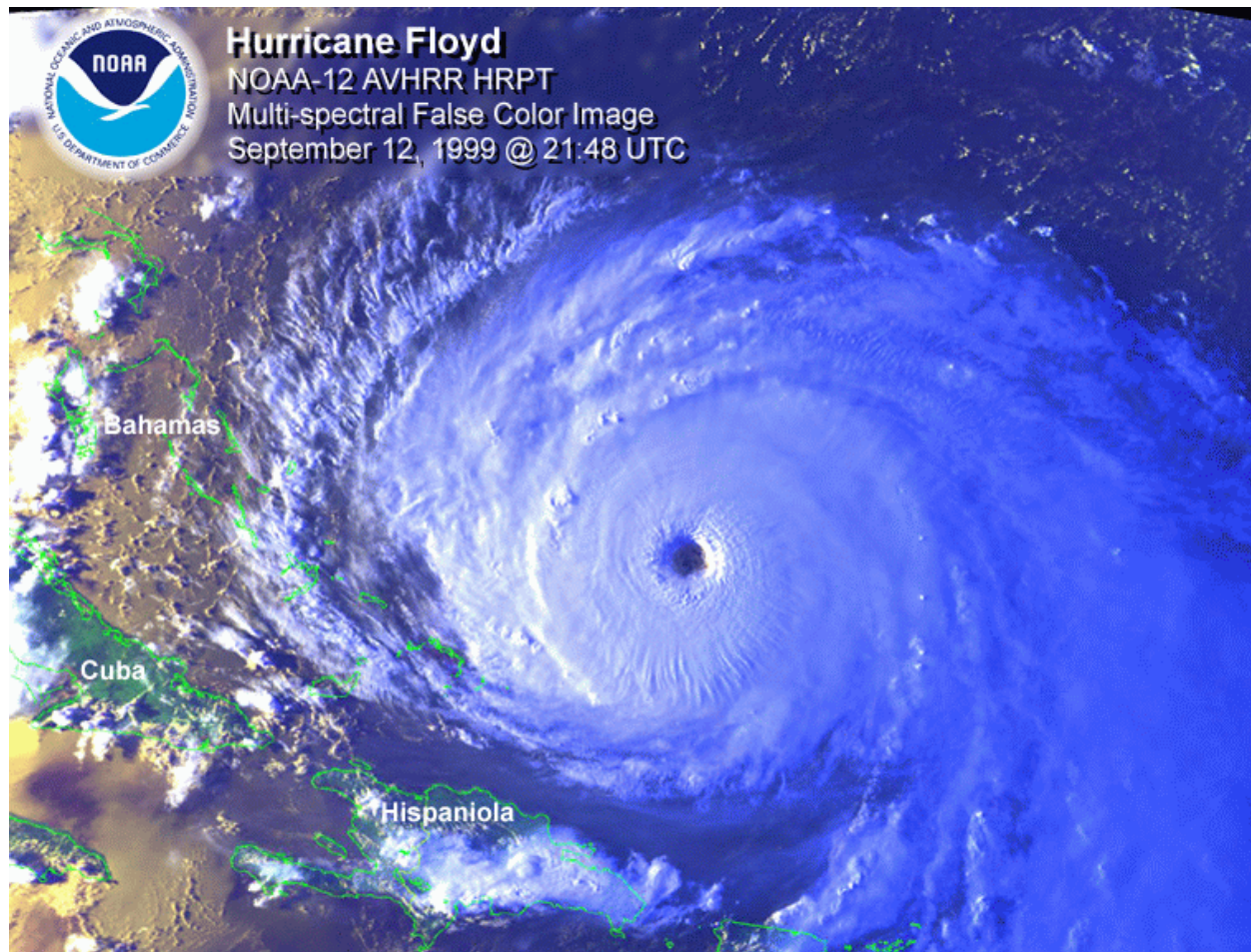


## EFFECTS OF HURRICANE FLOYD ON WATER LEVELS DATA REPORT



Silver Spring, Maryland  
January, 2000

**noaa** National Oceanic and Atmospheric Administration

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U.S. DEPARTMENT OF COMMERCE  
National Ocean Service  
Center for Operational Oceanographic Products and Services  
Products and Services Division

**Center for Operational Oceanographic Products and Services  
National Ocean Service  
National Oceanic and Atmospheric Administration  
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**EFFECTS OF HURRICANE FLOYD ON WATER LEVELS  
DATA REPORT**

**Chris Zervas, Scott Duncan, Dale Deitemyer, James Hubbard, Janet Culp,  
Thomas Landon, Michael Connolly, Darren Wright, Richard Bourgerie  
January, 2000**

**noaa** National Oceanic and Atmospheric Administration

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## List of Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
AFOS	Automation of Field Operations and Services
ARO	Atlantic Regional Office
AVHRR	Advanced Very High Resolution Radiometer
BA	Bahamas
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
FEMA	Federal Emergency Management Agency
FOD	Field Operations Division
GOES	Geostationary Operational Environmental Satellite
GMT	Greenwich Mean Time
GT	Great Diurnal Range
HAZMAT	Hazardous Materials Response Division
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NGWLMS	Next Generation Water Level Measurement System
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWLON	National Water Level Observation Network
NWLP	National Water Level Program
NWS	National Weather Service
PORTS	Physical Oceanographic Real-Time System
PSD	Products and Services Division
SeaWiFS	Sea-viewing Wide Field-of-View Sensor



## **I. Introduction**

Hurricane Floyd was the strongest and most damaging hurricane of the 1999 Atlantic season. At its peak strength it was classified as a Category 4 hurricane on the Saffir/Simpson Hurricane Scale. By the time it made landfall near Wilmington, NC it had weakened to a Category 2 hurricane. Most of the damage and casualties attributed to the storm were due to the heavy rainfall and flooding caused by the passage of the storm along the U.S. Atlantic coastline. The hardest hit area was eastern North Carolina.

This report presents the data collected by the Center for Operational Oceanographic Products and Services (CO-OPS) during the passage of Floyd in the week of September 13-19, 1999. The storm track resulted in significant storm surges at almost all of CO-OPS' National Water Level Observation Network (NWLON) stations along the Atlantic Coast. At three stations, observed water levels exceeded their historical records. Previous major storm event data reports are listed in the reference section at the end of this report.

The report begins with a description of the evolution of Hurricane Floyd from inception to dissipation, followed by a section indicating the NWLON stations affected by the hurricane at different times. The maximum observed water levels at the NWLON stations are then presented and compared with historical maximum elevations. Next, the maximum storm surges at the NWLON stations are discussed and compared, followed by a presentation and discussion of the ancillary meteorological data collected by some NWLON stations during this period. An example of currents driven by the hurricane's winds is presented using measurements obtained by two CO-OPS current meters. Finally, there is a discussion of operational problems and damage to NWLON stations, the operation of the real-time monitoring system, the newly-introduced Tides Online web site, and the interaction of CO-OPS with federal and state emergency management centers.



## II. Description of Hurricane Floyd

The information presented in this section has been collected from the National Weather Service (NWS) Monthly Tropical Weather Summary, the National Climatic Data Center (NCDC) Climate-Watch September 1999, the NOAA Atlantic Hurricane Season Summary 1999, and the hurricane advisories disseminated by the NOAA National Hurricane Center (NHC). The information from all of the NHC Hurricane Floyd advisories are listed in Table A of Appendix I. Table 1 below lists only those advisories when the storm changed its category on the Saffir/Simpson Hurricane Scale. The track of the storm is charted in Figure 1. The maximum wind speed and minimum pressure, plotted versus time in Figure 2, show that Floyd took slightly over 5 days to reach its peak intensity. The minimum pressure stayed below 935 mb and the maximum wind speed stayed above 130 mph for over 2 days showing the power and energy that the storm sustained. However, once Floyd passed over colder water and then made landfall, it degraded quickly in about 2 ½ days.

**Table 1. Hurricane Floyd weather advisories from the NOAA National Hurricane Center**

Advisory #	Category	Date	Time (GMT)	Wind Speed (mph)	Pressure(mb)
1	TD	9/7/99	2100	30	1008
3	TS	9/8/99	0900	40	1005
11A	H1	9/10/99	1200	80	989
15	H2	9/11/99	0900	105	963
19A	H3	9/12/99	1200	115	955
21A	H4	9/13/99	0000	145	932
24*	H4	9/13/99	1500	155*	921*
32	H3	9/15/99	1600	125	943
34B	H2	9/16/99	0800	110	956
35B	H1	9/16/99	1400	90	962
37	TS	9/16/99	2200	65	974

\* Advisory with highest wind speed and lowest pressure.

TD = Tropical Depression; TS = Tropical Storm; H# = Hurricane Category #.

The track of Hurricane Floyd closely resembles that of Hurricane Bertha in 1996. Hurricane Floyd originated as a tropical wave off the coast of Africa on September 2, 1999. Floyd was first named a tropical depression on September 7 at 2100 GMT and was about 1000 miles east of the Lesser Antilles in the mid-Atlantic Ocean. It became a tropical storm (winds exceeding 39 mph) six hours later on September 8 at 0900 GMT, when it was 850 miles east of the Lesser Antilles. Floyd became a Category 1 hurricane (winds exceeding 74 mph) on September 10 at 1200 GMT and was located about 240 miles northeast of the northern Leeward Islands. Tropical storm force winds extended out to 175 miles from the eye of the hurricane.

One day later, Floyd became a Category 2 hurricane and the following day, it was upgraded to a Category 3. Floyd became a Category 4 hurricane only 12 hours later. Maximum wind speeds continued to increase and minimum air pressure continued to decrease until Floyd reached its peak strength as a Category 4 hurricane on September 13 at about 1330 GMT. The maximum wind speed was 155 mph and the minimum pressure was 921 mb. If the wind speed had reached 156 mph, it would have been classified as a Category 5 hurricane. A NOAA-15 Advanced Very High Resolution Radiometer (AVHRR) multispectral false color image of Hurricane Floyd at its strongest point is shown in Figure 3.

Floyd remained a Category 4 hurricane for over 2 ½ days with peak sustained winds of 155 mph for more than 1 day. During this period, Floyd's eye passed over the islands of Eleuthera and Abaco in the Bahamas. Floyd then turned north-northwest and gradually weakened to become a Category 3 hurricane on September 15 at 1600 GMT. At this point, the eye was about 110 miles east-northeast of Cape Canaveral, FL with hurricane force winds extending out 125 miles and tropical storm force winds extending out 290 miles. As Floyd encountered cooler northern waters, its intensity decreased. On September 16 at approximately 0630 GMT (0230 EDT), Floyd made landfall near Cape Fear, NC. Moving north-northeast at 20 mph, it had become a Category 2 hurricane with sustained winds of 110 mph. Maximum storm surge was reported by NCDC to be 10.3 feet on Masonborough Island in New Hanover County, NC. A Geostationary Operational Environmental Satellite (GOES)-8 colorized IR image of Hurricane Floyd as it came ashore is shown in Figure 4. Several powerful hurricanes have made landfall near Cape Fear, including both Bertha (as a Category 2 hurricane) and Fran (as a Category 3 hurricane) in 1996. Hazel made landfall as a Category 4 hurricane in 1954 at the border between North and South Carolina.

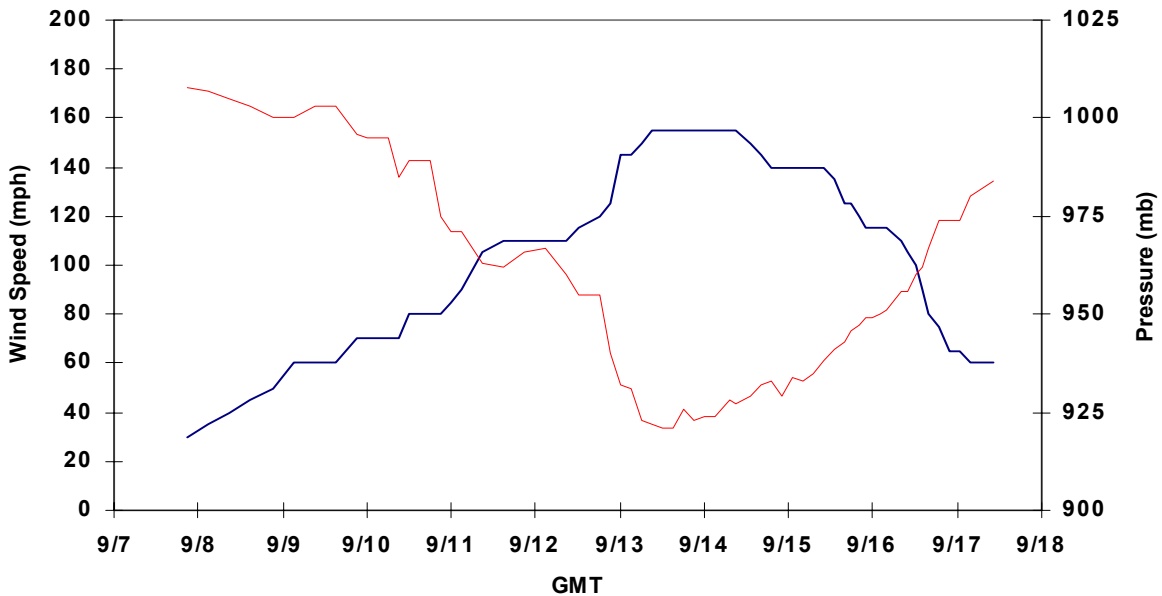
Floyd rapidly weakened over land becoming a Category 1 hurricane at 1400 GMT just before crossing into Virginia. Thereafter, Floyd generally followed the Atlantic coastline toward Connecticut, becoming a tropical storm on September 16 at 2200 GMT when it reached southern New Jersey. Over the open ocean, Floyd had been traveling at a speed of roughly 14 mph. After landfall, the storm accelerated up to a maximum speed of 35 mph as it passed through New England and into Maine.

Hurricane or tropical storm warnings were in effect at some point for all of the U.S. Atlantic coast from south Florida to Massachusetts. The largest peacetime evacuation in U.S. history took place with 2.6 million people evacuating their homes in Florida, Georgia, South Carolina, and North Carolina. Due to Hurricane Floyd's size, rainfall covered a large inland area and was responsible for flooding over many parts of the eastern United States, with the greatest totals in North Carolina. Wilmington, NC set a new 24-hour station rainfall record with 13.38 inches, breaking a 128-year old record, and over 19 inches was recorded for the entire storm (Figure 5). The death toll estimate is 75, making Floyd the deadliest United States hurricane since Agnes in 1972, with 122 deaths. The damage total is incomplete but could exceed the \$6 billion in damage caused by Hurricane Fran in 1996. A week after the passage of Floyd, flooded rivers which were causing severe environmental damage could be seen in a Sea-viewing Wide Field-of-View Sensor (SeaWiFS) image of eastern North Carolina (Figure 6).

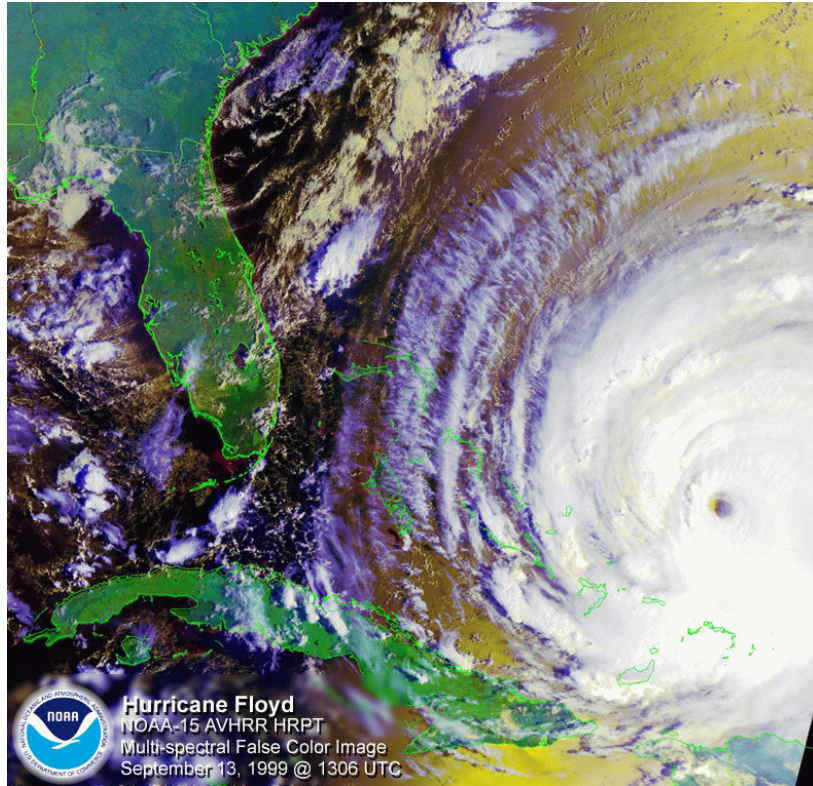




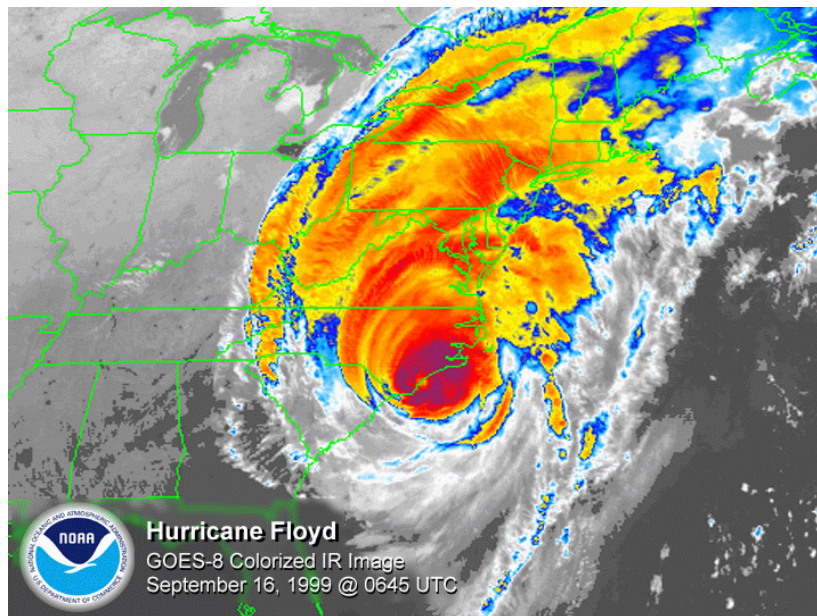
**Figure 1.** Track of Floyd from September 7 to September 17,1999. Change in Saffir/Simpson Hurricane Scale category indicated by color change and labeled with corresponding NHC advisory from Table 1. TD = Tropical Depression; TS = Tropical Storm; H# = Hurricane Category #.



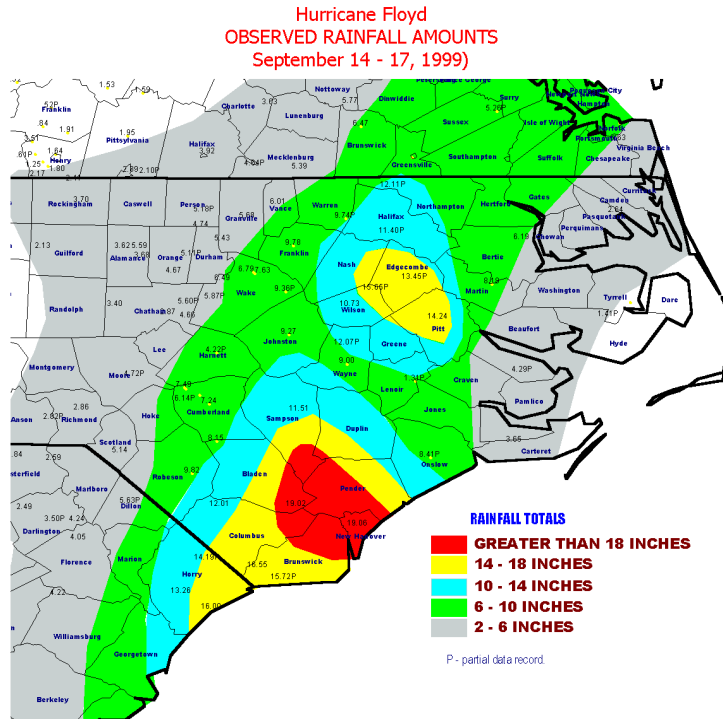
**Figure 2.** Hurricane Floyd maximum wind speed (blue line) and minimum pressure (red line) according to NHC advisories (see Table A in Appendix I).



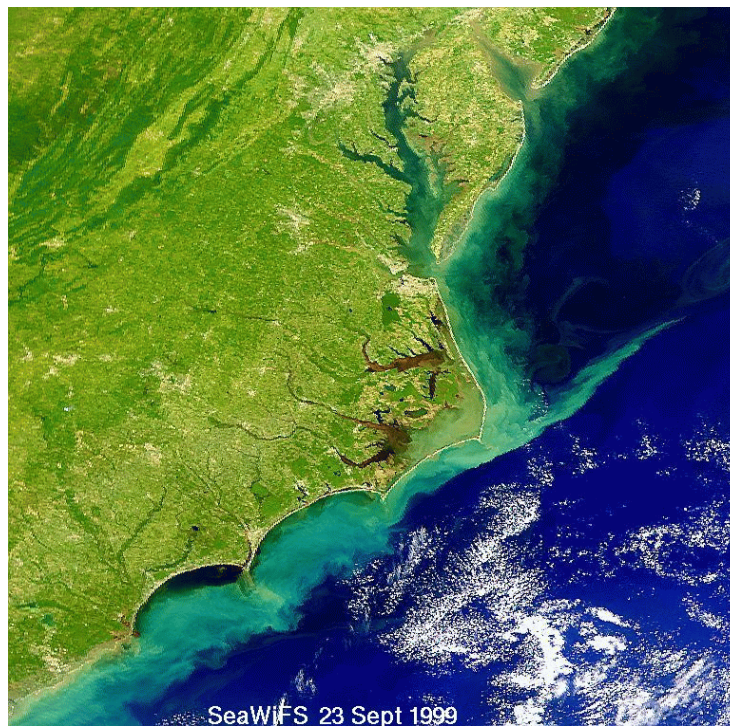
**Figure 3.** NOAA-15 AVHRR multi-spectral false color image of Hurricane Floyd at peak strength on September 13 at 1306 GMT [NCDC].



**Figure 4.** GOES-8 colorized IR image of Hurricane Floyd making landfall near Cape Fear, NC on September 16, 1999 at 0645 GMT [NCDC].



**Figure 5.** Total rainfall for September 14-17, 1999 [NWS Forecast Office, Wilmington, NC].



**Figure 6.** SeaWiFS image showing flooded rivers of eastern North Carolina on September 23, one week after passage of Floyd [NASA/Goddard Space Flight Center].





### III. The National Water Level Observation Network

CO-OPS, a component of the National Ocean Service (NOS), operates the NWLON which is composed of approximately 189 long term, continuously-operating stations distributed along the U.S. coast (including the Great Lakes) and on islands in the Atlantic and Pacific Oceans. As part of its National Water Level Program (NWLP), CO-OPS also installs, operates, and maintains additional short term water level stations in support of NOS hydrographic surveys and other federal and state projects.

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 climatological sea levels. These data are increasingly being required by users in real time. Coastal forecast applications include dissemination of data to the NWS Automation of Field Operations and Services (AFOS) network and for the development of coastal forecast models. Physical Oceanographic Real-Time Systems (PORTS), currently active in four U.S. ports, specifically provide data to users to ensure safe navigation.

The Next Generation Water Level Measurement System (NGWLMS) installed at most NWLON 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 level information with low power consumption, high reliability, and defined accuracy. The NGWLMS water level sensors have an accuracy of about one centimeter.

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 stations are the primary acoustic water level sensor and a pressure transducer for back-up water level measurements. The primary acoustic instrument is a non-contact device that returns 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.

Observed water levels at many NWLON stations recorded the effect of Hurricane Floyd as it moved north along the U.S. Atlantic coastline. In this report, NWLON stations between Virginia Key, FL and Boston, MA will be discussed including the station at Settlement Point in the Bahamas. The station numbers, names, latitudes, longitudes, and their periods of record are given in Table B of Appendix I. The locations of the stations and Hurricane Floyd's storm track are shown on the maps in Figures 7 and 8.

The data used in this report was preliminary 6-minute water level observations and hourly meteorological measurements. Some of the data may be adjusted after careful examination by

CO-OPS staff according to standard operating procedures, before an accepted data set is obtained. However, major changes to the results presented in this report are considered unlikely.

Since the hurricane made landfall and came closest to most of the stations on September 16, the period of interest was September 13 to September 19. The nearest NWLON station to the point where Floyd came ashore was Wilmington, NC which is on the Cape Fear River about 25 miles upriver from the coast. The NWLON stations closest to the storm track were Wilmington, NC, Chesapeake Bay Bridge Tunnel, VA, Kiptopeke Beach, VA, Cape May, NJ, Atlantic City, NJ, Sandy Hook, NJ, and Bridgeport, CT.



**Figure 7.** Northern U.S. Atlantic coast NWLON stations with the track of Hurricane Floyd.



**Figure 8.** Southern U.S. Atlantic coast NWLON stations with the track of Hurricane Floyd.





#### IV. Maximum Observed Elevations

A major concern during a storm 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, and the timing and strength of the tide when the storm reaches its peak strength. If a storm hits a location at low tide and/or during a period of neap tides, the maximum observed water level can be significantly less than when a storm hits at high tide and/or during a period of spring tides. The time period of Hurricane Floyd (September 13-19, 1999) fell between a new moon on September 9 and a full moon on September 25. Had the storm coincided with either a new moon or a full moon, higher maximum water levels could have occurred.

Information on the maximum observed water levels at NWLON stations during the period of September 13-19 is found in Table 2 which includes the following information: the date, time, and heights of the maximum observed water level above Mean Lower Low Water (MLLW) and Mean Higher High Water (MHHW), the mean Great Diurnal Range (GT), and the date and heights of the maximum historical water level above MLLW and MHHW. Elevations relative to a geodetic reference, the North American Vertical Datum of 1988 (NAVD88), are also available from CO-OPS (see the Summary of this report for contact information.)

The heights are referenced to the MLLW and MHHW datums at each location. These datums are based on the 1960-78 National Tidal Datum Epoch. 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. 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. 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. The maximum historical values are based on the entire period of record for each location, which is quite different at each station (see Table B in Appendix I for periods of record).

Appendix II contains time series plots for each station of the observed water levels and the predicted tides referenced to MLLW for the period September 13-19. 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 9 for the stations where Hurricane Floyd raised water levels above MHHW. The historical maxima caused by hurricanes occur between August and November and are labeled with the name of the hurricane or labeled "Unnamed" for hurricanes before 1950. The historical maxima caused by winter storms occur between October and March and are unlabeled. Hurricane Floyd approached or exceeded historical maxima south of and inside of Chesapeake Bay. North of Chesapeake Bay, the effect was much less than the historical maxima except at the recently installed station at Kings Point, NY, which was installed in late 1998 as a future replacement for the station at Willets Point, NY.

**Table 2. Maximum observed water level (meters)**

Station	Hurricane Floyd 1999			Great Diurnal Range (GT)	Historical Maximum		
	Date/Time (GMT) (mo/day, hr.min.)	MLLW	Above MHHW		Date (mo/yr)	MLLW	Above MHHW
Settlement Point, BA	9/14 1548	1.106	0.177	0.929			
Virginia Key, FL	9/15 0518	1.175	0.484	0.692	11/1994	1.335	0.643
Trident Pier, FL	9/15 0418	1.858	0.620	1.238	8/1995	1.881	0.643
St Augustine Beach, FL	9/15 1636	2.517	0.938	1.579	9/1992	2.395	0.816
Mayport, FL	9/15 1824	2.040	0.540	1.500	9/1964	2.299	0.799
Fernandina Beach, FL	9/15 1724	2.719	0.707	2.012	10/1898	4.197	2.185
Fort Pulaski, GA	9/15 1742	2.648	0.372	2.276	10/1947	3.398	1.122
Charleston, SC	9/15 1718	2.349	0.581	1.768	9/1989	3.901	2.133
Springmaid Pier, SC	9/16 0348	2.305	0.591	1.714	1/1987	2.903	1.189
Wilmington, NC	9/16 0754	2.254	0.876	1.378	10/1954	2.509	1.131
Duke Marine Lab, NC	9/16 0912	2.040	0.985	1.055	9/1996	1.941	0.886
Cape Hatteras, NC	9/16 0548	1.429	0.353	1.076	10/1997	1.822	0.746
Oregon Inlet Marina, NC	9/16 1454	1.847	1.480	0.367	8/1998	1.538	1.171
Duck Pier, NC	9/16 0400	1.517	0.374	1.143	10/1997	2.043	0.900
Ches. Bay Brdg. Tnl., VA	9/16 1636	1.846	0.946	0.900	2/1998	2.138	1.238
Money Point, VA	9/16 1718	2.275	1.326	0.949	2/1998	2.297	1.348
Hampton Roads, VA	9/16 1642	1.938	1.084	0.854	8/1933	2.558	1.704
Gloucester Point, VA	9/16 1542	1.654	0.822	0.832	3/1962	2.021	1.189
Windmill Point, VA	9/16 1818	1.146	0.710	0.436	2/1998	1.320	0.884
Lewisetta, VA	9/16 1800	1.158	0.692	0.466	2/1998	1.252	0.786
Colonial Beach, VA	9/16 1218	1.064	0.463	0.601	9/1996	1.667	1.066
Solomons, MD	9/16 1418	0.962	0.502	0.460	8/1955	1.380	0.920
Cambridge, MD	9/17 0006	1.051	0.427	0.624	9/1996	1.554	0.930
Kiptopeke Beach, VA	9/16 1706	1.884	0.961	0.923	3/1962	2.258	1.335
Wachapreague, VA	9/16 1754	2.314	0.912	1.402	2/1998	2.843	1.441
Lewes, DE	9/16 1900	2.062	0.620	1.442	3/1962	2.893	1.451
Reedy Point, DE	9/16 2006	2.291	0.468	1.823	10/1980	2.801	0.978
Philadelphia, PA	9/16 2242	2.848	0.748	2.100	11/1950	3.340	1.240
Cape May, NJ	9/16 1848	2.243	0.563	1.680	9/1985	2.771	1.091
Atlantic City, NJ	9/16 1612	1.896	0.469	1.427	12/1992	2.847	1.420
Sandy Hook, NJ	9/16 1748	2.003	0.418	1.585	9/1960	3.148	1.563
Bergen Point, NY	9/16 1718	2.123	0.428	1.695	3/1984	2.792	1.097
The Battery, NY	9/16 1800	1.972	0.412	1.560	9/1960	3.118	1.558
Montauk, NY	9/16 1924	1.061	0.271	0.790	8/1954	2.646	1.856
Willetts Point, NY	9/16 2136	2.883	0.512	2.371	9/1938	5.151	2.780
Kings Point, NY	9/16 2136	2.876	0.506	2.370	1/1999	3.146	0.776
Bridgeport, CT	9/16 2048	2.640	0.406	2.234	9/1938	3.791	1.557
New London, CT	9/16 1942	1.242	0.303	0.939	9/1938	3.280	2.341
Providence, RI	9/17 0512	1.796	0.284	1.512	9/1938	5.398	3.886
Newport, RI	9/17 0500	1.412	0.217	1.195	9/1938	4.124	2.929
Woods Hole, MA	9/17 0542	0.997	0.312	0.685	9/1938	3.349	2.664
Nantucket, MA	9/16 2224	1.201	0.103	1.098	10/1991	2.472	1.374
Boston, MA	9/16 2042	3.251	0.102	3.149	2/1978	4.648	1.499

The highest maximum observed elevation above MHHW due to Hurricane Floyd was 1.480 meters occurring at Oregon Inlet Marina, NC on September 16 at 1454 GMT. Money Point and Hampton Roads, VA also had maximum observed elevations more than 1 meter above MHHW. Although some of the NWLON stations dropped below MLLW during the period under consideration, none went more than 0.5 meters below MLLW. The NWLON stations in Virginia and North Carolina, with the exceptions of Duck and Cape Hatteras, NC, tended to have the highest maximum observed elevations relative to MHHW (Figure 9). Note that the Duck and Cape Hatteras stations are both on the ocean, adjacent to the narrowest part of the continental shelf on the U.S. Atlantic coast, and also that the storm track was over land to the west of that section of the North Carolina coastline (Figure 8).

At the three NWLON stations listed in Table 3, Floyd produced a maximum observed elevation greater than the historical record at the station. At Oregon Inlet Marina, the historical record from Hurricane Bonnie in August 1998 was exceeded by 0.309 meters. At Duke Marine Lab in Beaufort, NC, the previous record from Hurricane Fran in September 1996 was exceeded by 0.099 meters. The previous record at St. Augustine Beach was not associated with a hurricane.

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

<b>Station</b>	<b>Date of historical maximum</b>	<b>Years of data</b>	<b>Period of data</b>	<b>Increase in maximum</b>
St. Augustine Beach, FL	9/92	7+	5/92 - present	0.122 meters
Duke Marine Lab, NC	9/96	26+	2/73 - present	0.099 meters
Oregon Inlet Marina, NC	8/98	6+	5/77 - 4/78 4/94 - present	0.309 meters

The maximum elevations caused by Floyd approached within 0.3 meters of the maximum historical elevations at nine other locations within or south of Chesapeake Bay. At Wilmington, NC, the NWLON station closest to the location where Floyd came ashore as a Category 2 hurricane, Floyd failed to surpass the historical maximum by 0.255 meters, which was set by Hurricane Hazel in 1954 as it made landfall near the border between North and South Carolina as a Category 4 hurricane (Figure 10). However, Floyd did surpass, by 0.097 meters, the level reached in 1996 when Hurricane Fran made landfall near Cape Fear as a Category 3 hurricane.

The time series in Appendix II illustrate a variety of localized responses to the storm. While Hurricane Floyd passed less than 100 miles to the east of Settlement Point on the western tip of Grand Bahama Island, the storm had little effect on the water level at that station (Figure 41 in Appendix II), although the bathymetry of the area includes the shallow waters of Little Bahama Bank and the land mass of Grand Bahama Island. For several days before Hurricane Floyd, the stations from Trident Pier, FL to Charleston, SC exhibited elevated water levels at both high and low tides

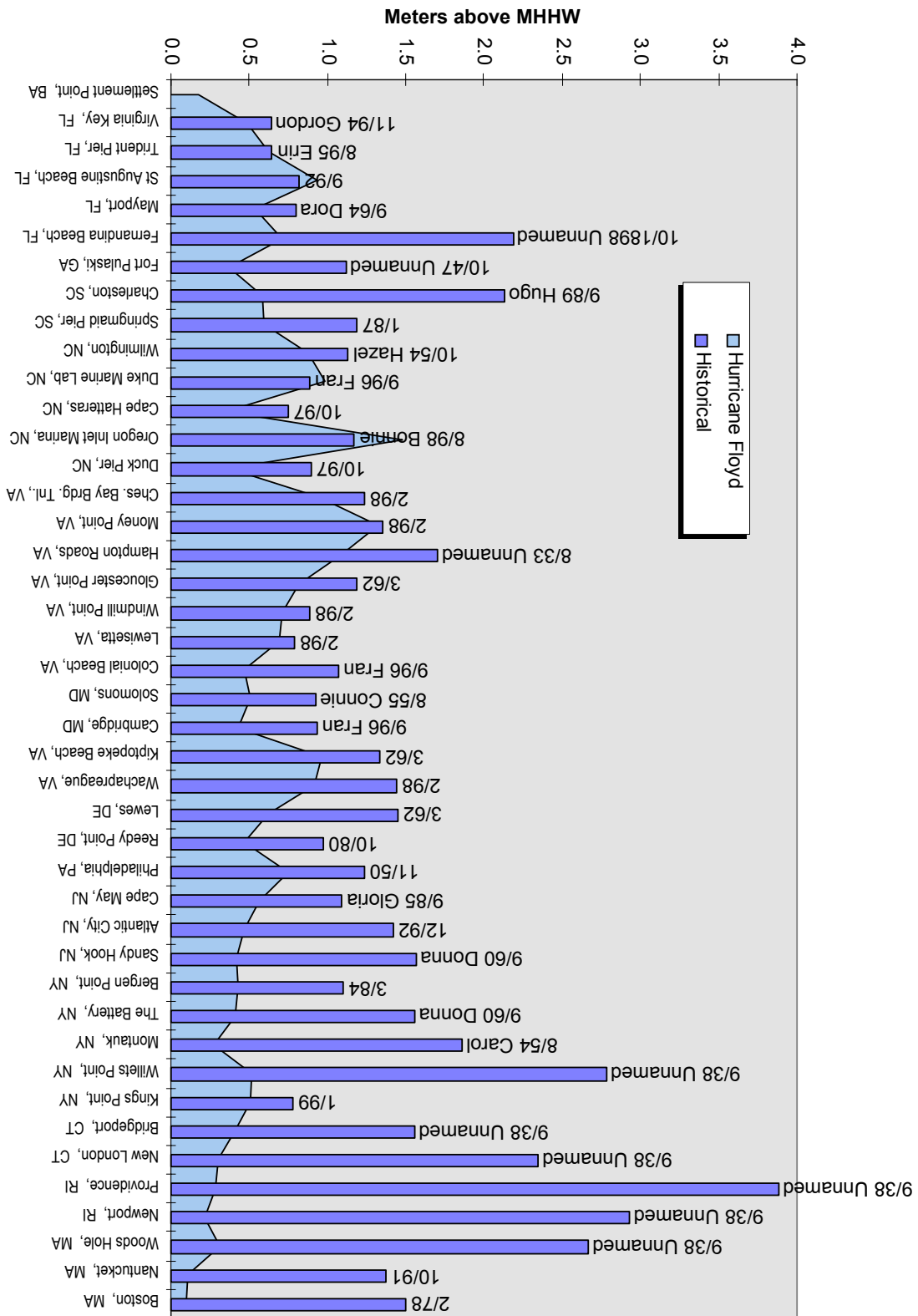
(Figures 43 to 48 in Appendix II). After the storm passed through the area, the water level returned near to predicted levels.

In contrast, for several days after the storm passed Wilmington, NC, the water levels at low tide were elevated 0.6 - 0.7 meters above predicted; the water levels at high tide were slightly above predicted (Figure 50 in Appendix II). This elevation was probably due to the increased flow of the Cape Fear River carrying the runoff from the heavy rainfall throughout the drainage basin of the river (Figure 5). The nonlinearity in the fluid dynamics of shallow bays and estuaries can cause the tidal range to change during periods of abnormal conditions (Parker, 1991). Higher than normal river flows tend to decrease the tidal range.

At most stations, the maximum observed elevation occurred very close to the time of a predicted high tide. However, at a few stations listed in Table 4, the intensity of the storm caused the maximum observed elevation to occur significantly earlier or later than the predicted high tide, with the greatest tide prediction error at Duke Marine Lab, NC.

**Table 4. Greatest timing differences of the maximum observed water levels during Hurricane Floyd relative to predicted high tide**

Wilmington, NC	1 hour 18 minutes later
Duke Marine Lab, NC	4 hours 30 minutes later
Gloucester Point, VA	2 hours 48 minutes earlier
Oregon Inlet Marina, NC	2 hours 12 minutes earlier
Cambridge, MD	2 hours 6 minutes earlier
Hampton Roads, VA	1 hour 36 minutes earlier
Money Point, VA	1 hour 30 minutes earlier
Chesapeake Bay Bridge Tunnel, VA	42 minutes earlier
Kiptopeke Beach, VA	36 minutes earlier



**Figure 9.** Comparison of historical maximum observed elevations (relative to MHHW) to the maximum observed elevations during Hurricane Floyd – September 13-19, 1999. Month and year of historical maximum elevations are indicated. Historical maximum elevations caused by hurricanes are labeled and those caused by winter storms are unlabeled. Hurricanes before 1950 were unnamed.



## V. Storm Surge

Storm surge is defined 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 predicted high tide. Information on the maximum storm surge calculated at each station is found in Table 5 which provides the following for each station: the date and time of the maximum storm surge; the observed elevation of the water above MLLW at that time; the predicted elevation of the water above MLLW at that time; 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 III. Maximum storm surge values for all stations are displayed in Figure 11. Figures 12 through 18 are simultaneous plots of the storm surge for various geographical regions over a seven-day time period centered around the time of the storm. The wide solid line in these figures is the track 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 largest storm surge occurred at Duke Marine Lab, NC. The calculated surge was 1.733 meters on September 16 at 0912 GMT. Storm surge values greater than 1.4 meters also occurred at Fernandina Beach, FL, Oregon Inlet Marina, NC, and Money Point, VA (Figure 11).

The storm surge plots for some of the stations show a degree of periodicity at the tidal frequencies. This is attributed to the subtraction of two curves (observed and predicted) that may be slightly out of phase because of the storm, and to the effect of a prolonged storm surge in modifying the normal shape of the observed tide curve.

First, the storm surge for nine selected stations that are closest to the open ocean are shown in Figure 12. These records are more representative of the storm's effect on continental shelf water levels and less influenced by the localized effects of bays and estuaries. There was a general correlation between the time of the maximum storm surge and the time of the passage of the hurricane, but several factors influenced 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 contributed to the amount of storm surge.

Storm surges for six regions of the Atlantic coast are shown along with the track of Hurricane Floyd (Figures 13 to 18): Florida/Georgia, the Carolinas, lower Chesapeake Bay, upper Chesapeake Bay/Potomac River, Delaware Bay/New Jersey/New York Harbor, and Long Island Sound/Rhode Island/Massachusetts. A wide variety of storm surges were observed. Many of the stations with larger surges are located in sounds or bays where persistent winds from the storm pushed water into enclosed areas and held it there through a complete tidal cycle causing the water level to remain unusually high during the time of the predicted low tide. After the storm passed and the wind

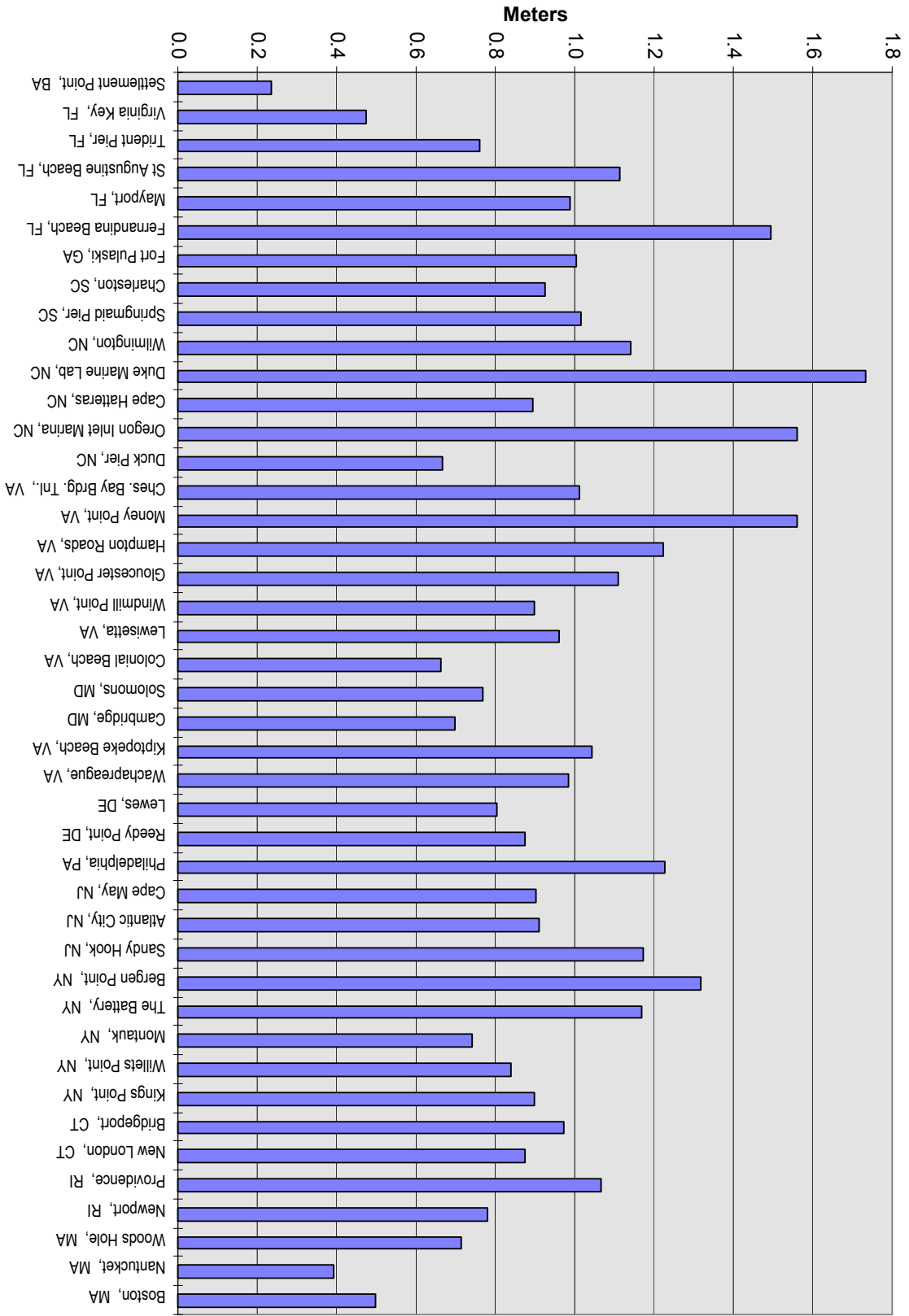
changed direction, these stations showed a rapid drop in water elevation as the water that was held in the embayment was pushed out to sea. Prominent negative storm surges were seen at Kings Point, NY (-1.073 m), Washington, DC (-0.977 m), Bridgeport, CT (-0.843 m), and Willets Point, NY (-0.838 m). Nine other stations showed negative storm surges greater than 0.5 meters.



**Table 5. Maximum storm surge (meters) for Hurricane Floyd 1999**

Station	Date/Time (GMT) (mo./day, hr.min.)	Elevation Above MLLW		Storm Surge
		Observed	Predicted	
Settlement Point, BA	9/15 0836	0.507	0.272	0.235
Virginia Key, FL	9/15 0730	0.943	0.470	0.473
Trident Pier, FL	9/15 0418	1.858	1.096	0.762
St Augustine Beach, FL	9/15 1112	1.450	0.338	1.112
Mayport, FL	9/15 1006	1.294	0.307	0.987
Fernandina Beach, FL	9/15 1018	1.584	0.088	1.496
Fort Pulaski, GA	9/15 0848	1.556	0.552	1.004
Charleston, SC	9/15 2018	1.772	0.845	0.927
Springmaid Pier, SC	9/15 1918	1.987	0.971	1.016
Wilmington, NC	9/16 0830	2.171	1.028	1.143
Duke Marine Lab, NC	9/16 0912	2.040	0.307	1.733
Cape Hatteras, NC	9/16 0942	1.127	0.232	0.895
Oregon Inlet Marina, NC	9/16 1454	1.847	0.285	1.562
Duck Pier, NC	9/16 1054	0.936	0.271	0.665
Ches. Bay Brdg. Tnl., VA	9/16 1606	1.829	0.816	1.013
Money Point, VA	9/16 1706	2.262	0.703	1.559
Hampton Roads, VA	9/16 1624	1.937	0.714	1.223
Gloucester Point, VA	9/16 1542	1.654	0.544	1.110
Windmill Point, VA	9/16 1554	1.130	0.233	0.897
Lewisetta, VA	9/16 1706	1.137	0.177	0.960
Colonial Beach, VA	9/16 1742	0.795	0.132	0.663
Solomons, MD	9/16 1636	0.953	0.185	0.768
Cambridge, MD	9/16 1854	0.864	0.166	0.698
Kiptopeke Beach, VA	9/16 1612	1.832	0.787	1.045
Wachapreague, VA	9/16 0912	1.461	0.476	0.985
Lewes, DE	9/16 1912	2.060	1.256	0.804
Reedy Point, DE	9/16 1524	1.170	0.295	0.875
Philadelphia, PA	9/17 0500	1.686	0.458	1.228
Cape May, NJ	9/16 1930	2.210	1.308	0.902
Atlantic City, NJ	9/16 2000	1.692	0.784	0.908
Sandy Hook, NJ	9/16 2330	1.515	0.344	1.171
Bergen Point, NY	9/16 2318	1.727	0.410	1.317
The Battery, NY	9/16 2248	1.649	0.482	1.167
Montauk, NY	9/17 0036	0.978	0.238	0.740
Willets Point, NY	9/17 0136	1.432	0.594	0.838
Kings Point, NY	9/16 1712	1.738	0.839	0.899
Bridgeport, CT	9/17 0154	1.449	0.476	0.973
New London, CT	9/17 0048	1.138	0.262	0.876
Providence, RI	9/17 0206	1.754	0.687	1.067
Newport, RI	9/17 0136	1.270	0.491	0.779
Woods Hole, MA	9/17 0100	0.959	0.245	0.714
Nantucket, MA	9/17 0312	0.579	0.188	0.391
Boston, MA	9/17 0100	1.508	1.008	0.500

**Figure 11. Maximum storm surge at water level stations during Hurricane Floyd -- September 13-19, 1999.**



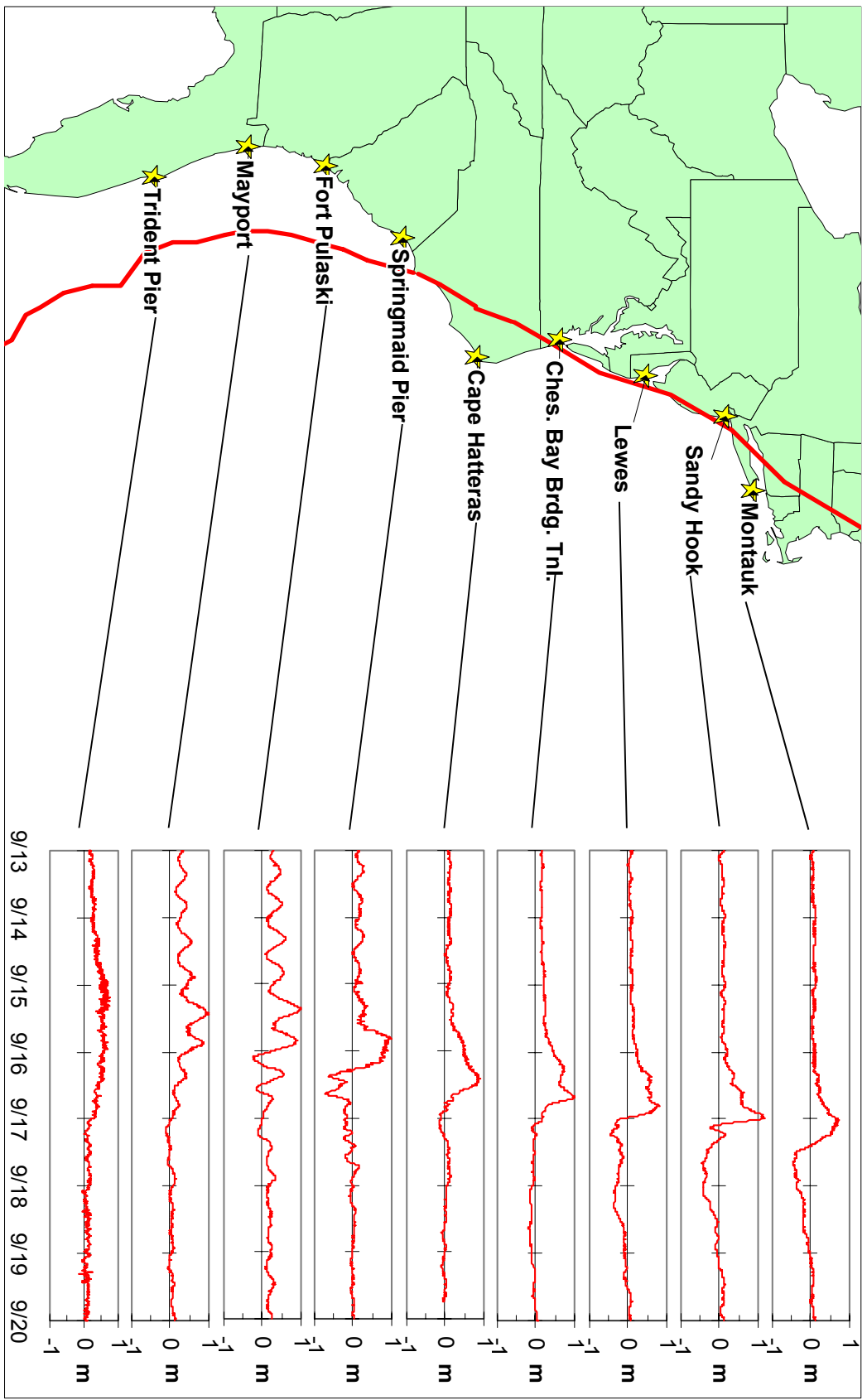


Figure 12. Hurricane Floyd storm surge at selected US Atlantic coast NWLON stations on or close to the ocean.

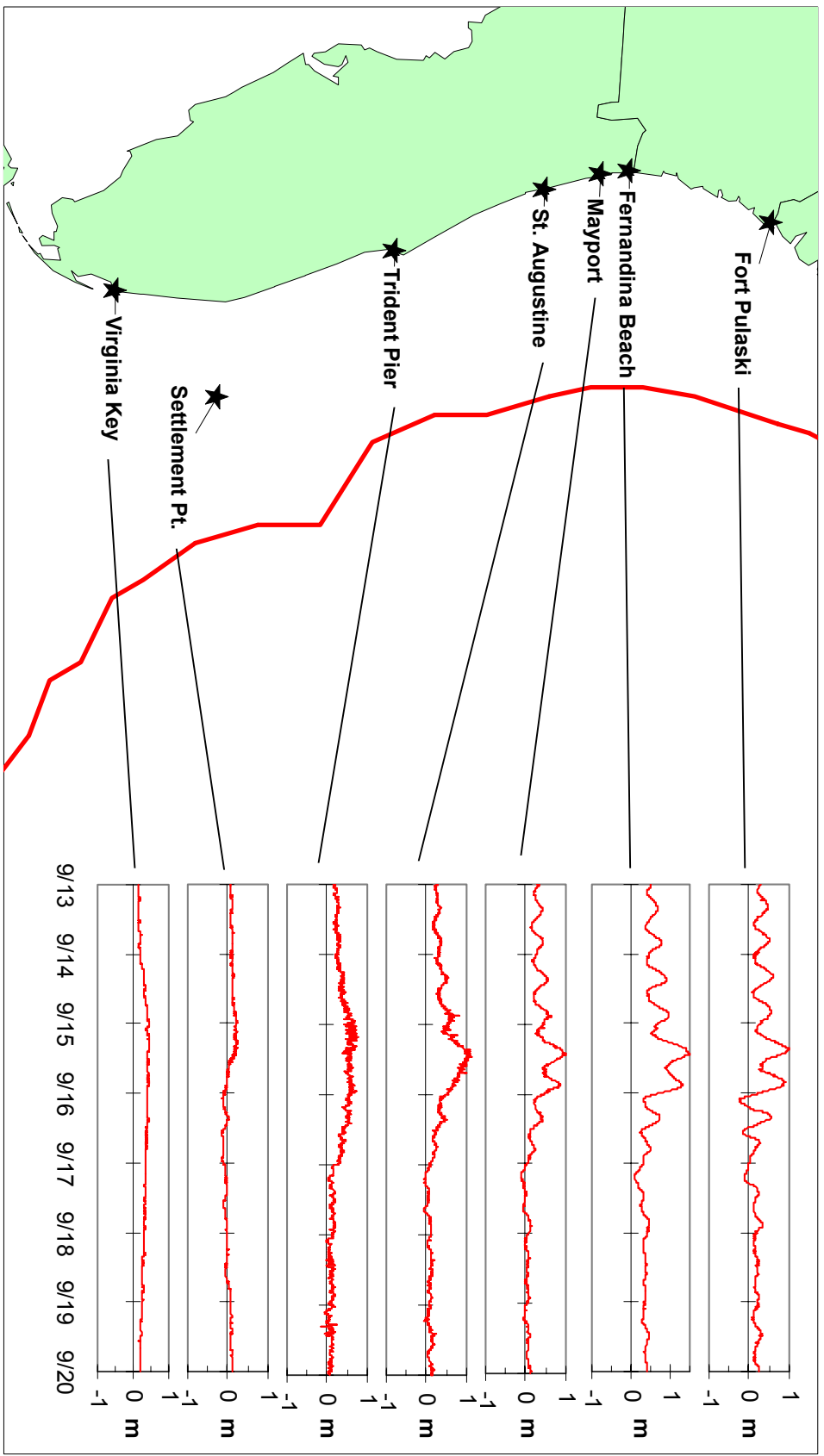


Figure 13. Hurricane Floyd storm surge at NWLON stations in Florida, Georgia, and the Bahamas.

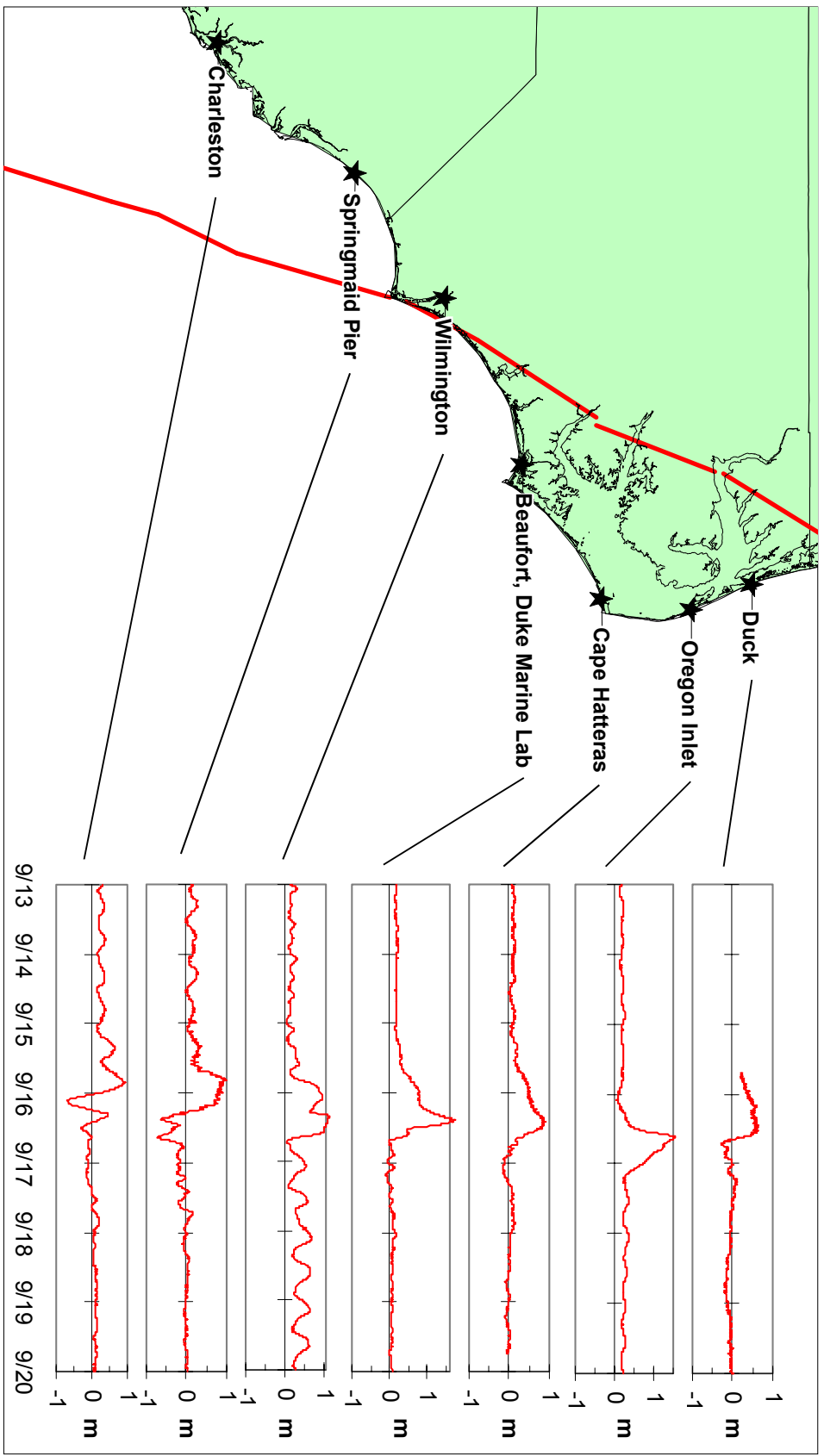


Figure 14. Hurricane Floyd storm surge at NWLON stations in North Carolina and South Carolina.

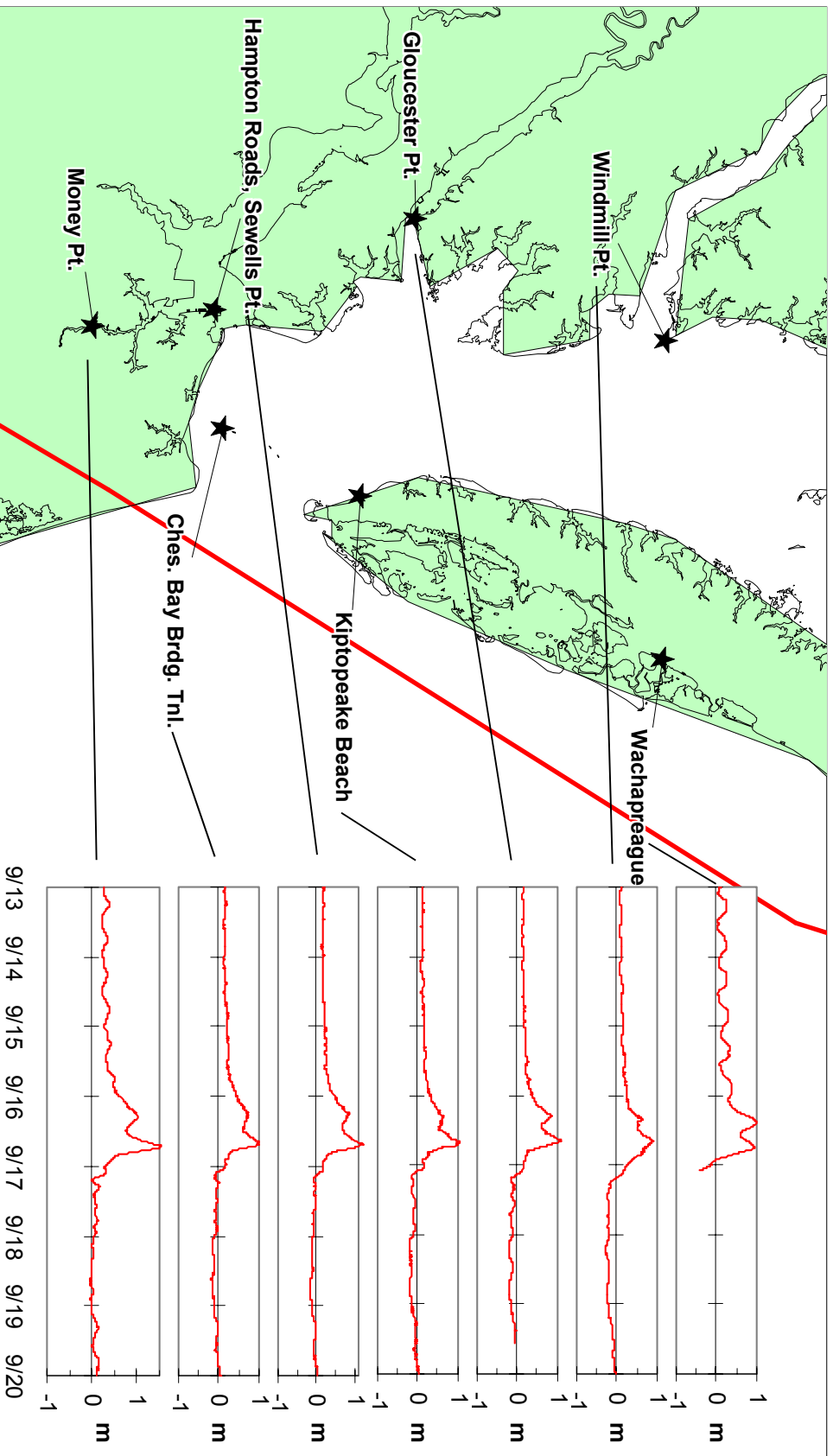


Figure 15. Hurricane Floyd storm surge at NWLON stations in southern Virginia.

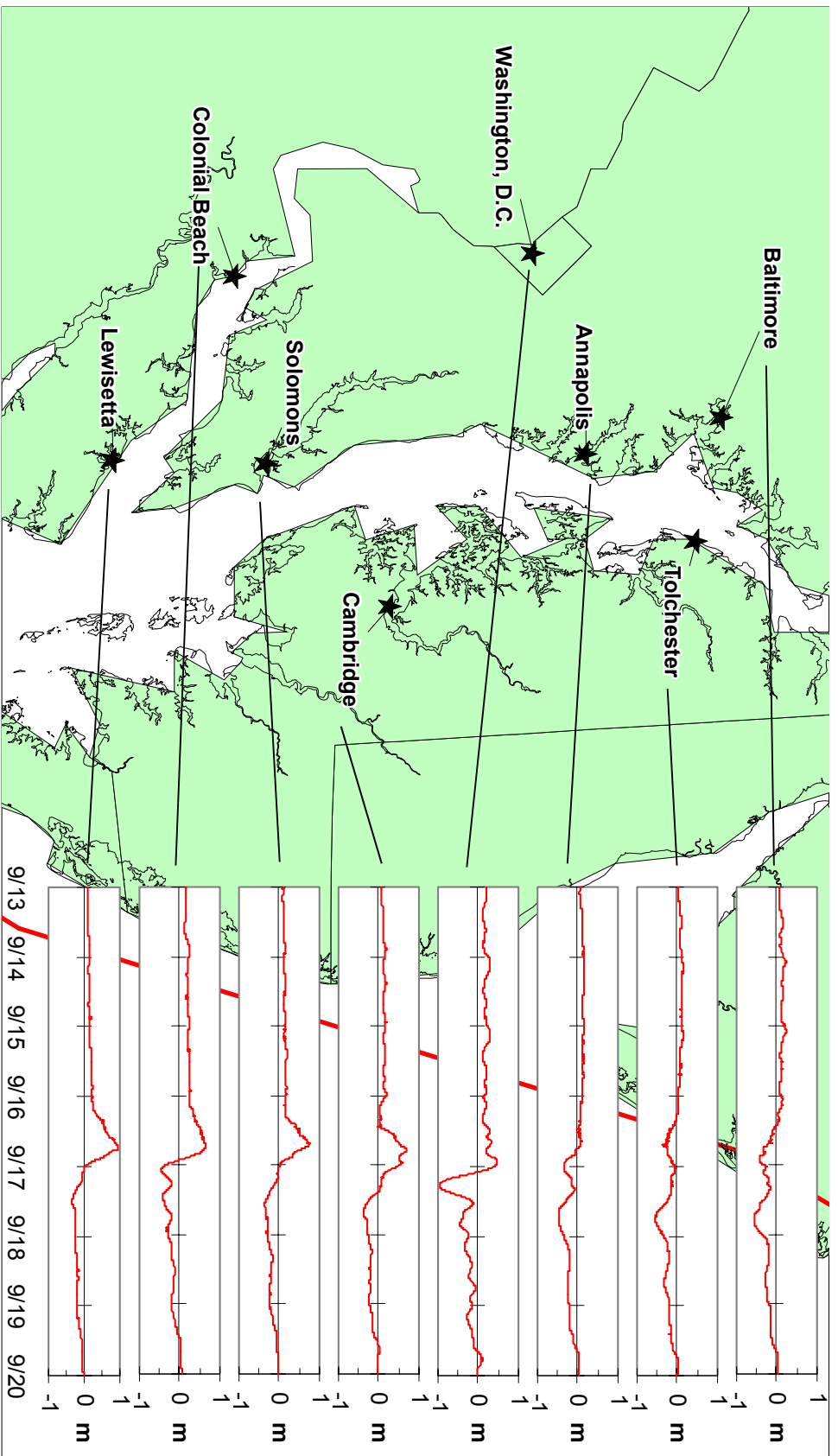


Figure 16. Hurricane Floyd storm surge at NWLON stations in northern Virginia, Maryland, and Washington, DC.

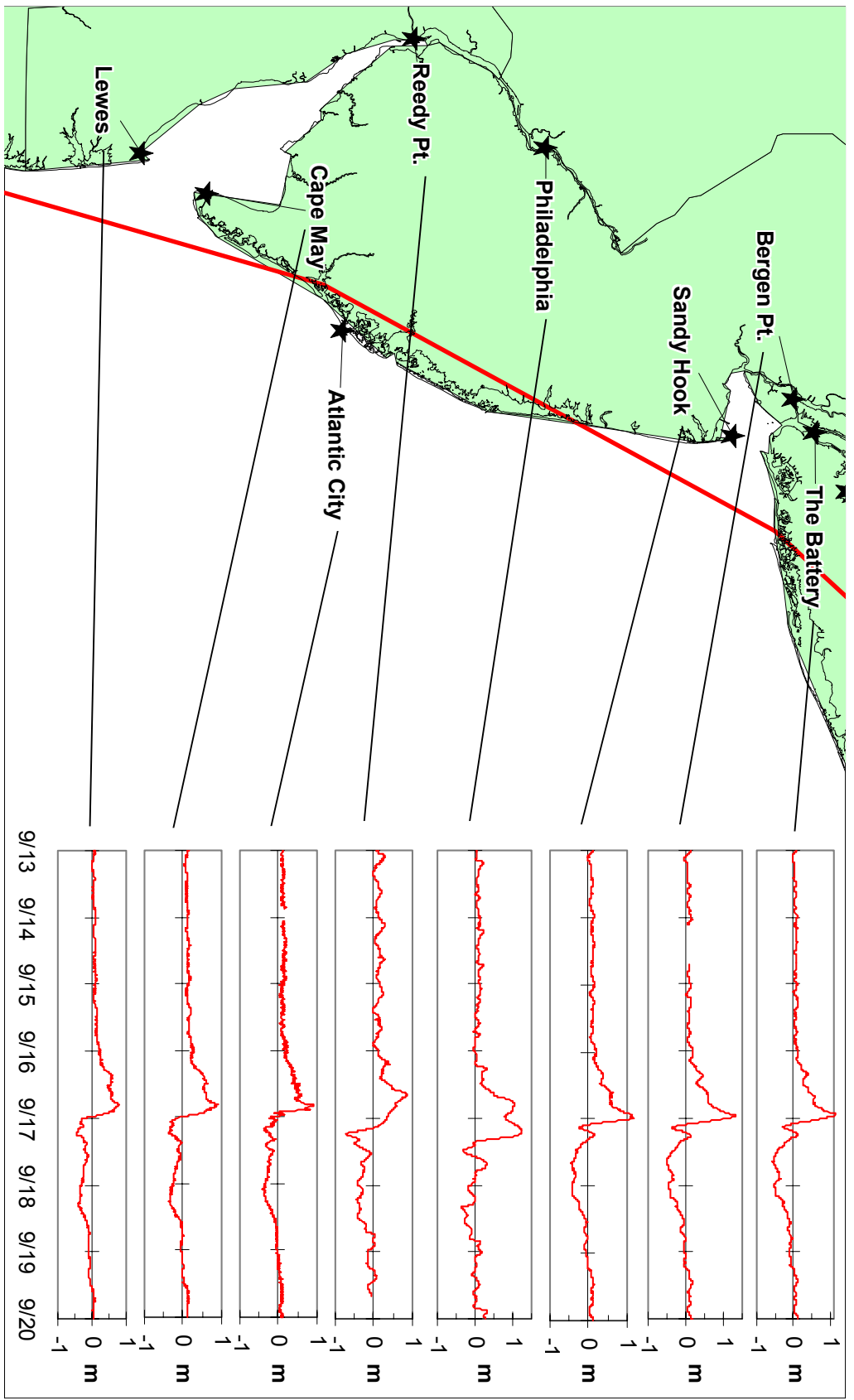


Figure 17. Hurricane Floyd storm surge at NWLON stations in Delaware, Pennsylvania, New Jersey, and New York City, NY.



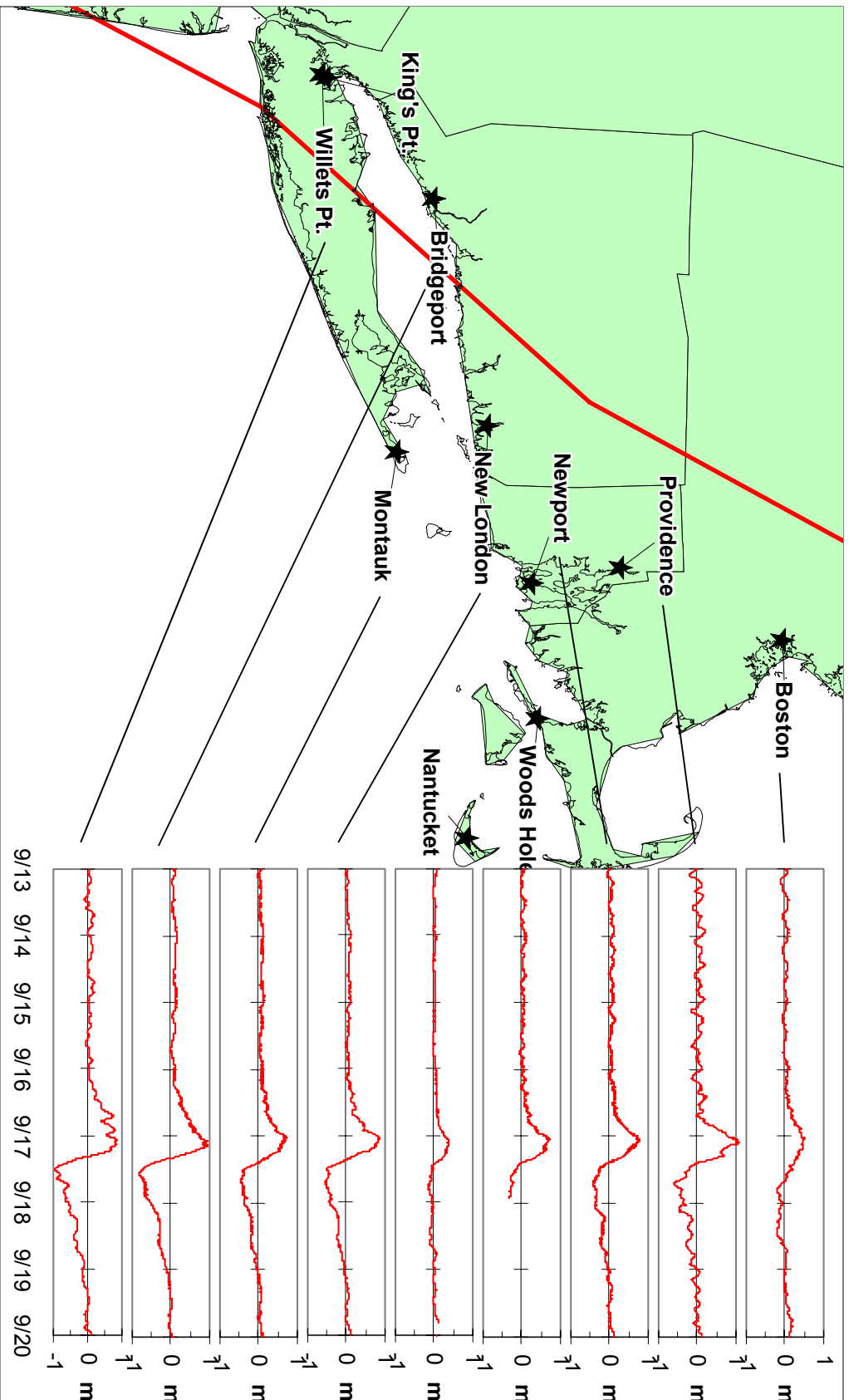


Figure 18. Hurricane Floyd storm surge at NWLON stations in New York, Connecticut, Rhode Island, and Massachusetts.



## VI. Meteorological Data

A total of sixteen east coast NWLON stations collected ancillary meteorological data including the wind speed, wind direction, and barometric pressure during the passage of Hurricane Floyd. The station at Mayport, FL collected wind speed but not wind direction. The stations at Newport, RI and Providence, RI collected barometric pressure but no wind data. The lowest point of a barometric pressure record at a water level station indicates the time that the storm came closest to that station; a rapid fall and rise in pressure indicates that the center of the hurricane came close to or passed over that station. Time series plots of all wind speed and barometric pressure data collected at NWLON stations are found in Appendix IV.

Barometric pressure at some representative NWLON stations are plotted in Figures 19 to 21. The lowest pressures recorded were at Duck, where the pressure dropped to 972.1 mb, and at Chesapeake Bay Bridge Tunnel, where the pressure reached 976.4 mb. The center of the hurricane passed Virginia Key around 2200 GMT on September 14, and Mayport around 2000 GMT on September 15. On September 16, it came close to Duck and Cape Hatteras at 1300 GMT, Chesapeake Bay Bridge Tunnel at 1600 GMT, the northern Chesapeake Bay stations near 2000 GMT, and Sandy Hook near 2300 GMT. It passed Newport around 0500 GMT on September 17 and Eastport later that day near midnight GMT.

A change in the air pressure over a body of water can raise or lower water levels due to an inverse barometer effect. Low air pressure results in a rise in the level of the water surface, while high air pressure depresses the level of the water surface. A simple rule of thumb is that a 1 millibar change in air pressure corresponds to a 1 centimeter change in water level over open ocean (Harris, 1963). Although many variables will change the magnitude of the inverse barometer effect, rough estimates can be made of the pressure effect of Hurricane Floyd on the water level. The maximum effect, at the instant of lowest barometric pressure, could range from about 10 centimeters at Virginia Key, FL to about 50 centimeters at Duck, NC.

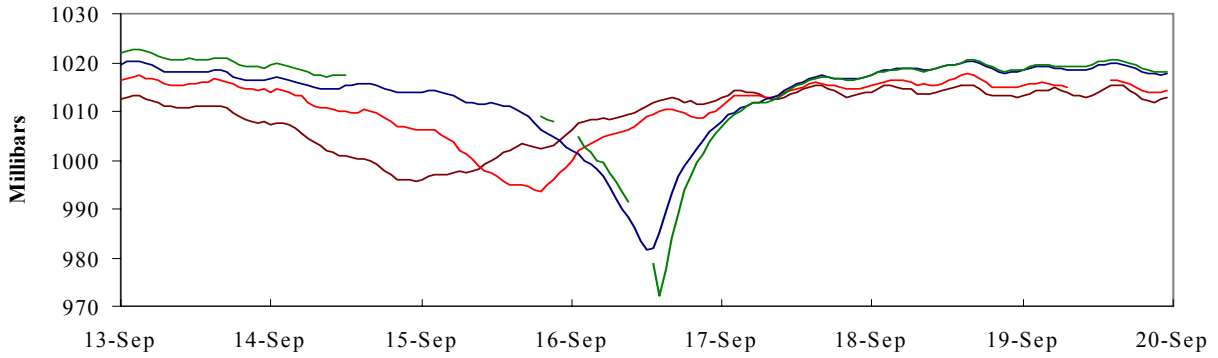
During a storm, the effect of the wind stress on water levels is often substantially greater than the inverse barometer effect. Wind stress acting on the surface of a shallow body of water with a solid boundary creates a slope against the boundary. A reduced slope forms for a deeper body of water since a countercurrent at depth is induced to oppose the effect of wind stress on the surface slope, resulting in upwelling or downwelling at the boundary. Since wind stress is proportional to the square of wind speed, large changes in water levels can be caused by winds over shallow water (Harris, 1963). In Figures 22 to 33, wind vectors and storm surges are plotted for the three days of September 15, 16, and 17, before and after the passage of the storm.

There was an interesting contrast in the storm surges of the three NWLON stations on the Outer Banks of North Carolina (Figures 22 to 24). The stations at Cape Hatteras and Duck, which are located on the ocean side of the Outer Banks, show rising water levels as Floyd approached with increasing easterly winds pushing water toward shore. The station at Oregon Inlet Marina, which is located on the Pamlico Sound side of the Outer Banks, initially did not respond to the approaching storm. As the storm passed by, the wind speed rose to a maximum of about 30 m/s and rotated to a southerly direction, followed by a westerly direction. The water levels at Cape Hatteras and Duck

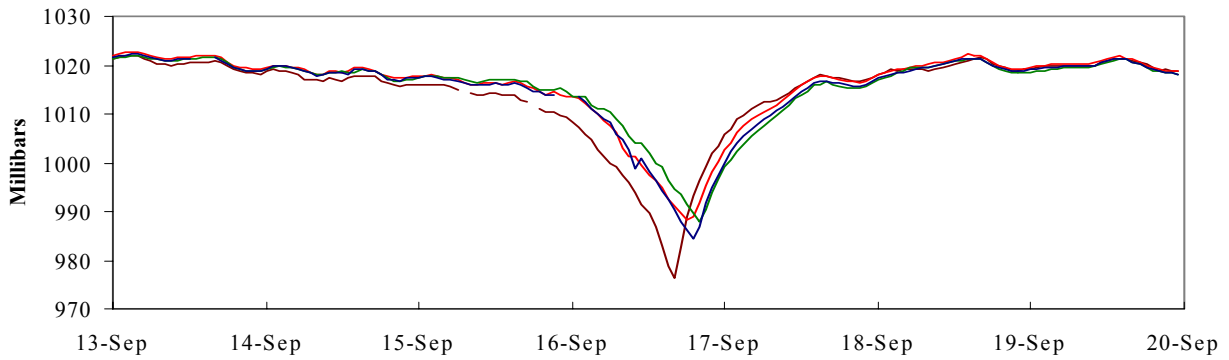
rapidly dropped back to normal as water was pushed away from shore. In contrast, the water level at Oregon Inlet Marina began a rapid rise in response to a southerly wind direction, reaching a maximum storm surge about twice the maximum storm surges at Cape Hatteras and Duck. This was likely caused by the water in shallow Pamlico Sound being pushed toward the north. As the wind speed dropped over a period of 24 hours, the water level at Oregon Inlet Marina slowly returned to normal.

At most of the NWLON stations, the storm surge level rose before the passage of the storm and fell after the passage of the storm. The change in wind direction as the center of the storm passed, indicated a change in the trend of the storm surge at the station. The closer the hurricane came to a station, the quicker the wind changed direction as the center passed by. At Chesapeake Bay Bridge Tunnel, VA, Hampton Roads, VA, Sandy Hook, NY, Bergen Point, NY and Kings Point, NY, the wind direction rotated over 90 degrees within an hour, near the time of maximum storm surge.

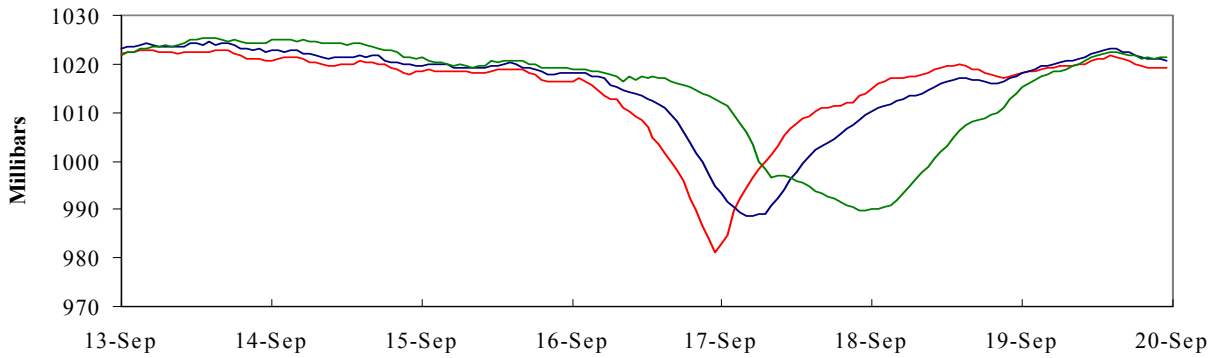
At some locations, where the winds following the storm's passage were sustained, the storm surge became negative. The largest negative storm surges occurred in upper Chesapeake Bay and western Long Island Sound. At Tolchester Beach, MD (Figure 30), there was no positive storm surge as the rise in water level from southern Chesapeake Bay did not propagate far enough north, before northerly winds began to push the water of northern Chesapeake Bay toward the south. At Kings Point, NY (Figure 33), unlike the nearby stations at Bergen Point and Sandy Hook, there was a delay of about 6 hours after the local winds shifted direction, before the water level began falling. This could be because the wind at Kings Point was not representative of the winds over Long Island Sound, which has an effect on Kings Point water levels.



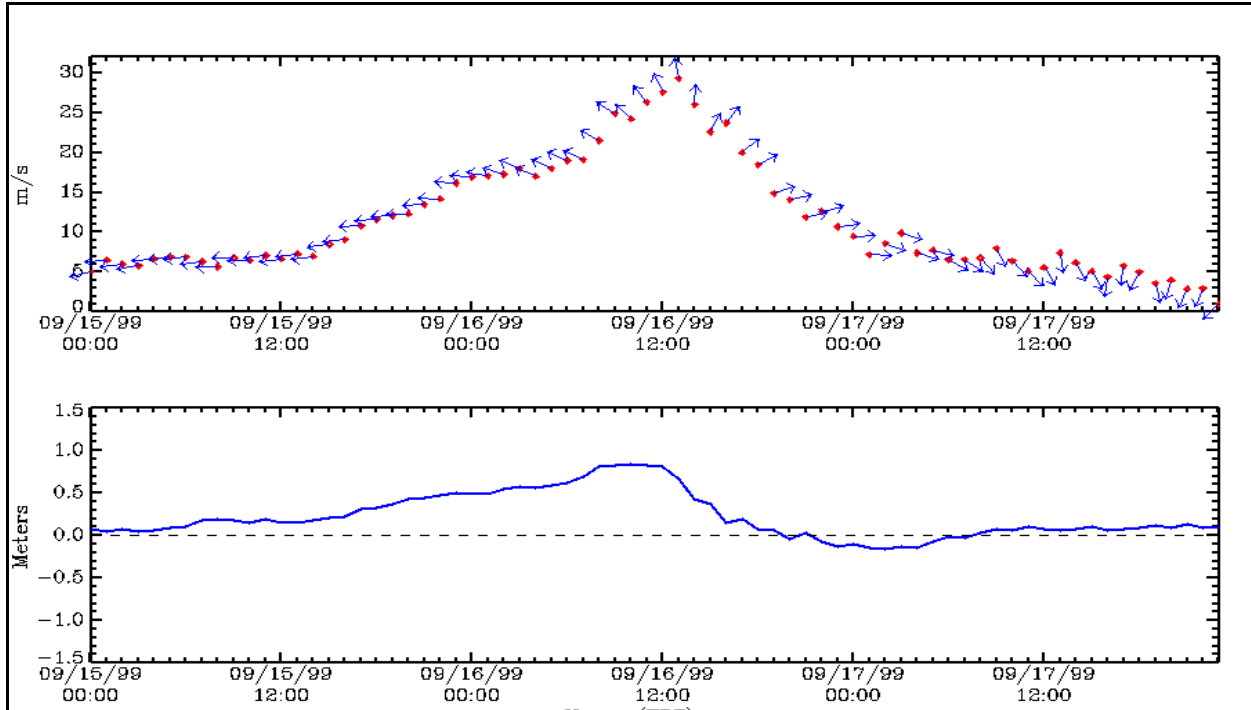
**Figure 19.** Barometric pressure at Virginia Key, FL (brown), Mayport, FL (red), Cape Hatteras, NC (blue), and Duck, NC (green).



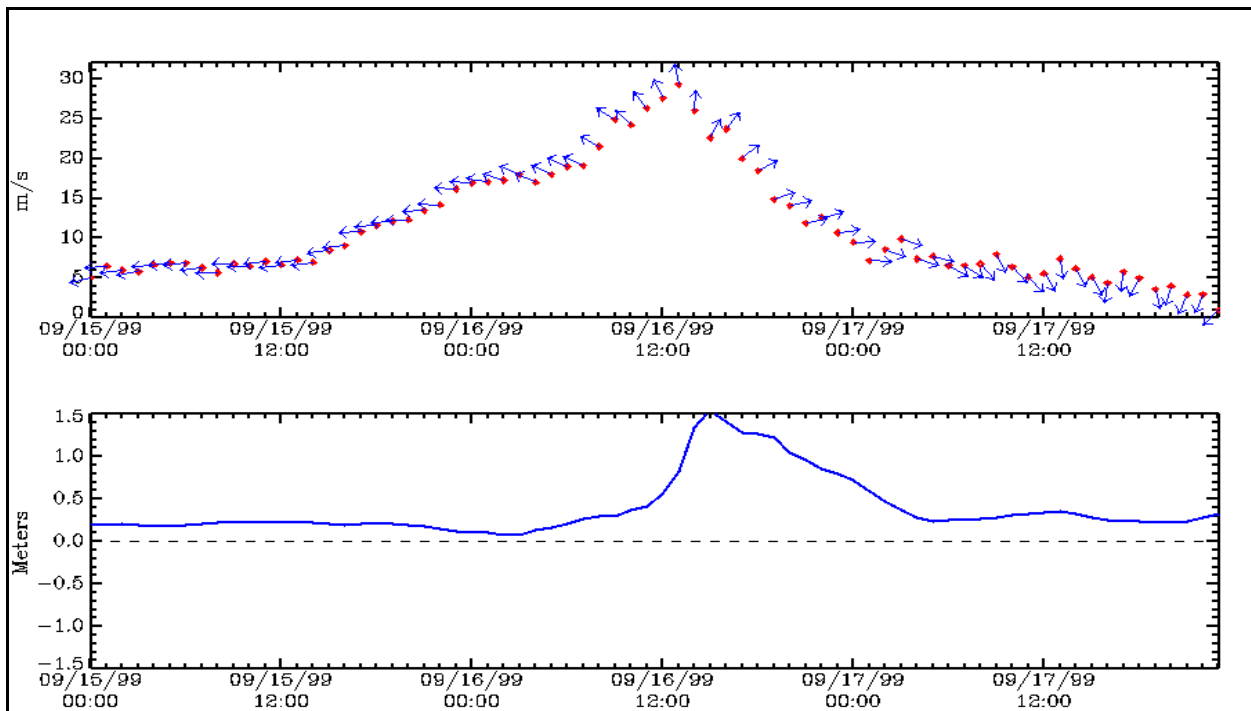
**Figure 20.** Barometric pressure at Chesapeake Bay Bridge Tunnel, VA (brown), Solomons Island, MD (red), Cambridge, MD (blue), and Tolchester Beach, MD (green).



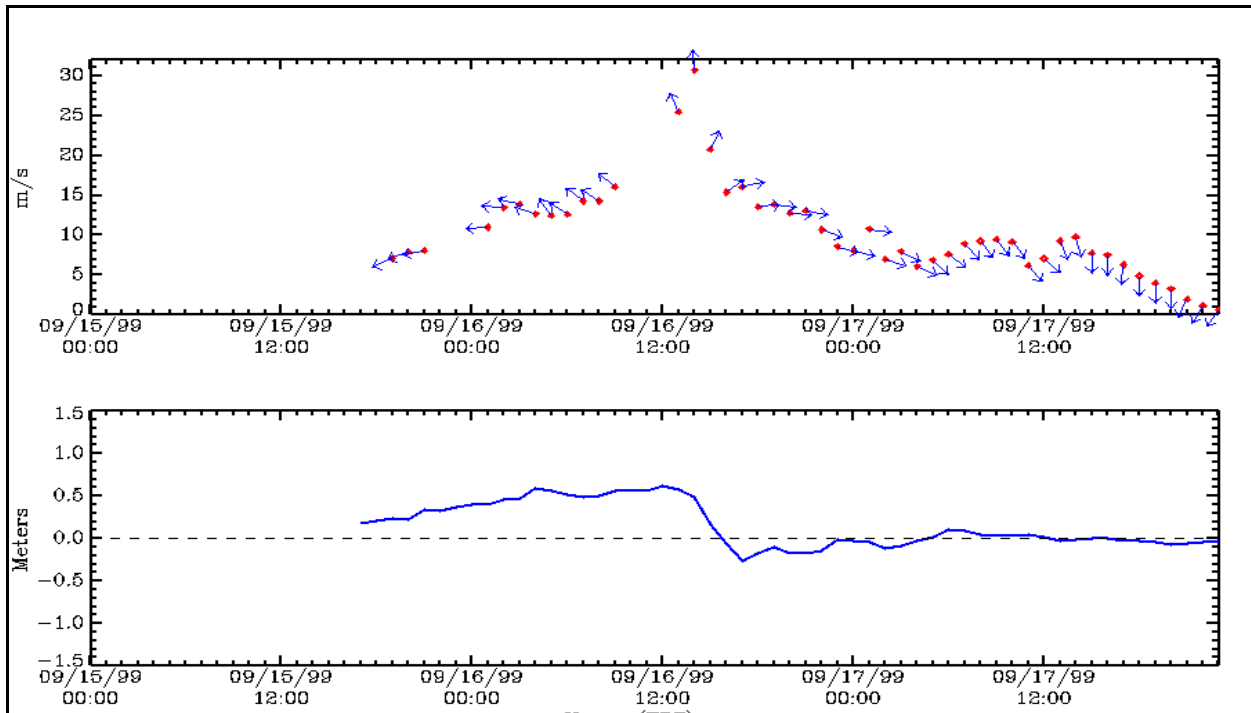
**Figure 21.** Barometric pressure at Sandy Hook, NJ (red), Newport, RI (blue), and Eastport, ME (green).



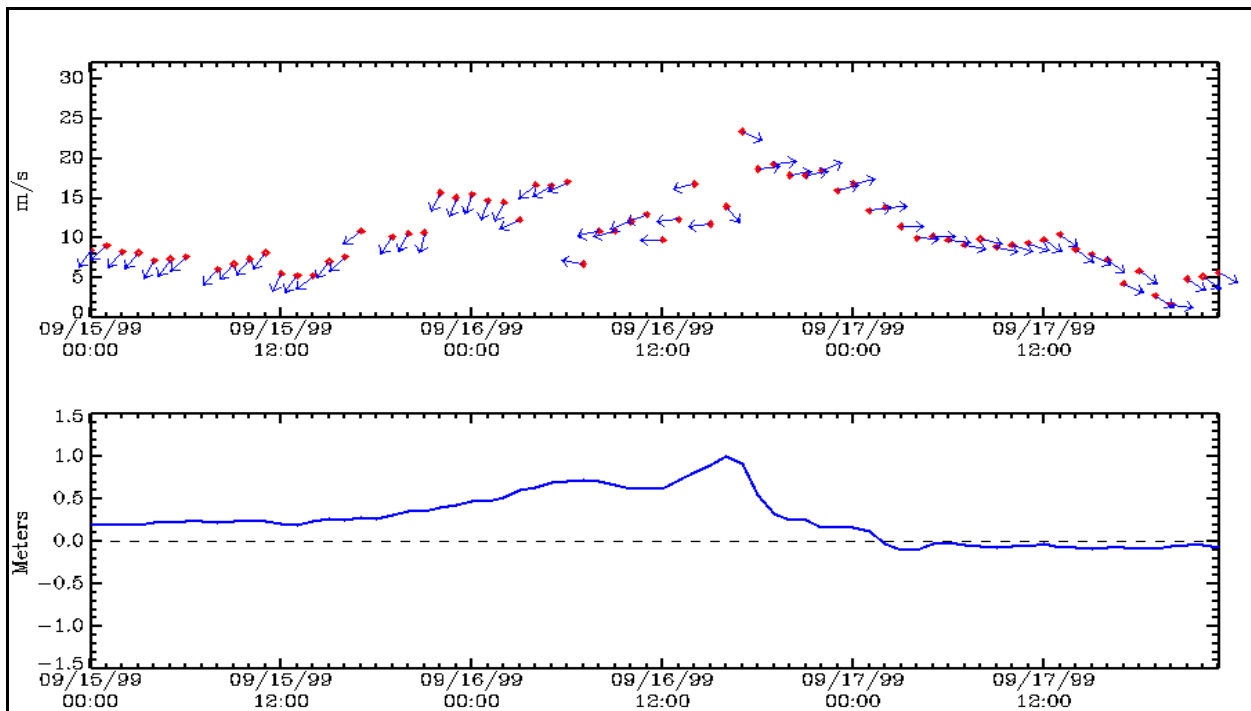
**Figure 22.** Hourly wind vectors and storm surge at Cape Hatteras, NC.



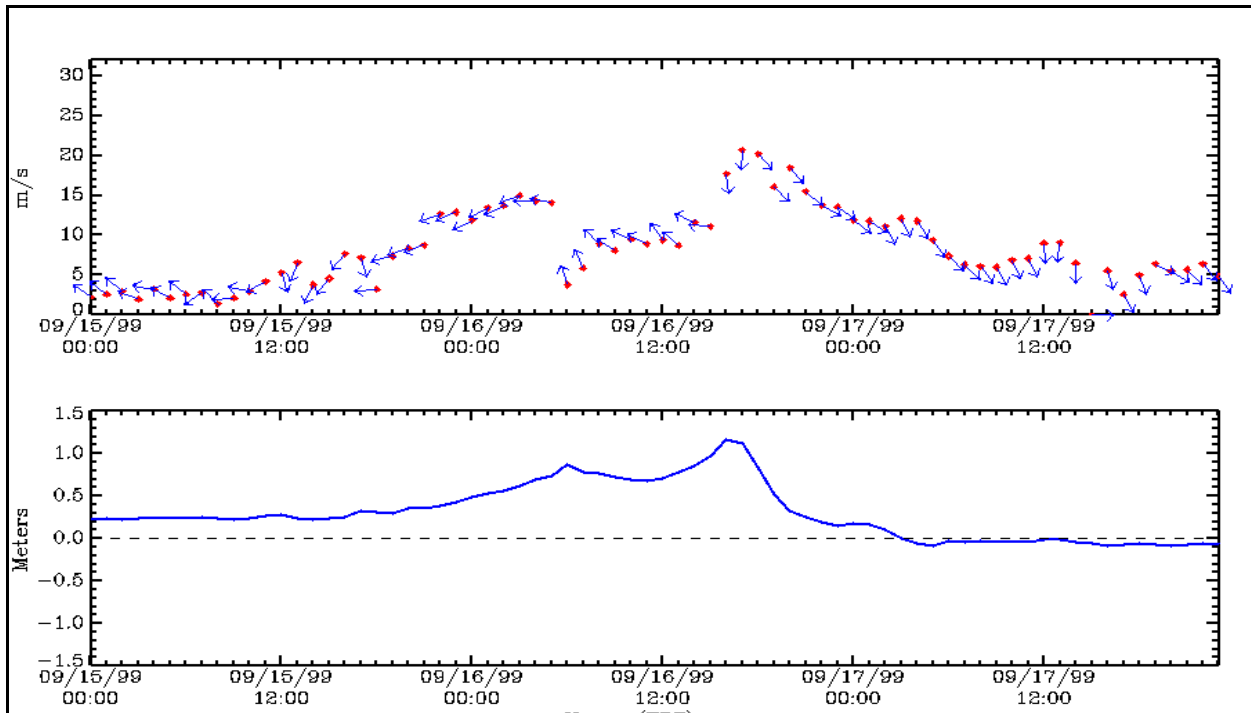
**Figure 23.** Hourly wind vectors at Cape Hatteras, NC and storm surge at Oregon Inlet, NC.



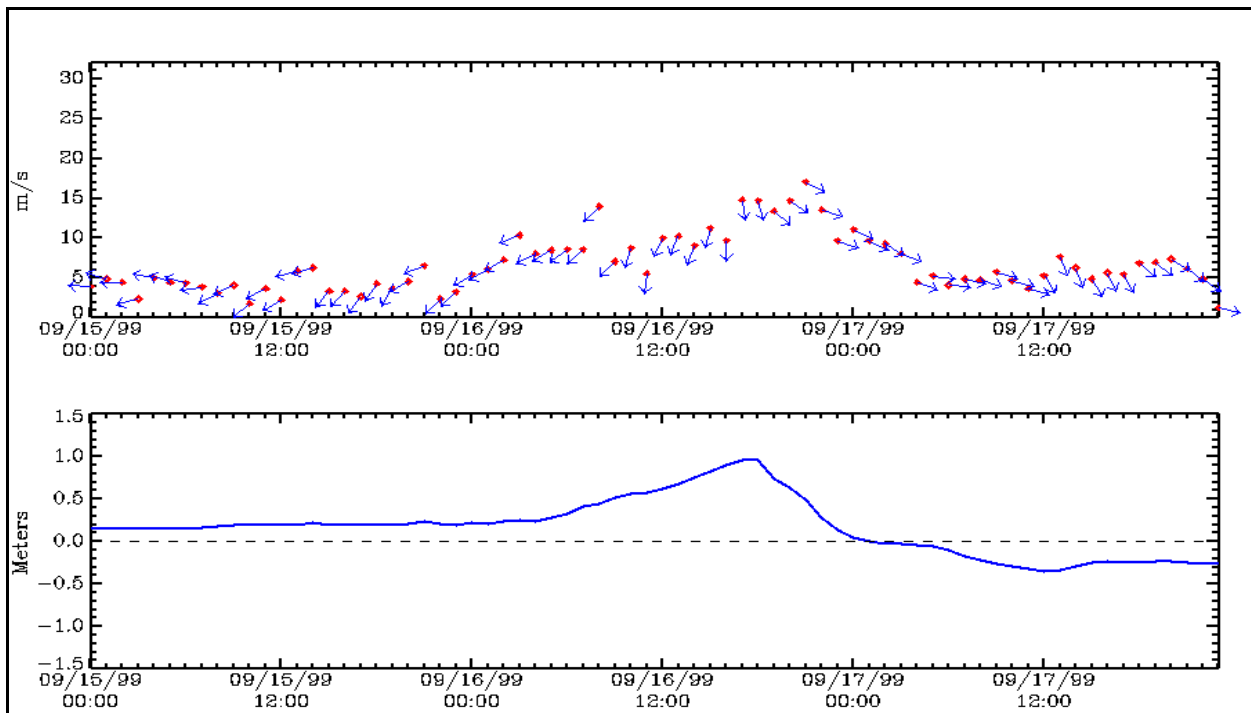
**Figure 24.** Hourly wind vectors and storm surge at Duck, NC.



**Figure 25.** Hourly wind vectors and storm surge at Chesapeake Bay Bridge Tunnel, VA.

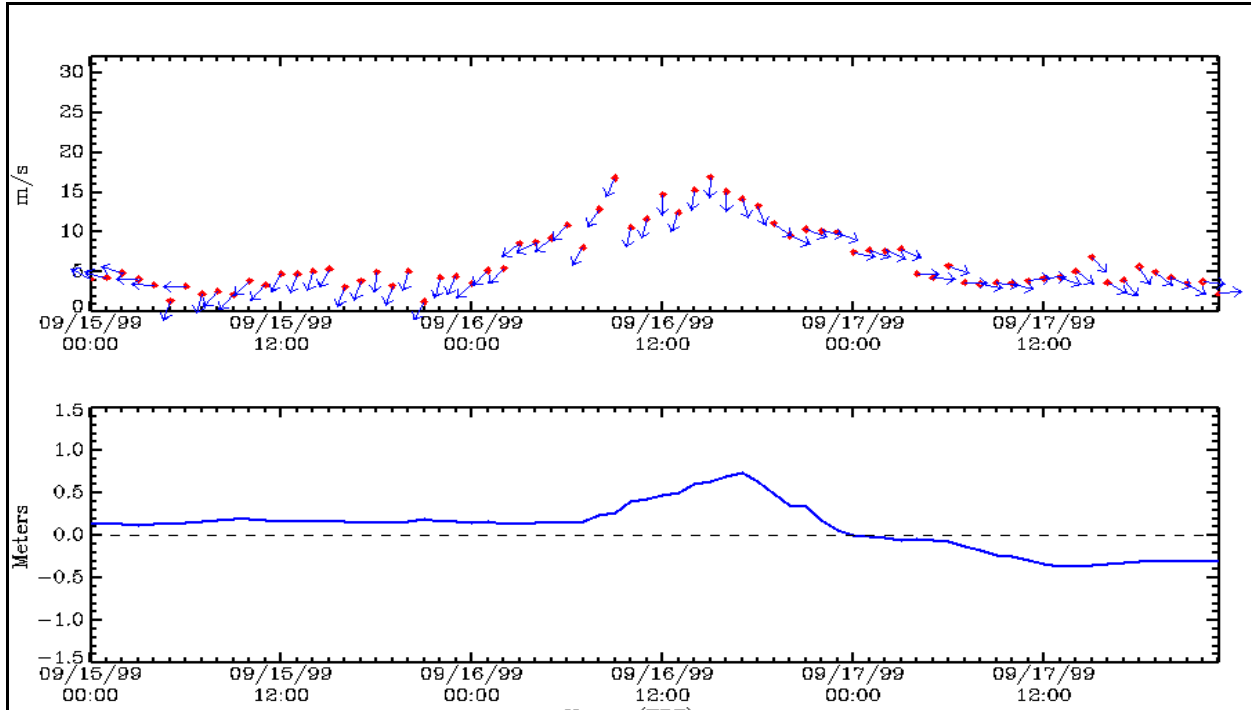


**Figure 26.** Hourly wind vectors and storm surge at Hampton Roads, VA.

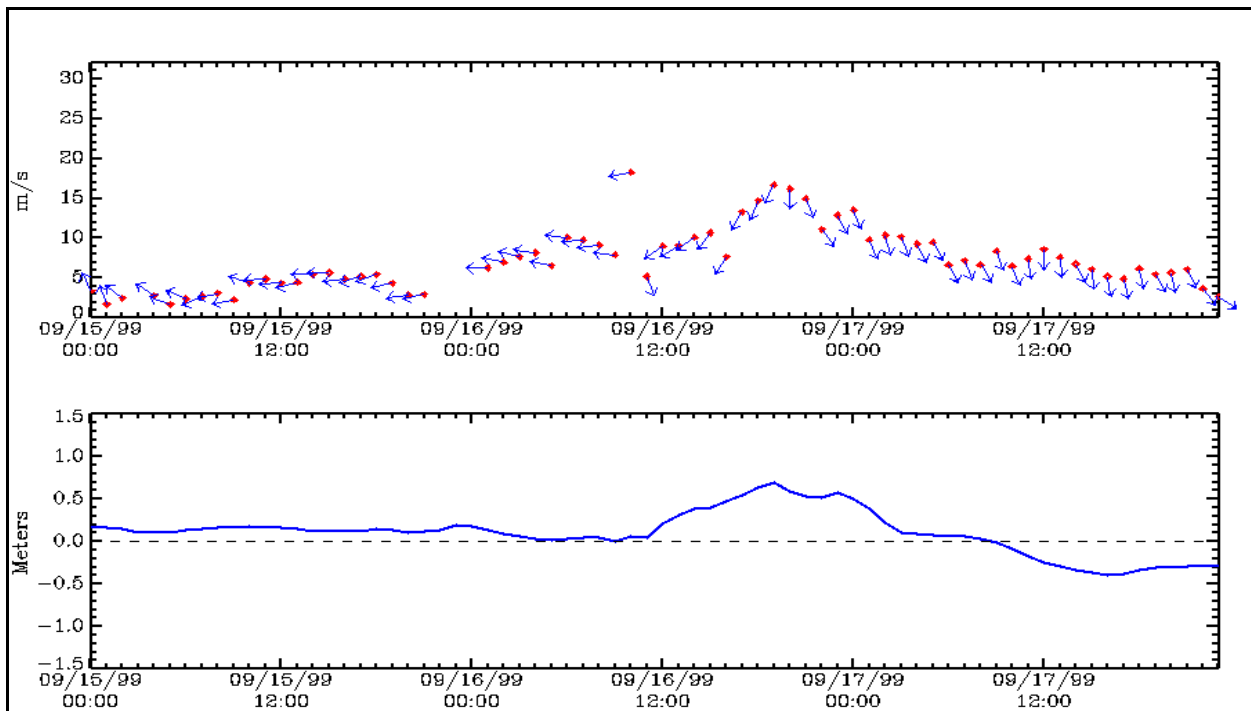


**Figure 27.** Hourly wind vectors and storm surge at Lewisetta, VA.

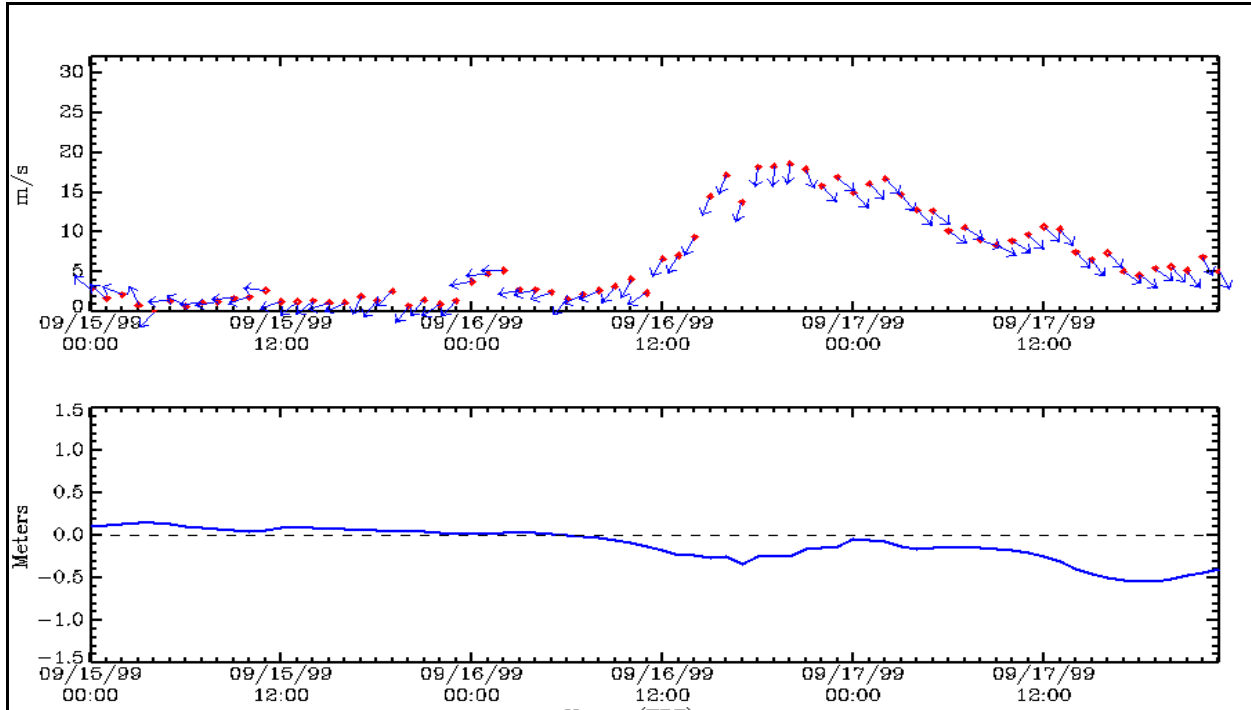




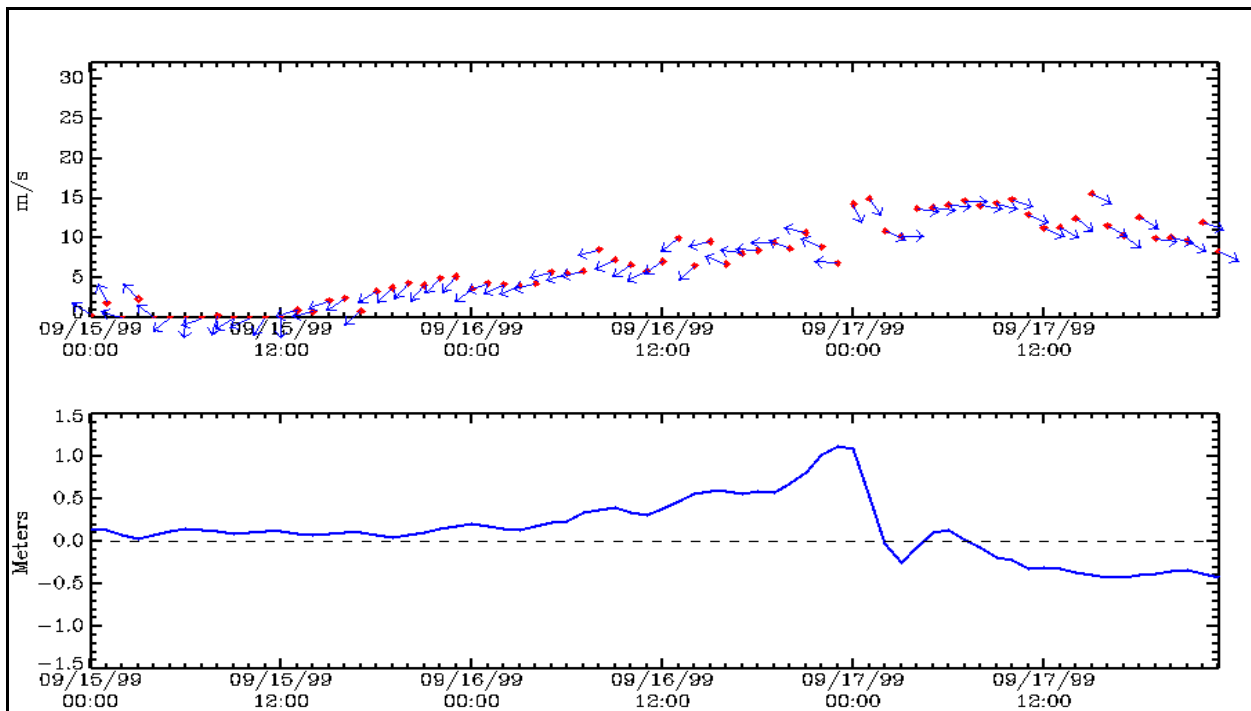
**Figure 28.** Hourly wind vectors and storm surge at Solomons Island, MD.



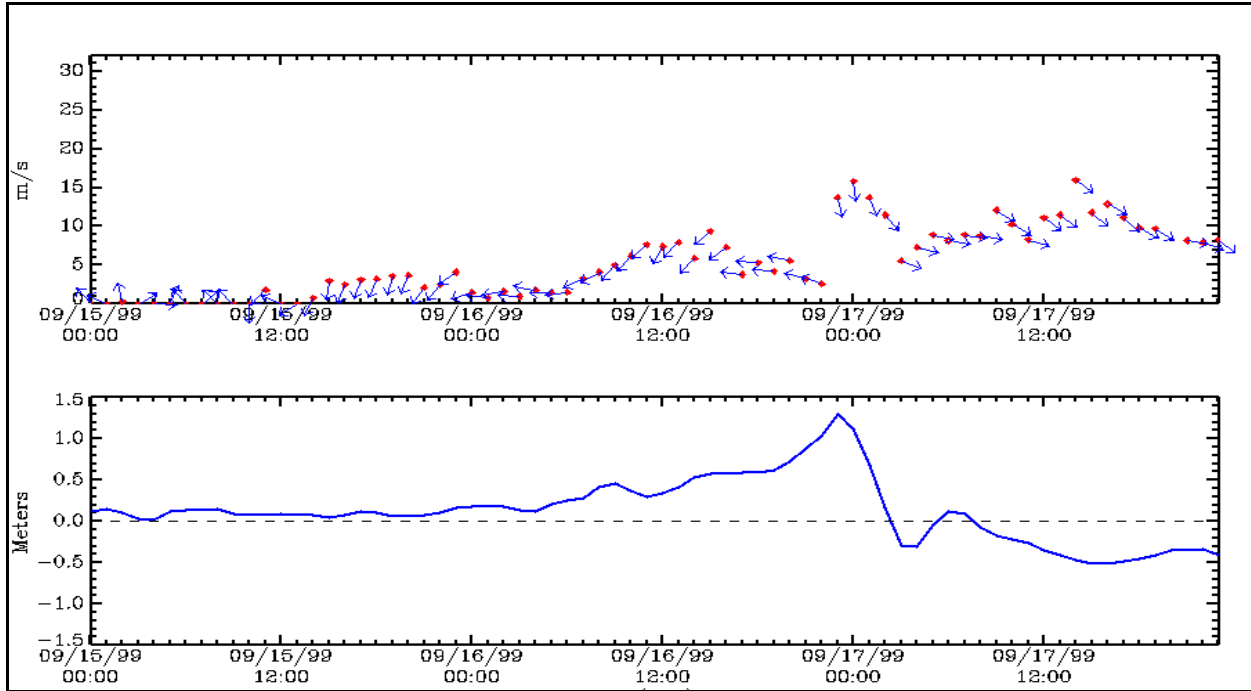
**Figure 29.** Hourly wind vectors and storm surge at Cambridge, MD.



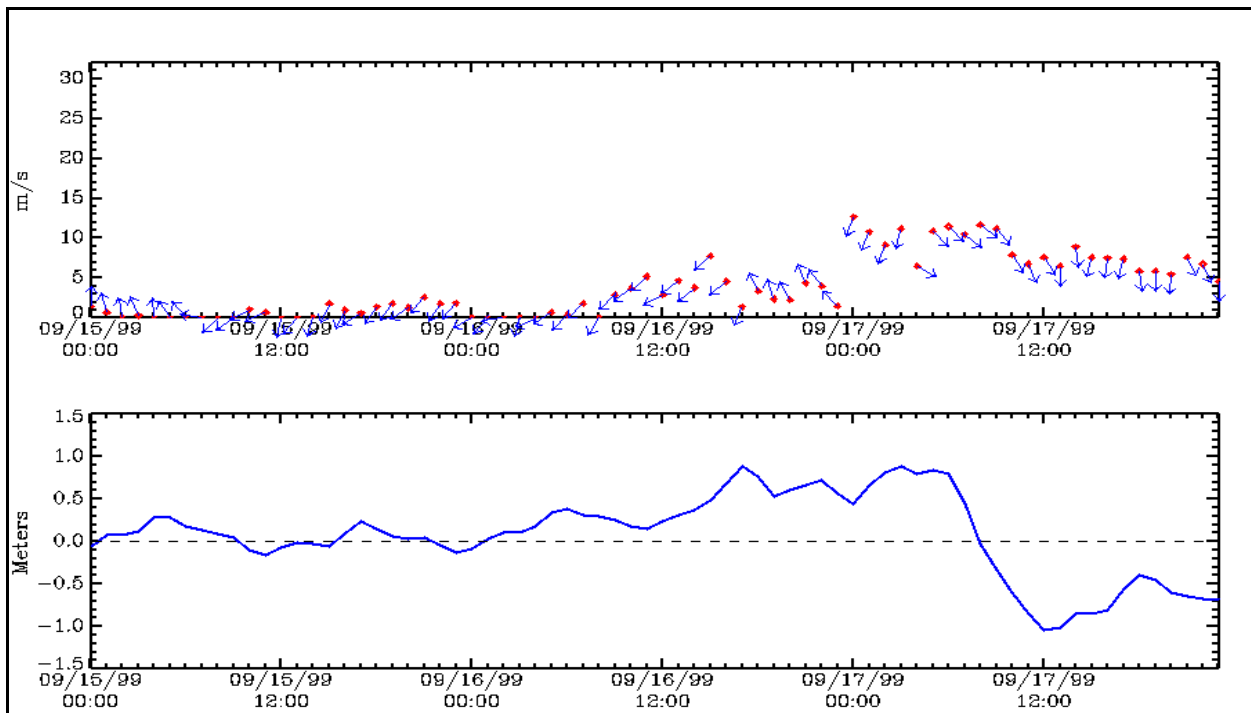
**Figure 30.** Hourly wind vectors and storm surge at Tolchester Beach, MD.



**Figure 31.** Hourly wind vectors and storm surge at Sandy Hook, NJ.



**Figure 32.** Hourly wind vectors and storm surge at Bergen Point, NY.



**Figure 33.** Hourly wind vectors and storm surge at Kings Point, NY.



## VII. Currents near Hampton Roads, VA

Mariners have always required accurate and dependable information on the movement of the waters in which they navigate, and this has become even more important in recent years as the volume of seagoing commerce and the size of ships has increased, leading to greater risk in the Nation's ports. One of the responsibilities of CO-OPS is to acquire, archive, and disseminate information on tidal currents in U.S. ports and estuaries. The CO-OPS Current Observation Program (COP) has the goal of improving the quality and accuracy of the NOS Tidal Current Tables. The information in the tables is a critical part of NOS' efforts toward promoting safe navigation in our Nation's waterways.

During the spring and summer months of 1999, CO-OPS conducted a small oceanographic survey of the currents in the lower Chesapeake Bay. Over the decades, the currents have been affected by extensive dredging and deepening of channels, new harbor and channel construction, and other natural and man-made modifications. In addition, the large military presence and heavy volume of shipping in the lower Chesapeake Bay called for the latest technology in evaluating the accuracy and adequacy of the NOS tidal current predictions. From the mouth of the Bay near Cape Henry to Newport News, five new current meter stations were occupied in a 23-mile stretch. An acoustic Doppler current profiler (ADCP) was deployed at the five stations, each for more than two months, producing valuable new information on the currents. The ADCPs are deployed on the bottom and sample currents in 1-meter layers from a level close to the instrument head to a level near the surface.

Currents in the lower Chesapeake Bay are tidally dominated; they are primarily driven by the astronomical tides on the mid-Atlantic continental shelf. The tidal currents are semidiurnal, consisting of two flood and two ebb periods each day. They are rectilinear and reversing, in that the water flows alternately in approximately opposite directions, with a slack water at each reversal of direction. Maximum tidal current velocities in the lower Bay generally range from less than  $\frac{1}{2}$  knot to slightly over 2 knots.

Two ADCP current meters were operating in the lower Chesapeake Bay during the time that Floyd transited the Norfolk area on September 16, 1999 (Figure 34). The first station was located just to the east of Craney Island in the main shipping channel near the mouth of the Elizabeth River, at a depth of approximately 54 feet below MLLW. The second station was located just off of the main shipbuilding docks of Newport News in the main shipping channel near the mouth of the James River, at a depth of approximately 53 feet below MLLW.

The highest current speeds measured by an ADCP are generally at the level nearest the water surface. Only the currents at this level will be discussed in this report. The maximum current speed observed during the 68-day measurement period at the Craney Island station was at a depth of 7.0 feet below MLLW. The maximum current speed observed during the 68-day measurement period at the Newport News station was at a depth of 5.6 feet below MLLW. Both maxima occurred on September 16 as Hurricane Floyd passed over the area.

Tidal current constituents were derived using a least squares harmonic analysis and used to predict the tidal currents for the entire measurement periods. A time series plot representing the measured currents and the tidal current predictions at Craney Island, along the flood current azimuth of  $183^\circ$

at a depth of 7.0 feet, is presented in Figure 35. The predicted values were then subtracted from the observed current to obtain the residual current, presented in Figure 36. A time series plot representing the measured currents and the tidal current predictions at Newport News, along the flood current azimuth of  $342^\circ$  at a depth of 5.6 feet, is presented in Figure 37; the residual current is presented in Figure 38.

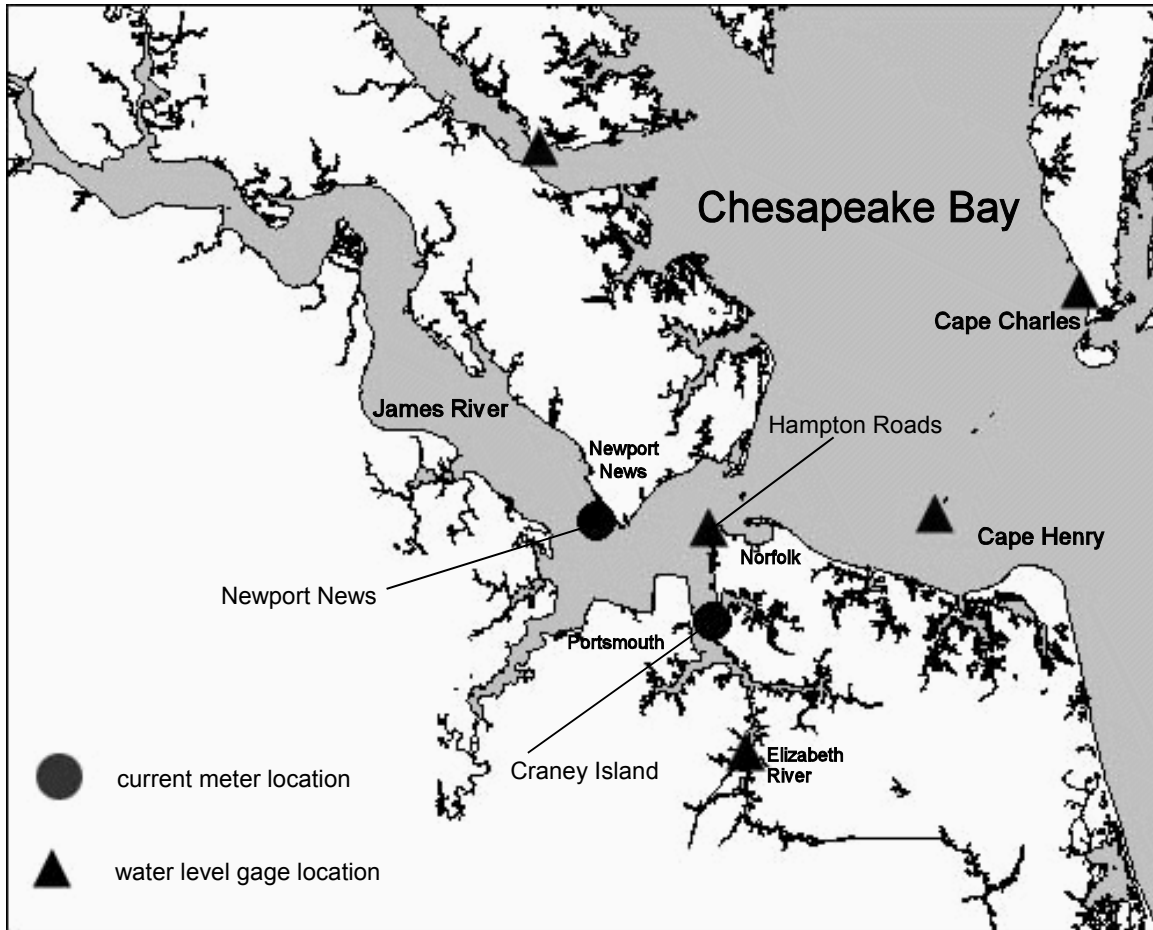
During storm events such as Hurricane Floyd, nontidal or residual currents can be driven by meteorological and hydrological factors such as strong winds, barometric pressure, heavy rain, and high streamflow. In a bay or estuary, the wind can affect the current both directly as the wind stress acting on the water surface and indirectly as wind-induced water level changes on a connected body of water such as a larger bay or the ocean.

Prior to the approach of Floyd on September 15 and after September 17, the observed currents at both Craney Island and Newport News closely followed the tidal current predictions. The causes of the nontidal currents at Craney Island and Newport News during the passage of Hurricane Floyd can be related to the wind record and the storm surge record at the nearest NWLON station at Hampton Roads, VA (Figure 26). The sequence of events at Hampton Roads caused by Hurricane Floyd can be divided into four periods of high wind speeds.

The first period of 8 hours, between 2200 GMT on September 15 and 0600 GMT on September 16, is characterized by strong easterly winds of about 14 m/s and slowly rising water levels in lower Chesapeake Bay. During this period, a nontidal upstream current of about  $\frac{1}{2}$  knot was induced in the James River at Newport News peaking near 1 knot at about 0400 GMT. No significant nontidal current was induced in the Elizabeth River at Craney Island in this period.

The second period of 10 hours, between 0600 and 1600 GMT on September 16, is marked by somewhat weaker east-southeasterly winds of about 10 m/s as Floyd approached the region over land after coming ashore near Cape Fear, NC. Nontidal water levels (storm surge) leveled off and then rose again to a peak at 1600 GMT. During this period, there was no significant nontidal current in the James River, while a  $\frac{1}{2}$  knot nontidal downstream current flowed in the Elizabeth River, possibly due to accumulating rainfall in the region.

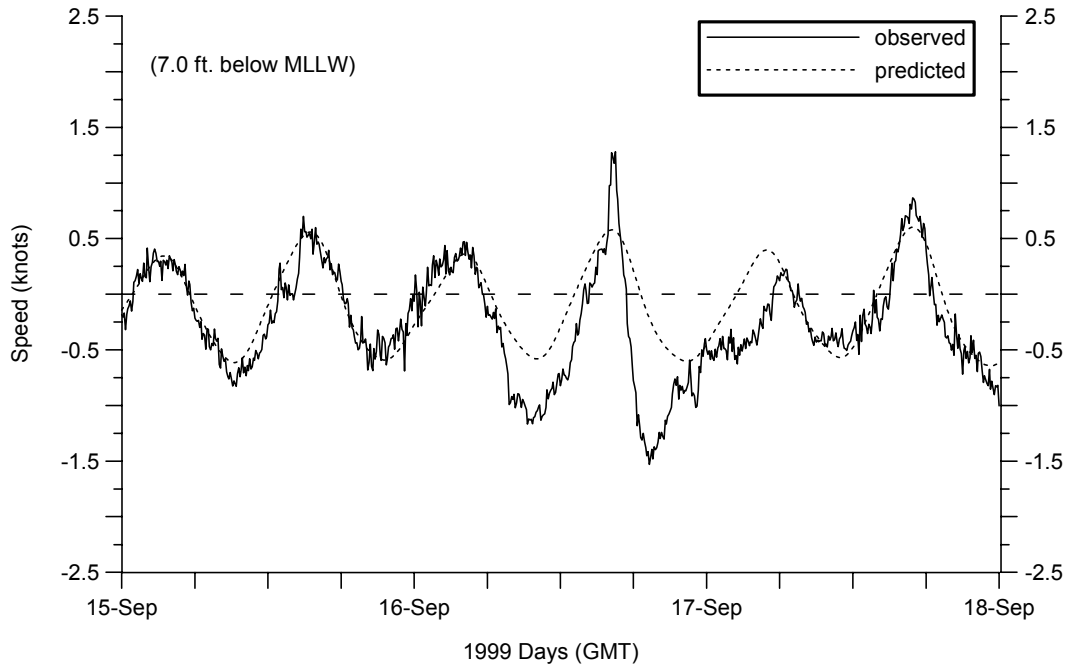
During the third period of 2 hours, between 1600 GMT and 1800 GMT on September 16, the center of Hurricane Floyd swept through the Hampton Roads region and out to sea near the entrance to Chesapeake Bay. The local wind rotated  $90^\circ$  to a northerly direction and doubled in speed to its highest value of 20 m/s. A strong 1 knot nontidal downstream current rapidly developed in the James River at the same time as a strong  $\frac{1}{2}$  knot nontidal upstream current appeared in the Elizabeth River. The fact that these simultaneous currents are of opposite polarity suggests that they are due directly to the wind stress on the James River pushing water toward Chesapeake Bay, with a portion being driven into the Elizabeth River.



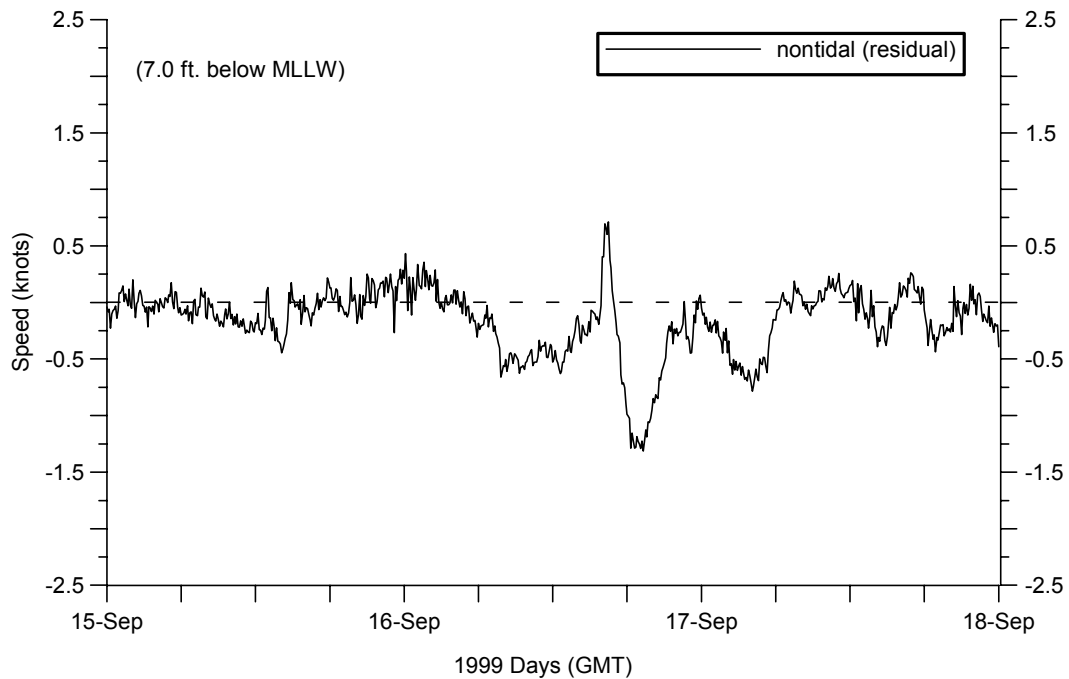
**Figure 34.** Station location map for the lower Chesapeake Bay area.

The fourth period of 11 hours, from 1800 GMT on September 16 to 0500 GMT on September 17, is characterized by northwesterly winds gradually weakening from 20 m/s to 10 m/s and dropping nontidal water levels due to water being driven out of Chesapeake Bay, rapidly at first and then more slowly. During this period, strong nontidal downstream currents were dominating the flows in both the James and the Elizabeth Rivers. These nontidal downstream currents peaked at about 2½ knots on the James River and about 1¼ knots on the Elizabeth River, at about 1900 GMT on September 16. A smaller current pulse with about half the speeds peaked at about 0400 GMT on September 17.

The nontidal currents caused by the passage of Hurricane Floyd over the Hampton Roads region were strong enough to significantly change the timing and amplitude of the predicted flood and ebb tidal currents. At Craney Island in the Elizabeth River, two floods and two ebbs were affected by Floyd (Figure 35). At Newport News in the James River, three floods and two ebbs were affected by Floyd (Figure 37). The timing of some of the predicted slack periods were also shifted by several hours at both locations.

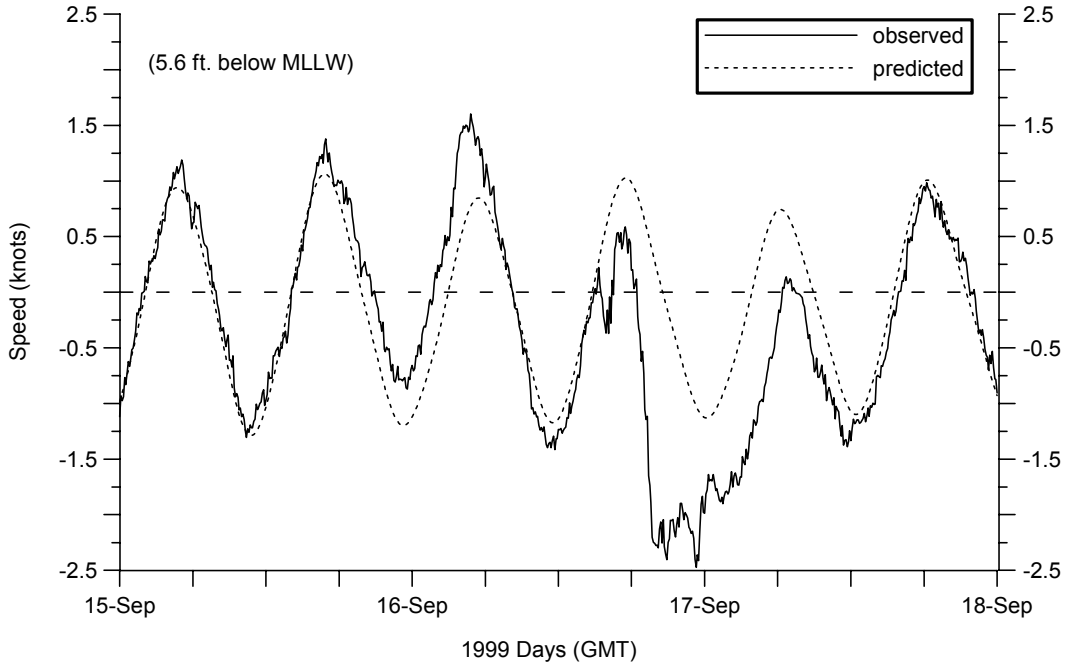


**Figure 35.** Observed current and tidal current prediction at Craney Island, 7.0 ft. below MLLW, during Hurricane Floyd. Positive current is flood along  $183^\circ$ .

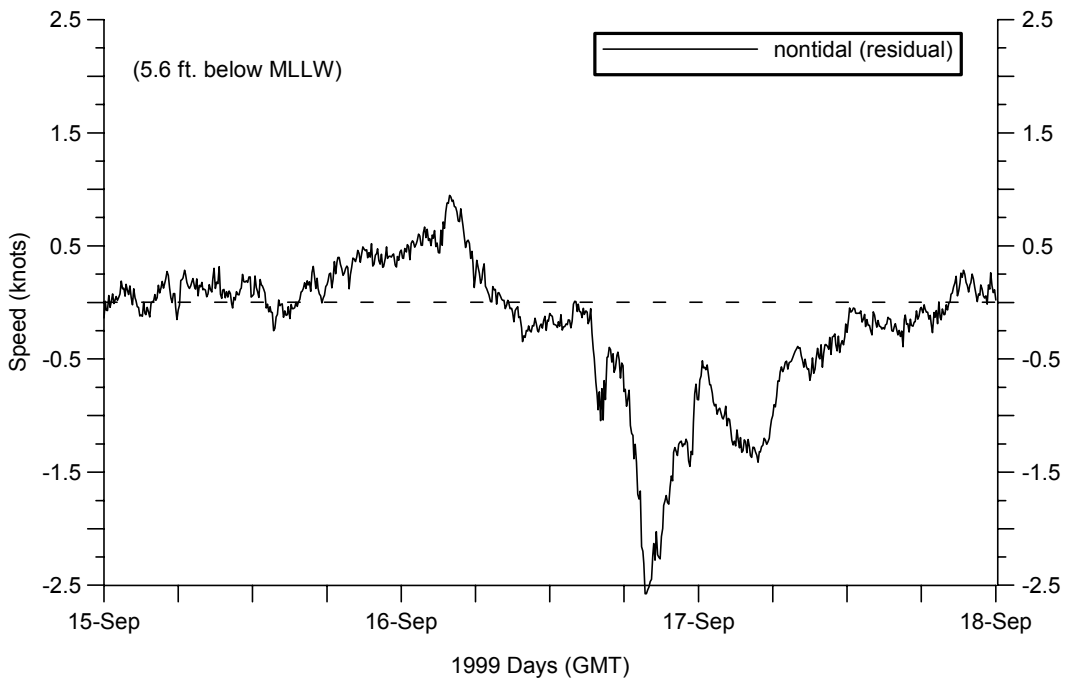


**Figure 36.** Nontidal (residual) current at Craney Island, 7.0 ft. below MLLW, during Hurricane Floyd. Positive current is flood along  $183^\circ$ .





**Figure 37.** Observed current and tidal current prediction at Newport News, 5.6 ft. below MLLW, during Hurricane Floyd. Positive current is flood along  $342^\circ$ .



**Figure 38.** Nontidal (residual) current at Newport News, 5.6 ft. below MLLW, during Hurricane Floyd. Positive current is flood along  $342^\circ$ .



## VIII. Operation of the Real-Time Monitoring System

In addition to running the NWLP, CO-OPS is responsible for the operation and maintenance of four Physical Oceanographic Real Time Systems (PORTS). To monitor the PORTS sensors and the data quality, the Continuous Operational Real-Time Monitoring System (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, some specific portions of the NWLON are monitored for operations and data quality. Data collection platforms (DCP) 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 AFOS 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 National Hurricane Center (NHC) reports of tropical formation of hurricanes and utilizes the NHC Landfall product to determine when to trigger the special reporting mode capability of the water level gauges. 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. These gauges provide data about the deviation of water levels from the predicted tide in order to assist state and federal emergency management teams in deciding strategies for evacuation. In addition, a new CO-OPS web site named Tides Online, developed to provide real-time water level data via the Internet, gives the public access to time series plots of the data.

CORMS operations staff were tracking Hurricane Floyd from its beginning as a tropical depression until its dissipation. The operations staff 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 and experienced only a few gauge failures during the storm.

One station experienced a significant operational problem; the acoustic sensor at Duck, NC was malfunctioning as Floyd made its way up the Florida east coast. A field crew from the Atlantic Regional Office (ARO) of the Field Operations Division of CO-OPS was sent to the site to make emergency repairs. The acoustic sensor became operational only one day before Floyd made landfall in North Carolina.

A total of six stations had phone line problems during the storm: Settlement Point, BA, Mayport, FL, Charleston, SC, Cape Hatteras, NC, Cambridge, MD, and Cape May, NJ. Since stations are activated into storm surge mode by calling the DCP by phone, these stations did not transmit data every 20 minutes. They did transmit data either hourly or every three hours, which are the normal transmission schedules. The station at Cape Hatteras, NC had a phone line problem until September

15, when continuous attempts to reach the DCP by phone were finally successful and it was set into storm surge reporting mode.

The station at Cape Hatteras, NC suffered considerable damage to the protective well and sounding tube (components of the water level gauge), as was discovered in a post storm inspection by ARO. The bottom half of the well was broken off by heavy wave action or possibly by debris tossed in the surf. This damage appears to have happened a few days after the storm passage.

## IX. Internet Dissemination of Storm Surge Data

CO-OPS has developed a new web site, named Tides Online, to give the public access to real-time water level, wind, and barometric pressure data from NWLON stations. Stations in storm surge mode are listed on the main page of the web site, giving the user quick access to available time series data plots. Currently, some NWLON stations are not equipped with meteorological instruments.

The Tides Online web page provides the most recent 48 hours of water level data along with tide predictions. Predictions are also provided 24 hours into the future so users can see when the next high or low tide is predicted to occur. Some stations also show wind and barometric pressure data available with concurrent time lines. Plotting these data on the same page paints an accurate picture of the course of a storm. Figure 39 is a plot of the data as it appeared on the web page for Lewisetta, VA on September 17 at 0948 Eastern Daylight Time (EDT), after the passage of Hurricane Floyd.

On September 14, NOAA issued a media advisory announcing the Tides Online web site. Newspaper weather page editors and broadcast meteorologists were encouraged to publicize the web site address. The text of the announcement is printed below. A special note was made that the data reflects what is happening at the time and is not a storm surge prediction system.

### **MEDIA ADVISORY**

#### **NOAA OPENS HURRICANE STORM SURGE WEB SITE – TIDES ON LINE**

NOAA's tides and water level experts have created a public web site that provides near real-time observations from tide gauge equipment along the coast to show the extent of 'storm surge' from hurricanes and other storms.

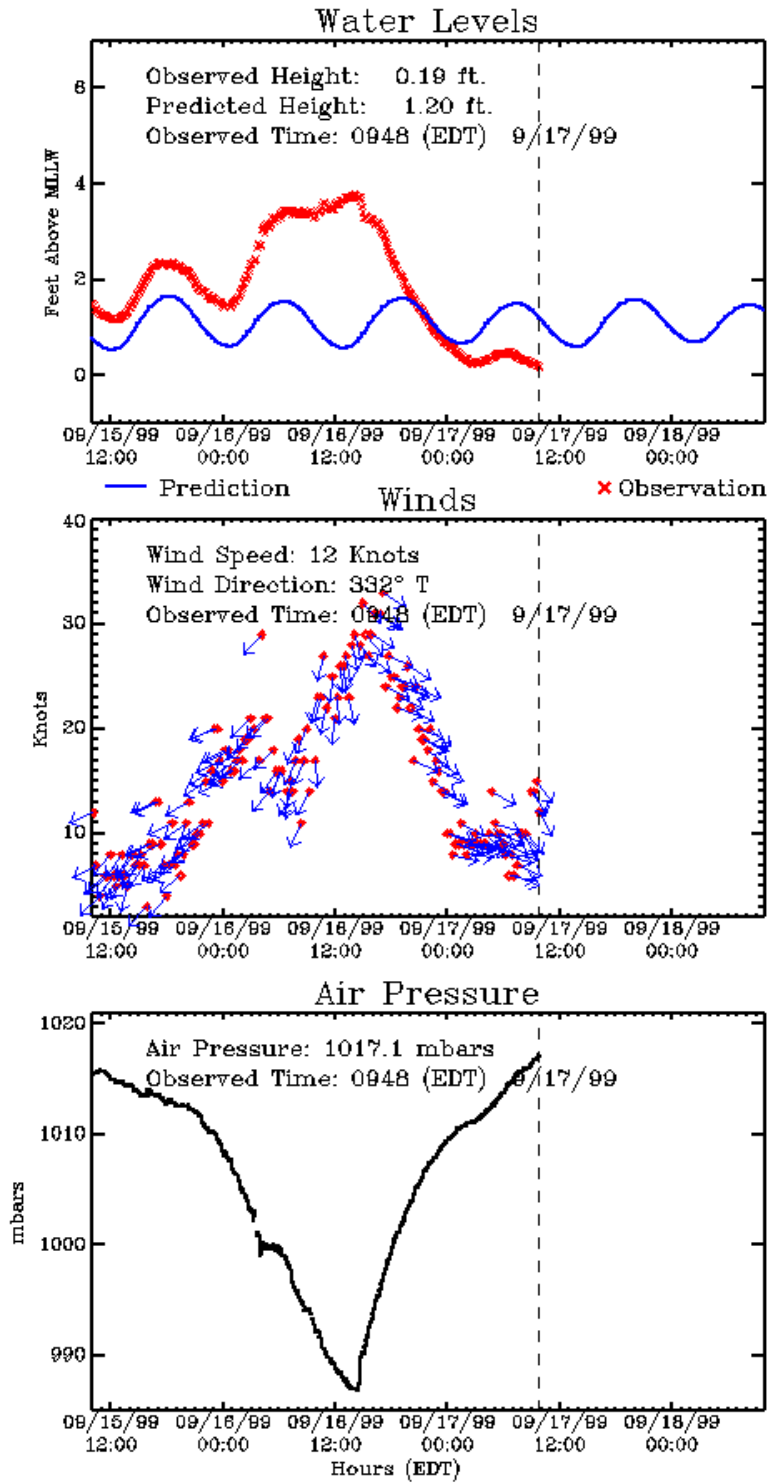
The web site: [www.tidesonline.nos.noaa.gov](http://www.tidesonline.nos.noaa.gov)

graphically illustrates tide levels which are actually being observed (shown by red line) as compared to long-range tide predictions (shown on a blue line) such as those published in newspapers and in tide forecast books.

The 'Tides On Line' system is always in operation giving hourly updates on tides and water levels around the nation and in some overseas locations. During major storms or hurricanes, certain observation stations are placed in "storm surge mode" and are automatically updated every twenty minutes. Some of the observation stations also include wind and barometric pressure data.

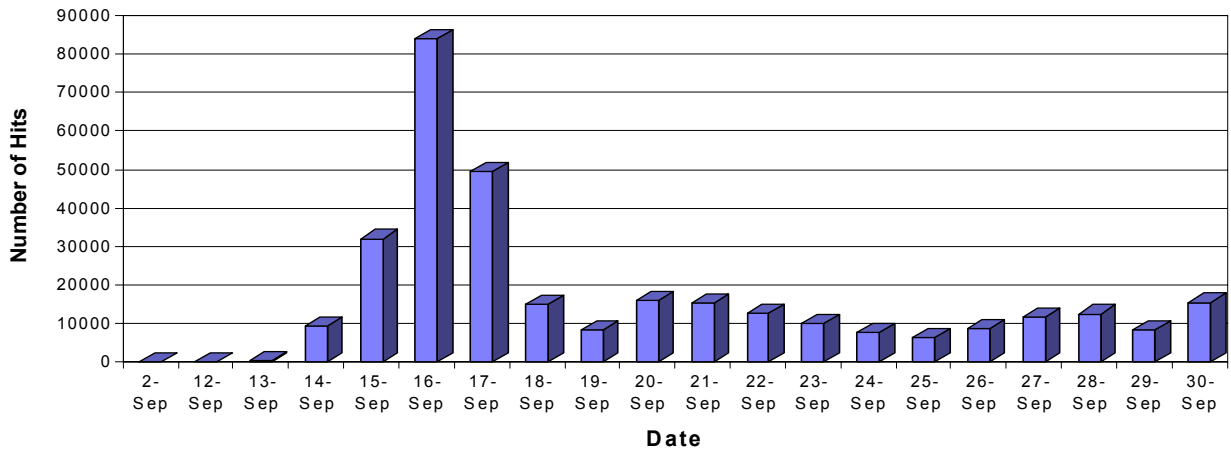
Weather page editors and broadcast meteorologists are encouraged to publish and publicize the web site, but with regard to storm and hurricane warnings they should remind readers and viewers that this web site only reflects what's happening AT THE TIME and is not a storm surge prediction system. NOAA provides storm surge prediction information as part of storm and hurricane forecasts and everyone should heed official warnings and forecasts and predictions about storm surge and flood threats issued by federal, state and local officials.

Real time Storm Surge Levels: [www.tidesonline.nos.noaa.gov](http://www.tidesonline.nos.noaa.gov)



**Figure 39.** Sample Tides Online web page for Lewisetta, VA on September 17, 1999 at 0948 Eastern Daylight Time (EDT), after the passage of Hurricane Floyd.

The media advisory had a significant effect on the number of web site hits during the storm. Figure 40 shows the number of hits on the Tides Online web site after it became operational. Note the increase in hits on September 14 when the press announcement of Tides Online was released. September 16 was the middle of Hurricane Floyd's interaction with the eastern U.S. coast; the public's response is evident. The rest of the graph shows normal use of Tides Online for accessing daily plots for any of the NWLON stations.



**Figure 40.** Number of hits on the Tides Online web site after it became operational. The media advisory was released on September 14. Hurricane Floyd came ashore on September 16.





## **X. Coordination with Federal and State Agencies**

In the summer of 1999, NOS created a Response Plan for Natural Disasters. The intent of the plan was to establish a formal response structure with activation and notification protocols to provide for the efficient use of NOS capabilities in responding to natural disasters such as hurricanes. Each NOS line office identified an office coordinator and key office capabilities which could be offered to assist the Federal Emergency Management Agency (FEMA) and other federal and state agencies in storm monitoring and disaster recovery. All requests for assistance and resulting actions by NOS were organized by the NOS coordinator.

Part of the NOS plan included a formal partnership with state emergency management centers in North Carolina, Georgia, Alabama, and Mississippi. During the period of Hurricane Floyd, NOS sent a representative to actively participate with state officials in the North Carolina emergency operations center. NOS also established a section of its HAZMAT web site, as a central communication point where all e-mails, reports assessments, and aerial photos regarding the storm could be reviewed by members of the NOS and state response teams.

The CO-OPS coordinator on the NOS response team provided daily email reports to the NOS coordinator and state officials on storm progress and water level station status. These email updates were also posted on the NOS HAZMAT web site. The basic operation of the Tides Online web site was explained to familiarize team members with its purpose and capabilities. Although the NWS AFOS network automatically receives storm surge transmissions from NOS water level stations, the NWS regional forecast offices were also notified of the Tides Online web site as an additional source of information for storm surge data.



## **XI. Summary**

Hurricane Floyd was the most powerful and destructive storm of the 1999 Atlantic hurricane season. Due to its storm track, it affected nearly the entire US Atlantic coast before and after making landfall early on September 16 near Cape Fear, NC. Widespread flooding caused by heavy rains associated with Floyd resulted in significant casualties, property loss, and environmental damage, particularly in eastern North Carolina.

Hurricane Floyd raised water levels significantly above MHHW at many of the east coast NWLON stations, with the highest maximum observed elevation at Oregon Inlet Marina, NC on Pamlico Sound, setting a new station record of 1.480 meters above MHHW. Historical maximum elevations were also exceeded at Duke Marine Lab, NC and at St. Augustine Beach, FL. At Duke Marine Lab, NC, the maximum observed elevation occurred 4½ hours after predicted high tide.

Storm surge, the difference between observed water levels and predicted tide levels, showed considerable variation between stations depending on wind speed and direction, air pressure, local orientation of the coastline, and the storm's speed and distance at time of passage. The greatest recorded storm surge was 1.733 meters at Duke Marine Lab, NC. Rapid changes in wind direction as the storm passed a station were quickly followed by changes in the trend of the storm surge. In addition, the effect of Floyd's winds on currents near Hampton Roads, VA was measured by two CO-OPS current meters that were in the water at the time.

The operation of CORMS during the period of Hurricane Floyd was described, including the procedure for setting NWLON DCPs into storm surge reporting mode, the resolution of communication problems, and a description of equipment damage. The newly-developed Tides Online website was announced to the public via a NOAA media advisory two days before Hurricane Floyd came ashore. The main page indicates which NWLON stations are in storm surge reporting mode and each station's web page gives time series plots of available water level, wind, and barometric pressure data. The number of web page hits peaked above 80,000 on September 16 as Floyd came ashore. Finally, there was a description of CO-OPS participation on the NOS natural disaster response team and its coordination with federal and state emergency management centers.

Preliminary data recorded during the storm were provided to NWS, FEMA, and the U.S. Army Corps of Engineers. Information on tidal datums, storm surge, and times series analyses from stations listed in this report and from other NOS stations can be obtained from:

NOAA/ National Ocean Service  
Center for Operational Oceanographic Products and Services  
Products and Services Division, N/OPS3  
1305 East-West Highway  
Silver Spring, MD 20910-3281  
Telephone: 301-713-2877  
Internet URL: [www.co-ops.nos.noaa.gov](http://www.co-ops.nos.noaa.gov)



## **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, Noriko Shoji researched historical station record periods, and Cheral Fitzgerald transcribed the NOAA media advisory. 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, and Stephen Lyles for their suggestions and reviews which helped to improve this report.



## References

- Harris, D. Lee, 1963. *Characteristics of the hurricane storm surge*, Weather Bureau, Technical Paper No. 48, U.S. Dept. of Commerce.
- Parker, Bruce B., 1991. The relative importance of the various nonlinear mechanisms in a wide range of tidal interactions (Review). In *Tidal Hydrodynamics*, (Ed.) Bruce B. Parker, pp 237-268, John Wiley & Sons, Inc., New York, NY.

### Storm Event Data Reports

The following data reports were compiled after major storm events. The formats of the reports vary; however, each contains tabular and graphical information on the maximum elevations of the water levels during the storm, as well as storm surge information calculated from the difference between observed and predicted tides.

1. Hurricane Hugo, Effects on water levels and storm surge recorded at NOAA/National Ocean Service water level stations. Data Report, November 30, 1989.
2. Effects of Hurricane Bob on water levels. Data Report, October 1991.
3. Effects of the late October 1991 North Atlantic extra-tropical storm on water levels. Data Report, January 1992.
4. Effects of the January 1992 Atlantic Ocean coastal storm on water levels. Data Report, May 1992.
5. Effects of Hurricane Andrew on water levels in coastal Florida and Louisiana. NOAA Technical Memorandum NOS OES 004, Data Report, December 1992.
6. Effects of December 1992 northeaster on water levels. NOAA Technical Memorandum NOS OES 006, Data Report, May 1993.
7. Effects of February 1998 northeaster on water levels. NOAA Technical Memorandum NOS CO-OPS 0019, Data Report, December 1998.





## **Appendix I.**

### **Data Tables**

**Table A. Hurricane Floyd weather advisories from the NOAA National Hurricane Center**

NHC Advisory	Date	Time (GMT)	Long. North	Lat. West	Wind Speed (mph)	Pressure (mb)	Direction/Speed	Saffir/Simpson Hurricane Scale
1	9/7/99	2100	14.6	46.2	30	1008	W/14	TD
2	9/8/99	0300	15.2	47.5	35	1007	WNW/16	TD
3	9/8/99	0900	15.6	49.1	40	1005	WNW/16	TS
4	9/8/99	1500	15.8	50	45	1003	WNW/15	TS
5	9/8/99	2100	16.6	51.7	50	1000	WNW/16	TS
6	9/9/99	0300	16.7	53.6	60	1000	WNW/16	TS
7	9/9/99	0900	17.3	54.6	60	1003	WNW/15	TS
8	9/9/99	1500	17.2	55.5	60	1003	W/14	TS
9	9/9/99	2100	18.2	56.9	70	996	WNW/15	TS
9A	9/10/99	0000	18.2	57.2	70	995	W/10	TS
10	9/10/99	0300	18.3	57.7	70	995	WNW/10	TS
10A	9/10/99	0600	18.4	57.7	70	995	WNW/10	TS
11	9/10/99	0900	18.9	58.7	70	985	WNW/12	TS
11A	9/10/99	1200	19.1	58.9	80	989	WNW/12	H1
12	9/10/99	1500	19.3	59.2	80	989	WNW/10	H1
12A	9/10/99	1800	19.9	59.7	80	989	WNW/10	H1
13	9/10/99	2100	20.5	60	80	975	NW/12	H1
13A	9/11/99	0000	20.8	60.4	85	971	NW/12	H1
14	9/11/99	0300	21.1	60.8	90	971	NW/12	H1
15	9/11/99	0900	21.7	61.6	105	963	NW/10	H2
16	9/11/99	1500	22.2	62.4	110	962	NW/10	H2
17	9/11/99	2100	22.7	63.5	110	966	WNW/12	H2
18	9/12/99	0300	22.7	64.5	110	967	WNW/12	H2
19	9/12/99	0900	22.8	65.9	110	960	W/13	H2
19A	9/12/99	1200	22.9	66.2	115	955	W/12	H3
20A	9/12/99	1800	23.2	67.5	120	955	W/14	H3
21	9/12/99	2100	23.4	68.2	125	940	W/14	H3
21A	9/13/99	0000	23.5	68.7	145	932	W/14	H4
22	9/13/99	0300	23.6	69.3	145	931	W/14	H4

NHC Advisory	Date	Time (GMT)	Long. North	Lat. West	Wind Speed (mph)	Pressure (mb)	Direction/Speed	Saffir/Simpson Hurricane Scale
22A	9/13/99	0600	23.6	70	150	923	W/14	H4
23	9/13/99	0900	23.7	70.6	155	922	W/14	H4
23A	9/13/99	1200	23.9	71.4	155	921	W/14	H4
24	9/13/99	1500	24.1	72.1	155	921	W/14	H4
24A	9/13/99	1800	24.2	73	155	926	W/15	H4
25	9/13/99	2100	24.2	73.7	155	923	W/16	H4
25A	9/14/99	0000	24.4	74.1	155	924	W/14	H4
26	9/14/99	0300	24.5	74.7	155	924	W/14	H4
26A	9/14/99	0700	24.9	75.3	155	928	WNW/14	H4
27	9/14/99	0900	25.1	75.9	155	927	WNW/14	H4
27A	9/14/99	1300	25.4	76.1	150	929	WNW/14	H4
28	9/14/99	1600	25.7	76.8	145	932	WNW/14	H4
28A	9/14/99	1900	26	77	140	933	WNW/14	H4
29	9/14/99	2200	26.5	77.4	140	929	NW/12	H4
29A	9/15/99	0100	27.1	77.6	140	934	NNW/12	H4
30	9/15/99	0400	27.7	77.6	140	933	NW/13	H4
30A	9/15/99	0700	28.2	78.5	140	935	NW/13	H4
31	9/15/99	1000	28.8	78.8	140	938	NNW/14	H4
31A	9/15/99	1300	29.3	78.8	135	941	NNW/14	H4
32	9/15/99	1600	29.9	79	125	943	NNW/14	H3
32A	9/15/99	1800	30.3	79.1	125	946	NNW/14	H3
32B	9/15/99	2000	30.8	79.1	120	947	N/15	H3
33	9/15/99	2200	31.3	79	115	949	N/17	H3
33A	9/16/99	0000	32.1	78.7	115	949	NNE/17	H3
33B	9/16/99	0200	32.4	78.6	115	950	NNE/17	H3
34	9/16/99	0400	32.9	78.3	115	951	NNE/18	H3
34B	9/16/99	0800	34	77.9	110	956	NNE/20	H2
35	9/16/99	1000	34.5	77.6	105	956	NNE/23	H2
35A	9/16/99	1200	35.2	77.1	100	960	NNE/24	H2
35B	9/16/99	1400	36	76.6	90	962	NNE/25	H1
36	9/16/99	1600	36.8	76	80	967	NNE/24	H1

NHC Advisory	Date	Time (GMT)	Long. North	Lat. West	Wind Speed (mph)	Pressure (mb)	Direction/Speed	Saffir/Simpson Hurricane Scale
36A	9/16/99	1900	37.8	75.2	75	974	NNE/29	H1
37	9/16/99	2200	39.3	74.6	65	974	NNE/30	TS
37A	9/17/99	0100	40.6	73.5	65	974	NNE/30	TS
38	9/17/99	0400	41.7	72.2	60	980	NE/35	TS
39	9/17/99	1000	43.5	70.8	60	984	NE/26	TS

TD= Tropical Depression; TS= Tropical Storm; H# = Hurricane Category #.

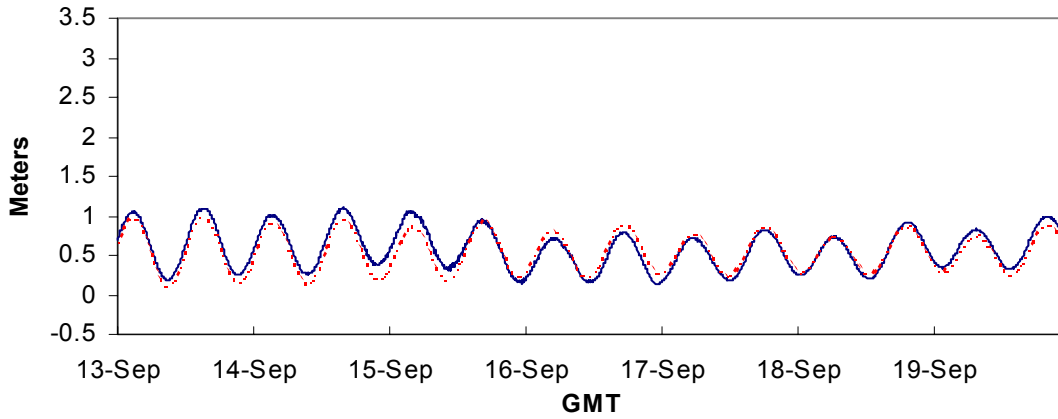
**Table B. Location and period of record for NWLON stations**

Station		Latitude		Longitude		Starting Year	Major Gaps
Number	Name	Deg.	Min.	Deg.	Min.		
8443970	Boston, Boston Harbor, MA	42	21.3N	71	3.1W	1921	
8447930	Woods Hole, Buzzards Bay, MA	41	31.4N	70	40.3W	1932	
8449130	Nantucket Island, Nantucket Sound, MA	41	17.1N	70	5.8W	1965	
8452660	Newport, Narragansett Bay, RI	41	30.3N	71	19.6W	1930	
8454000	Providence, Providence River, RI	41	48.4N	71	24.1W	1938	1947-1956
8461490	New London, Thames River, CT	41	21.3N	72	5.2W	1938	
8467150	Bridgeport, Bridgeport Harbor, CT	41	10.4N	73	10.9W	1964	
8510560	Montauk, Fort Pond Bay, NY	41	2.9N	71	57.6W	1947	
8516945	Kings Point, NY	40	48.6N	73	45.9W	1998	
8516990	Willetts Point, Little Bay, East R., NY	40	47.6N	73	46.9W	1931	
8518750	The Battery, New York Harbor, NY	40	42.0N	74	0.9W	1856	1879-1892
8519483	Bergen Point W. Reach, Kill Van Kull, NY	40	38.4N	74	8.8W	1981	1992-1993
8531680	Sandy Hook, NJ	40	28.0N	74	0.1W	1932	
8534720	Atlantic City, Atlantic Ocean, NJ	39	21.3N	74	25.1W	1911	1969-1971
8536110	Cape May, Cape May Canal, Del. Bay, NJ	38	58.1N	74	57.6W	1965	
8545240	Philadelphia, Delaware River, PA	39	56.0N	75	8.5W	1900	1921-1922
8551910	Reedy Point, C&D Canal, DE	39	33.5N	75	34.4W	1956	1967-1976
8557380	Lewes, Ft. Miles, DE	38	46.9N	75	7.2W	1919	1923-1936, 1940-1947, 1950-1952
8571892	Cambridge, Choptank River, MD	38	34.4N	76	4.1W	1942	1951-1970
8573364	Tolchester Beach, Chesapeake Bay, MD	39	12.8N	76	14.7W	1986	1987-1994
8574680	Baltimore, Fort Mchenry, Patapsco R., MD	39	16.0N	76	34.7W	1902	
8575512	Annapolis, Severn River, Ches. Bay, MD	38	59.0N	76	28.8W	1928	
8577330	Solomons Island, Patuxent River, MD	38	19.0N	76	27.1W	1937	

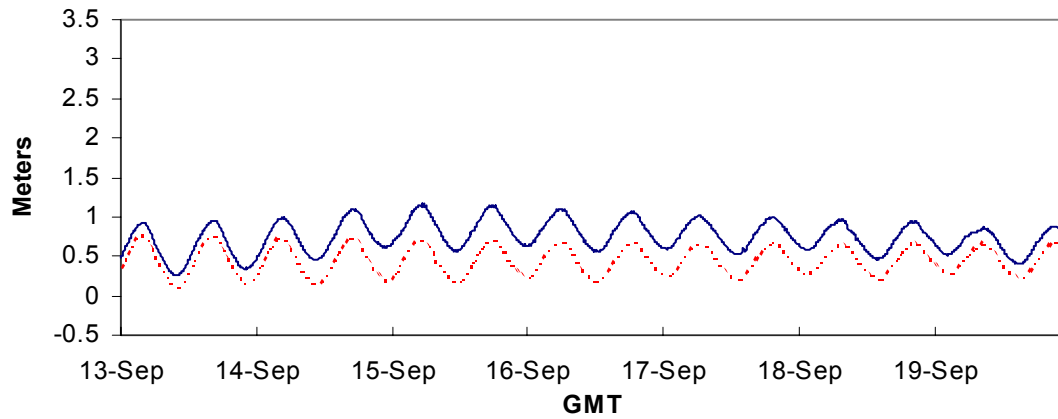
Station		Latitude		Longitude		Starting Year	Major Gaps
Number	Name	Deg.	Min.	Deg.	Min.		
8594900	Washington, Potomac River, D.C.	38	52.4N	77	1.3W	1931	
8631044	Wachapreague, Wachapreague Channel, VA	37	36.4N	75	41.2W	1978	
8632200	Kiptopeke, Chesapeake Bay, VA	37	10.0N	75	59.3W	1951	
8635150	Colonial Beach, Potomac River, VA	38	15.1N	76	57.6W	1972	
8635750	Lewisetta, Potomac River, VA	37	59.7N	76	27.9W	1974	
8636580	Windmill Point, VA	37	36.7N	76	16.5W	1994	
8637624	Gloucester Point, York River, VA	37	14.8N	76	30.0W	1950	1968-1969
8638610	Hampton Roads, VA	36	56.8N	76	19.8W	1927	
8638863	Chesapeake Bay Bridge Tunnel, VA	36	58.0N	76	6.8W	1975	
8639348	Money Point, S. Br. Elizabeth River, VA	36	46.7N	76	18.1W	1997	
8651370	Duck, FRF Pier, NC	36	11.0N	75	44.8W	1978	
8652587	Oregon Inlet Marina, NC	35	47.8N	75	33.0W	1977	1978-1994
8654400	Cape Hatteras Fishing Pier, NC	35	13.4N	75	38.1W	1973	1993-1994
8656483	Duke Marine Lab, Beaufort, NC	34	43.2N	76	40.2W	1973	
8658120	Wilmington, NC	34	13.6N	77	57.2W	1935	
8661070	Springmaid Pier, SC	33	39.3N	78	55.1W	1977	1989-1991
8665530	Charleston, Cooper River Entrance, SC	32	46.9N	79	55.5W	1921	
8670870	Fort Pulaski, Savannah River, GA	32	2.0N	80	54.1W	1935	1974-1977
8720030	Fernandina Beach, Amelia River, FL	30	40.3N	81	27.9W	1897	1924-1938
8720220	Mayport, FL	30	23.6N	81	25.9W	1928	
8720587	St. Augustine Beach, Atlantic Ocean, FL	29	51.4N	81	15.7W	1992	
8721604	Trident Pier, Port Canaveral, FL	28	24.9N	80	35.6W	1994	
8723214	Virginia Key, Biscayne Bay, FL	25	43.9N	80	9.7W	1994	
9710441	Settlement Point, Grand Bahamas, BA	26	42.6N	78	59.8W	1985	

## **Appendix II.**

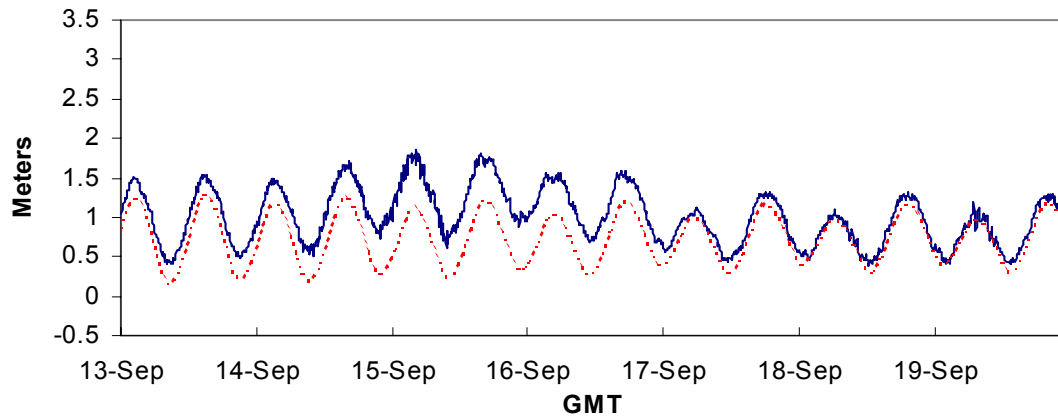
### **Time series of observed water level and predicted tide at NWLON stations**



**Figure 41.** Settlement Point, BA observed (solid) and predicted (dashed) water levels on MLLW.

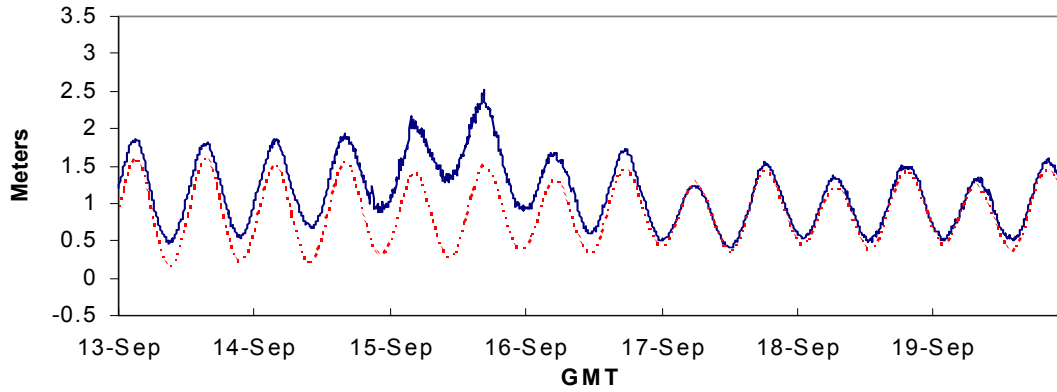


**Figure 42.** Virginia Key, FL observed (solid) and predicted (dashed) water levels on MLLW.

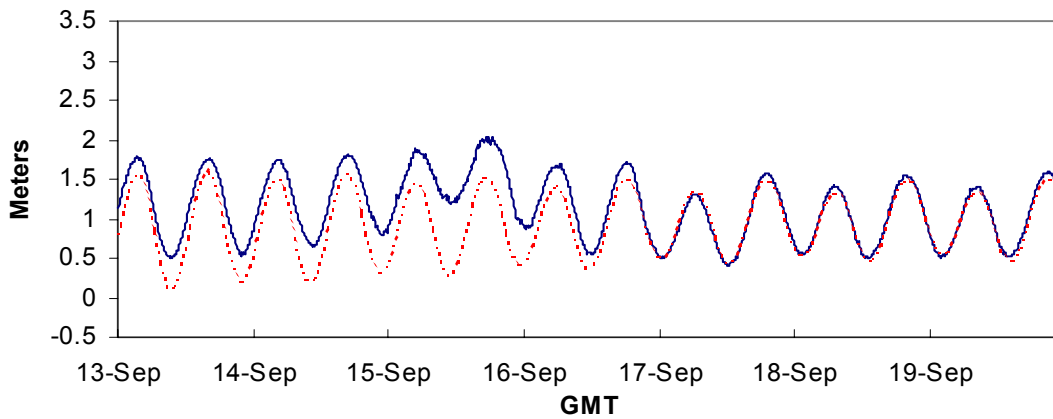


**Figure 43.** Trident Pier, FL observed (solid) and predicted (dashed) water levels on MLLW.

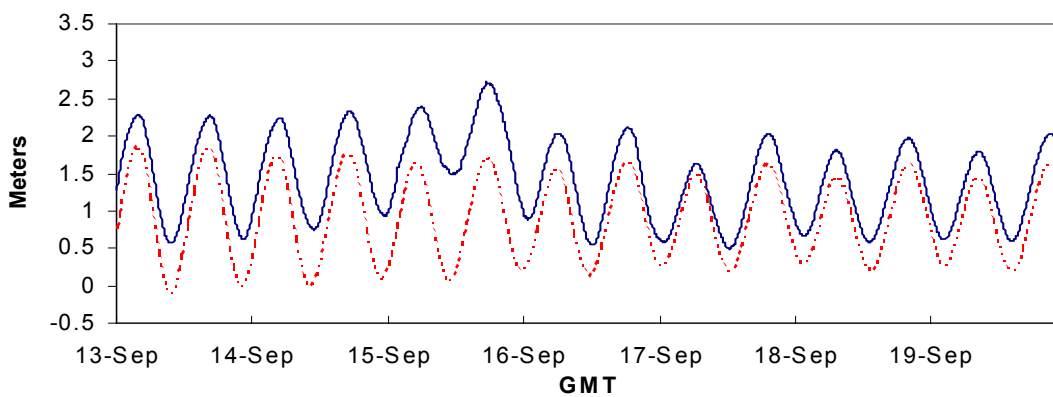




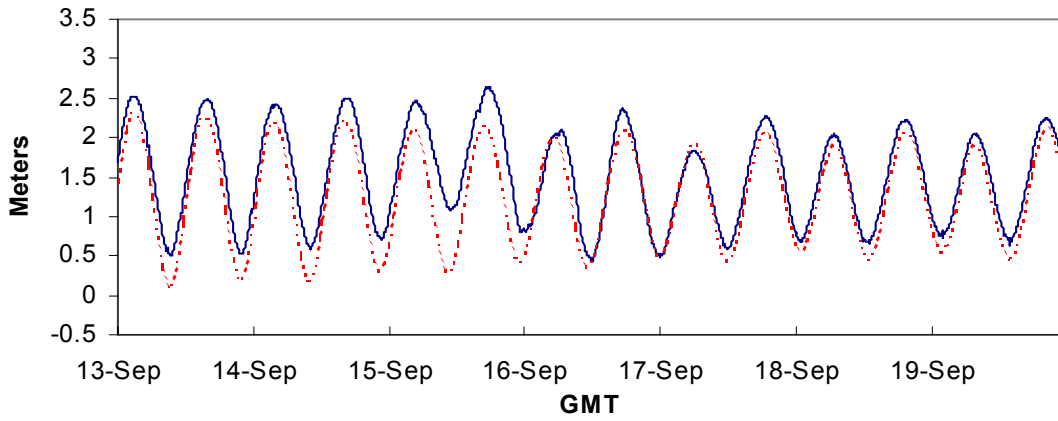
**Figure 44.** St. Augustine Beach, FL observed (solid) and predicted (dashed) water levels on MLLW.



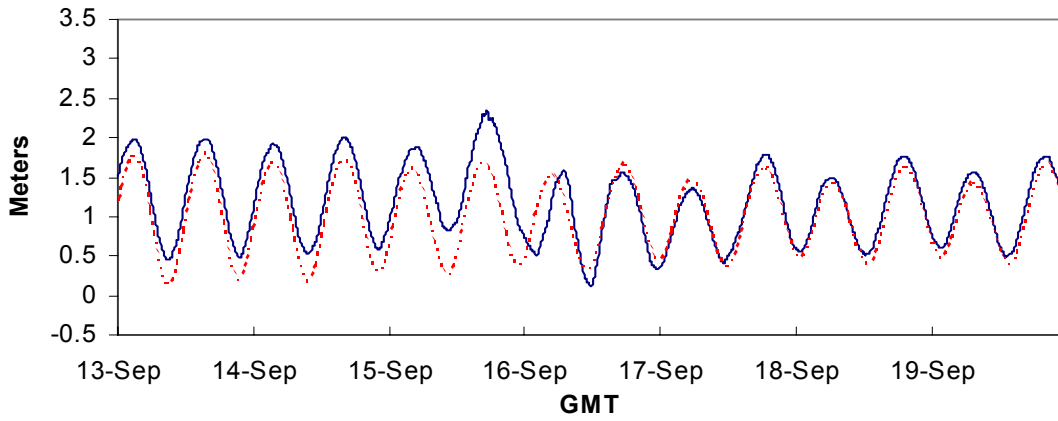
**Figure 45.** Mayport, FL observed (solid) and predicted (dashed) water levels on MLLW.



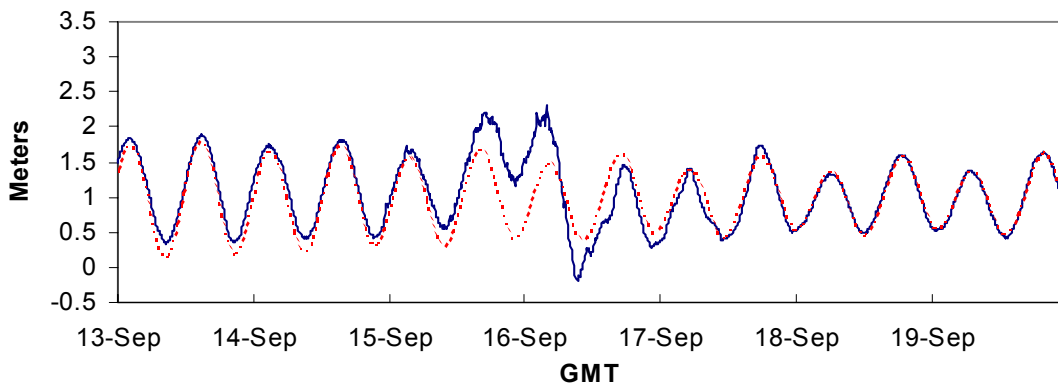
**Figure 46.** Fernandina Beach, FL observed (solid) and predicted (dashed) water levels on MLLW.



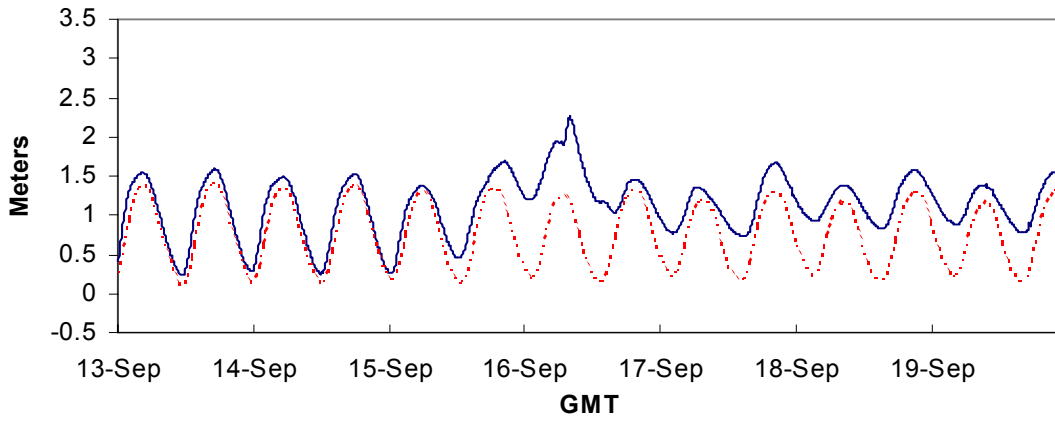
**Figure 47.** Fort Pulaski, GA observed (solid) and predicted (dashed) water levels on MLLW.



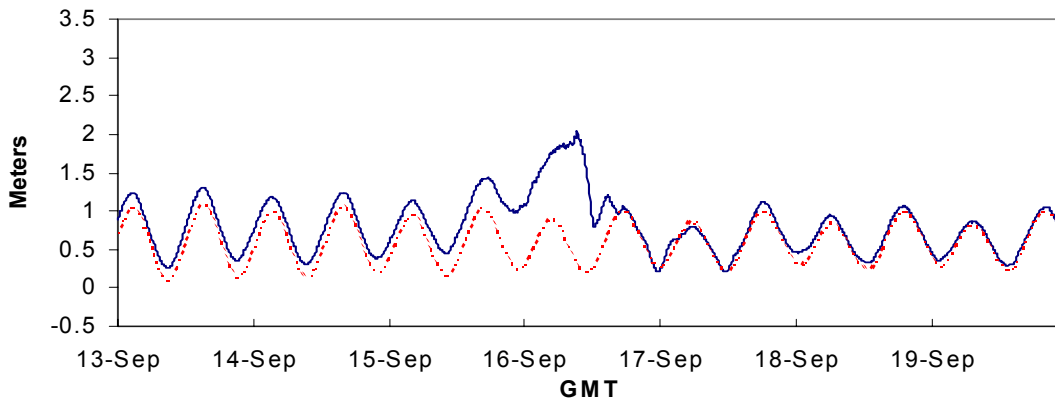
**Figure 48.** Charleston, SC observed (solid) and predicted (dashed) water levels on MLLW.



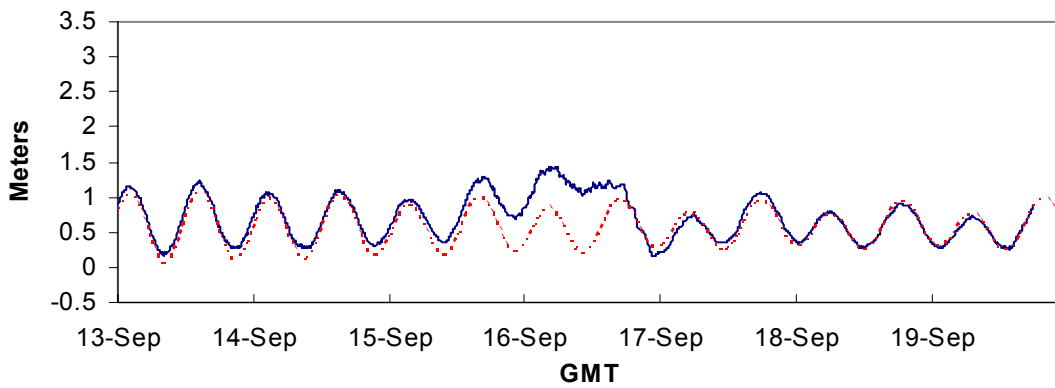
**Figure 49.** Springmaid Pier, SC observed (solid) and predicted (dashed) water levels on MLLW.



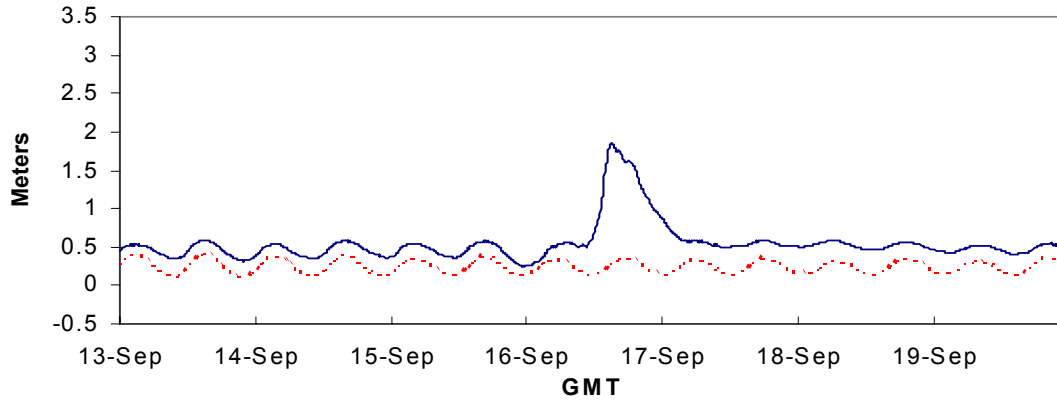
**Figure 50.** Wilmington, NC observed (solid) and predicted (dashed) water levels on MLLW.



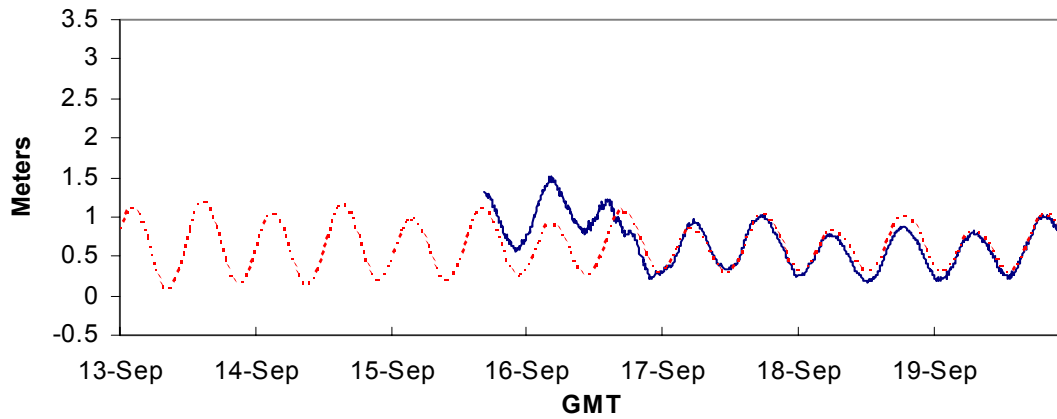
**Figure 51.** Duke Marine Lab, NC observed (solid) and predicted (dashed) water levels on MLLW.



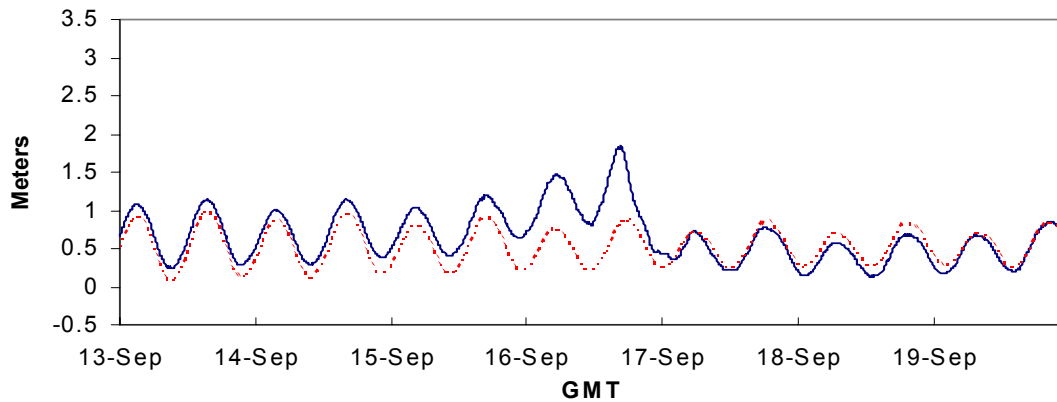
**Figure 52.** Cape Hatteras, NC observed (solid) and predicted (dashed) water levels on MLLW.



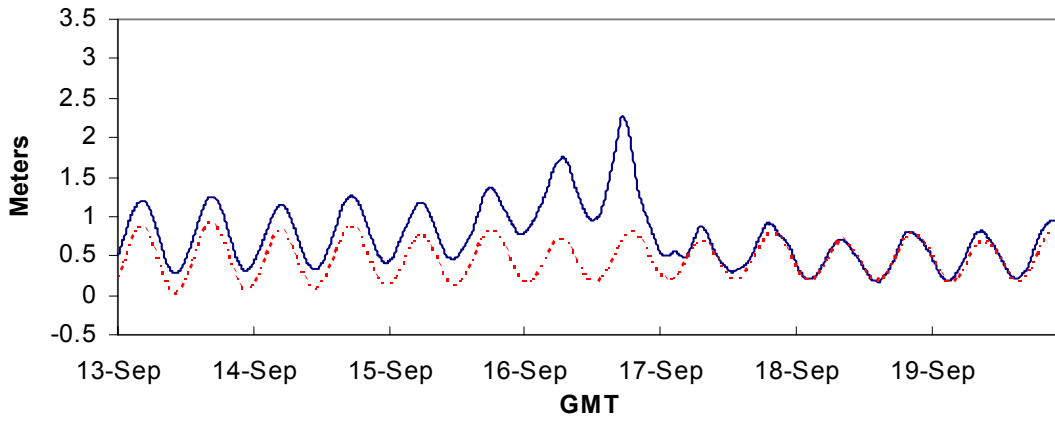
**Figure 53.** Oregon Inlet Marina, NC observed (solid) and predicted (dashed) water levels on MLLW.



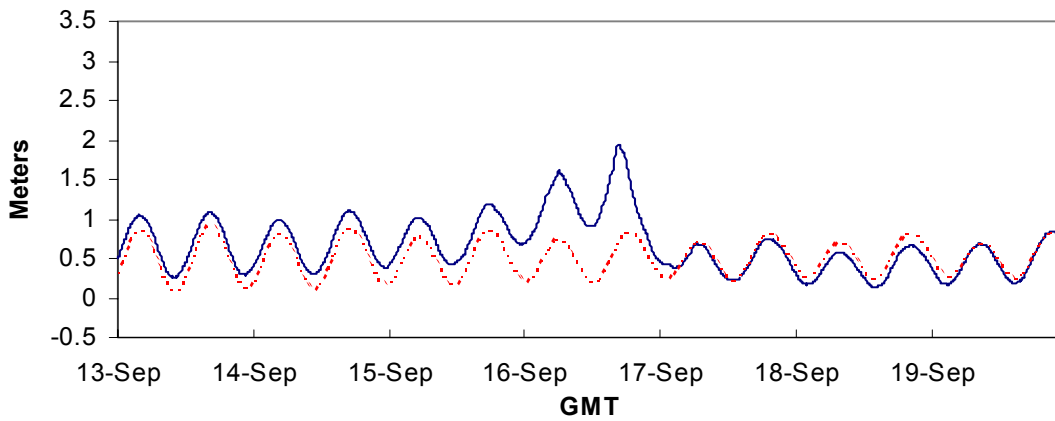
**Figure 54.** Duck Pier, NC observed (solid) and predicted (dashed) water levels on MLLW.



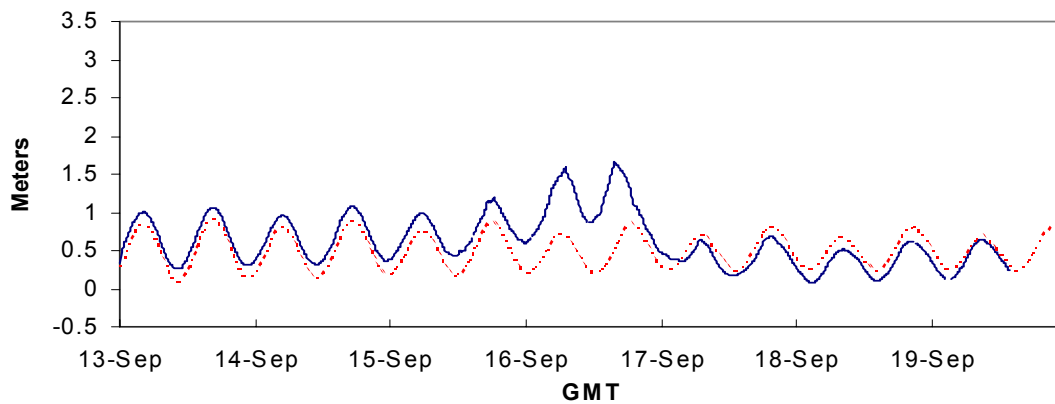
**Figure 55.** Chesapeake Bay Bridge Tunnel, VA observed (solid) and predicted (dashed) water levels on MLLW.



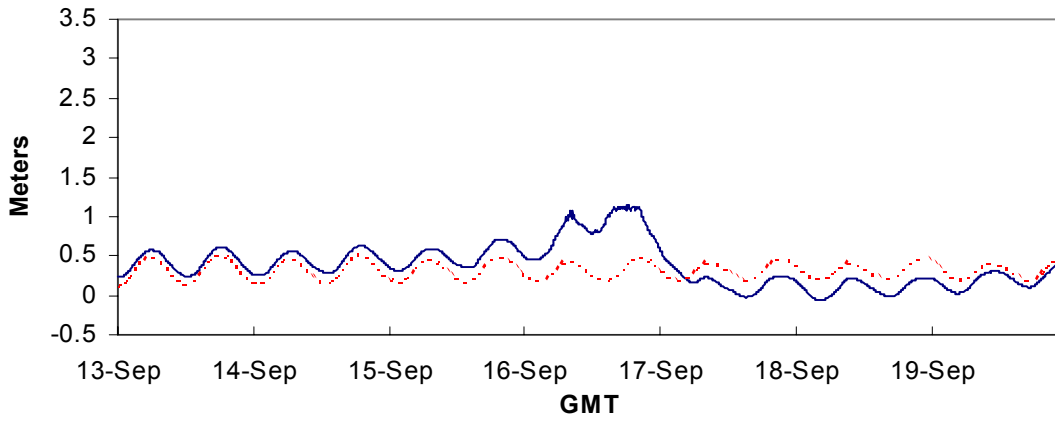
**Figure 56.** Money Point, VA observed (solid) and predicted (dashed) water levels on MLLW.



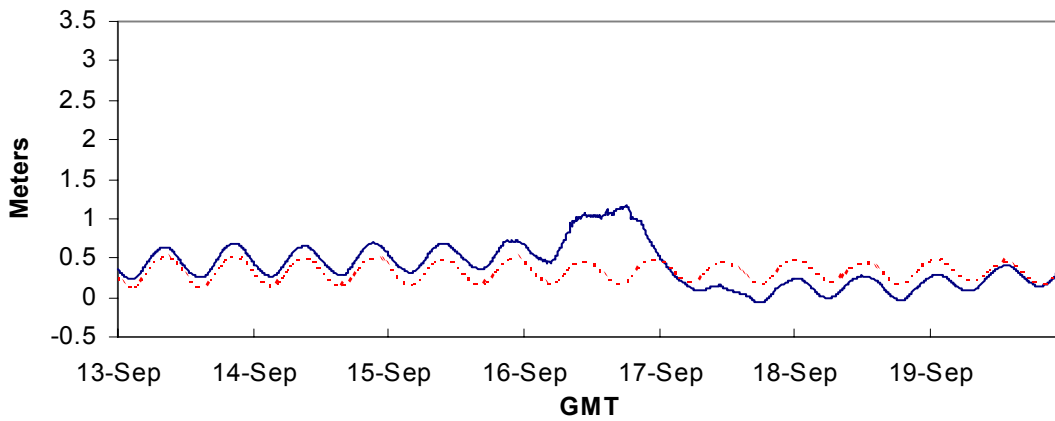
**Figure 57.** Hampton Roads, VA observed (solid) and predicted (dashed) water levels on MLLW.



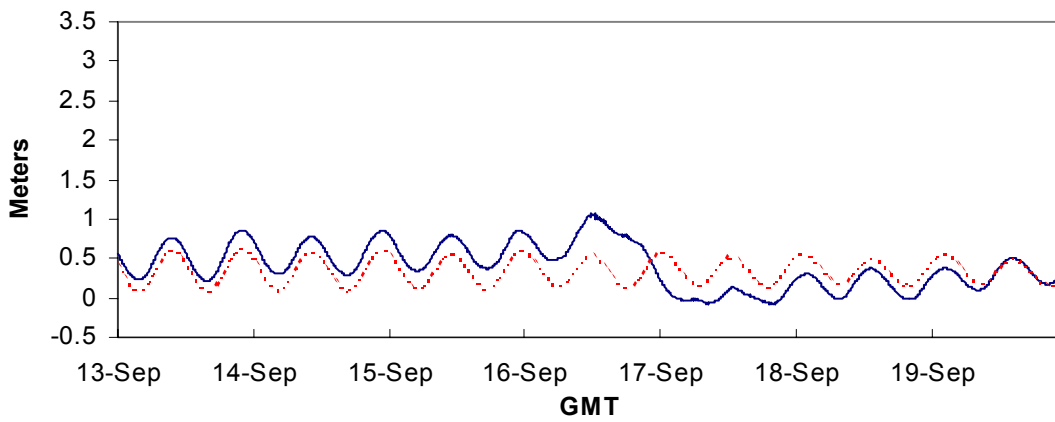
**Figure 58.** Gloucester Point, VA observed (solid) and predicted (dashed) water levels on MLLW.



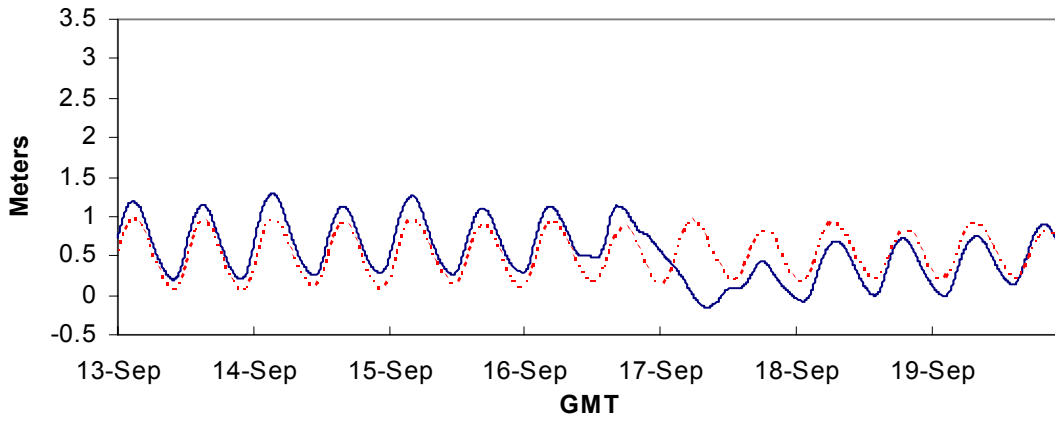
**Figure 59.** Windmill Point, VA observed (solid) and predicted (dashed) water levels on MLLW.



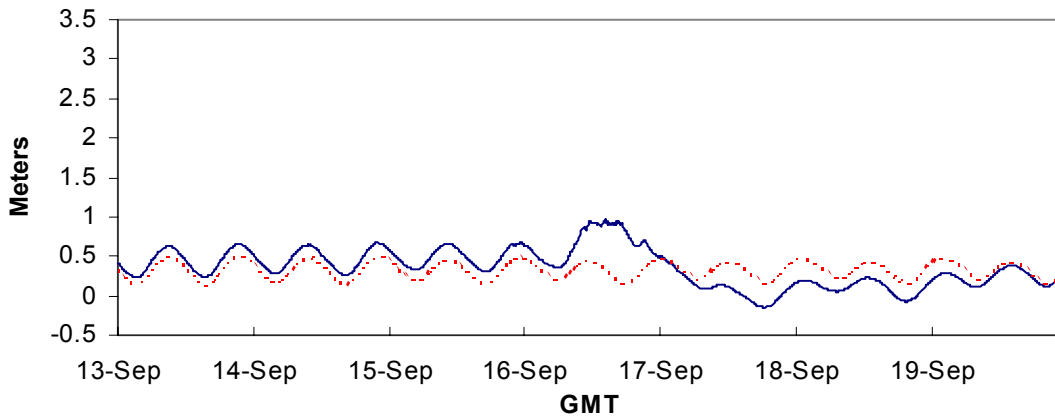
**Figure 60.** Lewisetta, VA observed (solid) and predicted (dashed) water levels on MLLW.



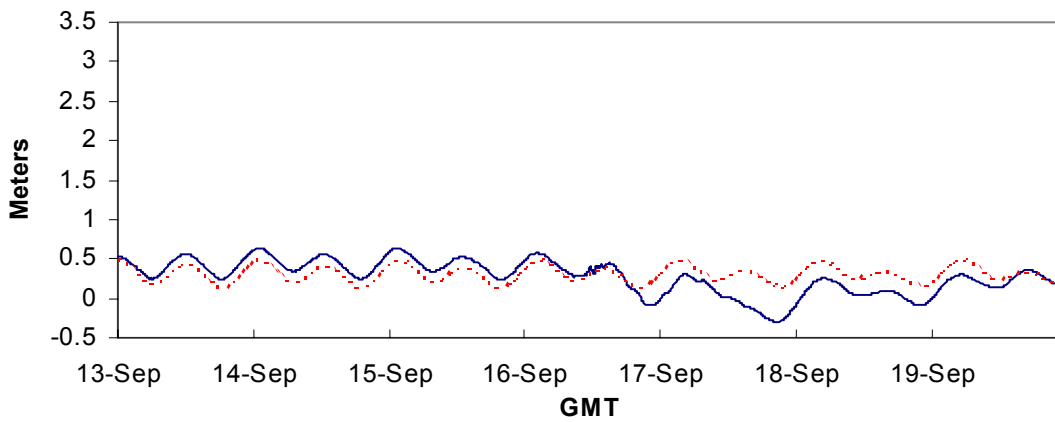
**Figure 61.** Colonial Beach, VA observed (solid) and predicted (dashed) water levels on MLLW.



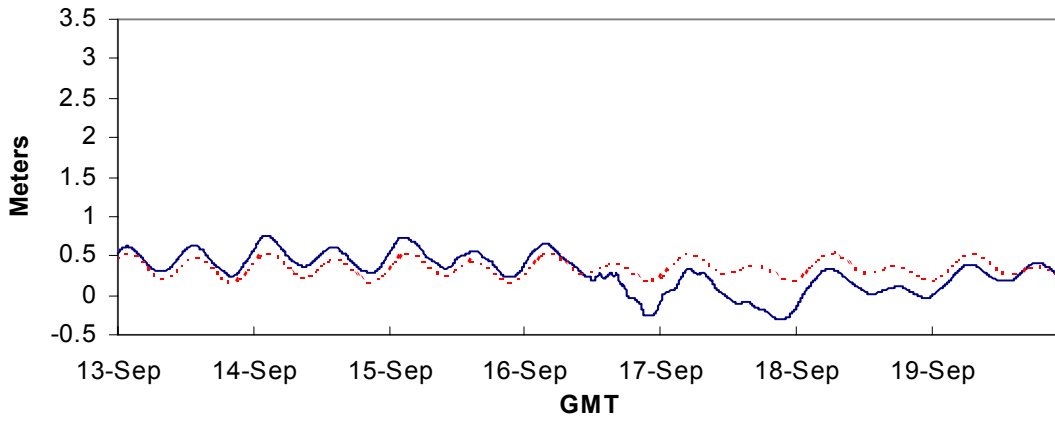
**Figure 62.** Washington, DC observed (solid) and predicted (dashed) water levels on MLLW.



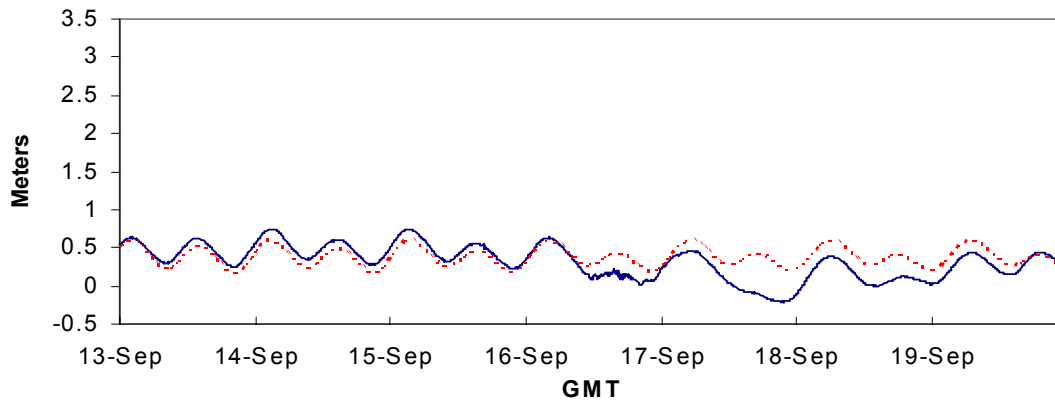
**Figure 63.** Solomons, MD observed (solid) and predicted (dashed) water levels on MLLW.



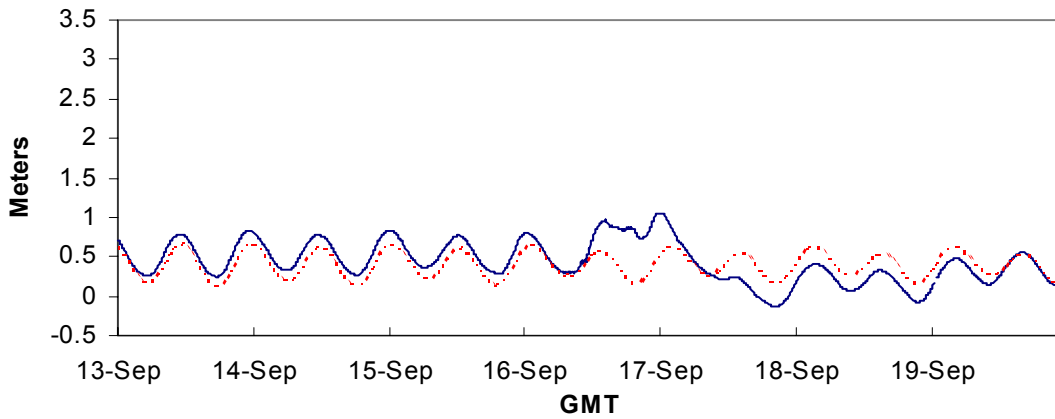
**Figure 64.** Annapolis, MD observed (solid) and predicted (dashed) water levels on MLLW.



**Figure 65.** Baltimore, MD observed (solid) and predicted (dashed) water levels on MLLW.

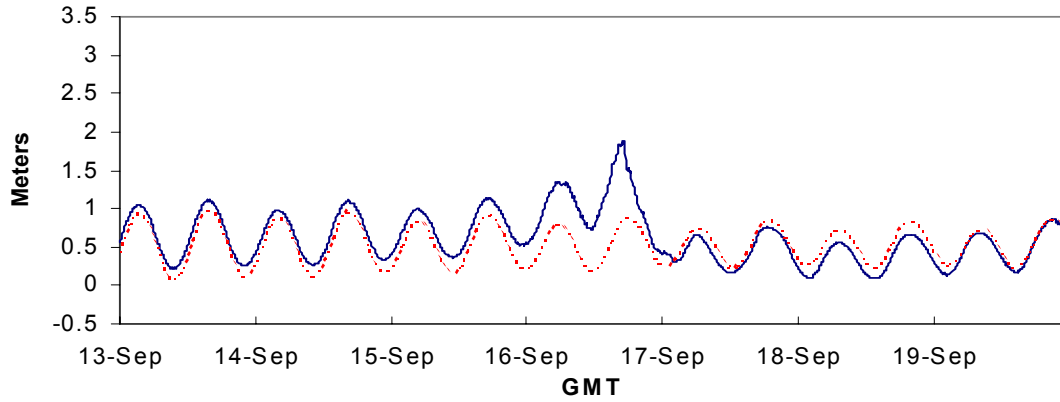


**Figure 66.** Tolchester Beach, MD observed (solid) and predicted (dashed) water levels on MLLW.

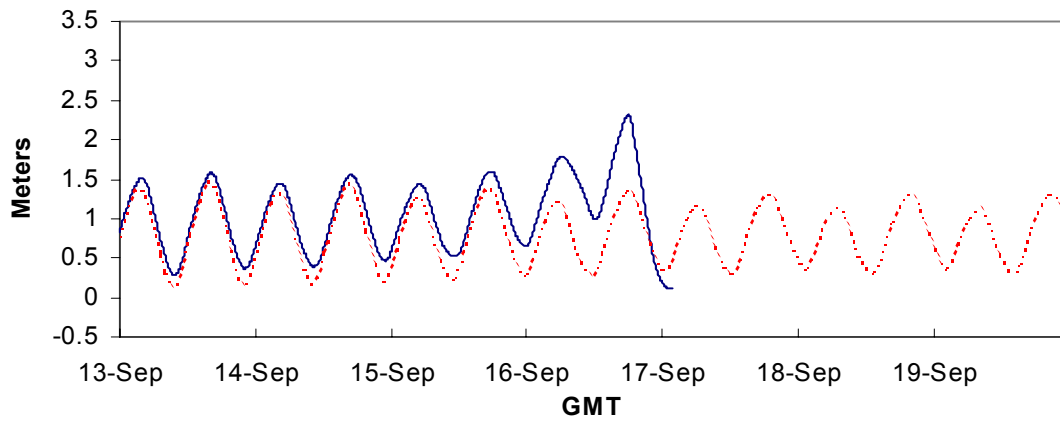


**Figure 67.** Cambridge, MD observed (solid) and predicted (dashed) water levels on MLLW.

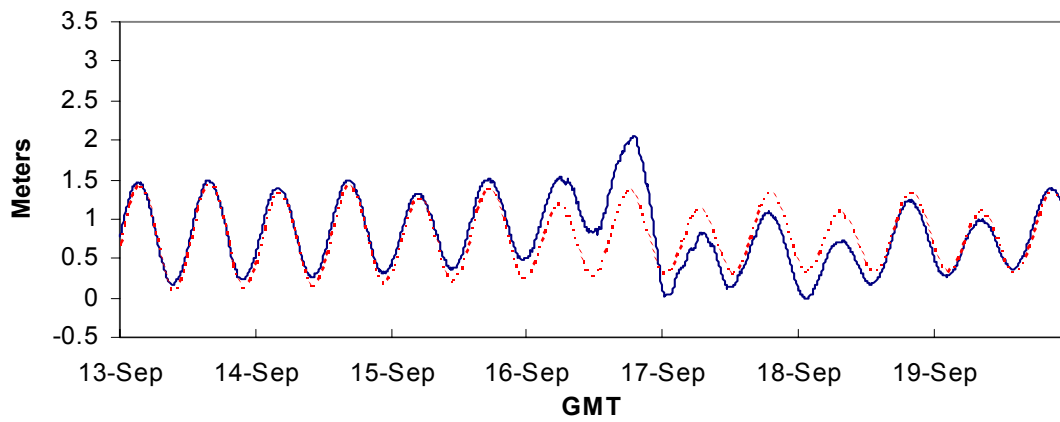




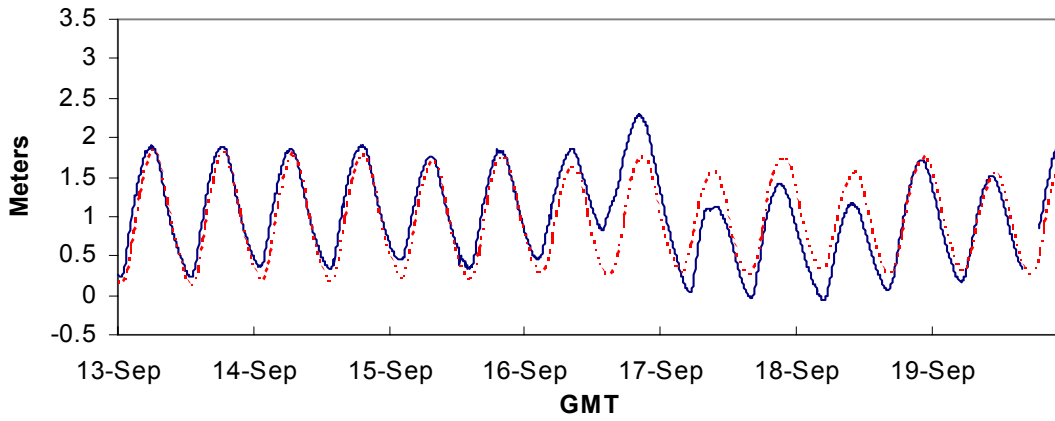
**Figure 68.** Kiptopeke Beach, VA observed (solid) and predicted (dashed) water levels on MLLW.



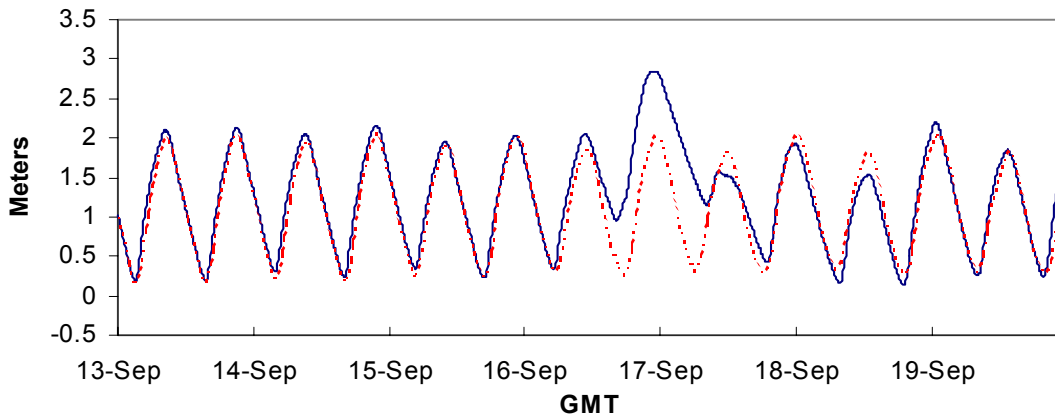
**Figure 69.** Wachapreague, VA observed (solid) and predicted (dashed) water levels on MLLW.



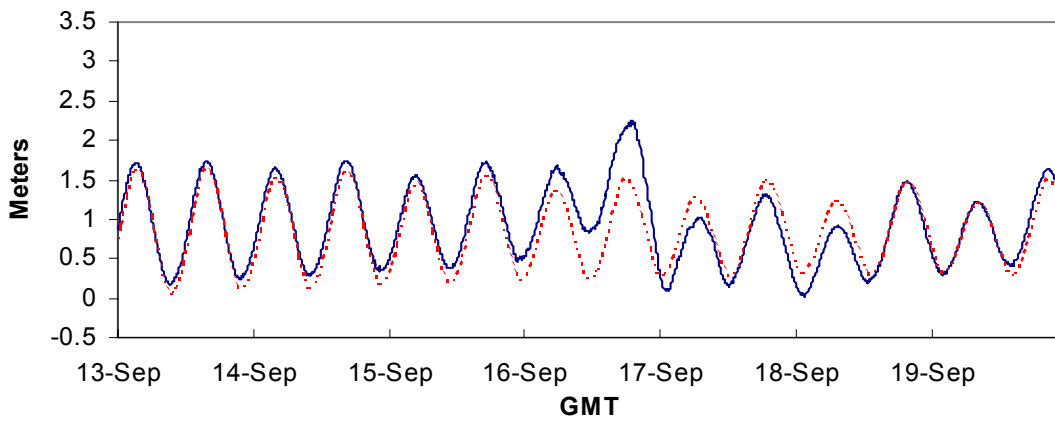
**Figure 70.** Lewes, DE observed (solid) and predicted (dashed) water levels on MLLW.



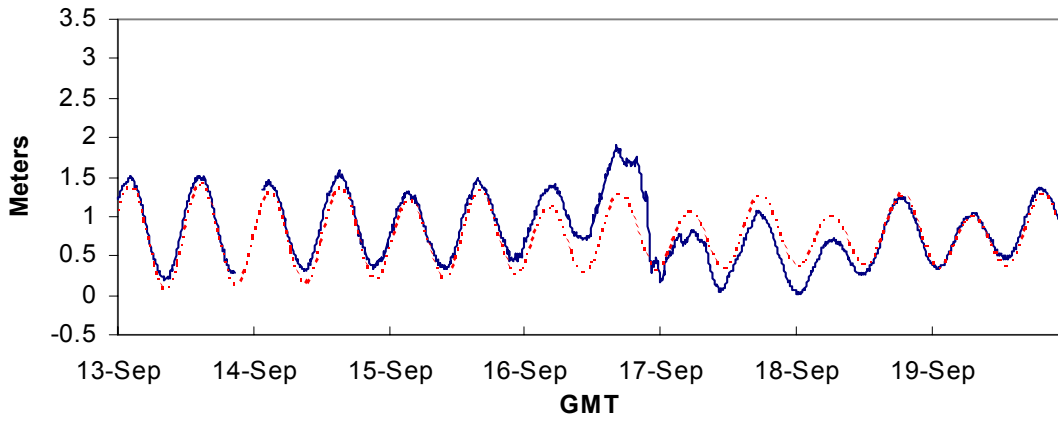
**Figure 71.** Reedy Point, DE observed (solid) and predicted (dashed) water levels on MLLW.



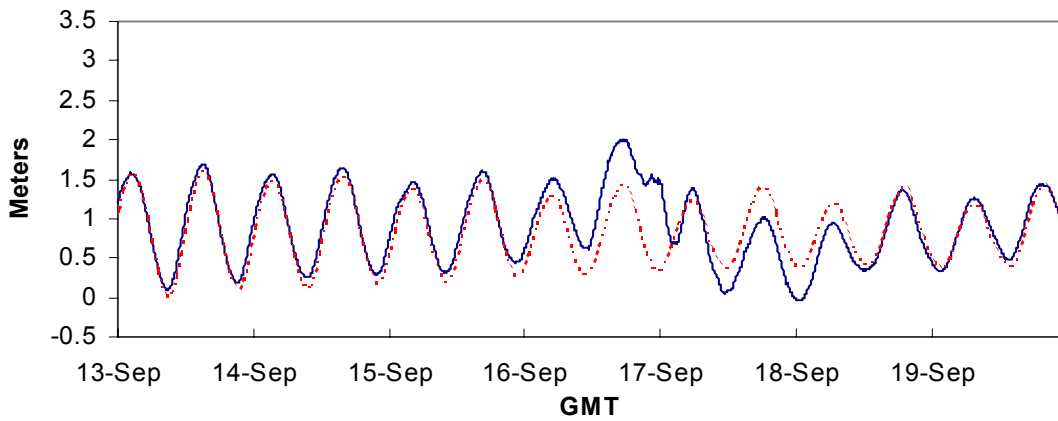
**Figure 72.** Philadelphia, PA observed (solid) and predicted (dashed) water levels on MLLW.



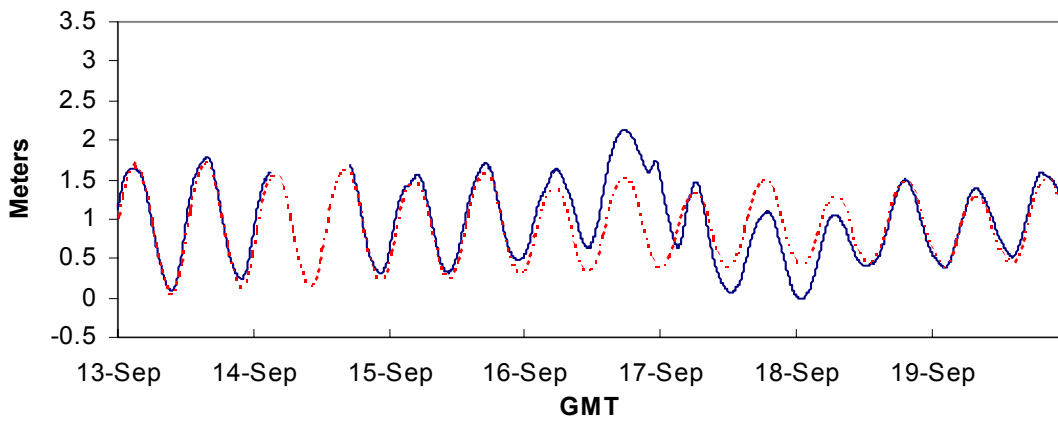
**Figure 73.** Cape May, NJ observed (solid) and predicted (dashed) water levels on MLLW.



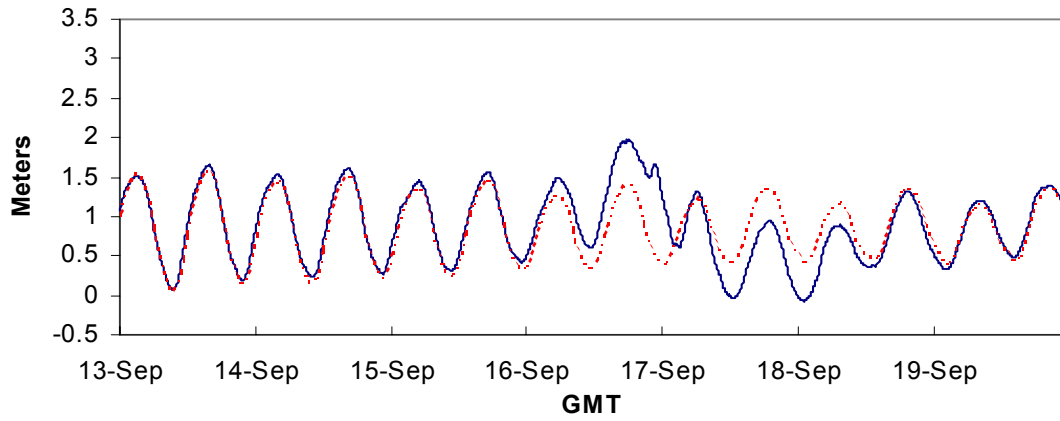
**Figure 74.** Atlantic City, NJ observed (solid) and predicted (dashed) water levels on MLLW.



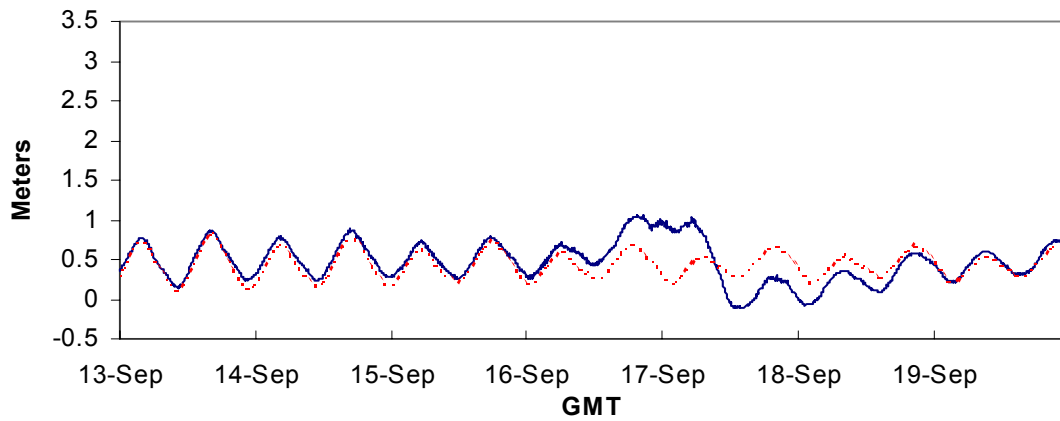
**Figure 75.** Sandy Hook, NJ observed (solid) and predicted (dashed) water levels on MLLW.



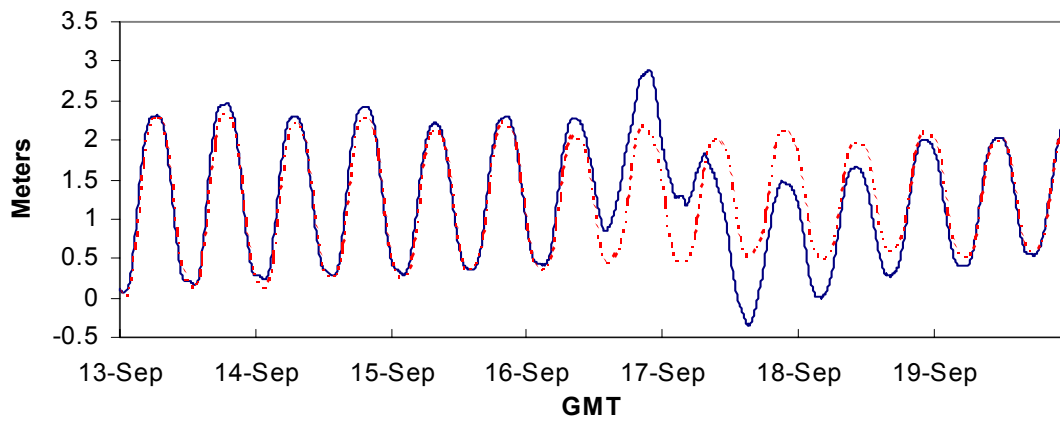
**Figure 76.** Bergen Point, NY observed (solid) and predicted (dashed) water levels on MLLW.



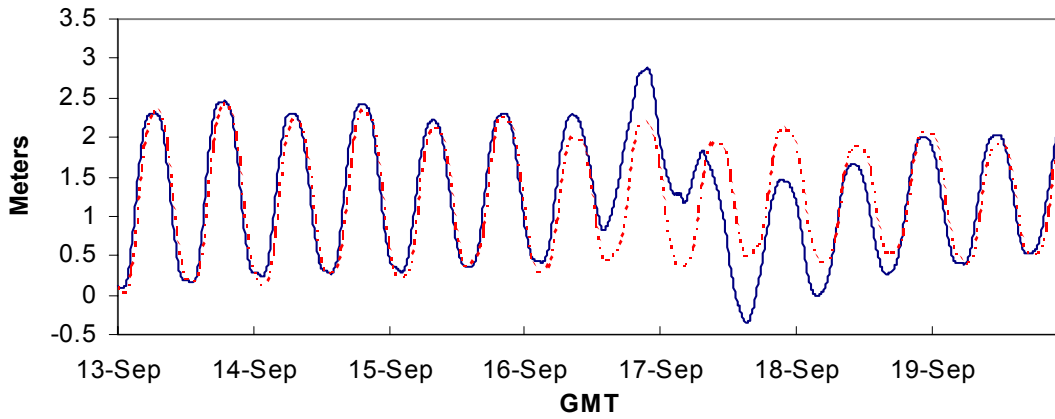
**Figure 77.** The Battery, NY observed (solid) and predicted (dashed) water levels on MLLW.



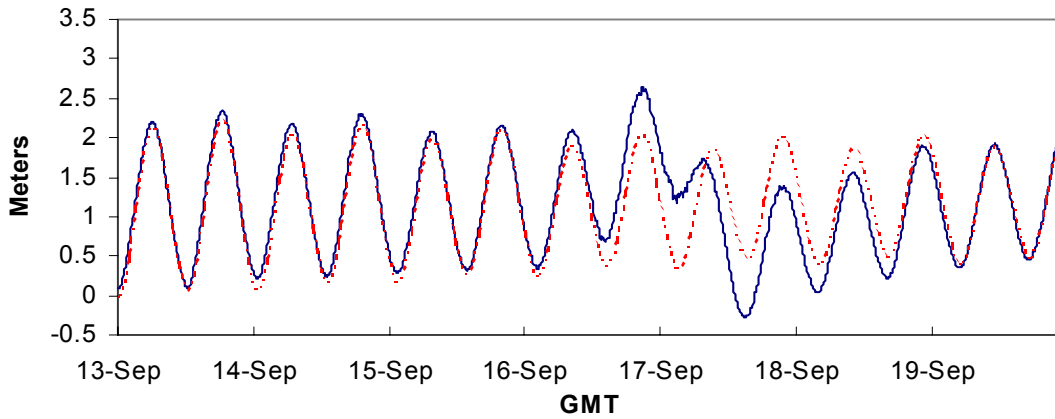
**Figure 78.** Montauk, NY observed (solid) and predicted (dashed) water levels on MLLW.



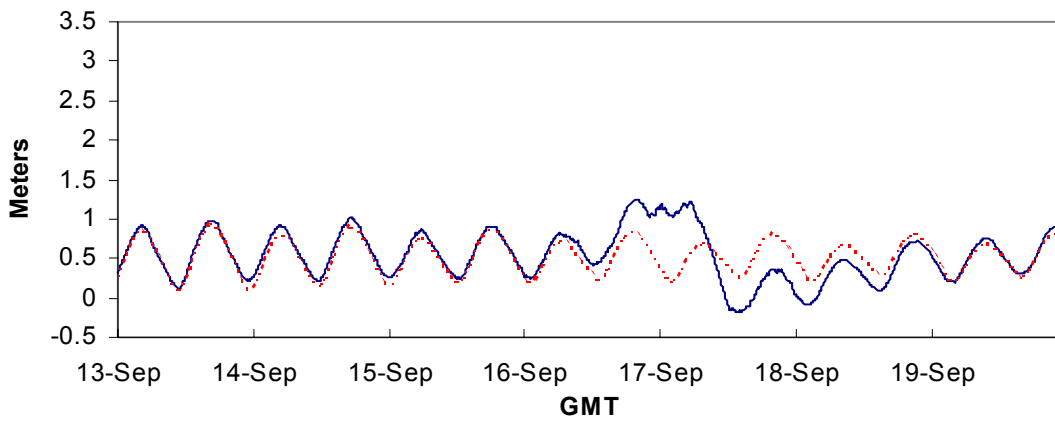
**Figure 79.** Willets Point, NY observed (solid) and predicted (dashed) water levels on MLLW.



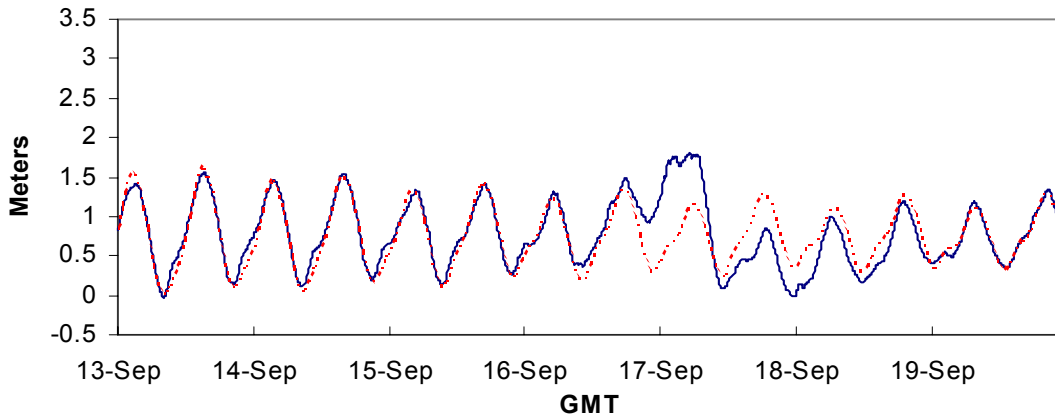
**Figure 80.** Kings Point, NY observed (solid) and predicted (dashed) water levels on MLLW.



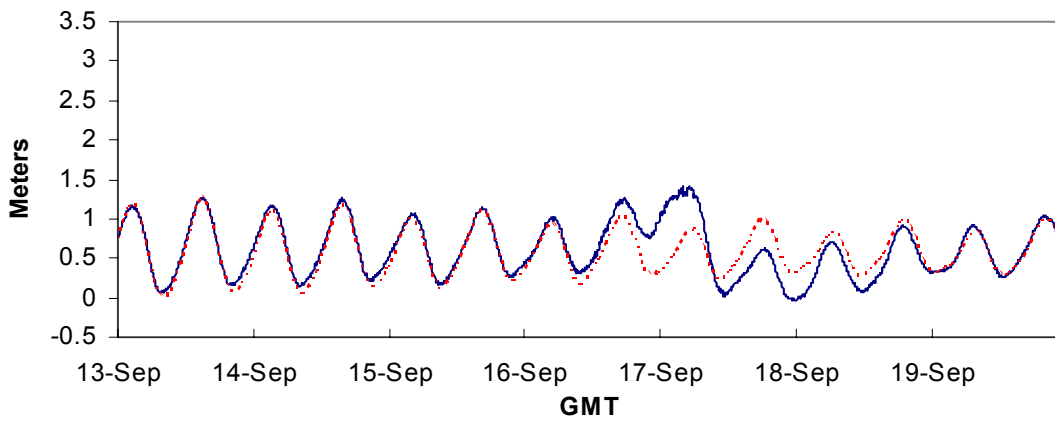
**Figure 81.** Bridgeport, CT observed (solid) and predicted (dashed) water levels on MLLW.



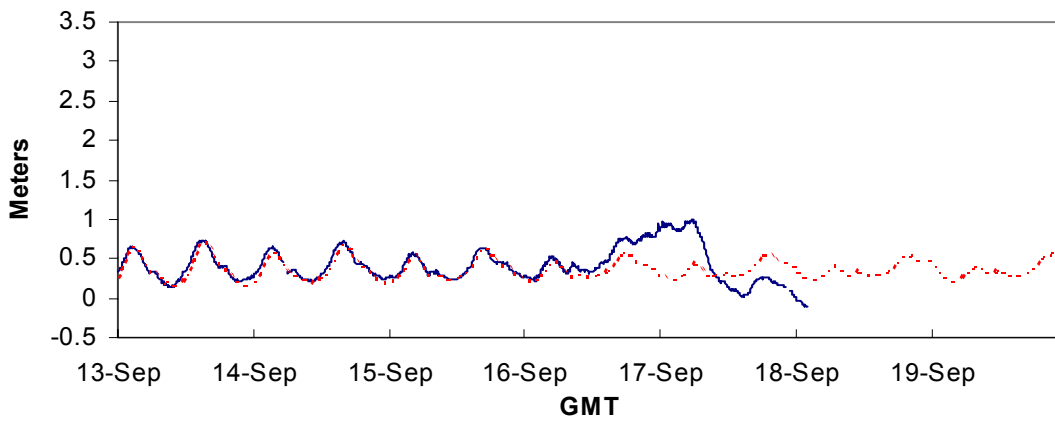
**Figure 82.** New London, CT observed (solid) and predicted (dashed) water levels on MLLW.



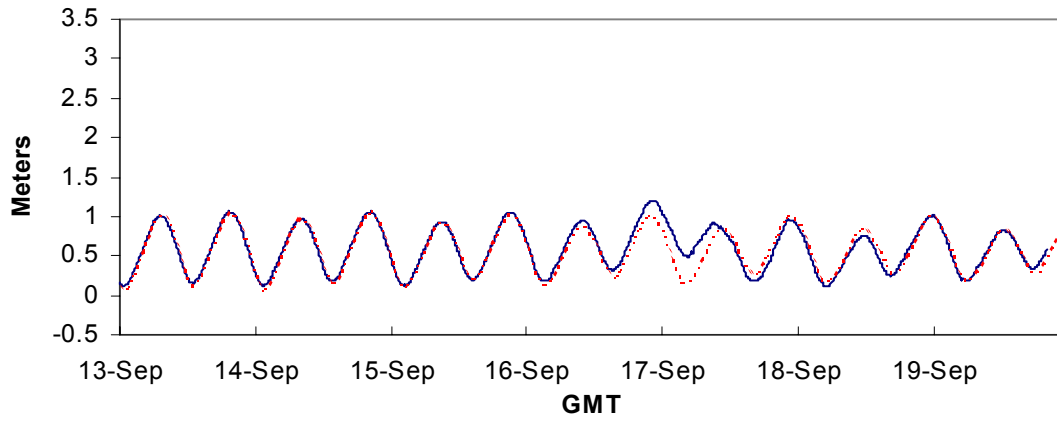
**Figure 83.** Providence, RI observed (solid) and predicted (dashed) water levels on MLLW.



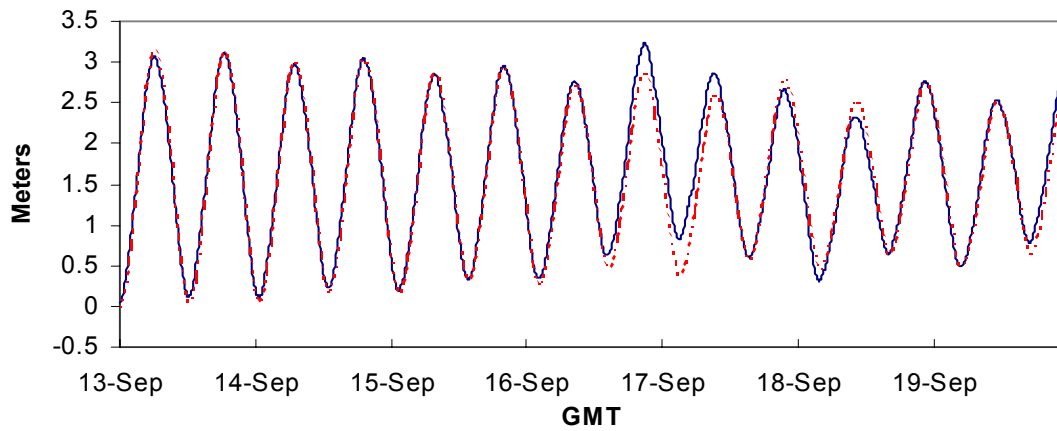
**Figure 84.** Newport, RI observed (solid) and predicted (dashed) water levels on MLLW.



**Figure 85.** Woods Hole, MA observed (solid) and predicted (dashed) water levels on MLLW.



**Figure 86.** Nantucket, MA observed (solid) and predicted (dashed) water levels on MLLW.



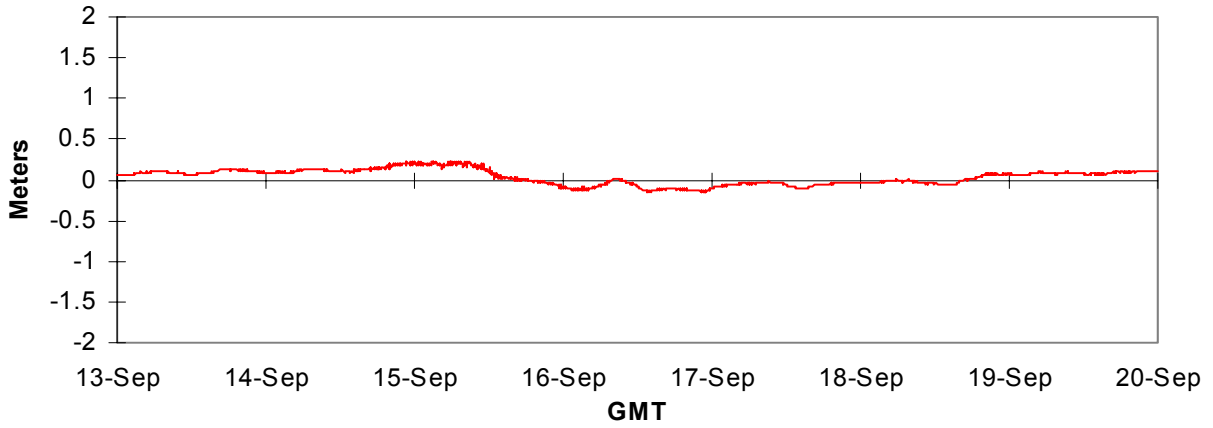
**Figure 87.** Boston, MA observed (solid) and predicted (dashed) water levels on MLLW.



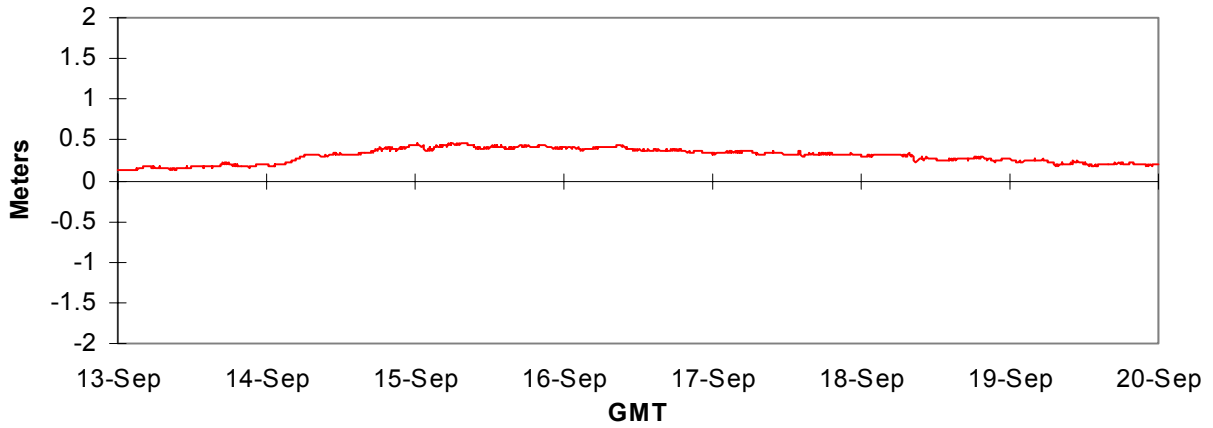


## **Appendix III.**

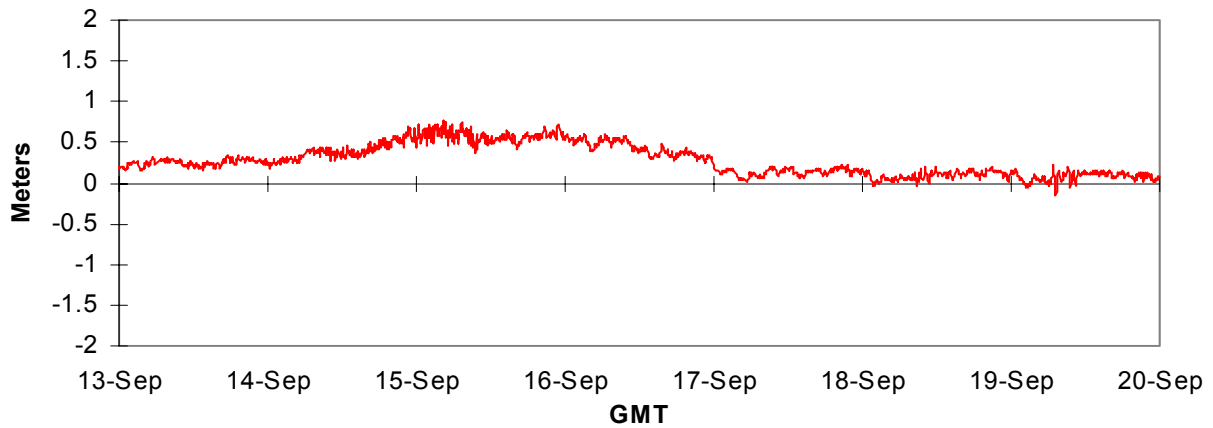
### **Time series of storm surge at NWLON stations**



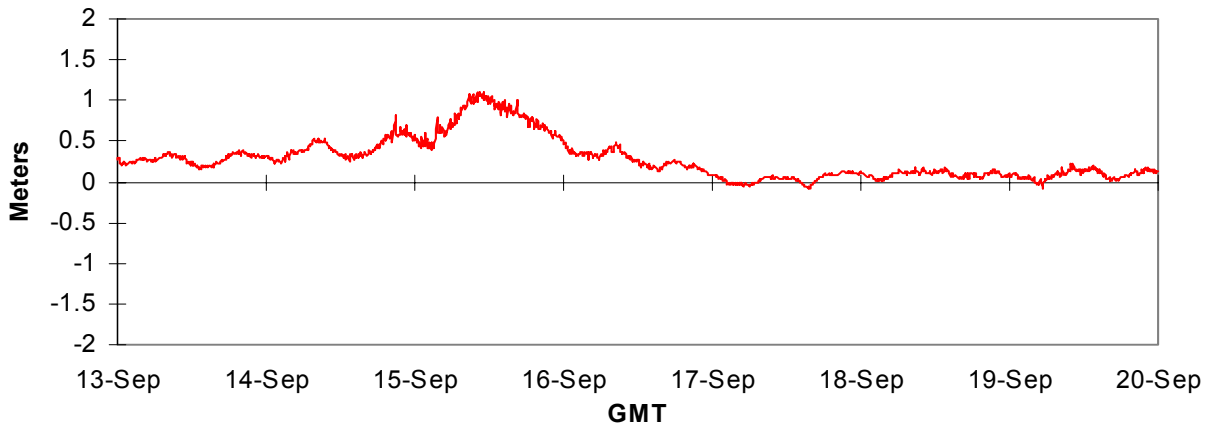
**Figure 88.** Settlement Point, BA storm surge.



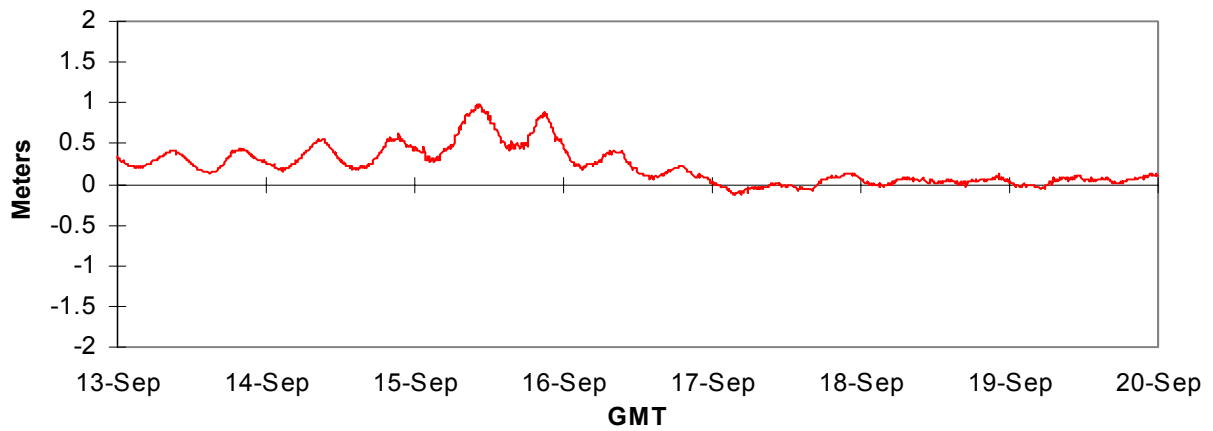
**Figure 89.** Virginia Key, FL storm surge.



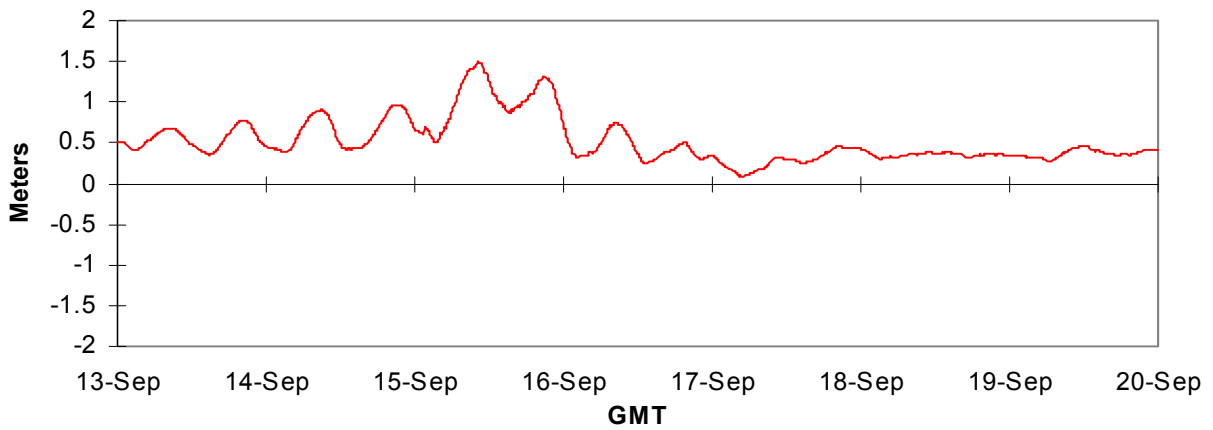
**Figure 90.** Trident Pier, FL storm surge.



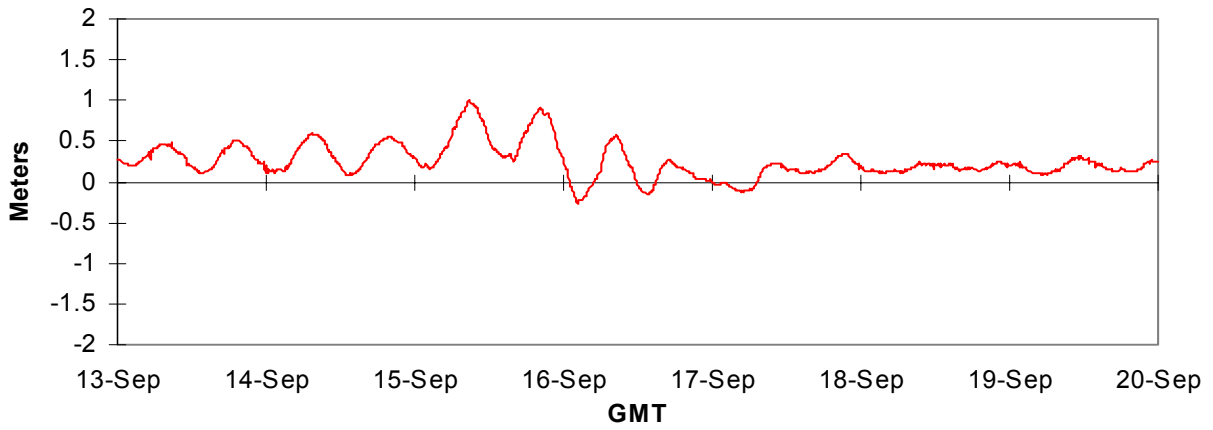
**Figure 91.** St. Augustine Beach, FL storm surge.



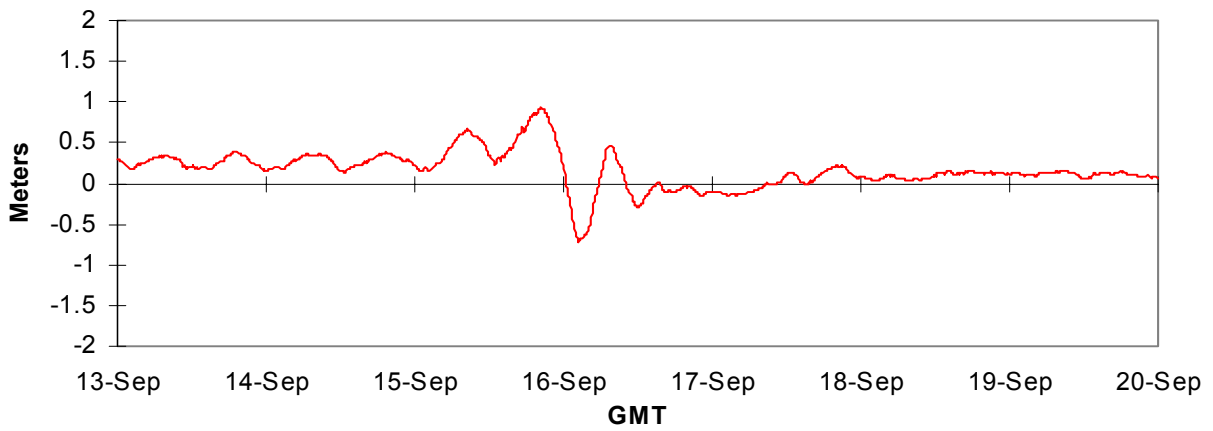
**Figure 92.** Mayport, FL storm surge.



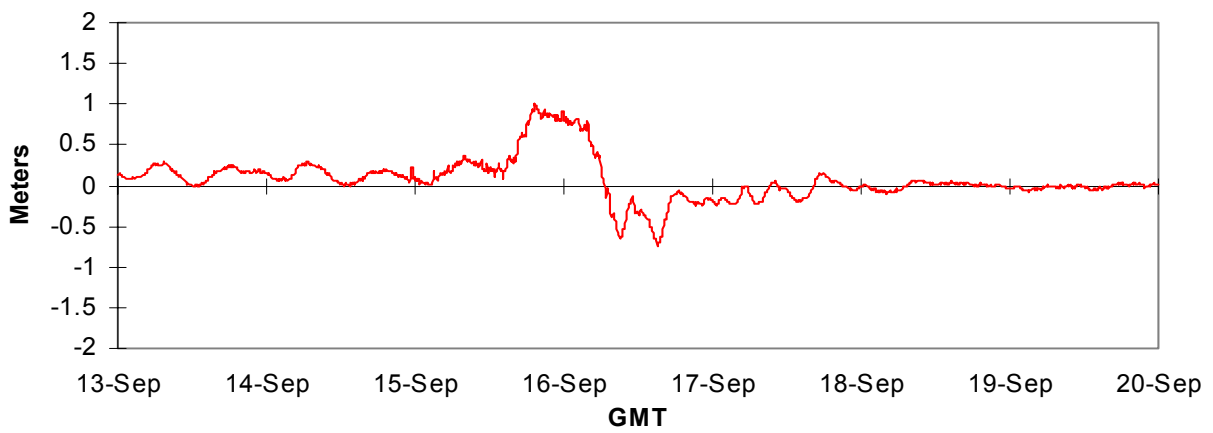
**Figure 93.** Fernandina Beach, FL storm surge.



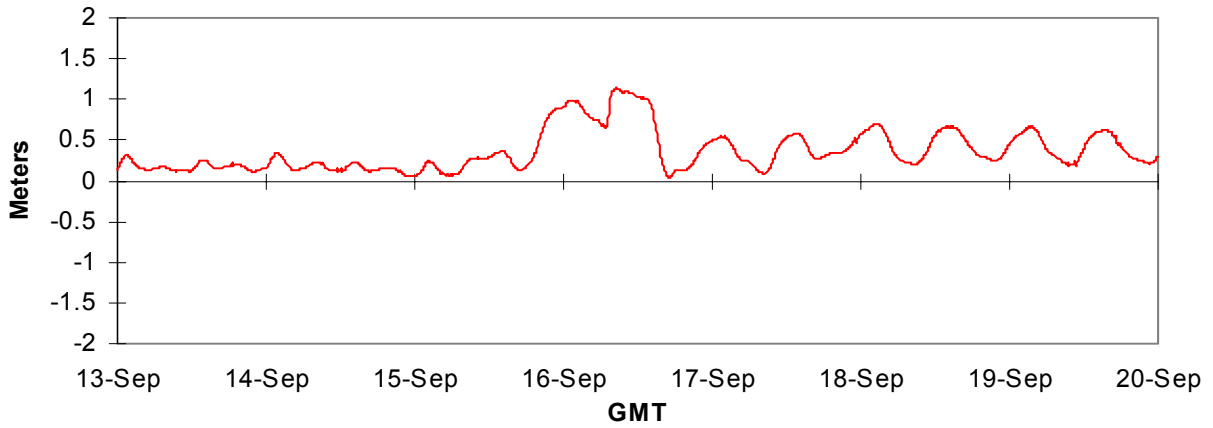
**Figure 94.** Fort Pulaski, GA storm surge.



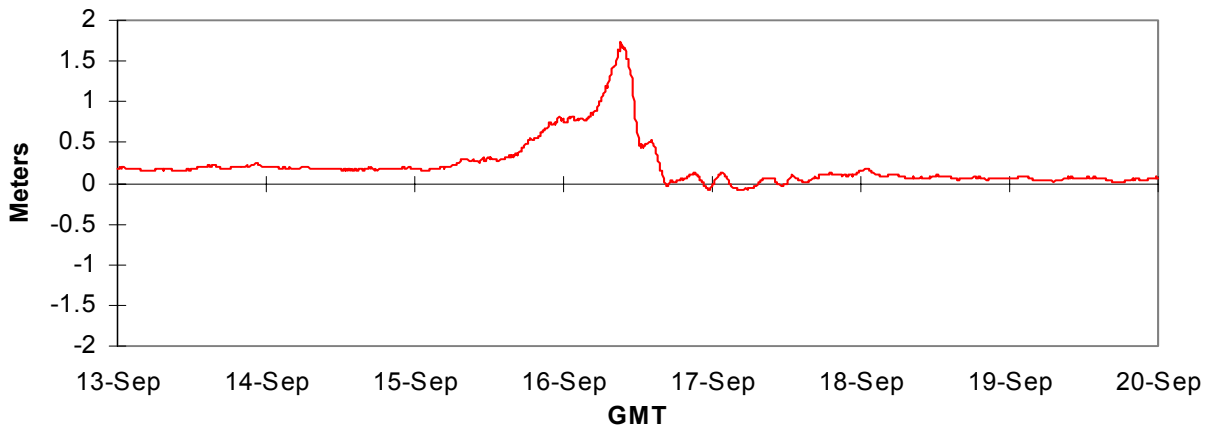
**Figure 95.** Charleston, SC storm surge.



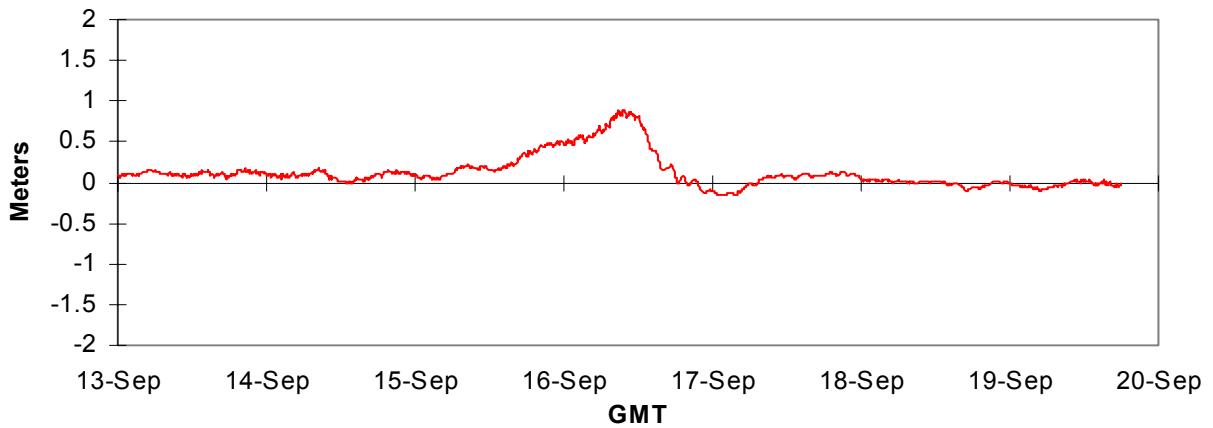
**Figure 96.** Springmaid Pier, SC storm surge.



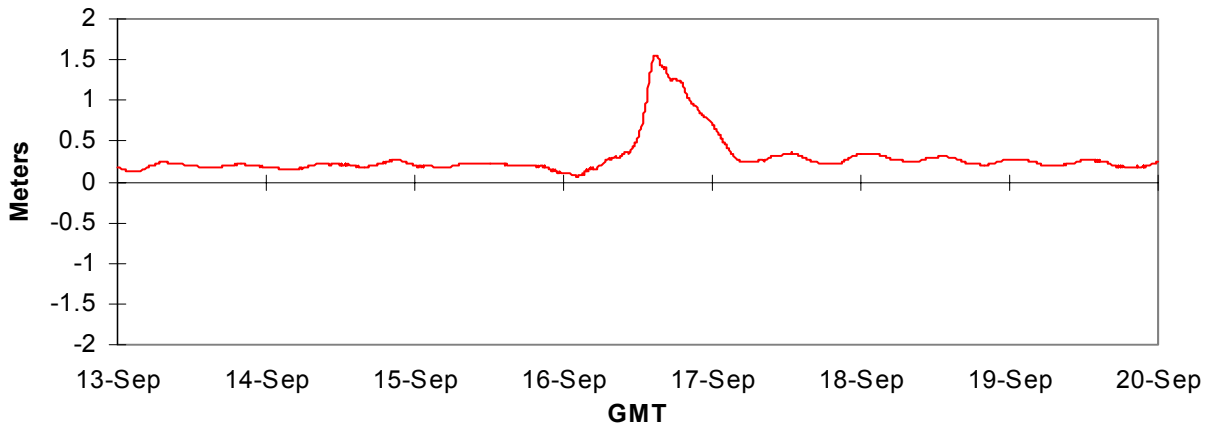
**Figure 97.** Wilmington, NC storm surge.



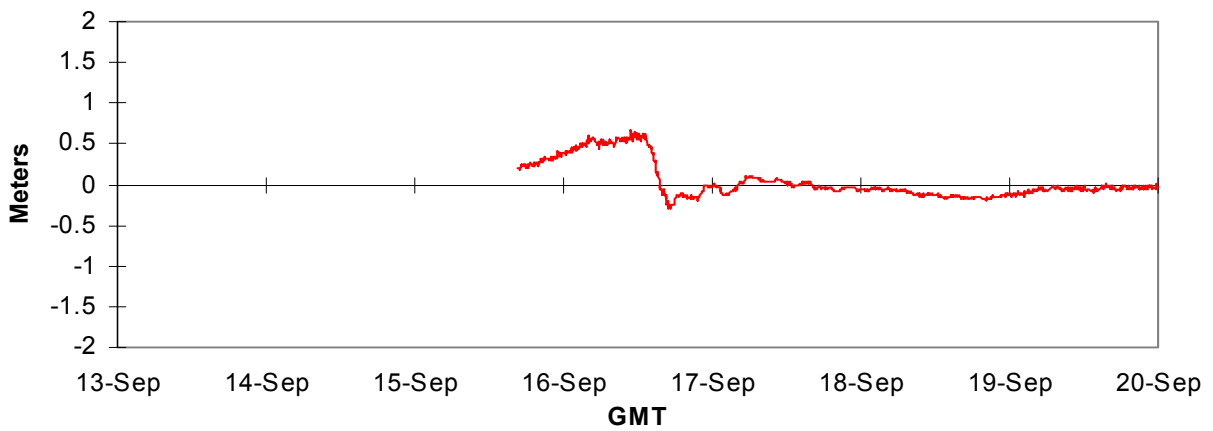
**Figure 98.** Duke Marine Lab, NC storm surge.



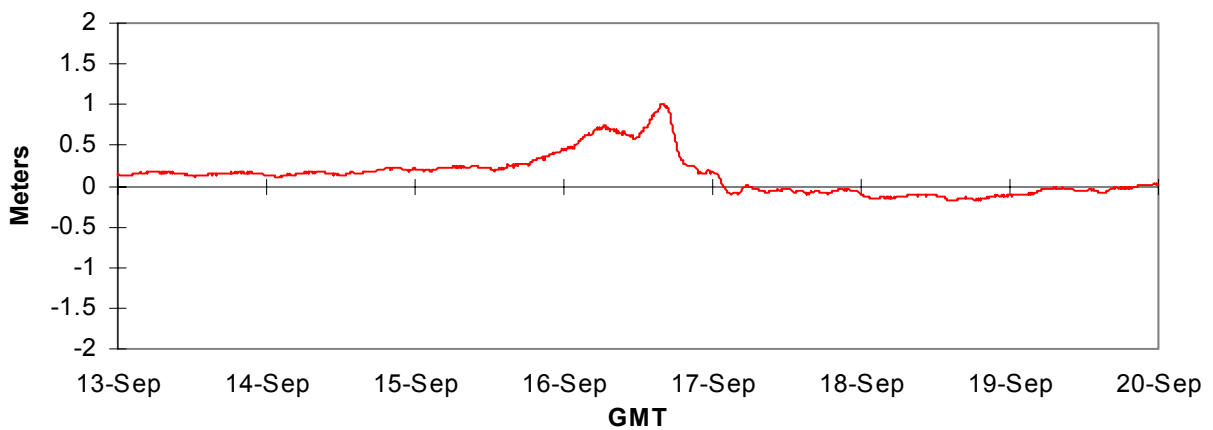
**Figure 99.** Cape Hatteras, NC storm surge.



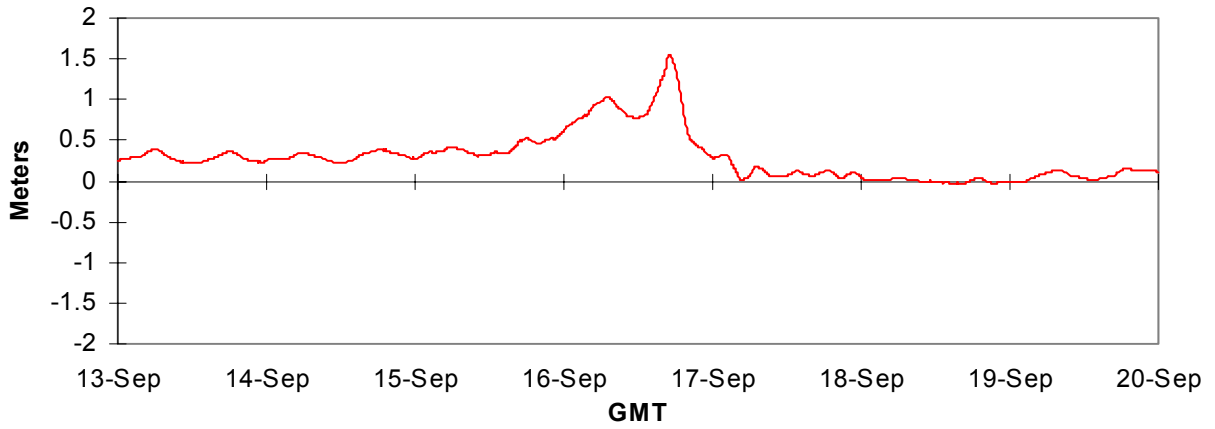
**Figure 100.** Oregon Inlet Marina, NC storm surge.



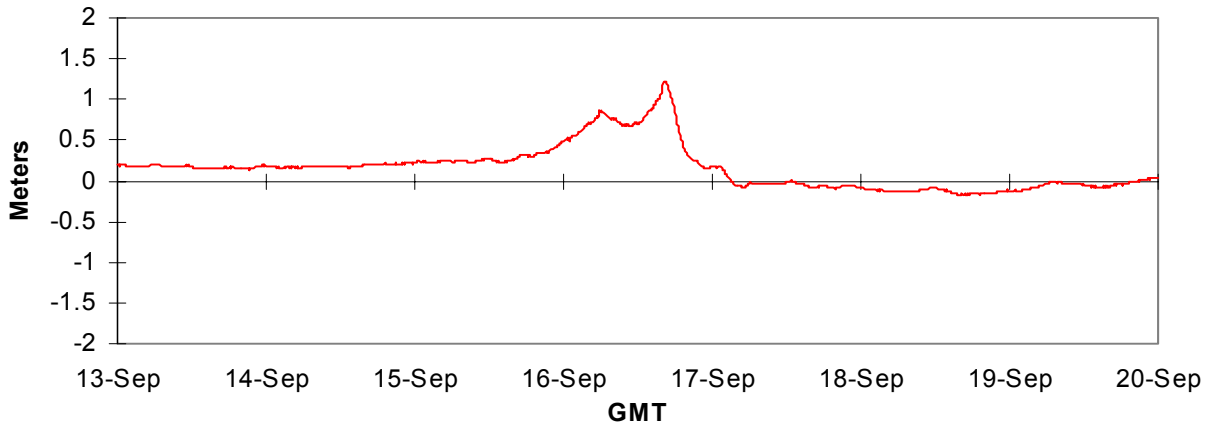
**Figure 101.** Duck Pier, NC storm surge.



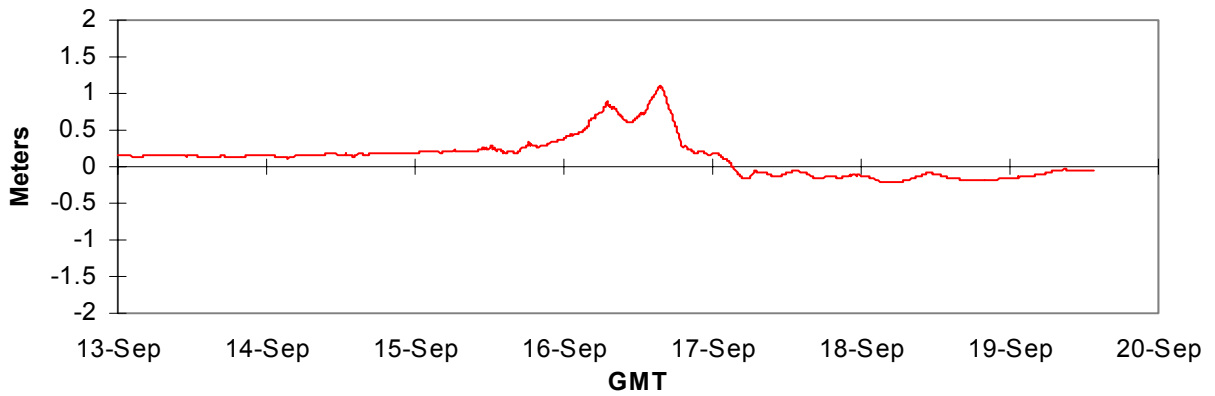
**Figure 102.** Chesapeake Bay Bridge Tunnel, VA storm surge.



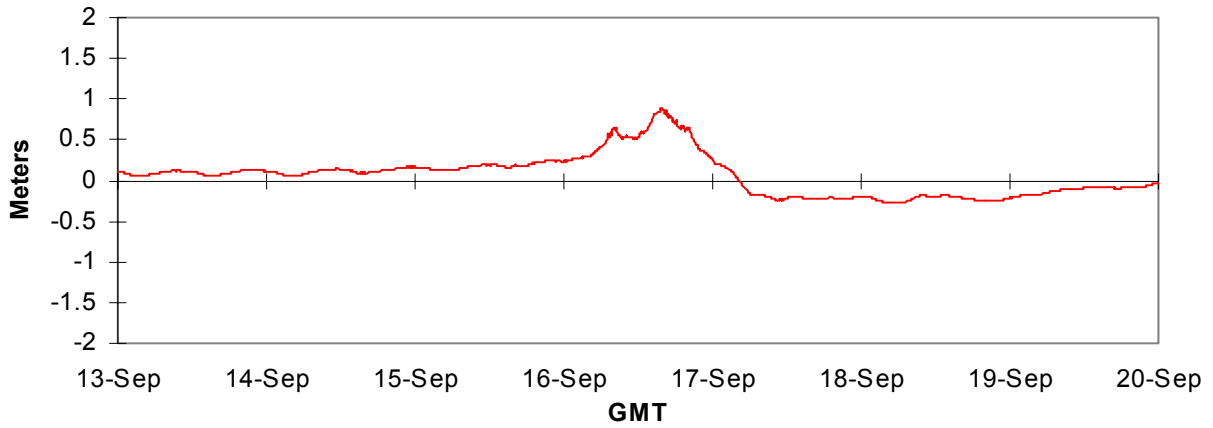
**Figure 103.** Money Point, VA storm surge.



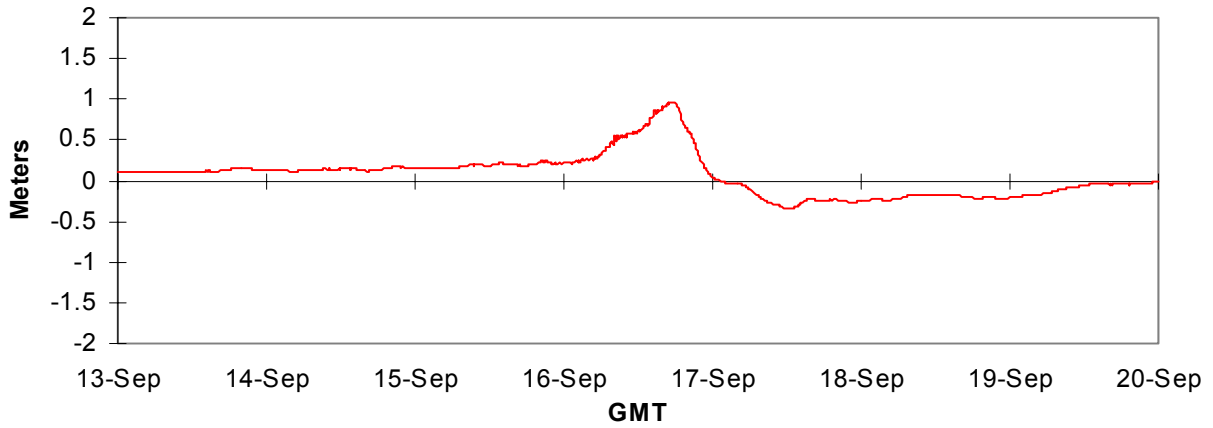
**Figure 104.** Hampton Roads, VA storm surge.



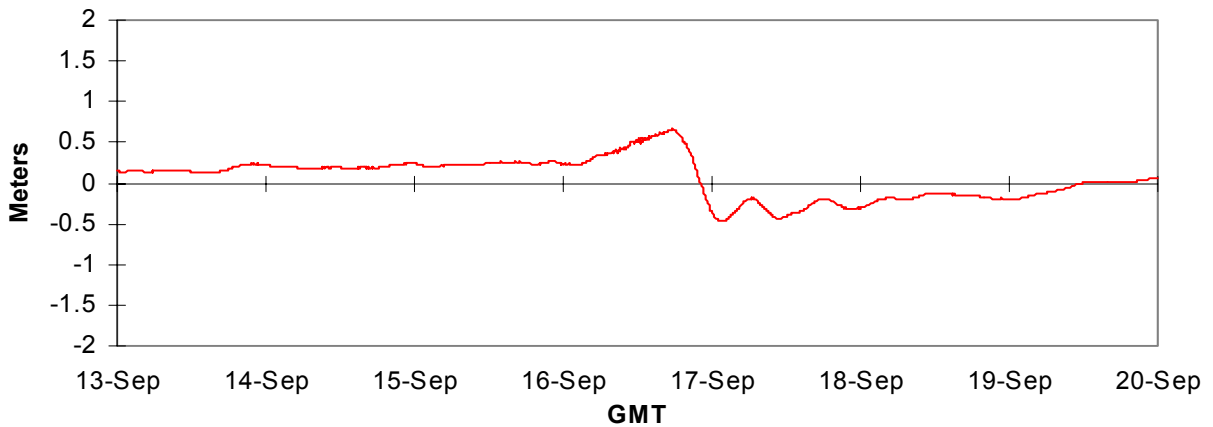
**Figure 105.** Gloucester Point, VA storm surge.



**Figure 106.** Windmill Point, VA storm surge.

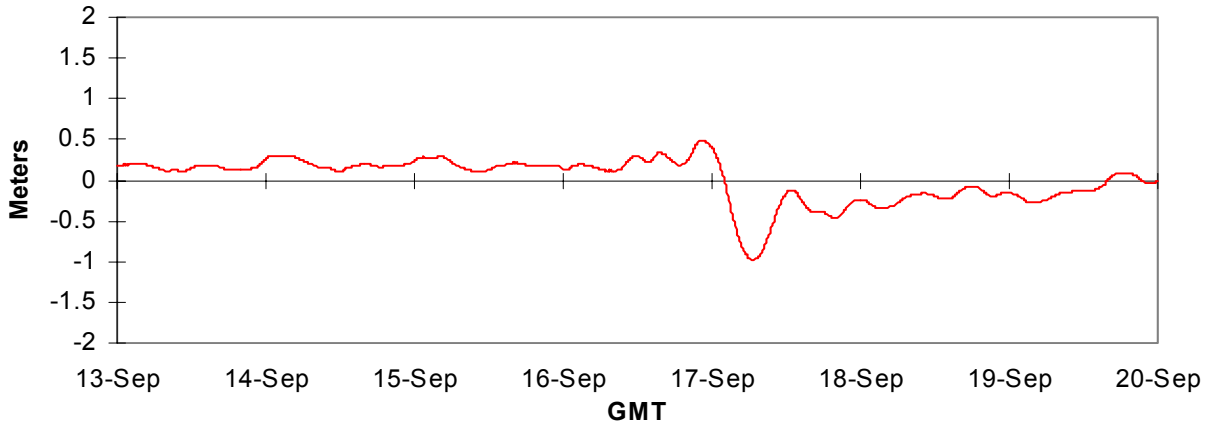


**Figure 107.** Lewisetta, VA storm surge.

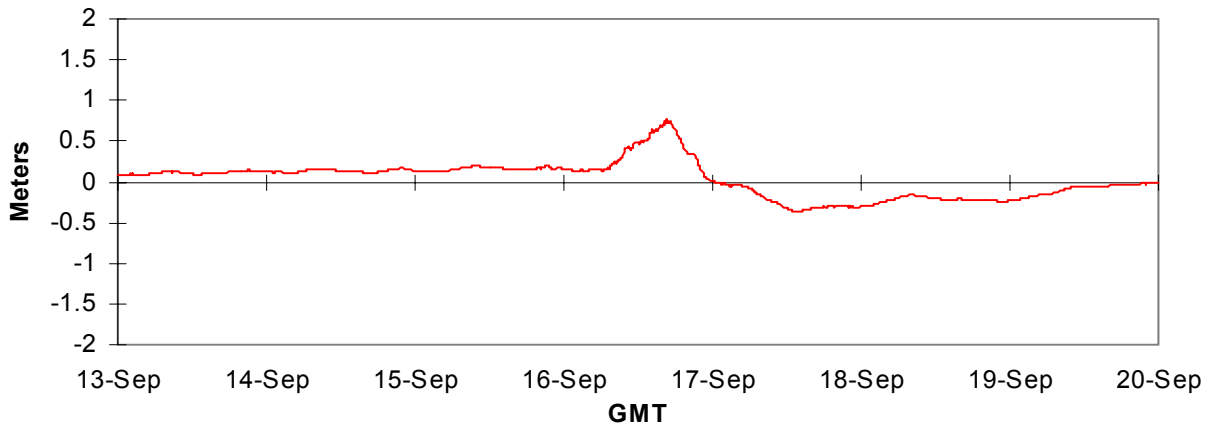


**Figure 108.** Colonial Beach, VA storm surge.

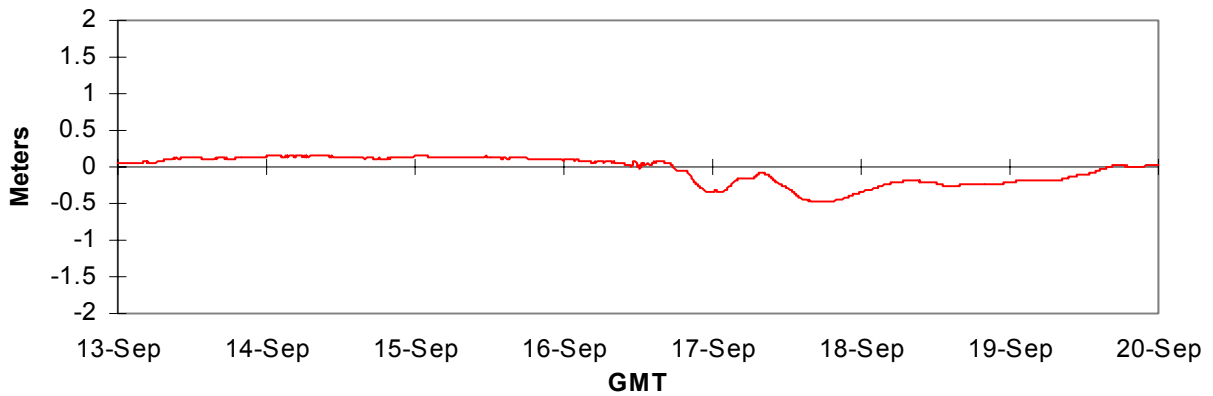




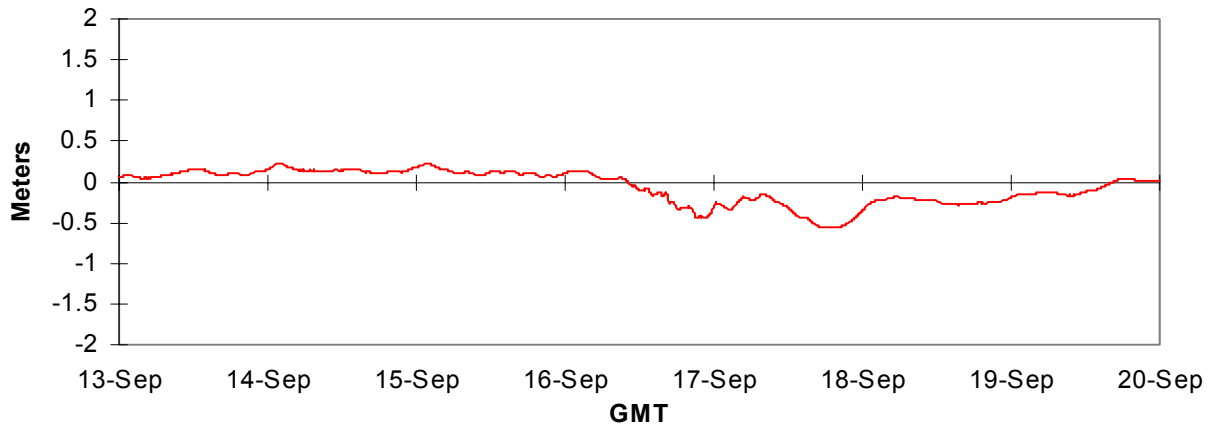
**Figure 109.** Washington, DC storm surge.



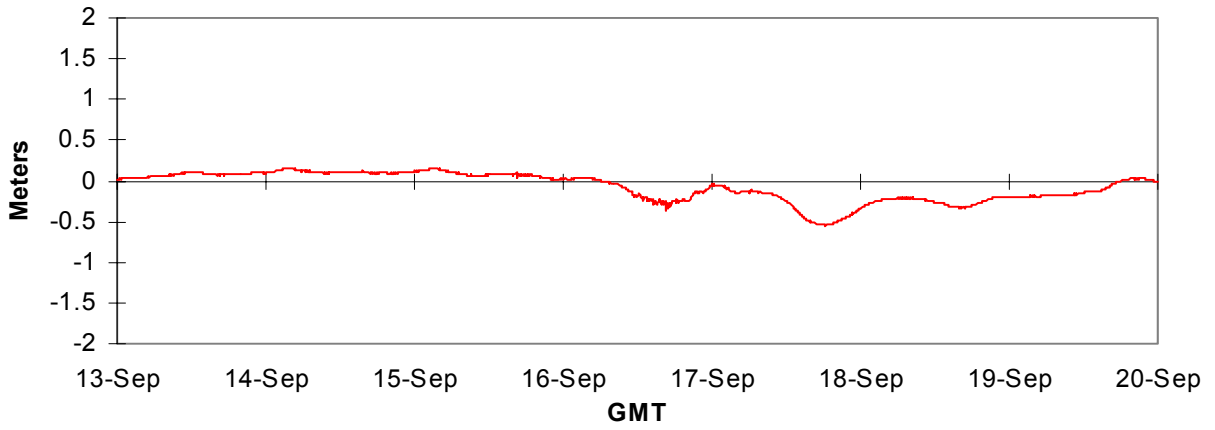
**Figure 110.** Solomons, MD storm surge.



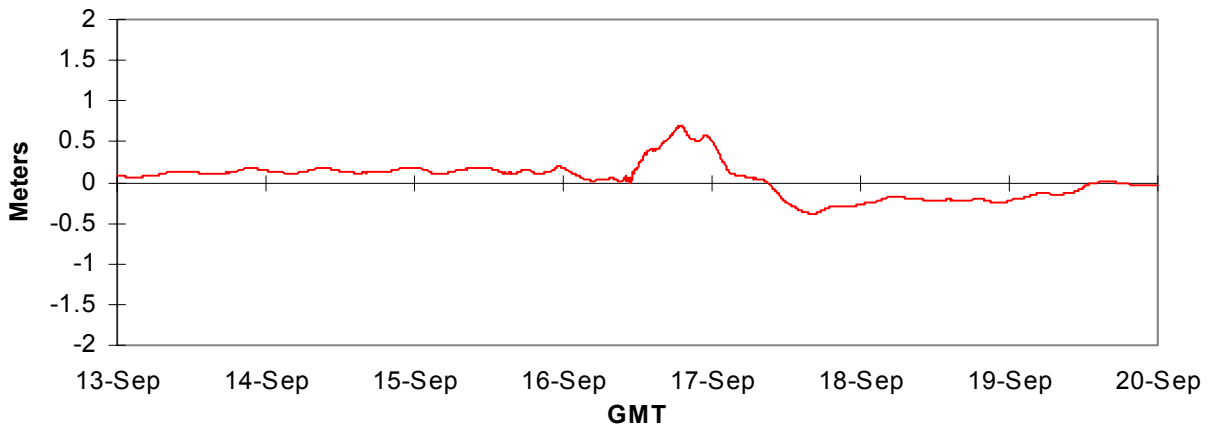
**Figure 111.** Annapolis, MD storm surge.



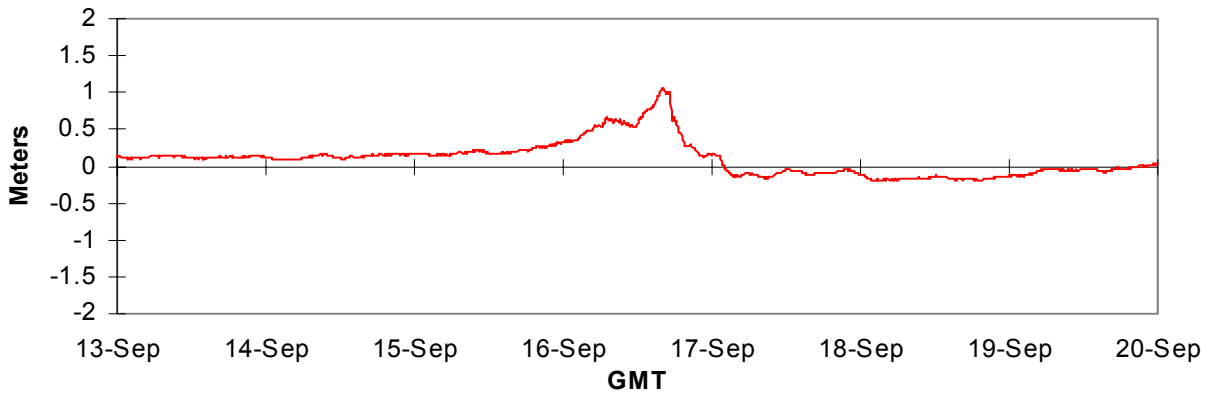
**Figure 112.** Baltimore, MD storm surge.



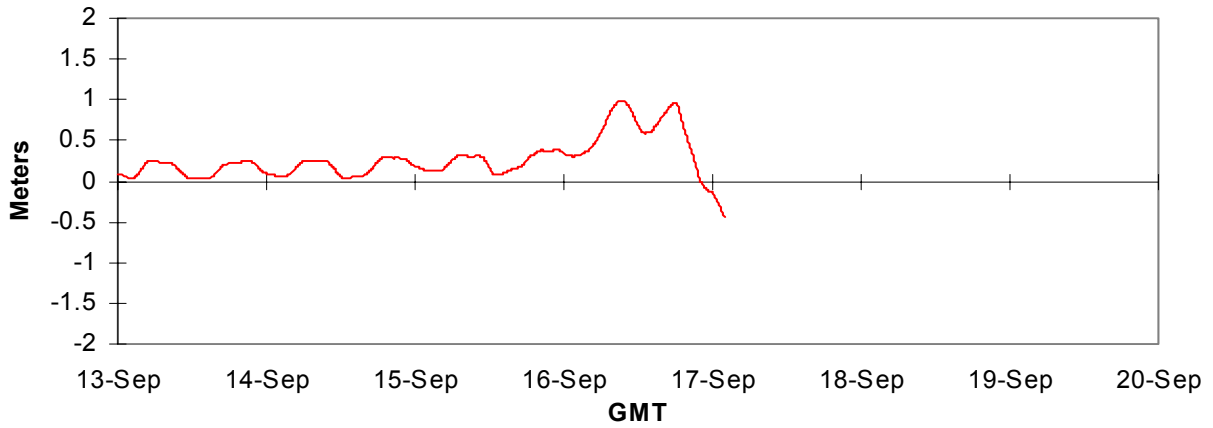
**Figure 113.** Tolchester Beach, MD storm surge.



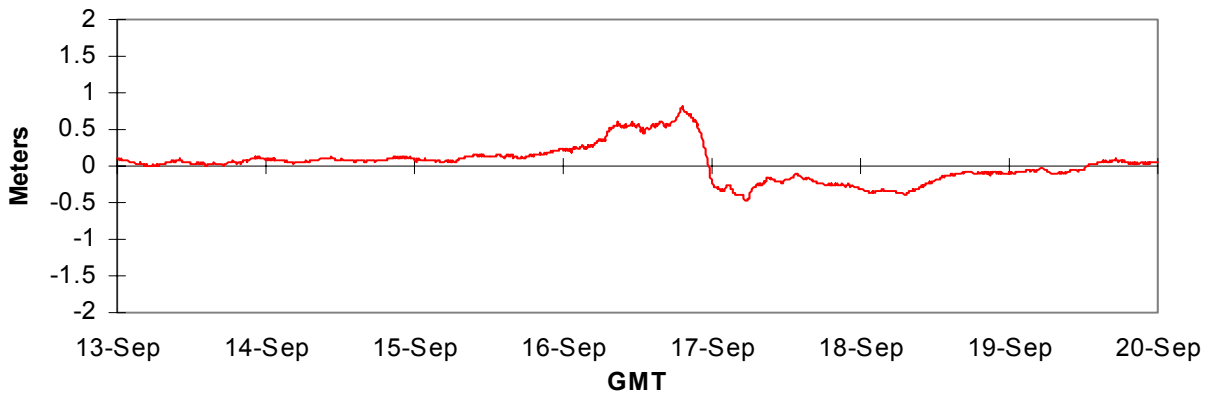
**Figure 114.** Cambridge, MD storm surge.



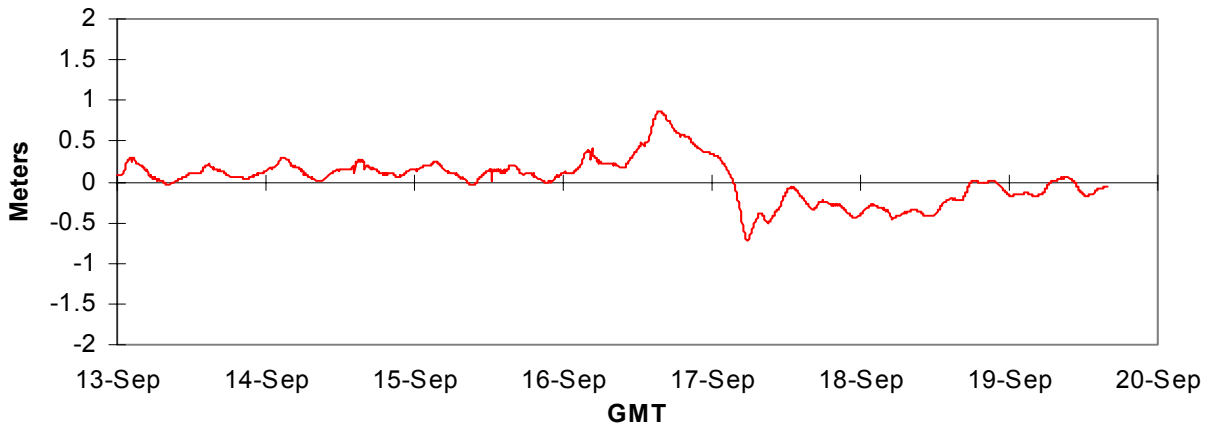
**Figure 115.** Kiptopeke Beach, VA storm surge.



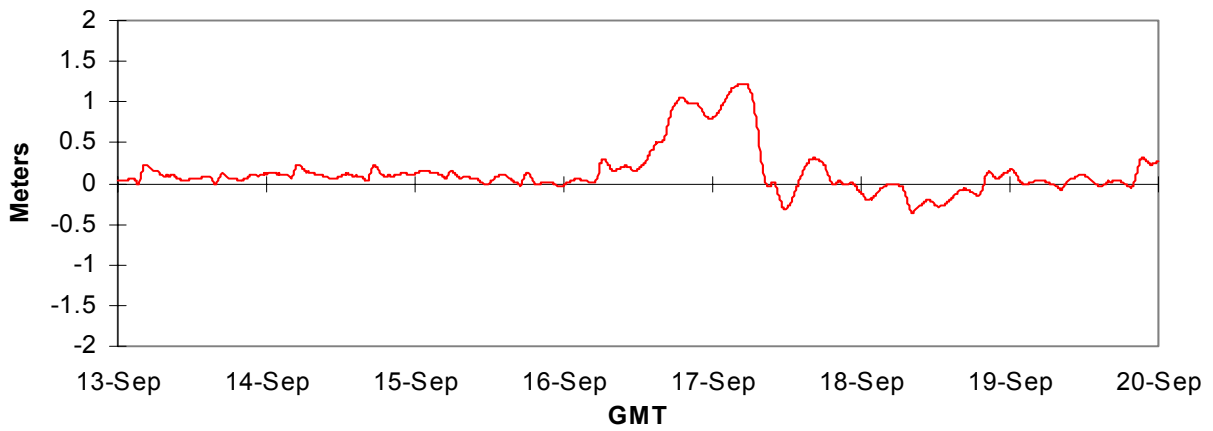
**Figure 116.** Wachapreague, VA storm surge.



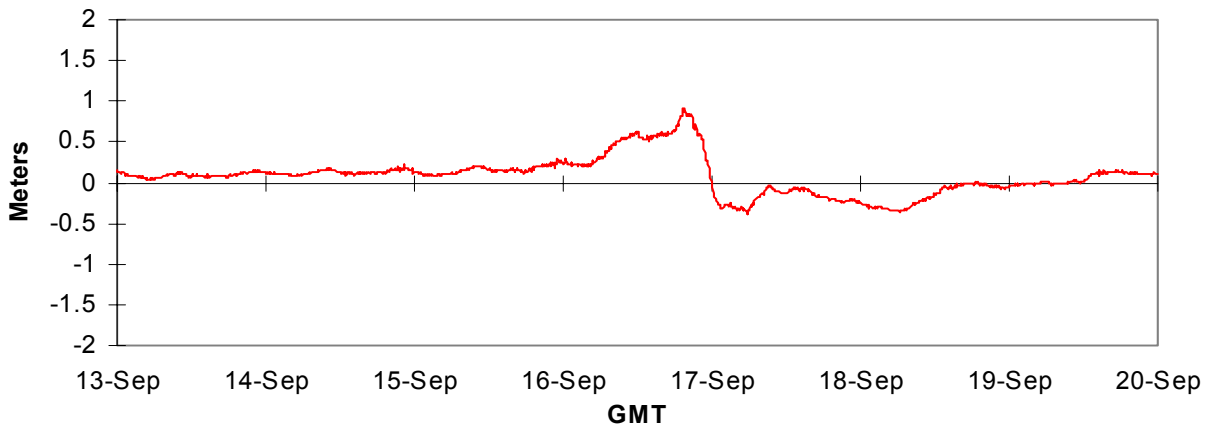
**Figure 117.** Lewes, DE storm surge.



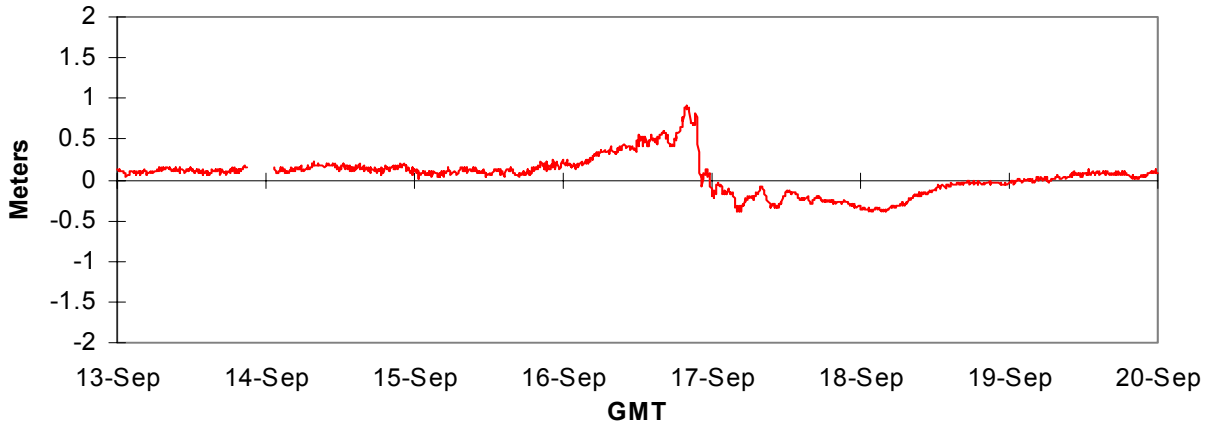
**Figure 118.** Reedy Point, DE storm surge.



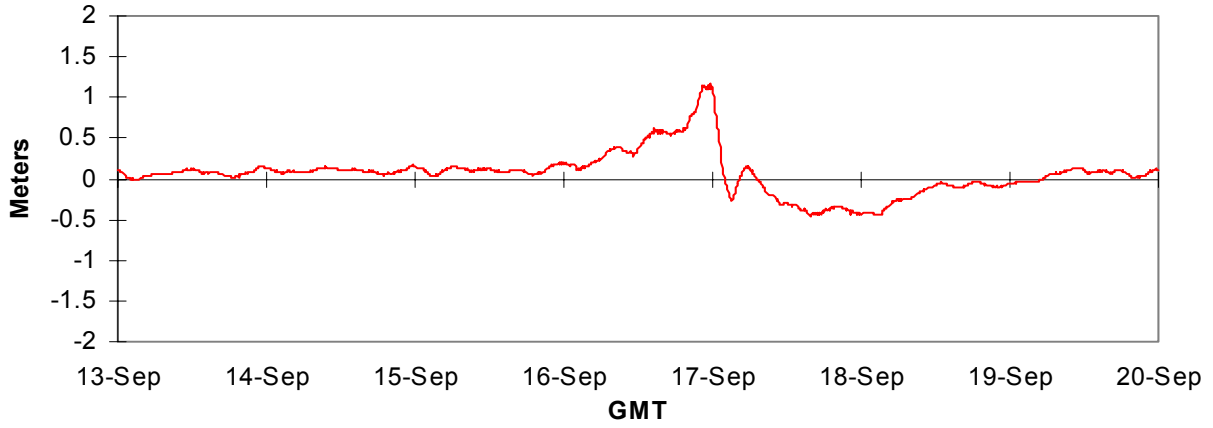
**Figure 119.** Philadelphia, PA storm surge.



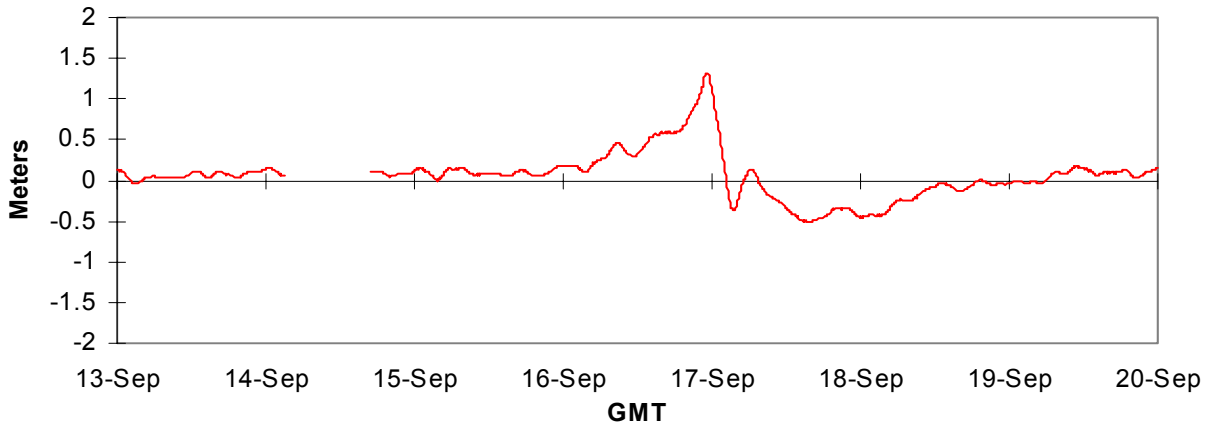
**Figure 120.** Cape May, NJ storm surge.



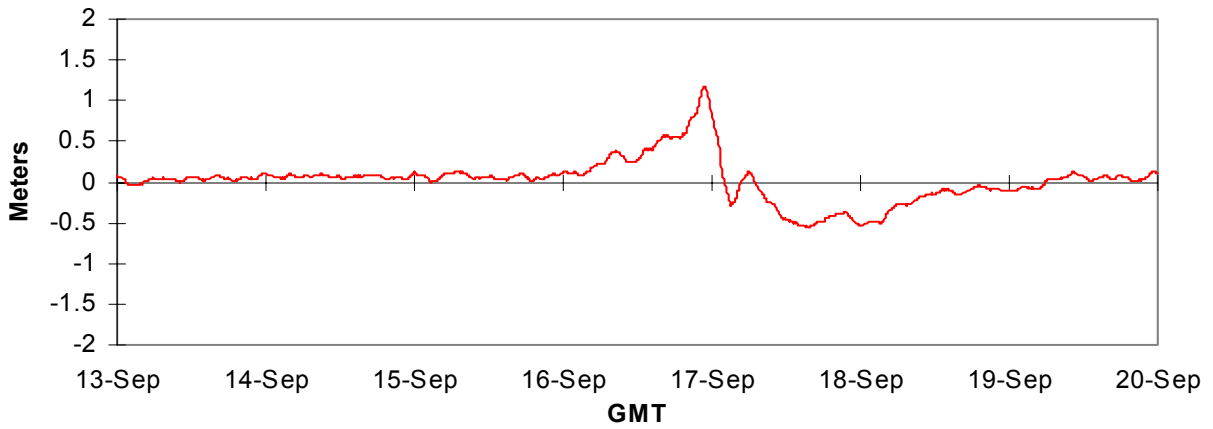
**Figure 121.** Atlantic City, NJ storm surge.



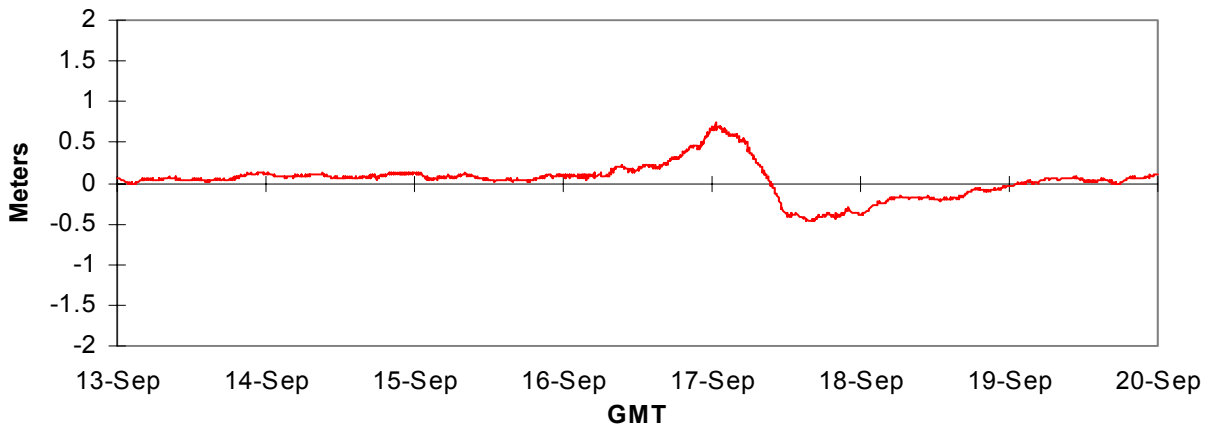
**Figure 122.** Sandy Hook, NJ storm surge.



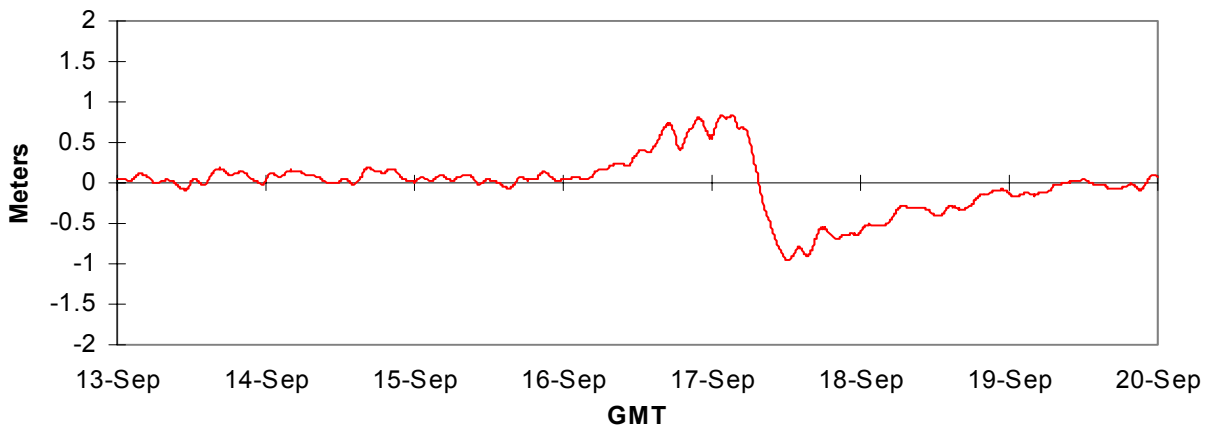
**Figure 123.** Bergen Point, NY storm surge.



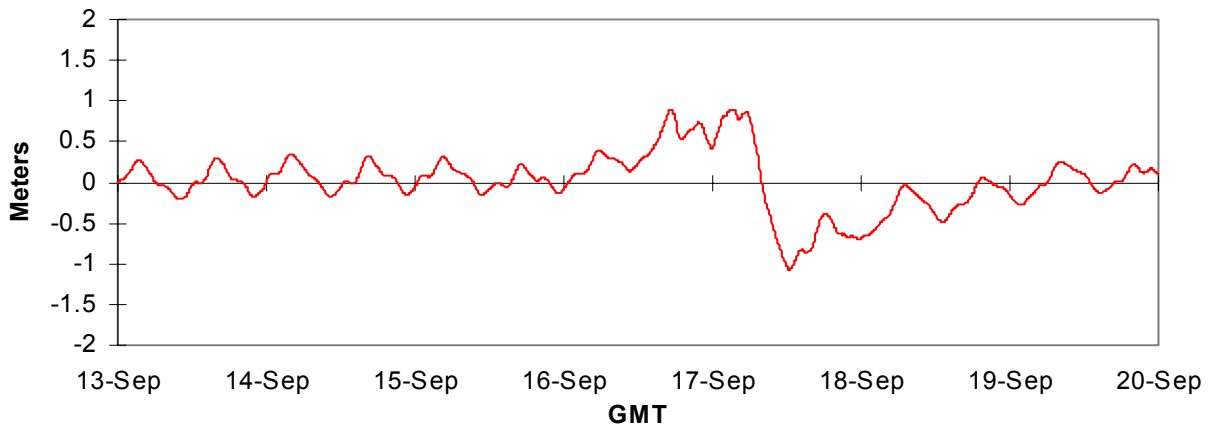
**Figure 124.** The Battery, NY storm surge.



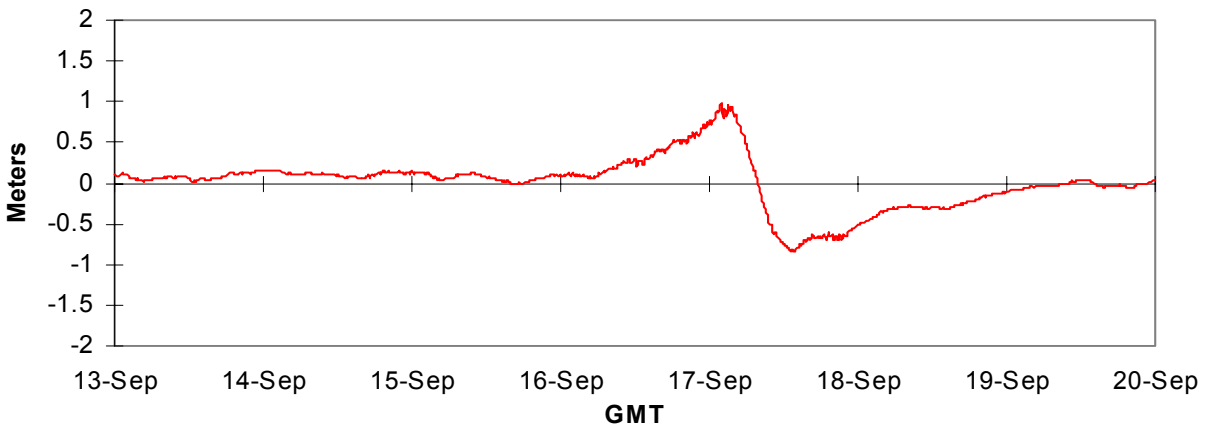
**Figure 125.** Montauk, NY storm surge.



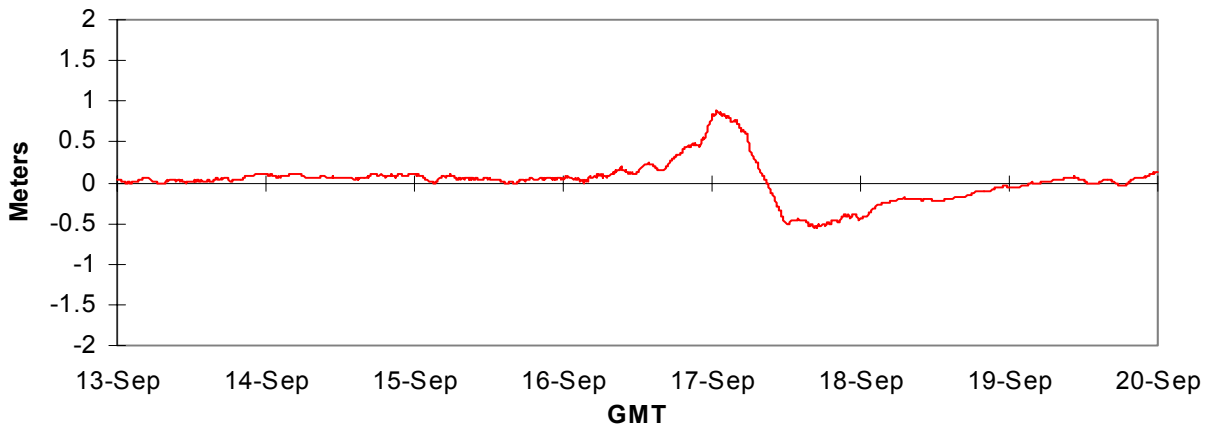
**Figure 126.** Willets Point, NY storm surge.



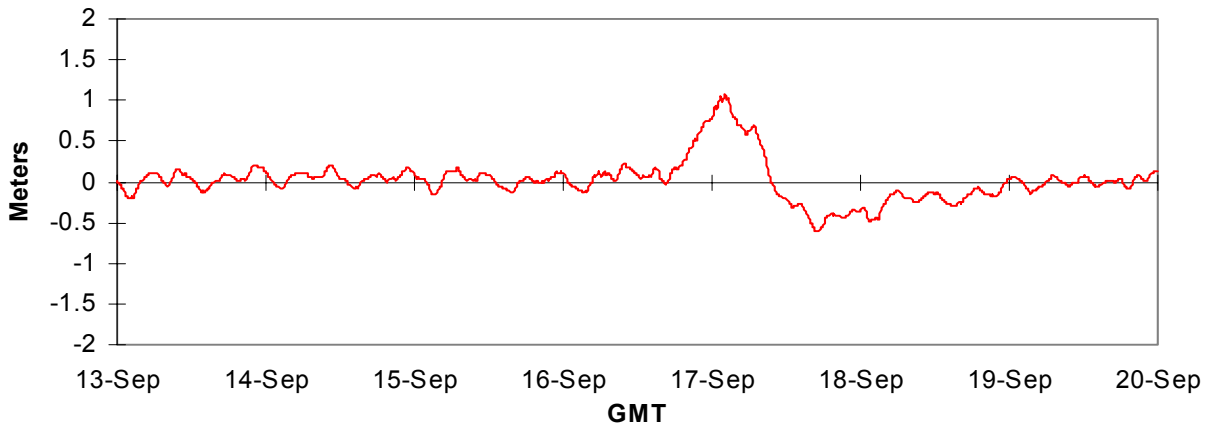
**Figure 127.** Kings Point, NY storm surge.



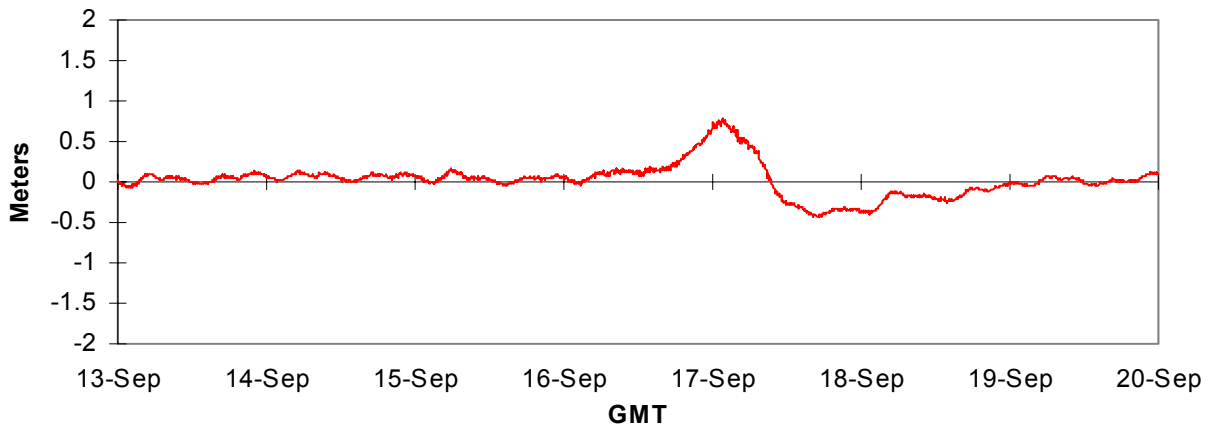
**Figure 128.** Bridgeport, CT storm surge.



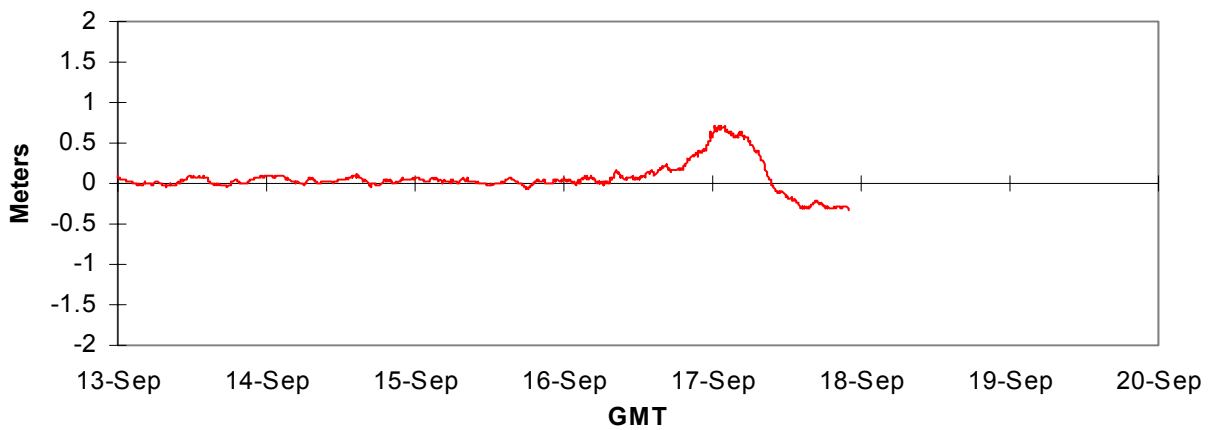
**Figure 129.** New London, CT storm surge.



**Figure 130.** Providence, RI storm surge.

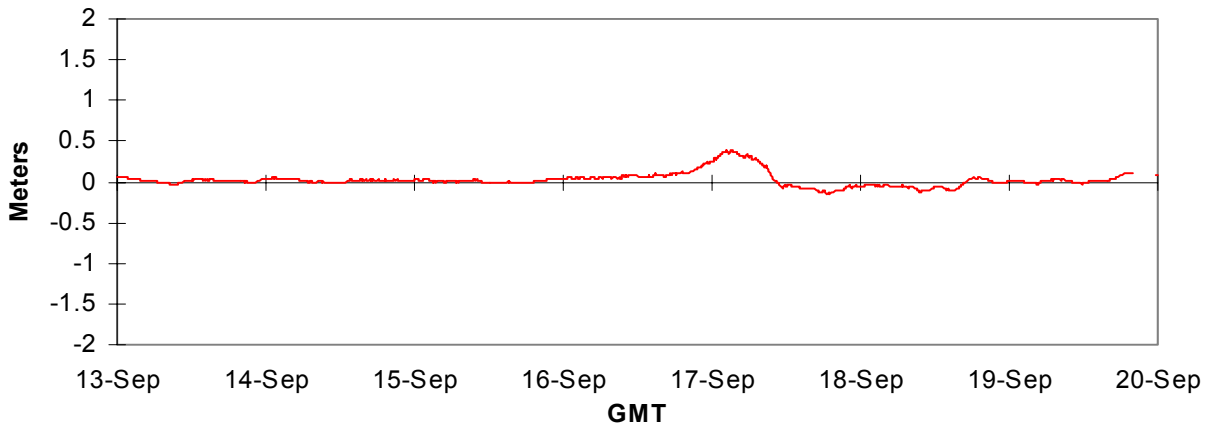


**Figure 131.** Newport, RI storm surge.

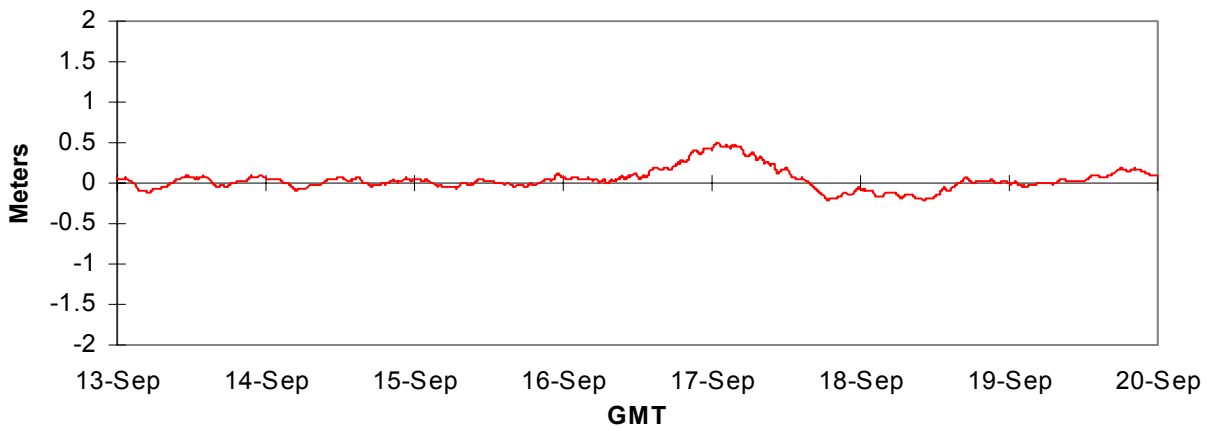


**Figure 132.** Woods Hole, MA storm surge.





**Figure 133.** Nantucket, MA storm surge.

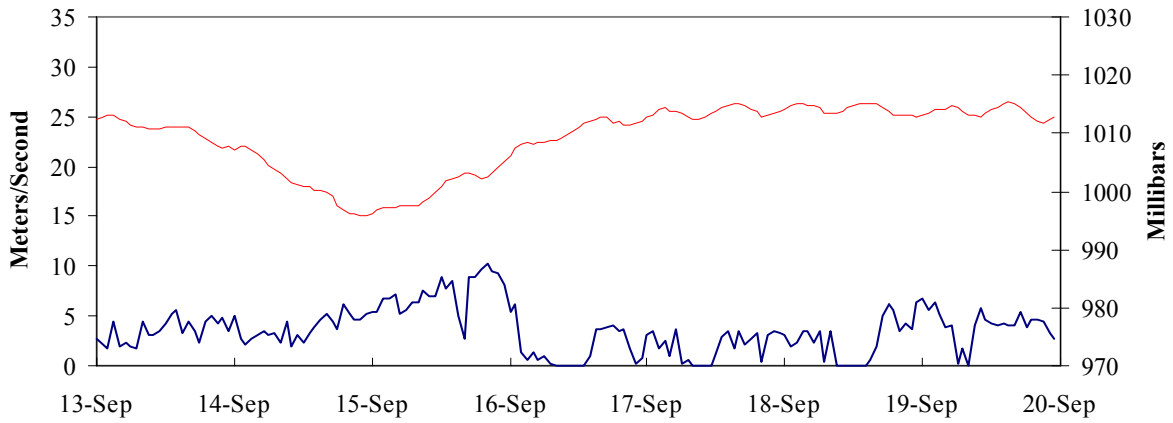


**Figure 134.** Boston, MA storm surge.

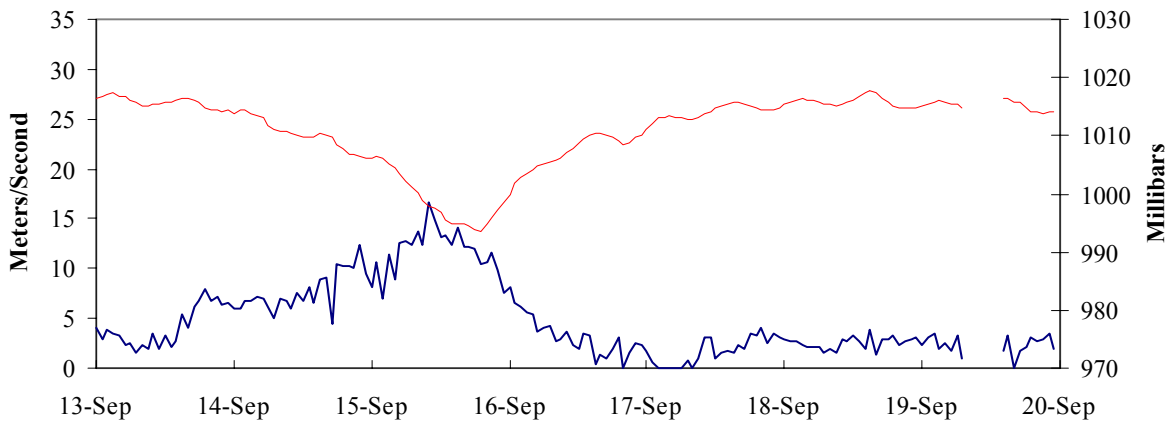


## **Appendix IV.**

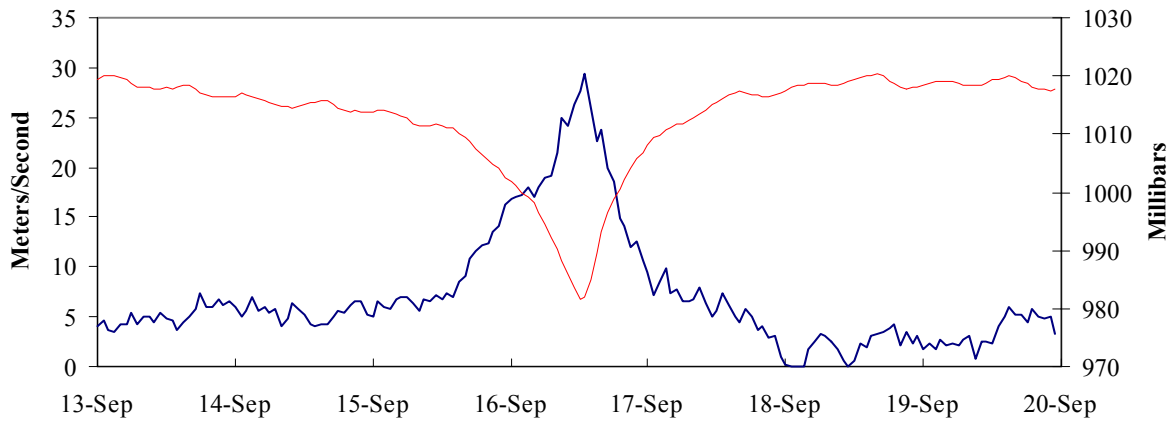
### **Time series of wind speed and barometric pressure at NWLON stations**



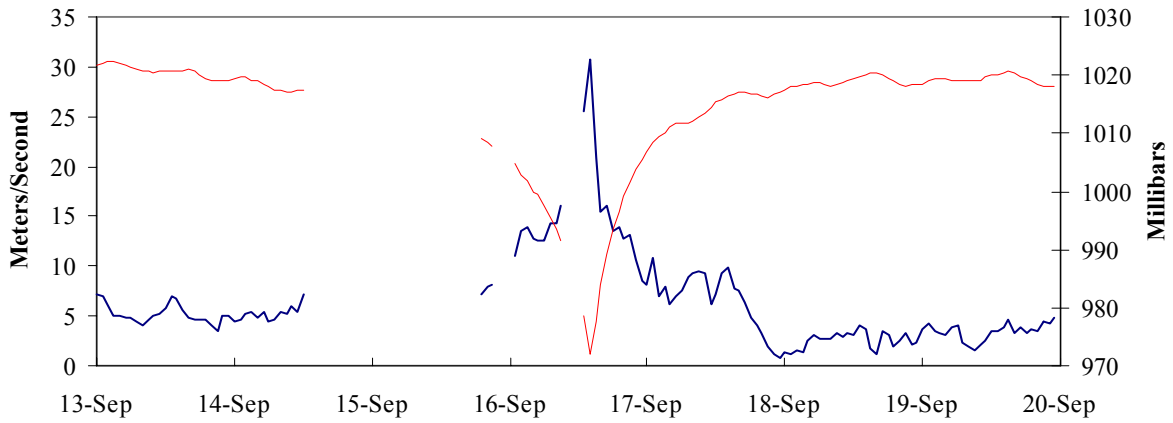
**Figure 135.** Virginia Key, FL wind speed (thick line) and barometric pressure (thin line).



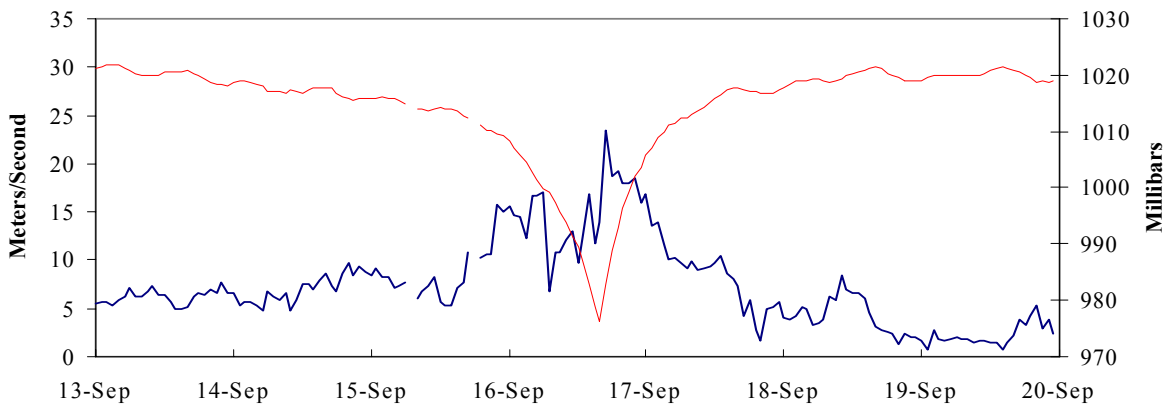
**Figure 136.** Mayport, FL wind speed (thick line) and barometric pressure (thin line).



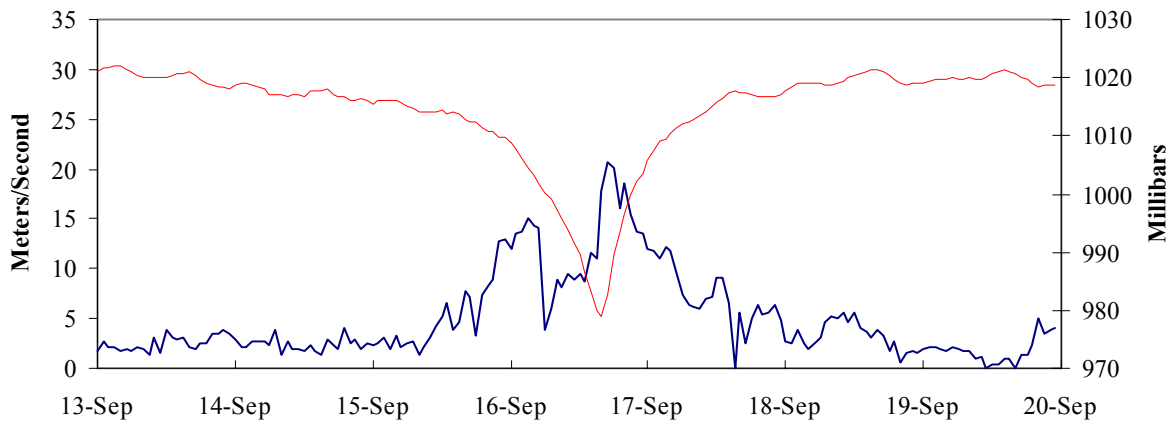
**Figure 137.** Cape Hatteras, NC wind speed (thick line) and barometric pressure (thin line).



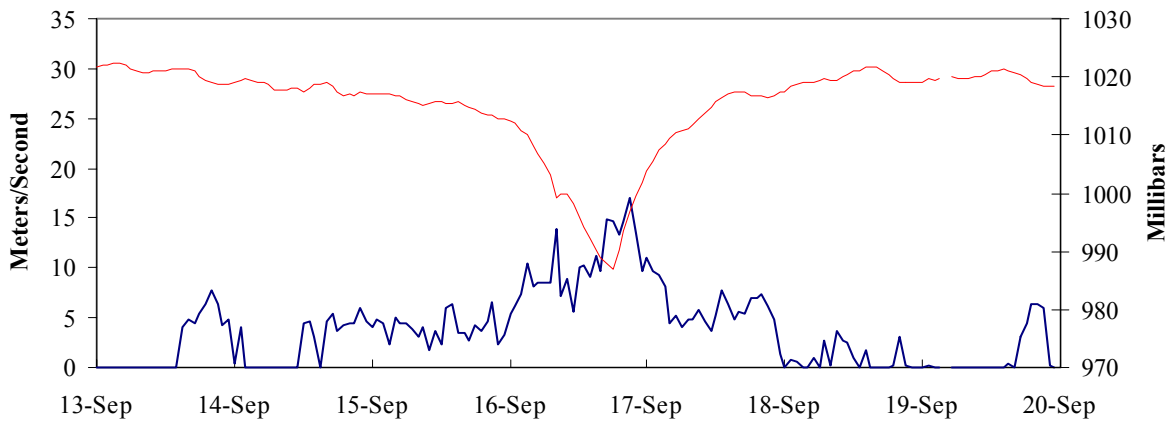
**Figure 138.** Duck Pier, NC wind speed (thick line) and barometric pressure (thin line).



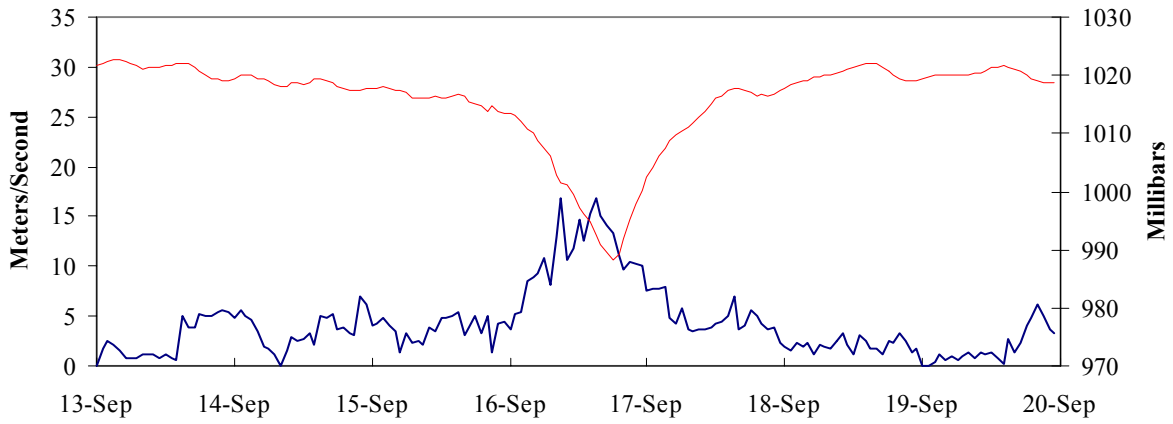
**Figure 139.** Chesapeake Bay Bridge Tunnel, VA wind speed (thick line) and barometric pressure (thin line).



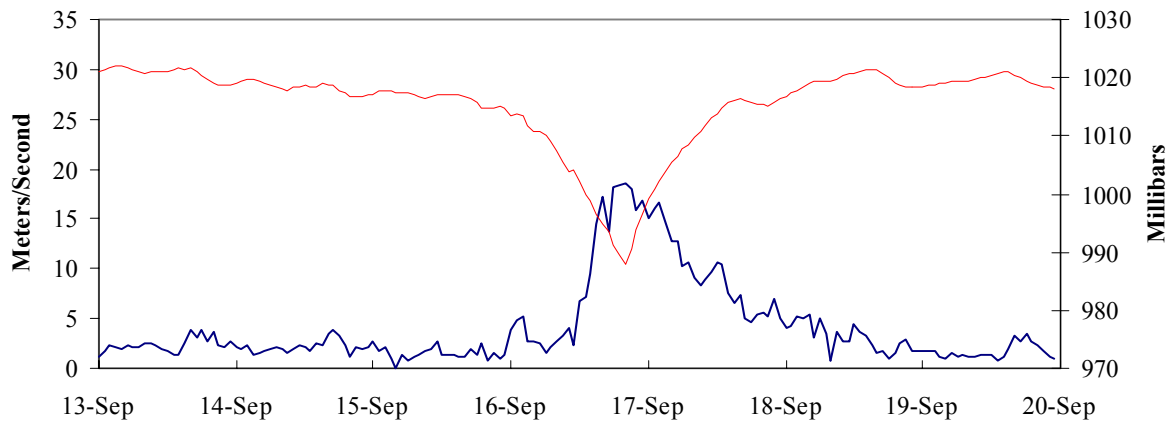
**Figure 140.** Hampton Roads, VA wind speed (thick line) and barometric pressure (thin line).



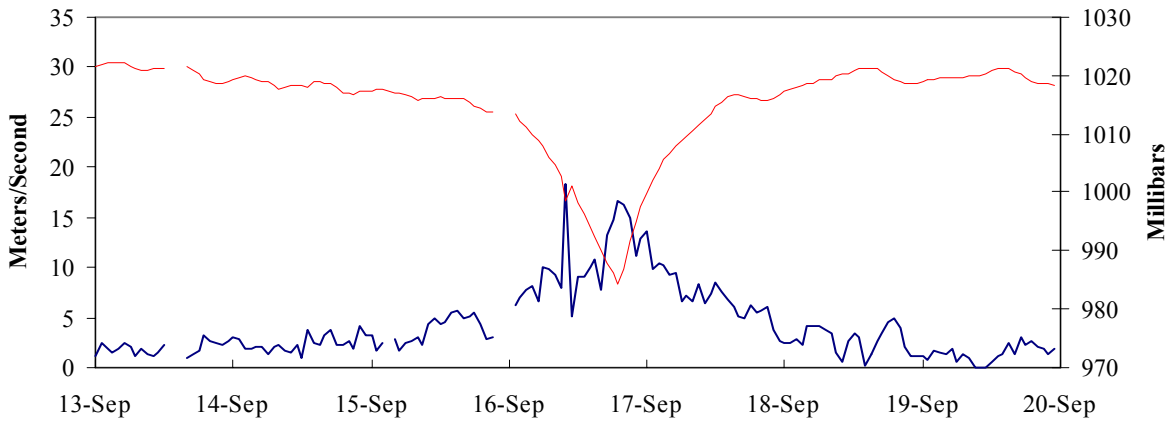
**Figure 141.** Lewisetta, VA wind speed (thick line) and barometric pressure (thin line).



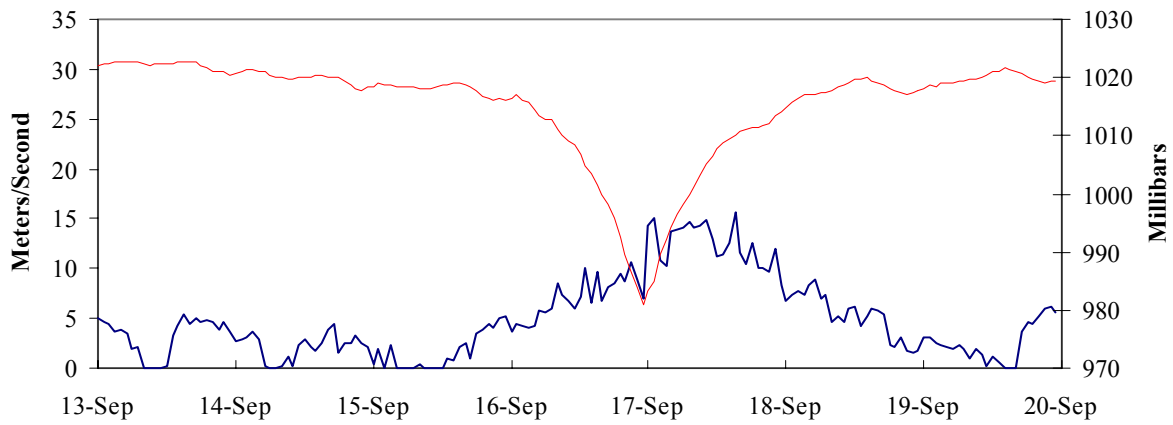
**Figure 142.** Solomons Island, MD wind speed (thick line) and barometric pressure (thin line).



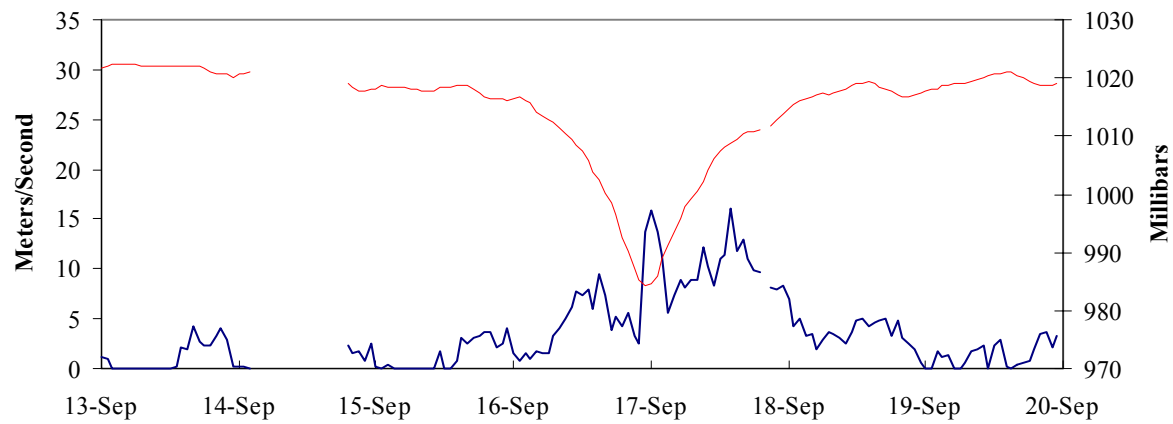
**Figure 143.** Tolchester Beach, MD wind speed (thick line) and barometric pressure (thin line).



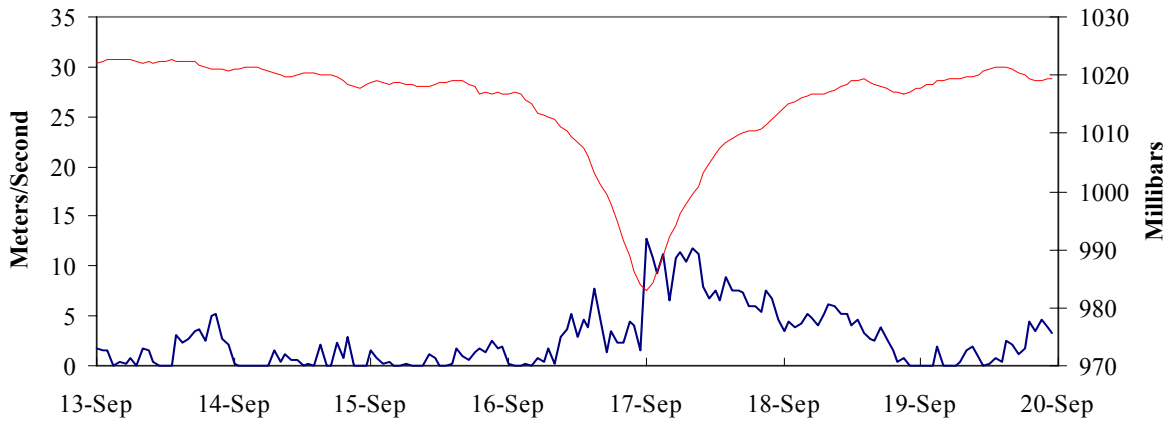
**Figure 144.** Cambridge, MD wind speed (thick line) and barometric pressure (thin line).



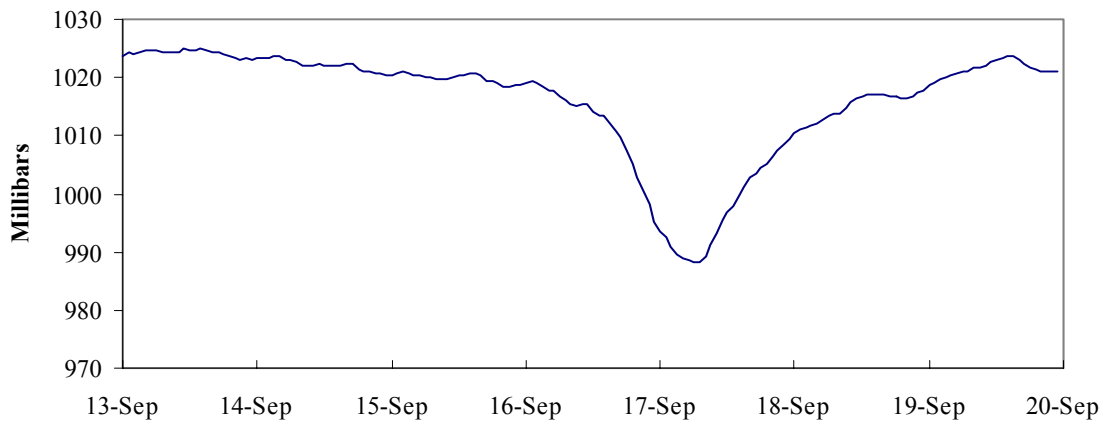
**Figure 145.** Sandy Hook, NJ wind speed (thick line) and barometric pressure (thin line).



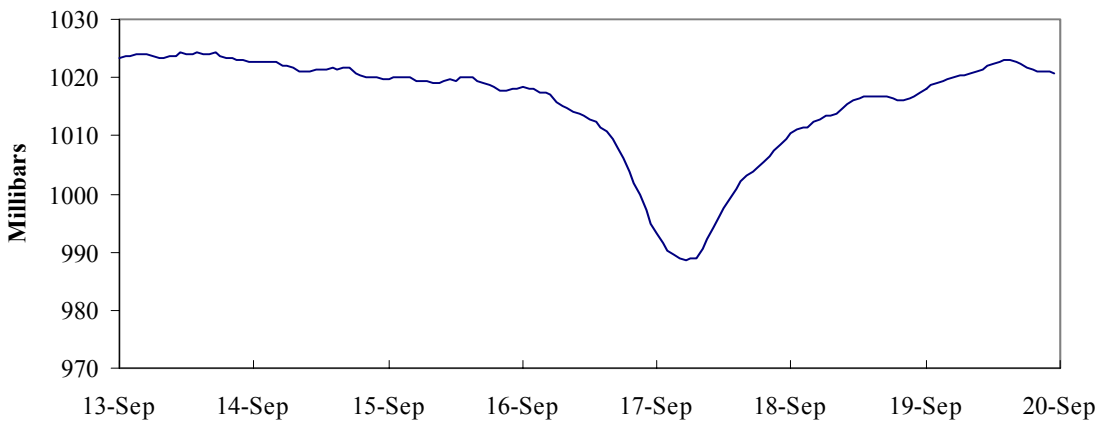
**Figure 146.** Bergen Point, NY wind speed (thick line) and barometric pressure (thin line).



**Figure 147.** Kings Point, NY wind speed (thick line) and barometric pressure (thin line).

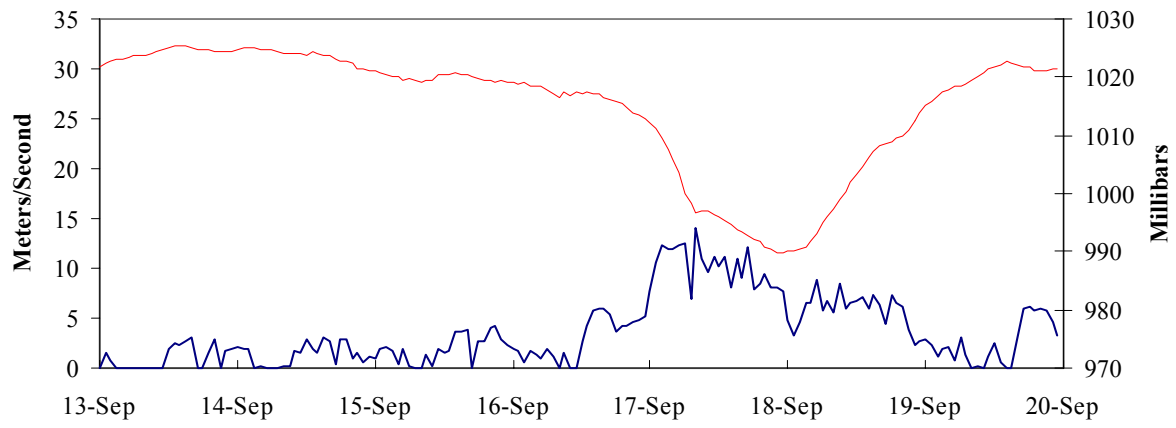


**Figure 148.** Providence, RI barometric pressure.



**Figure 149.** Newport, RI barometric pressure.





**Figure 150.** Eastport,ME wind speed (thick line) and barometric pressure (thin line).