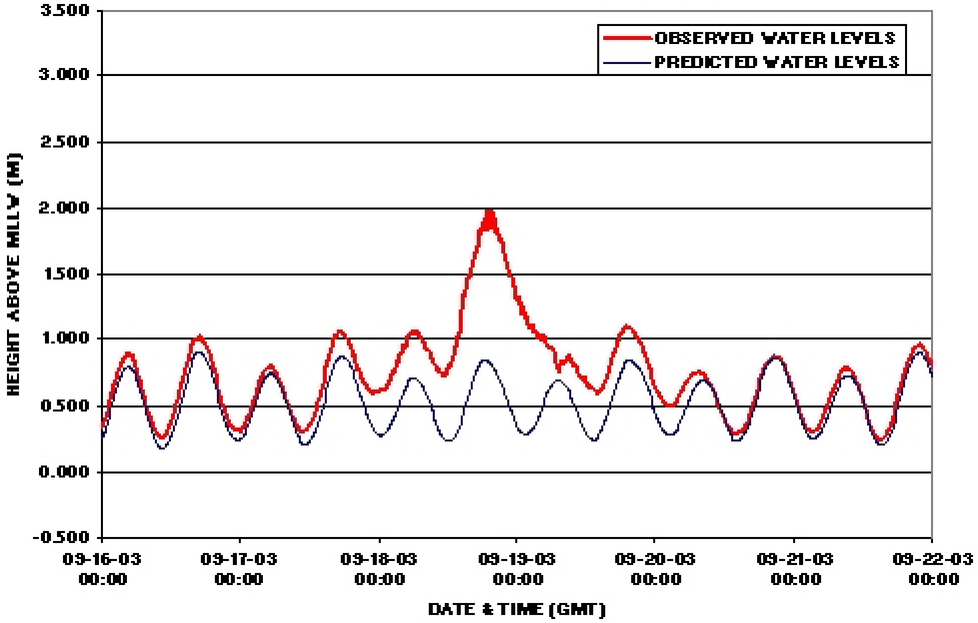


OBSERVED VS PREDICTED WATER LEVELS
8638424 KINGSMILL, JAMES RIVER VA
PEAK ELEVATION UNAVAILABLE

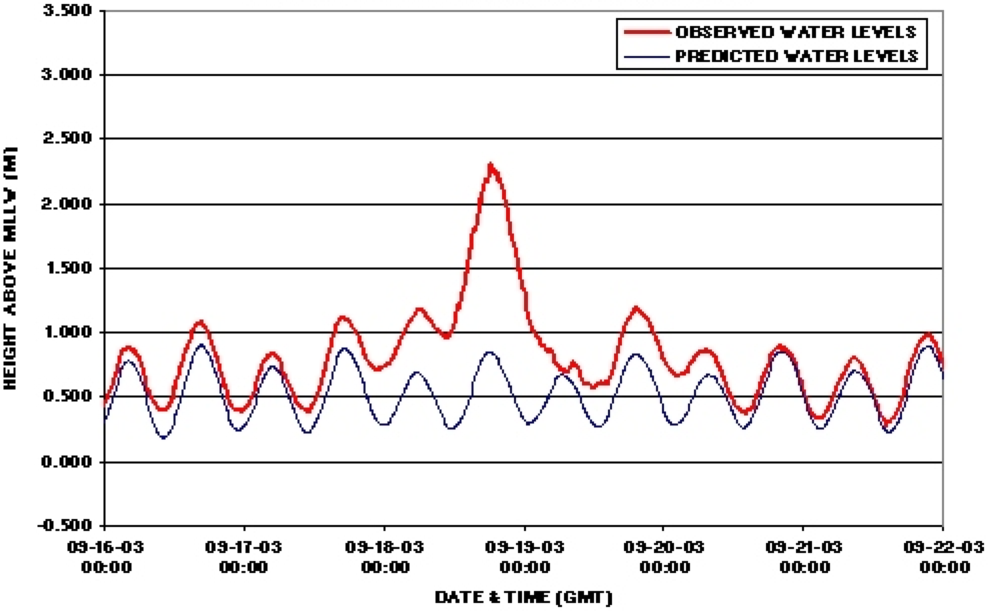

OBSERVED VS PREDICTED WATER LEVELS
8637624 GLOUCESTER POINT VA
PEAK ELEVATION UNAVAILABLE
OBSERVED WATER LEVELS
PREDICTED WATER LEVELS
HEIGHT ABOVE MLLW (M)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
09-16-03 00:00
09-17-03 00:00
09-18-03 00:00
09-19-03 00:00
09-20-03 00:00
09-21-03 00:00
09-22-03 00:00
DATE & TIME (GMT)

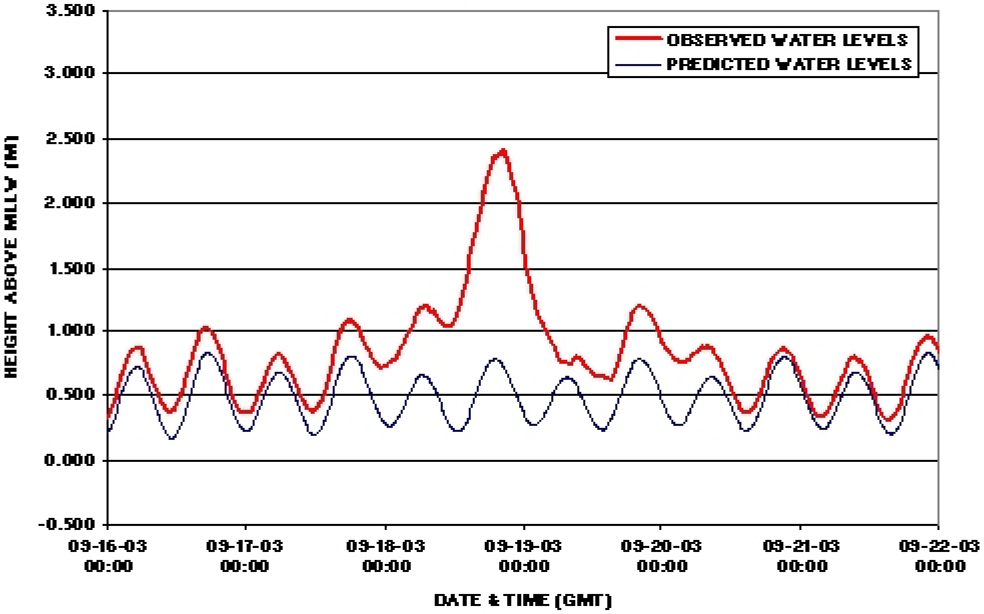

OBSERVED VS PREDICTED WATER LEVELS
8638433 SCOTLAND, JAMES RIVER VA
PEAK ELEVATION UNAVAILABLE
OBSERVED WATER LEVELS
PREDICTED WATER LEVELS
HEIGHT ABOVE MLLW (M)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
09-16-03 00:00
09-17-03 00:00
09-18-03 00:00
09-19-03 00:00
09-20-03 00:00
09-21-03 00:00
09-22-03 00:00
DATE & TIME (GMT)

OBSERVED VS PREDICTED WATER LEVELS
8632200 KIPTOPEKE, CHESAPEAKE BAY VA
PEAK ELEVATION 09-18-03 19:54 1.986 (M) 6.51 (FT)

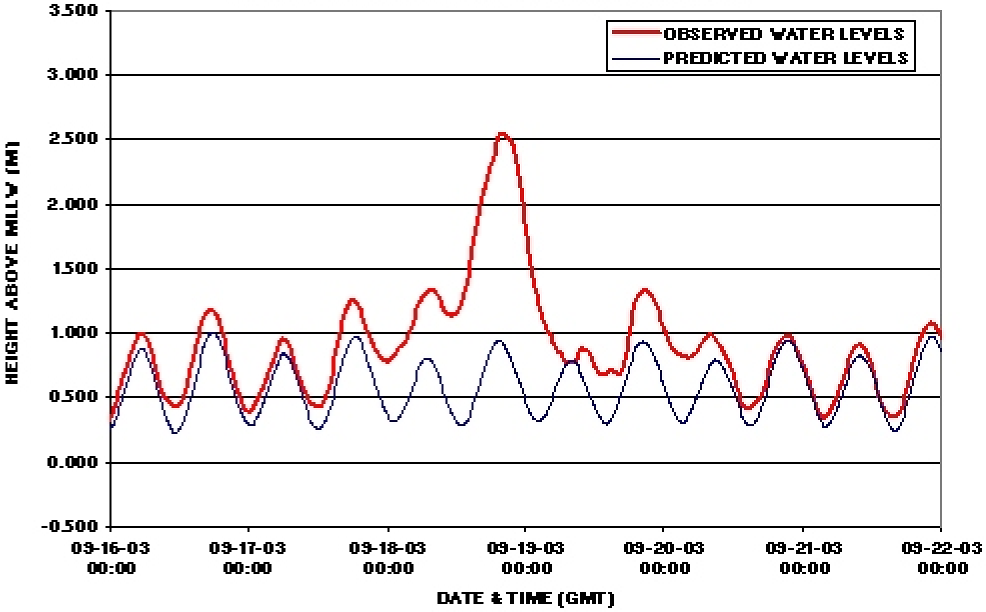


OBSERVED VS PREDICTED WATER LEVELS
8638863 CHESAPEAKE BAY BRIDGE TUNNEL VA
PEAK ELEVATION 09-18-03 18:18 2.297 (M) 7.53 (FT)

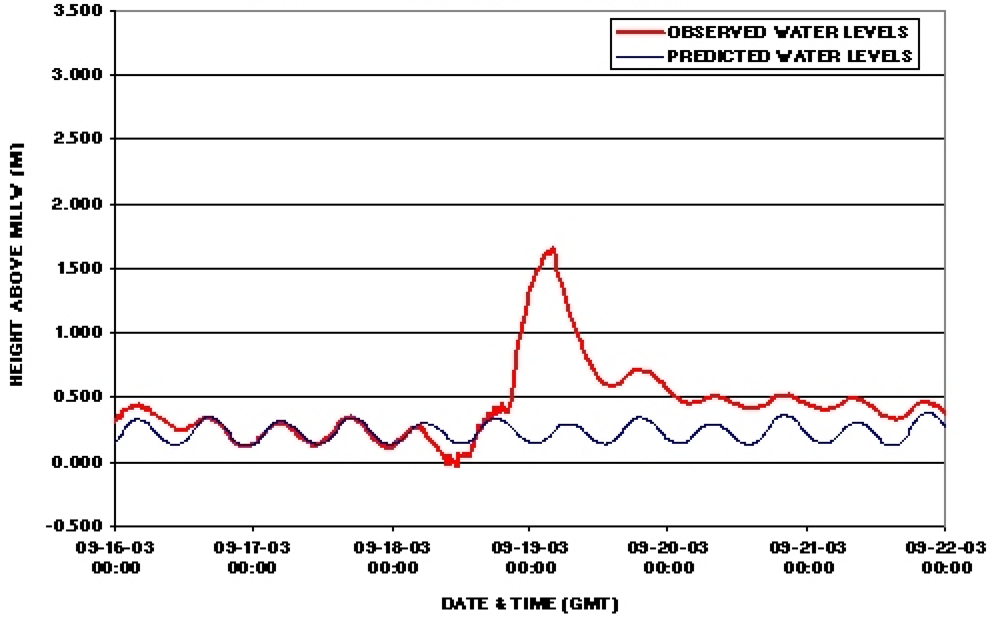




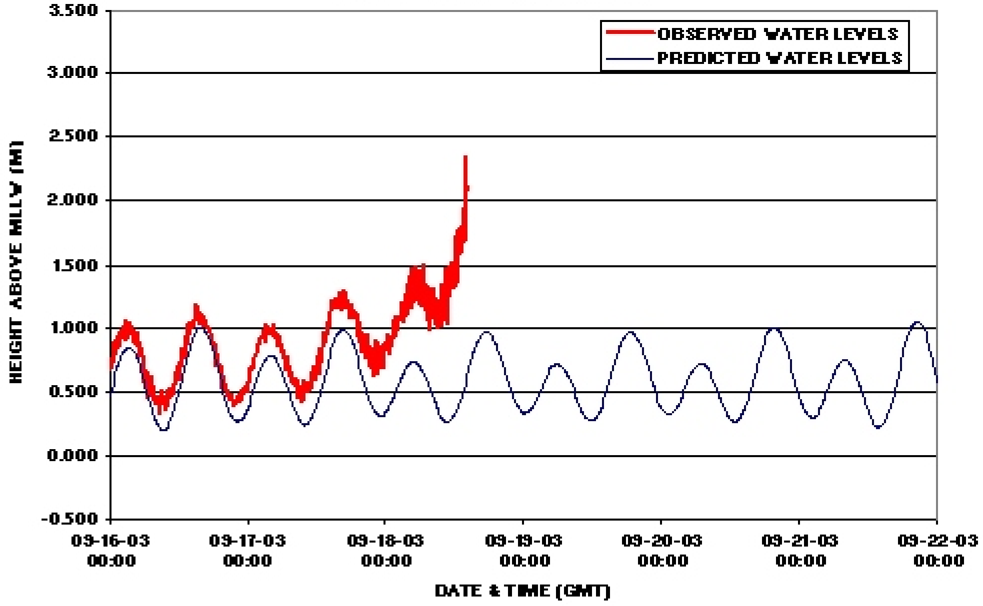
OBSERVED VS PREDICTED WATER LEVELS
8638610 SEWELLS POINT, HAMPTON ROADS VA
PEAK ELEVATION 09-18-03 21:00 2.404 (M) 7.89 (FT)



OBSERVED VS PREDICTED WATER LEVELS
8639348 MONEY POINT, VA
PEAK ELEVATION 09-18-03 19:54 2.539 (M) 8.372 (FT)

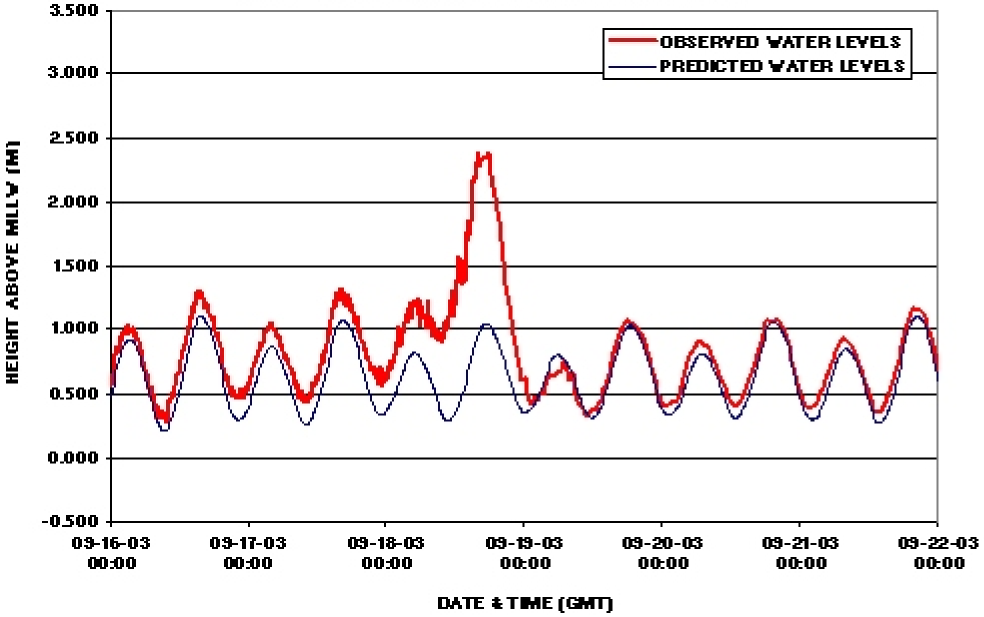


OBSERVED VS PREDICTED WATER LEVELS
8652587 OREGON INLET MARINA, PAMLICO SOUND NC
PEAK ELEVATION 09-19-03 04:00 1.652 (M) 5.42 (FT)

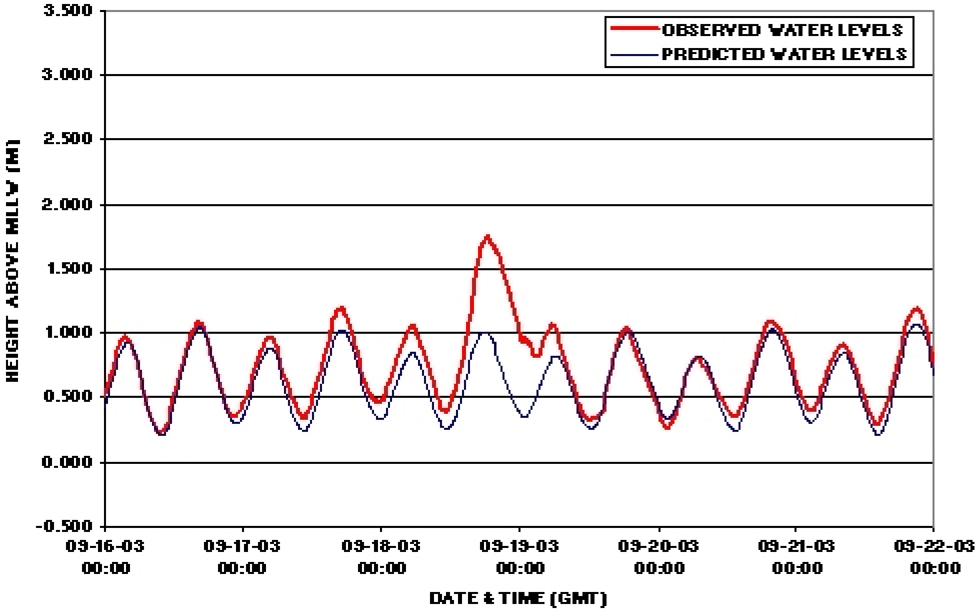


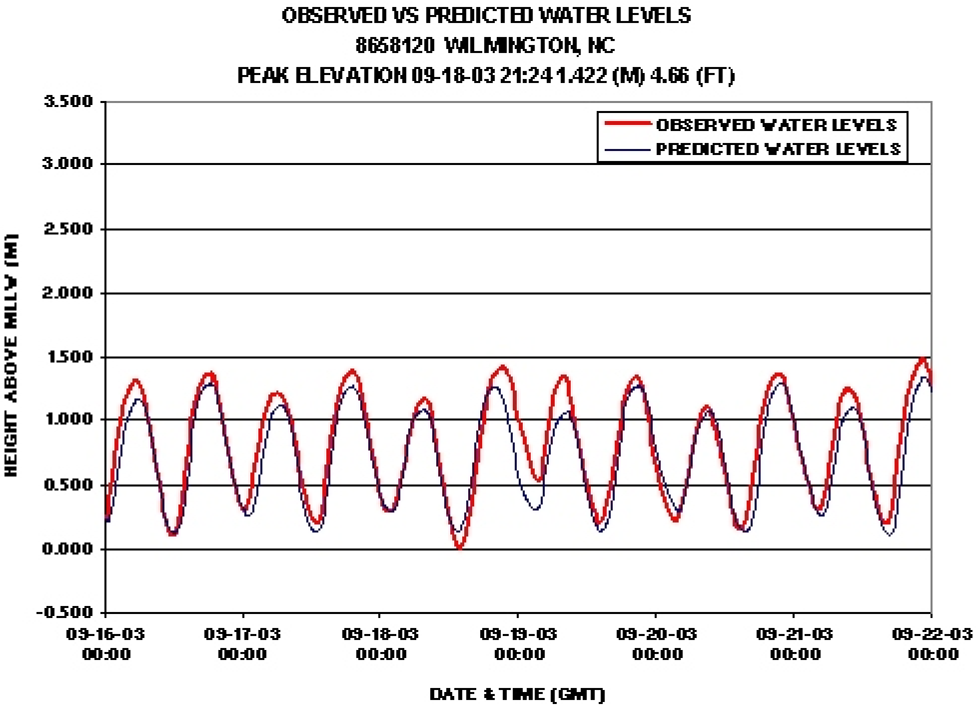
OBSERVED VS PREDICTED WATER LEVELS
8654400 CAPE HATTERAS FISHING PIER NC
PEAK ELEVATION UNAVAILABLE

OBSERVED VS PREDICTED WATER LEVELS
8651370 DUCK, NC
PEAK ELEVATION 09-18-03 16:16 2.383 (M) 7.82 (FT)



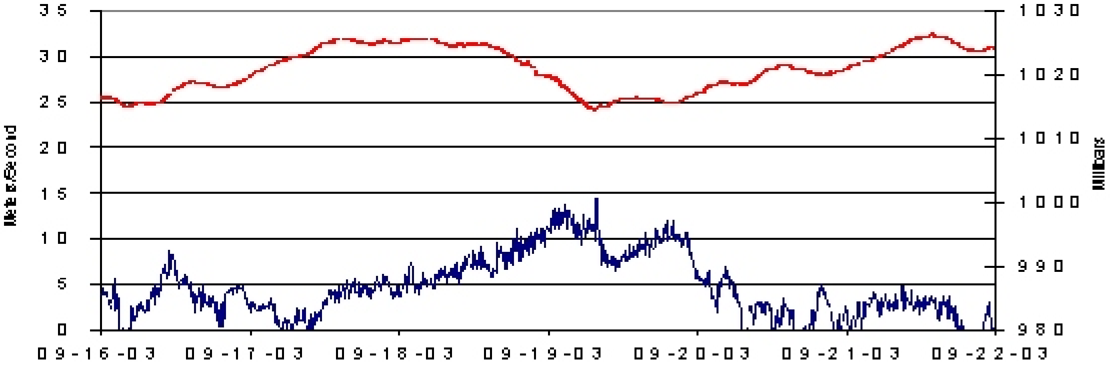
OBSERVED VS PREDICTED WATER LEVELS
8656483 BEAUFORT, DUKE MARINE LAB NC
PEAK ELEVATION 09-18-03 18:42 1.754 (M) 5.75 (FT)



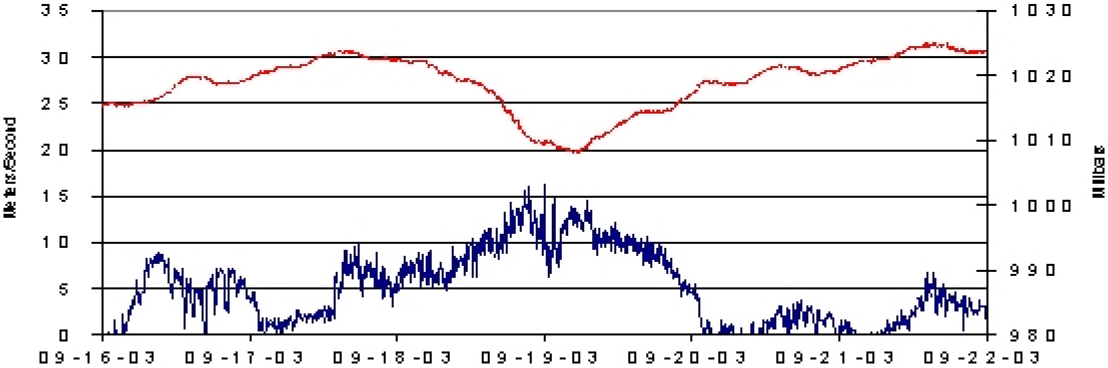

OBSERVED VS PREDICTED WATER LEVELS
8658120 WILMINGTON, NC
PEAK ELEVATION 09-18-03 21:24 1.422 (M) 4.66 (FT)
OBSERVED WATER LEVELS
PREDICTED WATER LEVELS
HEIGHT ABOVE MLLW (M)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
09-16-03 00:00
09-17-03 00:00
09-18-03 00:00
09-19-03 00:00
09-20-03 00:00
09-21-03 00:00
09-22-03 00:00
DATE & TIME (GMT)

Appendix III

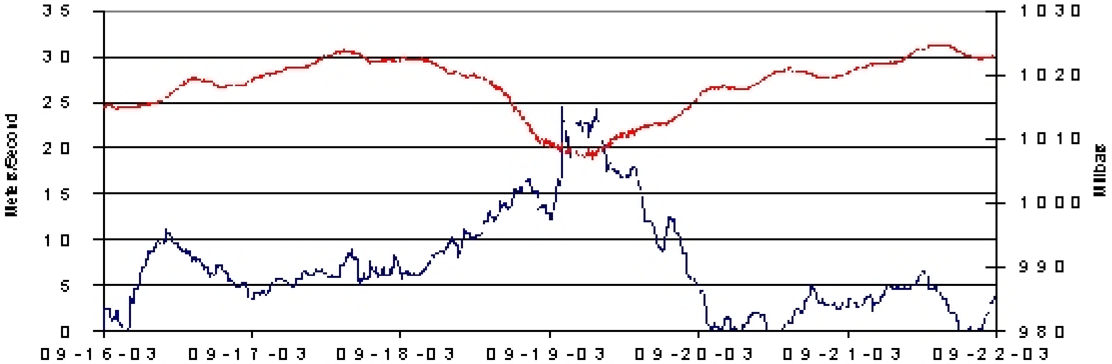
Time series of observed wind speed and barometric pressure at CO-OPS water level stations



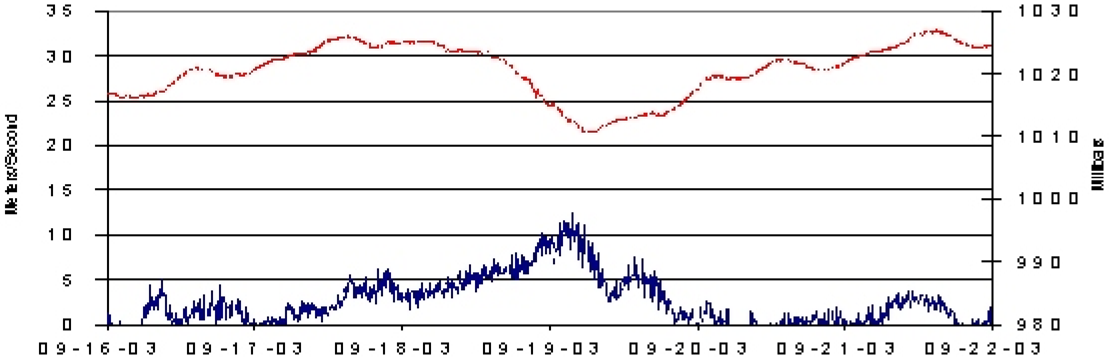
Sandy Hook, NJ wind speed (lower curve), barometric pressure (upper curve).



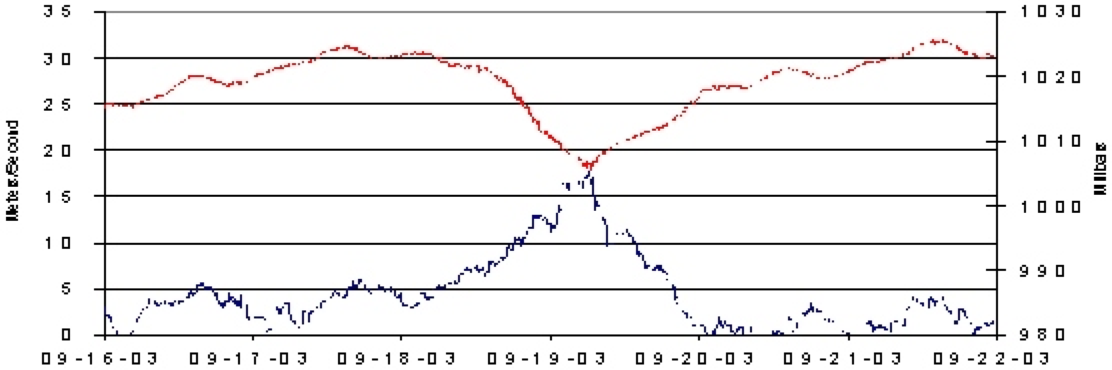
Cape May, NJ wind speed (lower curve), barometric pressure (upper curve).



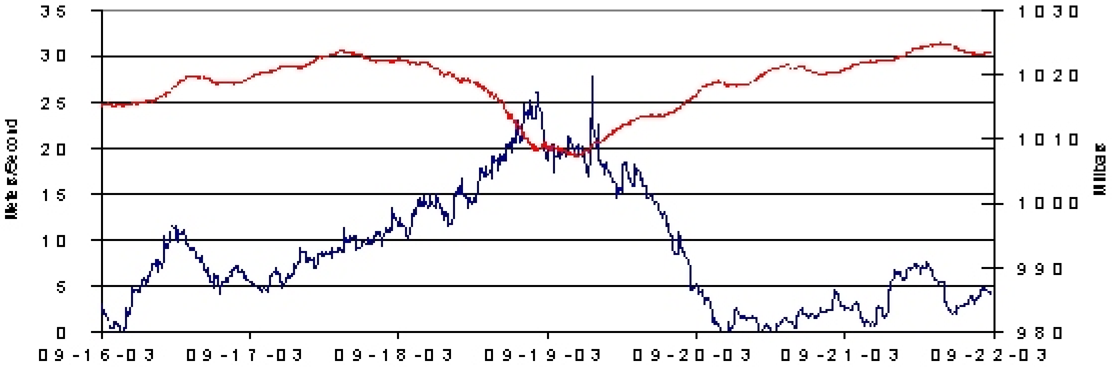
Ship John Shoal, NJ wind speed (lower curve), barometric pressure (upper curve).



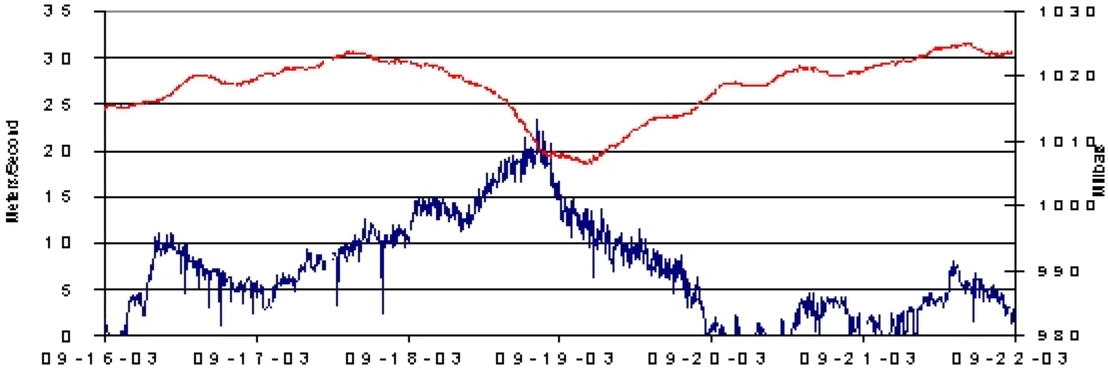
Philadelphia, PA wind speed (lower curve), barometric pressure (upper curve).



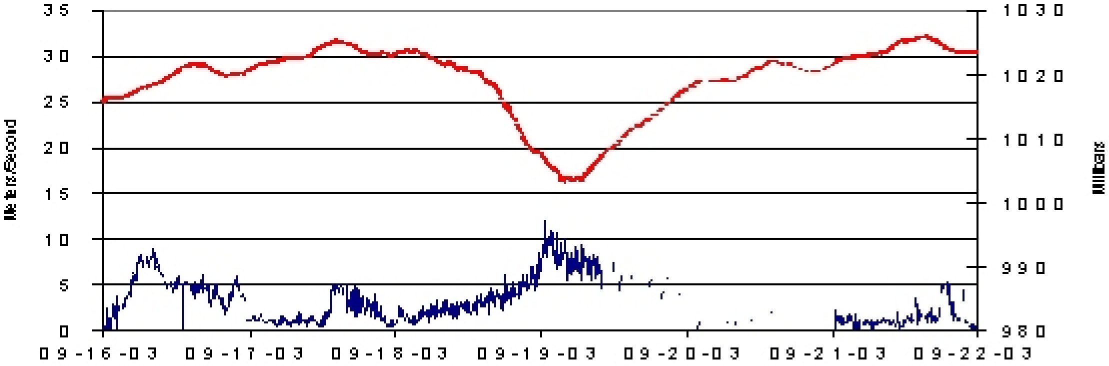
Delaware City, DE wind speed (lower curve), Barometric Pressure (upper curve).



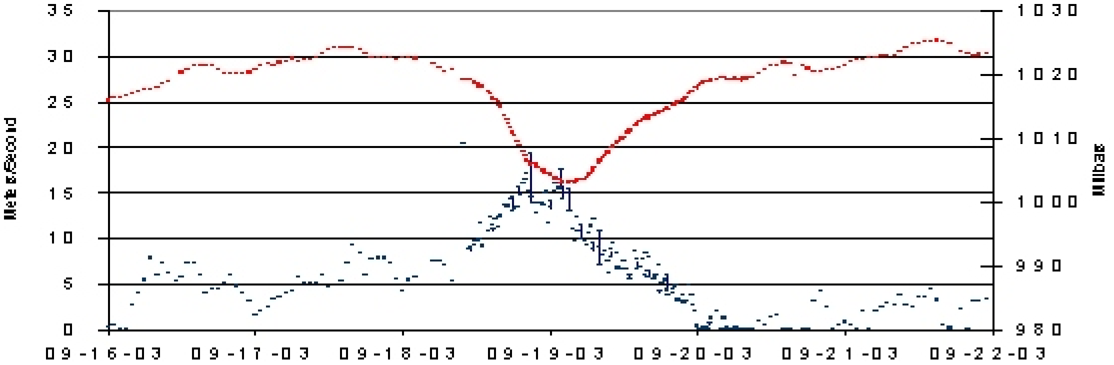
Brandywine Shoal, DE wind speed (lower curve), barometric pressure (upper curve).



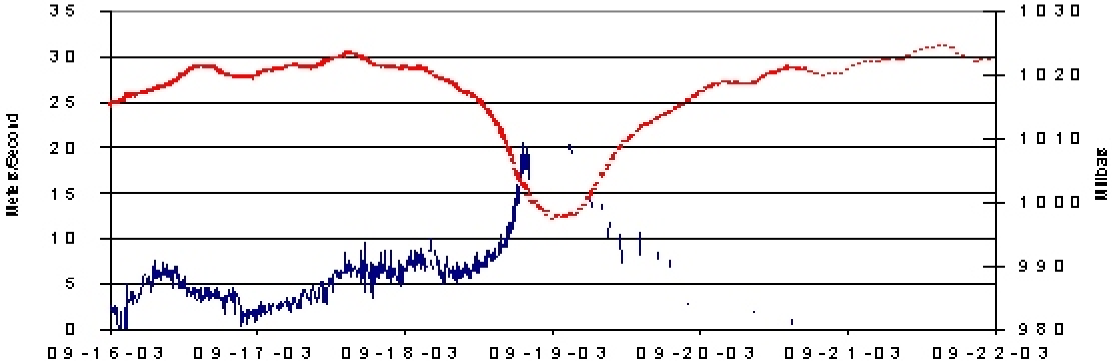
Lewes, DE wind speed (lower curve), barometric pressure (upper curve).



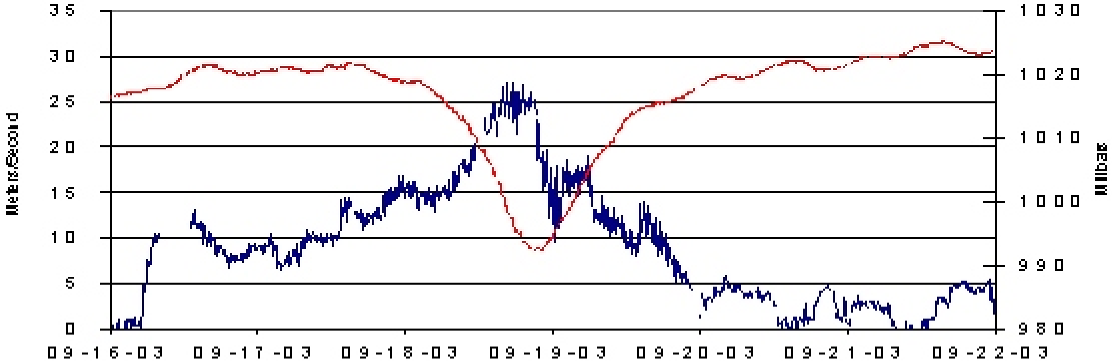
Tolchester Beach, MD wind speed (lower curve), barometric pressure (upper curve).



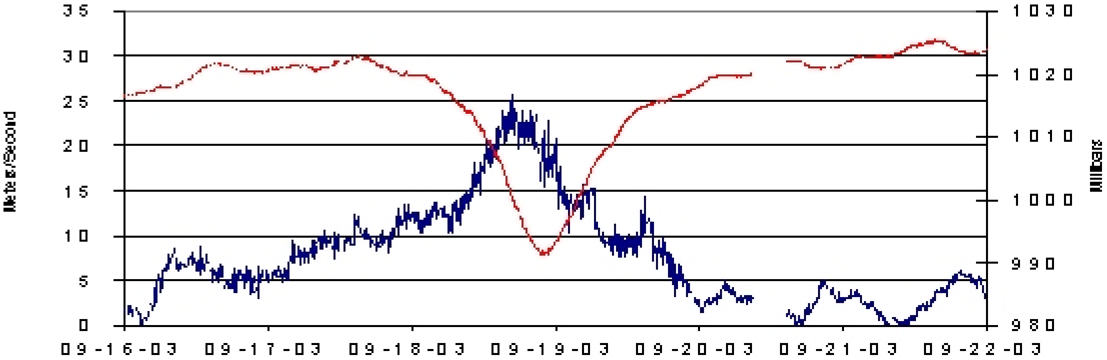
Cambridge, MD wind speed (lower curve), barometric pressure (upper curve).



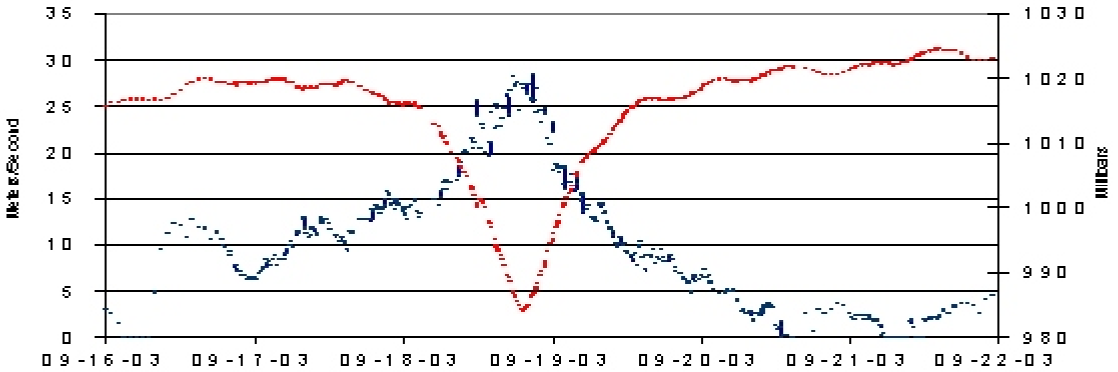
Lewisetta, VA wind speed (lower curve), barometric pressure (upper curve).



Chesapeake Bay Bridge Tunnel wind speed (lower curve), barometric pressure (upper curve)



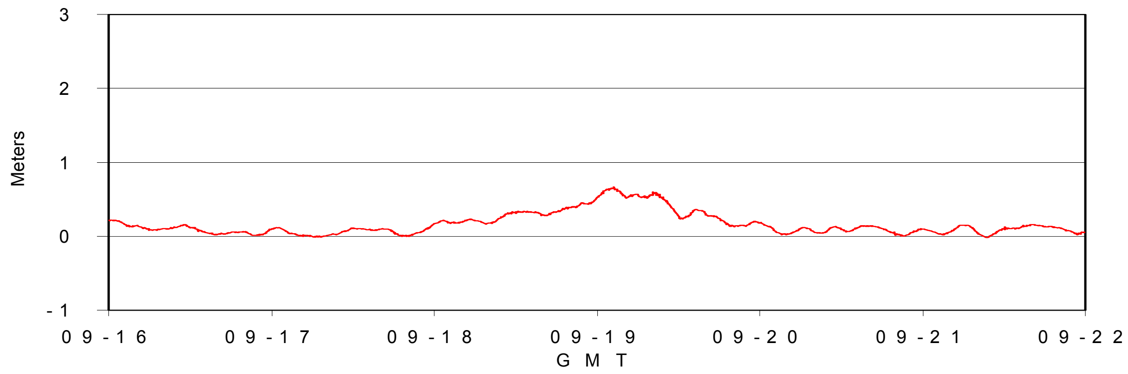
Sewells Point, VA wind speed (lower curve), barometric pressure (upper curve).



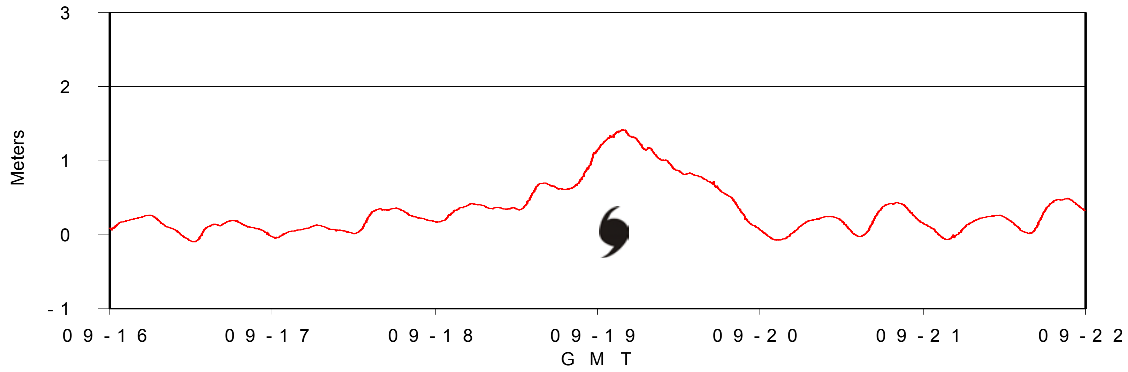
Duck, NC wind speed (lower curve), barometric pressure (upper curve).

Appendix IV

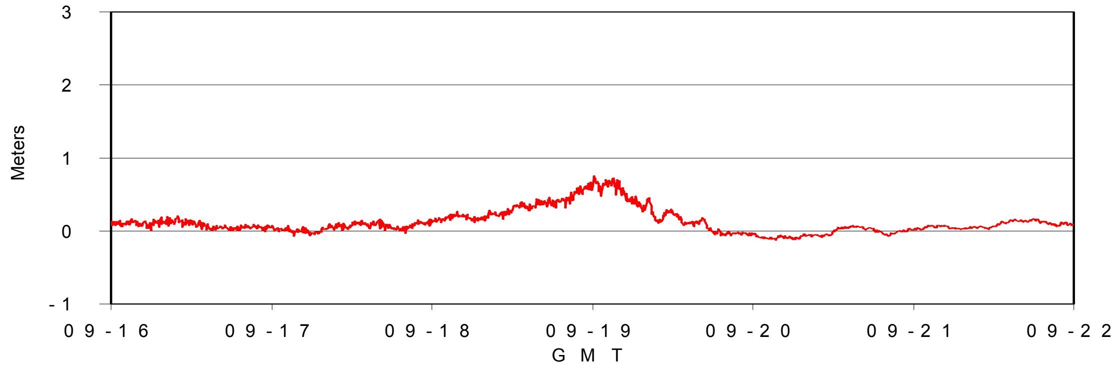
Time series of storm surge at CO-OPS water level stations



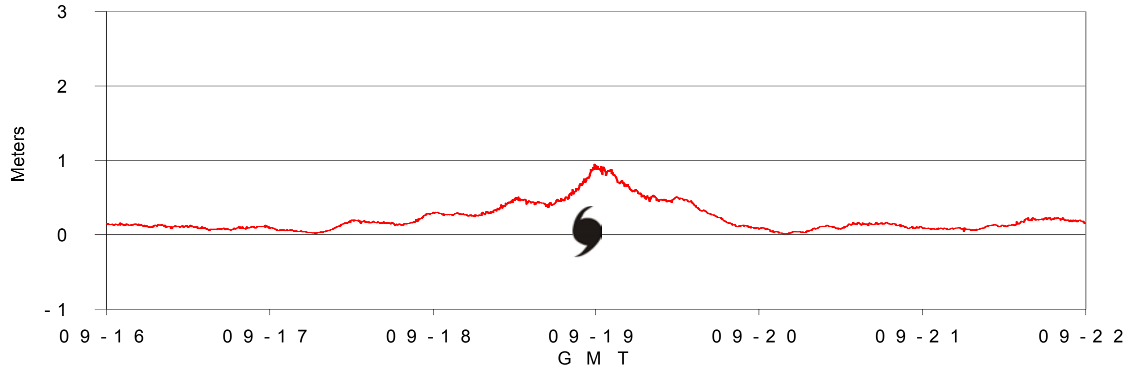
Sandy Hook, NJ storm surge.



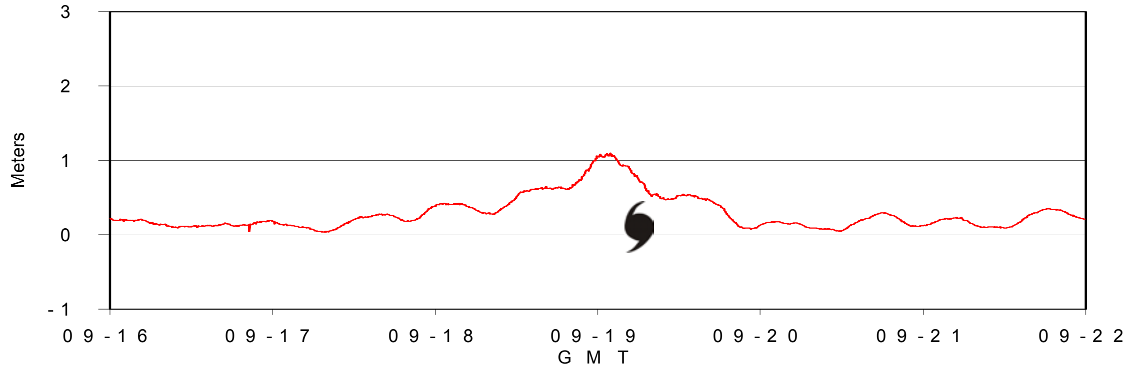
Ship John Shoal, NJ storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 02:06.



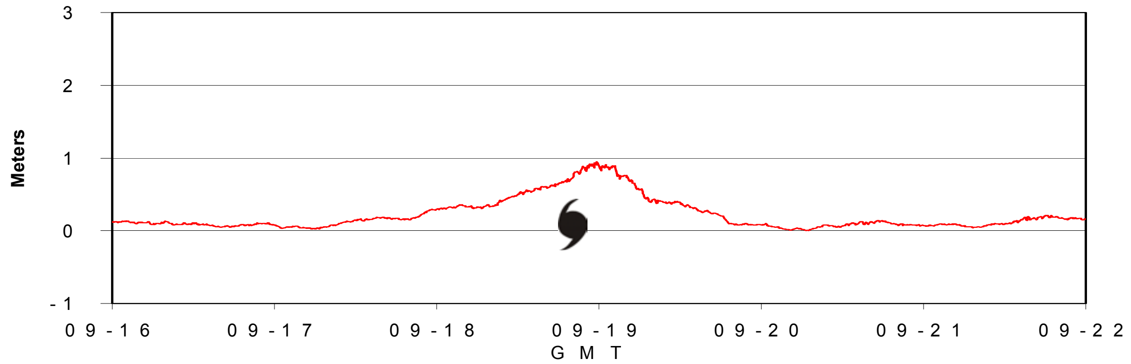
Atlantic City, NJ storm surge.



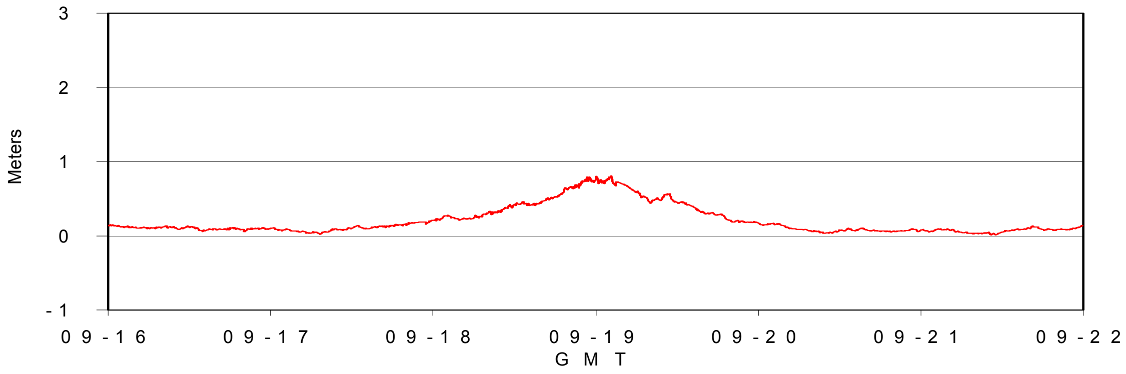
Cape May, NJ storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 00:00.



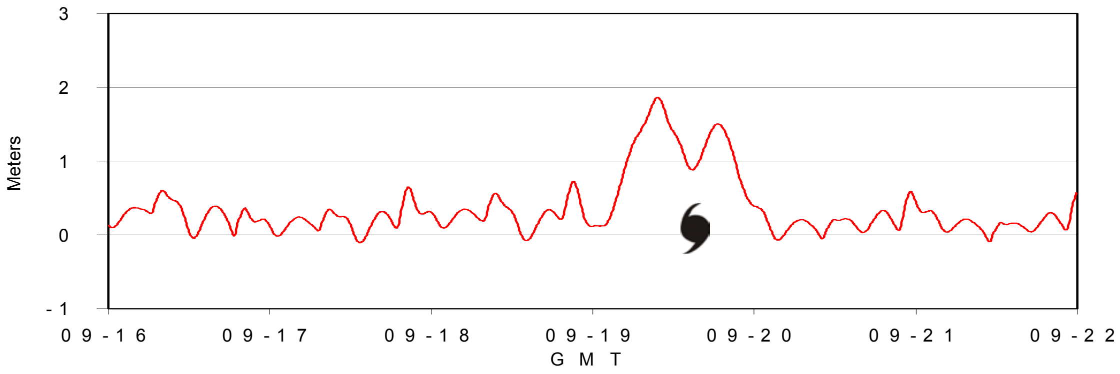
Brandywine Shoal Light, DE storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 07:06.



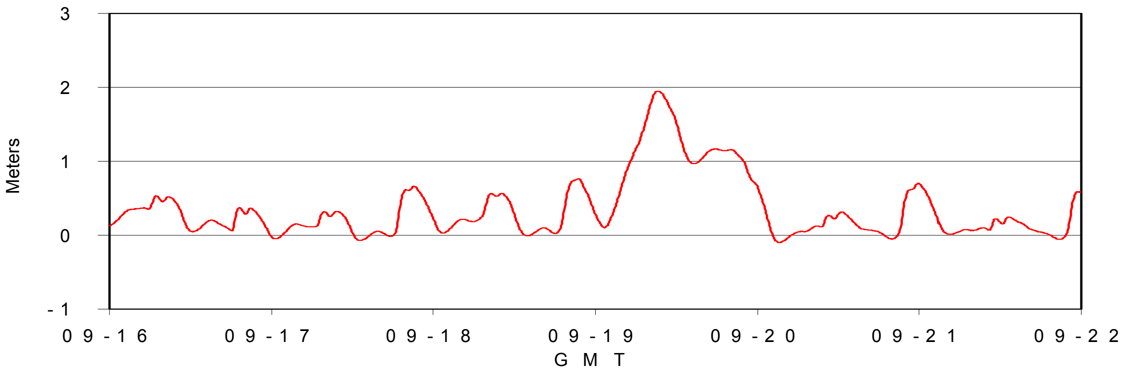
Lewes, DE storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 20:24.



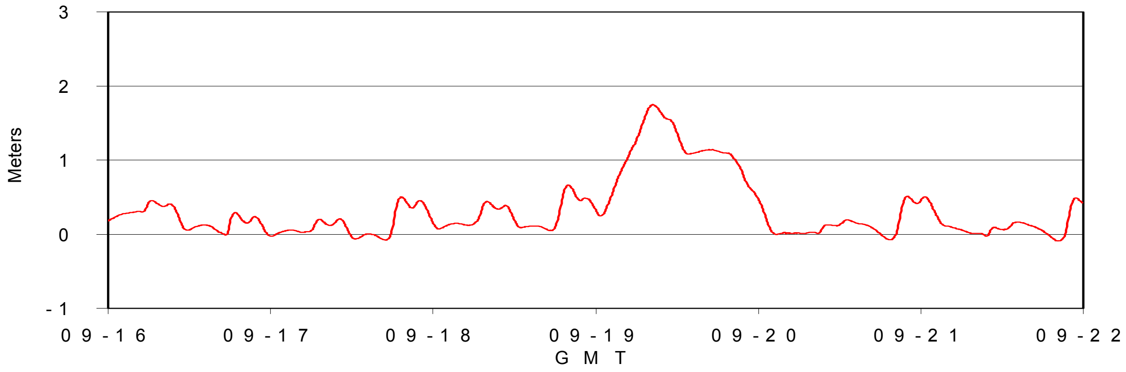
Ocean City Inlet, MD storm surge.



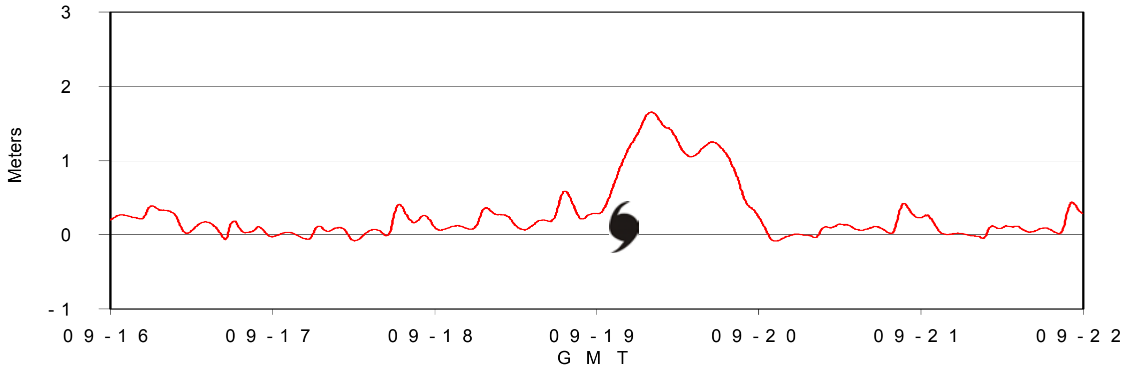
Newbold, PA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 16:42.



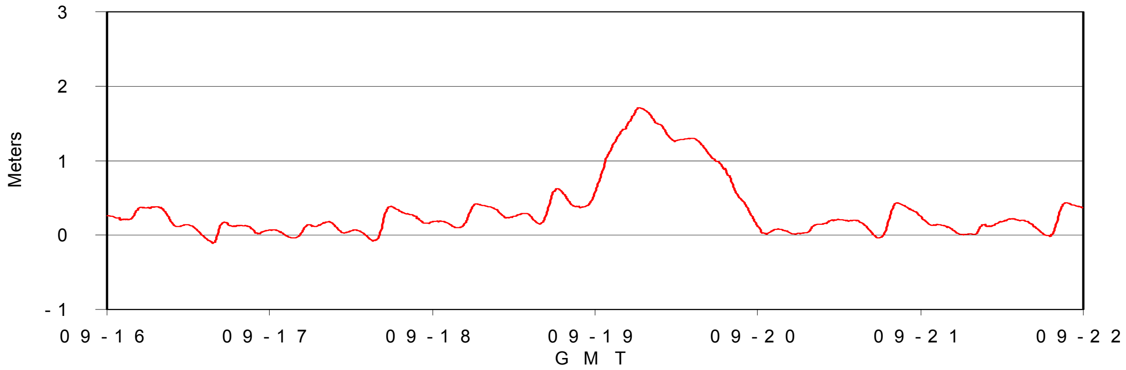
Burlington, NJ storm surge.



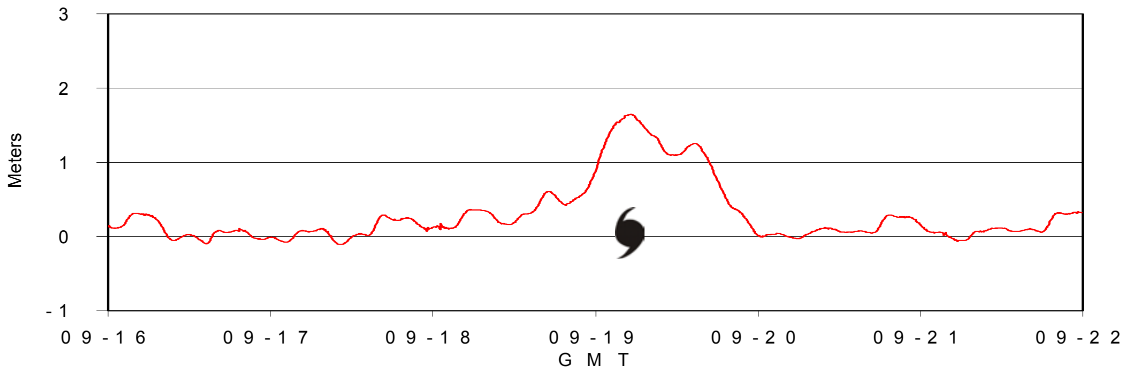
Tacony-Palmyra, NJ storm surge.



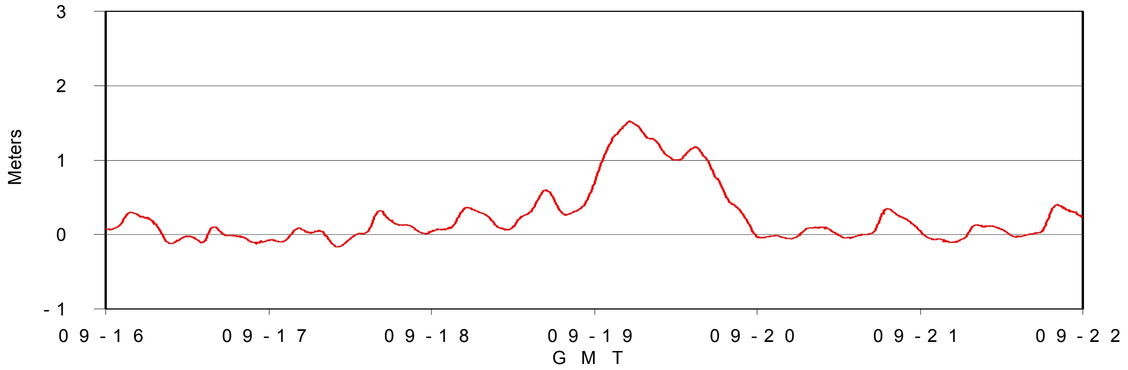
Philadelphia, PA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 03:42.



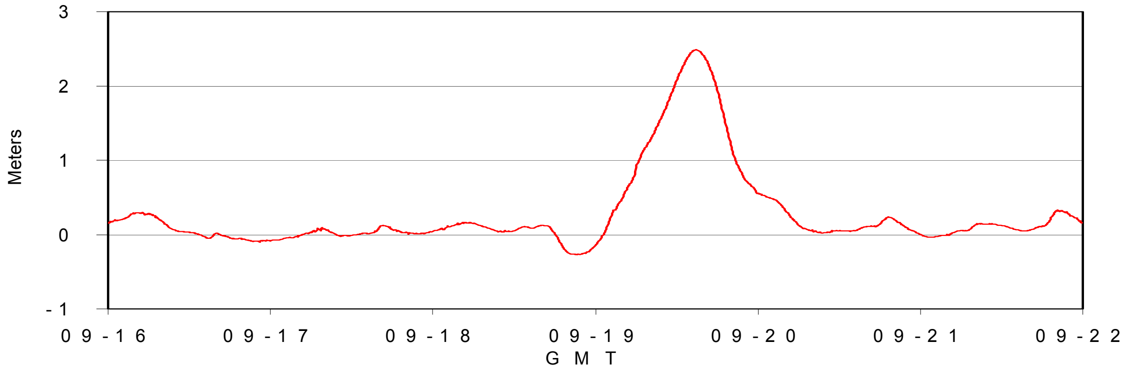
Marcus Hook, PA storm surge.



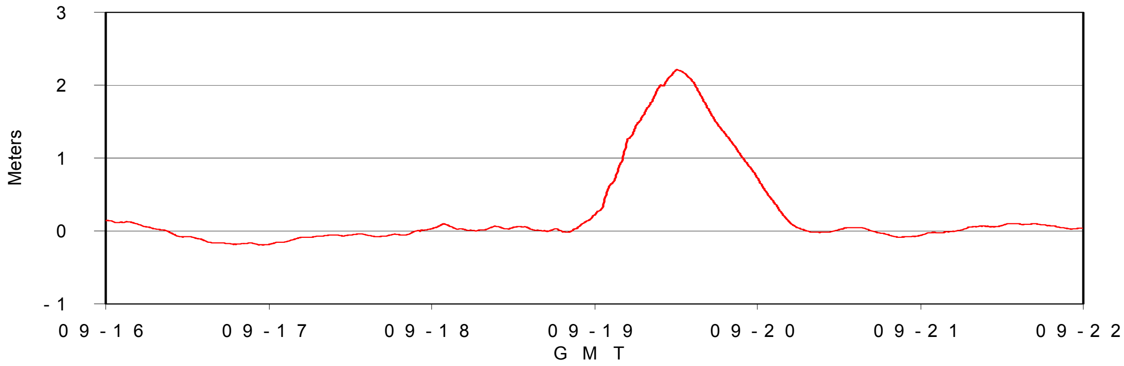
Delaware City, DE storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 06:06.



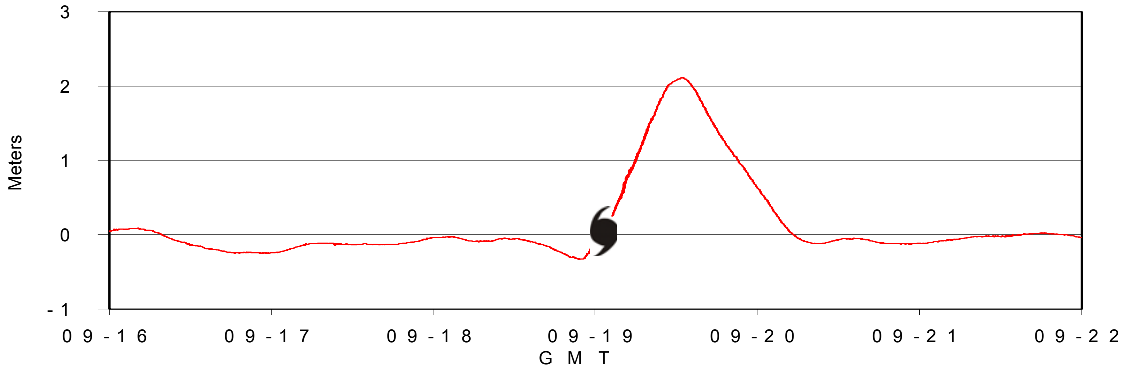
Reedy Point, DE storm surge.



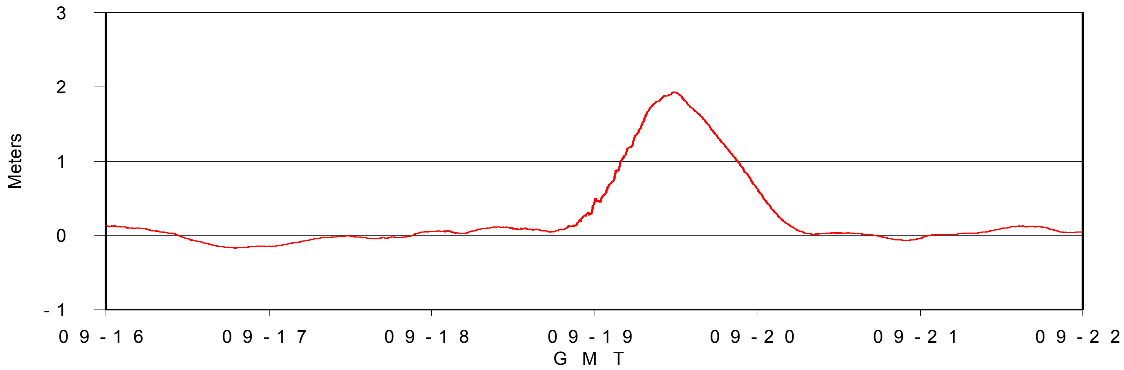
Chesapeake City, MD storm surge.



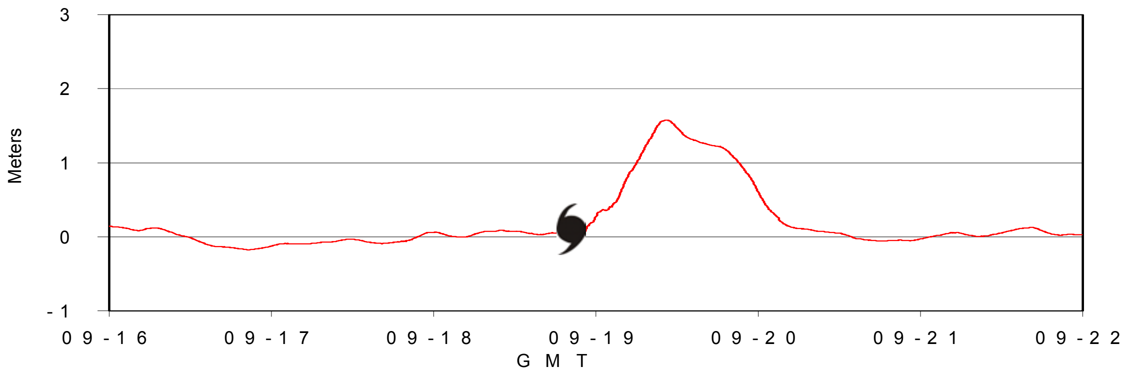
Baltimore, MD storm surge.



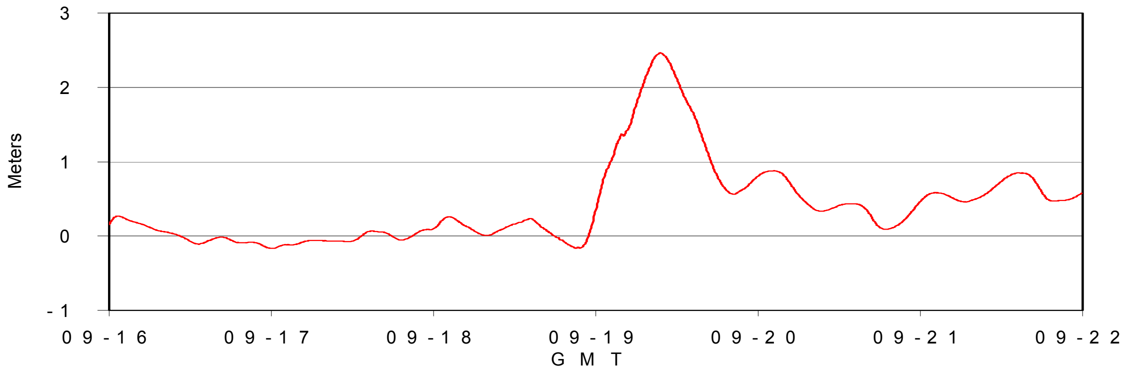
Tolchester, MD storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-19 @ 00:54.



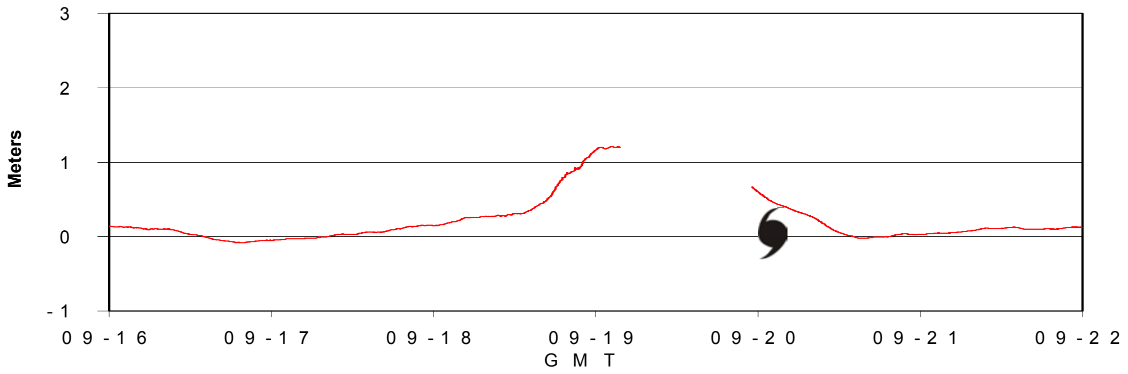
Annapolis, MD storm surge.



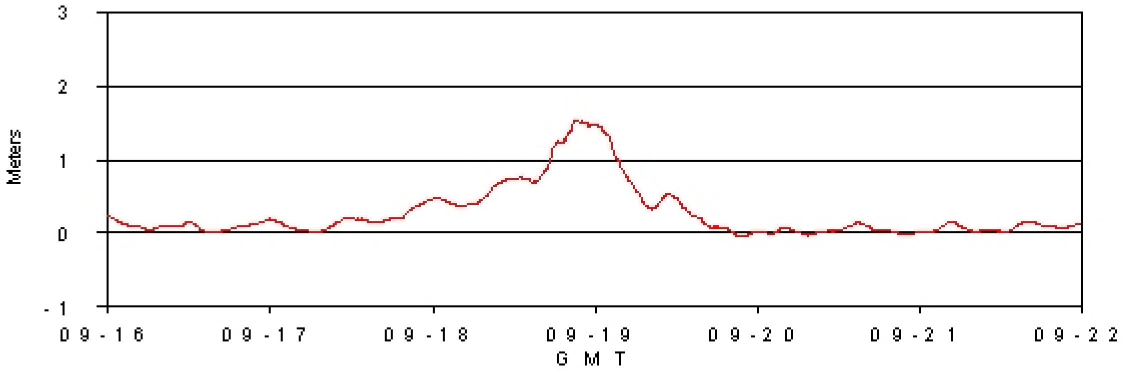
Cambridge, MD storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 20:54.



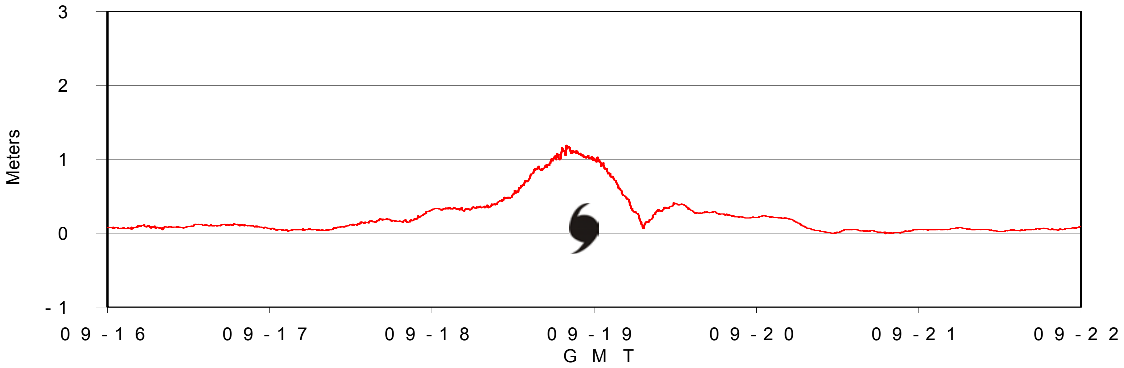
Washington DC storm surge.



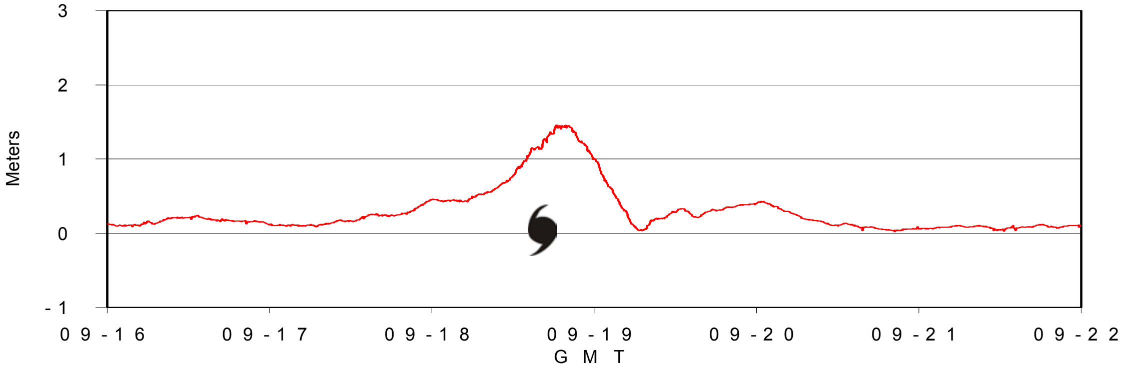
Lewisetta, VA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-20 @ 04:24.



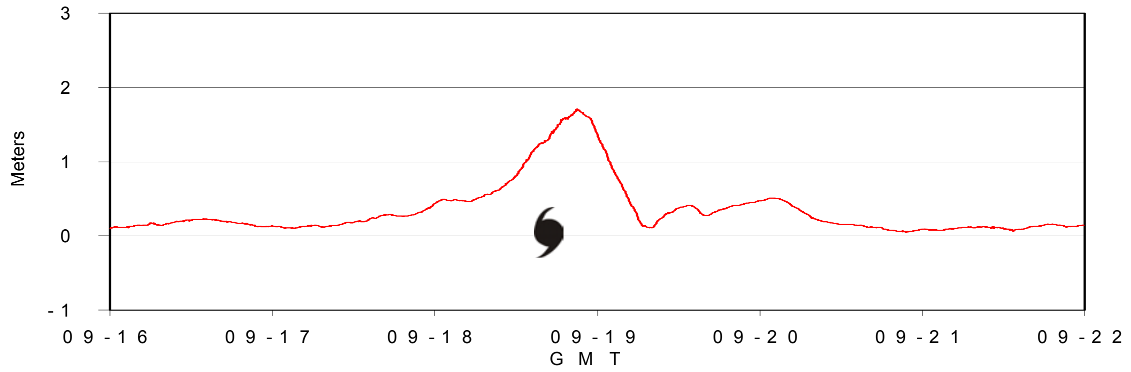
Wachapreague, VA storm surge.



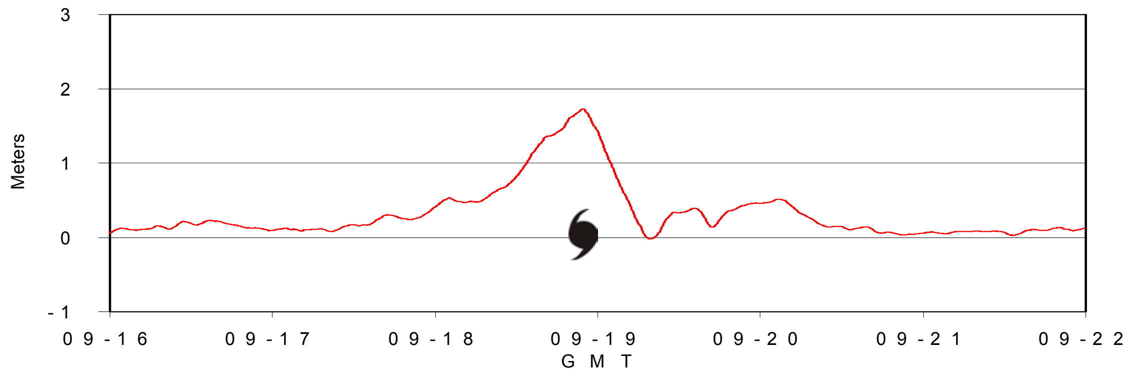
Kiptopeke, VA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 23:42.



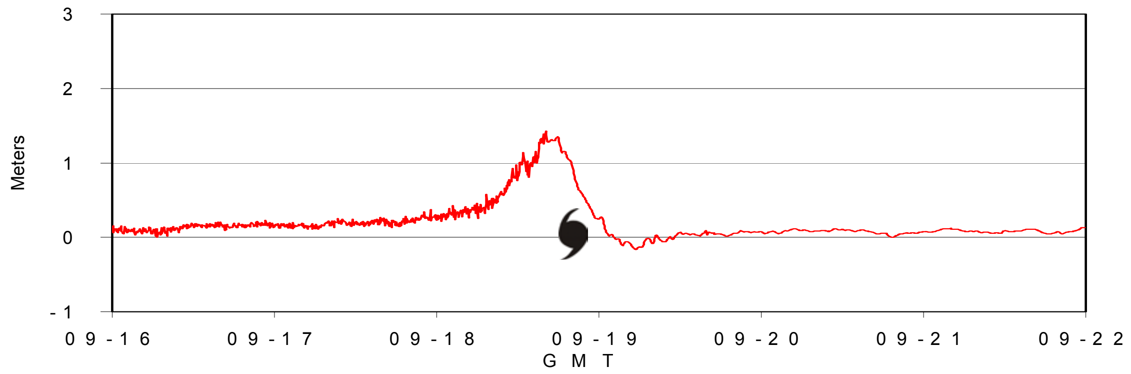
Chesapeake Bay Bridge Tunnel, VA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 16:36.



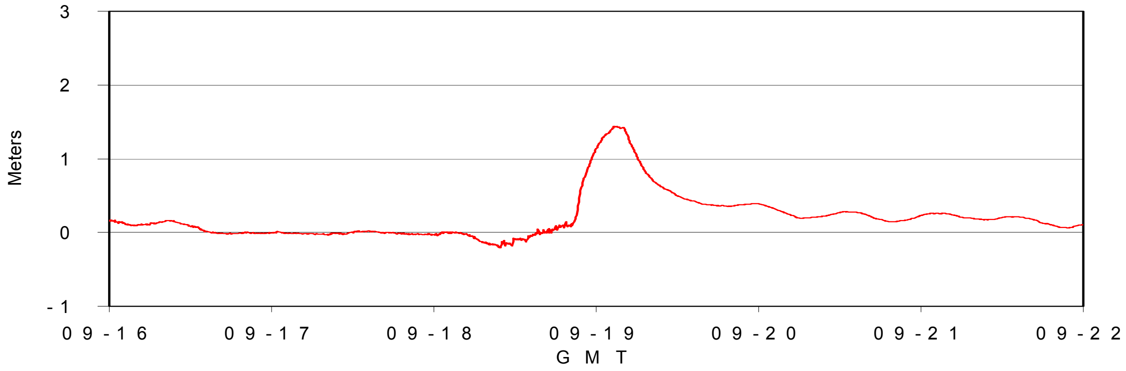
Sewells Point, VA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 16:42.



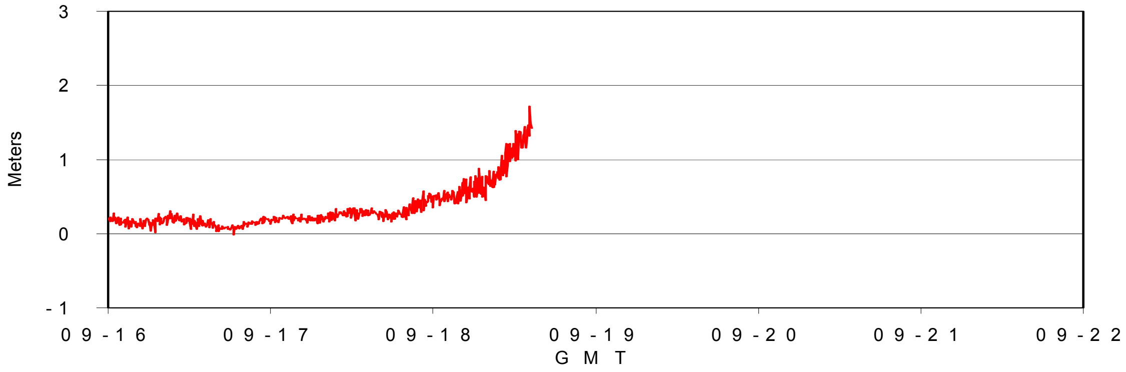
Money Point, VA storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 23:18.



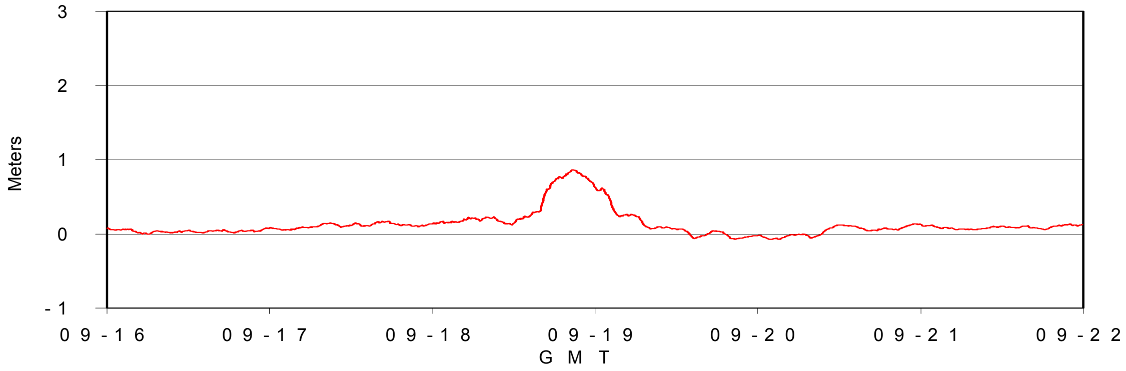
Duck, NC storm surge. Hurricane symbol denotes time of maximum recorded wind speed on 9-18 @ 21:00.



Oregon Inlet, NC storm surge.



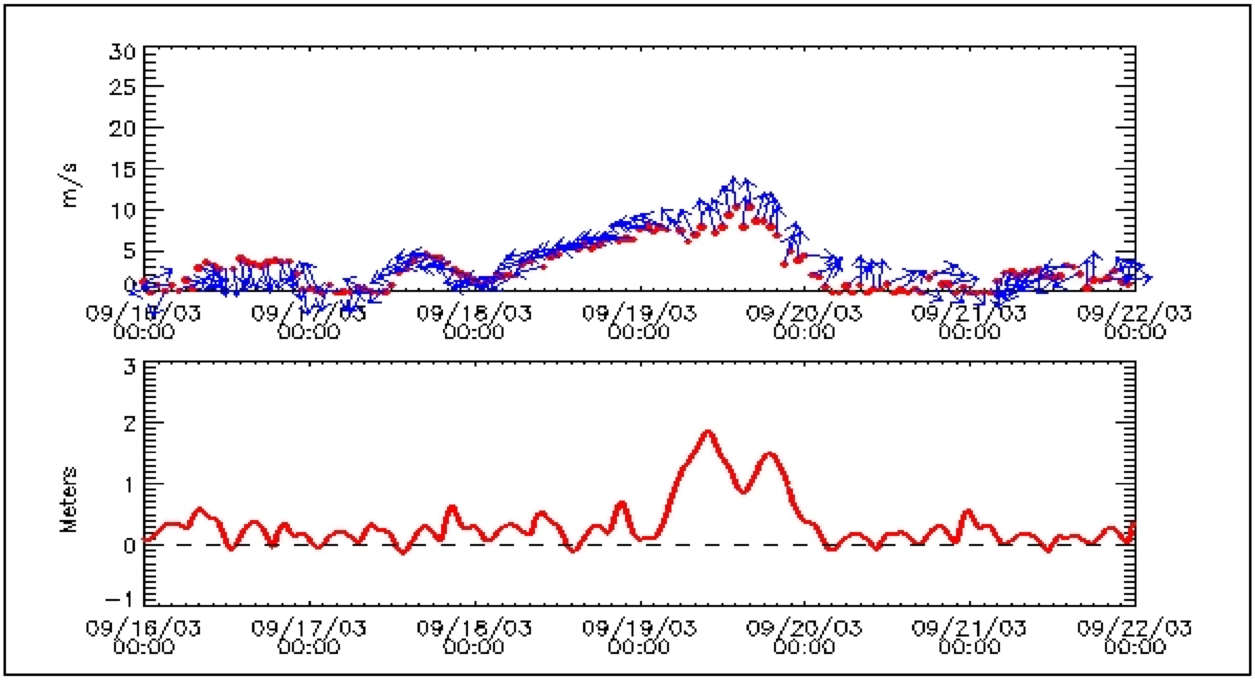
Cape Hatteras, NC storm surge.



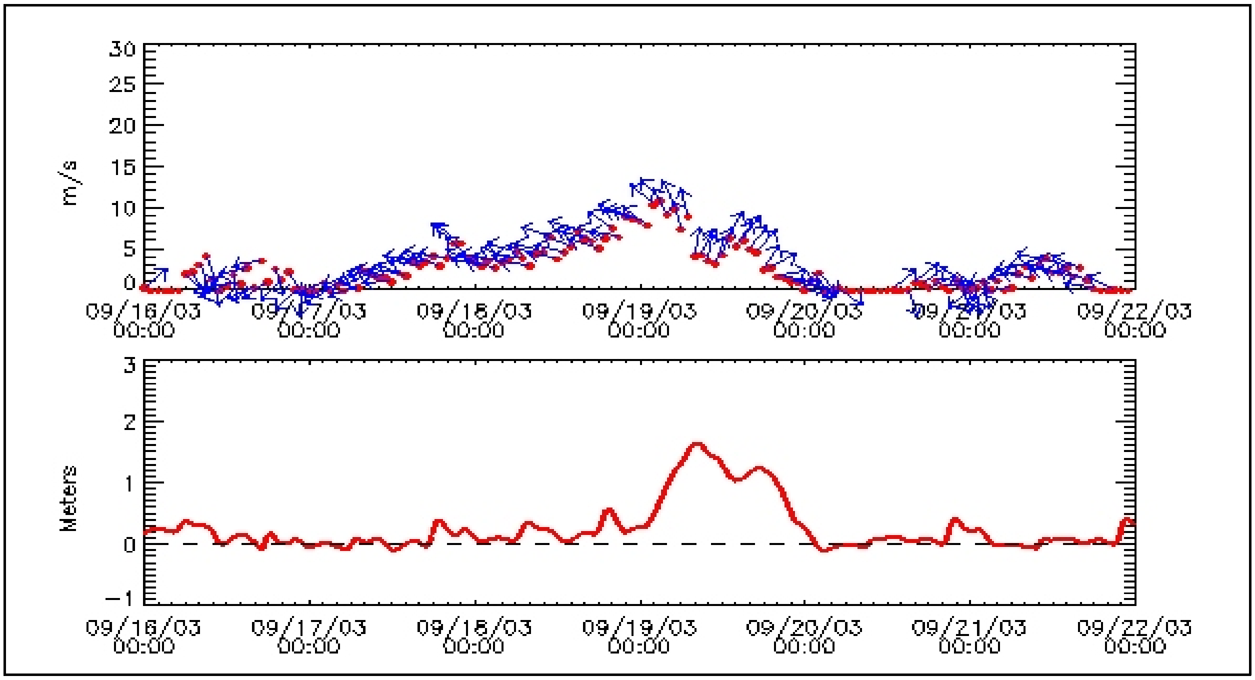
Beaufort, NC storm surge.

Appendix V

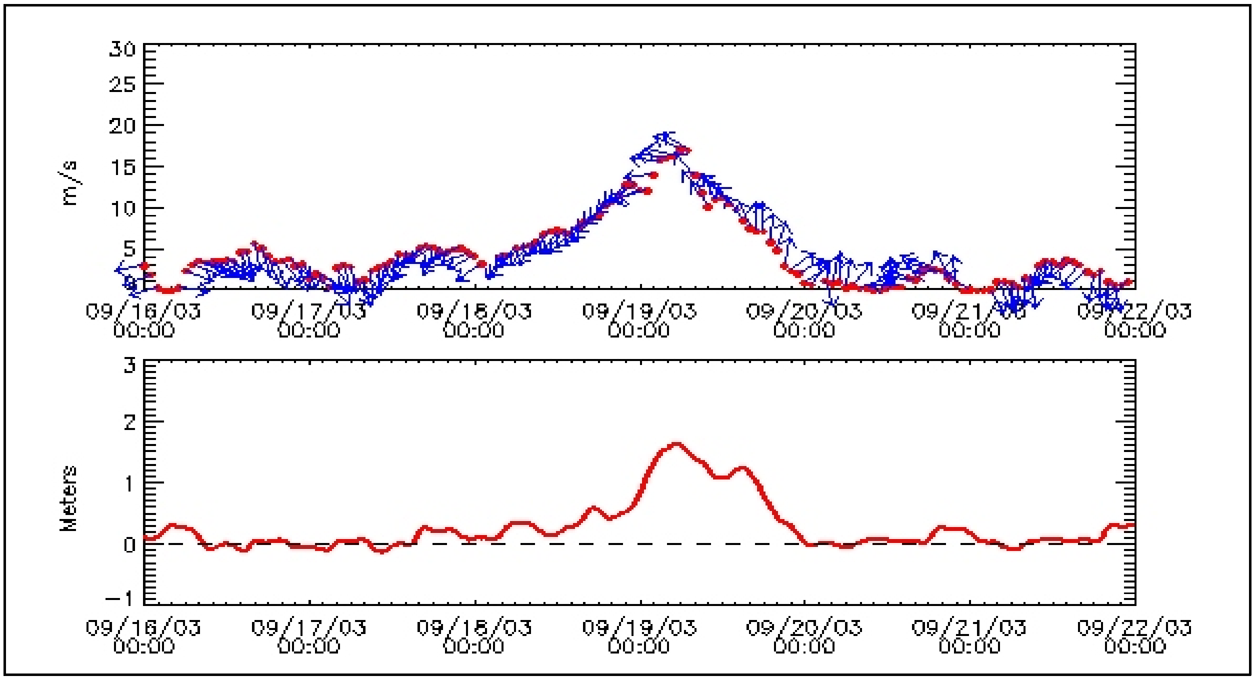
Wind and storm surge at selected CO-OPS water levels stations



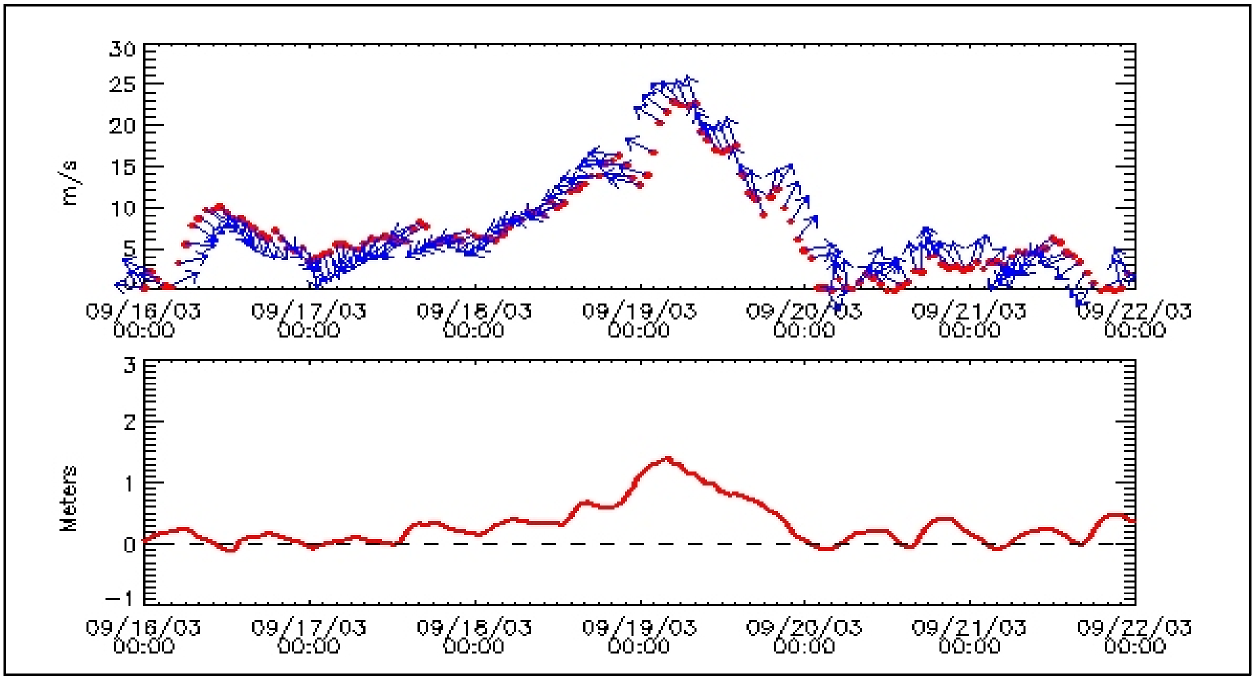
Hourly wind vectors and storm surge at Newbold, PA.



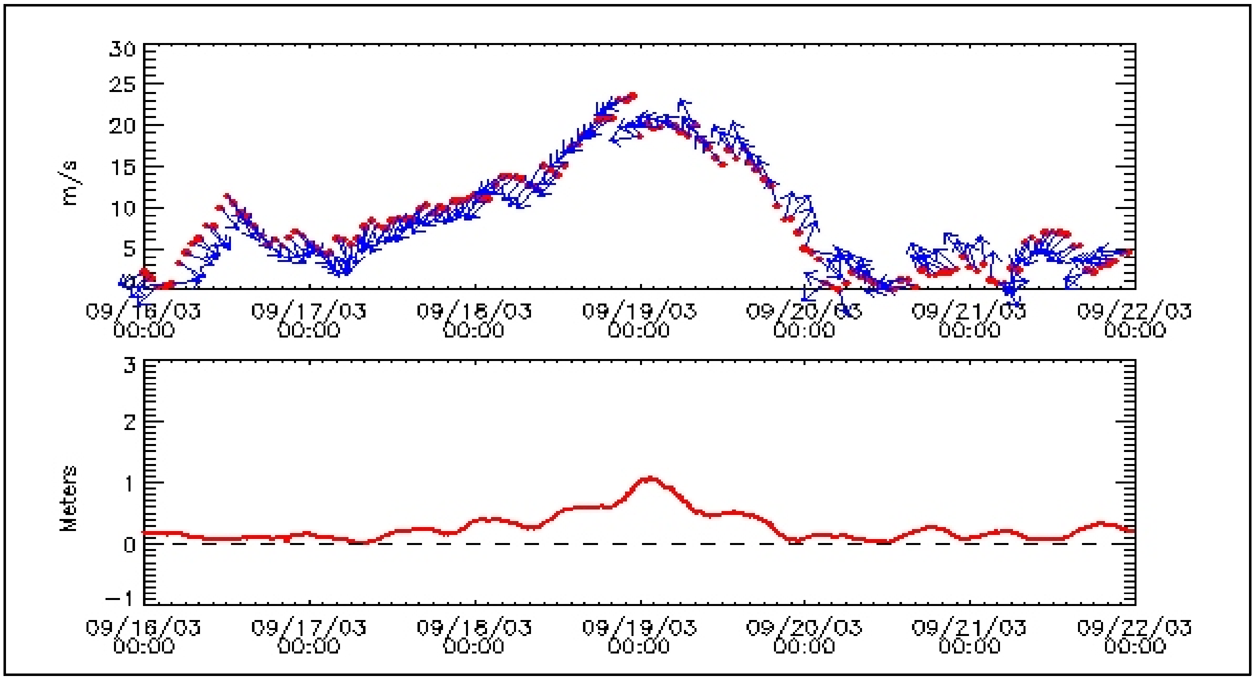
Hourly wind vectors and storm surge at Philadelphia, PA.



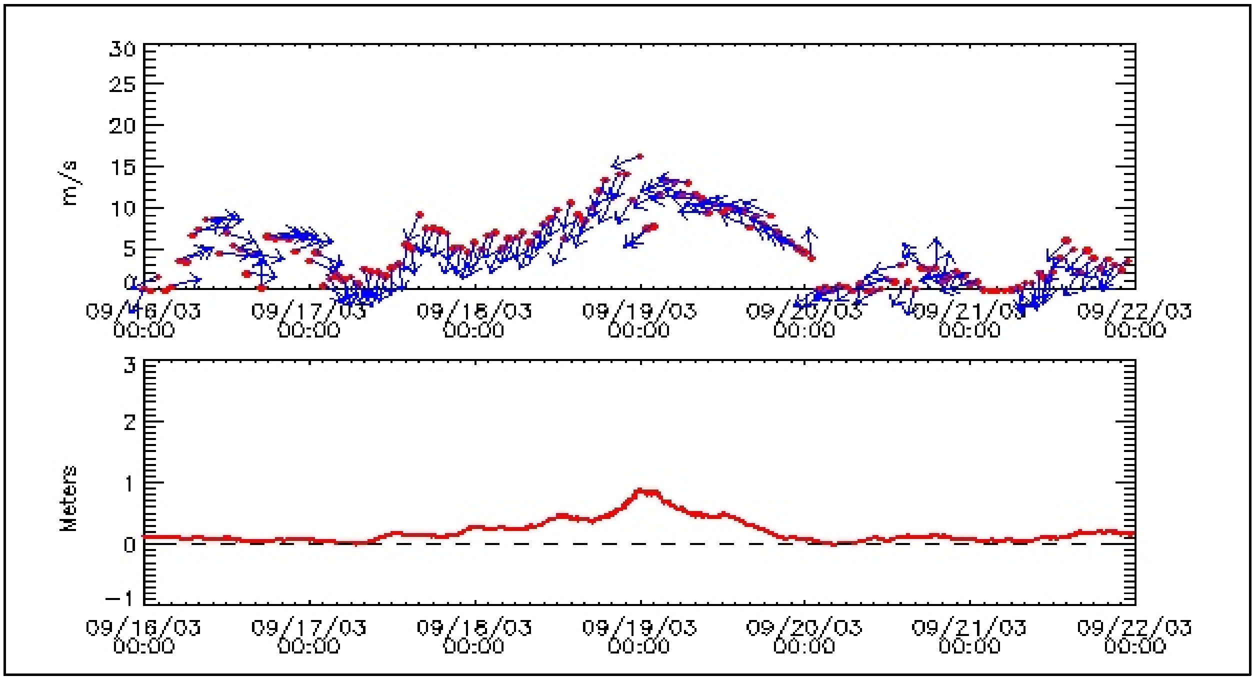
Hourly wind vectors and storm surge at Delaware City, DE.



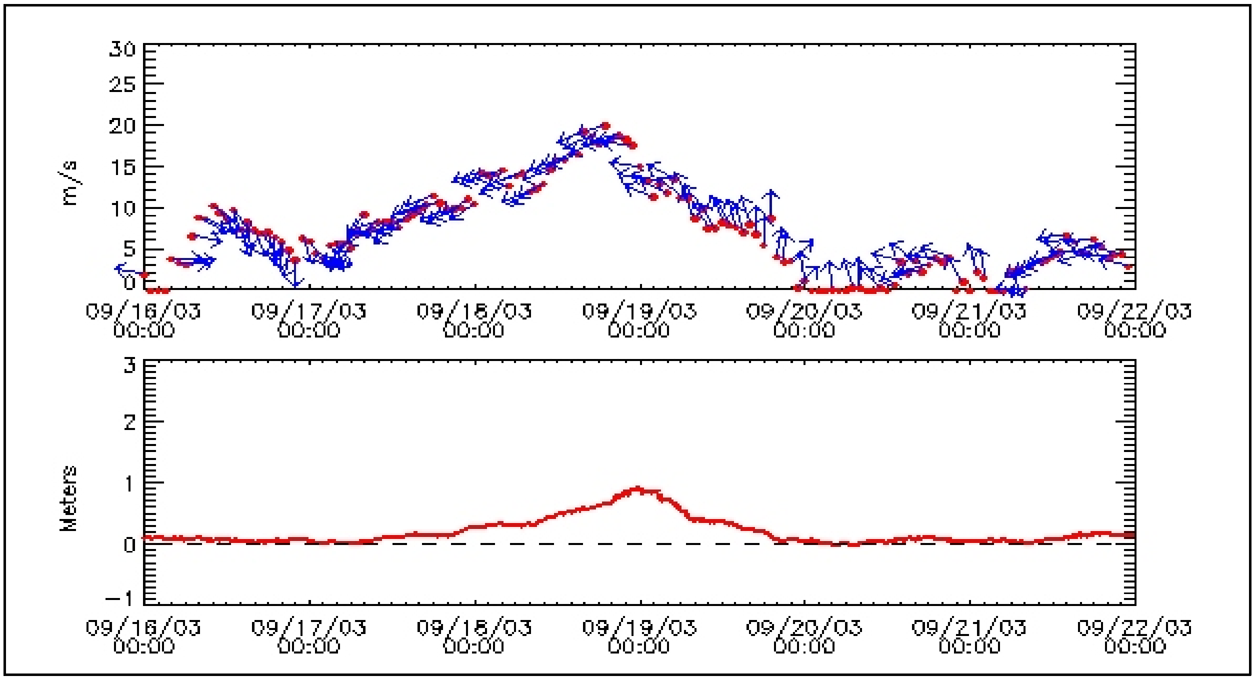
Hourly wind vectors and storm surge at Ship John Shoal, NJ.



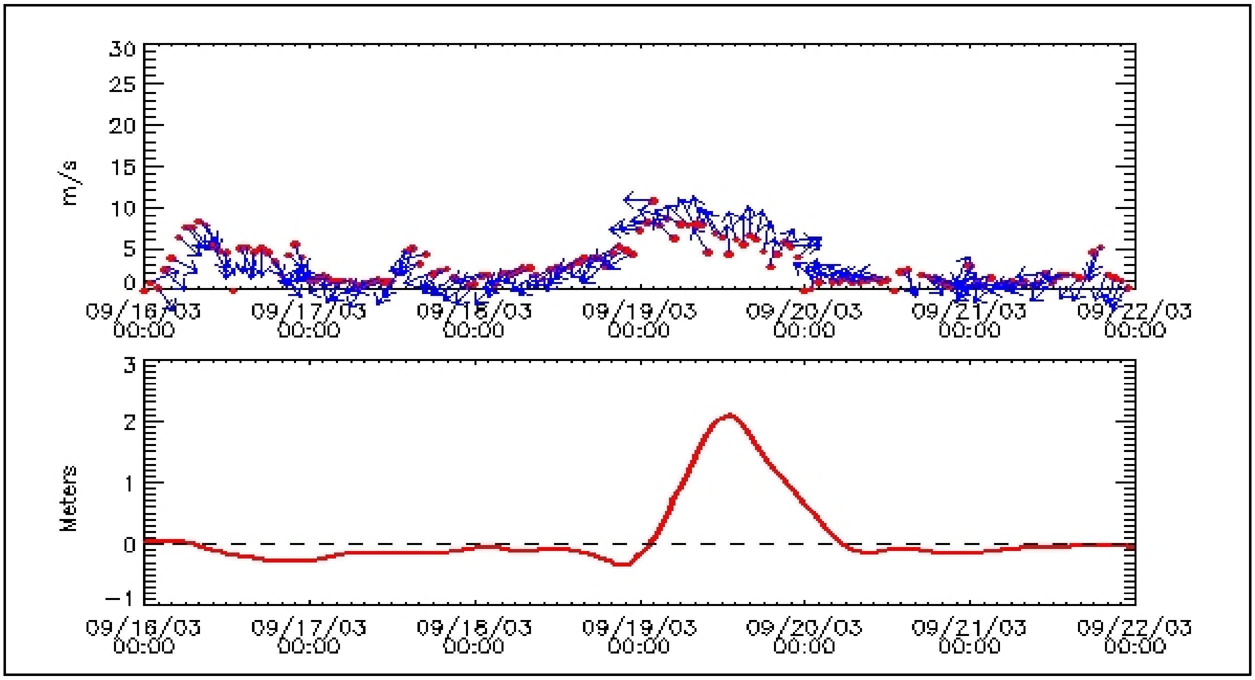
Hourly wind vectors and storm surge at Brandywine Shoal Light, DE.



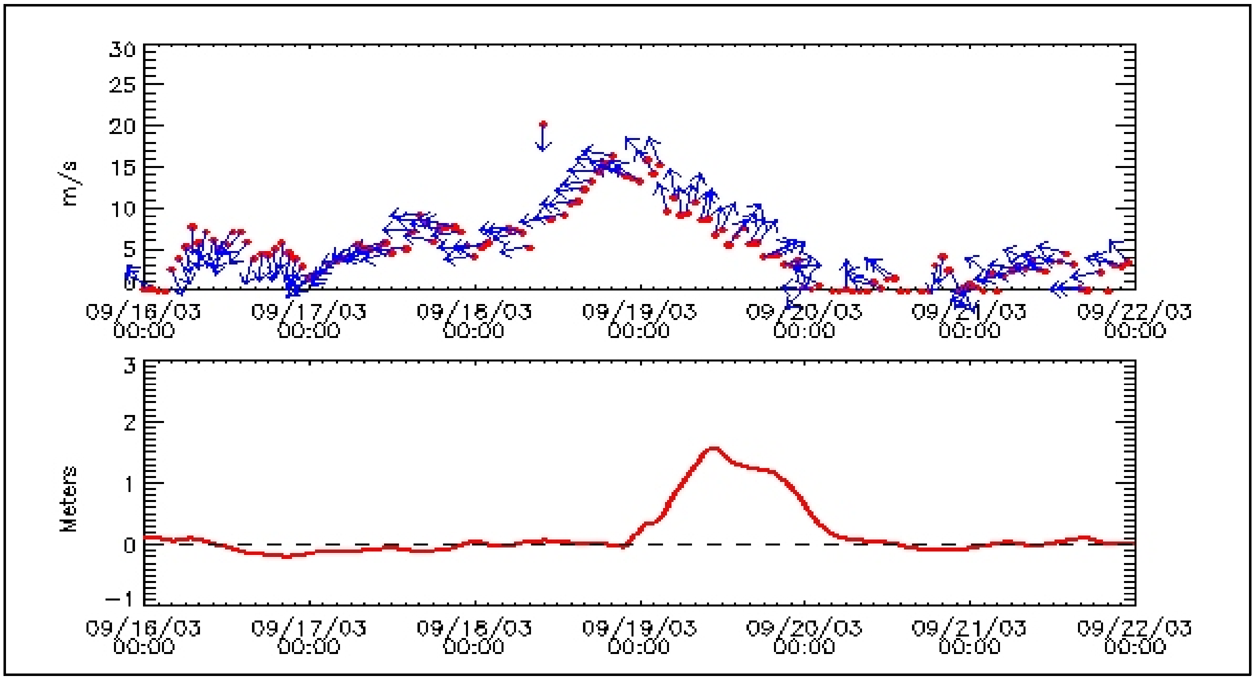
Hourly wind vectors and storm surge at Cape May, NJ.



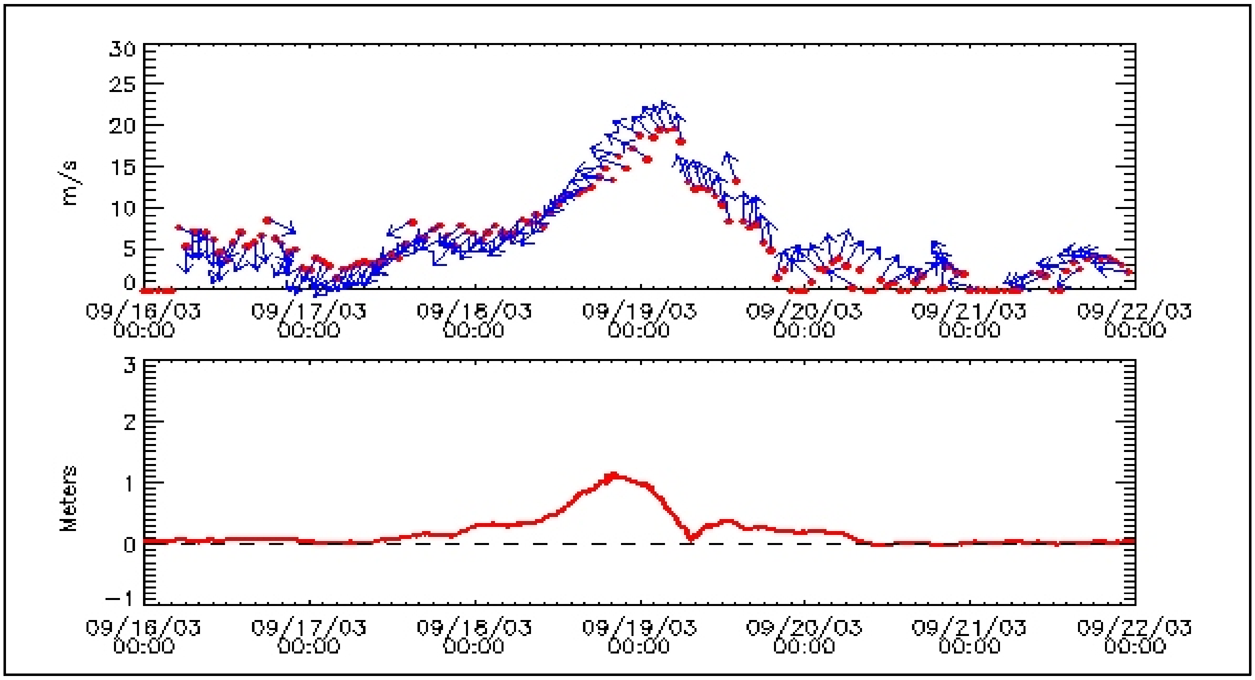
Hourly wind vectors and storm surge at Lewes, DE.



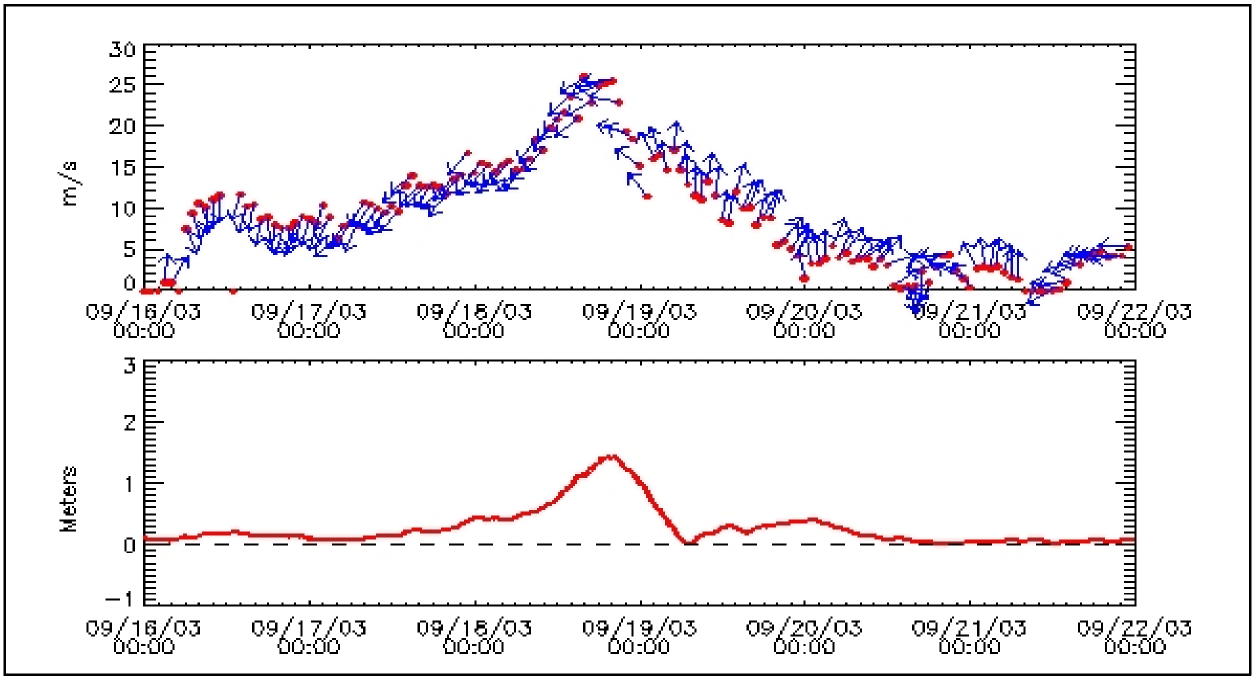
Hourly wind vectors and storm surge at Tolchester, MD.



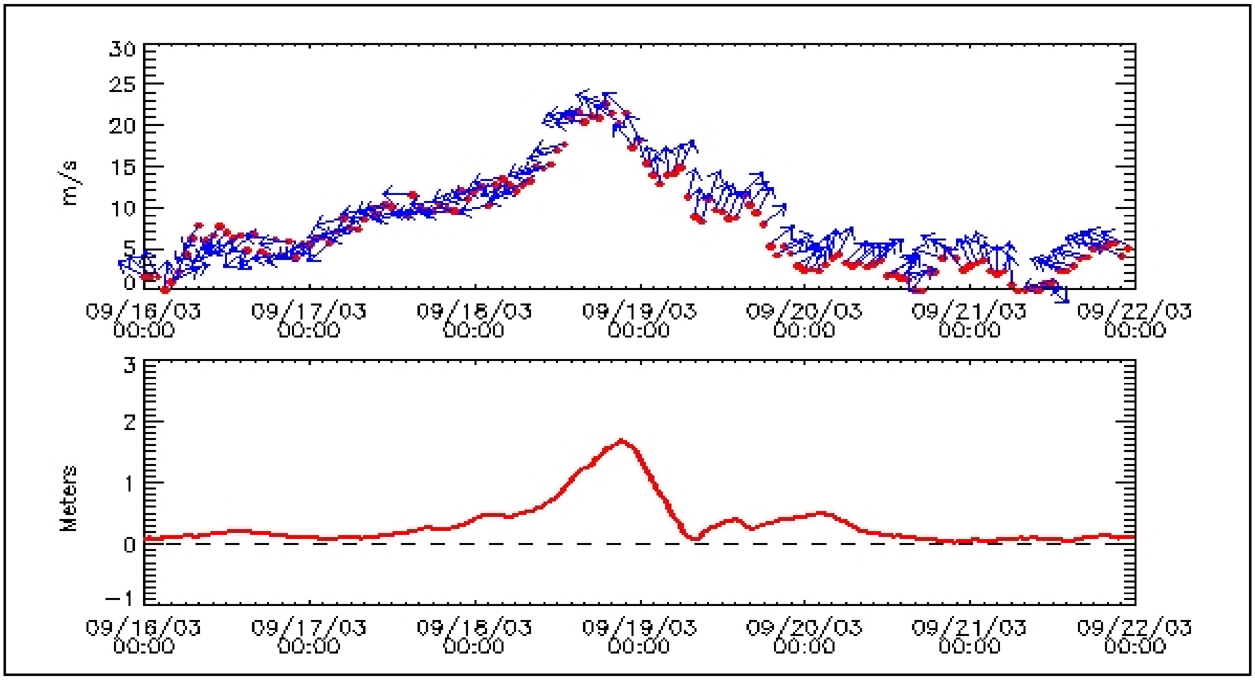
Hourly wind vectors and storm surge at Cambridge, MD.



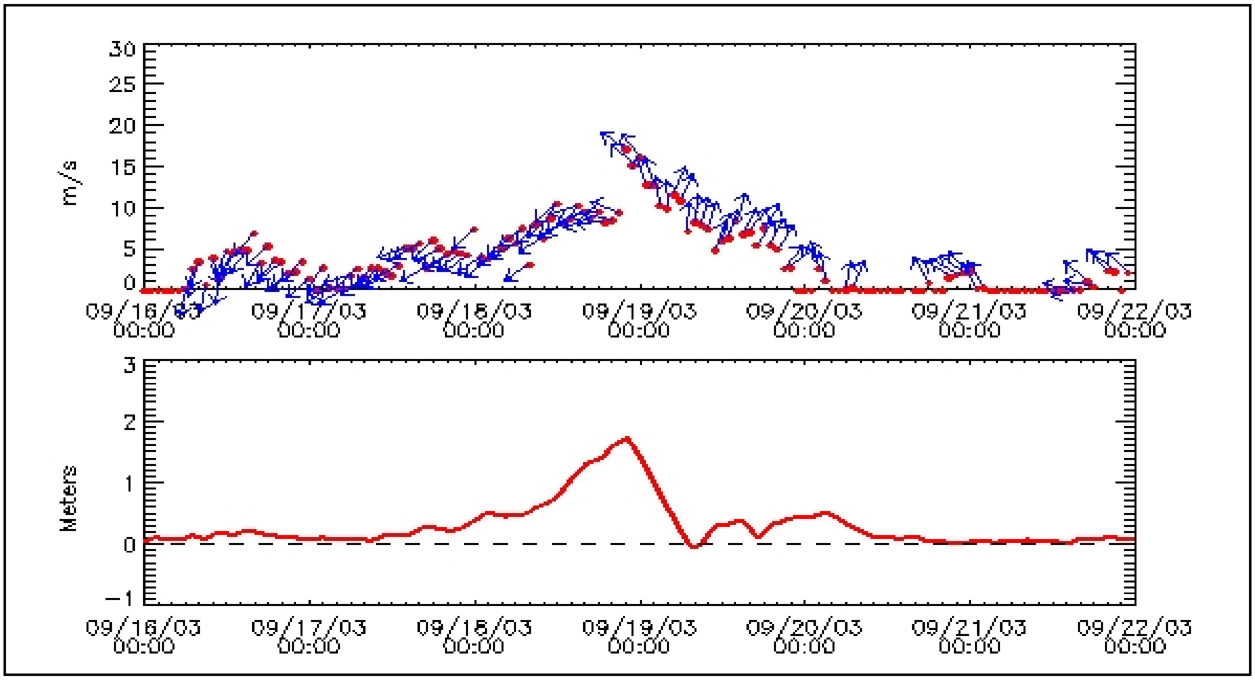
Hourly wind vectors and storm surge at Kiptopeke, VA



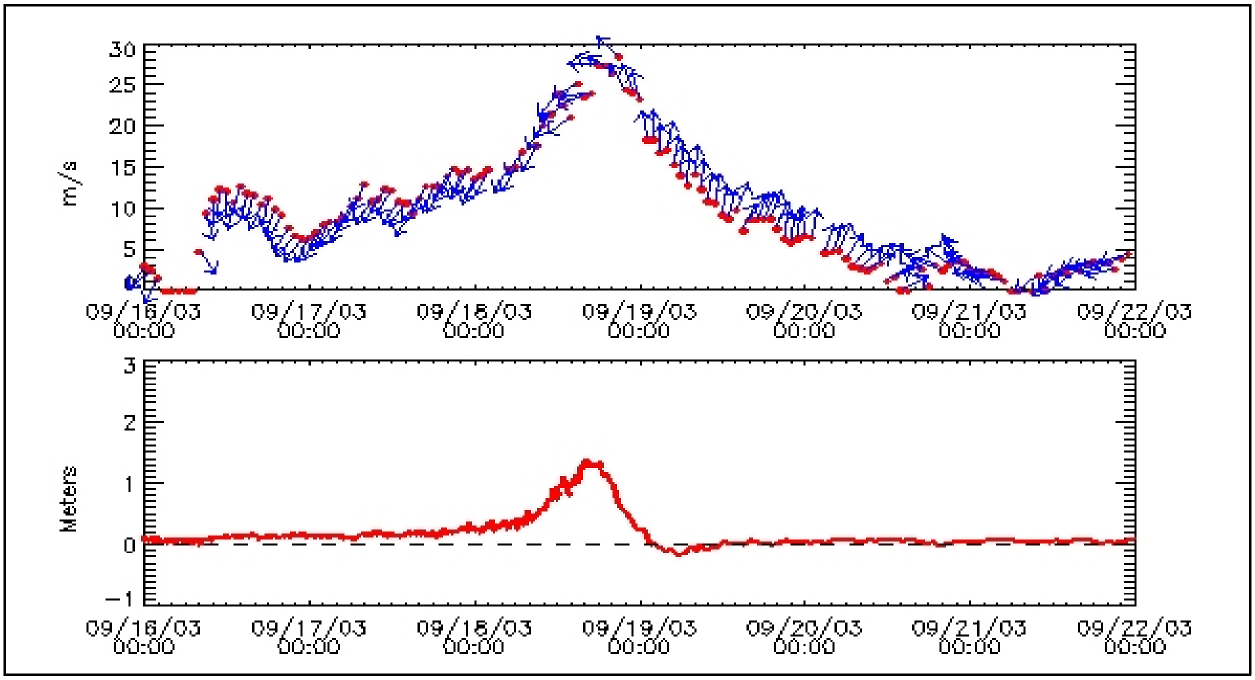
Hourly wind vectors and storm surge at Chesapeake Bay Bridge Tunnel, VA.



Hourly wind vectors and storm surge at Sewells Point, VA.



Hourly wind vectors and storm surge at Money Point, VA.



Hourly wind vectors and storm surge at Duck, NC.