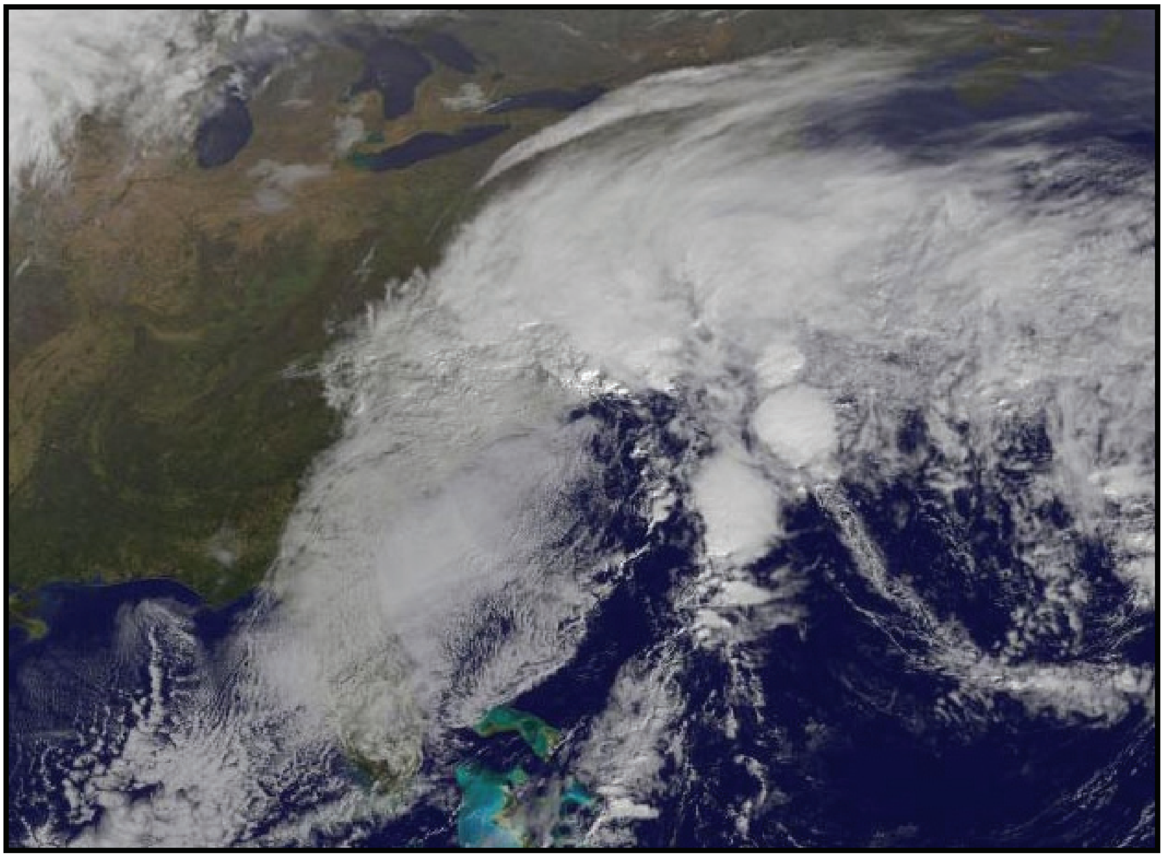
Technical Report NOS CO-OPS 056

Effects of the November 2009 Nor'easter on Water Levels



Silver Spring, Maryland
May 2010

noaa National Oceanic and Atmospheric Administration

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

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
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INTRODUCTION

The November 2009 Nor'easter, which impacted the East Coast from November 11 through 14, 2009, caused highly elevated water levels, especially in the Outer Banks, NC, the southern Chesapeake Bay region, Delaware Bay, and coastal New Jersey. This coastal low was especially damaging because of the long duration of sustained north and northeasterly winds that caused significant flooding and beach erosion. Thankfully, temperatures were still warm enough to spare coastal areas from a significant snow storm, as many Nor'easters are notorious for. As a result of the damage to coastal areas, the President declared counties in Virginia and New Jersey a major disaster after the storm to provide federal aid to communities.

The NOAA National Ocean Services (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) recorded the Nor'easter event via a network of water level and current meter stations. CO-OPS operates and maintains 210 water level stations as part of the National Water Level Network, as well as 21 Physical Oceanographic Real-Time Systems (PORTS®), each comprising from 1 to 40 individual oceanographic and meteorological stations. This large amount of coastal weather and water level data allowed CO-OPS to monitor the storm and provide the public and emergency officials with real-time data for their own monitoring and assessment.

This report compiles six-minute data from 22 NOS water level stations and 11 current meters (including 3 stations operated through Old Dominion University) from New Jersey to North Carolina to provide an overall view of the storm (Figure 1). Data referenced are water level, current speed and direction, winds (speed, direction and gust) and barometric pressure. Storm surge, which is the difference between the observed and astronomically predicted water levels, is computed for each station and is provided along with storm tide, defined as observed water level referenced to Mean Lower Low Water datum. Five stations measured record breaking water level elevations, slightly exceeding those measured during Hurricane Isabel in 2003. In fact, four stations in the Chesapeake Bay, where both Isabel and the Nor'easter made the biggest impact, measured higher storm surges during the Nor'easter.

The subsequent chapters of this report begin with a meteorological synopsis and then examine the data recorded at water level and current meter stations, as well as results from a CO-OPS Operational Forecast Model in the Chesapeake Bay. A comparison to water levels recorded during Hurricane Isabel relates the impact of the Nor'easter to a storm that had previously reset water level records at eight stations in the Chesapeake Bay. CO-OPS meteorological data collected at the water levels stations also supplement the oceanographic measurements in the Appendix. These different data types allow a holistic view of the storm's impact along the East Coast and also provide insight into the regional responses to the storm.

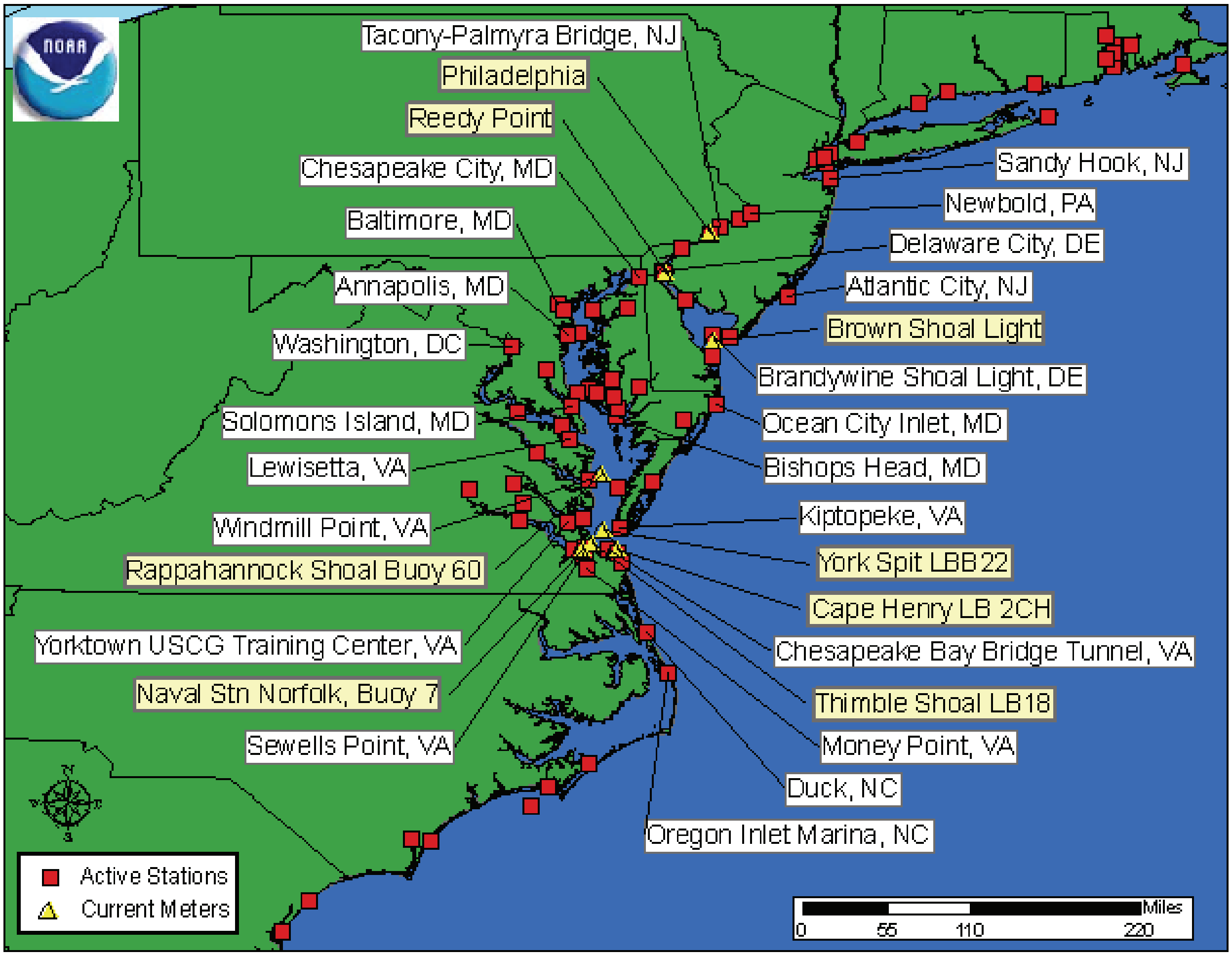
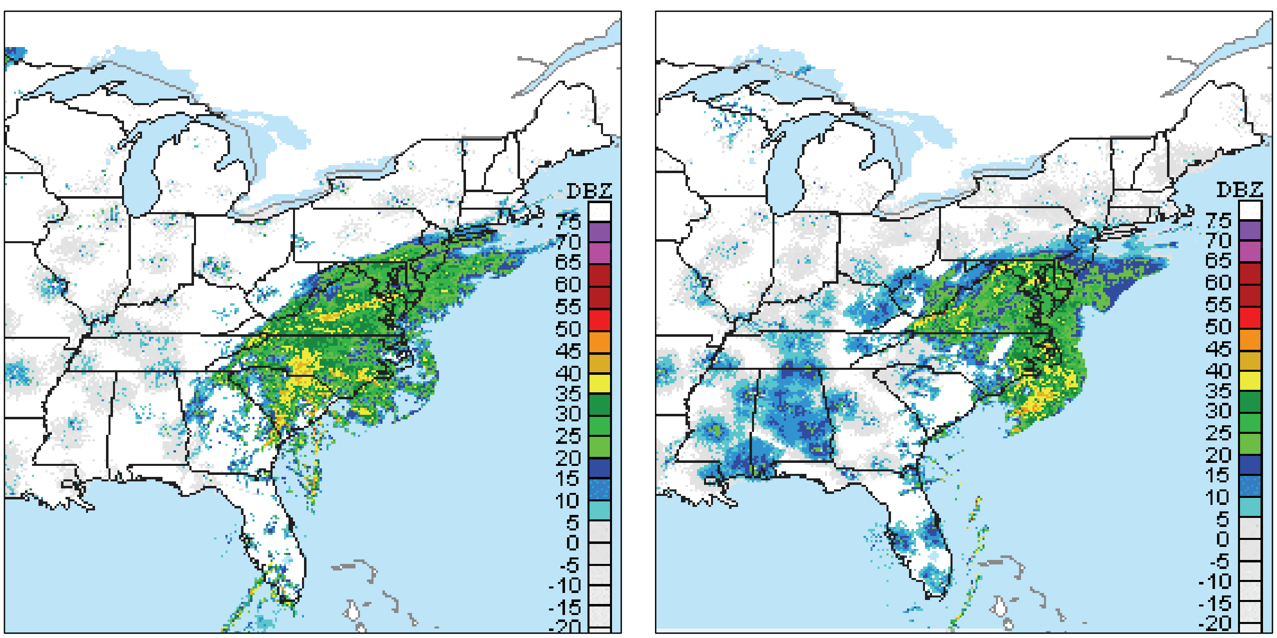


Figure 1: CO-OPS water level stations (red) and current meter stations (yellow). Labeled stations are used in this report. All stations are part of the NOS/PORTS® and/or NWLON programs.

1.0 BACKGROUND METEOROLOGICAL INFORMATION AND SYNOPTIC OVERVIEW

On November 10, 2009, Tropical Storm Ida made landfall at Dauphin Island, AL and weakened into a low pressure system. Ida's remnants crossed over the southeast US, weakening and losing all tropical characteristics. The system redeveloped off coastal Carolina in the Atlantic Ocean. The resulting coastal low became the November 2009 Nor'easter that affected the Mid-Atlantic region of the eastern US, as seen in the surface analysis plots throughout this chapter. This low, combined with an unusually strong Canadian high over New England resulted in a strong pressure gradient over Coastal Virginia and the Carolinas. This tight pressure gradient resulted in a concentrated area of strong northeasterly winds to develop and remain throughout the storm, causing high waves and record high water levels.

On November 11 at 12:00 GMT, the low pressure center was situated over southern Georgia with a central barometric pressure of 1005 mb. A large high pressure system that stretched across New England and the Great Lakes with a barometric pressure of 1036 mb caused a stationary front across the coast of the Carolinas. The Nor'easter, which was slow moving, created the potential for a large storm surge as a result of the constant, strong winds. Radar images of the first 12 hours of the storm are shown in Figure 1.1 below, illustrating the slow movement of the storm system. Figure 1.2 illustrates how the winds channeled from the northeast towards the Chesapeake Bay along the east coast, with speeds peaking between 20 and 25 kt. Time-series plots of winds in the Appendix also show that throughout the day the directions shifted northeasterly and speeds increased dramatically, especially at the mouth of the Chesapeake and Delaware Bays. Light rain was reported in Maryland, New Jersey and Philadelphia, and moderate rain was reported in Virginia (Figures 1.2 and 1.3).



November 11 12:00 GMT November 12 00:00 GMT

Figure 1.1. Radar imagery during the November Nor'easter. Courtesy: NOAA/National Climatic Data Center (NCDC).

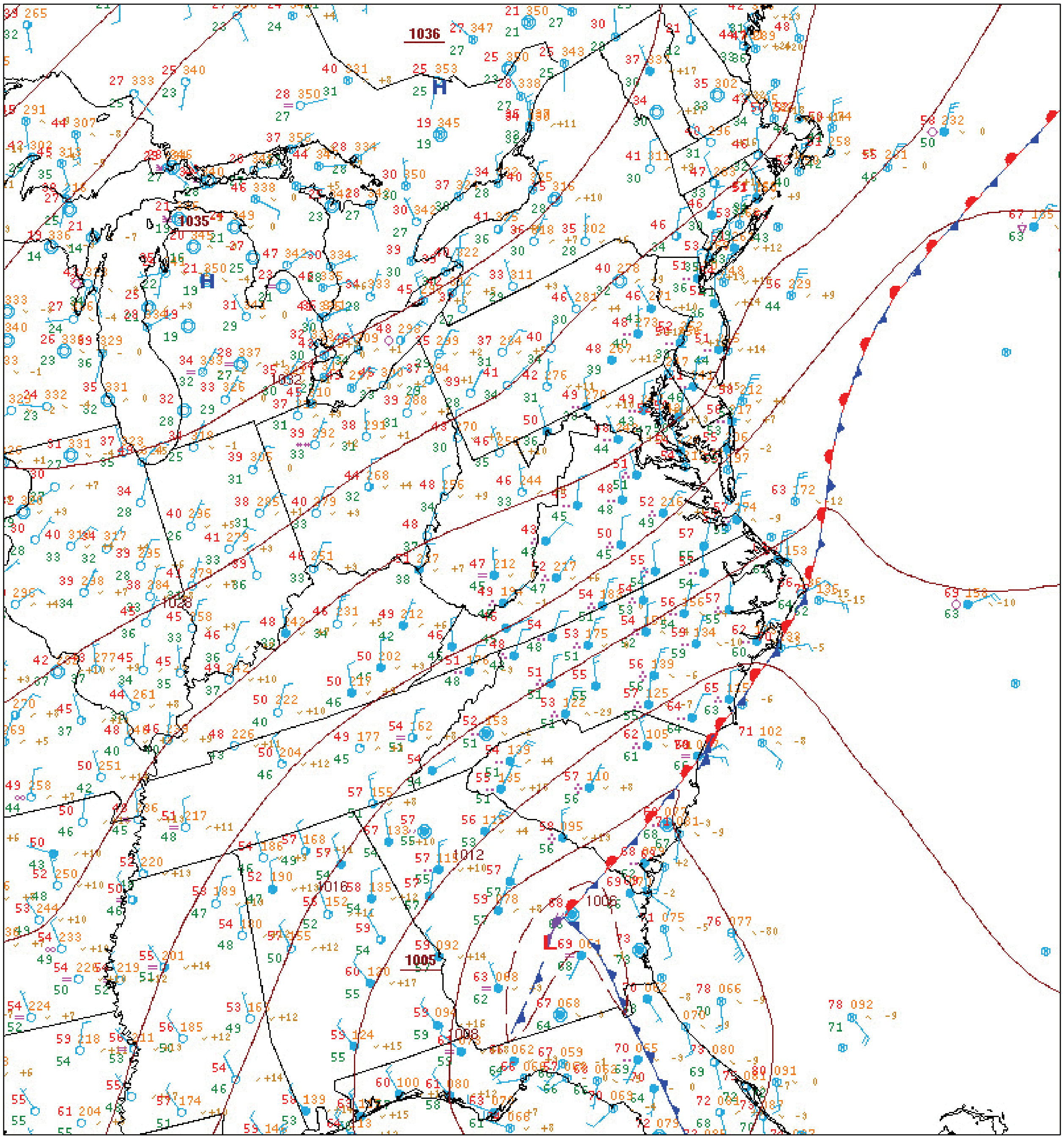


Figure 1.2. East Coast surface analysis on November 11 12:00 GMT. Courtesy: NOAA/NWS/ HPC.

An example of how to read a station plot can be found on the National Weather Service Hydrometeorological Prediction Center website: http://www.hpc.ncep.noaa.gov/html/stationplot.shtml

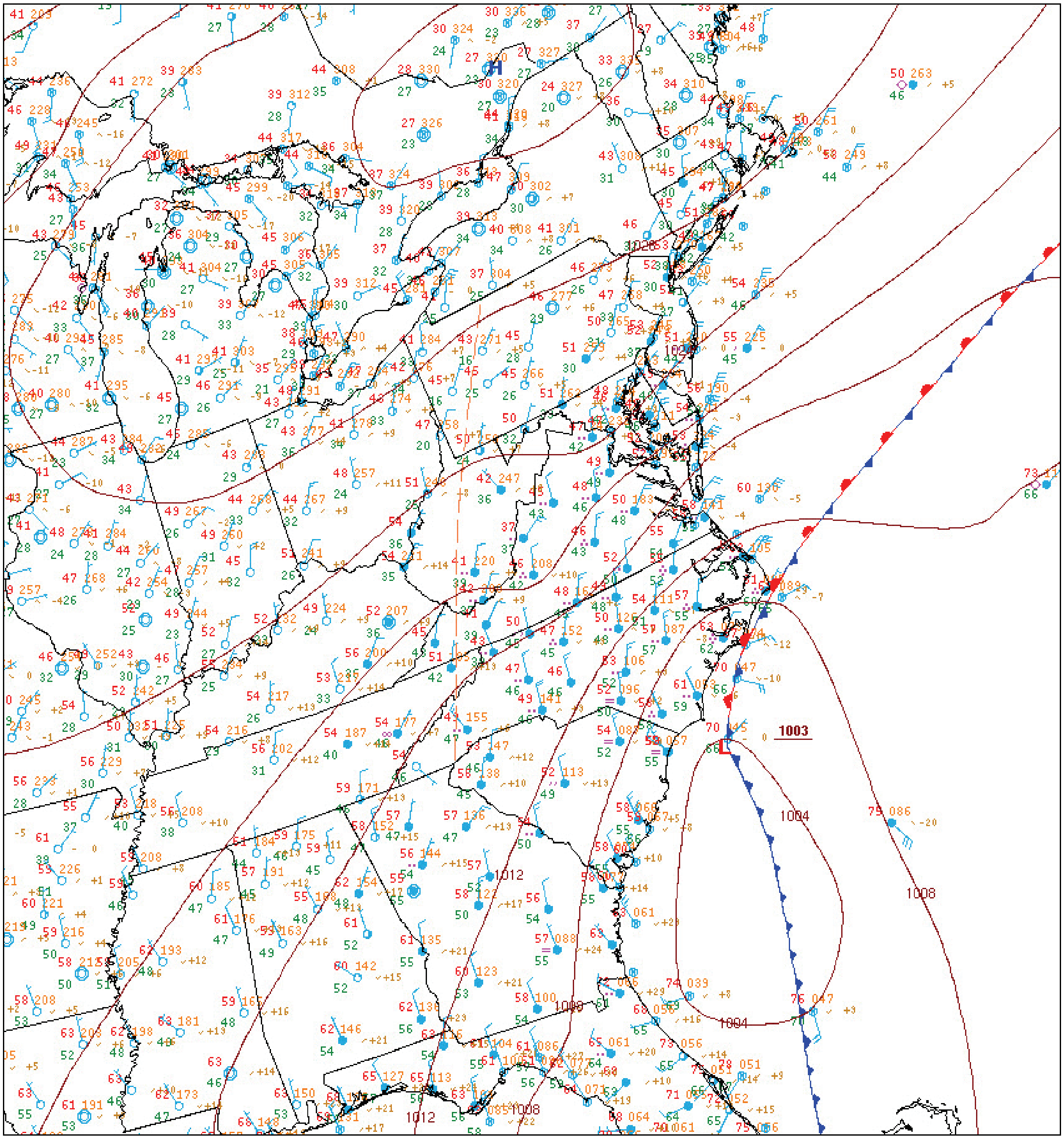


Figure 1.3. East Coast surface analysis on November 12 00:00 GMT. Courtesy: NOAA/NWS/ HPC.

By November 12, 12:00 GMT, the low had slowly advanced northeast along the eastern shore of North Carolina and deepened to 992 mb, the storm's minimum pressure (Figure 1.4). At this time, the center of the high had continued to advance to the east and was situated over Vermont. The position of the low created a tighter pressure gradient, resulting in stronger northeasterly winds. Wind speeds were consistently over 30 kt throughout the lower Chesapeake Bay and off the coast of New Jersey. Rainfall became heavy in Virginia and southern Maryland during the previous 12 hours with radar images showing the location of the heaviest rain (Figure 1.5), with

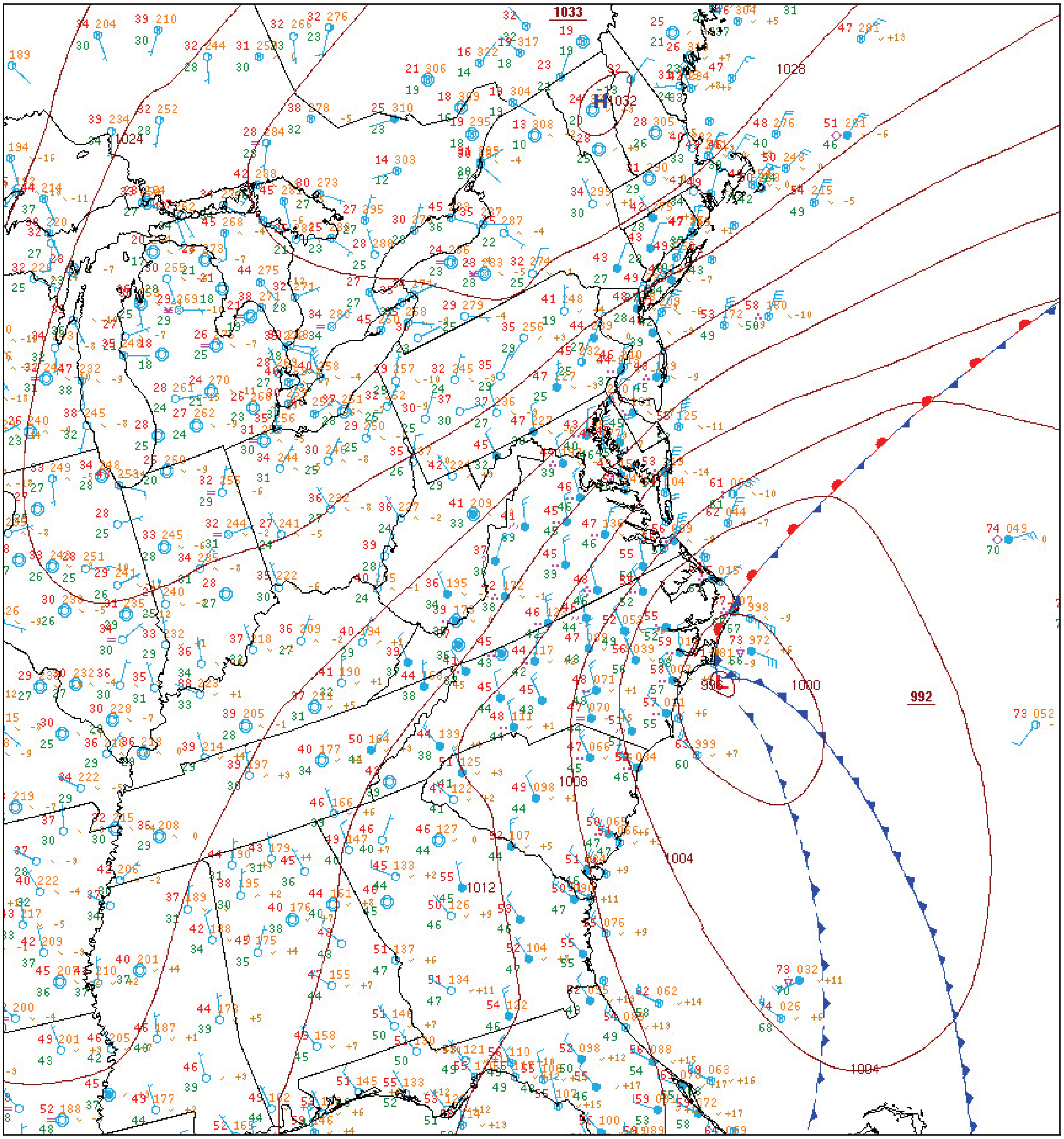
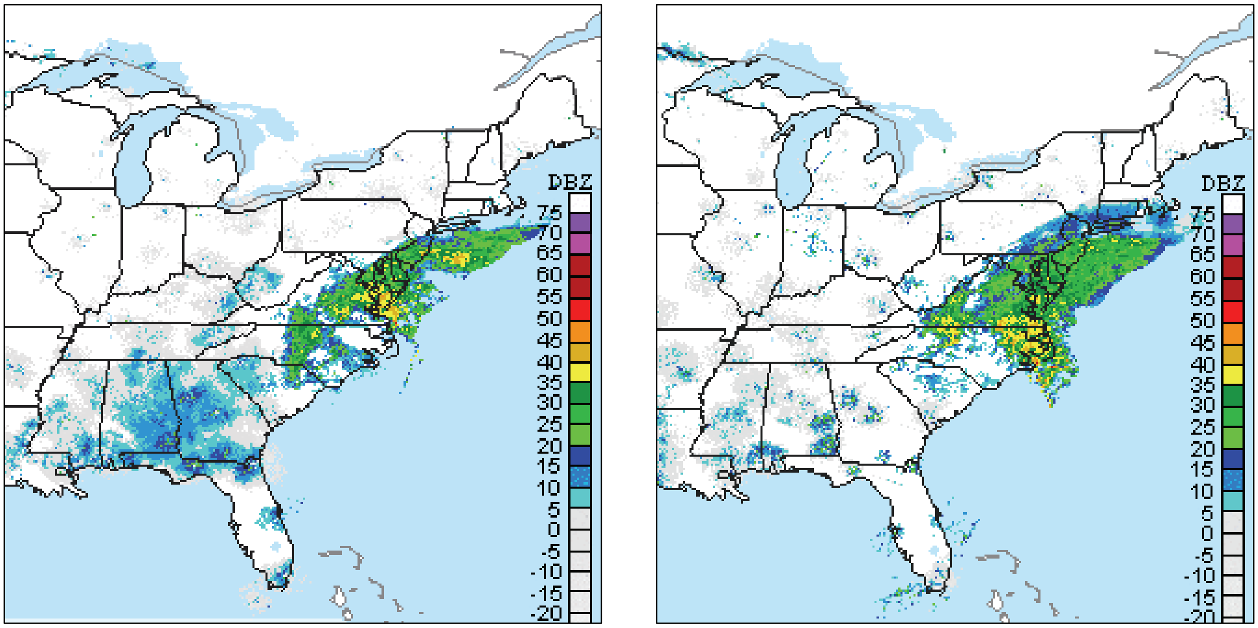


Figure 1.4. East Coast surface analysis on November 12 12:00 GMT. Courtesy: NOAA/NWS/ HPC.

24-hour totals between 2.0 and 4.0 inches (Figure 1.6). By the end of the day, the storm winds were peaking along the East Coast, as seen in the plots in the Appendix.



November 12 12:00 GMT November 13 00:00 GMT

Figure 1.5. Radar imagery during the November Nor'easter. Courtesy: NOAA/National Climatic Data Center (NCDC).

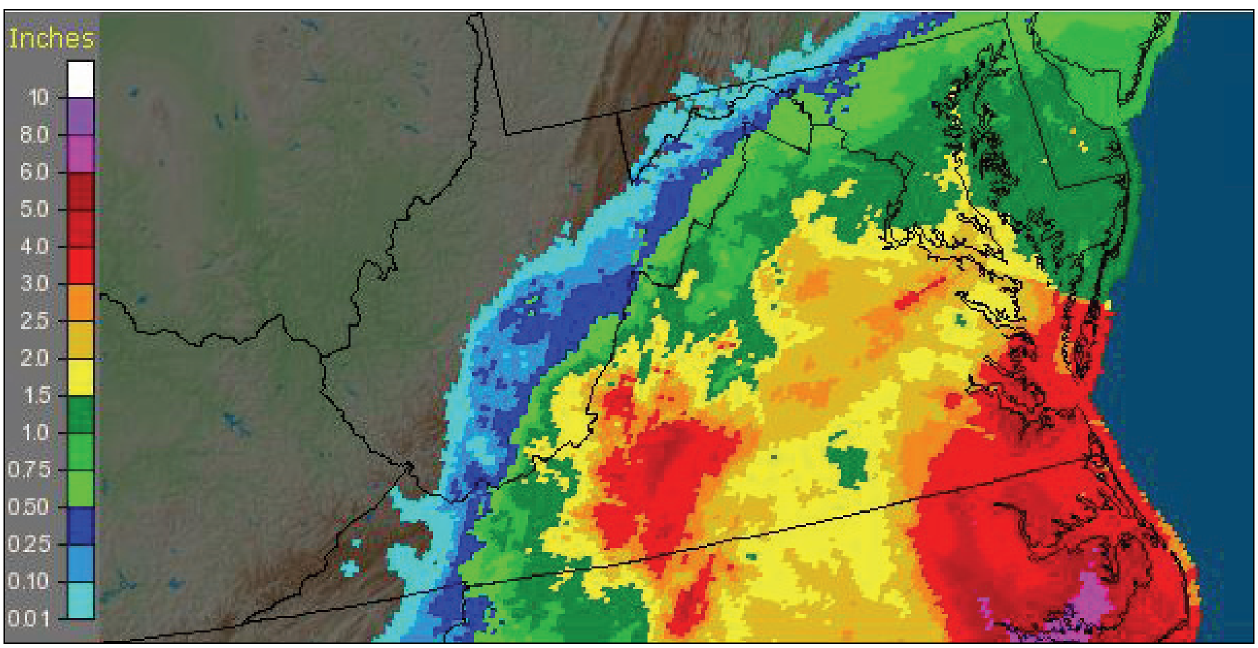


Figure 1.6. 24 hour rainfall totals ending November 12 12:00 GMT. Courtesy: NOAA/NWS/Advanced Hydrologic Prediction Service (AHPS).

On November 13 00:00 GMT, the low was located directly over Cape Hatteras, NC and was beginning to push further offshore as a result of high pressure advancing from the west. Although the central barometric pressure (993 mb) was starting to rise (Figure 1.7), several stations in the southern Chesapeake Bay measured maximum winds (Table 1.1 and Appendix) during the storm at this time. Notably, Chesapeake Bay Bridge Tunnel and Yorktown, VA measured maximum wind speeds of 52 kt and 42 kt, respectively, and at Brandywine Shoal Light in Delaware Bay speeds reached 43 kt (Table 1.1). Maximum water levels at these stations also occurred around this time, as discussed in Chapter 2 of this report. Figure 1.8 shows that overall, wind speeds along the east coast averaged 35 to 40 kt, following the pressure gradient, and heavy rainfall continued to be reported throughout the Bay area. As the approaching high pressure system continued to force the low further offshore, the low continued to weaken, with a central barometric pressure of 995 mb by 12:00 GMT. The weakening pressure gradient decreased wind speeds, though directions remained northeasterly. Wind speeds slowly began to drop though remained relatively high (Figure 1.8 and Appendix). Scattered areas of rainfall were still prevalent in eastern Virginia and the Delmarva Peninsula. Twenty-four hour rainfall totals also peaked during this time with the lower Delmarva Peninsula ranging from 4 to 8 inches of rain, as seen in Figure 1.9. Elsewhere, eastern Virginia and parts of Maryland ranged between 2 to 5 inches of rain. Delaware, New Jersey and the Philadelphia area measured up to 2.5 inches of rain.

Table 1.1. Maximum observed wind speeds, gusts and barometric pressure for the November 2009 Nor'easter. Stations are ordered North to South, following the coastline.

Station Name	Maximum Wind Speed			Maximum Wind Gust			Minimum Barometric Pressure	
	Date & Time (GMT)	m/s	kt	Date & Time (GMT)	m/s	kt	Date & Time (GMT)	mb
Sandy Hook, NJ	11/13 23:00	11.8	23	11/13 12:18	19.1	37	11/14 10:36	1009.4
Newbold, PA	11/13 21:12	10.3	20	11/13 20:48	16.6	32	11/14 09:18	1009.6
Delaware City, DE	11/12 18:54	12.1	23	11/12 19:00	16.1	31	11/14 07:36	1009.0
Brandywine Shoal Light, DE*	11/12 19:12	22.0	43	11/12 19:06	25.3	49	11/13 19:36	1006.7
Ocean City Inlet, MD	11/13 18:42	13.3	26	11/13 18:42	22.6	44	11/13 19:12	1004.6
Bishops Head, MD	11/12 23:24	15.1	29	11/12 23:24	19.7	38	11/13 09:06	1005.1
Chesapeake City, MD	11/13 09:42	8.5	17	11/13 18:24	14.3	28	11/14 07:48	1009.6
Baltimore, MD	11/13 18:24	11.2	22	11/13 18:30	14.5	28	11/14 17:06	1010.1
Solomons Island, MD	11/13 10:42	13.6	26	11/13 08:54	20.3	39	11/13 17:30	1007.1
Washington, DC	11/13 08:36	6.3	12	11/13 00:24	11.2	22	11/14 05:24	1010.2
Kiptopeke, VA	11/13 00:00	14.7	29	11/12 21:12	22.3	43	n/a	n/a
Lewisetta, VA	11/12 00:00	12.3	24	11/12 21:30	19.5	38	11/13 08:24	1006.7
Yorktown USCG Training Center, VA *	11/12 23:06	21.4	42	11/12 23:12	25.9	50	11/12 23:06	1001.5
Chesapeake Bay Bridge Tunnel, VA*	11/12 22:42	26.6	52	11/13 04:24	33.4	65	11/13 04:24	997.0
Money Point, VA*	11/13 02:00	13.7	27	11/13 02:00	25.0	49	11/13 01:54	999.0
Duck, NC	11/13 19:36	20.4	40	11/13 19:30	25.2	49	11/12 21:18	995.3
Oregon Inlet Marina, NC	11/12 01:12	14.3	28	11/12 01:12	20.4	40	11/12 21:48	995.3

* Maximum recorded storm tide exceeded Maximum Recorded Historical Water Level

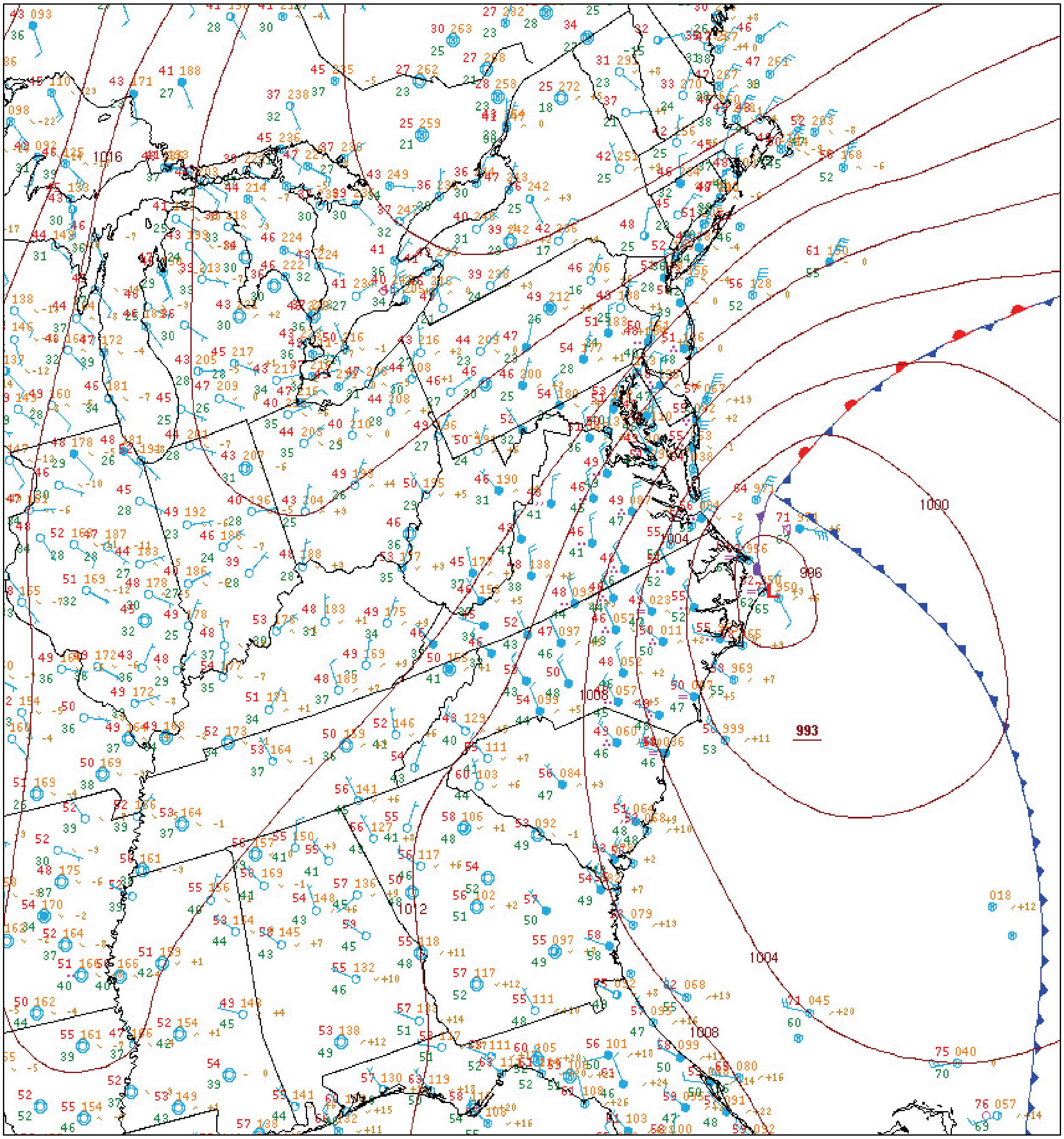


Figure 1.7. East Coast surface analysis on November 13 00:00 GMT. Courtesy: NOAA/NWS/ HPC.

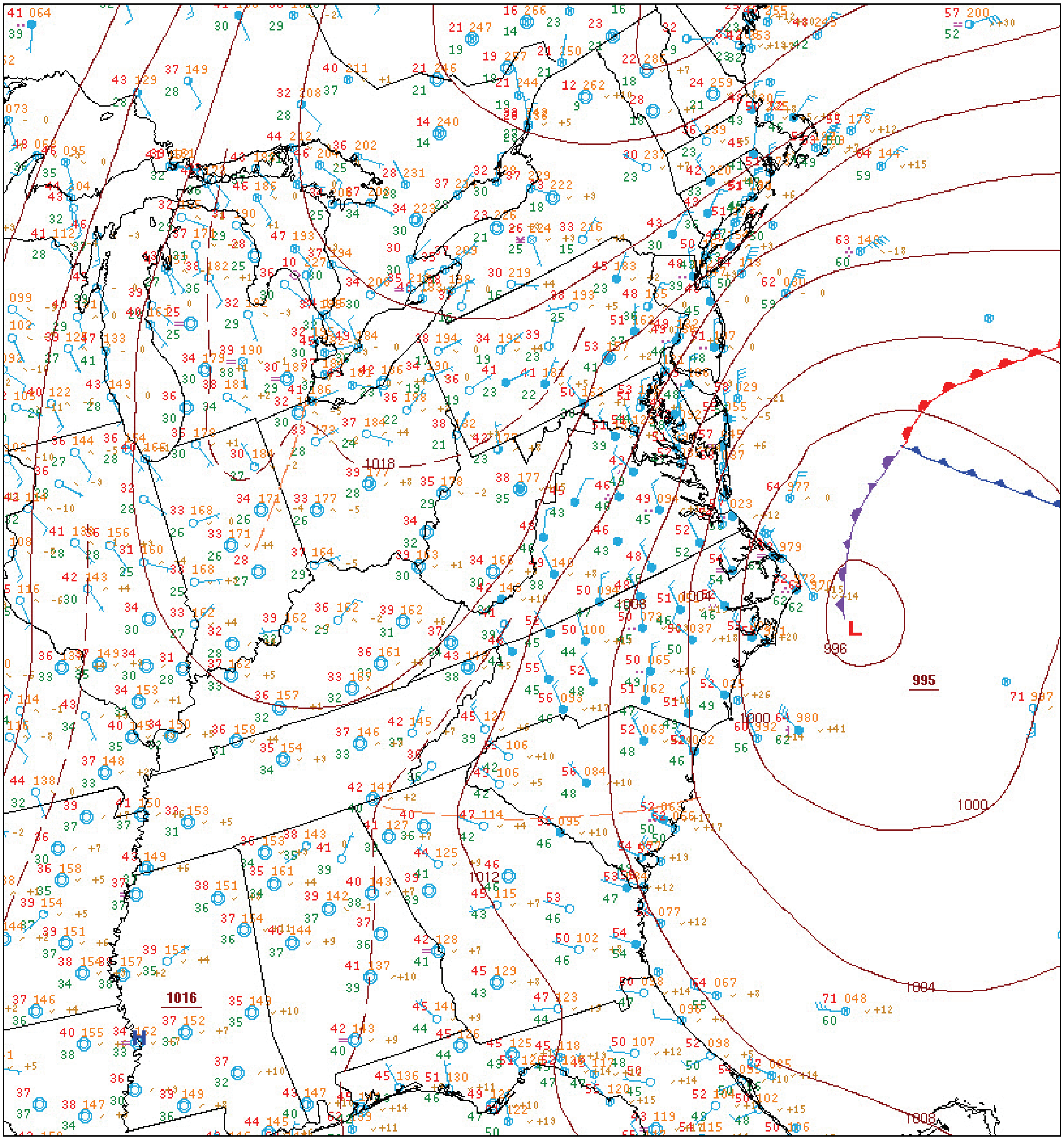


Figure 1.8. East Coast surface analysis on November 13 12:00 GMT. Courtesy: NOAA/NWS/ HPC.

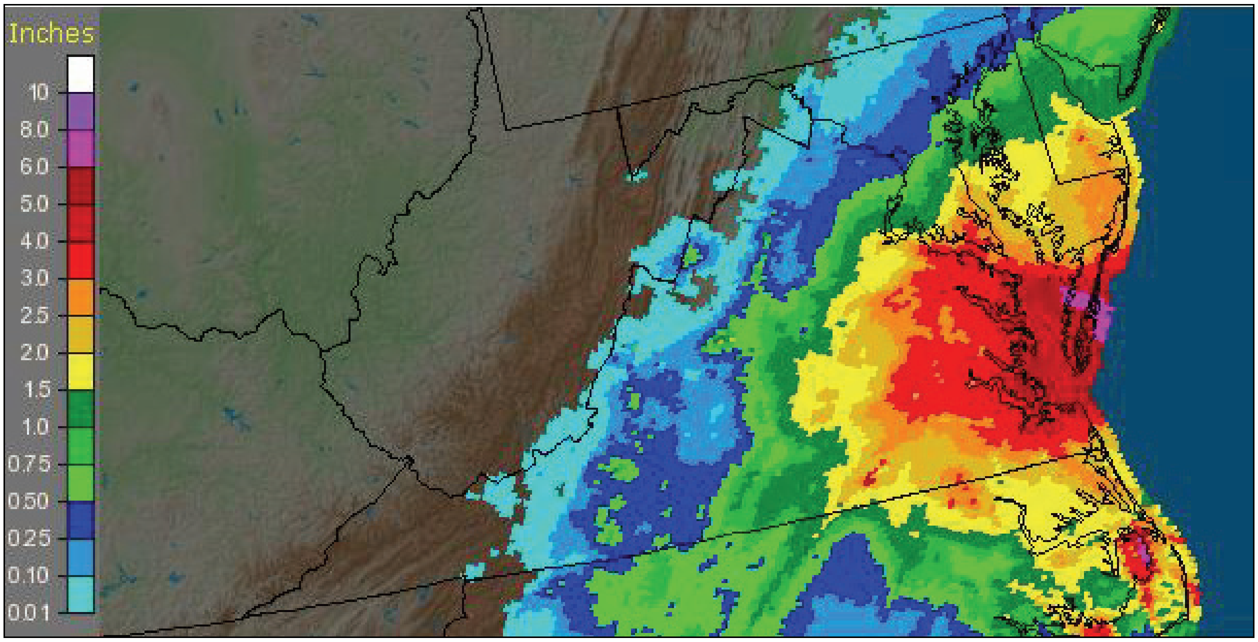


Figure 1.9. 24 hour rainfall totals ending November 13 12:00 GMT. Courtesy: NOAA/NWS/AHPS.

By November 14 00:00 GMT, the low continued to weaken and move offshore, with a central barometric pressure of 998 mb. Wind speeds continued to drop with onshore winds between 20 and 25 kt (Figure 1.10). Rainfall continued to diminish and was light to moderate and located mostly along the Delmarva Peninsula and the eastern tip of Virginia. By 12:00 GMT, wind directions changed to northwesterly and speeds dropped to around 5 kt, due to the narrow difference in pressure between the low and the neighboring air masses (Figure 1.11). Few, if any effects are felt at any of the CO-OPS stations by this time.

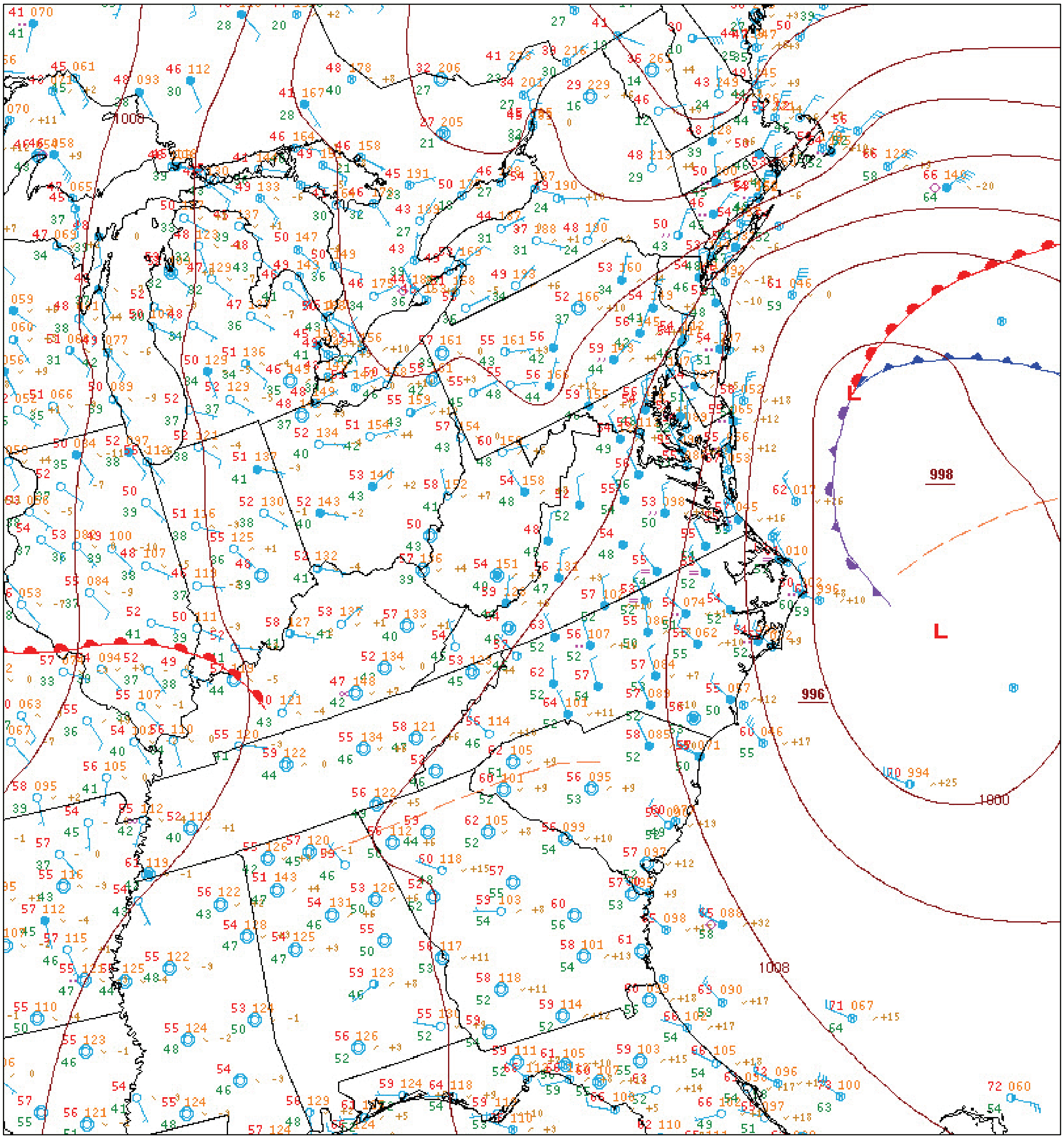


Figure 1.10. East Coast surface analysis on November 14 00:00 GMT. Courtesy: NOAA/NWS/ HPC.

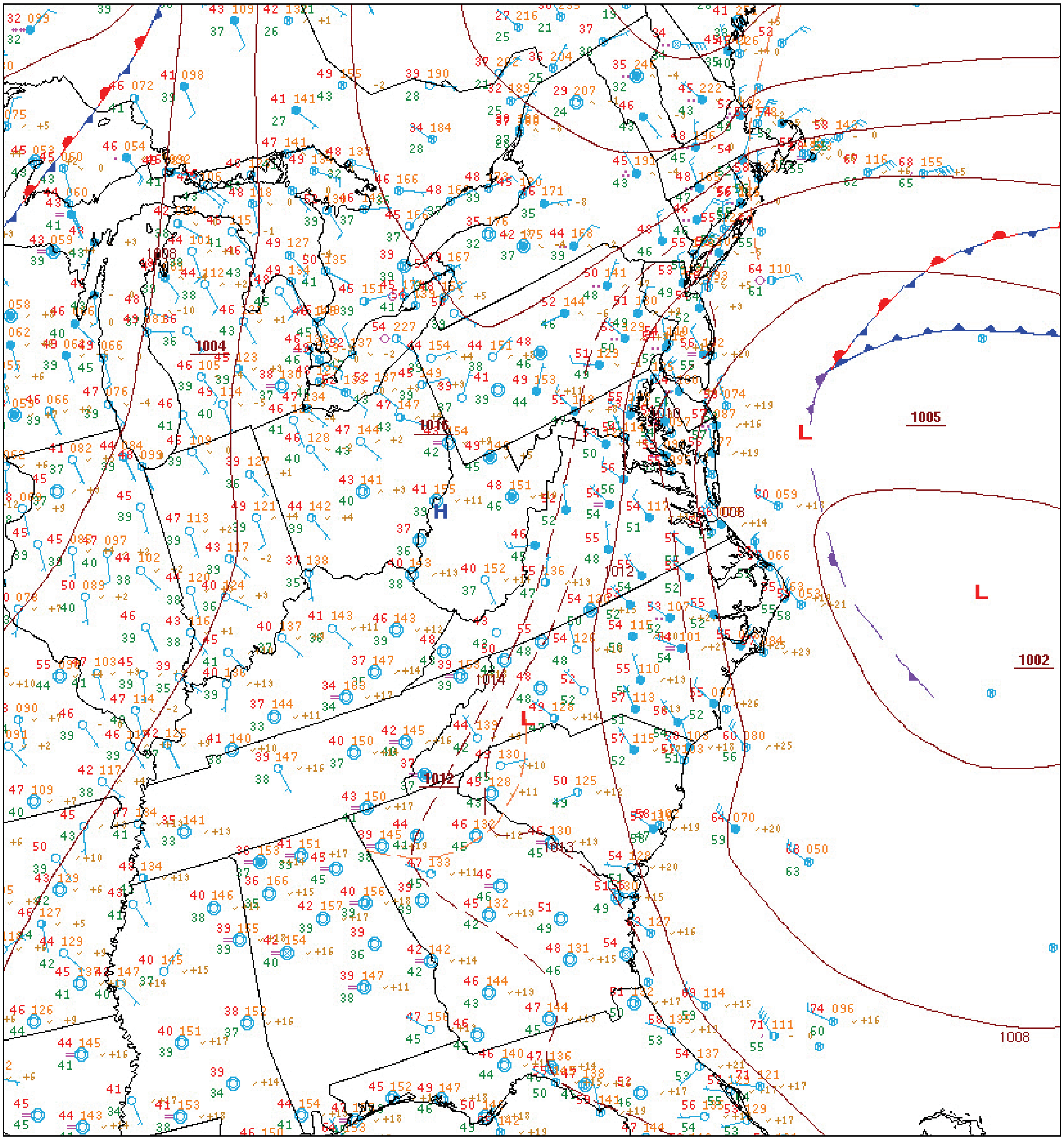


Figure 1.11. East Coast surface analysis on November 14 12:00 GMT. Courtesy: NOAA/NWS/ HPC.

The Nor'easter was slow moving as it progressed along the Mid-Atlantic region of the eastern United States, but brought strong, steady winds combined with rainfall amounts topping over 9 inches in parts of the Lower Chesapeake Bay. Rainfall totals for the 72 hour time period ending November 13 12:00 GMT peaked in the Norfolk, VA area, near the Money Point tide station, at 9.77 inches. Other specific values through the region can be seen on the Middle Atlantic River Forecast Center website (http://www.erh.noaa.gov/er/marfc/IDA2009.png). An extrapolated version of that plot can be seen in Figure 1.12. While the rainfall was significant in certain areas, the resulting runoff did not affect the local water levels at the stations at the same magnitude that the regional storm surge did. The Lower Chesapeake Bay was affected the most by the storm, with the upper Chesapeake Bay and parts of the Philadelphia area experiencing milder effects. Overall, the strongest winds were at the entrance to the Chesapeake Bay at 27 m/s (52 kt), gusting to 33.4 m/s (65 kt) at the Chesapeake Bay Bridge Tunnel water level station (Table 1.1).

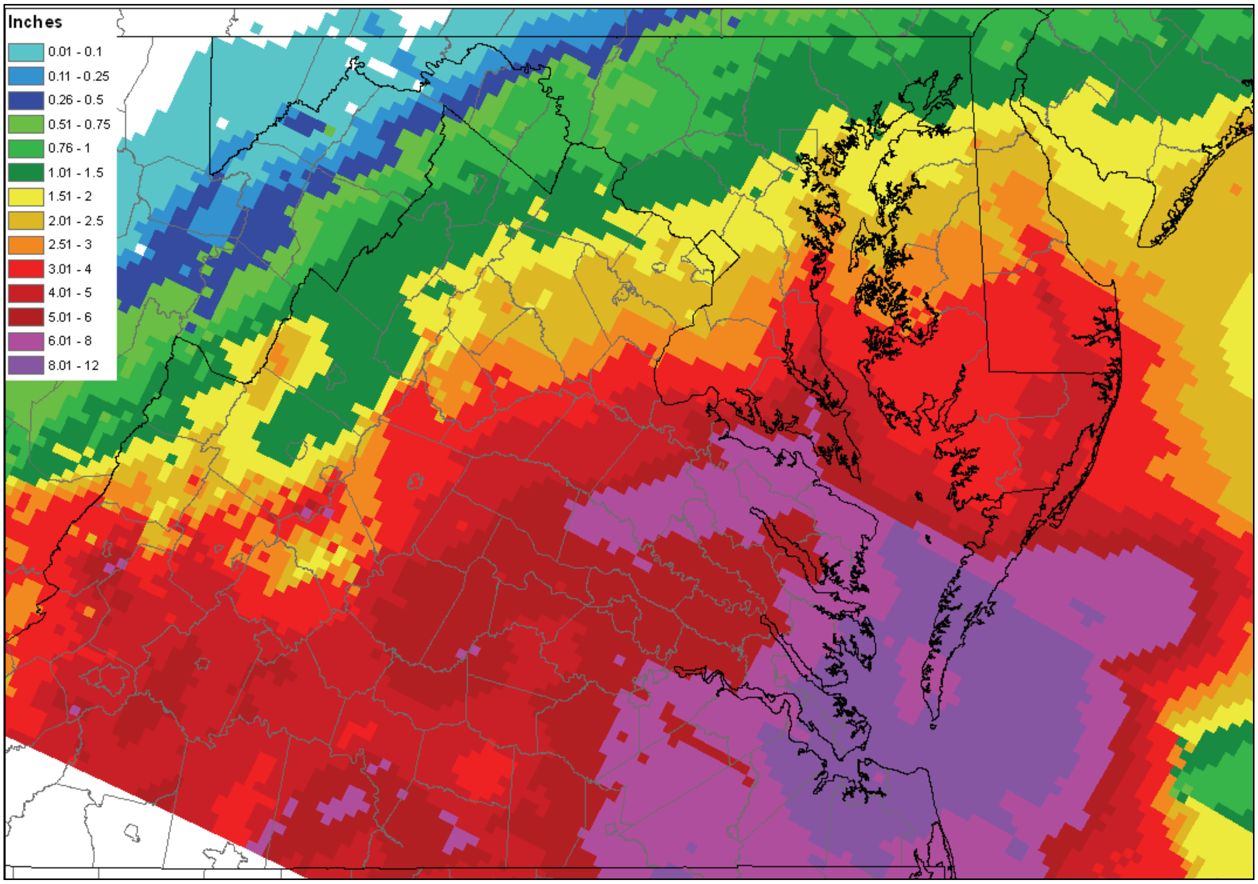


Figure 1.12. 72 hour rainfall total extrapolation ending November 13 12:00 GMT. Courtesy: NOAA/NWS/Middle Atlantic River Forecast Center.

2.0 STORM TIDE AND STORM SURGE

During the November 2009 Nor'easter, sustained elevated water levels and high waves were a major concern for coastal communities, mainly due to the high potential for flooding and beach erosion. A subset of CO-OPS water level stations are used to examine the effects of the Nor'easter on water levels along the US Coast (Figure 2.1).

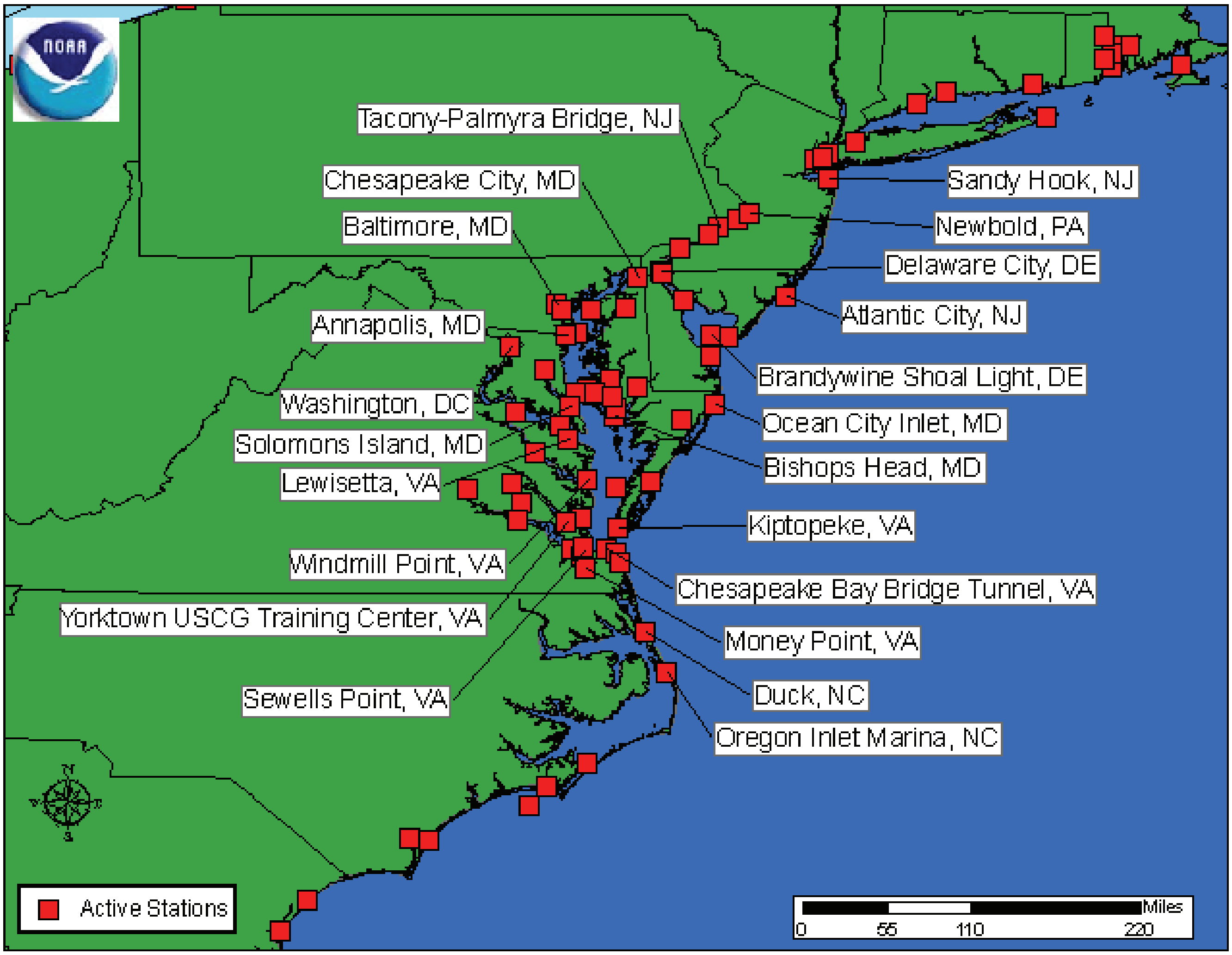


Figure 2.1. CO-OPS water level stations (red). Labeled stations are examined in this report.

Time-series plots of these stations' data are provided to illustrate the long duration and regional effects that the storm had on coastal water levels (Appendix). Observed water levels and predicted tides are referenced to Mean Lower Low Water (MLLW), and storm surge and a line denoting the Mean Higher High Water (MHHW) datum are included, as well as the recorded historical maximum water level, if available. Storm surge, as defined by CO-OPS, is the difference between observed water level and the astronomically predicted tide. Storm tides are defined as the maximum elevation of the observed water levels during the storm event (Figure 2.2).

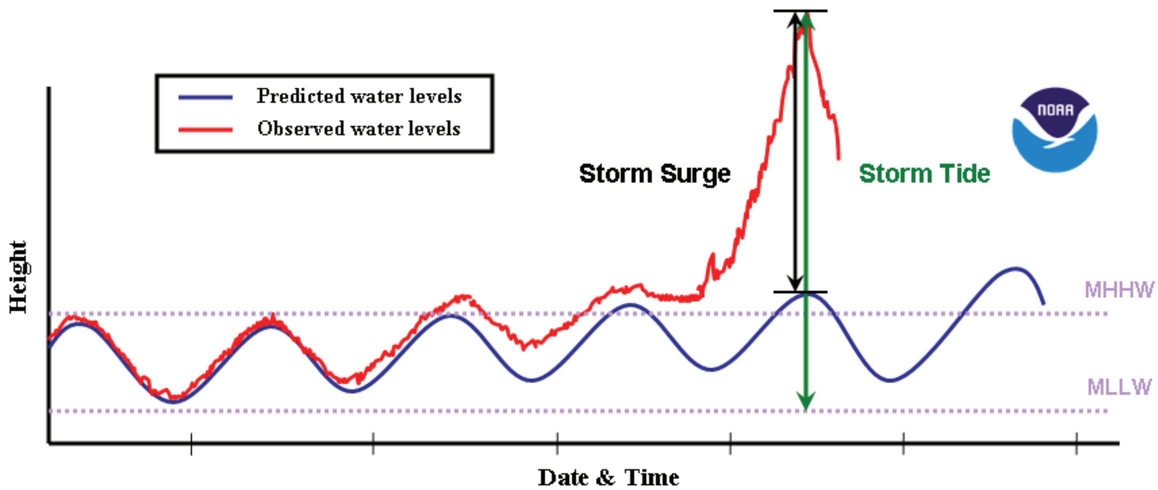


Figure 2.2. Graphical representation of Storm Surge (Residual) and Storm Tide.

Timing, duration and strength of a storm, along with the height of astronomical tide during a storm have significant effects and increase the storm's potential for flooding. The Nor'easter occurred between a third quarter moon and a new moon, two days before a monthly modulation maximum of the tide, or spring tide, occurred. Spring tides have the greatest amplitude and thus the highest and lowest waters of each month are recorded during these times. Because this storm occurred near a period of spring tides, the maximum water levels were higher than if the storm had occurred during a period of neap tides.

The slow-moving nature of this low pressure system after it reached the East Coast proved to be vital to the impacts that the system had on the entire Northeast US shoreline. Water levels were significantly impacted from North Carolina to New Jersey, and remained elevated throughout the region for 8 to 9 tidal cycles, signifying both the strength and duration of the storm. Water level stations located in the Lower Chesapeake Bay measured the highest storm surges, with the highest being 2.055 m (6.74 ft) at Money Point, VA on November 13 02:24 GMT. Storm surge at the other locations ranged from 1.817 m (5.96 ft) at Sewells Point, VA to 0.533 m (1.75 ft) at Baltimore, MD. Persistent northeasterly winds were likely the main cause of the highest observed storm surges, as opposed to rainfall runoff. The water levels at Money Point in particular were exacerbated by its location on the southern branch of the Elizabeth River, where the narrowing channel magnified the water level elevations. The mouth of the Delaware Bay was also substantially affected, with Brandywine Shoal Light, DE recording a storm surge of 1.304 m (4.28 ft). The northern Chesapeake Bay, although affected, experienced minimal impact as evidenced by the lowest surge at Baltimore, followed by several stations north of Solomons Island, which is located about halfway up the Bay. Likewise, Delaware River stations, although sheltered from the open ocean, also measured relatively low storm surges of about 0.8 m, though they were slightly higher than those in the Upper Chesapeake Bay area. Stations more exposed to the Atlantic Ocean tended to feel the effects of the storm more, as these stations were more exposed to open ocean waters being pushed towards the shore. For example, Ocean City Inlet, MD recording a maximum surge of 1.146 m (3.76 ft), Duck, NC at 1.107 m (3.63 ft), and Sandy Hook, NJ at 1.010 m (3.31 ft). Atlantic City, however, only recorded a surge of 0.897 m (2.94 ft), similar to surges recorded in the northern Delaware Bay and the Delaware River (Table 2.2).

The plots in the Appendix clearly show the relationship between the sustained onshore winds and the rising water levels along the East Coast.

The November 2009 Nor'easter observed storm tides exceeded historical maxima at one station in the Delaware Bay, and four stations in the Lower Chesapeake Bay. Yorktown, VA exceeded the historical maxima by the most, at 0.232 m (0.76 ft); however, data have only been available at this station for six years. The maxima were also exceeded at Windmill Point, VA by 0.166 m (0.54 ft), Money Point, VA, by 0.079 m (0.26 ft), Brandywine Shoal Light, DE by 0.055 m (0.18 ft) and Chesapeake Bay Bridge Tunnel (CBBT), VA by a mere 0.022 m (0.07 ft). Three other stations examined in this report, from northern North Carolina to the northern Delaware River came within 0.15 m (0.5 ft) of exceeding historical maxima (Table 2.3). Two of the four Chesapeake stations that measured record storm tides (CBBT and Money Point) had exceeded historical maxima set by Hurricane Isabel in September, 2003. The next section examines the differences between the November 2009 Nor'easter and Hurricane Isabel in relation to water levels at four stations in the lower Chesapeake Bay.

Table 2.1. Maximum observed water level referenced to MLLW for the November 2009 Nor'easter. Stations are ordered by Station ID, which is North to South, following the coastline.

Station Name	Station ID	Date & Time (GMT)	Storm Tide (m, MLLW)	Astronomical Predicted Tide (m, MLLW)	Storm Surge/ Residual (m)	Storm Tide (ft, MLLW)	Astronomical Predicted Tide (ft, MLLW)	Storm Surge/ Residual (ft)
Sandy Hook, NJ	8531680	11/14 10:54	2.401	1.699	0.702	7.88	5.57	2.30
Atlantic City, NJ	8534720	11/13 08:42	2.231	1.388	0.843	7.32	4.55	2.77
Tacony-Palmyra Bridge, NJ	8538886	11/14 17:12	2.752	2.264	0.488	9.03	7.43	1.60
Newbold, PA	8548989	11/14 18:00	3.130	2.692	0.438	10.27	8.83	1.44
Delaware City, DE	8551762	11/14 14:18	2.437	1.835	0.602	8.00	6.02	1.98
Brandywine Shoal Light, DE*	8555889	11/13 11:12	2.461	1.676	0.785	8.07	5.50	2.58
Ocean City Inlet, MD	8570283	11/13 11:24	1.628	0.692	0.936	5.34	2.27	3.07
Bishops Head, MD	8571421	11/13 15:18	1.230	0.628	0.602	4.04	2.06	1.98
Chesapeake City, MD	8573927	11/15 01:24	1.474	1.053	0.421	4.84	3.45	1.38
Baltimore, MD	8574680	11/14 21:42	0.916	0.502	0.414	3.01	1.65	1.36
Annapolis, MD	8575512	11/14 20:12	0.872	0.431	0.441	2.86	1.41	1.45
Solomons Island, MD	8577330	11/13 15:36	1.083	0.423	0.660	3.55	1.39	2.17
Washington, DC	8594900	11/14 23:06	1.431	0.989	0.442	4.69	3.24	1.45
Kiptopeke, VA	8632200	11/13 10:30	2.122	0.957	1.165	6.96	3.14	3.82
Lewisetta, VA	8635750	11/13 15:18	1.252	0.467	0.785	4.11	1.53	2.58
Windmill Point, VA*	8636580	11/13 12:30	1.408	0.477	0.931	4.62	1.56	3.05
Yorktown USCG Training Center, VA*	8637689	11/12 23:18	2.092	0.702	1.390	6.86	2.30	4.56
Sewells Point, VA	8638610	11/12 23:24	2.360	0.731	1.629	7.74	2.40	5.34
Chesapeake Bay Bridge Tunnel, VA*	8638863	11/12 22:30	2.319	0.766	1.553	7.61	2.51	5.10
Money Point, VA*	8639348	11/13 00:12	2.618	0.740	1.878	8.59	2.43	6.16
Duck, NC	8651370	11/13 08:48	2.036	1.201	0.835	6.68	3.94	2.74
Oregon Inlet Marina, NC	8652587	11/13 10:12	0.994	0.398	0.596	3.26	1.31	1.96

*Maximum Recorded Storm Tide exceeded Maximum Recorded Historical Water Level

Table 2.2. Maximum storm surge/residual water levels, ranked by amplitude for the November 2009 Nor'easter.

Station Name	Station ID	Date & Time GMT	Storm Surge/Residual (m)	Storm Surge/Residual (ft)
Money Point, VA	8639348	11/13 02:24	2.055	6.74
Sewells Point, VA	8638610	11/13 01:36	1.817	5.96
Chesapeake Bay Bridge Tunnel, VA	8638863	11/13 04:30	1.681	5.52
Yorktown USCG Training Center, VA	8637689	11/13 04:24	1.442	4.73
Kiptopeke, VA	8632200	11/13 01:54	1.365	4.48
Brandywine Shoal Light, DE	8555889	11/13 03:30	1.304	4.28
Ocean City Inlet, MD	8570283	11/13 01:42	1.146	3.76
Duck, NC	8651370	11/13 01:00	1.107	3.63
Windmill Point, VA	8636580	11/13 07:48	1.038	3.41
Sandy Hook, NJ	8531680	11/14 02:12	1.010	3.31
Lewisetta, VA	8635750	11/13 09:06	0.937	3.07
Delaware City, DE	8551762	11/13 06:42	0.905	2.97
Atlantic City, NJ	8534720	11/12 23:36	0.897	2.94
Newbold, PA	8548989	11/14 14:24	0.803	2.63
Tacony-Palmyra Bridge, NJ	8538886	11/13 09:36	0.799	2.62
Solomons Island, MD	8577330	11/13 10:36	0.784	2.57
Bishops Head, MD	8571421	11/13 10:12	0.773	2.54
Washington, DC	8594900	11/13 18:06	0.713	2.34
Oregon Inlet Marina, NC	8652587	11/13 23:00	0.682	2.24
Chesapeake City, MD	8573927	11/14 20:30	0.623	2.04
Annapolis, MD	8575512	11/13 13:12	0.538	1.77
Baltimore, MD	8574680	11/14 16:54	0.533	1.75

Table 2.3. A comparison of the maximum observed water level elevation (storm tide) recorded during the November Nor'easter to the maximum historical elevation recorded at each station.

Station Name	Station ID	Period of Data (years)	November 2009 Nor'easter			Historical Maximum			Difference	
			Date & Time (GMT)	Above		Date	Above			
				(m, MLLW)	(ft, MLLW)		(m, MLLW)	(ft, MLLW)	(m)	(ft)
Sandy Hook, NJ	8531680	78	11/14 10:54	2.401	7.88	09/12/1960	3.074	10.09	-0.673	-2.21
Atlantic City, NJ	8534720	99	11/13 08:42	2.231	7.32	12/11/1992	2.738	8.98	-0.507	-1.66
Tacony-Palmyra Bridge, NJ	8538886	8	11/14 17:12	2.752	9.03	04/03/2005	3.118	10.23	-0.366	-1.20
Newbold, PA	8548989	9	11/14 18:00	3.130	10.27	09/19/2003	3.402	11.16	-0.272	-0.89
Delaware City, DE	8551762	14	11/14 14:18	2.437	8.00	09/19/2003	2.628	8.62	-0.191	-0.63
Brandywine Shoal Light, DE*	8555889	26	11/13 11:12	2.461	8.07	02/17/2003	2.406	7.89	0.055	0.18
Ocean City Inlet, MD	8570283	13	11/13 11:24	1.628	5.34	02/05/1998	1.860	6.10	-0.232	-0.76
Bishops Head, MD	8571421	5	11/13 15:18	1.230	4.04	05/12/2008	1.307	4.29	-0.077	-0.25
Chesapeake City, MD	8573927	38	11/15 01:24	1.474	4.84	09/19/2003	2.670	8.76	-1.196	-3.92
Baltimore, MD	8574680	108	11/14 21:42	0.916	3.01	09/19/2003	2.483	8.15	-1.567	-5.14
Annapolis, MD	8575512	81	11/14 20:12	0.872	2.86	09/19/2003	2.195	7.20	-1.323	-4.34
Solomons Island, MD	8577330	73	11/13 15:36	1.083	3.55	08/13/1955	1.303	4.27	-0.220	-0.72
Washington, DC	8594900	79	11/14 23:06	1.431	4.69	10/17/1942	3.368	11.05	-1.937	-6.35
Kiptopeke, VA	8632200	59	11/13 10:30	2.122	6.96	03/08/1962	2.156	7.07	-0.034	-0.11
Lewisetta, VA	8635750	36	11/13 15:18	1.252	4.11	09/19/2003	1.668	5.47	-0.416	-1.36
Windmill Point, VA*	8636580	28	11/13 12:30	1.408	4.62	02/05/1998	1.242	4.07	0.166	0.54
Yorktown USCG Training Center, VA *	8637689	6	11/12 23:18	2.092	6.86	10/07/2006	1.860	6.10	0.232	0.76
Sewells Point, VA	8638610	35	11/12 23:24	2.360	7.74	08/23/1933	2.444	8.02	-0.084	-0.28
Chesapeake Bay Bridge Tunnel, VA*	8638863	34	11/12 22:30	2.319	7.61	09/18/2003	2.297	7.54	0.022	0.07
Money Point, VA*	8639348	13	11/13 00:12	2.618	8.59	09/18/2003	2.539	8.33	0.079	0.26
Duck, NC	8651370	31	11/13 08:48	2.036	6.68	09/18/2003	2.380	7.81	-0.344	-1.13
Oregon Inlet Marina, NC	8652587	33	11/13 10:12	0.994	3.26	09/16/1999	1.725	5.66	-0.731	-2.40

*Maximum Recorded Storm Tide exceeded Maximum Recorded Historical Water Level

Comparison to Hurricane Isabel Water Levels in the Chesapeake Bay

Hurricane Isabel swept up just west of the axis of the Chesapeake Bay in September, 2003 as a Category 2 hurricane. The storm wreaked the worst havoc that the Chesapeake Bay region had experienced in years, and even in its weakened state it caused considerable damage in the Delaware Bay region as well. Several CO-OPS water level stations measured the highest water levels on record during this storm, mostly in the Chesapeake Bay region (Hovis, 2004). Although the Nor'easter was not as severe of a storm event as Hurricane Isabel, the highly persistent northeasterly winds elevated water levels enough to rival those from Hurricane Isabel at several CO-OPS water level stations in the southern Chesapeake Bay. This chapter focuses on the Chesapeake Bay area, where both storms affected water levels the most, and on stations that measured higher water levels during the Nor'easter event than during Hurricane Isabel.

Hurricane Isabel and the 2009 Nor'easter were very different storms. The main difference is that the hurricane was still a warm-core system and thus tropical in nature (until it passed over Pennsylvania), whereas the Nor'easter was a cold-core system, and was thus extratropical. The intensity of the storms differed greatly--Hurricane Isabel was swift but intense, with 90-kt winds at the time of landfall at Drum Inlet, NC. The storm blew through the East Coast region within 24 hours, dramatically elevating water levels throughout the entire Chesapeake Bay with a pronounced storm surge wave progressing up into the Bay as the storm passed inland. The Nor'easter, by stark contrast, moved slowly but with persistent north and northeasterly winds of 30 – 50 kt. As the coastal low deepened and the high pressure system over New England strengthened, the resulting pressure gradient caused strong northeasterly winds to pile water onshore over a period of about 2 to 3 days. Along the East Coast, the Chesapeake Bay area was most affected by both Hurricane Isabel and the Nor'easter. Tables 2.4 and 2.5 compare the storm surge and storm tides, respectively, among four Virginia stations on the Chesapeake Bay where the Nor'easter had a greater impact than Hurricane Isabel.

Table 2.4. Comparison of storm surge levels from Hurricane Isabel and the November 2009 Nor'easter. A positive difference indicates higher storm surge from the Nor'easter.

Station	Hurricane Isabel 2003 Storm Surge		November 2009 Nor'easter Storm Surge		Difference	
	(m)	(ft)	(m)	(ft)	(m)	(ft)
Money Point	1.733	5.69	2.055	6.74	0.32	1.06
Sewells Pt	1.712	5.62	1.817	5.96	0.11	0.34
Chesapeake BBT	1.457	4.78	1.681	5.52	0.22	0.73
Kiptopeke	1.195	3.92	1.365	4.48	0.17	0.56

Of the stations shown in Table 2.4, Money Point recorded the highest storm surge for both storms; the Nor'easter storm surge exceeded that of Isabel by 0.32 m (1.06 ft). This station is situated on the Elizabeth River, and although it was probably more affected by local runoff from rainfall than the other stations shown, it is likely that the northeast winds pushing waters up the river were the largest factor in driving water levels to this peak elevation. Similarly, Sewells Point, although in a somewhat sheltered location from direct northeast winds at the mouth of the James River, most likely recorded high water levels due to a volume of water flowing in from the Bay and up the James River. Water levels at Chesapeake Bay Bridge Tunnel (CBBT) and

Kiptopeke, both located near the mouth of the Chesapeake Bay, were influenced more directly by the onshore winds. CBBT is in open water and is especially susceptible to nor'easter events.

Table 2.5. Comparison of storm tide levels between Hurricane Isabel and the November 2009 Nor'easter. A positive difference indicates higher storm tide from the Nor'easter.

Station	Hurricane Isabel 2003 Storm Tide		November 2009 Nor'easter Storm Tide		Difference	
	(m, MLLW)	(ft, MLLW)	(m, MLLW)	(ft, MLLW)	(m)	(ft)
Money Point	2.539	8.33	2.618	8.59	0.08	0.26
Sewells Pt	2.404	7.89	2.360	7.74	-0.04	-0.15
Chesapeake BBT	2.297	7.54	2.319	7.61	0.02	0.07
Kiptopeke	1.986	6.52	2.122	6.96	0.14	0.45

The swift yet intense passage of Hurricane Isabel caused water levels to elevate quickly and recede back to predicted levels all within about two days, three at most. Thus, maximum storm surge and storm tide occurred at the same time for many of the lower Chesapeake Bay stations during Isabel, whereas during the Nor'easter the maxima occurred at different times for all of the stations included in this report.

This temporal difference and relationship to the timing of the astronomical (predicted) tide point to why Sewells Point had a larger storm surge during the Nor'easter than during Isabel, but a smaller storm tide. At Sewells Point, the maximum storm tide occurred on 11/12/09 23:24 GMT, whereas the maximum storm surge occurred 2 hours later on 11/13/09 01:36 GMT. During this time, predictions (i.e. the tidal forcing) dropped 0.35 m (from 0.73 m to 0.38 m above MLLW), while observed water levels had only receded about 0.16 m (from 2.360 m to 2.198 m above MLLW). This slower rate of decline in observed water levels allowed the Nor'easter storm surge levels (i.e. the differential between the observed and predicted water levels) to continue rising during that hour to exceed the surge recorded during Isabel. Overall, however, absolute water levels (i.e. storm tide) during the Nor'easter came very close (0.04 m) but never exceeded those during Isabel.

In addition, related to the temporal difference between the two storms, the predicted low tide during Isabel on 9/19/03 ~02:00 GMT was overwhelmed at the four Chesapeake Bay stations, whereas the Nor'easter did not mask the signal at all and lasted through about 8 tide cycles. This is another indication of the slow movement of the Nor'easter, and also the degree of impact that the sustained high water levels had on the areas affected by the large pressure gradient.

Interestingly, Isabel was retired from the list of Hurricane names in 2003 and was replaced by Ida, whose moisture and energy helped generate the November 2009 Nor'easter that caused water levels to exceed records set by Isabel.

3.0 CURRENTS IN CHESAPEAKE AND DELAWARE BAYS

As the November Nor'easter passed through the Mid-Atlantic region, currents were captured by several CO-OPS current meters. Specifically, the Chesapeake and Delaware Bay and the Delaware River currents were continuously measured to provide a picture of how the waters were affected by the northeasterly winds. The different types of current meters used are: bottom-mounted meters that measure the currents from the meter to the surface; sidelookers that measure flow at a single depth across a channel; and buoys that measure flow from near the surface to the bottom of the channel. Additionally, High Frequency Radar (HFR) measured surface currents at the mouth of the Chesapeake Bay. The Chesapeake and Delaware Bay and River are the focus of this chapter, as currents were most affected in these areas.

Chesapeake Bay

The Chesapeake Bay contains twelve current meter stations established in support of the Chesapeake Bay PORTS®. Four near the entrance of the Chesapeake Bay (Figure 3) are deployed on US Coast Guard Aids to Navigation (ATON) buoys, and are well-positioned to capture the flow of water in and out of the Bay. Each of these buoy mounted systems consist of a 1 MHz Nortek current profiler oriented downward with all three beams profiling the water in one-meter increments from near the surface down to the channel bottom. Each system utilizes acoustic Doppler technology to measure current speed, current direction, and echo intensity, as well as water temperature and water pressure, all of which are examined in this report.

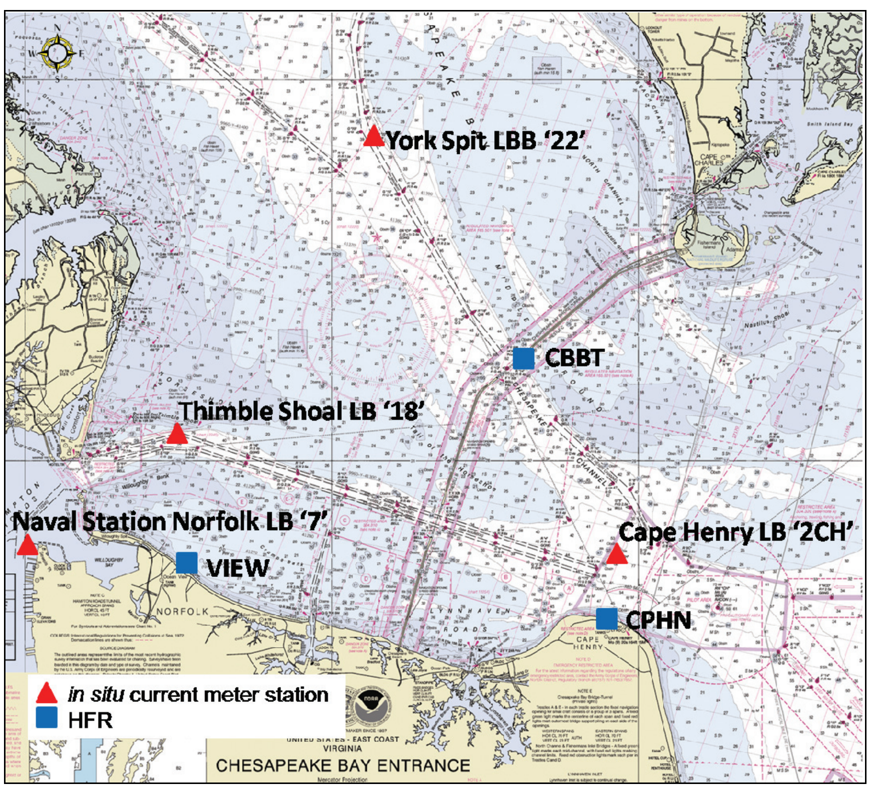


Figure 3. Chesapeake Bay real-time buoy-mounted current stations (red triangles) and surface mapping high frequency radar (HFR) stations (blue squares).

The November 2009 Nor'easter caused an initial influx of water into the Bay. The dynamics of this flux were best measured by the Cape Henry, LB '2CH' current meter, ideally positioned on the southern side at the mouth of the Bay near the Chesapeake Bay Bridge Tunnel (CBBT) water level station. Figure 3.1a shows the flooding (flow into the Bay, positive speeds) and ebbing (flow out of the Bay, negative speeds) of the water at the mouth of the Bay over the entirety of the event.

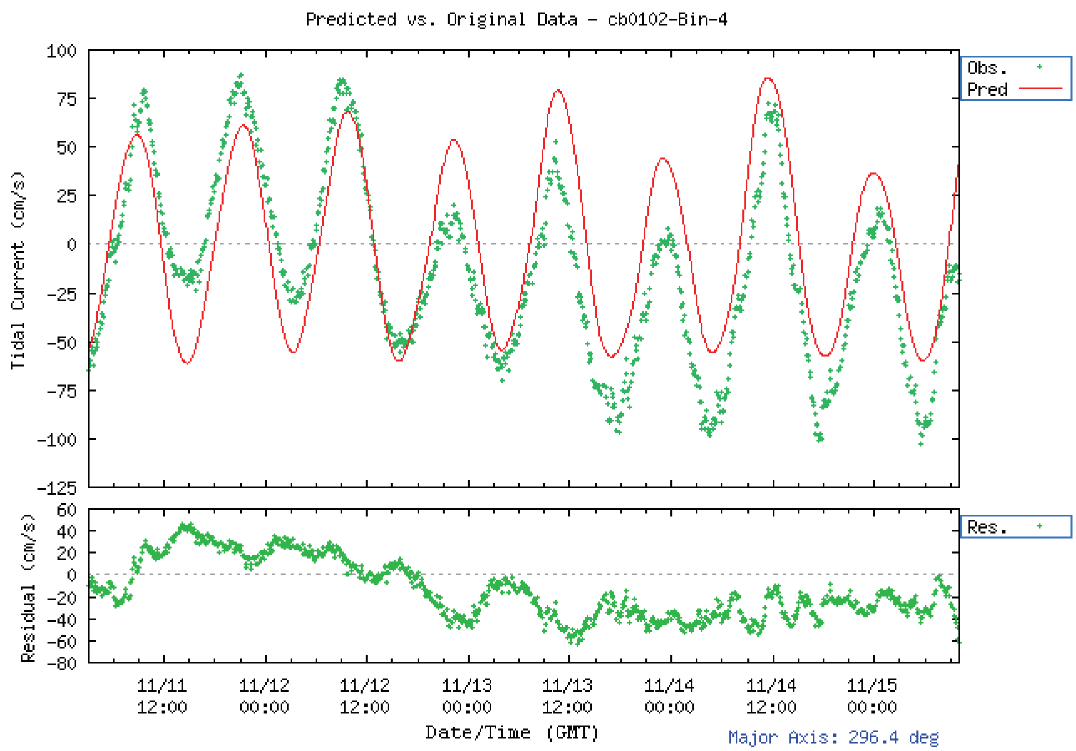


Figure 3.1a. Cape Henry LB 2 CH current observations and predictions at 6.6 m below the surface (upper panel) and residual currents (lower panel). (+ flood current, - ebb current)

The flooding exceeded predicted current speeds by up to 50 cm/s (1.0 kt) from November 11 12:00 GMT until November 12 12:00 GMT. After a day of near equilibrium, the ebbing flow at the mouth of the Bay exceeded predicted current speeds by up to 60 cm/s (1.2 kt) on November 13. Ebb currents continued to exceed predicted flow until November 16, when observations returned to match predictions, indicating the end of the Nor'easter's influence on flow in the Bay. The four current meters illustrate the progression of water moving up the Bay (Figure 3.1a-d) and similar behavior to LB '2CH' is shown with a time lag of events.

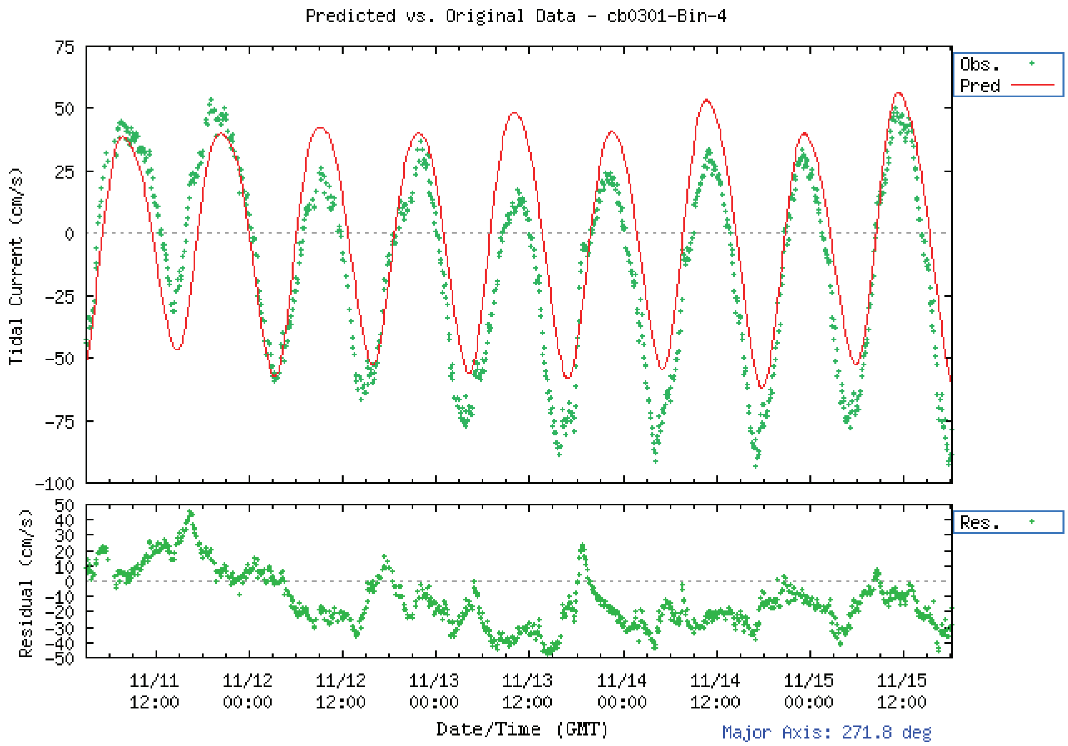


Figure 3.1b. Thimble Shoals buoy LB 18 current observations and predictions at 6.4 m below the surface (upper panel) and residual currents (lower panel). (+ flood current, - ebb current)

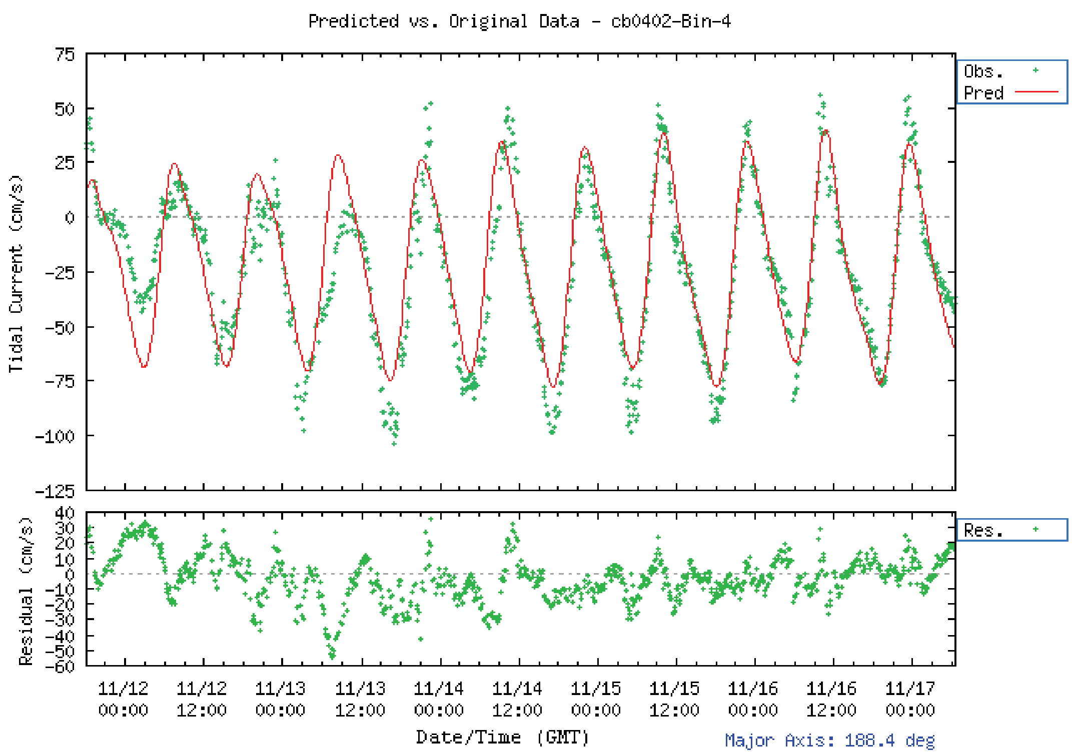


Figure 3.1c. Naval Station Norfolk buoy LB 7 current observations and predictions at 6.3 m below the surface (upper panel) and residual currents (lower panel). (+ flood current, - ebb current)

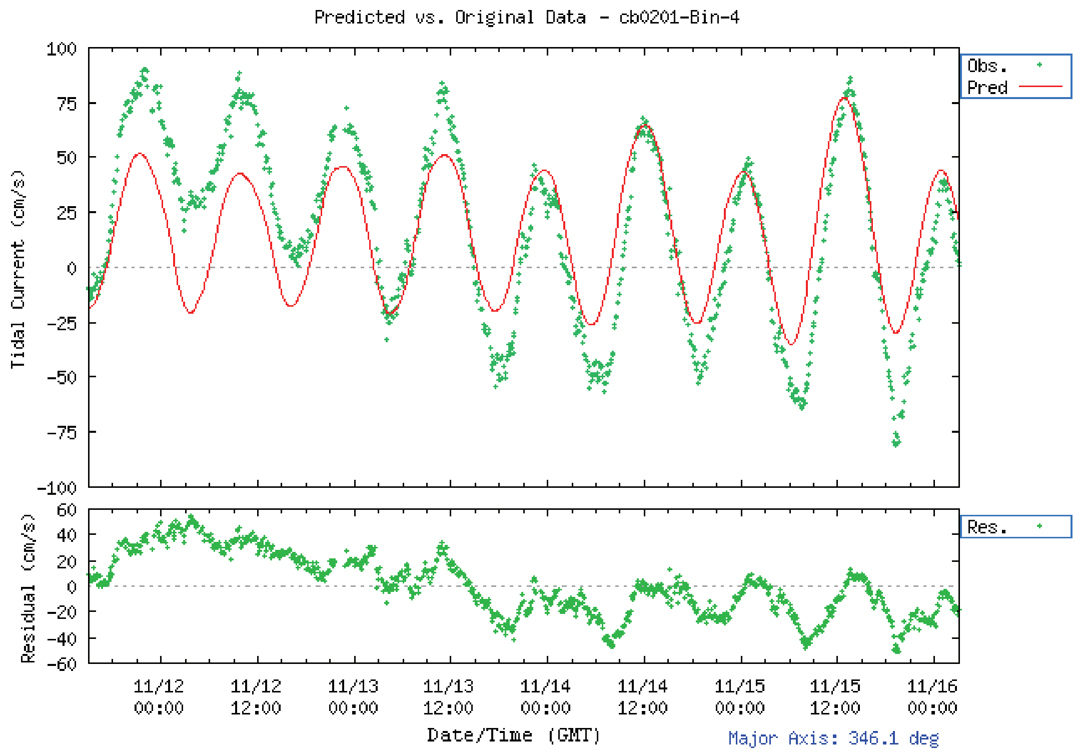


Figure 3.1d. York Spit buoy LBB 22 current observations and predictions at 6.2 m below the surface (upper panel) and residual currents (lower panel). (+ flood current, - ebb current)

The flood waters of slower speeds tend to persist for a longer period before equilibrium is reached, then speed of ebb currents increase and persist for several days. Figure 3.2 displays the temporal change in Cape Henry LB '2CH' current speed and direction in the vertical profile, where the bottom is at bin 15 (17.6 m below the surface).

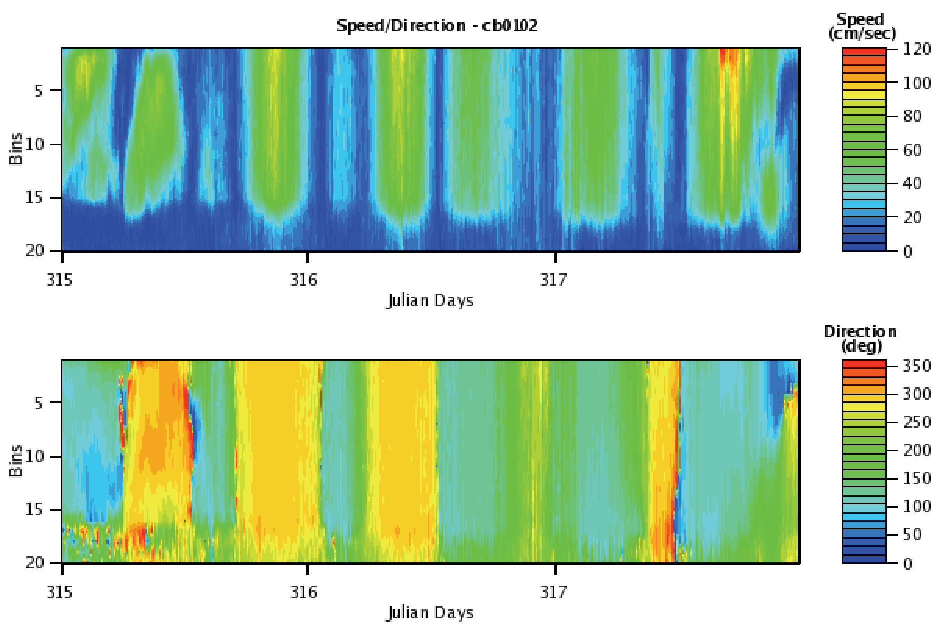


Figure 3.2. Contour plots of buoy Cape Henry LB 2 CH current speed (upper) and direction (lower) from November 11 - 14 (Julian Days 315-318 GMT).

The flood direction 6.6 m below the surface (bin 4 in Figure 3.2) is towards the north-northeast (295°), and changed to ~275° at approximately the same time the storm surge and winds peaked at CBBT (Appendix). Ebb currents towards the surface, in the upper 7 bins, exceeded 100 cm/s (1.9 kt) on November 13 (Julian Day 317).

The strong northeasterly winds increased the wave heights, creating a disturbance in the upper water column. The flood waters brought an influx of colder water from the Atlantic into the Bay after November 12 01:00 GMT, as noted by a decrease of about 1.5 ºC (2.7 ºF) (Figure 3.3a-d, upper panel). Increased echo intensities near the surface due to these wind disturbances can especially be seen in Figure 3.3a, lower panels, at Cape Henry LB '2CH.' The echo intensities in all beams are higher when they hit an obstruction, such as the channel bottom at 17.6 m below the surface (bin 15) on November 11 (Julian Day 315). The higher echo intensities measured in the water column indicate an increase in particulate matter due to increased wave energy that coincides with peak changes in winds, water temperature and water pressure. The variability seen in the water pressure is simply the motion of the buoy itself, as it is pushed by high winds. Note that the Thimble Shoals buoy motion corresponds with the period of high wind speeds at CBBT, on November 13 (Figure 3.3b, second panel, and Appendix). The peak water levels and winds at CBBT (Appendix) coincide with these disturbances that were captured by the nearby LB '2CH.'

The three HFR sites, Cape Henry (CPHN), Ocean View Beach, VA (VIEW), and Chesapeake Bay Bridge Tunnel (CBBT) measured surface currents during the Nor'easter. The data are an average of each site's radial data, covering an area of ~20 km^2 representing the upper meter of the water column. Figure 3.4a-c provides a comparison the HFR surface currents to the currents data that are displayed in PORTS®, which are about 6 m below the surface. The spatial interpolation projects the velocity from each of the three HFR sites on to *the location* of each PORTS® current meter station. The interpolation is based on neighboring values from the standard HFR (CODAR) processing grid where 2 or more sites overlap. Also, the HFR data are rotated to match the direction of flood current at the PORTS® site.

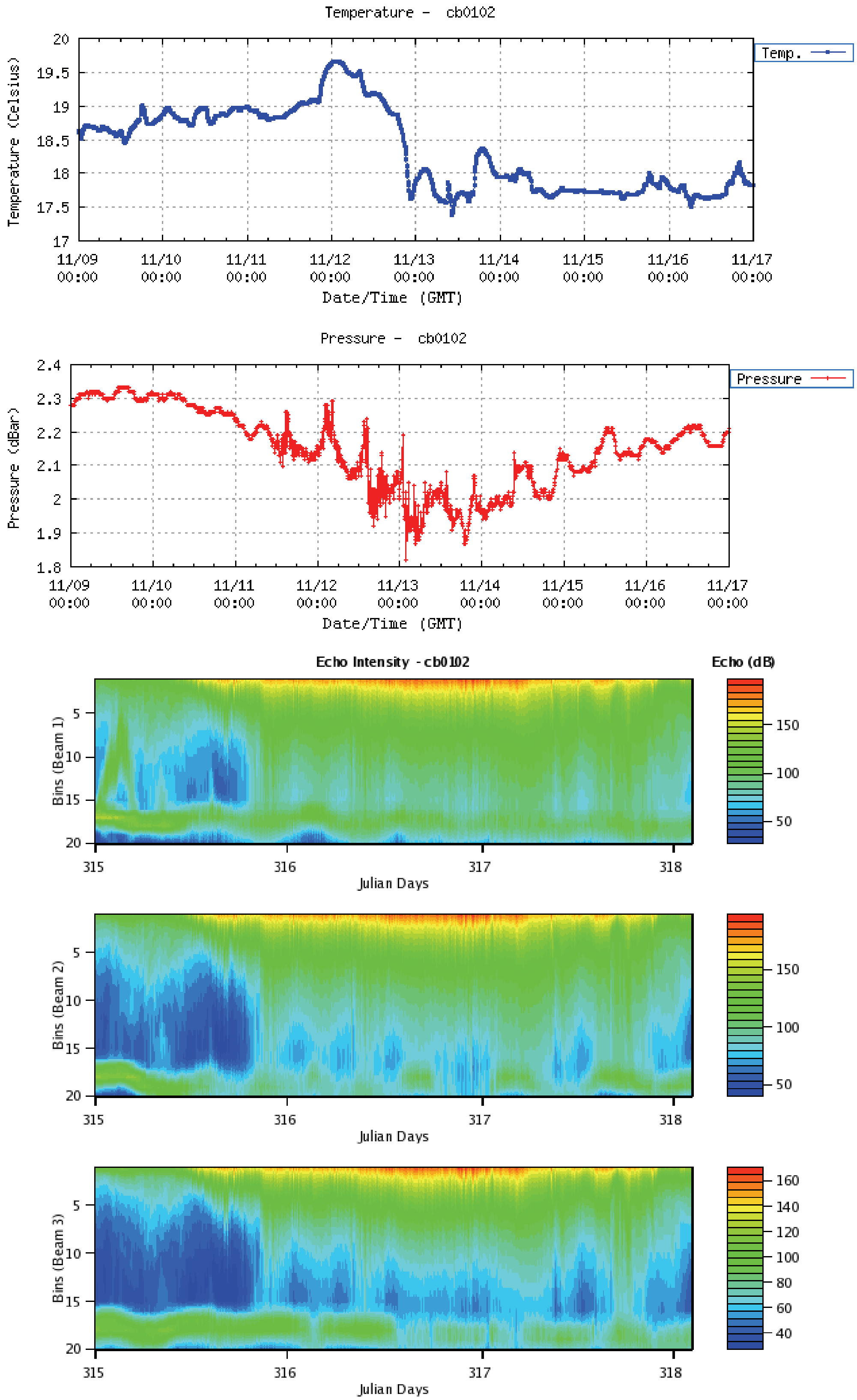


Figure 3.3a. Water temperature, water pressure and echo intensities measured at Cape Henry LB 2 CH (Julian Days 315 to 318 correspond to November 11 to 14 GMT).

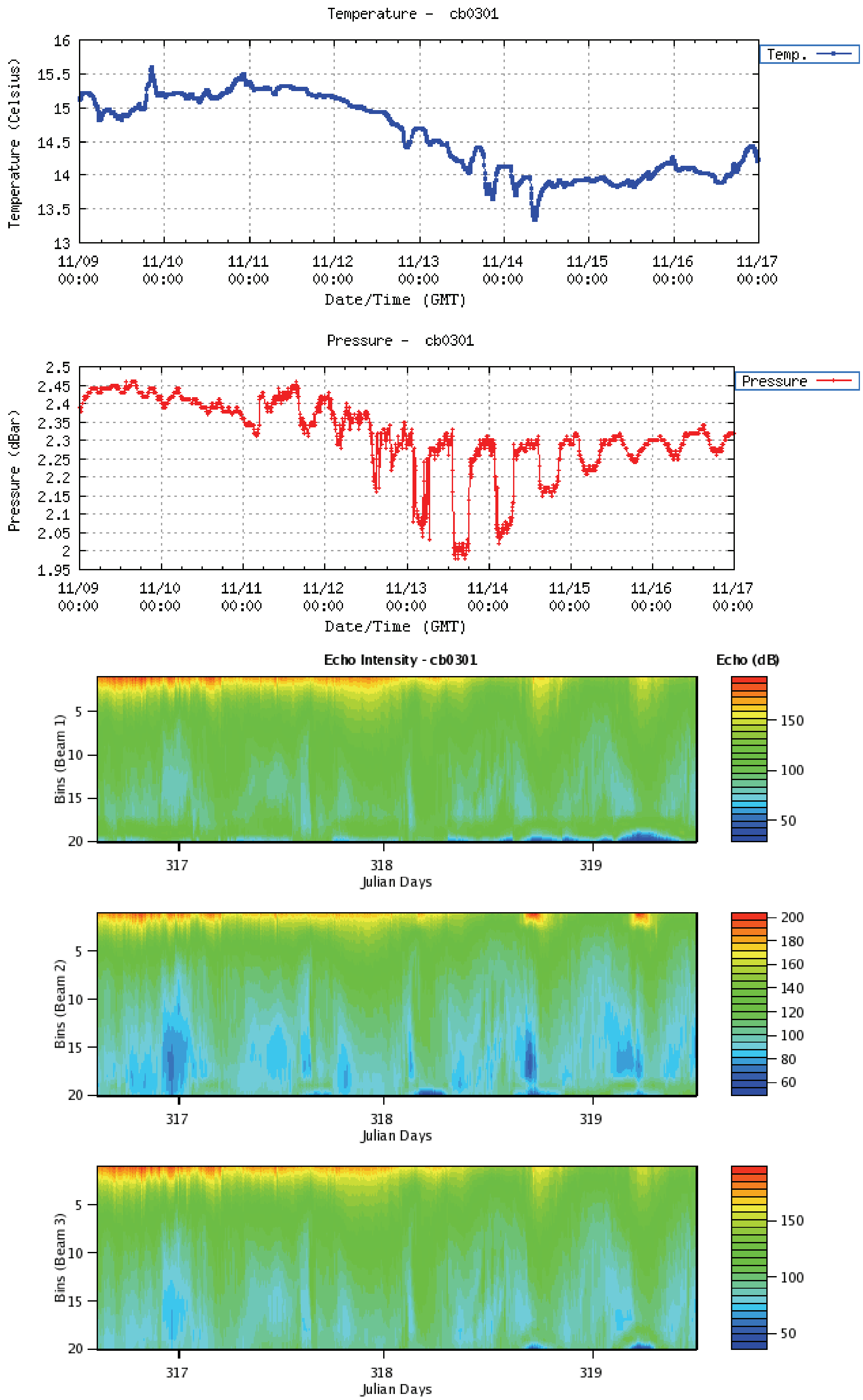


Figure 3.3b. Water temperature, water pressure and echo intensities measured at Thimble Shoals LB 18 from November 12 to 16 (Julian Day 316 to 320 GMT).

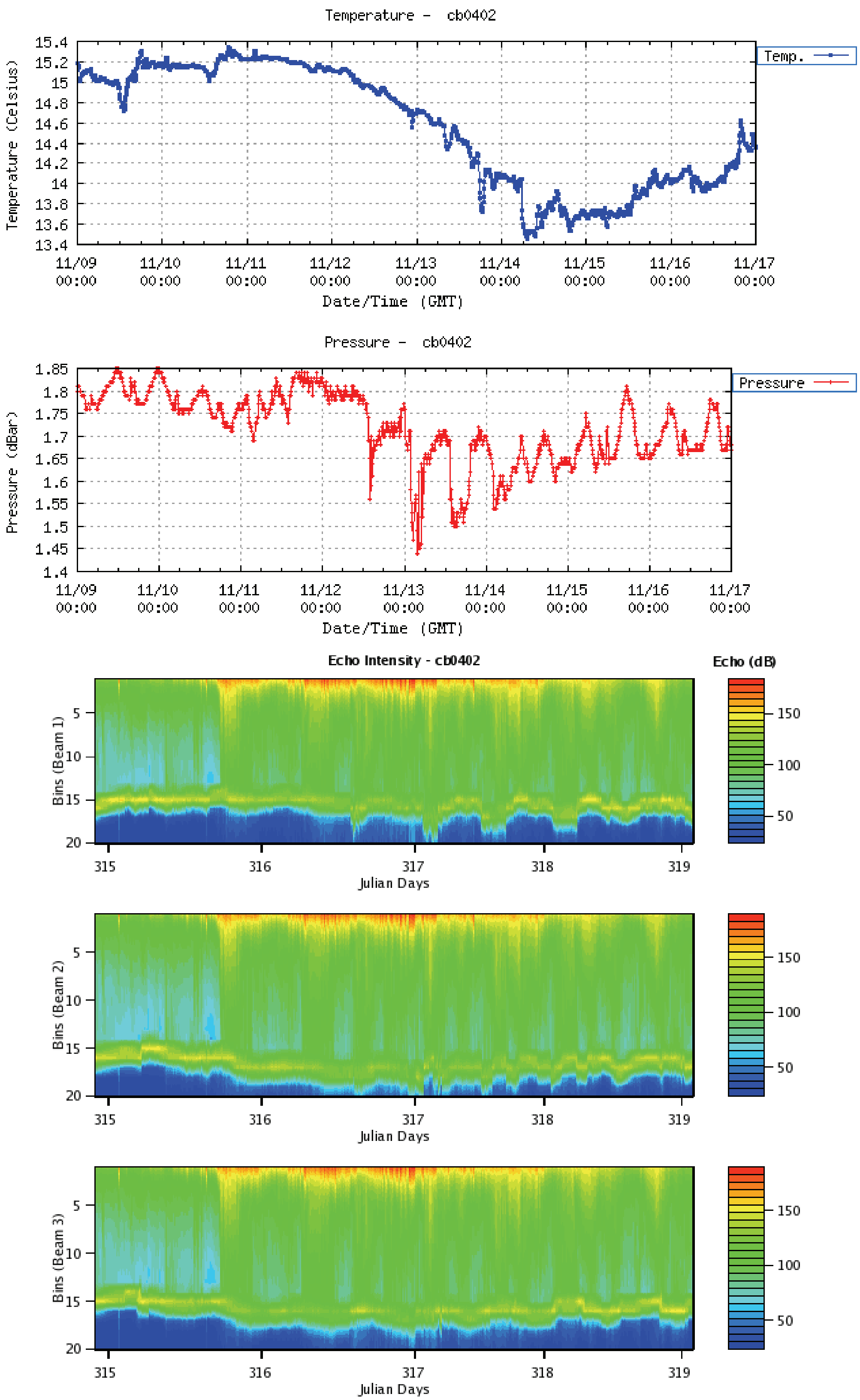


Figure 3.3c. Water temperature, water pressure and echo intensities measured at Naval Station Norfolk LB 7 buoy from November 11 to 15 (Julian Day 315 to 319 GMT).

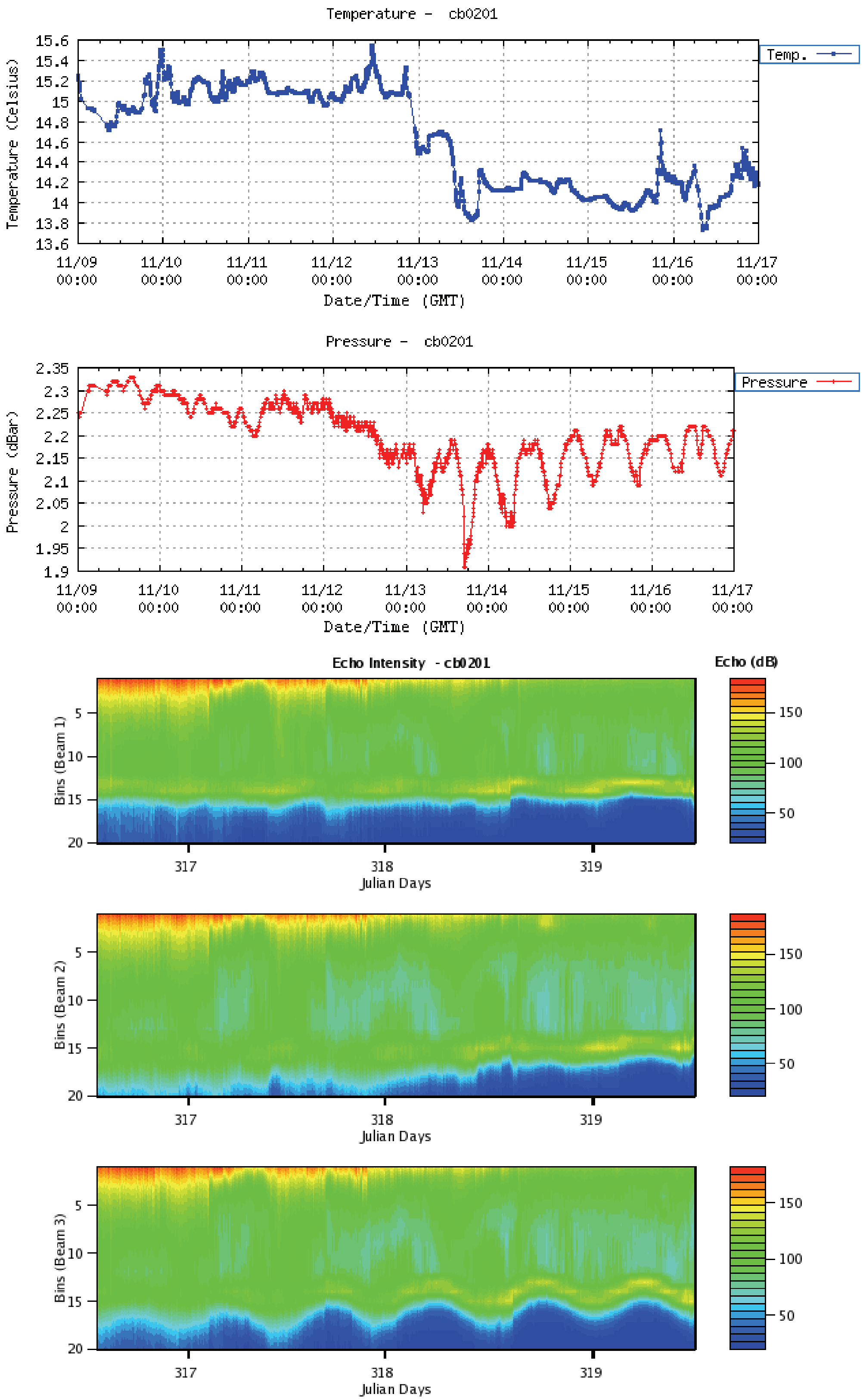


Figure 3.3d. Water temperature, water pressure and echo intensities measured at York Spit LBB 22 during November 12 to 16 (Julian Day 316 to 320 GMT).

The comparisons at the three current meter stations show that the deeper currents measured by the in-situ current meters were faster during ebb flow, with the exception of York Spit LBB ‘22’, which measured faster currents during flood flow. In fact, at peak ebb flows, the 6-m currents were about 50 – 80 cm/s (1 – 1.3 kt) on November 14, when winds were slackening. Differences in velocity may be due to wind shear at the surface, and bathymetry at the sites; however, geometry of the beams and of the comparison can also cause disparity.

CBBT water levels and winds peaked on November 13 at 00:00 GMT. Figure 3.5a-b is a display of the surface currents as vectors at about the time of peak water levels and winds, and clearly shows the waters flooding into the Bay at about 100 cm/s (2 kt). Farther into the mouth of the Bay, where the Sewells Point water level station is located, the current was diverted southward at 50 cm/s (1 kt).

It is clear that the mouth of the Chesapeake experienced strong currents as a result of high winds oriented from the northeast. Delaware Bay was the other region of the Mid-Atlantic that experienced substantial current flow as a result of the Nor’easter winds.

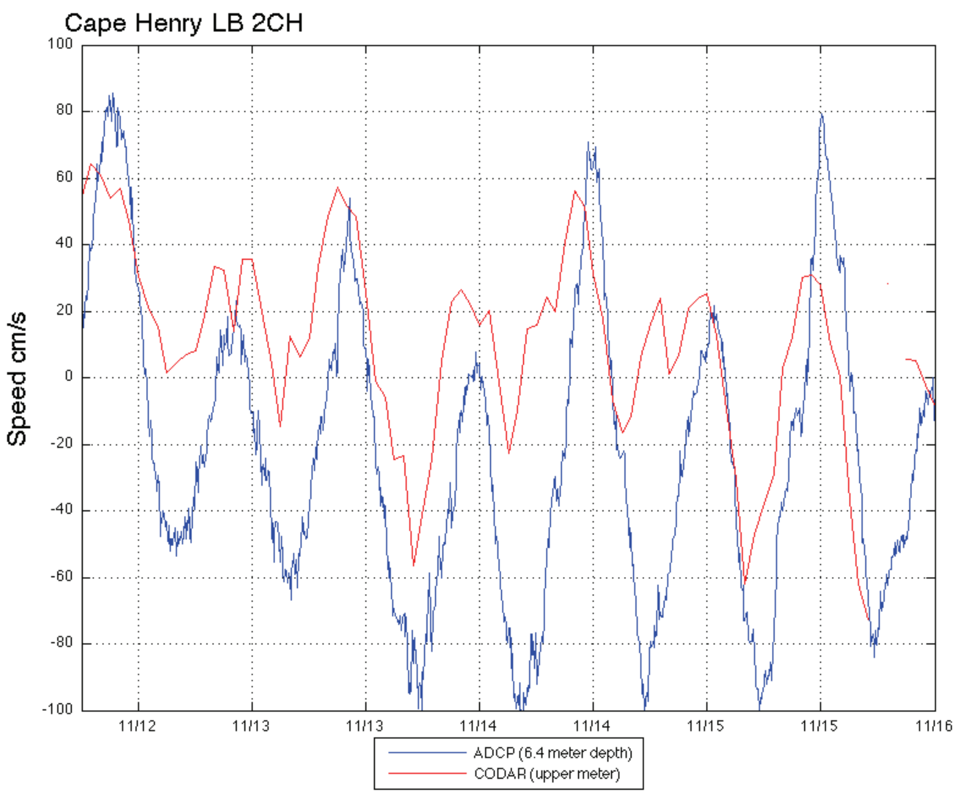


Figure 3.4a. Comparison of HFR-measured surface currents and currents at buoy Cape Henry LB 2CH.

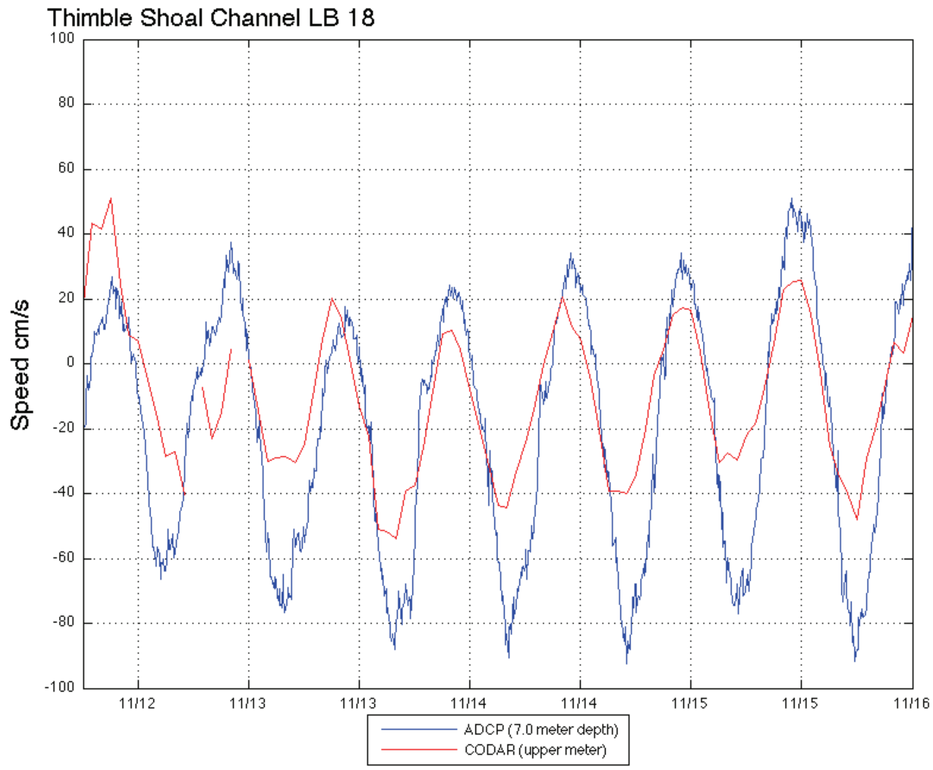


Figure 3.4b. Comparison of HFR-measured surface currents and currents at buoy Thimble Shoal Channel LB 18.

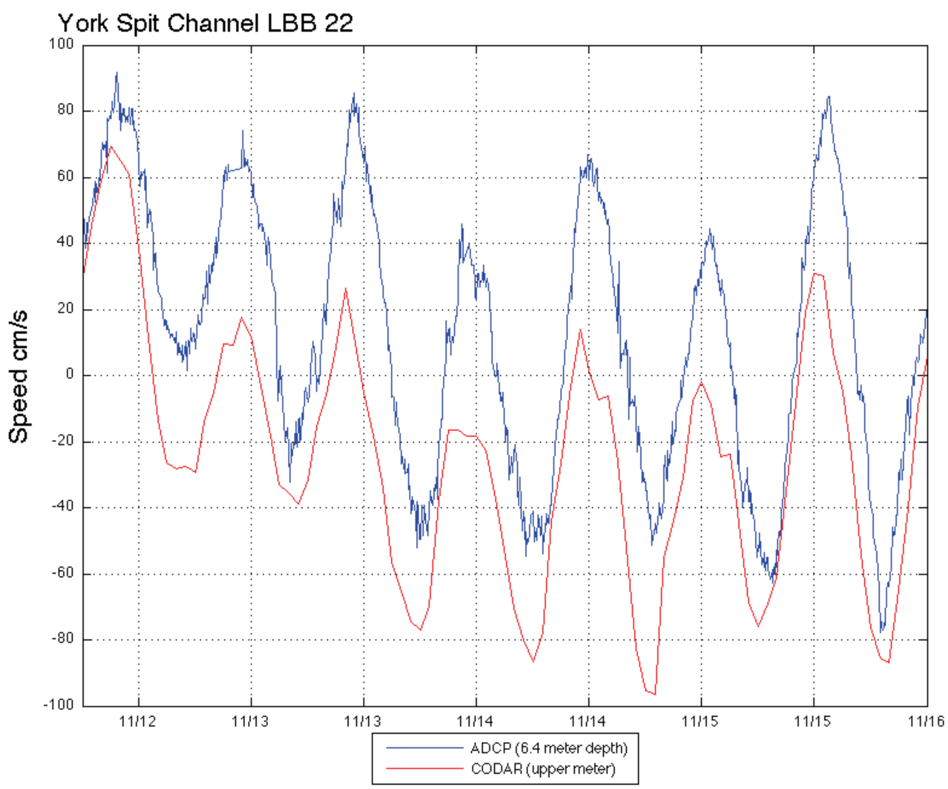


Figure 3.4c. Comparison of HFR-measured surface currents and currents at buoy York Spit LBB 22.

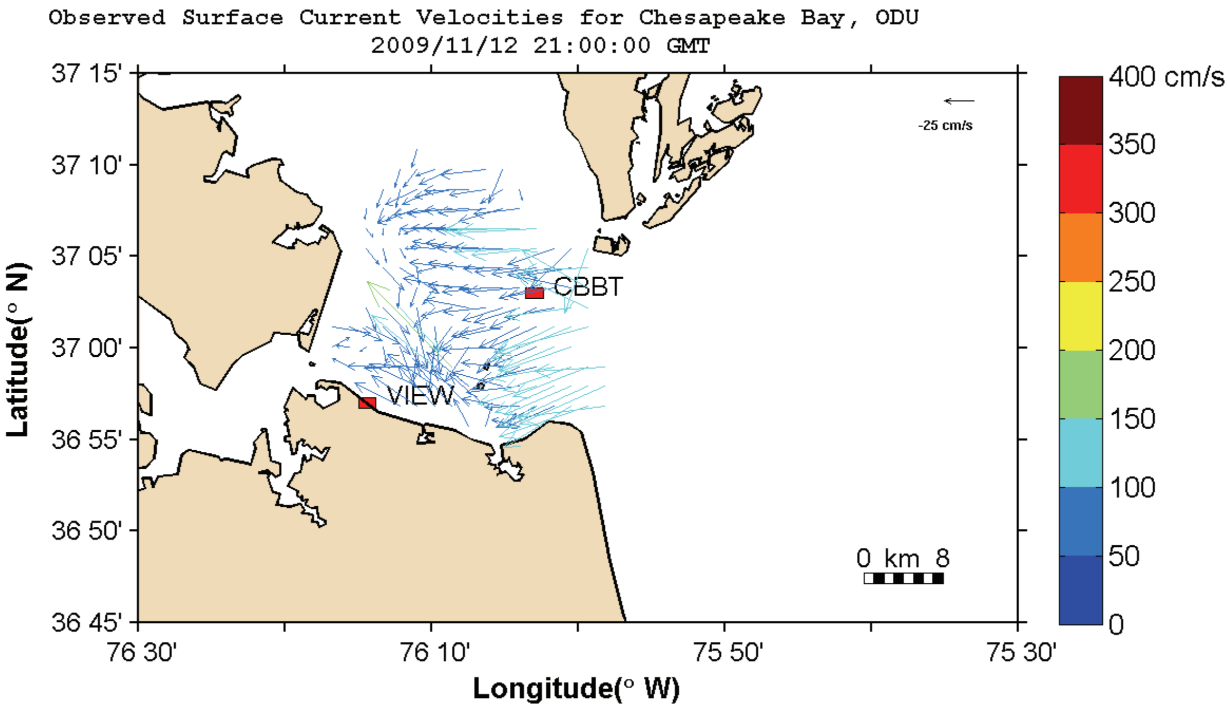


Figure 3.5a. HFR surface currents at the entrance to Chesapeake Bay, November 12 at 21:00 GMT.

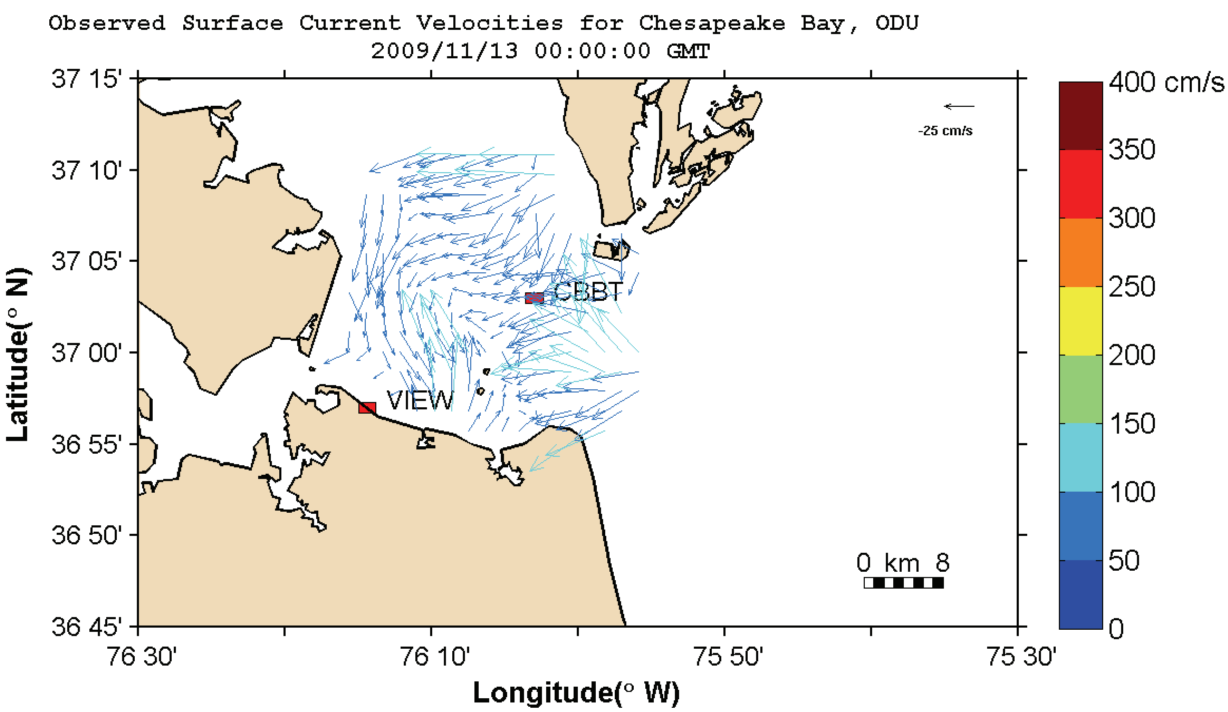


Figure 3.5b. HFR surface currents at the entrance to Chesapeake Bay, November 13 at 00:00 GMT.

Delaware Bay

CO-OPS maintains three current meter stations in the Delaware River and Bay in support of the Delaware River and Bay PORTS® that captured real-time current speed and direction data during the passage of the Nor'easter. Brown Shoal Light is located about ten miles within the entrance of the Bay, Reedy Point is situated at the mouth of the Delaware River, and Philadelphia is located farther up the River (Figure 3.6). Both Brown Shoal and Reedy Point utilize bottom mounted meters and Philadelphia utilizes a sidelooker. The bottom mounted platforms do not react to changes in wind as quickly as the buoy mounted sensors in the Chesapeake Bay.

Figure 3.6. Delaware River and Bay real-time current meter stations.

The water level and meteorological station closest to Brown Shoal Light (Brandywine Shoal Light) recorded maximum winds of 22 m/s on November 12 19:12 GMT (though strong winds persisted over November 12 and 13) and a maximum storm tide of 2.461 m on November 13 12:00 GMT (Appendix). The Brown Shoal Light surface currents (in the flood direction) were about 20 cm/s (0.39 kt) faster than predicted speeds and stronger than ebb flow late on November 12 (Figure 3.7). Figure 3.7, a display of current speeds 4.6 m below the surface, shows that speeds continued to exceed predictions for more than one day after the maximum

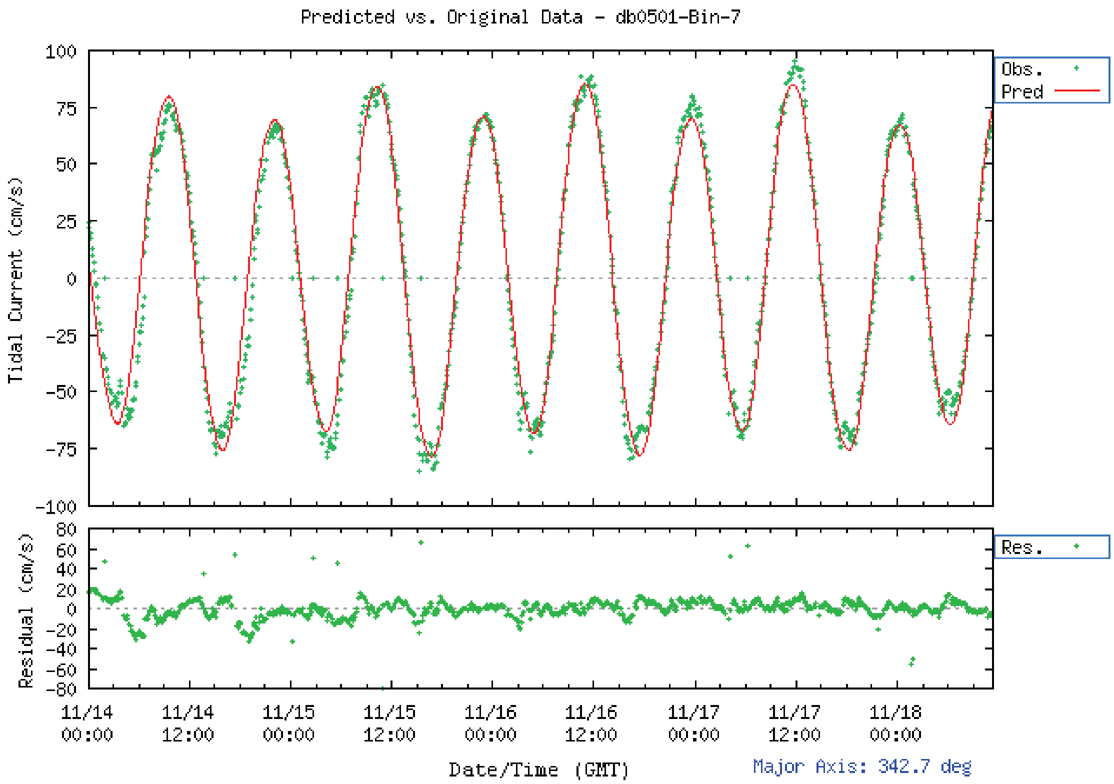


Figure 3.7. Brown Shoal Light current observations and predictions at 4.6 m below the surface (upper panel) and residual currents (lower panel) after the passage of the Nor'easter. (+ flood current, - ebb current). Prior to November 14 a data outage occurred, as seen in Figure 3.8.

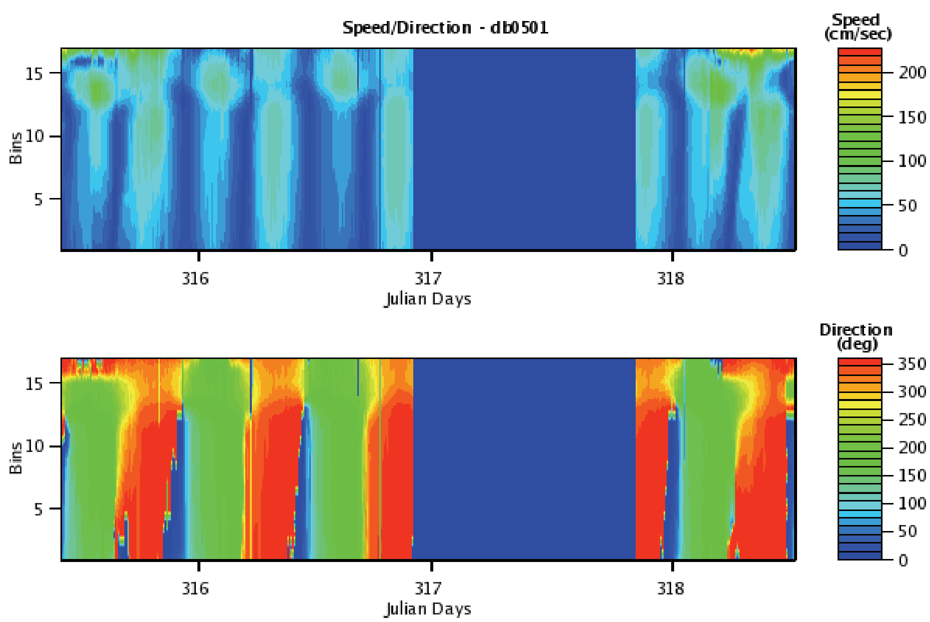


Figure 3.8. Contour plots of current speed (upper panel) and direction (lower panel) at Brown Shoal Light (near the mouth of the Delaware Bay) from November 11 to 14 (Julian Days 315 – 318 GMT). Solid blue areas denote time of data outage.

wind speeds, most likely due to the lag response of the water column to surface winds. Shortly after the maximum wind speeds hit the area, the Brown Shoal Light current meter lost shore-side connectivity, resulting in a loss of data on November 13. When the data resumed on November 14, the ebb current was stronger, up to 40 cm/s beyond predictions (Figures 3.7 and 3.8). Currents then returned to expected values beginning on November 15.

Reedy Point, at the entrance to the Chesapeake & Delaware Canal, recorded flood currents in excess of 100 cm/s approximately 4.9 m below the surface. This was almost 50 cm/s greater than predictions (Figure 3.9). This strong flood current counteracted the tidal ebb flow, which consistently fell short of predictions until about November 14. Closer to the surface, the meter measured stronger ebb flow, with speeds of 150 cm/s (bin 10 in Figure 3.10) roughly twelve hours after peak storm surge at Delaware City, DE (Appendix). The resulting shear was influenced by winds at the surface and rising water levels.

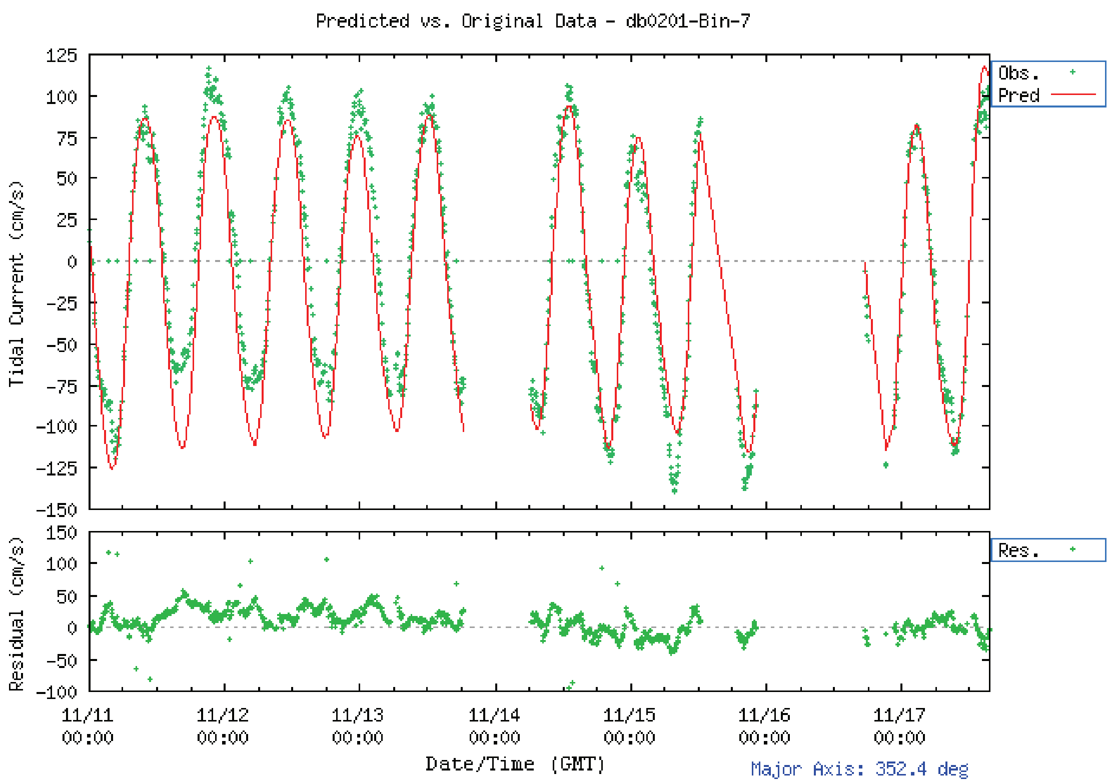


Figure 3.9. Reedy Point current observations and predictions at 4.9 m below the surface (upper panel) and residual currents (lower panel). Note loss of data transmission occurs on November 14 and 16. (+ flood current, - ebb current).

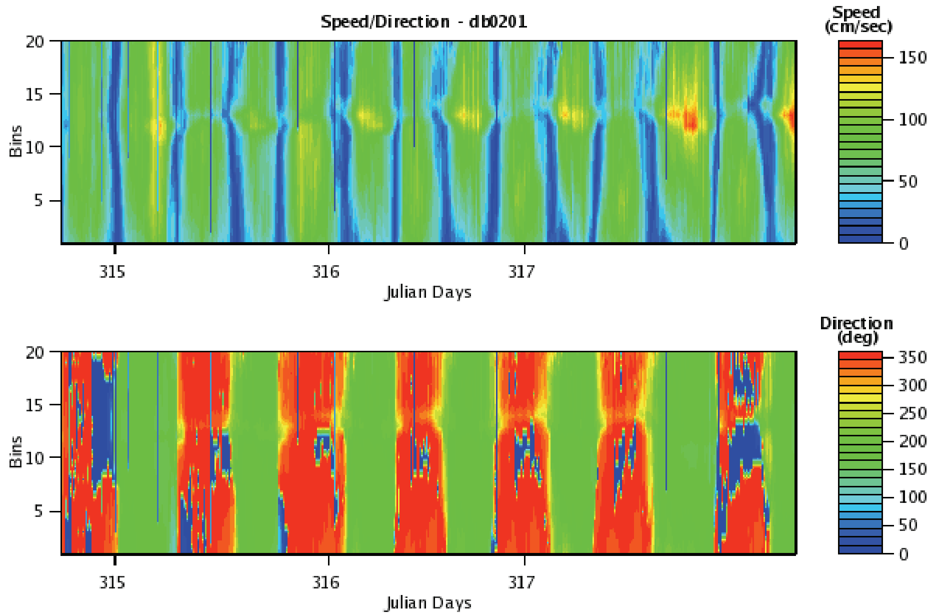


Figure 3.10. Contour plots of Reedy Point current speed (upper panel) and direction (lower panel) from November 10 to 14 (Julian Day 314 to 318 GMT). Current observations are reliable from Bin 1 to Bin 10 (1.9 below the surface). Flood currents are along 354^o with peak speed in excess of 100 cm/s at the surface..

Farther up the Delaware River the horizontal ADP, deployed at Penns Landing in Philadelphia, Pennsylvania, profiles across the Delaware River towards Camden, New Jersey, collecting current data at 4 m intervals at a depth of 4.4 m. The closest water level station to Philadelphia is Tacony-Palmyra Bridge, NJ (Appendix) where maximum storm surge was recorded on November 13 09:36 GMT. Current speeds increase over 100 cm/s out in the main ship channel (Bins 20-30, 540 m from the shore) during ebb flow, shortly after peak storm surge (Figure 3.11a-b). This is likely due to the northeasterly winds, which were somewhat aligned with the orientation of the River, pushing water downstream towards the Bay.

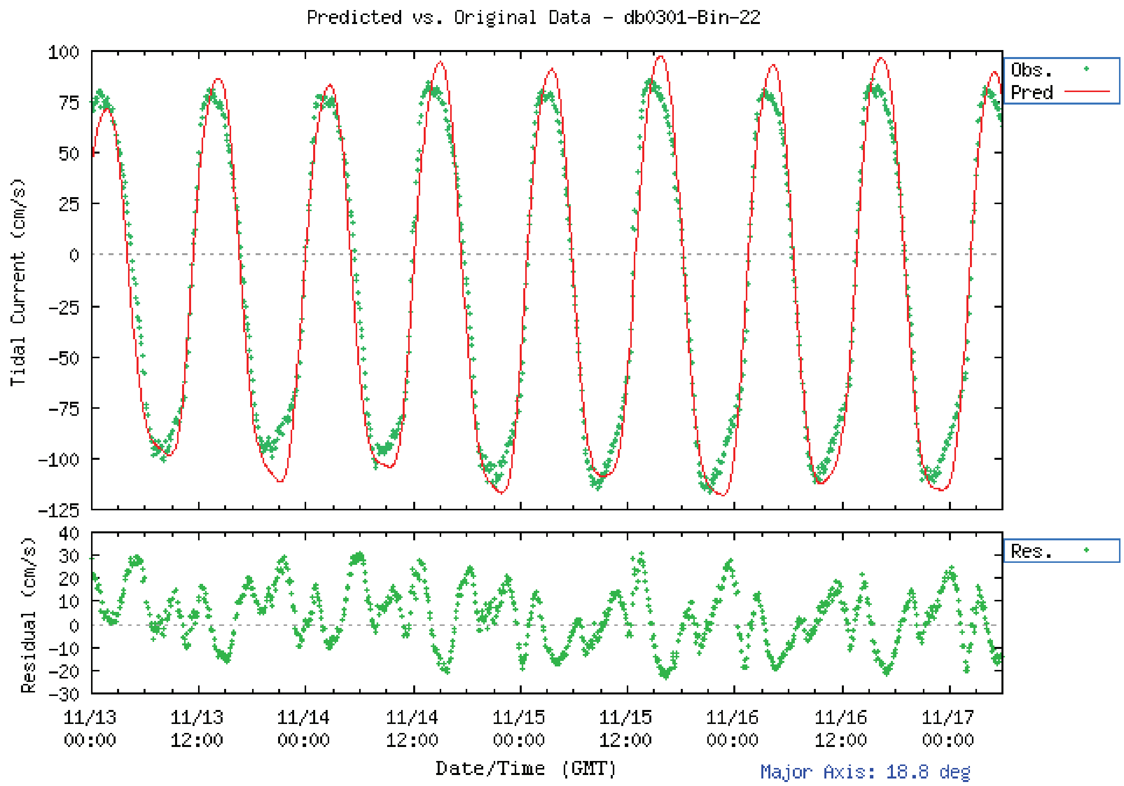


Figure 3.11a. Philadelphia current observations and predictions at 4.4 m below the surface, 540.0 m from the sidelooker (upper panel) and residual currents (lower panel). (+ flood current, - ebb current)

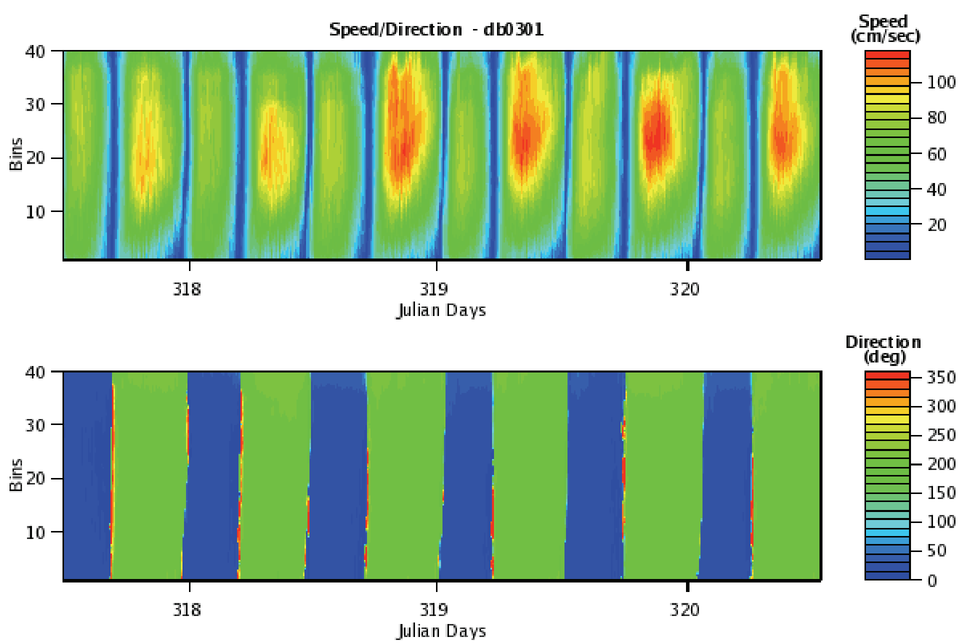


Figure 3.11b. Contour plots of Philadelphia current speed (upper panel) and direction (lower panel) from November 13 to 17 (Julian Day 317 to 321 GMT). Ebb currents are along 200° and peak above 100 cm/s in the middle of the main ship channel.

4.0 WATER LEVEL FORECASTS FROM CHESAPEAKE BAY OPERATIONAL FORECAST SYSTEM

The National Ocean Service (NOS) has been developing and implementing coastal and estuarine operational forecast model systems to support navigational and environmental applications in U.S. coastal waters for many years. These operational forecast systems are designed to enhance the navigational guidance supplied by PORTS® by providing information regarding both the present (nowcast) and future (forecast) oceanographic conditions along the U.S. coast and within estuaries. Chesapeake Bay Operational Forecast System (CBOFS) provides short-term water level forecast guidance to marine users in the Chesapeake Bay. The core of the CBOFS is a two-dimensional hydrodynamic model, the Model for Estuarine and Coastal Circulation Assessment (MECCA) (Hess 1989; Hess 2000) with a square horizontal grid cell of size 5.6 km. CBOFS runs four cycles per day to produce a nowcast of water levels for the most recent day and a forecast of water levels for the next 24 hours. It incorporates tidal forcing, wind fields and coastal water levels from National Weather Service weather and ocean forecast models, real-time wind and water-level observations from the in Chesapeake Bay PORTS®, plus historical river inputs. A retrofitted Chesapeake Bay Operational Forecast System (CBOFS2) is in the process of transitioning to operational. The core model of CBOFS2 is a fully three-dimensional, baroclinic hydrodynamic model, the Regional Ocean Modeling System (ROMS). The CBOFS2 horizontal model grid is curvilinear and orthogonal with high resolution ranging from 30 m along navigation channels to 5 km near the offshore open boundary. A terrain-following sigma coordinate with 20 layers is employed.

Numerical studies (Luettich et al. 1992, Westrink et al. 1992, Shen et al. 2009) show that a large model domain with higher grid resolution is necessary to predict accurately storm surge inundation in the Chesapeake Bay to resolve the complex bathymetry and irregular shorelines. The grid resolution of the current version of CBOFS of 5.6 km is probably not appropriate for storm surge simulations caused by systems such as Nor'easters. On the other hand, the surface wind forcing for CBOFS forecast runs is interpolated from the NCEP's North American Model (NAM) with resolution of 12 km.

Although CBOFS is not designed to simulate storm surge, the model forecasts can still provide insight into water level responses to storm surge when storm events occur. Figure 4.1a-c shows a comparison of time series of modeled water level forecasts with the observations at six stations from the lower Bay, the middle Bay, and the upper Bay. In general, the model captured the surge height and the time of occurrence of surge peak well in the lower Bay, and over-predicted surge height in the middle and upper Bay during the surge peak.

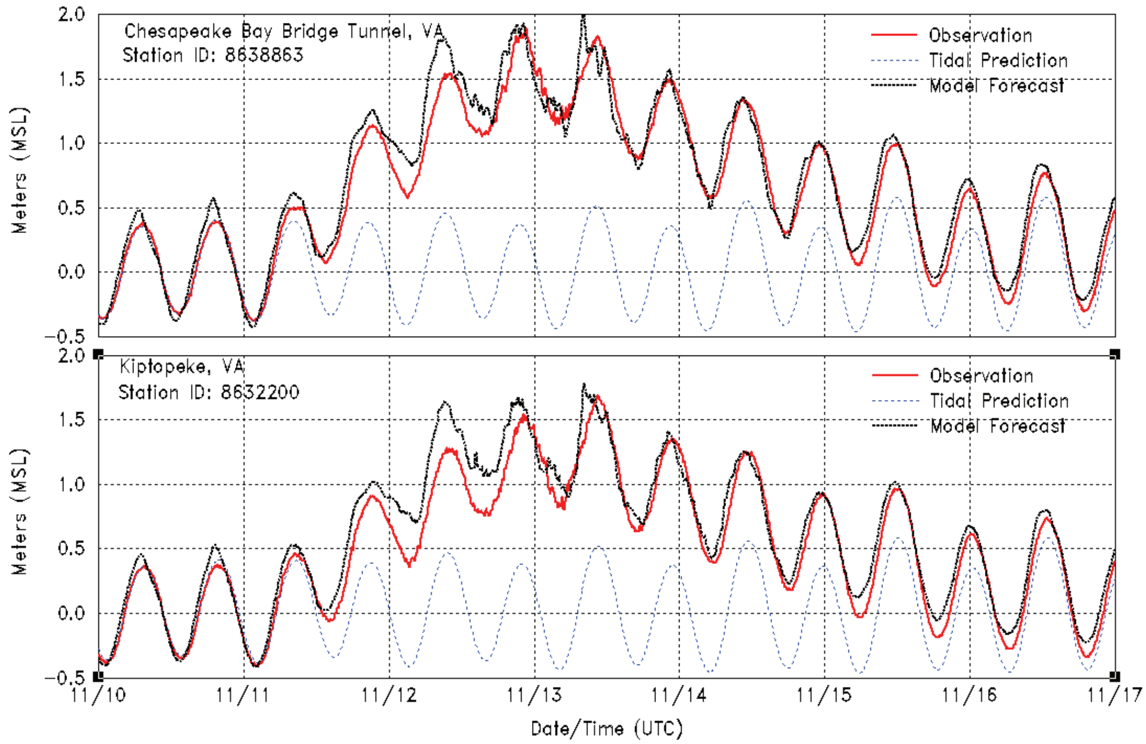


Figure 4.1a. Water level time series at CBBT and Kiptopeke, VA in the lower Chesapeake Bay. Data are from CBOFS.

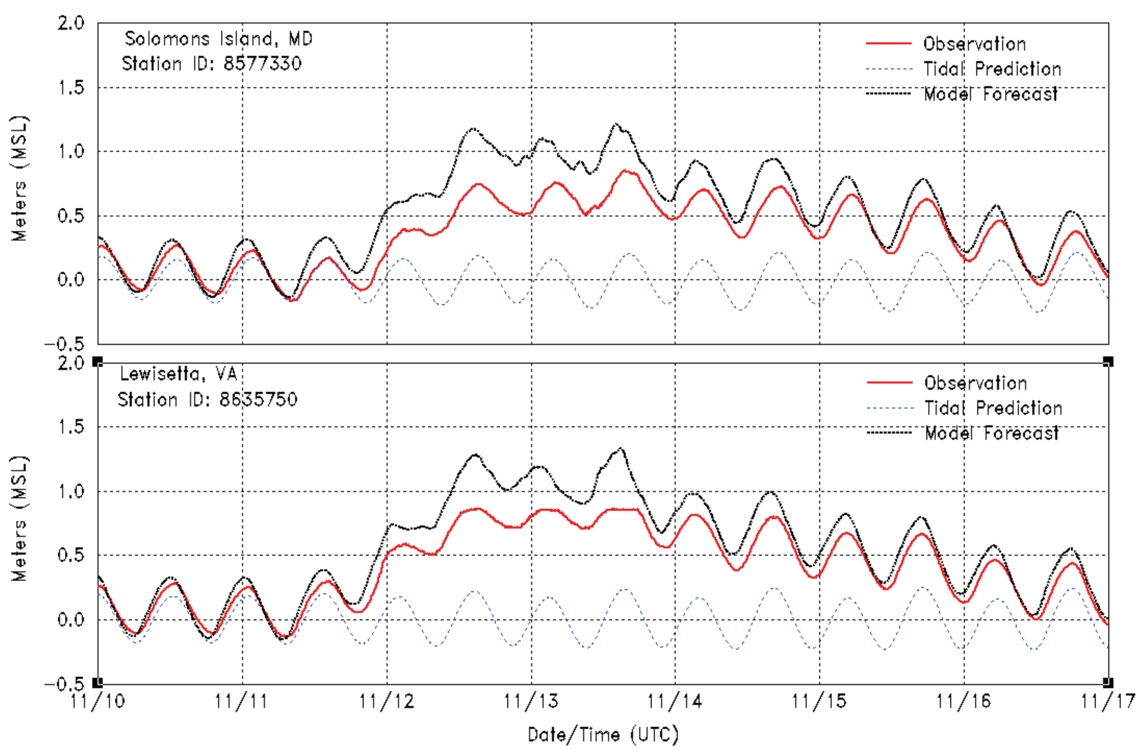


Figure 4.1b. Water level time series at Solomons Island, MD and Lewisetta, VA in the middle Bay. Data are from CBOFS.

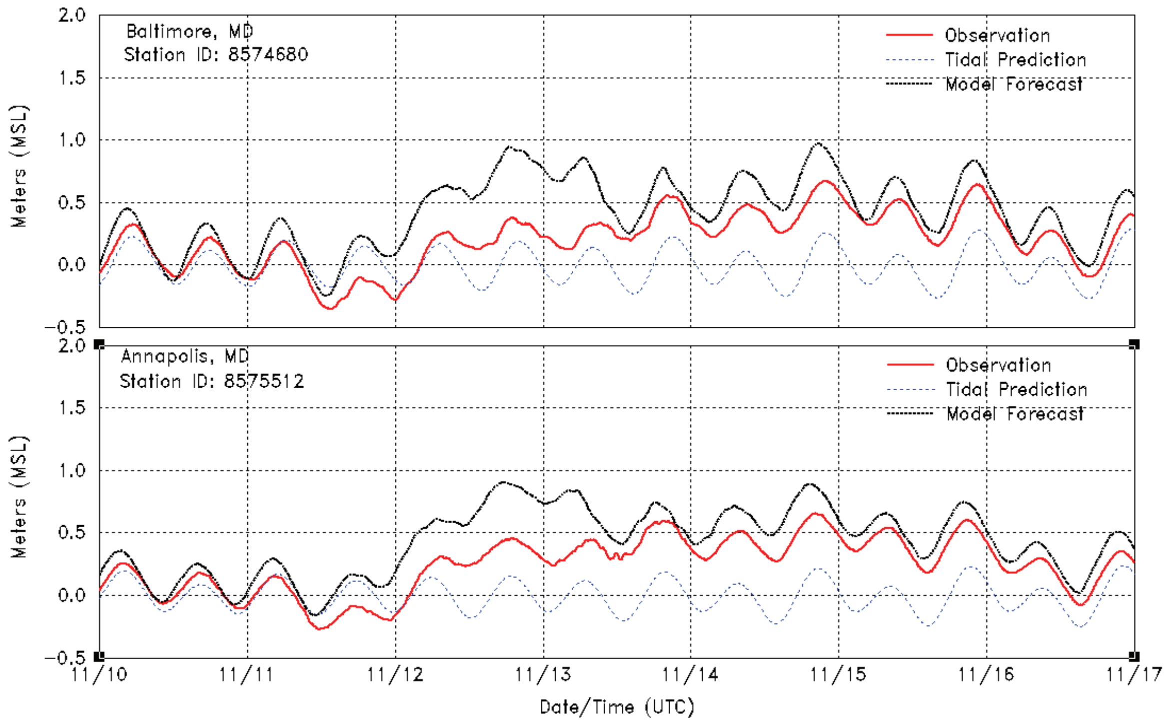


Figure 4.1c. Water level time series at Baltimore and Annapolis, MD in the upper Bay. Data are from CBOFS.

Figure 4.2a-b shows contours of water level forecasts from the CBOFS2 and its surface forcing wind vectors from NCEP North American Model (NAM) forecasts during the Nor'easter (from November 12 to November 13) in the Chesapeake Bay. It can been seen that NAM-forecasted winds are dominated by northerly and northeasterly winds and are generally uniform in the entire Chesapeake Bay during the Nor'easter event. The maximum surge occurred right at the mouth of Chesapeake Bay with a height of over 2 m (8 ft) above mean sea level (MSL), and the surge generated offshore propagated into James River and York River, and was magnified upstream since the rivers become shallower and narrower. The surge was restrained in the lower Bay area (south of Mobjack Bay) and was prevented from propagating further into middle Bay since dominant northerly and northeasterly winds drove water from the upper Bay into the lower Bay.

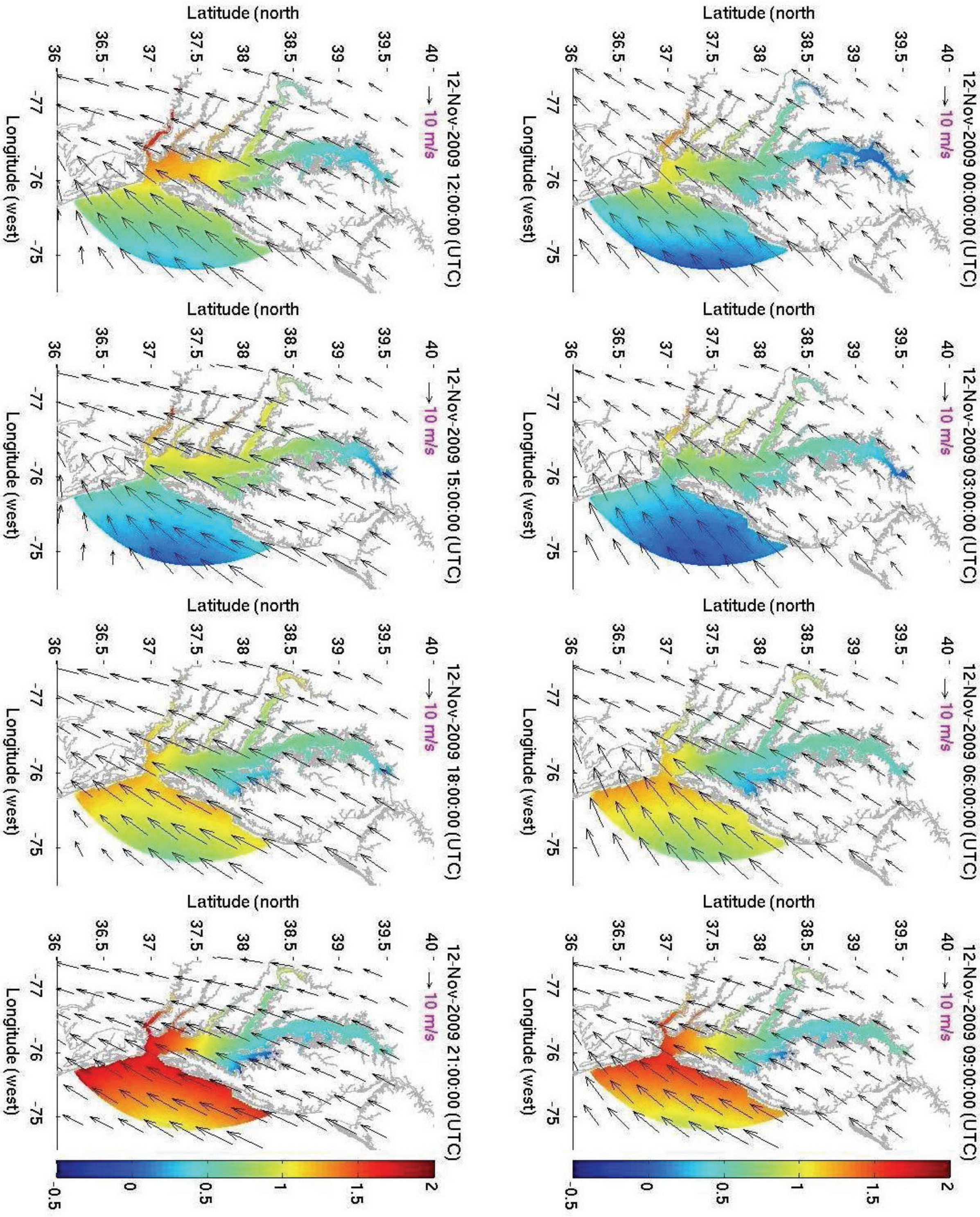


Figure 4.2a. Modeled water level contours and surface wind vectors from NAM forecasts on November 12. Data are from CBOFS2.

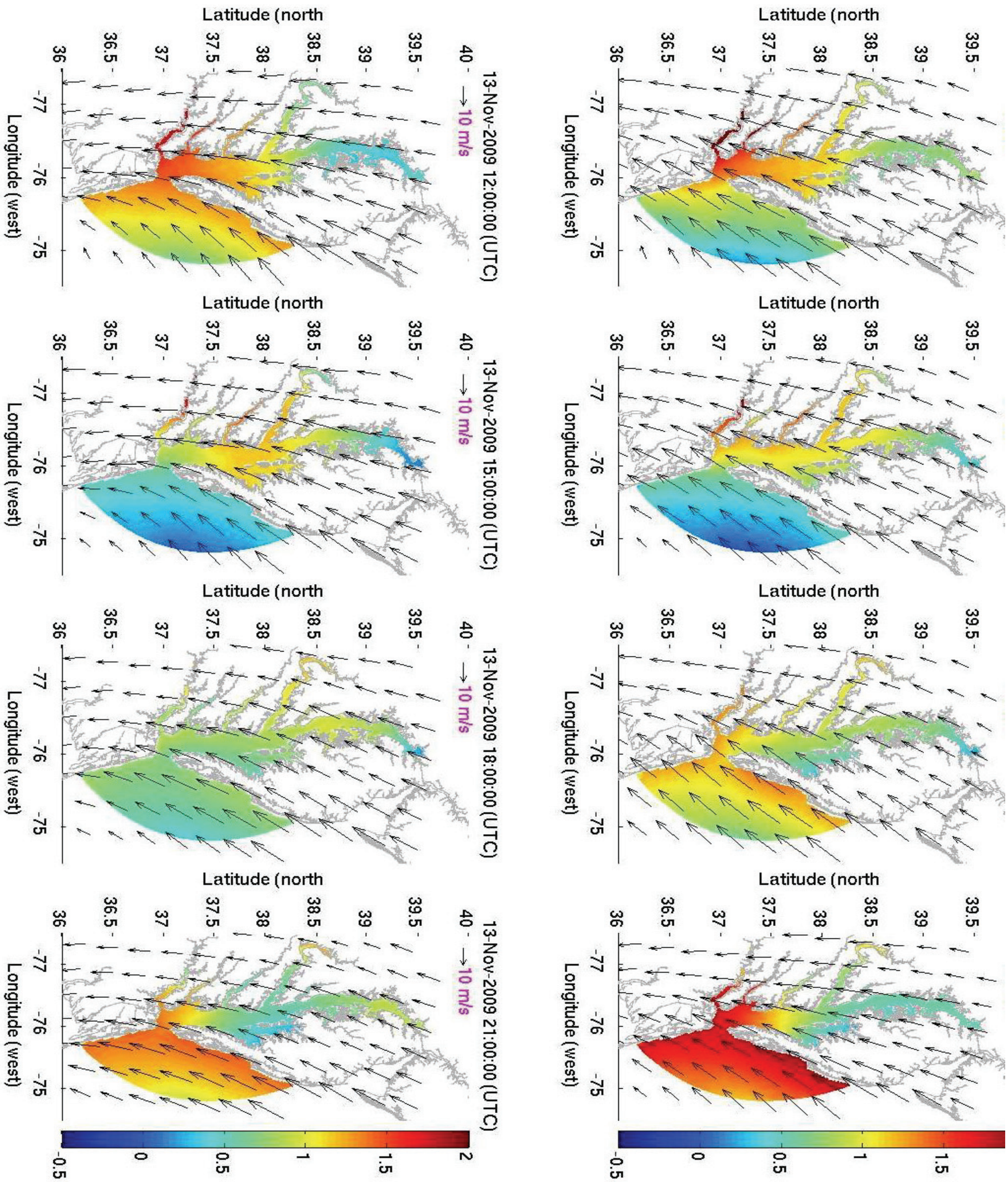


Figure 4.2b. Modeled water level contours and surface wind vectors from NAM forecasts on November 13. Data are from CBOFS2.

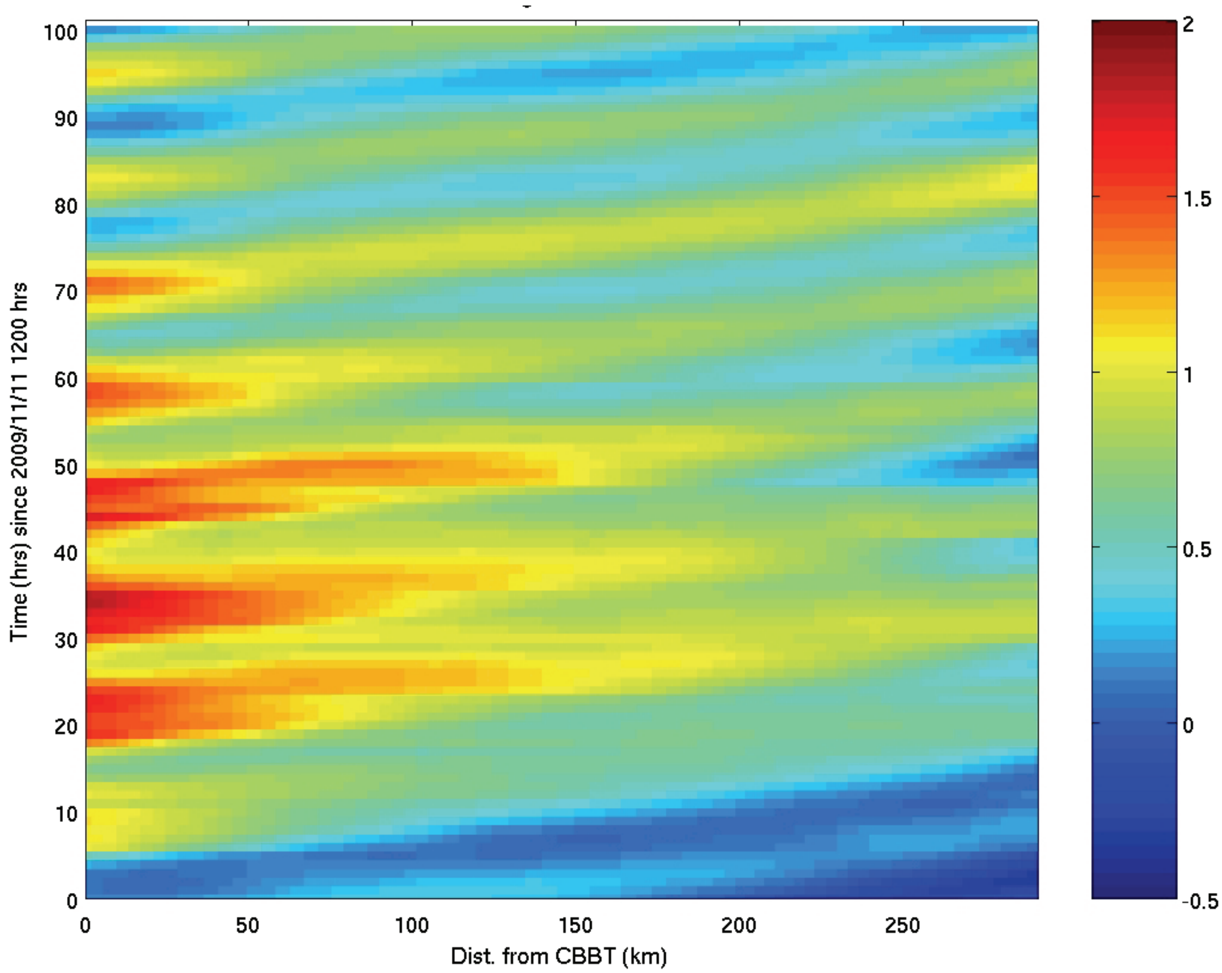


Figure 4.3. Modeled water elevation variations along the main navigational channel in the Chesapeake Bay. The time starts at 00:00 UTC on November 11, 2009 and the distance is calculated from the first location in the lower Bay (near Chesapeake Bay Bridge Tunnel) to the upstream near Susquehanna Flats. Data are from CBOFS2.

Figure 4.3 shows the forecasted water level distribution along the main navigational channel (from Chesapeake Bay Bridge Tunnel (CBBT) to Susquehanna Flats) of the Bay during the Nor'easter. The transect is shown in Figure 4.4. There are three significant surge peaks (surge height greater than 1.5 m) in the lower Bay, and the area with surge height greater than 1.5 m is limited to 50 km from CBBT. The surge height is generally less than 1.5 m in the middle Bay and the upper Bay.

Upon the comparison with observations, CBOFS2 is capable of accurately forecasting surge height in the lower Bay, but it over-predicted peak heights in the middle Bay and upper Bay. This should mostly attribute to the coarser surface wind forcing which failed to resolve the local wind nature in the middle and upper Bay.

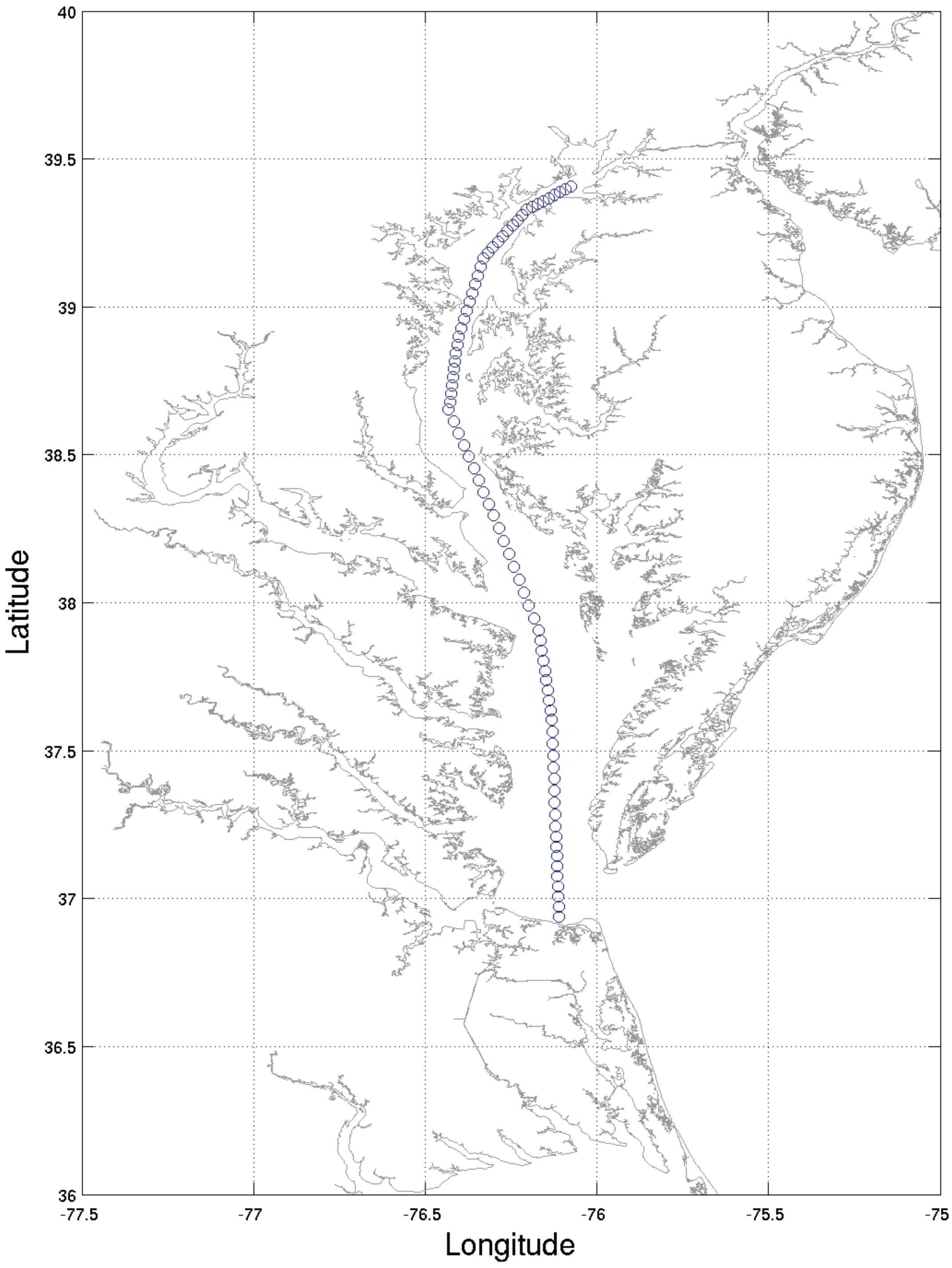


Figure 4.4. The transect used in Figure 4.3 along the main stem of the Chesapeake Bay.

SUMMARY

The coastal low that became the November 2009 Nor'easter formed by entraining moisture and energy from the remnants of Tropical Storm Ida, as it progressed toward the Atlantic Ocean. As the previous chapters illustrate, this Nor'easter was not a particularly strong or intense storm, but it is historic in its effects on the water levels along the entire Mid-Atlantic Coast, mainly due to the steady north and northeasterly winds that sustained the high waters over several days. The water levels varied regionally, with the highest impacts at the mouth of major bays. The mouth of the Chesapeake Bay was most affected, followed by the mouth of the Delaware Bay. These two areas contain five NOS water level stations where historic water level maxima were exceeded, meaning that the Nor'easter had a greater effect on water levels in these regions than any previous storms.

Chesapeake Bay

Several previous studies (Elliot 1978; Wang and Elliot 1978; Elliot and Wang 1978; Wang 1979a; Wang 1979b; Shen 2006; and Shen 2009) determine that storm surge elevation in the Chesapeake Bay is mainly caused by superposition of two distinct physically-driven mechanisms: offshore surge propagation into the Bay and local wind effect. The interactions of the incoming surge propagating into the Bay and the local wind forcing from N and NE directions result in an enhanced setup in the lower and middle portions of the Bay, whereas the combination of incoming surge and local wind forcing from S and SE directions enhances the surge in the upper Bay. The water level in the lower Bay is more influenced by the offshore condition, and the surge in the upper Bay is mainly caused by local wind forcing. The Chesapeake Bay experienced a range of effects from the Nor'easter, with rivers at the mouth of the Bay experiencing the largest storm surge, the open area at the mouth of the Bay following in magnitude, and the Upper Chesapeake showing relatively little response to the storm.

As chapter 2 indicates, four of the five water level stations that exceeded historical water level maxima were located at or near the mouth of the Chesapeake. Winds were strongest at CBBT, with speeds of 26 m/s (52 kt) and gusts up to 33 m/s (65 kt). Likewise, CBBT experienced a record storm tide of 2.319 m above MLLW, barely topping the previous record, by 0.022 m (0.07 ft). As expected, currents were also substantially affected at the mouth of the Bay. Current measurements from Buoy 2CH captured a strong inflow of water on November 11 and 12, followed by a strong outflow of water on November 13 and 14, as wind speeds began to drop. Residual current speeds during both the flood and ebb events had reached about 60 cm/s (~1 kt). These data clearly reflect the amount of forcing that the northeasterly winds had on waters at the mouth of the Bay.

An examination of storm surge allows a regional comparison of the impact of the Nor'easter as measured at various stations. Although the mouth of the Bay was affected most by the northeasterly winds, the rivers near the mouth of the Bay experienced the highest storm surges mainly due to changing geography. The largest storm surge of 2.055 m (6.74 ft) was measured at Money Point, where water levels along the Elizabeth River were amplified due to the narrowing channel. In fact, winds at Money Point were generally less than 10 m/s (19 kt) throughout the storm, roughly 10 m/s lower than CBBT winds. Water level contours and surface wind vectors from NAM forecasts on November 13 illustrate the higher response in the rivers near the mouth of the Bay, as well as the diminished effects in the upper Bay (Figure 4.2b).

Although the incoming surge was propagating up the Bay, the upper Chesapeake was less affected, most likely due to lack of S and SE wind forcing. The Chesapeake City water level station, located at the northern tip of the Bay, measured relatively lower water levels and wind speeds. In this area, the friction from land likely kept wind speeds below 10 m/s during most of the storm. The northeasterly winds kept storm surge levels low in the upper Bay, acting against the surge that was propagating upwards from the mouth of the Bay, and therefore surge levels hardly exceeded 0.500 m (1.50 ft).

Delaware Bay
The Delaware Bay is much smaller than the Chesapeake Bay but it is also highly influenced by wind forcing from the northeast. In general, Nor'easters have major a impact on the Bay, as the winds move parallel to the shelf causing flood currents and rising water levels. One NOS water level station (Brandywine Shoal Light) exceeded historical maxima in the Delaware Bay. The mouth of the Bay, where Brandywine Shoal Light is located, experienced the highest water levels as well as very high winds. Water levels at Brandywine Shoal Light exceeded the previous record by 0.055 m (0.18 ft), and winds peaked at 23 m/s (45 kt) gusting to 25 m/s (49 kt). Delaware City, at the mouth of the Delaware River, the water levels and wind speeds were lower relative to Brandywine Shoal Light. In this area, the current meter at Reedy Point (near the entrance to the C&D canal) measured ebb flow of up to 150 cm/s (~3 knots). Also, the Philadelphia current meter on the Delaware River measured currents greater than 100 cm/s (~2 knots) during ebb flow. Farther up the river, water levels and winds were lower than at the mouth of the Bay. Generally, the current meter data indicate that the water flow was stronger down-river and towards the Bay, most likely pushed by the persistent northeasterly winds. This also explains why the River stations measured relatively lower water levels, as opposed to the situation in the southern Chesapeake Bay, where rivers experienced amplified levels. Storm surge was not allowed to propagate as far up the Delaware River, due to opposing winds and currents.

Outer Coastal areas
Outer coastal areas measured fairly high water levels during the Nor'easter. Regional winds tend to be higher in marine areas, as surface friction increases over land rather than water. Therefore, outer coastal areas are susceptible to winds that have encountered less resistance than areas inland, in turn, leaving these areas more susceptible to high water levels. The orientation of the coastline, however, also factors into water level heights. Duck, NC, for example, experienced the highest winds of the CO-OPS stations at 15 to 20 m/s, and storm surge was over 1 m. Further up the coast (at Ocean City Inlet, MD) winds were weaker, although the storm surge levels were basically the same as measured at Duck. This difference is likely due to the shape of the coastline, as Ocean City Inlet is located at the entrance to the Isle of Wight Bay, in a narrow channel. Overall, the coastal regions affected most were near the Outer Banks, with storm surge levels comparable to those seen in the North.

CONCLUSION

Although the November 2009 Nor'easter will not be remembered as a significantly strong storm, meteorologically, its sustained northeasterly winds over a long duration marked the storm as an historical event, as evidenced by record-setting water levels. Coastal erosion was substantial from the Outer Banks, NC to New Jersey. It is clear that regions of the East Coast were all affected differently by the November Nor'easter. Coastline orientation played a large part (in addition to wind strength) sometimes causing winds to be dampened, or exacerbating water levels in river areas near the mouth of bays. Figure 5.1 shows that among the various regions, the timing of elevated water levels was similar, though clearly varied based on specific location. Most importantly, water levels were elevated over a period of five days, which is unusual for a Nor'easter, as these storms typically sweep through an area within 24-36 hours. This long duration was possibly the most damaging feature of the storm, and caused several record-setting water levels as well as flood damage and associated coastal erosion from the sustained high waves.

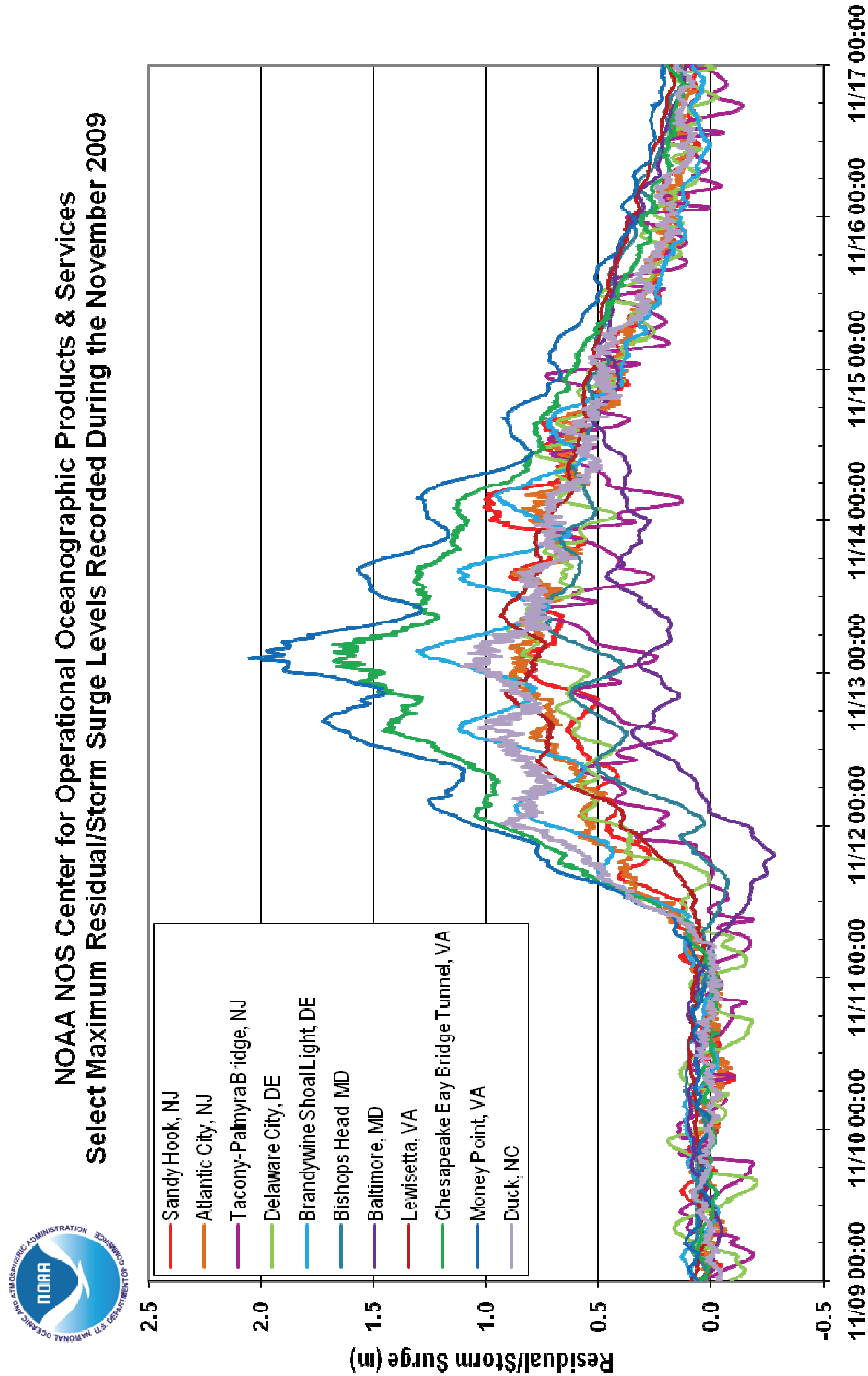


Figure 5.1. Storm surge levels for East Coast water level stations.

ACKNOWLEDGEMENTS

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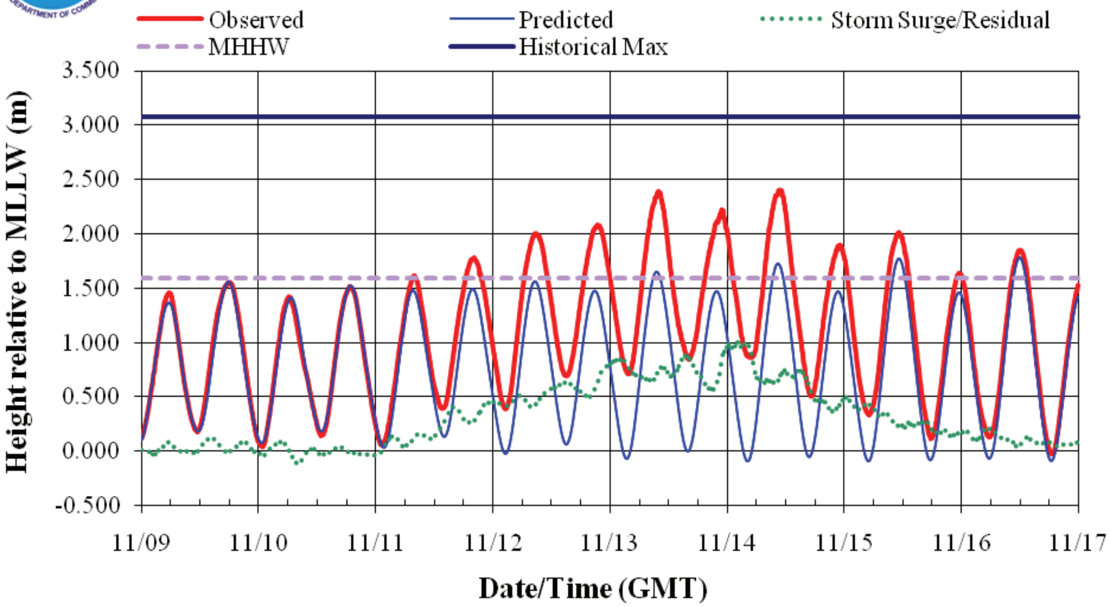
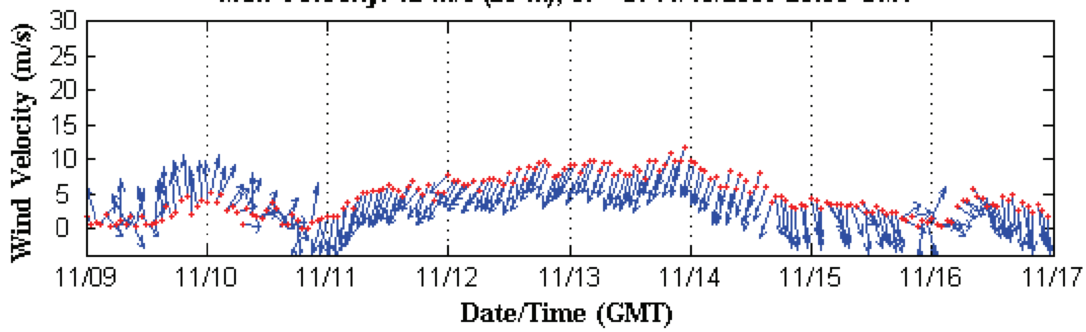
APPENDIX

Time Series of Observed Water Level, Predicted Tide, Storm Surge, Winds and Barometric Pressure Data at CO-OPS Water Level Stations

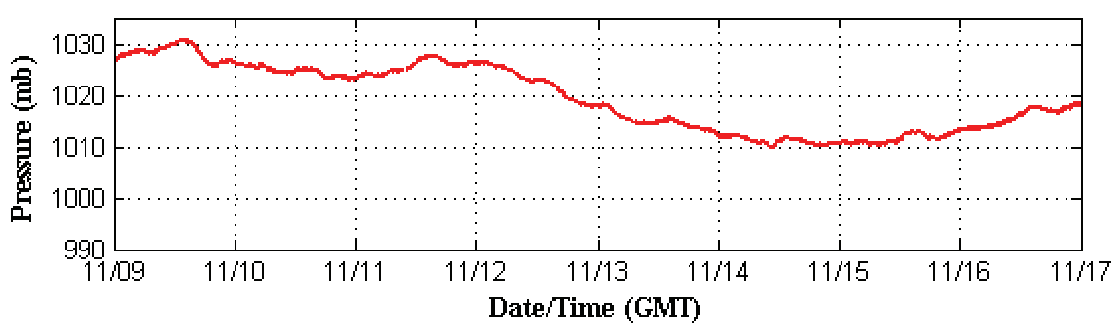
8531680 Sandy Hook, NJ - November 2009 Nor'easter
Max Storm Tide: 2.401 m (7.88 ft) 11/14/2009 10:54 GMT
Max Storm Surge/Residual: 1.010 m (3.31 ft) 11/14/2009 02:12 GMT

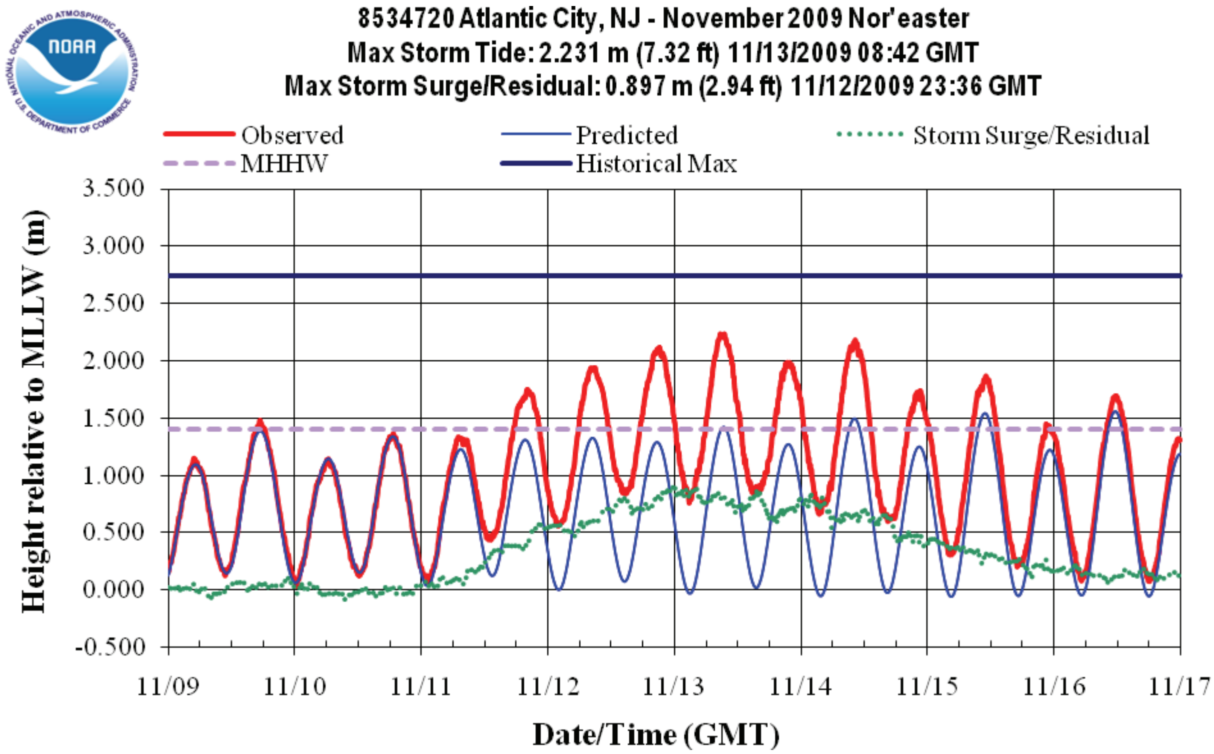


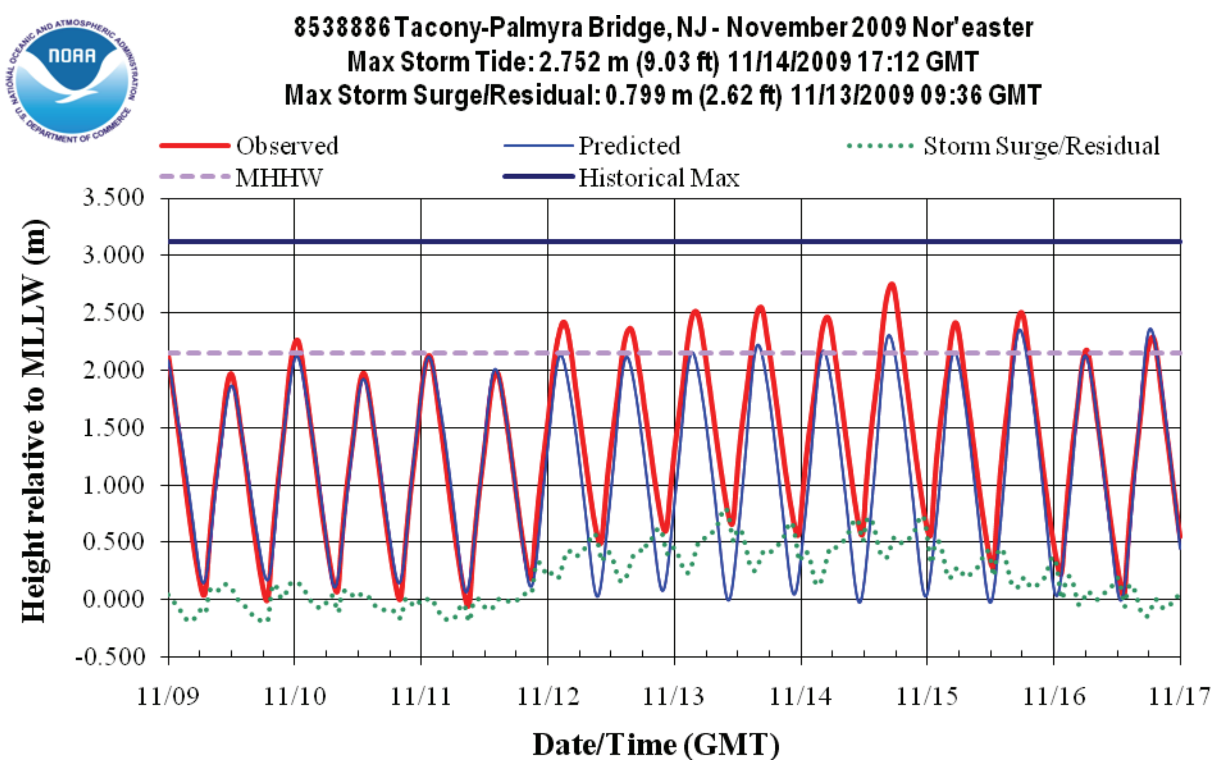
Winds
Max Velocity: 12 m/s (23 kt), 37° at 11/13/2009 23:00 GMT

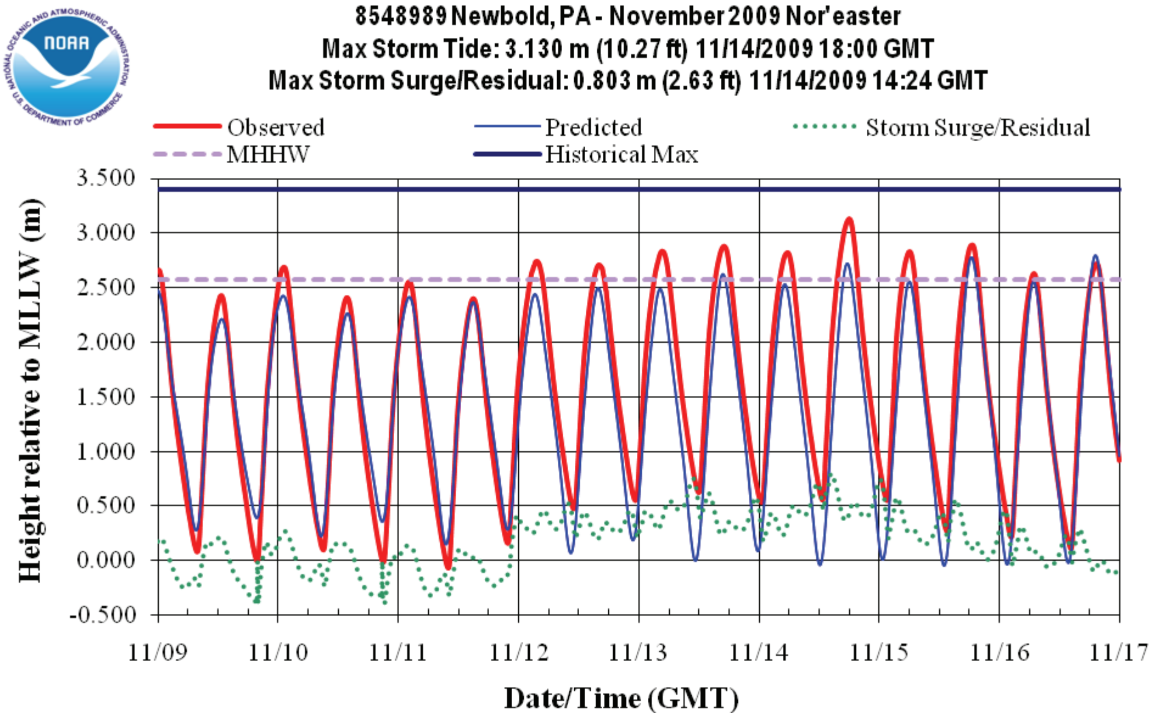


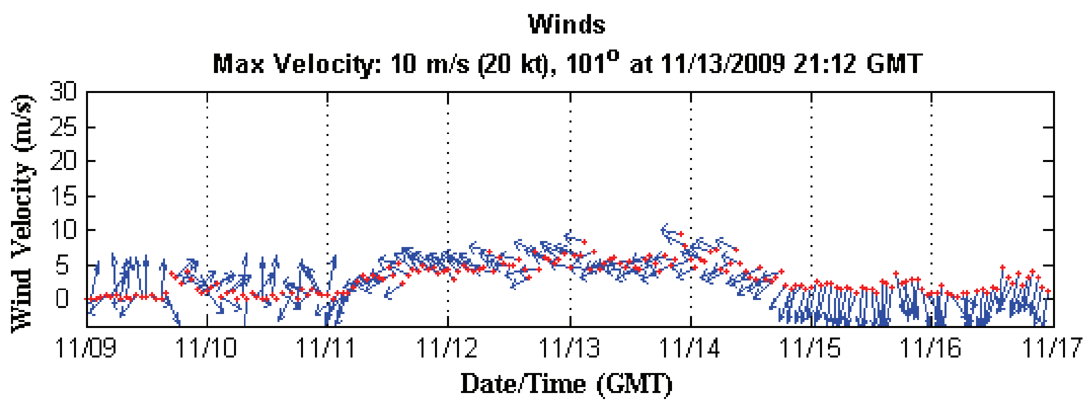
Barometric Pressure
Min Pressure: 1009 mb at 11/14/2009 10:36 GMT

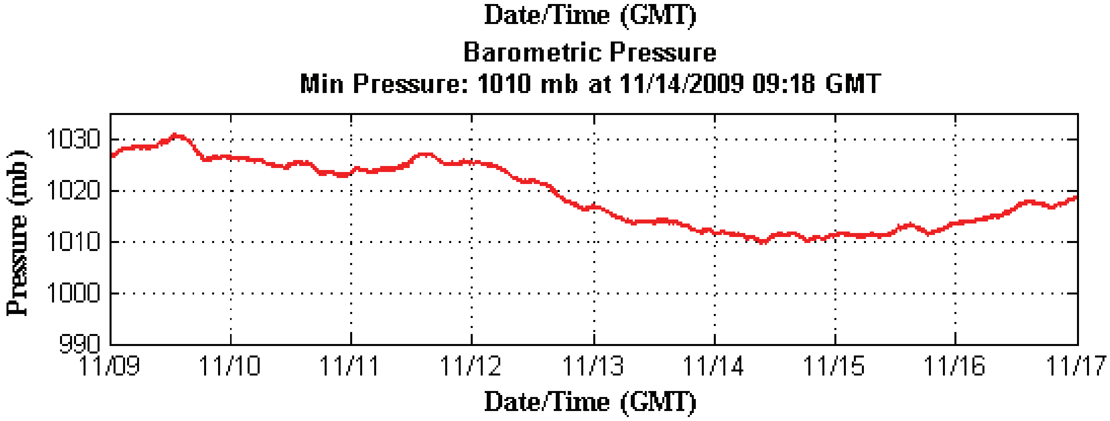



8534720 Atlantic City, NJ - November 2009 Nor'easter
Max Storm Tide: 2.231 m (7.32 ft) 11/13/2009 08:42 GMT
Max Storm Surge/Residual: 0.897 m (2.94 ft) 11/12/2009 23:36 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

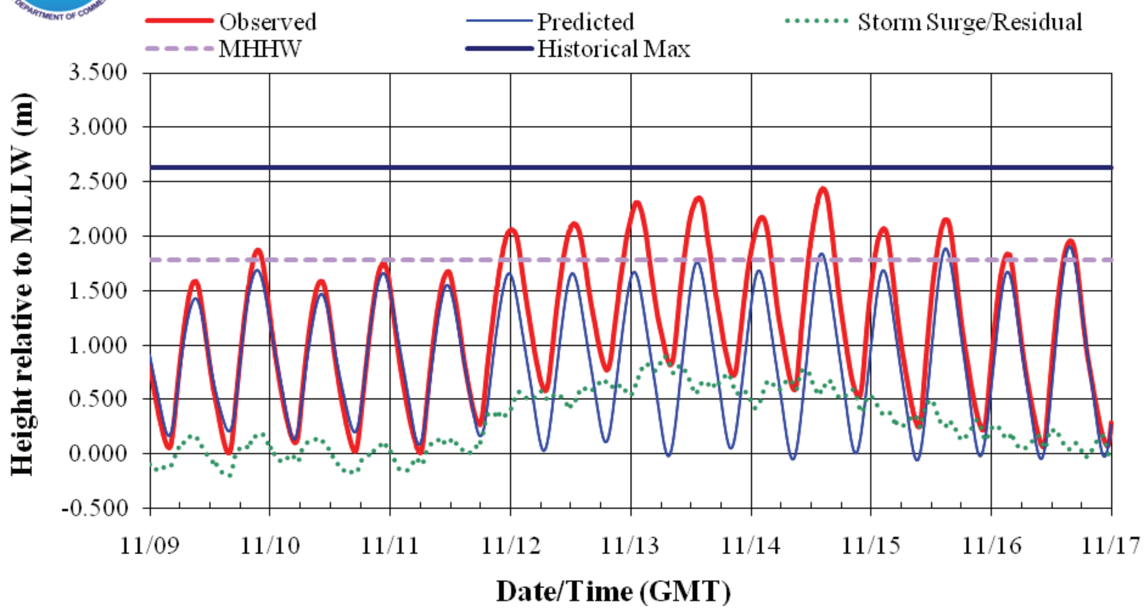

8538886 Tacony-Palmyra Bridge, NJ - November 2009 Nor'easter
Max Storm Tide: 2.752 m (9.03 ft) 11/14/2009 17:12 GMT
Max Storm Surge/Residual: 0.799 m (2.62 ft) 11/13/2009 09:36 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


8548989 Newbold, PA - November 2009 Nor'easter
Max Storm Tide: 3.130 m (10.27 ft) 11/14/2009 18:00 GMT
Max Storm Surge/Residual: 0.803 m (2.63 ft) 11/14/2009 14:24 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
Date/Time (GMT)

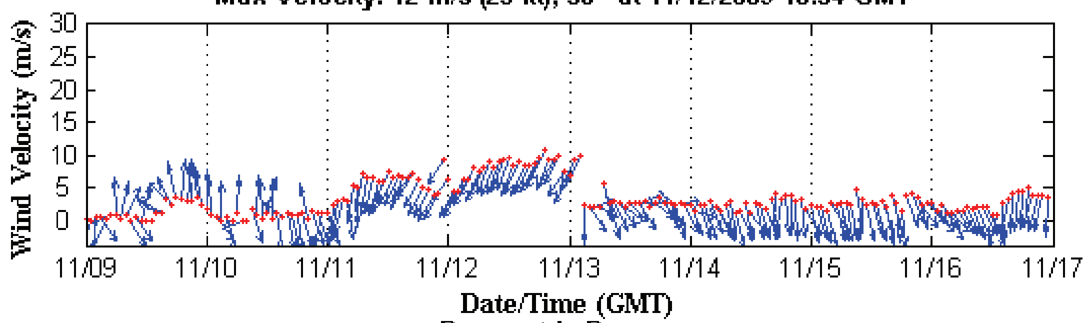

Winds
Max Velocity: 10 m/s (20 kt), 101° at 11/13/2009 21:12 GMT
Wind Velocity (m/s)
Date/Time (GMT)


Barometric Pressure
Min Pressure: 1010 mb at 11/14/2009 09:18 GMT
Pressure (mb)
Date/Time (GMT)

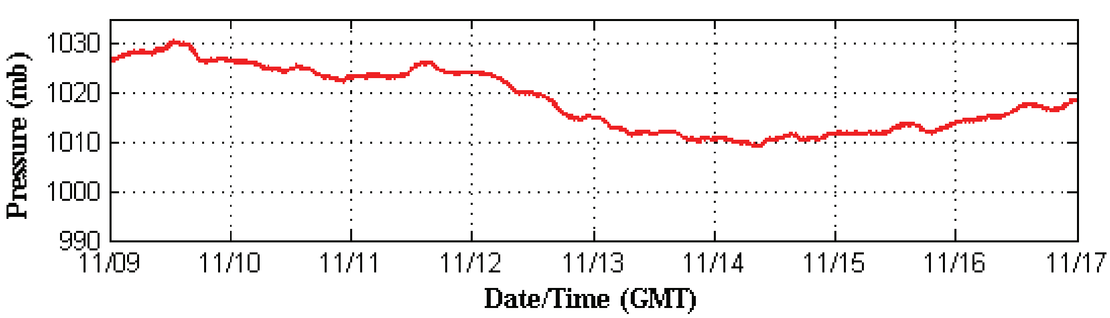
8551762 Delaware City, DE - November 2009 Nor'easter
Max Storm Tide: 2.437 m (8.00 ft) 11/14/2009 14:18 GMT
Max Storm Surge/Residual: 0.905 m (2.97 ft) 11/13/2009 06:42 GMT

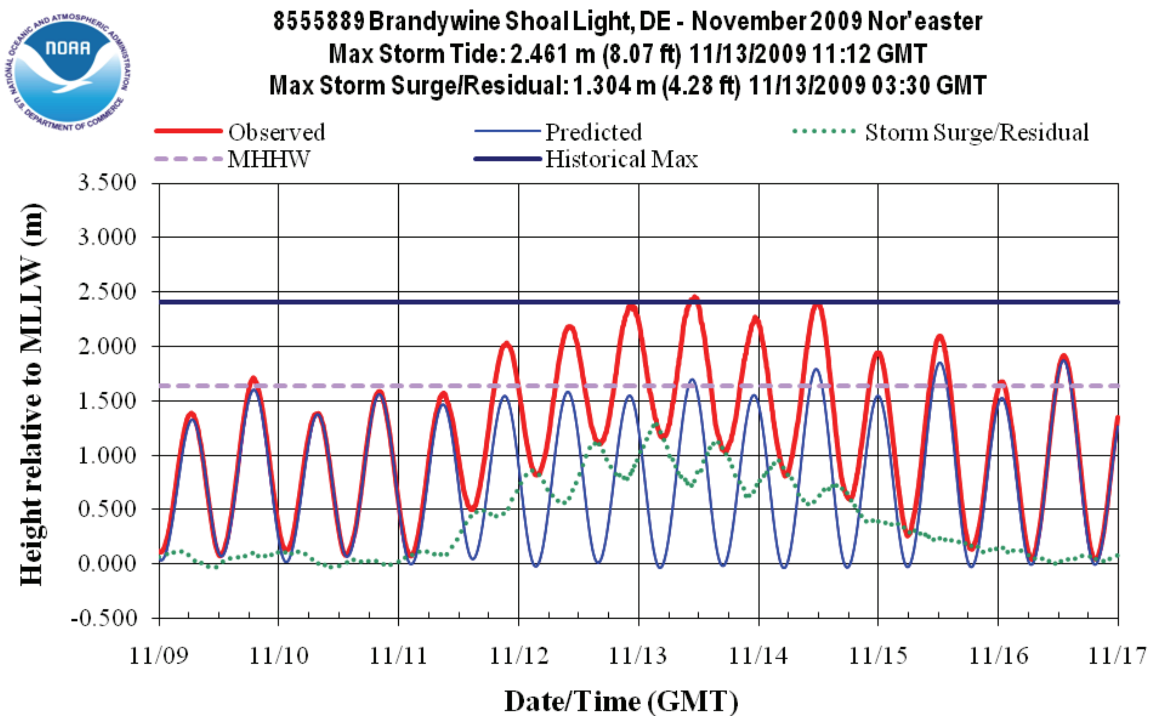


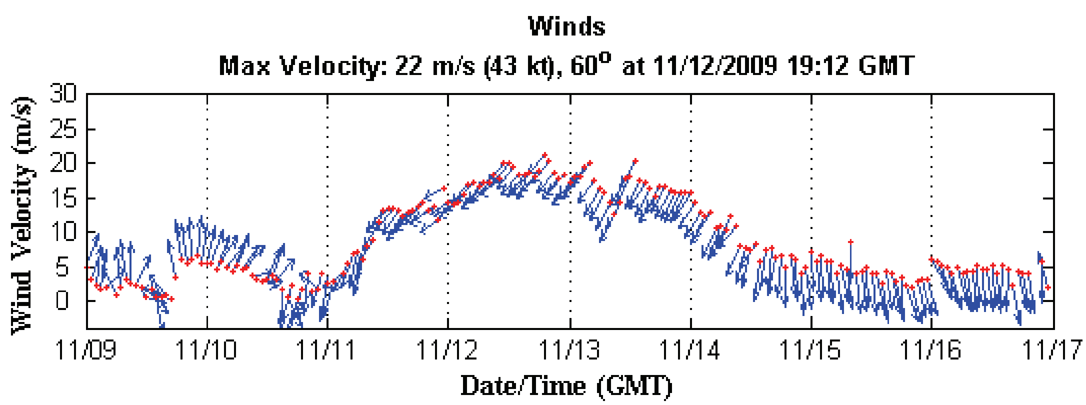
Winds
Max Velocity: 12 m/s (23 kt), 50° at 11/12/2009 18:54 GMT

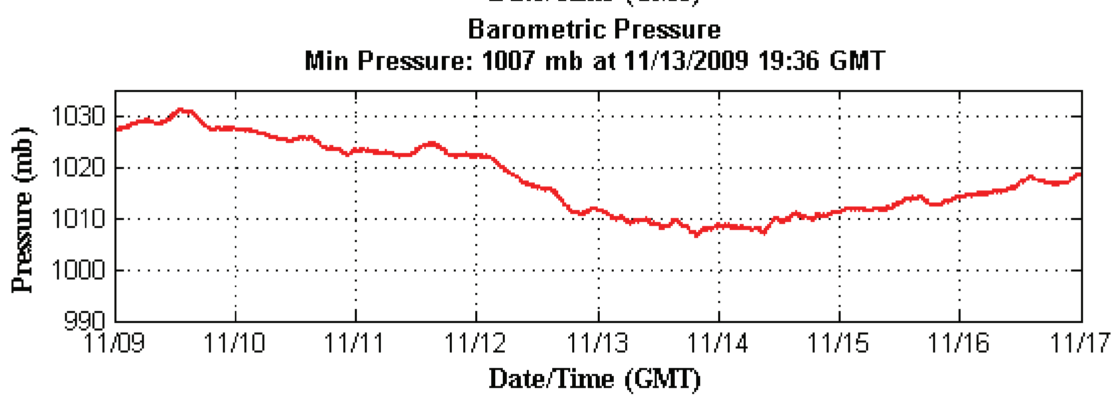


Barometric Pressure
Min Pressure: 1009 mb at 11/14/2009 07:36 GMT

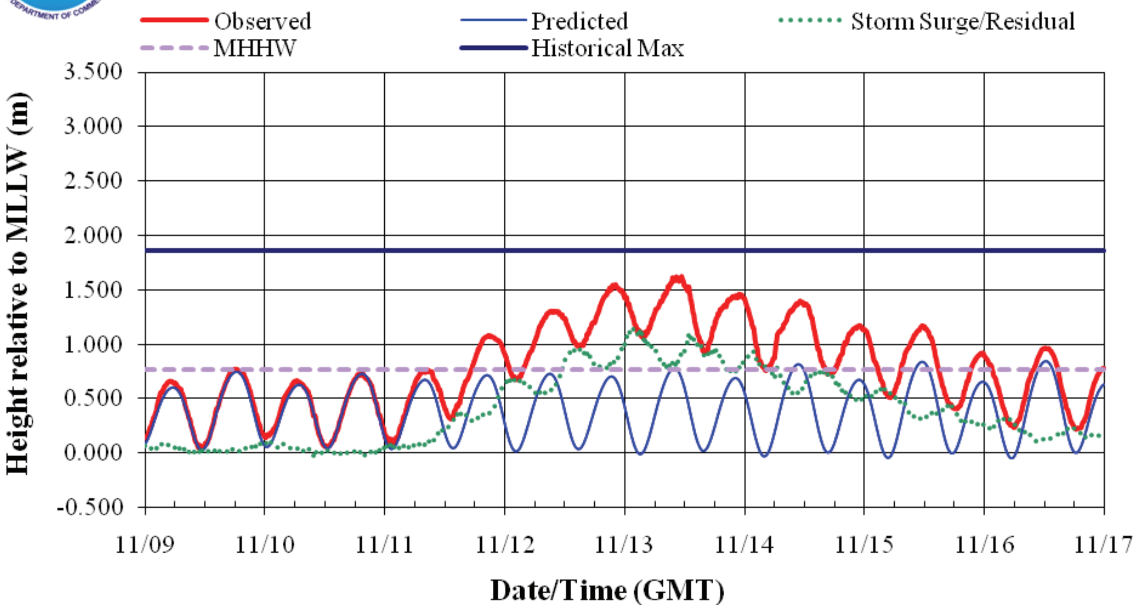



8555889 Brandywine Shoal Light, DE - November 2009 Nor'easter
Max Storm Tide: 2.461 m (8.07 ft) 11/13/2009 11:12 GMT
Max Storm Surge/Residual: 1.304 m (4.28 ft) 11/13/2009 03:30 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
Date/Time (GMT)

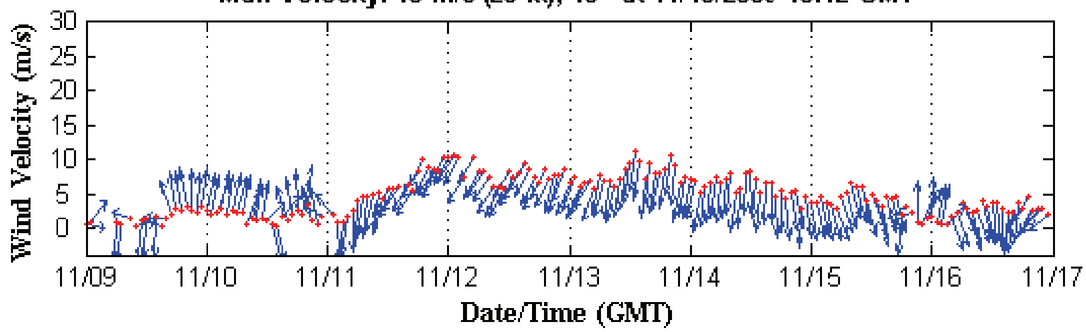

Winds
Max Velocity: 22 m/s (43 kt), 60° at 11/12/2009 19:12 GMT
Wind Velocity (m/s)
Date/Time (GMT)


Barometric Pressure
Min Pressure: 1007 mb at 11/13/2009 19:36 GMT
Pressure (mb)
Date/Time (GMT)

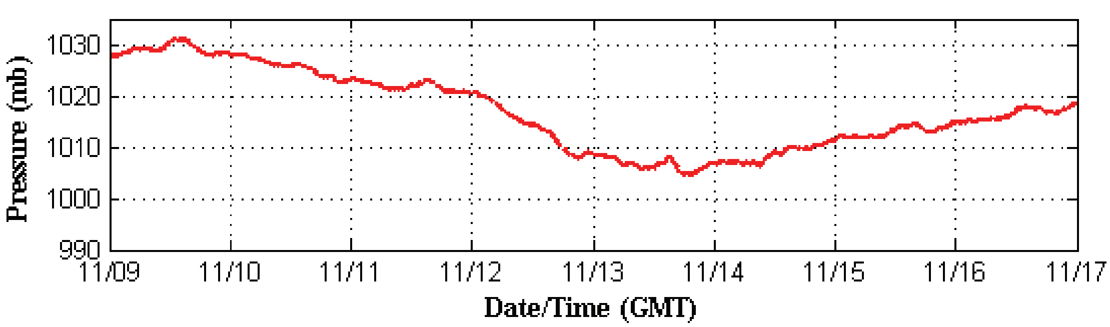
8570283 Ocean City Inlet, MD - November 2009 Nor'easter
Max Storm Tide: 1.628 m (5.34 ft) 11/13/2009 11:24 GMT
Max Storm Surge/Residual: 1.146 m (3.76 ft) 11/13/2009 01:42 GMT

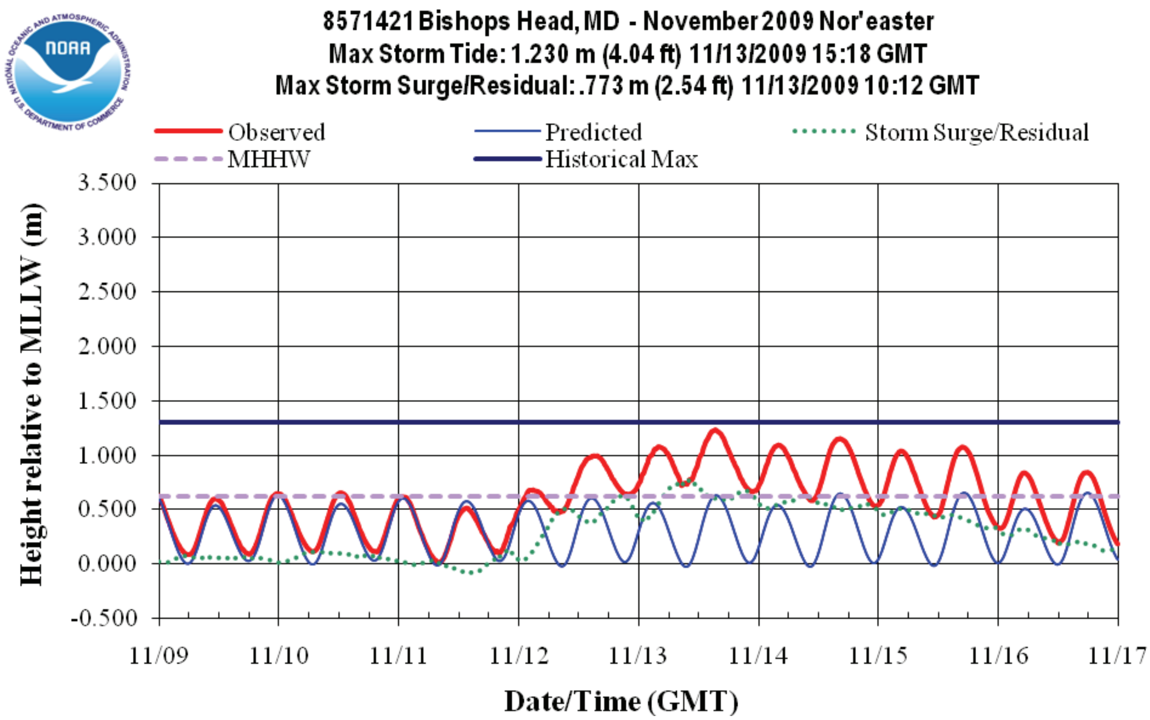


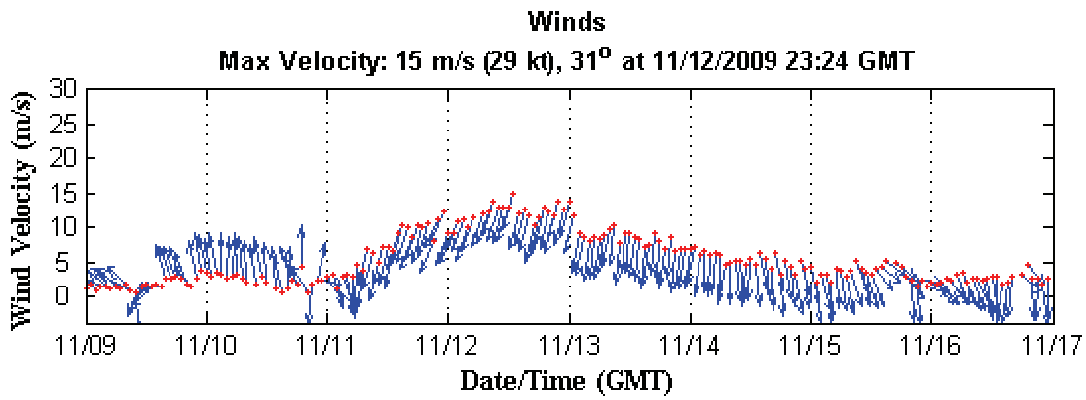
Winds
Max Velocity: 13 m/s (26 kt), 18° at 11/13/2009 18:42 GMT

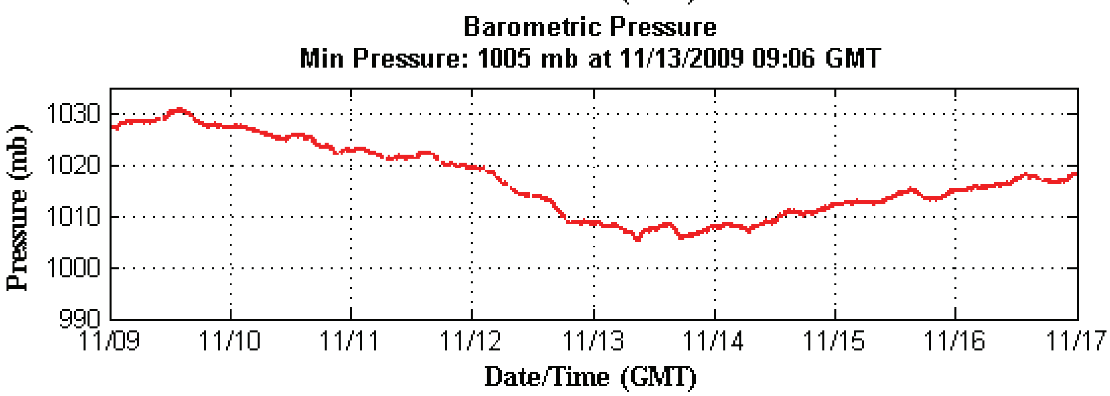


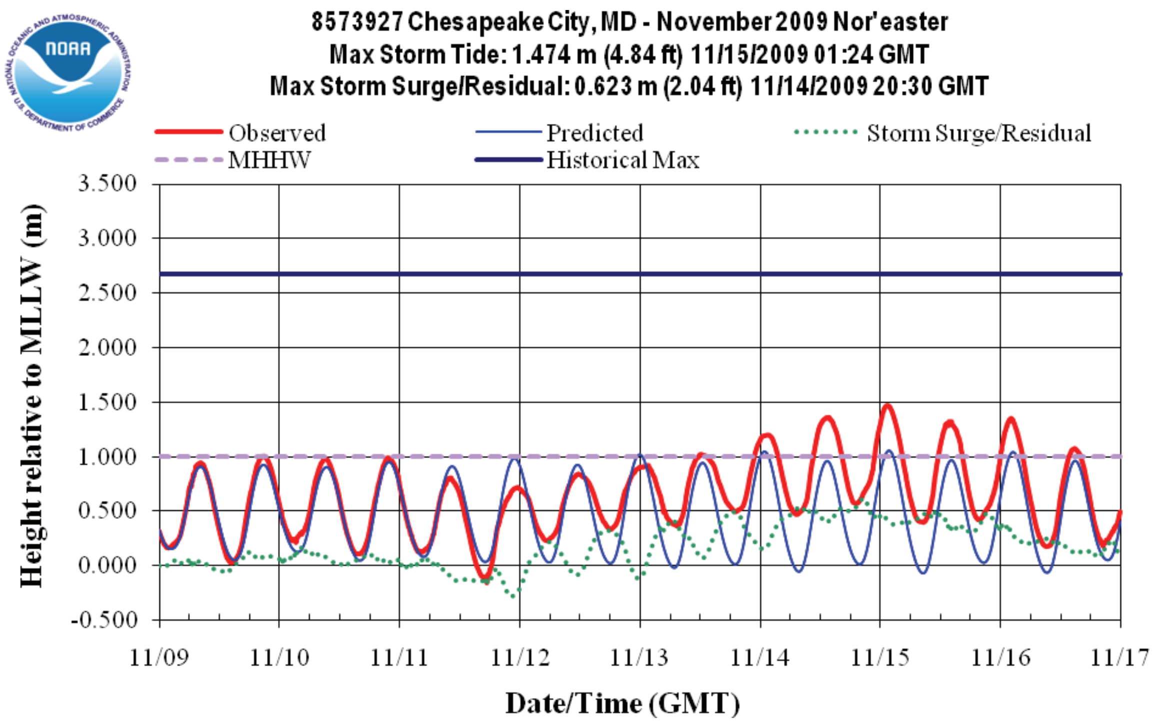
Barometric Pressure
Min Pressure: 1005 mb at 11/13/2009 18:42 GMT



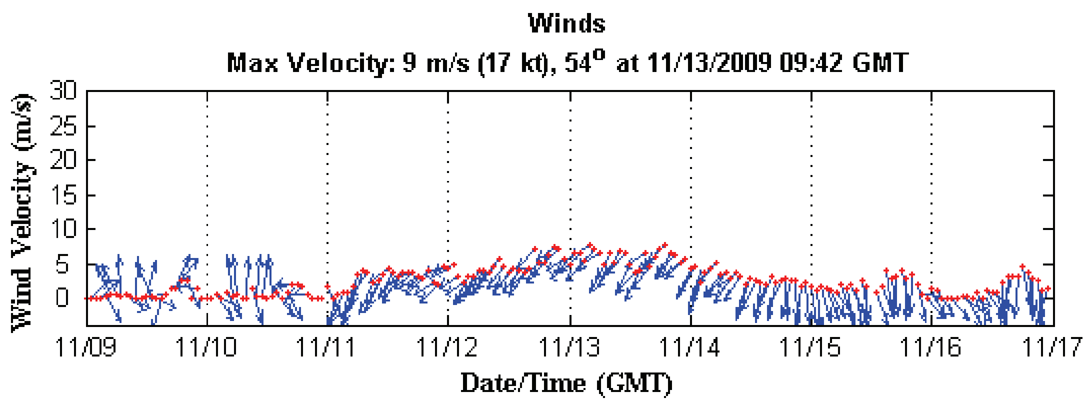

8571421 Bishops Head, MD - November 2009 Nor'easter
Max Storm Tide: 1.230 m (4.04 ft) 11/13/2009 15:18 GMT
Max Storm Surge/Residual: .773 m (2.54 ft) 11/13/2009 10:12 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Winds
Max Velocity: 15 m/s (29 kt), 31° at 11/12/2009 23:24 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

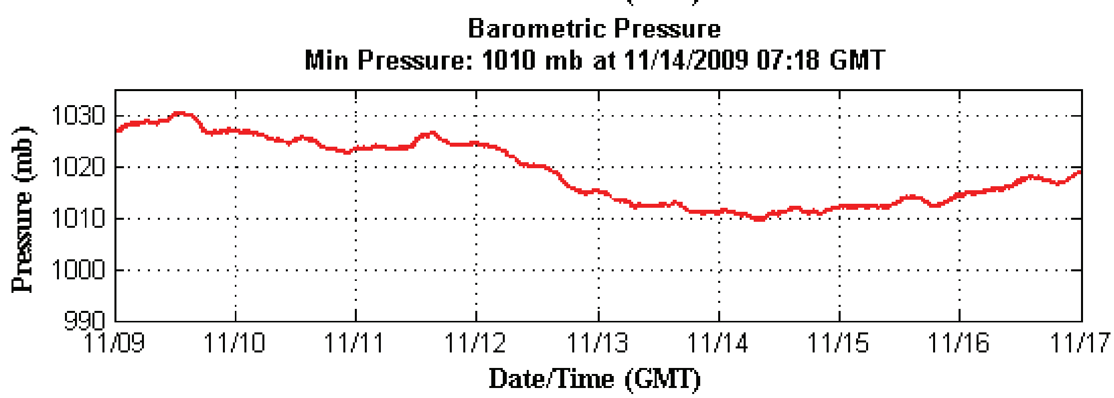

Barometric Pressure
Min Pressure: 1005 mb at 11/13/2009 09:06 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)



8573927 Chesapeake City, MD - November 2009 Nor'easter
Max Storm Tide: 1.474 m (4.84 ft) 11/15/2009 01:24 GMT
Max Storm Surge/Residual: 0.623 m (2.04 ft) 11/14/2009 20:30 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

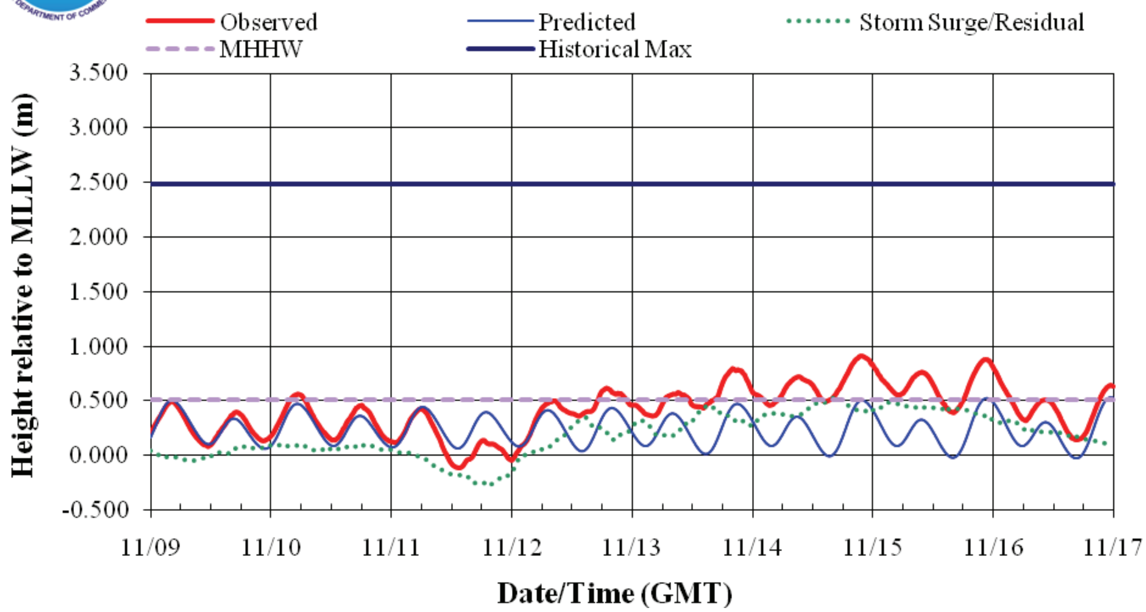


Winds
Max Velocity: 9 m/s (17 kt), 54° at 11/13/2009 09:42 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

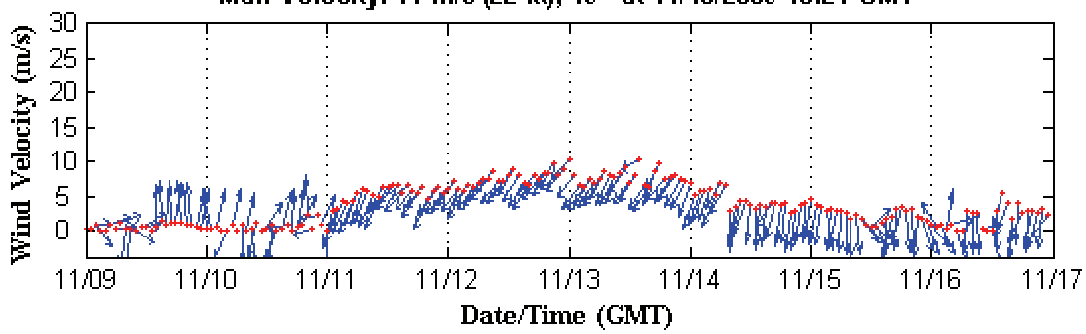


Barometric Pressure
Min Pressure: 1010 mb at 11/14/2009 07:18 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

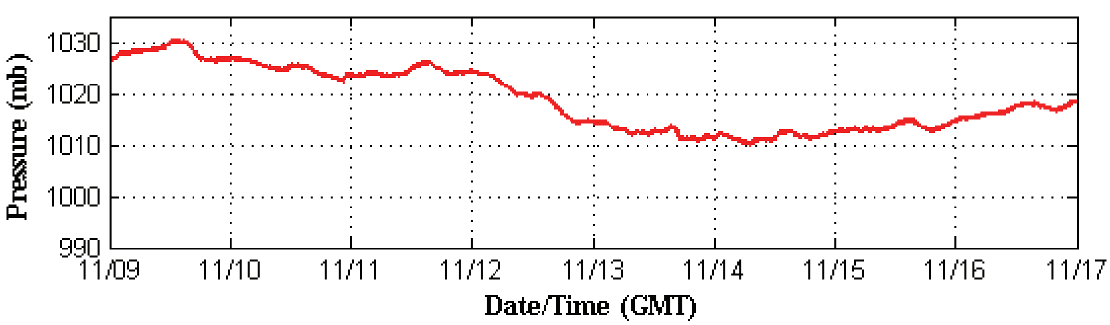
8574680 Baltimore, MD - November 2009 Nor'easter
Max Storm Tide: 0.916 m (3.00 ft) 11/14/2009 21:42 GMT
Max Storm Surge/Residual: 0.533 m (1.75 ft) 11/14/2009 16:54 GMT

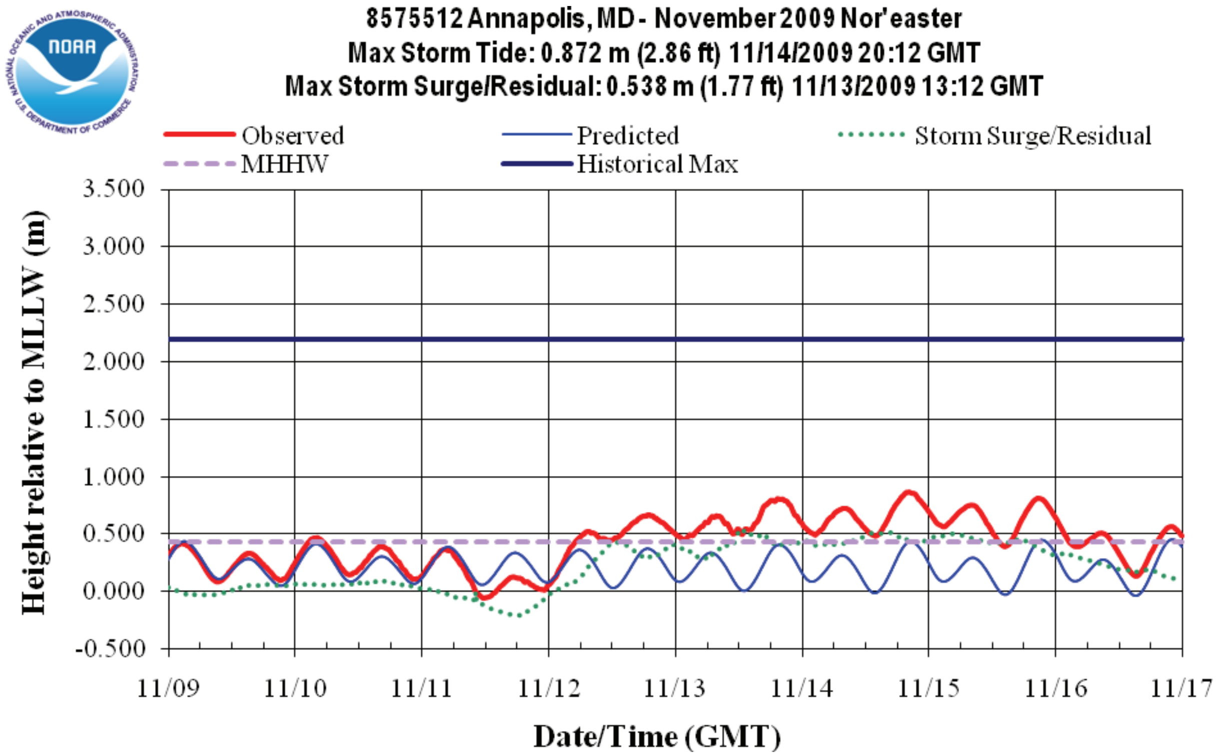


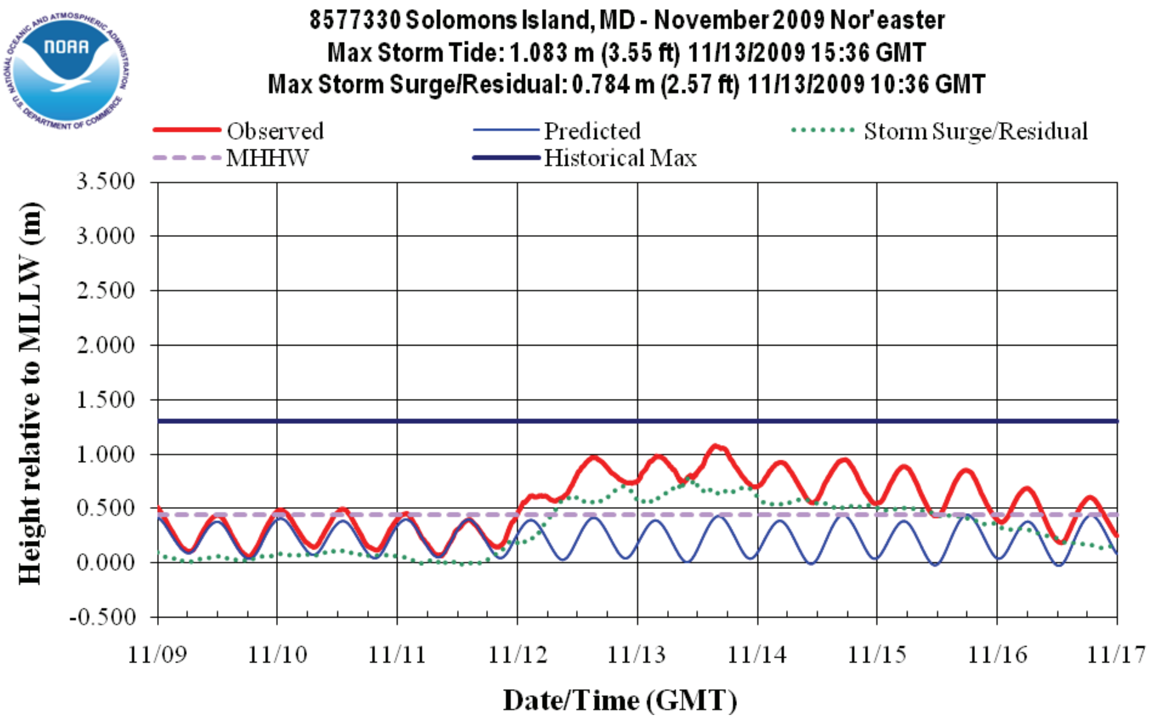
Winds
Max Velocity: 11 m/s (22 kt), 49^{o} at 11/13/2009 18:24 GMT



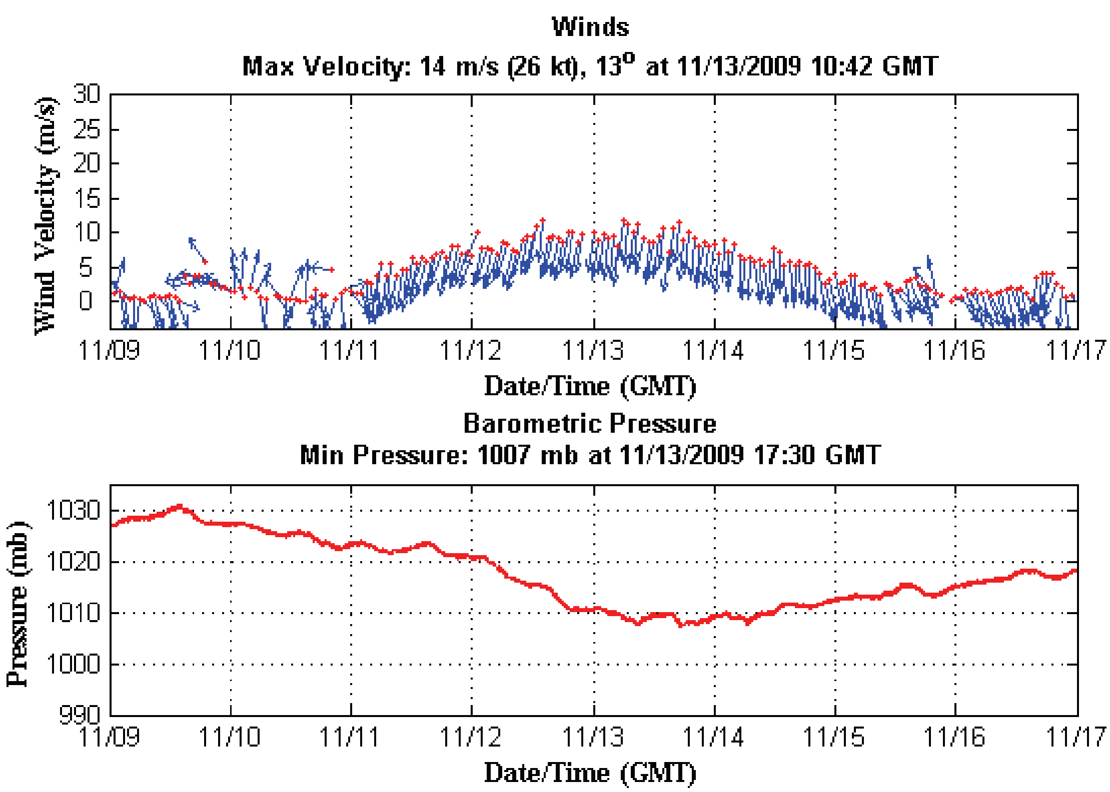
Barometric Pressure
Min Pressure: 1010 mb at 11/14/2009 07:06 GMT



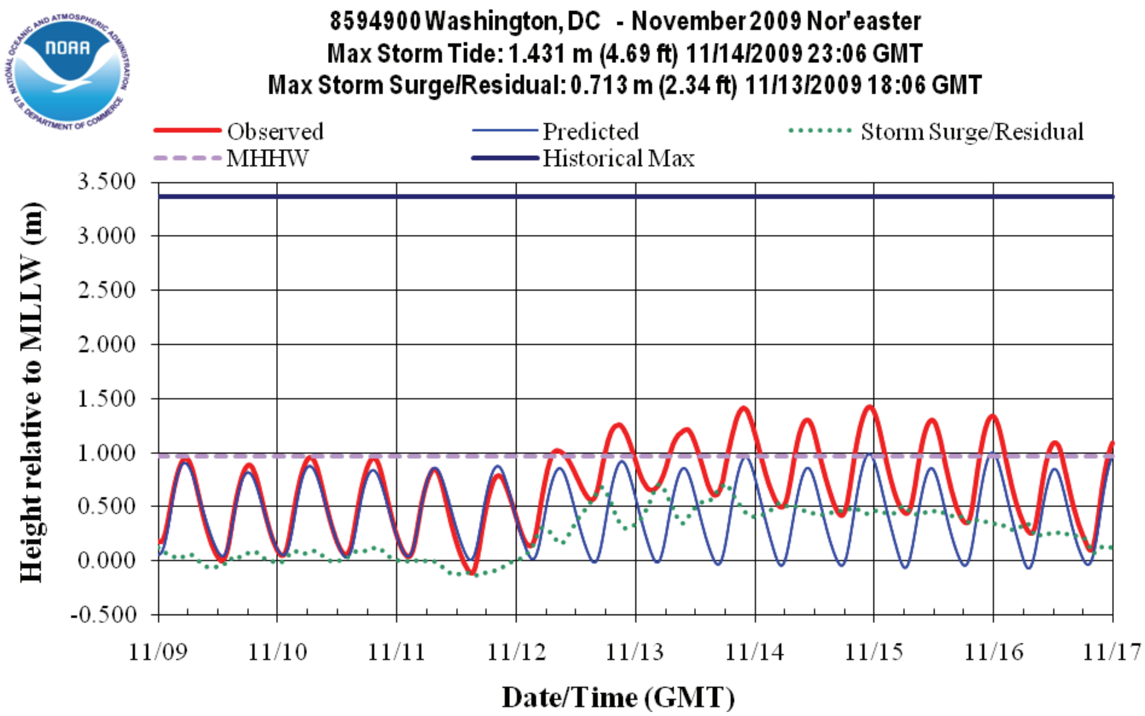

8575512 Annapolis, MD - November 2009 Nor'easter
Max Storm Tide: 0.872 m (2.86 ft) 11/14/2009 20:12 GMT
Max Storm Surge/Residual: 0.538 m (1.77 ft) 11/13/2009 13:12 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

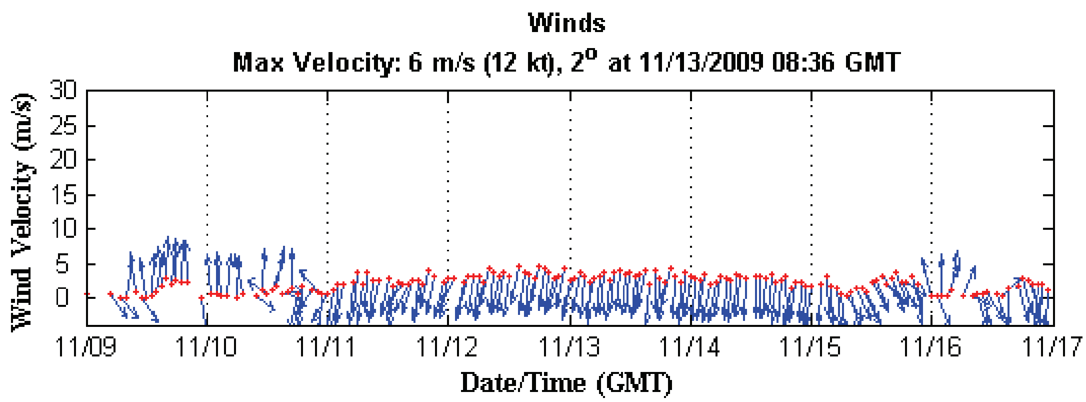


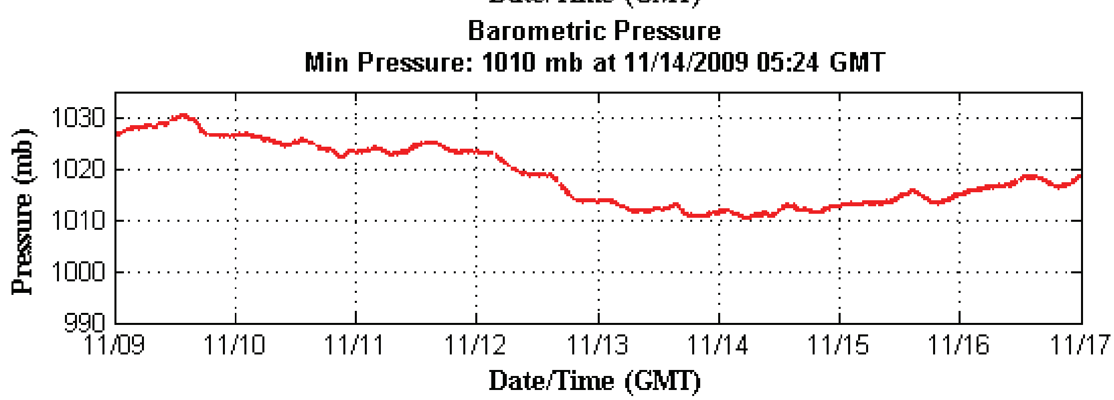
8577330 Solomons Island, MD - November 2009 Nor'easter
Max Storm Tide: 1.083 m (3.55 ft) 11/13/2009 15:36 GMT
Max Storm Surge/Residual: 0.784 m (2.57 ft) 11/13/2009 10:36 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

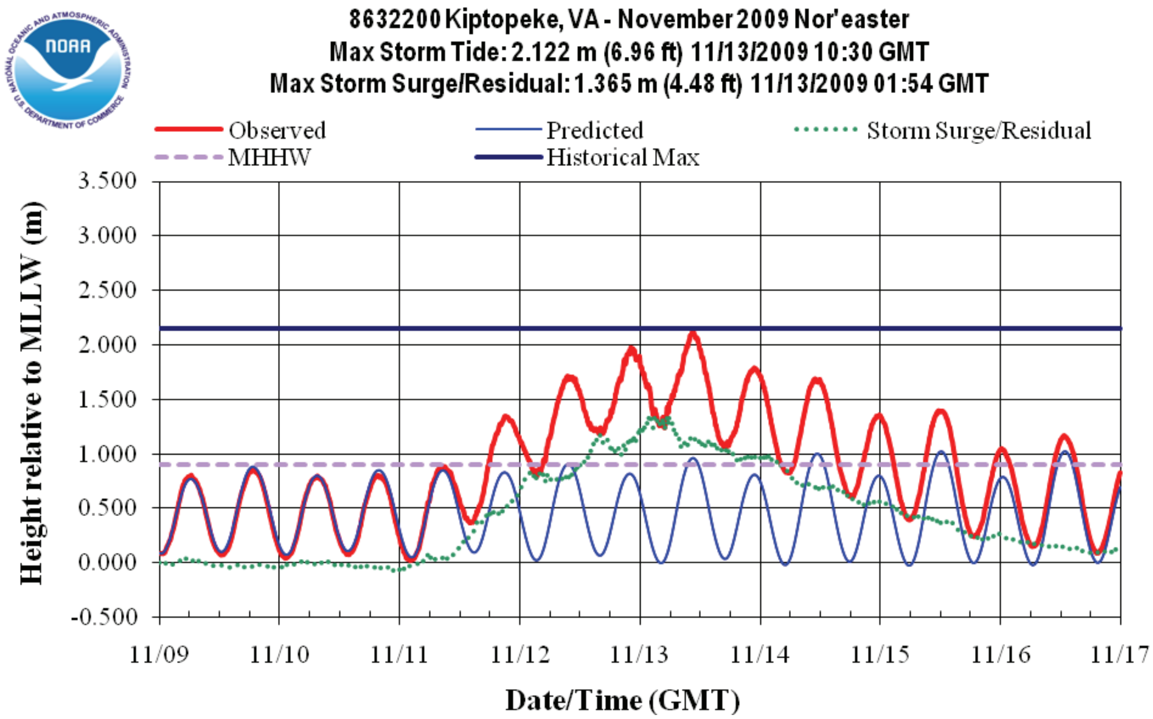


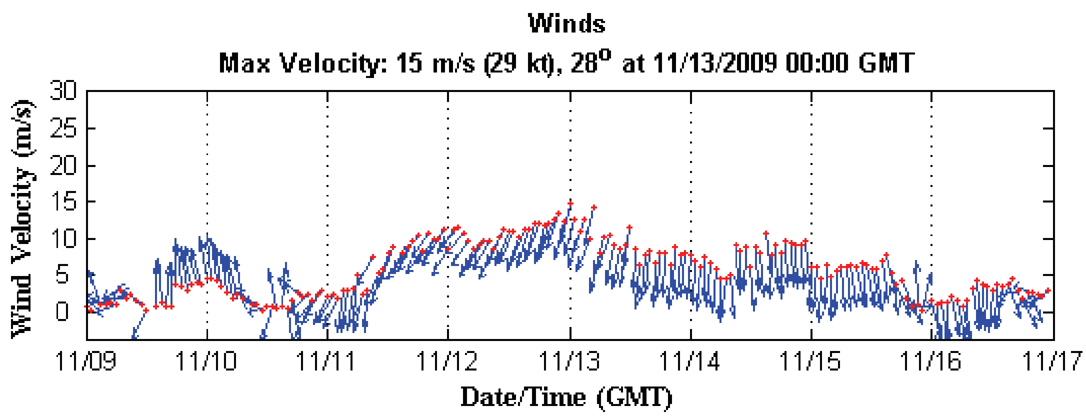
Winds
Max Velocity: 14 m/s (26 kt), 13° at 11/13/2009 10:42 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)
Barometric Pressure
Min Pressure: 1007 mb at 11/13/2009 17:30 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


8594900 Washington, DC - November 2009 Nor'easter
Max Storm Tide: 1.431 m (4.69 ft) 11/14/2009 23:06 GMT
Max Storm Surge/Residual: 0.713 m (2.34 ft) 11/13/2009 18:06 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

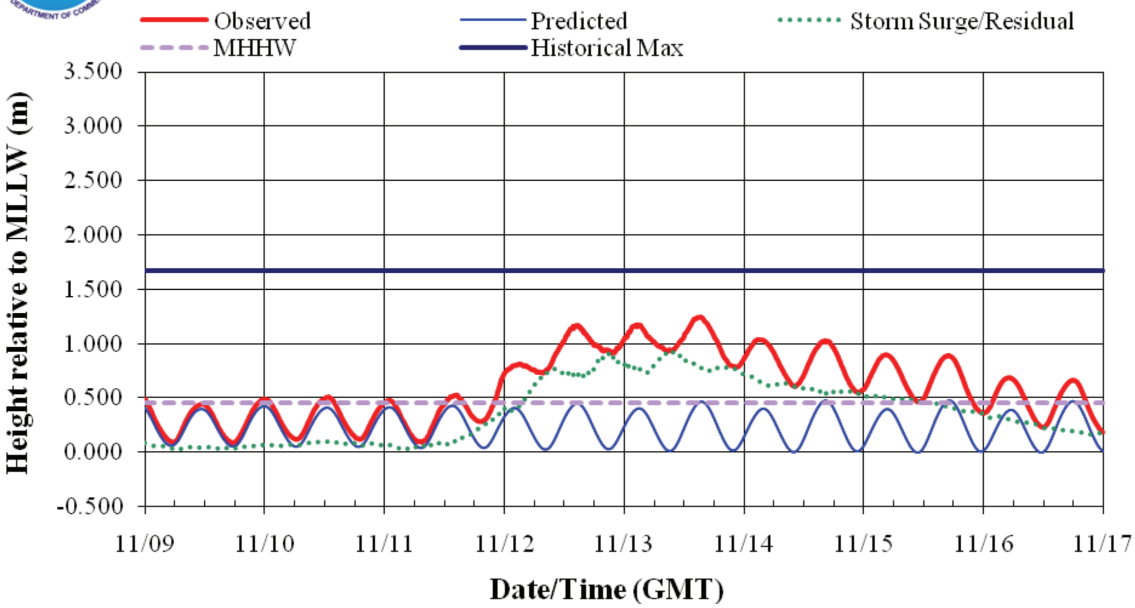

Winds
Max Velocity: 6 m/s (12 kt), 2° at 11/13/2009 08:36 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Barometric Pressure
Min Pressure: 1010 mb at 11/14/2009 05:24 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

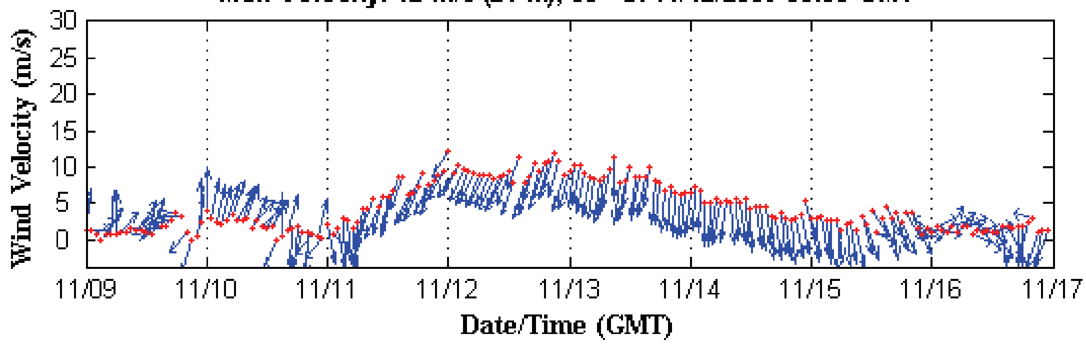

8632200 Kiptopeke, VA - November 2009 Nor'easter
Max Storm Tide: 2.122 m (6.96 ft) 11/13/2009 10:30 GMT
Max Storm Surge/Residual: 1.365 m (4.48 ft) 11/13/2009 01:54 GMT
NOAA
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Winds
Max Velocity: 15 m/s (29 kt), 28° at 11/13/2009 00:00 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

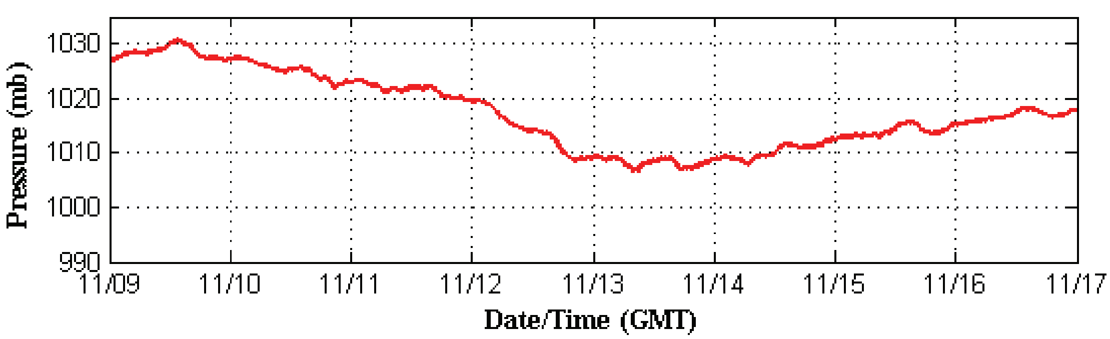
8635750 Lewisetta, VA - November 2009 Nor'easter
Max Storm Tide: 1.252 m (4.11 ft) 11/13/2009 15:18 GMT
Max Storm Surge/Residual: 0.937 m (3.07 ft) 11/13/2009 09:06 GMT

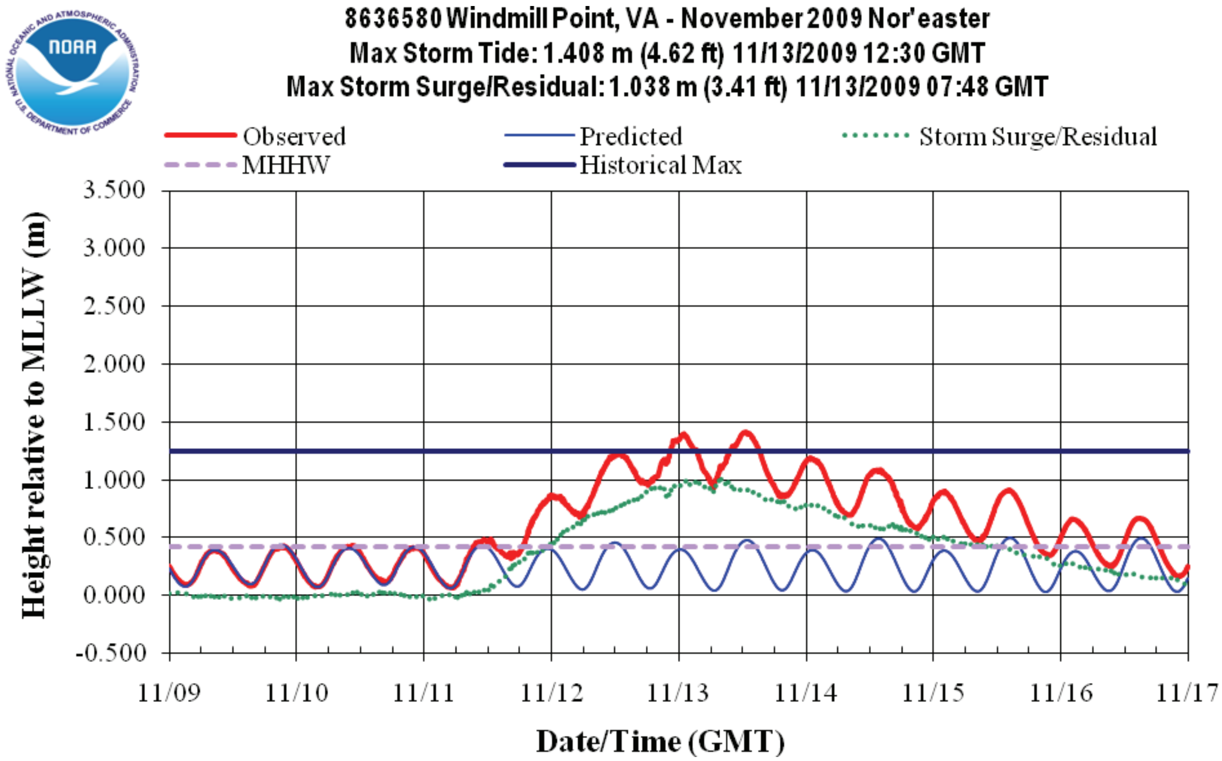


Winds
Max Velocity: 12 m/s (24 kt), 53^{o} at 11/12/2009 00:00 GMT



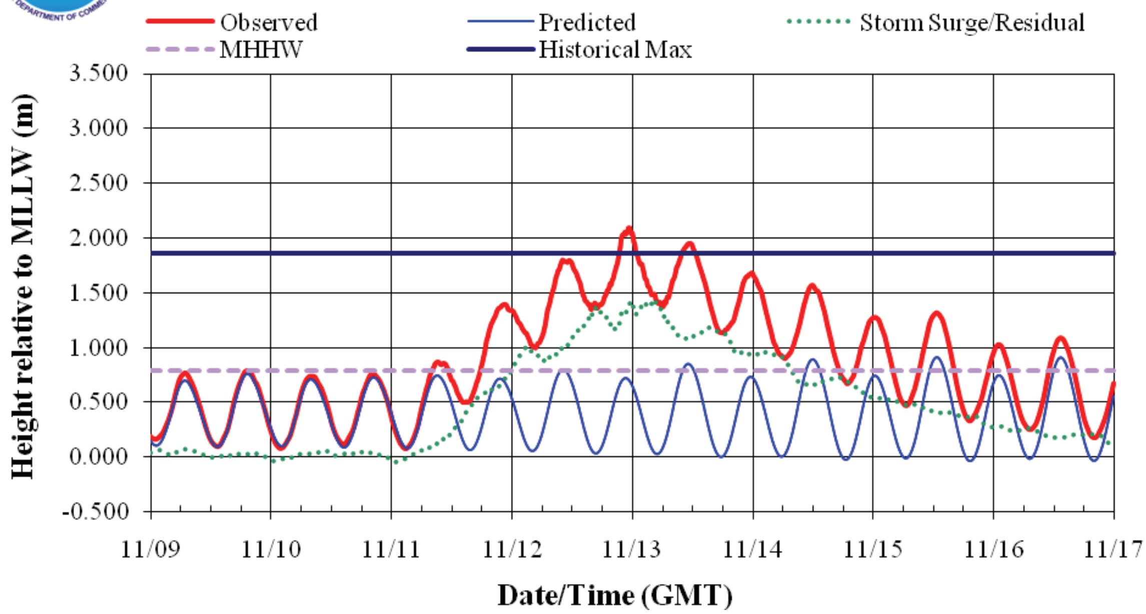
Barometric Pressure
Min Pressure: 1007 mb at 11/13/2009 08:24 GMT



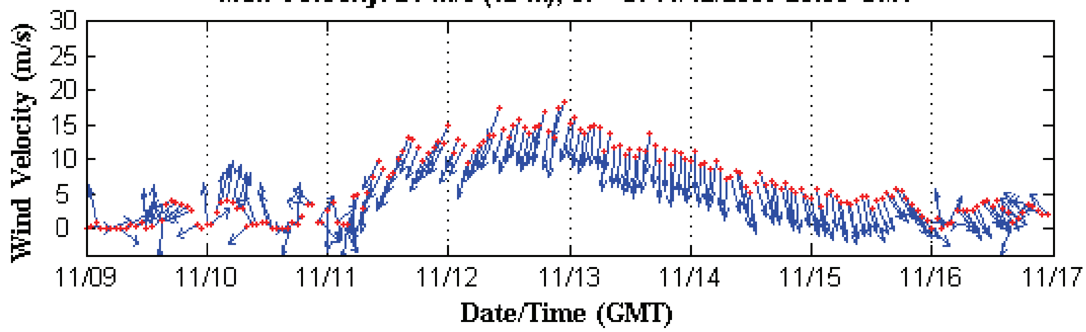


8636580 Windmill Point, VA - November 2009 Nor'easter
Max Storm Tide: 1.408 m (4.62 ft) 11/13/2009 12:30 GMT
Max Storm Surge/Residual: 1.038 m (3.41 ft) 11/13/2009 07:48 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

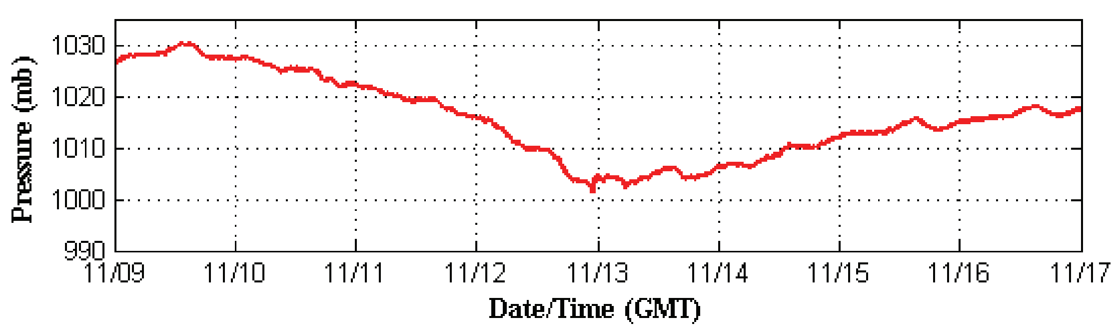
8637689 Yorktown USCG Training Center, VA - November 2009 Nor'easter
Max Storm Tide: 2.092 m (6.86 ft) 11/12/2009 23:18 GMT
Max Storm Surge/Residual: 1.442 m (4.73 ft) 11/13/2009 04:24 GMT

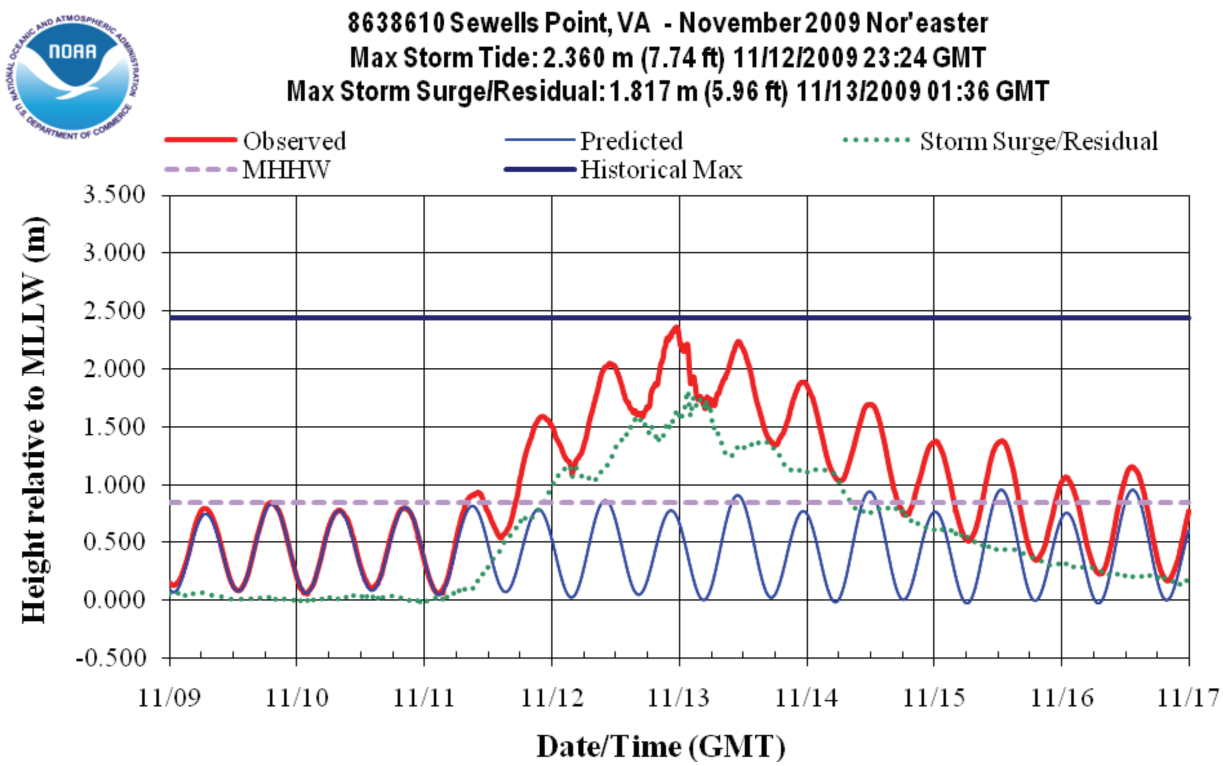


Winds
Max Velocity: 21 m/s (42 kt), 37° at 11/12/2009 23:06 GMT

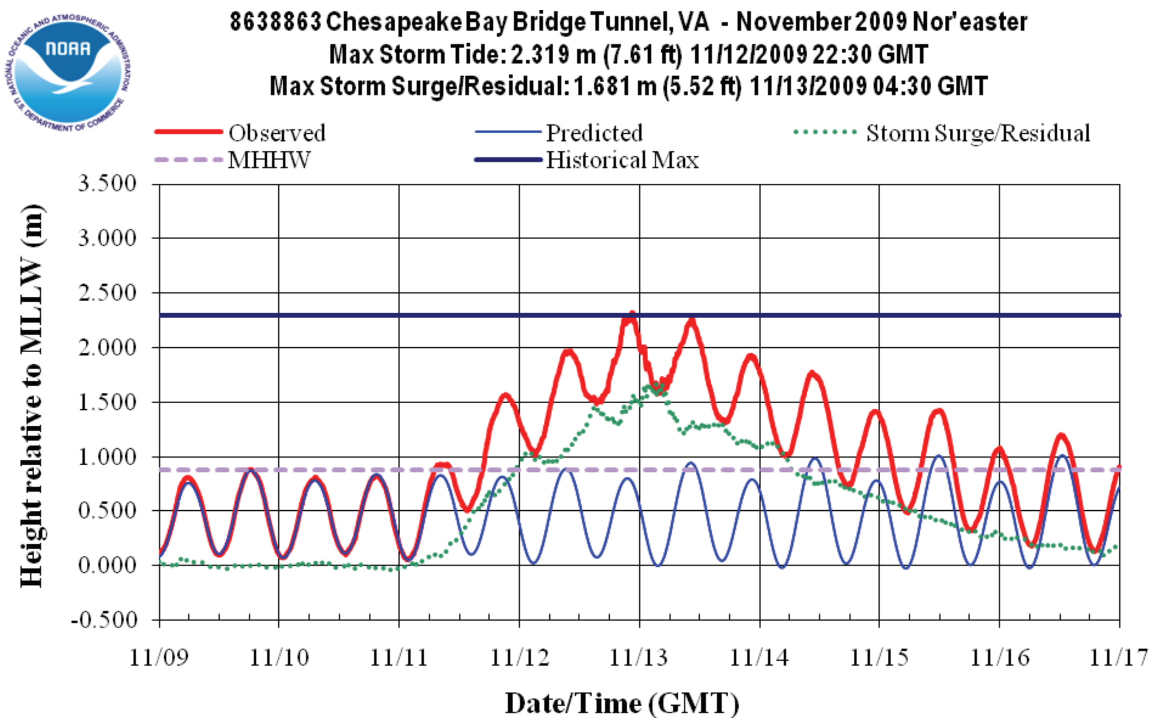


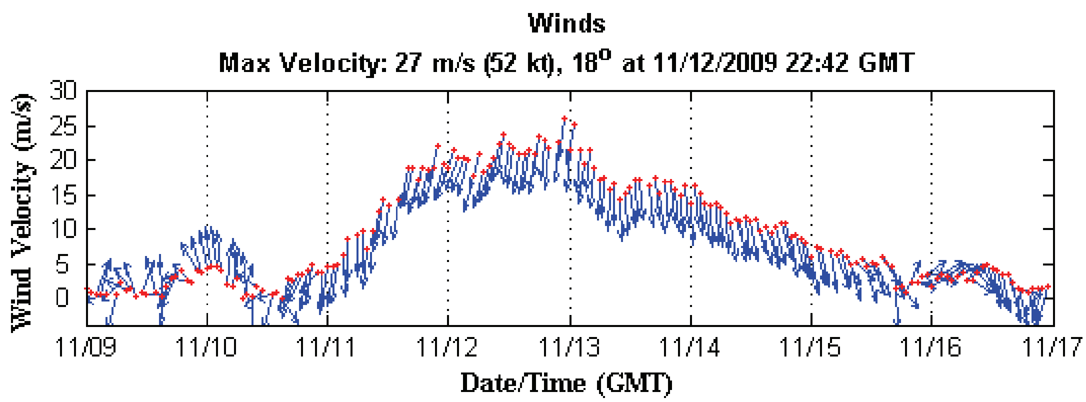
Barometric Pressure
Min Pressure: 1001 mb at 11/12/2009 23:06 GMT

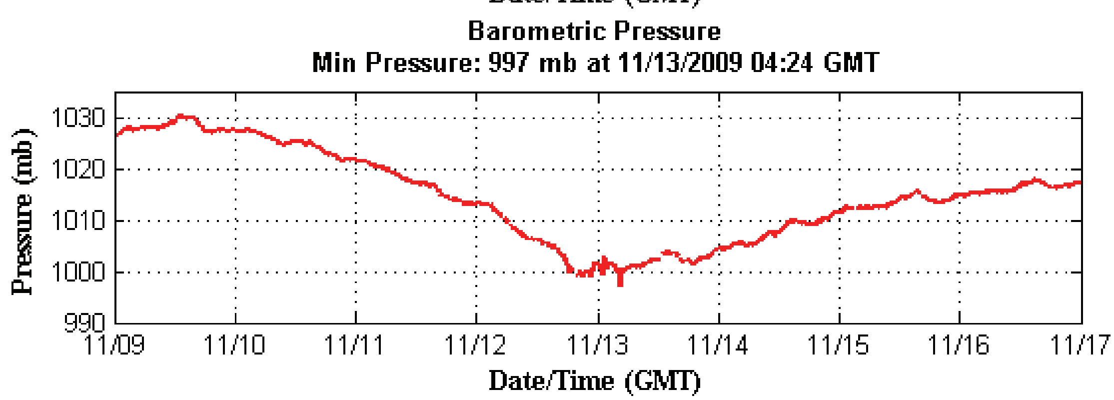




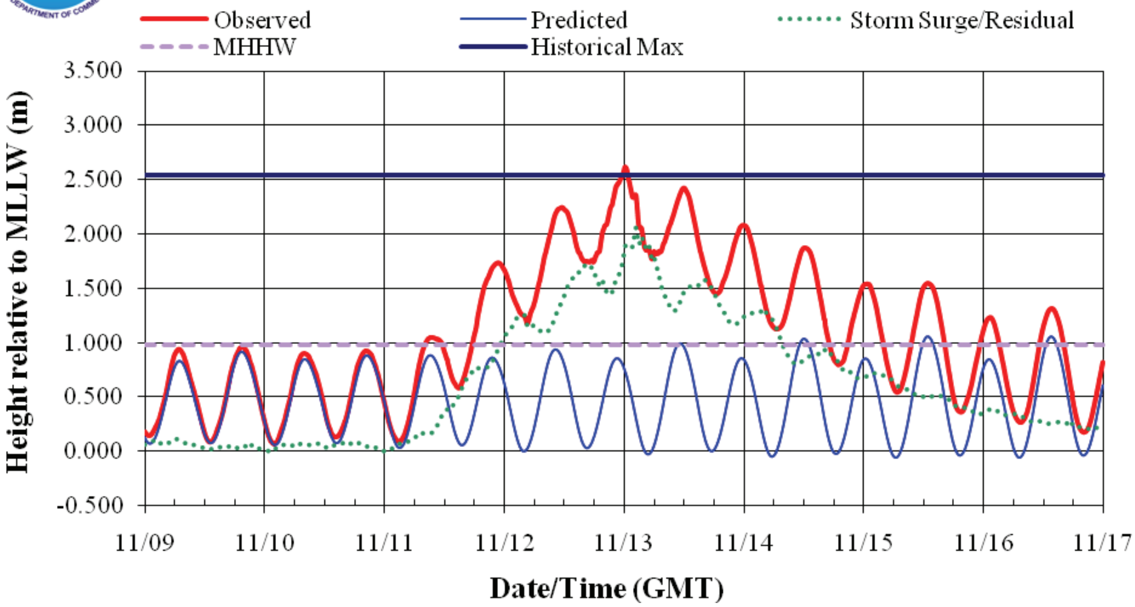
8638610 Sewells Point, VA - November 2009 Nor'easter
Max Storm Tide: 2.360 m (7.74 ft) 11/12/2009 23:24 GMT
Max Storm Surge/Residual: 1.817 m (5.96 ft) 11/13/2009 01:36 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


8638863 Chesapeake Bay Bridge Tunnel, VA - November 2009 Nor'easter
Max Storm Tide: 2.319 m (7.61 ft) 11/12/2009 22:30 GMT
Max Storm Surge/Residual: 1.681 m (5.52 ft) 11/13/2009 04:30 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

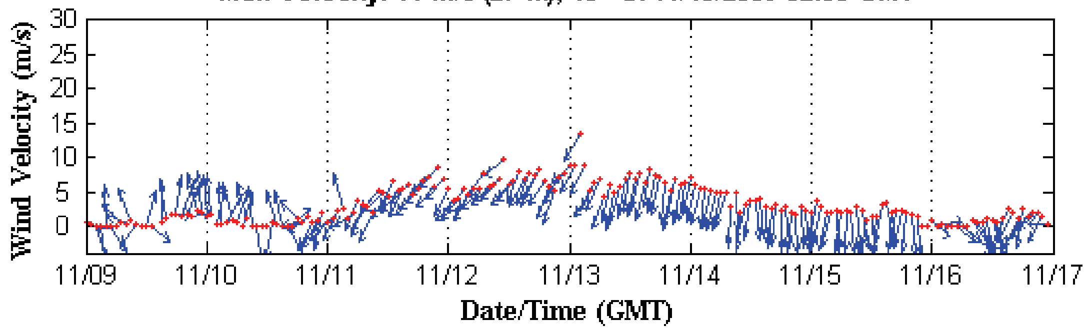

Winds
Max Velocity: 27 m/s (52 kt), 18° at 11/12/2009 22:42 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Barometric Pressure
Min Pressure: 997 mb at 11/13/2009 04:24 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)

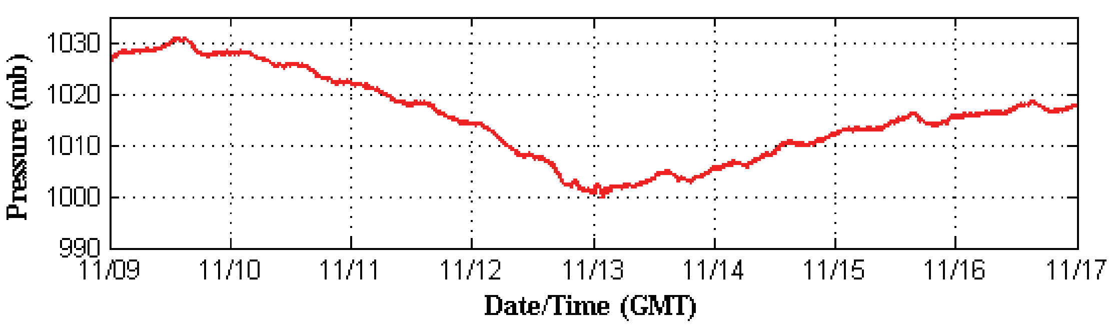
8639348 Money Point, VA - November 2009 Nor'easter
Max Storm Tide: 2.618 m (8.59 ft) 11/13/2009 00:12 GMT
Max Storm Surge/Residual: 2.055 m (6.74 ft) 11/13/2009 02:24 GMT

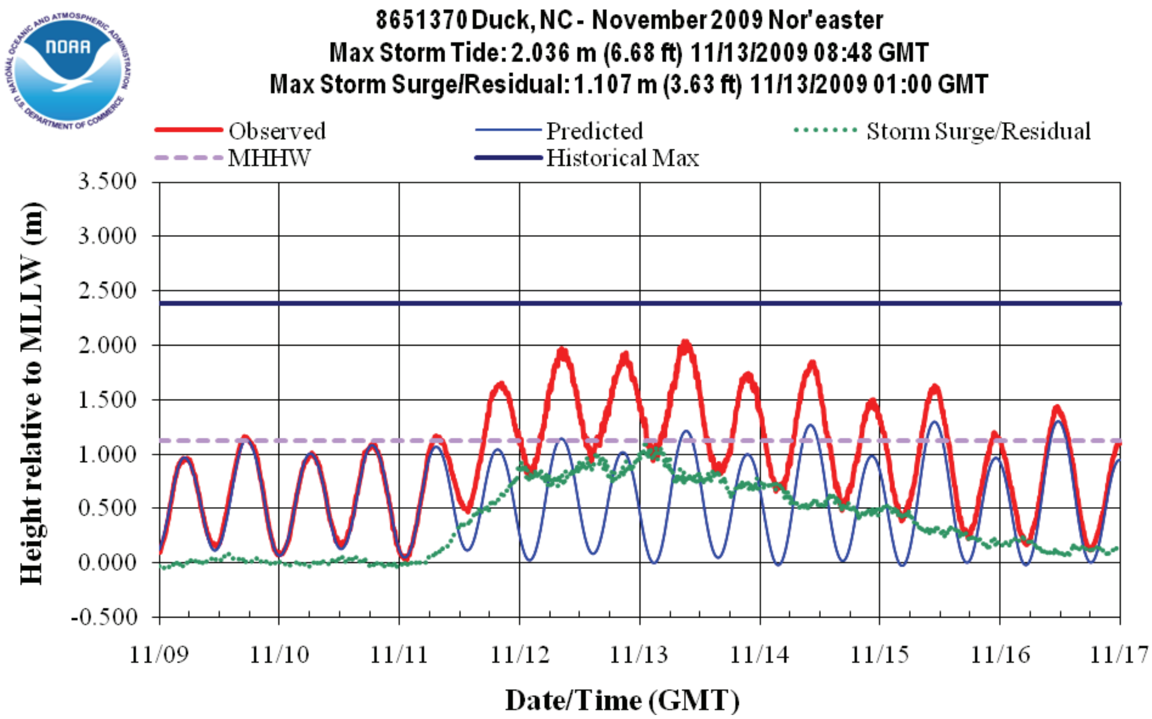


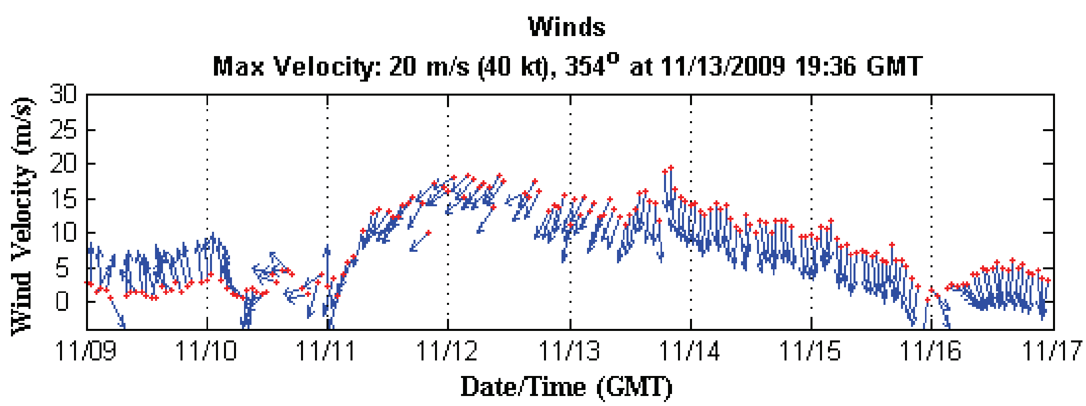
Winds
Max Velocity: 14 m/s (27 kt), 48° at 11/13/2009 02:00 GMT

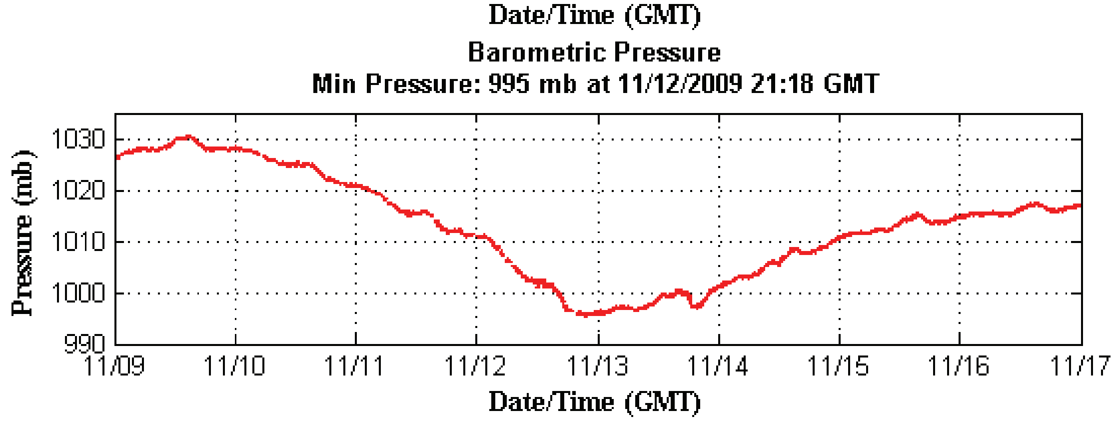


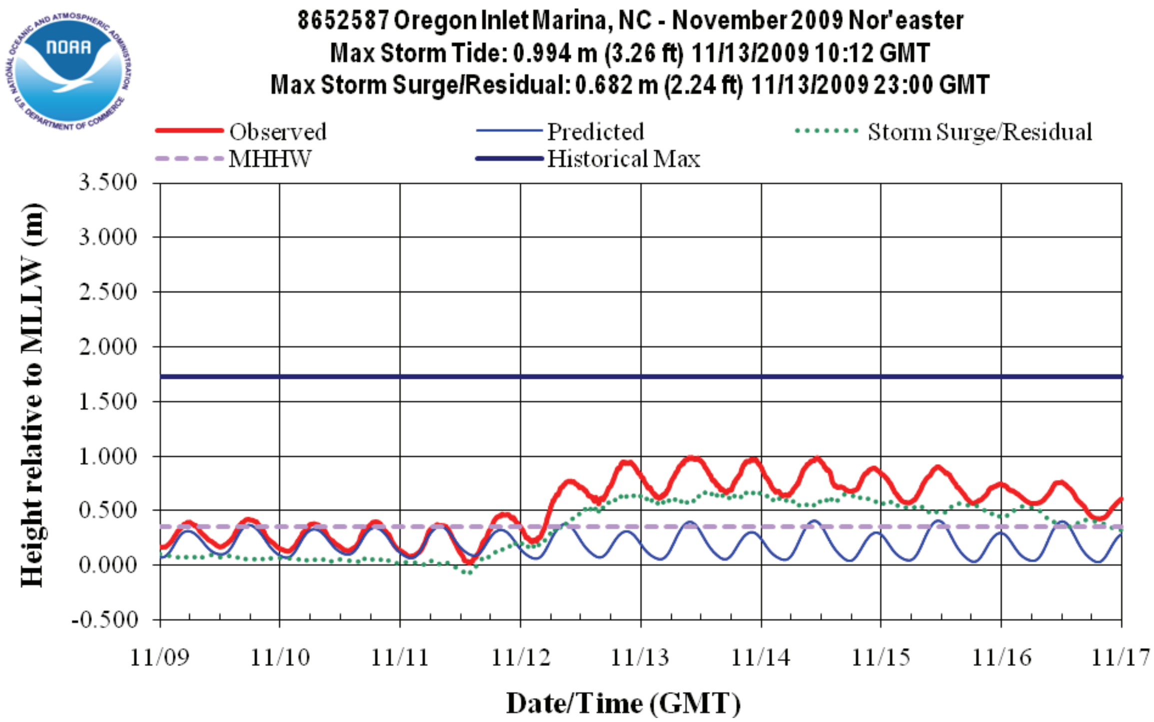
Barometric Pressure
Min Pressure: 1000 mb at 11/13/2009 01:54 GMT

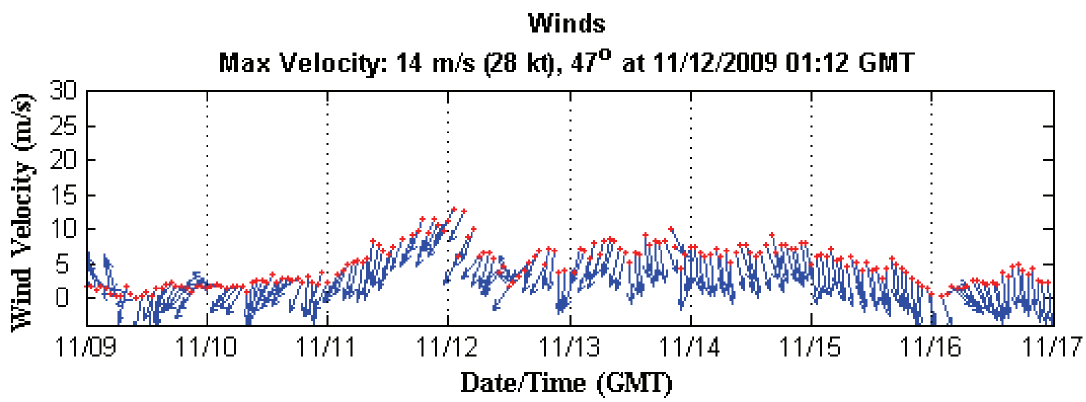


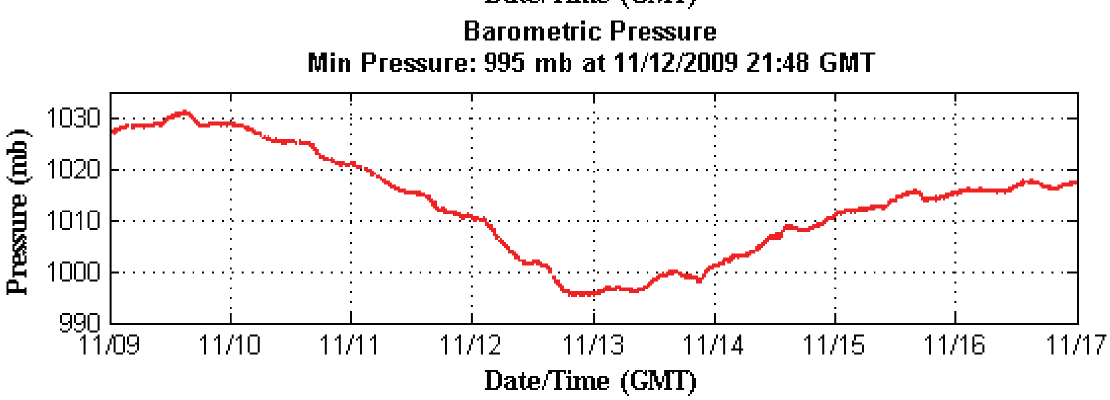

8651370 Duck, NC - November 2009 Nor'easter
Max Storm Tide: 2.036 m (6.68 ft) 11/13/2009 08:48 GMT
Max Storm Surge/Residual: 1.107 m (3.63 ft) 11/13/2009 01:00 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Winds
Max Velocity: 20 m/s (40 kt), 354° at 11/13/2009 19:36 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Barometric Pressure
Min Pressure: 995 mb at 11/12/2009 21:18 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


8652587 Oregon Inlet Marina, NC - November 2009 Nor'easter
Max Storm Tide: 0.994 m (3.26 ft) 11/13/2009 10:12 GMT
Max Storm Surge/Residual: 0.682 m (2.24 ft) 11/13/2009 23:00 GMT
Observed
Predicted
Storm Surge/Residual
MHHW
Historical Max
Height relative to MLLW (m)
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Winds
Max Velocity: 14 m/s (28 kt), 47° at 11/12/2009 01:12 GMT
Wind Velocity (m/s)
30
25
20
15
10
5
0
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)


Barometric Pressure
Min Pressure: 995 mb at 11/12/2009 21:48 GMT
Pressure (mb)
1030
1020
1010
1000
990
11/09
11/10
11/11
11/12
11/13
11/14
11/15
11/16
11/17
Date/Time (GMT)