Appendix B

Comparison of Observed SLOSH/Tide Model Computed Storm Tide for Hurricane Isabel (2003) in North Carolina, Virginia, Maryland and the Delaware Bay and River

COMPARISON OF OBSERVED AND SLOSH/TIDE MODEL COMPUTED STORM TIDE FOR HURRICANE ISABEL (2003) IN NORTH CAROLINA, VIRGINIA, MARYLAND AND THE DELAWARE BAY AND RIVER

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1. INTRODUCTION

The U. S. Army Corps of Engineers, Office of Homeland Security/Federal Emergency Management Agency (OHS/FEMA) and the National Oceanographic and Atmospheric Administration/National Weather Service (NOAA/NWS) are extensively involved in determining the areas that are prone to flooding by hurricane storm surge along the U.S. Atlantic and Gulf of Mexico coastlines. Determination of areas prone to storm surge flooding is an essential prerequisite to evacuation planning.

Flood potential could be specified through a study of past events if, for the region of interest, a horizontal network of meteorological (pressure and wind) and hydrographic (tide gage) sensors had continuously recorded data during hundreds of historic hurricanes of varying intensity, direction and forward speed. In reality, hurricanes are very rare events for any region along the Atlantic and Gulf coastlines. Also, in the historical cases that do exist, many of the meteorological and hydrographic sensors failed during passage of the hurricane. Thus, for most of the U.S. coastline, the climatology of hurricane storm surge flooding is very limited.

To compensate for this lack of historical data, the NOAA/NWS developed a numerical storm surge model termed SLOSH (Sea, Lake, and Overland Surges from Hurricanes), Jelesnianski, et al (1992). The SLOSH model, given hurricane input parameters, computes storm surge heights over a geographic area that is covered by a mesh of computational grid points. This network, or model domain, is called a basin. At present, 35 basins cover the U.S. Atlantic and Gulf of Mexico flood plains. The basin that covers the flood plain of Eastern North Carolina has been designated the Pamlico Sound basin. The Chesapeake Bay basin covers the flood plains of Virginia, Maryland and Delaware.

Hurricane evacuation studies have been completed for these two basins. In each of these studies a series of hypothetical hurricanes of varying intensity, direction and forward speed, based upon historical records, has been simulated using the SLOSH model in each of the basins. The storm surge data generated by the SLOSH model simulations determines the flood-prone regions. With this knowledge, evacuation plans have been formulated for future use. During an evacuation study, historical hurricanes were also simulated with the SLOSH model. The comparison of the SLOSH model storm surge values and the observed storm surge values determine the confidence in the model (Jarvinen and Lawrence, 1985). Unfortunately, in both basins, simultaneous observations of both the storm surge and hurricane meteorological parameters for historical hurricanes have been almost nonexistent. For example, the last major hurricane to affect all of the Chesapeake Bay area was the 1933 hurricane. Limited meteorological data were obtained at a few observing sites situated around the Bay but no data was obtained at over-the-water observing sites in the Bay. Also, high water survey data were limited to the southern part of the Chesapeake Bay and only a few tide gage readings were available in the north part of the Bay. However, during the 2003 hurricane season, Isabel presented an opportunity for a comparison in these two basins. The purpose of this paper is a comparison of observed high water mark data versus SLOSH/Tide model computed values as well as a comparison of observed tide station hydrographs and SLOSH calculated hydrographs for both of the basins for hurricane Isabel.

2. PAMILICO SOUND AND CHESAPEAKE BAY SLOSH BASINS

The Chesapeake Bay basin grid, which covers the states of Virginia, Maryland and Delaware, is shown in Figure 1a. The grid is a telescoping polar coordinate system with 79 arcs and 84 radials. Similarly, but with a different mathematical coordinate system, the Pamlico Sound basin grid, which covers Eastern North Carolina, is shown in Figure 1b. The grid is a telescoping elliptical coordinate system with 180 arcs and 130 radials. Unlike typical coordinate grids, which would have a radial increment that was invariant with radius, these grids use a radial increment that increases with increasing distance from the grid's pole. The result is that, in each cell of the computational grid, the radial increment of the square is approximately equal to its arc length.

The two telescoping grids are a compromise. It is desired that a large geographical area with small detailed topography be modeled. In the Cartesian coordinate system, this combination of large area and spatially small grid increments requires a computational grid with many cells. A large computational grid requires a computer with a large central processing unit as well as time to perform calculations in the numerous grid squares. The telescoping grids, by comparison, resolve this conflicting needs: it has an acceptably small spatial resolution over land which is the area of the greatest interest. Thus, topographic details, such as highway and railroad embankments and dikes in harbors of cities, are included in the model. However, the range increment contained in each grid square becomes progressively larger with increasing distance from the pole. As a result, a large geographic area is included in the model, and the effects of the model's boundaries on the dynamics of the storm surge are diminished.

Thus, for the Chesapeake Bay basin, the small grid increments allow for good resolution of the bay itself as well as the rivers that flow into the Bay. Similarly, in the Pamlico Sound basin the small grid increments allow good resolution of the Pamlico and Albemarle Sounds including the rivers that flow into them.

3. SLOSH MODEL AND HURRICANE INPUT PARAMETERS

The SLOSH model's governing equations are those given by Jelesnianski (1967), plus a finite amplitude effect. Coefficients for surface drag, eddy viscosity and bottom slip are given by Jelesnianski (1972). There is no calibration or tuning to force agreement between observed and computed surges; coefficients are fixed and do not vary from one geographical region to another.

Special techniques are incorporated to model two-dimensional inland inundation, routing of surges inland when barriers are over-topped, the effect of trees, the movement of surge up rivers, and flow through channels and cuts and over submerged sills.

The SLOSH model requires hurricane input parameters at specified time intervals. These parameters include the latitude and longitude of the storm center, the atmosphere sea-level pressure in the center, and the radius of the maximum surface wind speed (RMW).

4. METEOROLOGY:

4.1 Track

Figure 2 shows hurricane Isabel's track with positions marked every 12 h at 0000 and 1200 UTC (see legend). After forming in the Cape Verde region on September 6, Isabel moved generally in a west-northwest direction for 9 days. During this time Isabel strengthened to a Category 5 hurricane on the Saffir/Simpson scale with a maximum wind speed of 165 mph. On September 15, the hurricane turned toward the north-northwest and began to weaken. Isabel maintained this direction with a gradual increase in forward speed until well after landfall in North Carolina. Isabel became extratropical on 19 September at 1200 UTC in western Pennsylvania where it turned to a more northerly direction and moved into Canada where it was absorbed into a larger low pressure system on the 20th.

Figure 3 shows hourly center locations of Isabel starting several hours before landfall in North Carolina and ending in western Pennsylvania. The hourly locations are labeled by three values separated by slashes. The first value is UTC. The second value is the central sea-level pressure in millibars. The final value is the RMW in statute miles. For example, 1100 /970/52 means 1100 UTC, 970 mb central sea-level pressure, and a radius of maximum wind of 52 statute miles.

The hourly center locations were obtained by a two-dimensional isobaric analysis using all available surface pressure observations which included land stations, offshore light towers, ships of opportunity and locations of minimum central sea-level pressure as observed by reconnaissance aircraft. Three hourly analyses after landfall, with the observations, including wind speed and direction, are shown in Figure 4a, 4b and 4c.

4.2 Intensity and Radius of Maximum Wind (RMW)

The lowest central sea-level pressure values in hurricane Isabel are shown for selected times in Figure 2. Isabel's lowest pressure of 915 mb occurred on 11 September at 1800 UTC. By the time Isabel made landfall at Drum Inlet, North Carolina the pressure had risen to 957 mb with a maximum wind speed of 105 mph, or a category 2 hurricane on the Saffir/Simpson scale. Even as a category 5 hurricane in the mid-Atlantic Isabel had a large eye and large RMW. As Isabel made landfall in North Carolina the RMW was estimated to be 52 st mi. The hourly central sea-level pressure values and RMW are shown in Figure 3. Of interesting note is the decrease in pressure but increase of the RMW as the system moves into northern Virginia, eastern West Virginia and western Pennsylvania. This very large size has not been observed in other historical hurricanes in this region. This large size produced a large wind field of tropical storm force winds with a long fetch over the Chesapeake Bay as shown in Figure 4c. This in turn helped to produce large storm tide values at the northern end of Chesapeake Bay and the upper reaches of the Delaware Bay.

4.3 SLOSH Model Run

Using the data shown in Figure 3 a SLOSH model run was made in both the Pamlico Sound and the Chesapeake bay basins. Comparisons of the SLOSH results with observed high water mark data (see section 5.1) in Pamlico Sound and the lower part of Chesapeake Bay showed typical results. However, the comparison in the upper or northern part of the bay showed the SLOSH values as being much too low. This suggested that the model wind speeds were too low and this in turn suggested that the model input parameters for this part of the SLOSH basin would not generate the observed wind. To compensate for this in the SLOSH model, the track and RMW remained the same but the pressure was adjusted so that the storm surge observed at Baltimore Harbor and Anapolis, Maryland were very close to the SLOSH calculated values. This compensation resulted in increased wind speeds which were slightly higher than the observed wind data in Baltimore Harbor (see next section).

4.4 Observed Surface Wind Profiles Over Water

Three locations in the region recorded wind data over water that are co-located with tide gages. These locations are unique because most wind recording sites are located inland and have frictionally modified winds. These locations are the eastern end of the Duck pier, the Chesapeake Bay Bridge Tunnel (CBBT) and the Francis Scott Key Bridge (FSKB) over Baltimore Harbor.

The anemometers at the three sites were at different heights. The Duck pier and the CBBT site had their anemometers close enough to the standard 10 meter elevation above mean sea level that no adjustment was made to the wind speeds. The FSKB site is located on the bridge at an altitude of 275 feet above mean sea level. The winds from this site were reduced to the 10 meter level by a logarithmic wind profile formula. For example, the observed wind maximum at 275 feet of a one-minute sustained wind of 76 mph (with a gust to 90 mph) was reduced to 62 mph at the 10 meter level. The plots of the wind speed versus time are shown in figures 5 a, b and c. The figure for the Duck pier also includes the wind direction. Wind direction values at the other two sites were not available. Also plotted in each figure is the one-minute sustained wind speed from the SLOSH model for that site. This is the wind speed used in the model (along with a direction) to calculate the wind stress terms that drive the water. The comparisons are reasonable but a bias can be seen in the SLOSH model calculated wind near the maximum observed values. The SLOSH model is over calculating the wind speed by about 8 to11 mph when compared to the observed.

Of interest in the observed data is the decrease of the wind speed maximum that occurred as one moves from Duck (79 mph) to CBBT (73 mph) to FSKB (62 mph). Intuitively, this is what one would expect for a system moving inland and weakening. However, the wind blowing at the FSKB site in Baltimore Harbor is much higher than calculated by wind decay models(i.e. 46 mph) and by observations at nearby inland sites. For example, the maximum wind observed at an inland site near Baltimore Harbor was at the Baltimore International Airport (BWI) with a one-minute sustained wind of 44 mph and a gust to 55 mph. Graham and Hudson (1960) compared the winds at the Baltimore Harbor Airport and the Baltimore Weather Bureau Office (BWBO) near downtown Baltimore for different wind directions at low wind speed conditions using hourly averages. For the

southeast direction the ratio of BWBO's wind to the location used for the bay was found to be 0.64. In other words, the wind at BWBO should be increased by 1.56 to get a wind that would be observed in the harbor that was blowing from the southeast. We assumed that we could use this same ratio for BWI and the FSKB and that it would apply to one-minute averages and at high wind conditions. In the above example, using 44 mph from BWI gives 69 mph at FSKB. This further supports the 62 mph surface wind speed that was calculated from the FSKB wind data mentioned above.

Another source of "snap shot" wind data is aircraft reconnaissance (recon). During the time of landfall an aircraft recon flight flew approximately parallel and near the coastline and recorded wind information at an altitude of 7600 feet (see figure 6). The wind observations, in knots, are plotted every 2 minutes and labeled in UTC . Also located in figure 6 are the locations of Duck (FRF), CBBT, Cape Hatteras and the Maryland/Virginia border (M/V) on the Delmarva Peninsula. The aircraft observation that is closest to Duck is 1714 UTC and is 95 knots (109 mph)/130 degrees. The reduction factor down to the 10 meter surface elevation is 0.75 which gives 82 mph / 130 degrees. This can be compared to the observed value of 79 mph / 122 degrees at 1920 UTC. At CBBT the aircraft observation used for comparison was 1724 UTC or 85 knots (98 mph). Reduced to the surface by 0.75 gives 73 mph identical to the observed value of 73 mph. At Cape Hatteras the maximum flight level wind of 118 kts (136 mph) / 162 degrees was recorded at 1707 UTC. If we also use the reduction factor of 0.75 we get a surface wind speed of 102 mph. The SLOSH model maximum wind at this location is 101 mph at 1700 UTC. Finally, the wind speed value at M/V from recon is 75 knots (86 mph) at 1742 UTC or a surface value of 65 mph. The SLOSH model value at this location is 64 mph. The recon did not go any farther north so one is left to extrapolate the wind speed profile toward the north. Without to much imagination one could advect this aircraft profile along the track of Isabel and realize that the observed wind speed at the FSKB is very realistic especially considering the size of Isabel. This could happen even though the storm is continually filling after landfall, at least near the center.

5. HYDROLOGY

5.1 High Water Marks and Reference Datum

Under an OHS/FEMA requirement, post Isabel high water mark surveys were conducted in North Carolina, Virginia and Maryland. The survey teams were instructed to obtain as many "still water marks" as possible. Still water marks generally reflect the storm tide elevation without the effect of waves. However, because of time delays and the resultant post Isabel clean-up efforts many of these marks were lost. As a result "debris line" elevations, which generally are taken on the outside of buildings or where debris piles have been created by the rise in water, were obtained when a still water mark could not. Debris line elevations are generally higher than high water marks because of waves. About 70 percent of the high water marks are debris line observations. Figure 7a shows the location of these marks for the state of North Carolina and Figure 7b for the states of Virginia and Maryland. A total of 454 high water marks (received via personal communication with Mr. Bob Shapiro OHS/FEMA Region II) are shown on these figures. Overall the coverage of the high water marks is very good with many of them being located in the sections of the rivers where

some of the highest storm tide occurred. NOTE: Some marks in the original data set were taken very far "up river" and well inland and represent fresh water flooding due to rainfall. These marks were not included in the data set or our figures.

The reference datum used for the high water marks in this study is the National Geodetic Vertical Datum of 1929 or NGVD29. This is where sea-level was in 1929 and this was the "zero" elevation. Since 1929 the tide gages along the Atlantic seaboard and inside of Chesapeake Bay have indicated a rise in sea-level on the average of about 0.75 feet. Thus, if a structure has a floor elevation of 10.0 feet above NGVD29 it is really 9.25 feet above the current day sea-level. The NGVD29 vertical datum is used for three main reasons. One, this has and still is the datum used for many buildings. Two, the SLOSH model uses this as the reference datum for all of its land elevations, bottom depths and calculated water elevations. (NOTE: In the structure mentioned above, if the SLOSH model calculated a value of 12.0 feet above NGVD29 in a grid square that the structure is located in, how much water would there be in the house? The answer is two feet.) Three, the water elevations taken after the 1933 hurricane and other historical hurricanes also reference NGVD29. To take the rise in sea-level into account for the high water marks, all of the Isabel SLOSH model simulations will include 0.75 feet in their initial water elevations.

5.2 Astronomical Tide and Initial SLOSH Model Elevations

As hurricane Isabel made landfall in North Carolina and continued into Virginia the daily astronomical tide was approaching high tide. In most instances peak storm surge occurred near the time of high astronomical tide for all of the North Carolina outer coast and most of southern Chesapeake Bay. For the outer coasts (i.e. Atlantic coasts) of both the Pamlico Sound and Chesapeake Bay basins the value used to simulate this high tide was 1.65 feet. For the inside of Chesapeake Bay the value was set at 1.25 feet. Although the peak storm surge began to get out of phase with the high tide in the northern part of the Chesapeake Bay the tide elevations were only slightly less than the southern portion and thus the 1.25 foot value for the high tide elevation could be used. Since the SLOSH models reference datum is NGVD29 we add 0.75 feet (see section 5.1) plus the 1.65 feet for high tide on the outer coast/ 1.25 feet inside Chesapeake Bay to the current day mean sea level to give 2.40 feet/ 2.0 feet above NGVD29 as the initial water elevations for the SLOSH model runs. Note: Pamlico and Albemarle Sounds in North Carolina have almost no tidal signal so the initial elevation for the Sounds was determined by tide gage readings before the hurricane arrived. This value was 1.0 feet above NGVD29.

5.3 Comparison of Observed High Water Marks to SLOSH/Tide Values

SLOSH model runs were made in both basins. The maximum SLOSH/Tide calculated value in a particular grid cell was compared to the observed high water mark located in the same cell. A scatter diagram was created for all of the marks and is shown in Figure 8. If the SLOSH/Tide calculated and observed are the same they will fall on the 45 degree line. As can be seen in the Figure 8 many of the observed values are much larger than SLOSH/Tide calculated. All of these observations have a wave component added to the storm tide value. This was mentioned as a

possibility in section 5.1. In the comments section of each of the observed high water marks the survey team indicated if the mark might contain a wave component. We re-investigated all of the observed high water marks and removed all that contained contributions by waves. This reduced the number of observations from 454 to 397. Another scatter diagram with these values is shown in Figure 9 and the dramatic improvement in the results is evident.

Finally, the 397 pairs of values were subtracted from each other (i.e. SLOSH/tide minus observed) and a bar graph of the differences was created and is shown in Figure 10. The error characteristics are indicated in the legend. Eighty (80) percent of the differences fall between plus 1.5 to minus 1.5 feet while 96 percent are in the range plus 2.5 to minus 2.5 feet.

5.4 Comparison of Tide Gage and SLOSH Storm Surge Hydrographs

Hydrographic records from 27 tide or river gages in the region of Isabel's impact were obtained. Most of the tide gage data came from the National Ocean Survey (Hovis, et al, 2004). Figure 7a shows the locations and names of the gages in North Carolina and Figure 7b shows the locations in Virginia, Maryland, Delaware and Pennsylvania. Some of the records are incomplete because of a malfunction or loss of the gage. The hydrographs from these gages are also shown because they contain useful information about the initial rise of the water at that location. The hydrographs are shown in APPENDIX A and are labeled as Figure 1a through 27a. The hydrograph recorded at Duck, NC is shown in Figure 1a. The period is from 0000 UTC 17 September to 0000 UTC 19 September. The dominant regular feature is the semi-diurnal tide oscillation. Superimposed on this tide oscillation on 18 September is the storm surge caused by Hurricane Isabel. Storm surge is defined as the observed tide minus the predicted astronomical tide. Thus, to determine the hydrograph of the storm surge, it is necessary to subtract the astronomical tide. This was done by using predicted hourly and maximum and minimum National Ocean Service (NOS) tide values and subtracting them from the actual hydrograph. Figure 1b shows the same hydrograph as Figure 1a. with the NOS-predicted tide curve and the storm surge hydrograph. It is useful to note that the peak storm surge occurred near high astronomical tide.

Using this technique to remove the astronomical tide, the storm surge hydrographs for the remaining 26 stations were determined. Note that the 3 river tide gages that flow into Pamlico Sound in North Carolina, which were supplied to us via the internet from the USGS, have almost no tidal signal. For these locations no adjustments were done. The 27 measured storm surge hydrographs are shown in figures 1b through 27b.

Plotted in figures 1c through 27c are the observed storm surge hydrographs from figures 1b through 27 b and the SLOSH model-generated storm surge hydrographs for the same location based upon Hurricane Isabel input parameters as shown in Figure 3. However, the initial water elevation for these SLOSH model runs were set to zero elevation because we are comparing storm surges only.

COMPARISON OF THE RESULTS IN THE PAMLICO SOUND, NC BASIN:

1. At Duck the peak storm surge value generated by SLOSH as well as the time of arrival of the

surge compare very well with the observed.

2. At the Hatteras Fishing Pier the tide gage was destroyed before the peak storm surge arrived. The SLOSH hydrograph starts off lower than the observed but does capture the rate of rise of the water. Because of this the SLOSH hydrograph appears to be running about 2 hours late. However, it is evident from the observed storm surge hydrograph that the water surface was elevated about a foot at about 2100 UTC on the 17th of September which was not captured by the SLOSH model. If the SLOSH hydrograph is elevated by this amount the phase problem disappears and the comparison improves dramatically. This adjustment is shown in Figure 1 in APPENDIX B. Figure 2 in APPENDIX B shows a computation of a hypothetical tide gage hydrograph for the Hatteras Fishing Pier based upon the addition of the SLOSH adjustment in Figure 1 and the predicted astronomical tide. The resulting hypothetical storm tide maximum at this location is 7.7 feet above mean sea level or 8.8 feet above NGVD29.

3. The Oregon Inlet Marina is located inside of Pamlico Sound and just north of the inlet. As can be seen, the tidal signal is relatively small at this location compared to the Atlantic side. As Isabel approached landfall, the east and southeast winds on the right side of the center drove the water away from the shoreline inside the sound (note: while at the same time piling it up on the Atlantic side as seen in the Duck and the Hatteras Fishing Pier figures). This is seen in the observed tide gage as negative storm surge. As the hurricane continued inland the wind turned toward the south, then southwest and finally west and drove the water in Pamlico Sound up against the east side of the Sound causing a rise in the observed tide gage. The SLOSH hydrograph shows that the model produces a peak surge comparable to the observed but is about 6 hours early and creates a negative surge of about minus two feet which was not observed. The results suggest that the radial extent of the SLOSH model wind field used to drive the water on the southern side of the hurricane (i.e. often referred to the back side of the hurricane) is not large enough and in this case would need to be expanded. This would force the SLOSH model peak closer to the observed.

4. The river gages at Pollockville, Swift Creek and Washington, NC all begin at elevations well above zero, which reflects the fact that they are slightly “up river”. In these three cases, the SLOSH model hydrograph at each location was moved up to have the same initial starting elevation as the river hydrograph. Comparisons at Pollockville and Swift Creek are very reasonable. At Washington, NC located on the Pamlico river the SLOSH model calculated a peak surge that was about a foot too high and about 4 hours late.

COMPARISON OF THE RESULTS IN THE CHESAPEAKE BAY BASIN:

1. At Wachapreague the SLOSH model is a little slow in reaching the maximum storm surge but is near the observed maximum value.

2. At Kiptopeke the phasing is very good but the SLOSH model is high by about 1.7 feet.

3. At the Chesapeake Bay Bridge Tunnel the comparison is very good.

4. At Sewells Point the SLOSH is higher than observed and just a bit late.

5. At Money Point the SLOSH maximum is lower than observed but they occur near the same time.

6. The Richmond Locks are located on the James River near Richmond, Virginia. This is also about 95 river miles from Sewells Point. At this location the highest storm surge of 10.8 feet was observed and can be compared to the next two highest values of 8.1 feet and 8.2 feet at Washington, DC and Chesapeake City, MD respectively. As Isabel moved inland into North Carolina and Southern Virginia the wind field on the right hand side of the hurricane drove water into southern Chesapeake Bay and up the rivers that drain into the bay. The James River is oriented roughly in a west-northwest to east-southeast direction. At some time during the passage of the hurricane Isabel's winds were blowing parallel to the orientation of the river, thus creating optimal wind stress forces on the river's water surface and driving the water up river. Since the river gets narrower as one approaches Richmond the water began to funnel and produced the storm surge as seen in the figure. Later, as the storm surge decreased, freshwater flooding began and produced the higher of the two maxima about two days later. It is interesting to note that the tidal signal is totally removed by the force of the fresh water flooding.

The SLOSH model grid for the Chesapeake Bay basin ends about 12 miles down river from the Richmond Locks. Thus, no grid cell was available to do a direct comparison. Instead, the last grid cell representing the James River at the boundary of the grid was used for the comparison. The phasing of the SLOSH model seems to be good but, as somewhat expected, the amplitude is about four feet too low. If the SLOSH grid extended to Richmond one would expect the SLOSH hydrograph amplitude to be higher.

7. At Gloucester Point, Windmill Point, Lewissetta and Colonial Beach the initial rise of the water in the SLOSH model with the observed is very reasonable.

8. At Washington, DC the hydrographs look very similar but the SLOSH lags behind the observed by about 4 hours.

9. At Annapolis, Baltimore and Tolchester Beach the comparisons are very good.

10. At Chesapeake City the SLOSH peak storm surge is a little low and lags behind the observed by about six hours.

COMPARISON OF THE RESULTS IN DELAWARE BAY:

1. At Lewes the peaks are comparable but the SLOSH is about one hour late.

2. At Ship John Shoal and Reedy Point the SLOSH model is 1.5 and 2.4 feet too high respectively and lags behind the observed by about 5 to 6 hours.

3. At Philadelphia the SLOSH peak is a little low and about 8 hours late.

5.5 Summary of the Comparisons

Table 1 gives a summary of the comparisons of observed storm surge height and time of occurrence and the SLOSH calculated storm surge and time of occurrence. The last column is the gage time minus the SLOSH time to determine the lag at a particular location. Analysis of the time lags suggested a bias in the river data. A second table was created stratifying the data into 3 groups. Open coastal gages, including the Atlantic shoreline and the bay, the river gages, and gages that do not fit either category. Last but not least, a scatter diagram, using the data in table 1, of the observed storm surge and SLOSH calculated storm surge is shown in figure 11. The results of figure 11 and table 2 are discussed in the conclusions.

6.0 CONCLUSIONS

Comparison of the SLOSH model winds to two over-the-water observing sites, Duck, NC and the Chesapeake Bay Bridge Tunnel, showed reasonable results, with the SLOSH model maximum wind about 10 mph higher than the observed. However, with these winds the SLOSH model produced very reasonable storm surge hydrographs when compared to the observed. The maximum winds observed at the northern end of Chesapeake Bay were much larger than standard wind decay models calculated. When the SLOSH model wind field was adjusted to produce the observed wind field (i.e. with a 10 mph high bias), the storm surge results improved dramatically in the northern end of the Chesapeake Bay.

For hurricane Isabel (2003), comparison of 397 observed high water marks (i.e. wave contaminated marks removed) in North Carolina, Virginia and Maryland yielded typical storm surge model error characteristics, with a majority of the SLOSH/Tide calculated values within plus or minus 20 percent of the observed. Also, the differences between the observed high water marks and the SLOSH/Tide generated values showed that 80% of the values fell between plus 1.5 to minus 1.5 feet and 96% are within plus 2.5 to minus 2.5 feet.

Figure 11 shows the comparison of the maximum observed storm surge to the SLOSH model calculated storm surge maximum for 21 tide gages. Over all the comparison is reasonable except at two locations in the Delaware Bay - Reedy Point and Ship John Shoal and two locations in the Chesapeake Bay - Kiptopeke and Money Point. Comparison of the time of observed maximum storm surge to the time of the SLOSH generated maximum in Table 1 showed significant differences

in errors in time between gages near the coast and gages in the rivers. From Table 1 the locations of the tide gage locations were broken into three groups; coastal or near coastal gages, river gages and miscellaneous (i.e. does not fit either coastal or river). The results are presented in table 2 and show very good phase comparisons for the coastal locations but a large negative lag in the rivers. In other words, the storm surge in the SLOSH model is arriving many hours late when compared to the observed, even though the maximum heights of the storm surge are very reasonable when compared to each other at these locations.

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Table 1. Comparison of Observed and SLOSH Storm Surge maximums and time of occurrence for 22 locations for hurricane Isabel (2003). * Comparison not at same location. 5 locations NA means incomplete record. Gage time differences in last column.

Station Name	Gage MAX (ft)	Time of Gage MAX (UTC)	SLOSH MAX (ft)	Time of SLOSH MAX (UTC)	Gage Time minus SLOSH Time (hrs)
Annapolis, US Naval Academy, MD	6.3	9/19/04 12:00	6.4	9/19/04 12:00	0
Baltimore, MD	7.3	9/19/04 12:00	7.2	9/19/04 12:00	0
Cambridge, Choptank River, MD	5.2	9/19/04 10:00	4.6	9/19/04 15:00	-5
Cape Hatteras Fishing Pier	NA	NA	5	9/18/04 16:00	NA
Chesapeake Bay Bridge Tunnel, VA	4.8	9/18/04 20:00	4.7	9/18/04 19:00	-1
Chesapeake City, MD	8.2	9/19/04 14:00	6.6	9/19/04 21:00	-6
Colonial Beach, Potomac River, VA	NA	NA	6.9	9/19/04 6:00	NA
Duck USACE FRF, NC	4.7	9/18/04 16:00	4.6	9/18/04 17:00	-1
Gloucester Point, York River, VA	NA	NA	7.5	9/18/04 23:00	NA
Kiptopeke, Chesapeake Bay, VA	3.9	9/18/04 20:00	5.4	9/18/04 21:00	-1
Lewes, DE	3.1	9/19/04 1:00	3.4	9/19/04 2:00	-2
Lewisetta, Potomac River, VA	4.0	9/19/04 1:00	4.9	9/19/04 3:00	0
Money Point, Elizabeth River, VA	5.7	9/18/04 22:00	4.4	9/18/04 22:00	0
Oregon Inlet Marina, NC	4.7	9/19/04 3:00	4.3	9/18/04 22:00	5
Philadelphia, PA	5.4	9/19/04 8:00	4.7	9/19/04 16:00	-8
Pollockville, NC	5.6	9/18/04 23:00	6	9/18/04 21:00	2
Reedy Point, DE	5.0	9/19/04 5:00	7.4	9/19/04 10:00	-5
Richmond Locks, VA	10.8	9/19/04 5:00	6.8*	9/19/2004 6:00*	-1
Sewells Point, VA	5.6	9/18/04 21:00	6.8	9/18/04 22:00	-1
Ship John Shoal, NJ	4.7	9/19/04 3:00	6.4	9/19/04 9:00	-5
Solomon Island, MD	NA	NA	5	9/19/04 7:00	NA
Swift Creek, NC	5.0	9/19/04 0:00	5.4	9/19/04 0:00	0
Tolchester Beach, MD	6.9	9/19/04 13:00	6.8	9/19/04 13:00	0
Wachapreague, VA	5.0	9/18/04 21:00	5	9/18/04 23:00	-2
Washington, NC	6.2	9/19/04 0:00	7	9/19/04 3:00	-3
Washington, DC	8.1	9/19/04 10:00	8	9/19/04 14:00	-4
Windmill Point, VA	NA	NA	7.6	9/18/04 23:00	NA

Table 2. The range of the Coastal areas are 0 to -2 hours and the river areas are ranging +2 to -8.

Station Name	Coastal	Rivers	Miscellaneous
Annapolis, US Naval Academy, MD	0		
Baltimore, MD	0		
Cambridge, Choptank River, MD		-5	
Cape Hatteras Fishing Pier			NA
Chesapeake Bay Bridge Tunnel, VA	-1		
Chesapeake City, MD		-6	
Colonial Beach, Potomac River, VA			NA
Duck USACE FRF, NC	-1		
Gloucester Point, York River, VA			NA
Kiptopeke, Chesapeake Bay, VA	-1		
Lewes, DE	-2		
Lewisetta, Potomac River, VA	0		
Money Point, Elizabeth River, VA	0		
Oregon Inlet Marina, NC			5
Philadelphia, PA		-8	
Pollockville, NC		2	
Reedy Point, DE		-5	
Richmond Locks, VA		-1	
Sewells Point, VA	-1		
Ship John Shoal, NJ		-5	
Solomon Island, MD			NA
Swift Creek, NC		0	
Tolchester Beach, MD	0		
Wachapreague, VA	-2		
Washington, NC		-3	
Washington, DC		-4	
Windmill Point, VA			NA

Figure Captions

Figure 1a. Chesapeake Bay SLOSH basin grid.

Figure 1b. Pamilico Sound SLOSH basin grid.

Figure 2. Track of Hurricane Isabel, 6 September to 20 September 2003. Positions are given at every 12 hours at 0000 and 1200 UTC. The date is located at the 1200 UTC position. (See legend).

Figure 3. Track of Hurricane Isabel. Hourly locations are indicated with a hurricane symbol. Legend example: 1500/957/54 – 1500 UTC/ 957 mb central sea level pressure / 54 statute miles radius of maximum winds.

Figure 4a. Surface isobaric analysis at 1800 UTC18 September 2003. Contour interval is 5 mb. Surface wind speed and direction are also included.

Figure 4a. Surface isobaric analysis at 1800 UTC18 September 2003. Contour interval is 5 mb. Surface wind speed and direction are also included.

Figure 4b. Surface isobaric analysis at 0200 UTC19 September 2003. Contour interval is 5 mb. Surface wind speed and direction are also included.

Figure 4c. Surface isobaric analysis at 1000 UTC19 September 2003. Contour interval is 5 mb. Surface wind speed and direction are also included.

Figure 5a. Observed and SLOSH calculated one-minute wind speeds at the Duck, North Carolina Field Research Facility (FRF).

Figure 5b. Observed and SLOSH calculated one-minute wind speeds at the Chesapeake Bay Bridge Tunnel (CBBT), Virginia.

Figure 5c. Observed and SLOSH calculated one-minute wind speeds at the Francis Scott Key Bridge, Baltimore, MD.

Figure 6. Aircraft Reconnaissance wind observations at two minute intervals near the time of Isabel landfall, elevation is 7600 ft msl.

Figure 7a. Location of Observed High Water marks and tide gages in North Carolina.

Figure 7b. Location of Observed High Water marks and tide gages in Virginia, Maryland, Delaware and Pennsylvania.

Figure 8. Observed high water marks vs. SLOSH/Tide Values. With waves.

Figure 9. Observed high water marks vs. SLOSH/Tide Values. With no waves. N = 397

Figure 10. SLOSH/Tide values minus Observed High Water Marks for Hurricane Isabel (2003) with no waves.

Figure 11. Observed Tide Gage Storm Surge Maximum vs. SLOSH Maximum.

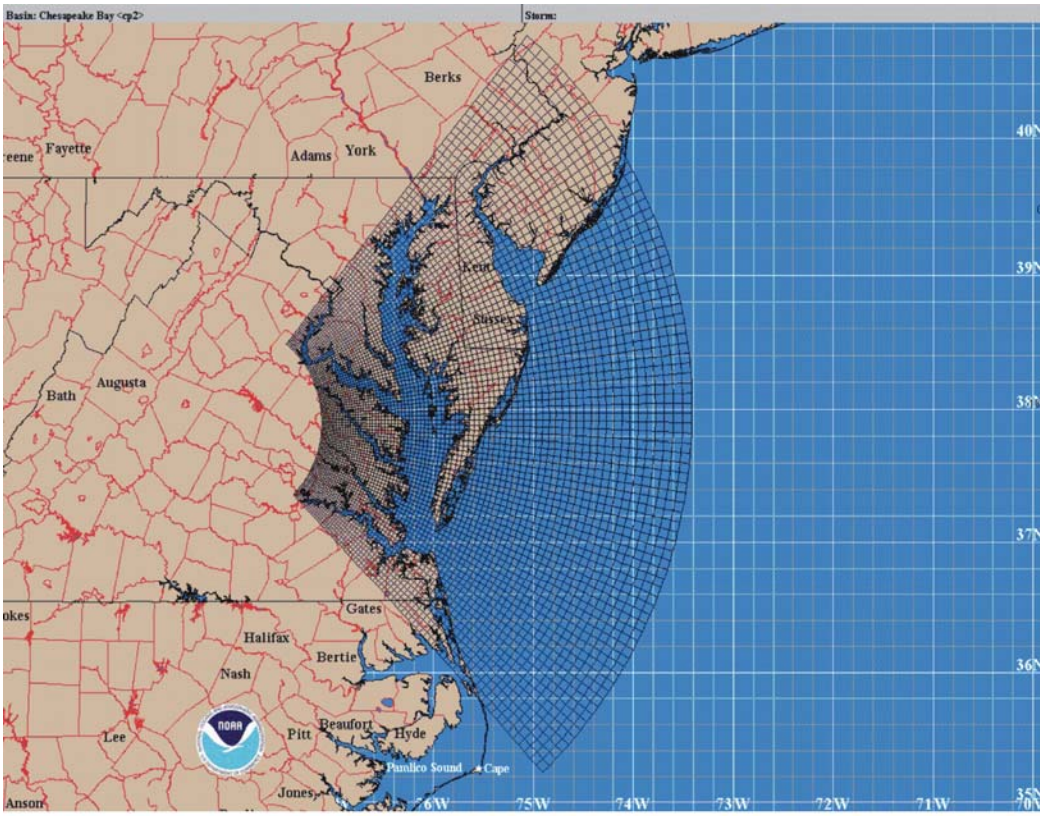


Figure 1a. Chesapeake Bay SLOSH basin grid.

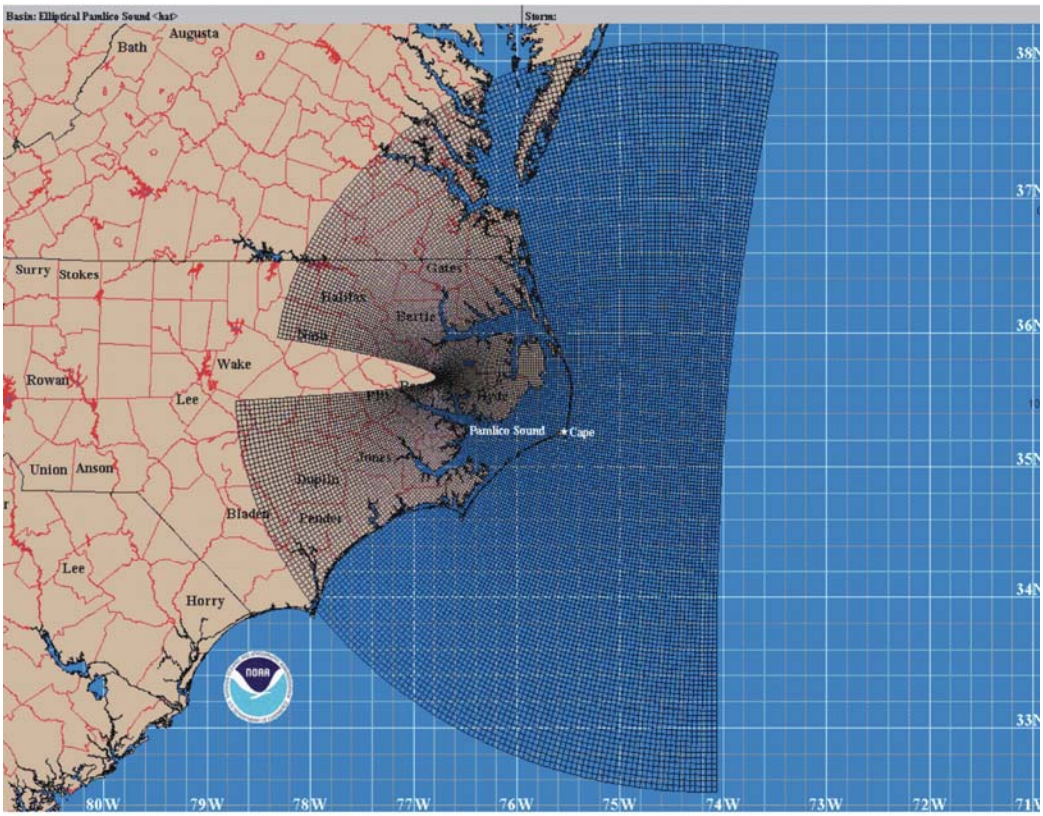


Figure 1b. Pamilico Sound SLOSH basin gri.d.

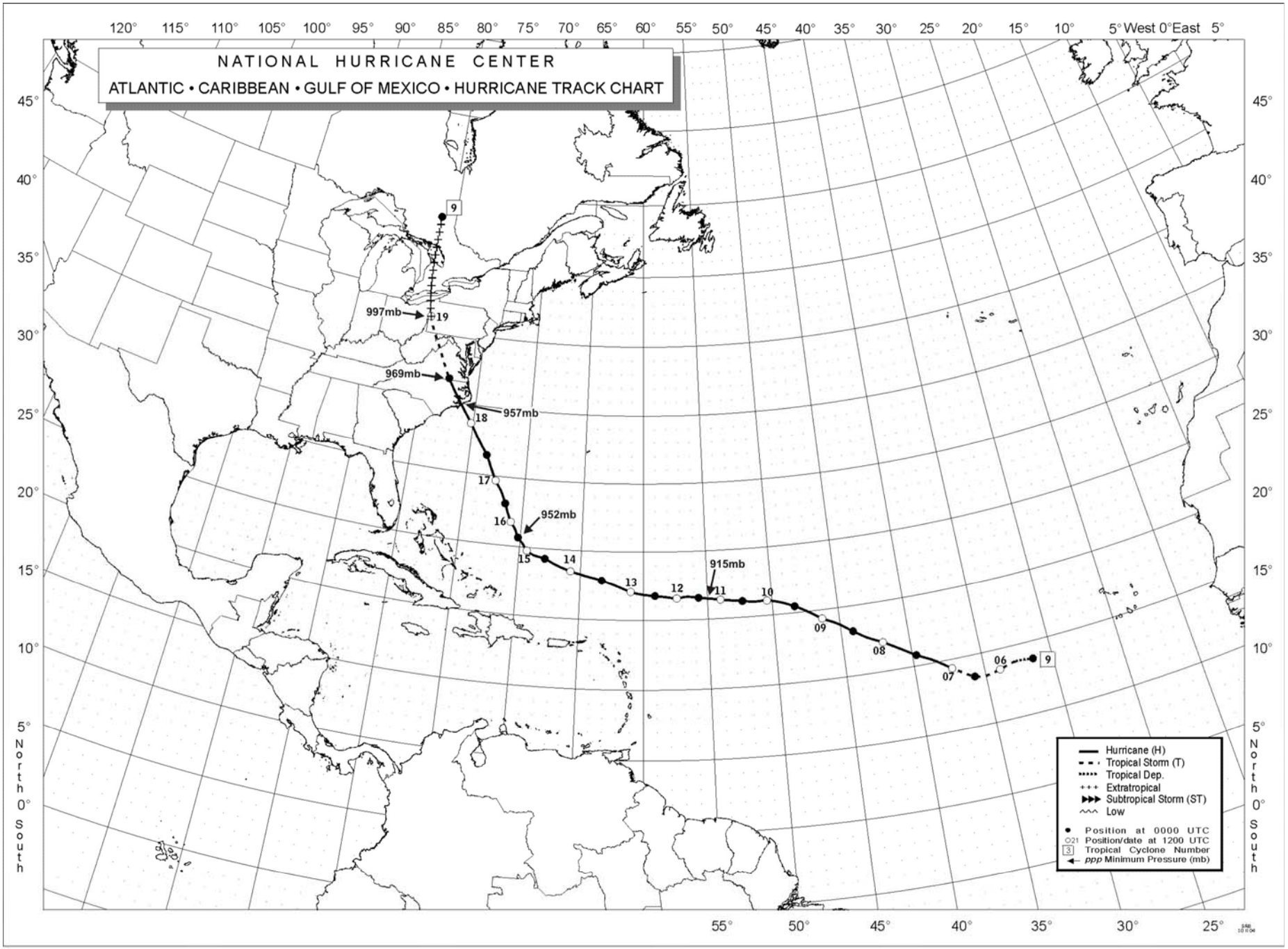


Figure 2. Track of Hurricane Isabel, 6 September to 20 September 2003. Positions are given at every 12 hours at 0000 and 1200 UTC. The date is located at the 1200 UTC position. (See legend).

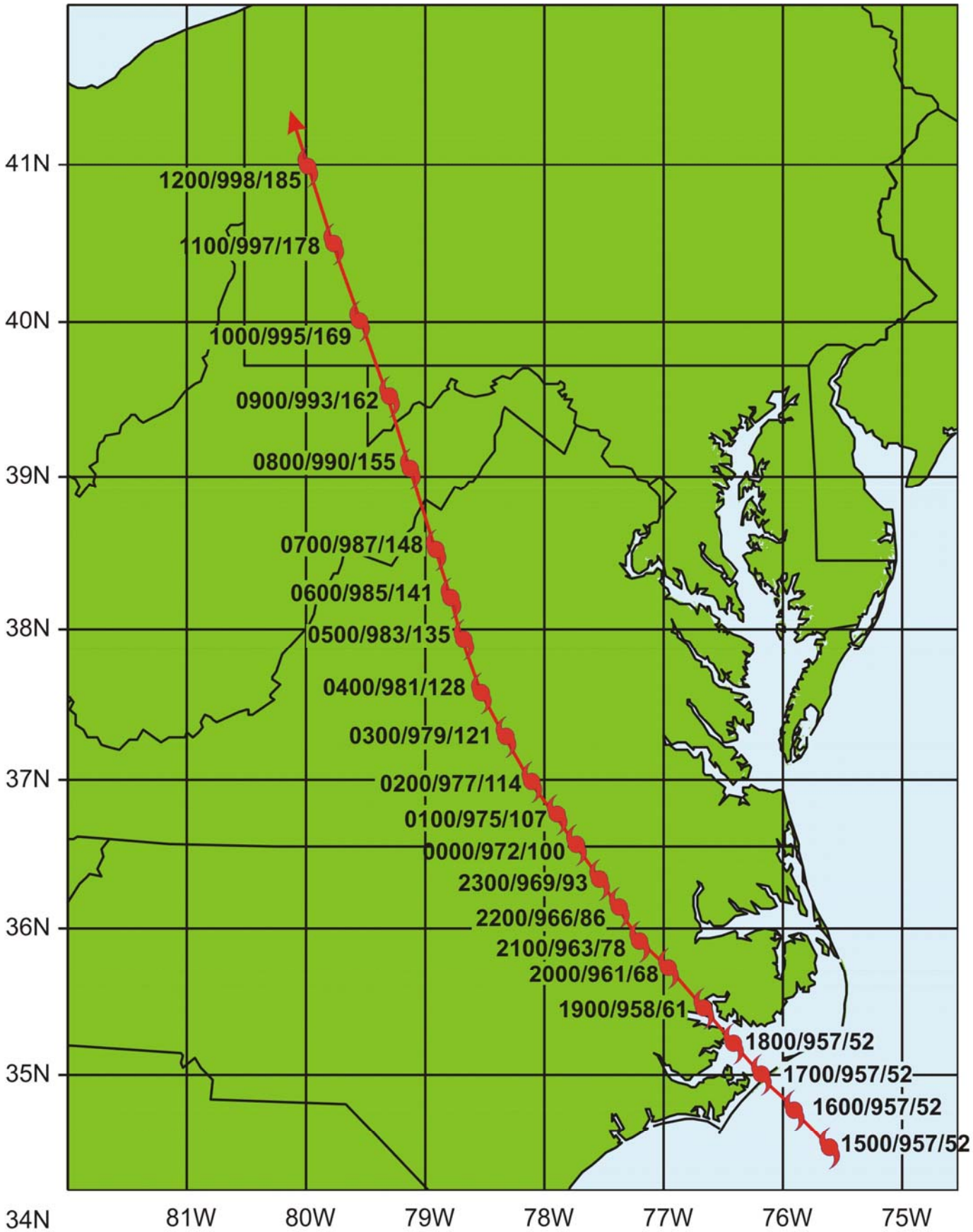


Figure 3. Track of Hurricane Isabel. Hourly locations are indicated with a hurricane symbol. Legend example: 1500/957/54 – 1500 UTC/ 957 mb central sea level pressure / 54 statute miles radius of maximum winds

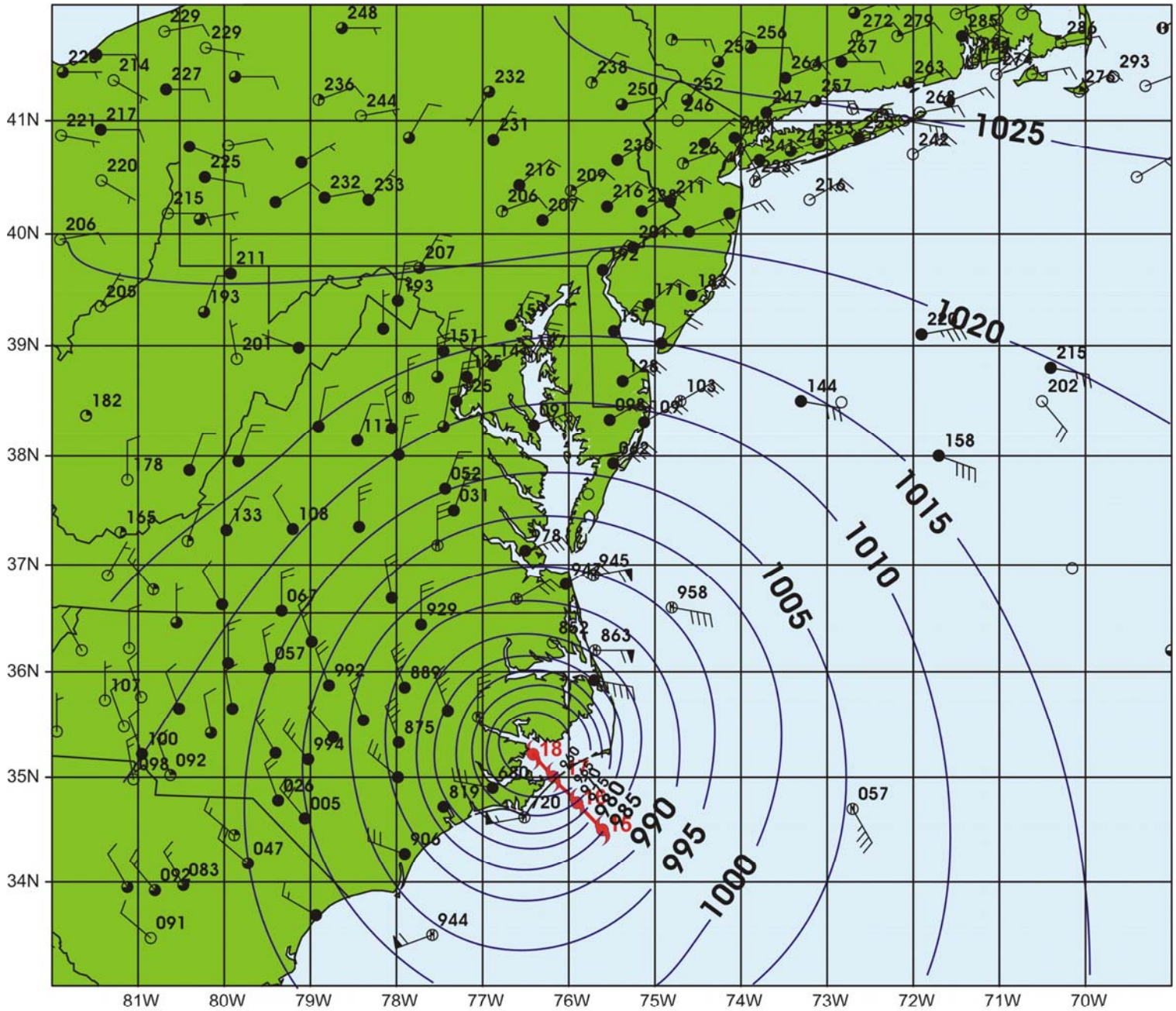


Figure 4a. Surface isobaric analysis at 1800 UTC18 September 2003. Contour interval is 5 mb. Location of observation is indicated by a circle. The pressure value in millibars (mb) is given to the upper right of the circle. Examples: 958 = 995.8 mb; 057 = 1005.7 mb. Wind arrows blow in the direction the wind is going. The barbs indicate speed in knots (kts). A full barb is 10 kts; a one-half barb is 5 kts; a flag is 50 kts. For example, an arrow with 3 full barbs and one-half barb is blowing at 35 kts.

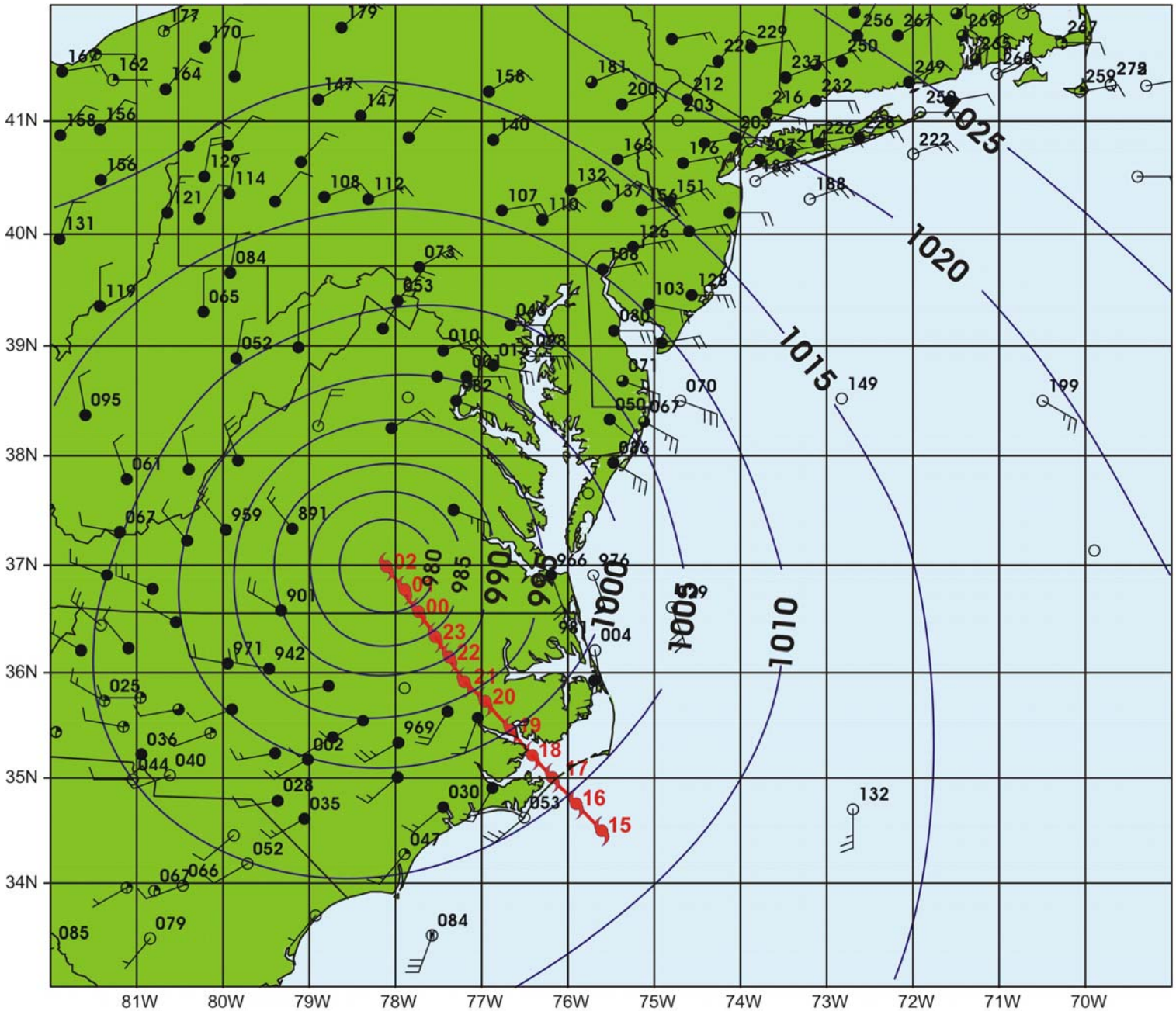


Figure 4b. Surface isobaric analysis at 0200 UTC19 September 2003. Contour interval is 5 mb. Location of observation is indicated by a circle. The pressure value in millibars (mb) is given to the upper right of the circle. Examples: 958 = 995.8 mb; 057 = 1005.7 mb. Wind arrows blow in the direction the wind is going. The barbs indicate speed in knots (kts). A full barb is 10 kts; a one-half barb is 5 kts; a flag is 50 kts. For example, an arrow with 3 full barbs and one-half barb is blowing at 35 kts.

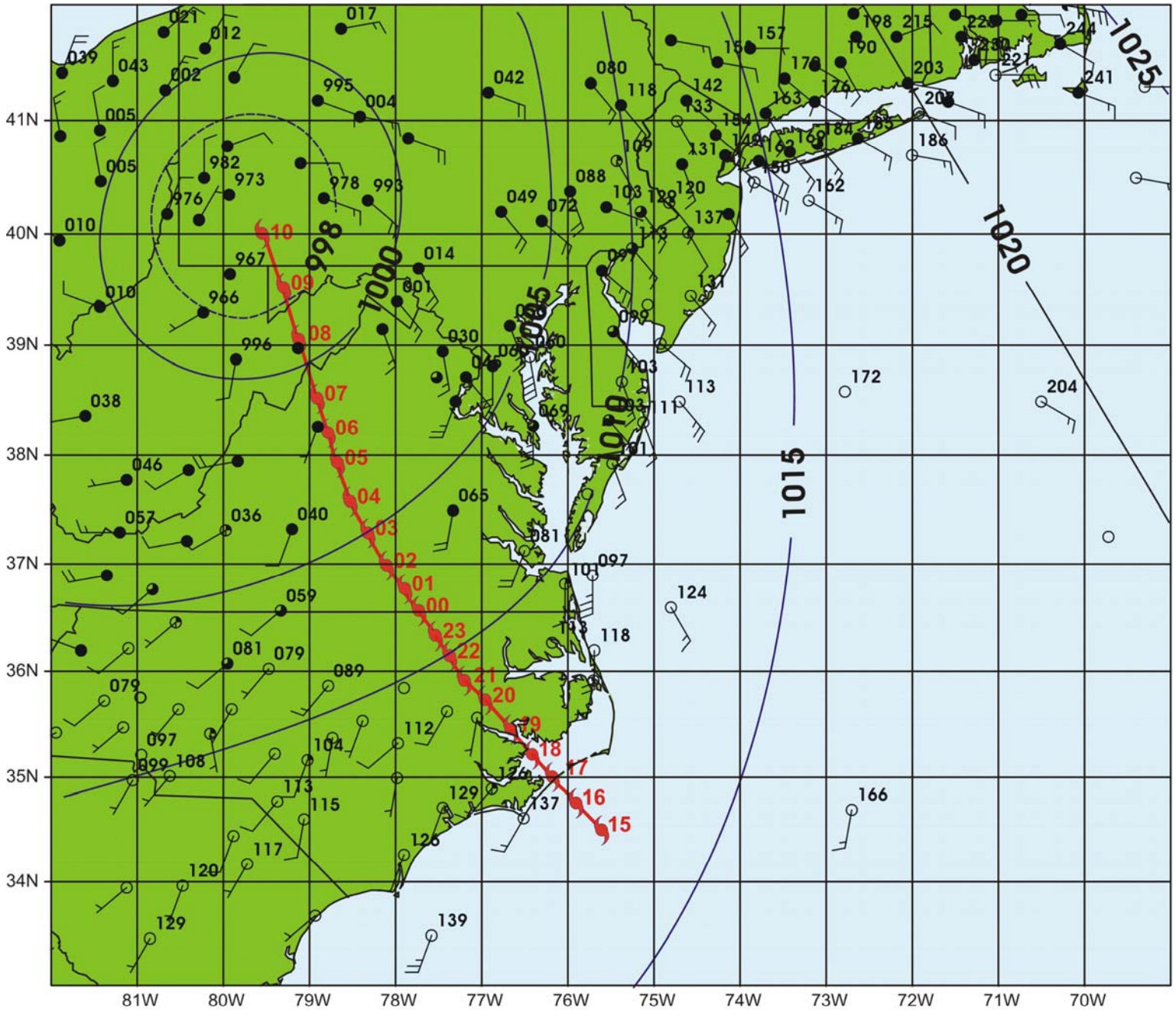


Figure 4c. Surface isobaric analysis at 1000 UTC19 September 2003. Contour interval is 5 mb. Location of observation is indicated by a circle. The pressure value in millibars (mb) is given to the upper right of the circle. Examples: 958 = 995.8 mb; 057 = 1005.7 mb. Wind arrows blow in the direction the wind is going. The barbs indicate speed in knots (kts). A full barb is 10 kts; a one-half barb is 5 kts; a flag is 50 kts. For example, an arrow with 3 full barbs and one-half barb is blowing at 35 kts.

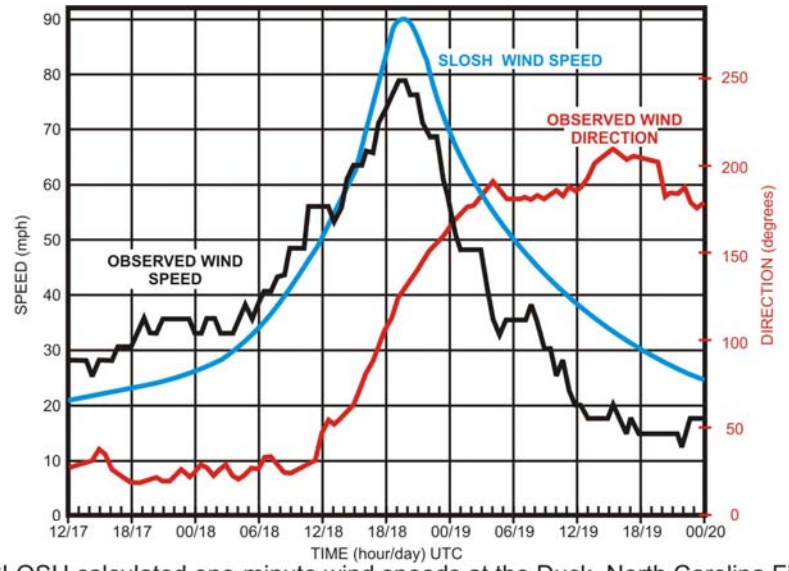


Figure 5a. Observed and SLOSH calculated one-minute wind speeds at the Duck, North Carolina Field Research Facility (FRF).

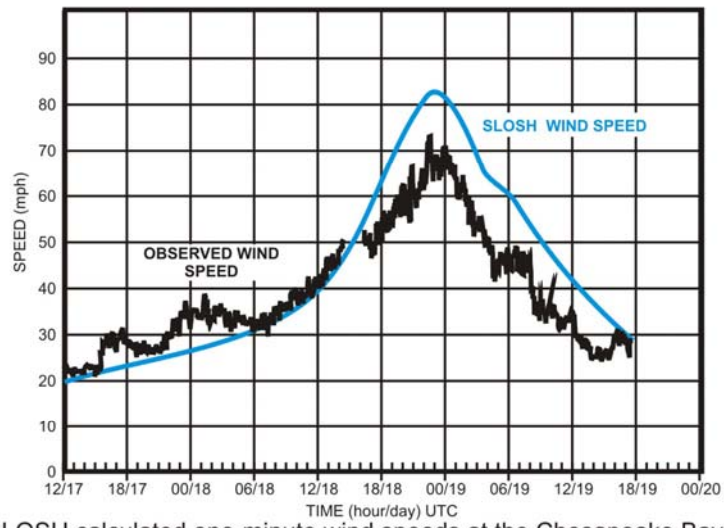


Figure 5b. Observed and SLOSH calculated one-minute wind speeds at the Chesapeake Bay Bridge Tunnel (CBBT), Virginia

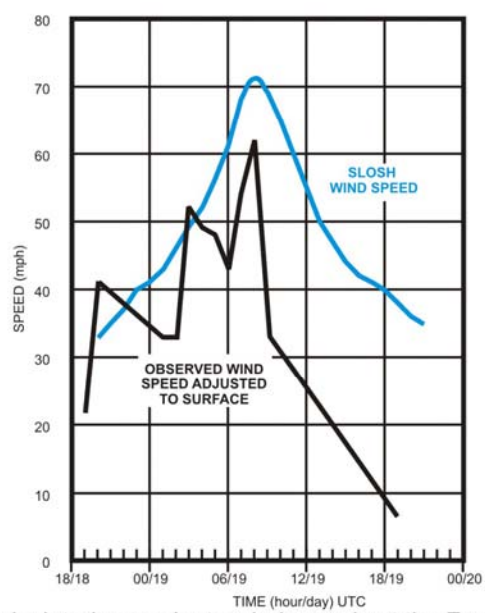


Figure 5c. Observed and SLOSH calculated one-minute wind speeds at the Francis Scott Key Bridge, Baltimore, MD.

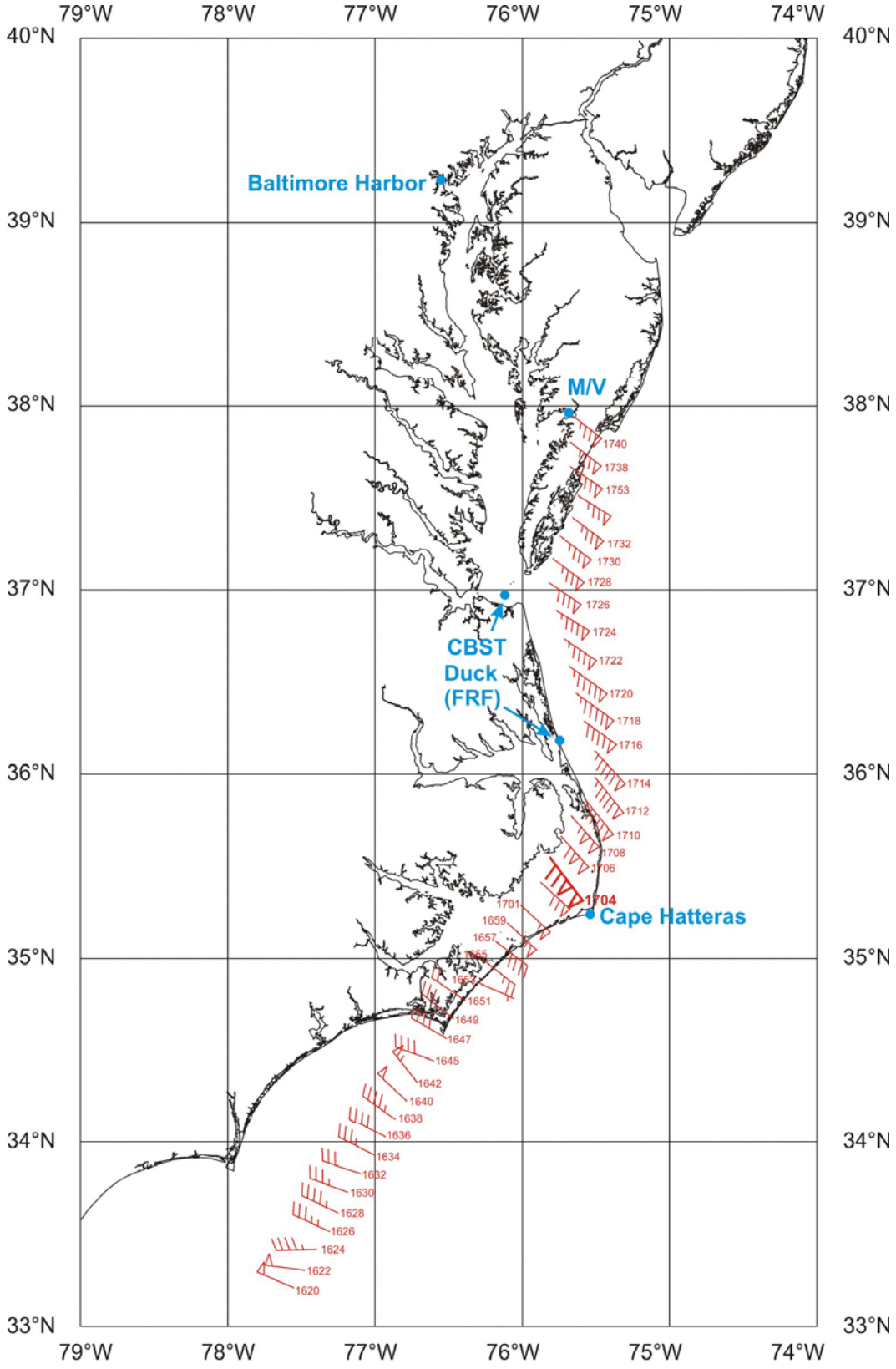


Figure 6. Aircraft Reconnaissance wind observations at two minute intervals near the time of Isabel landfall, elevation is 7600 ft msl.

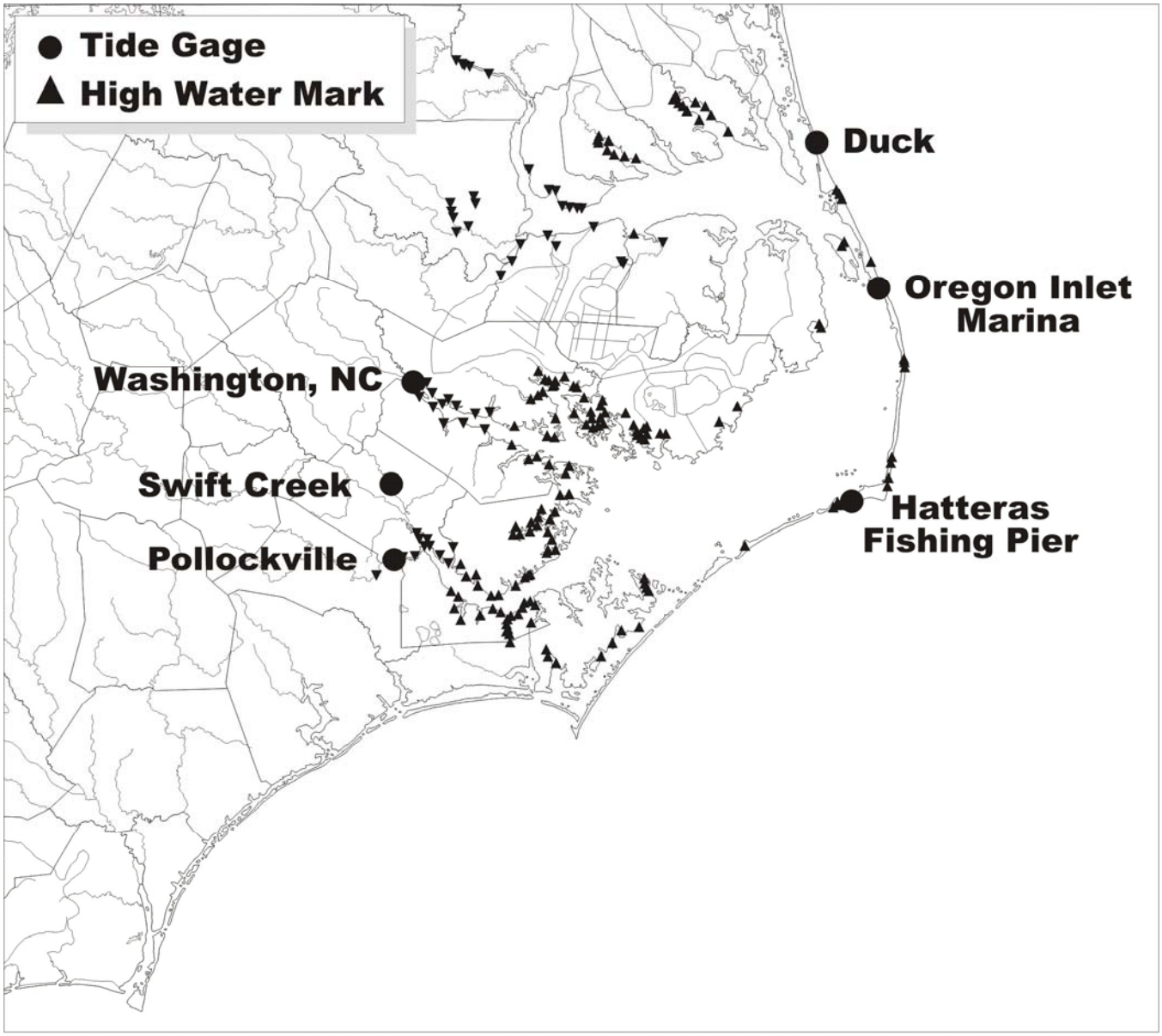


Figure 7a. Location of Observed High Water marks and tide gages in North Carolina.

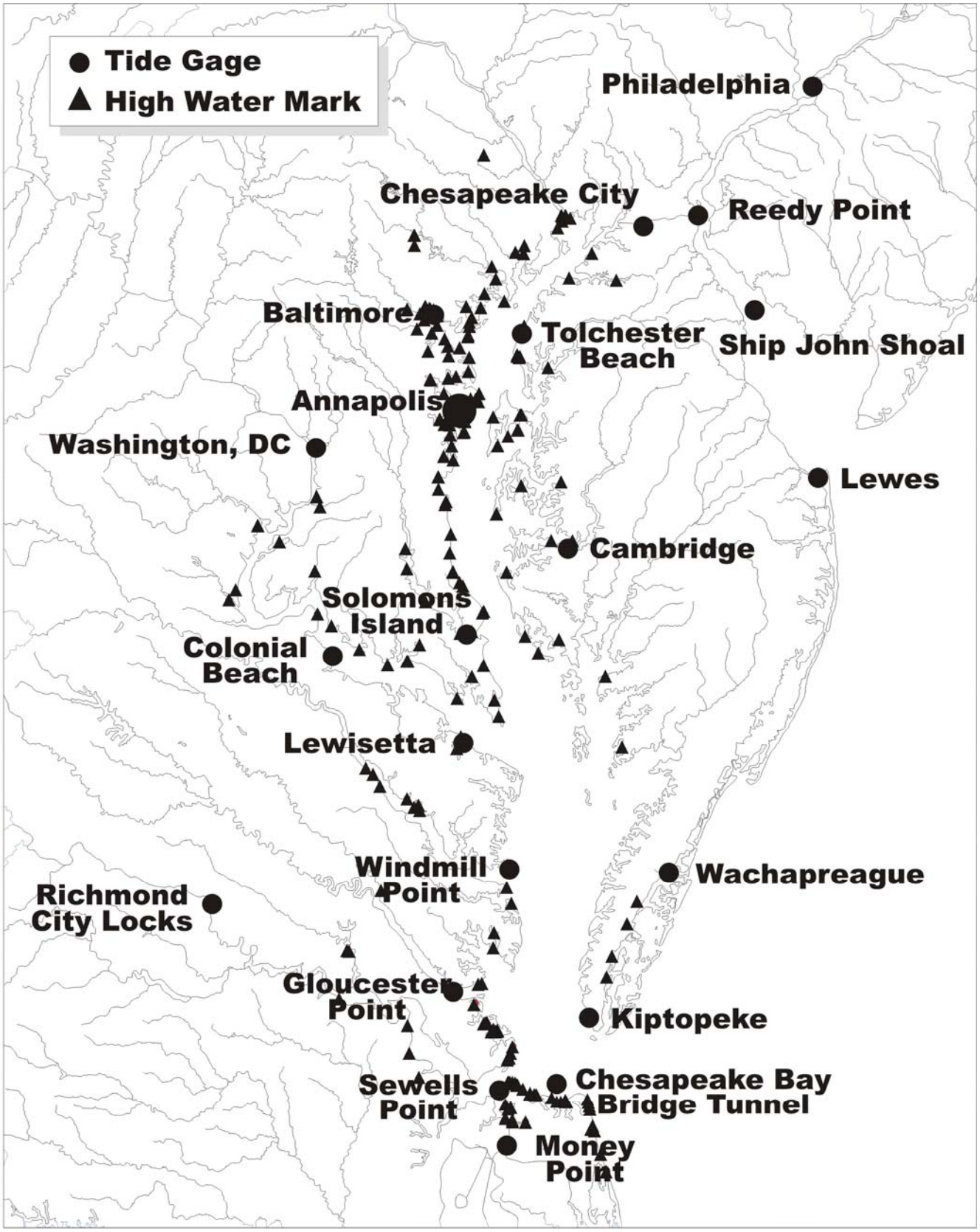


Figure 7b. Location of Observed High Water marks and tide gages in Virginia, Maryland, Delaware and Pennsylvania.

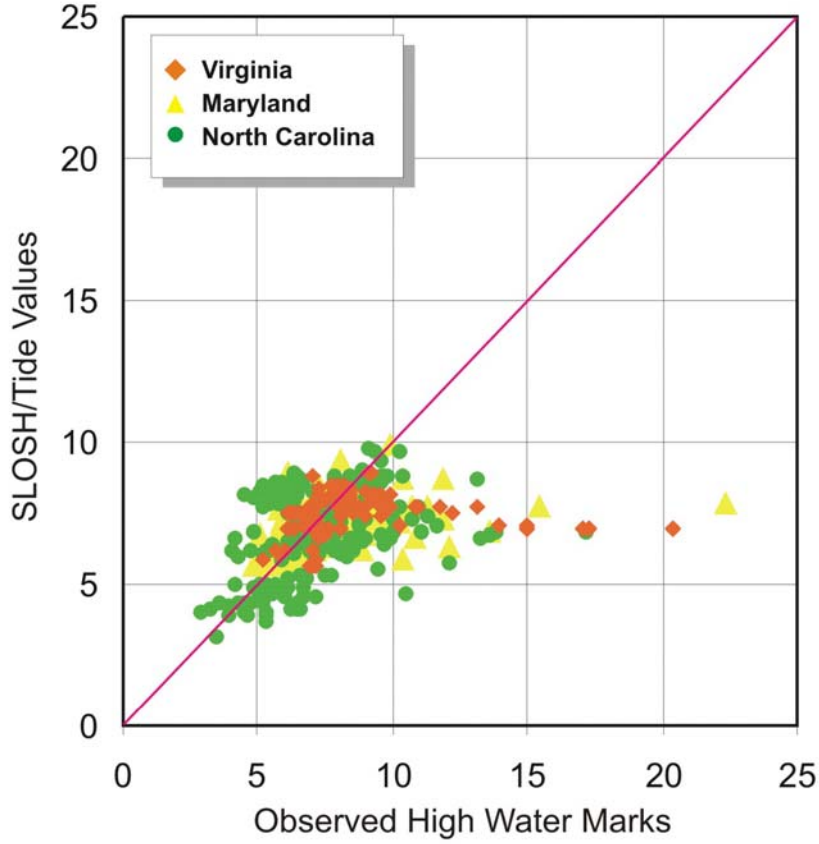


Figure 8. Observed high water marks vs. SLOSH/Tide Values. With waves. N = 454.

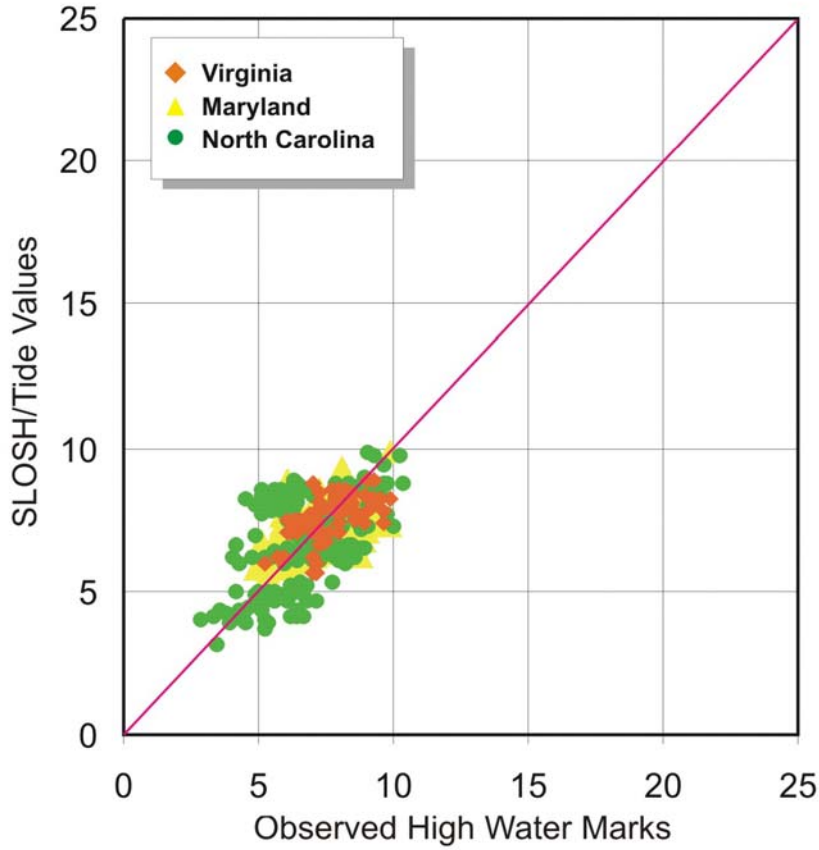


Figure 9. Observed high water marks vs. SLOSH/Tide Values. With no waves. N = 397

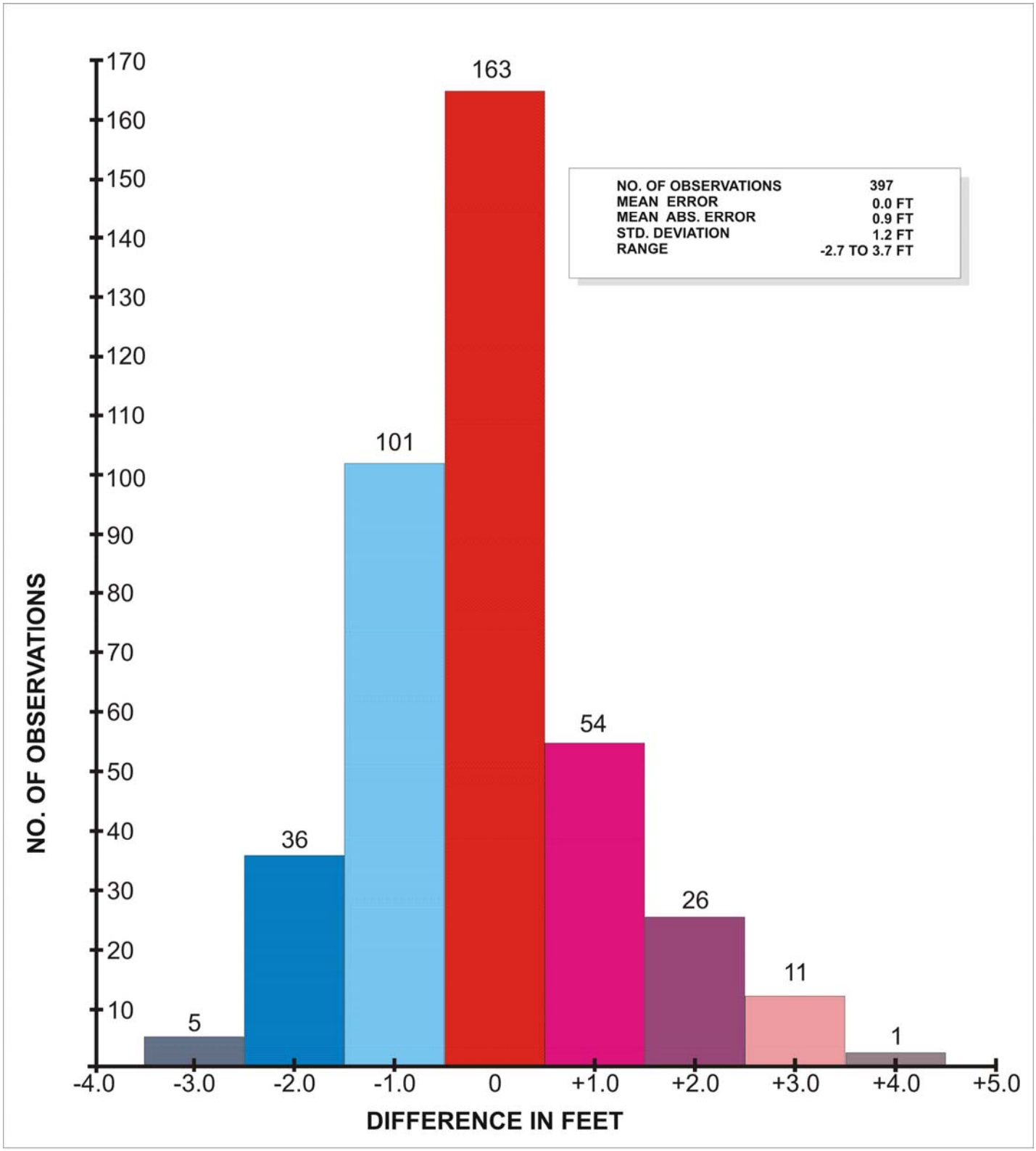


Figure 10. SLOSH/Tide values minus Observed High Water Marks for Hurricane Isabel (2003) (with no waves).

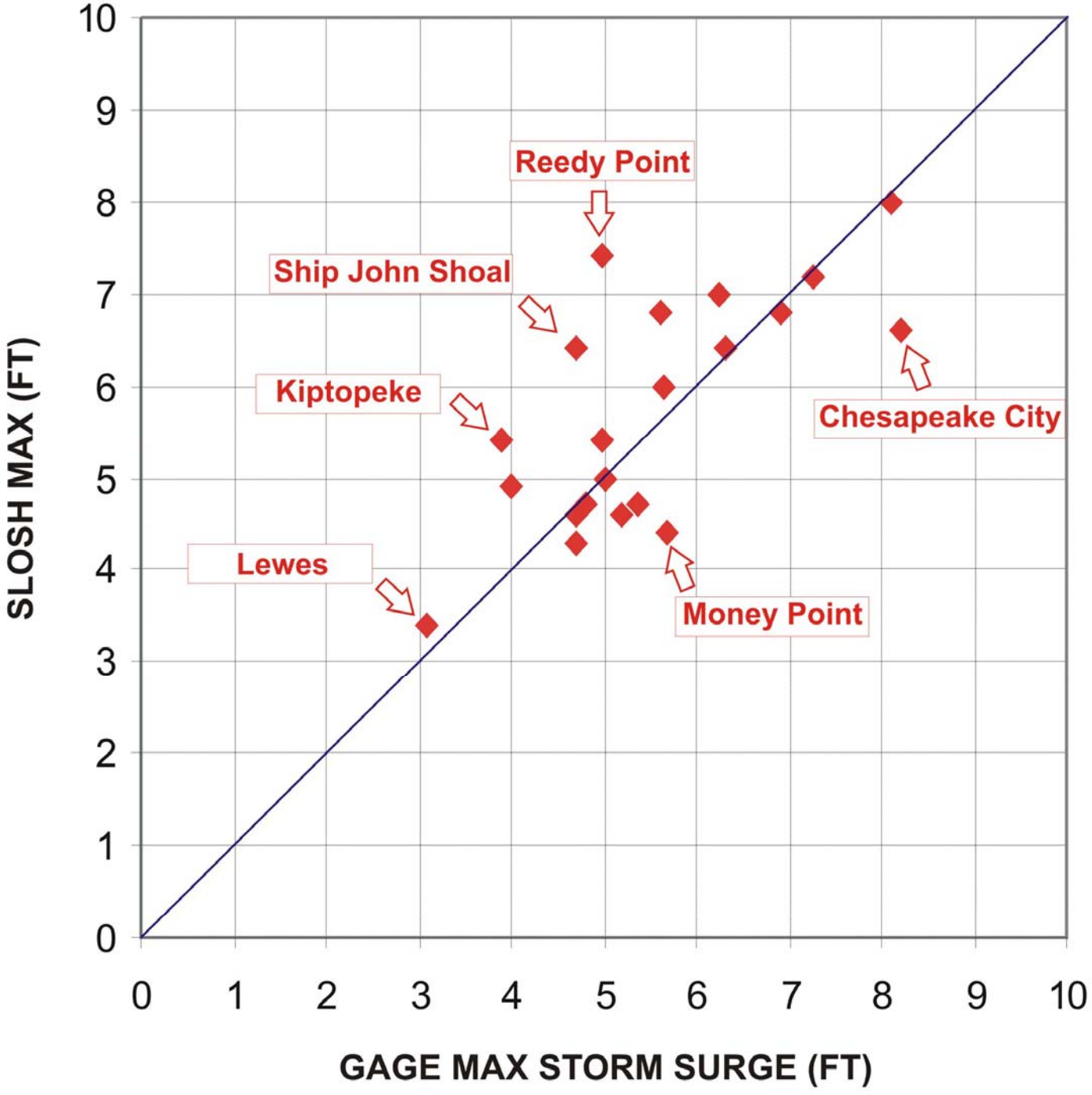
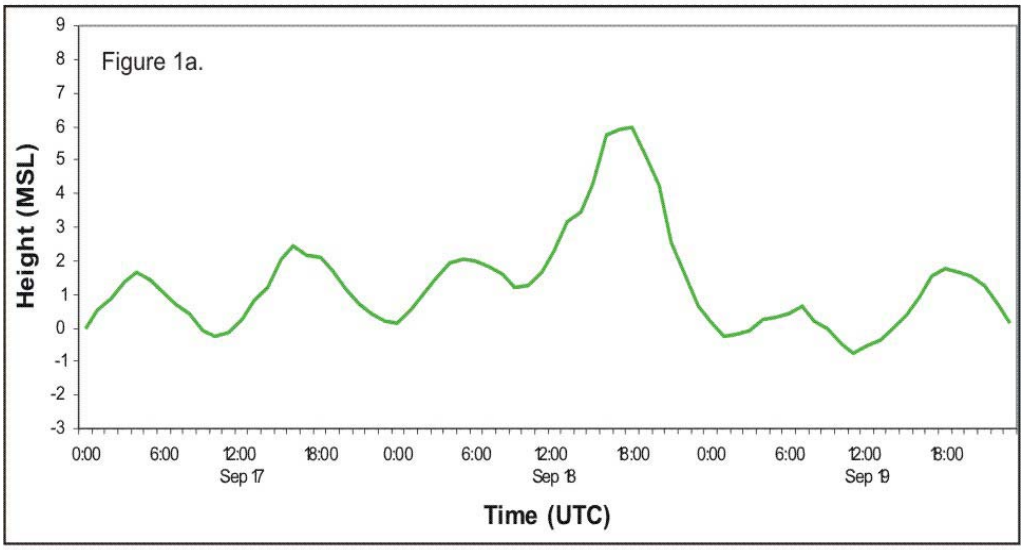
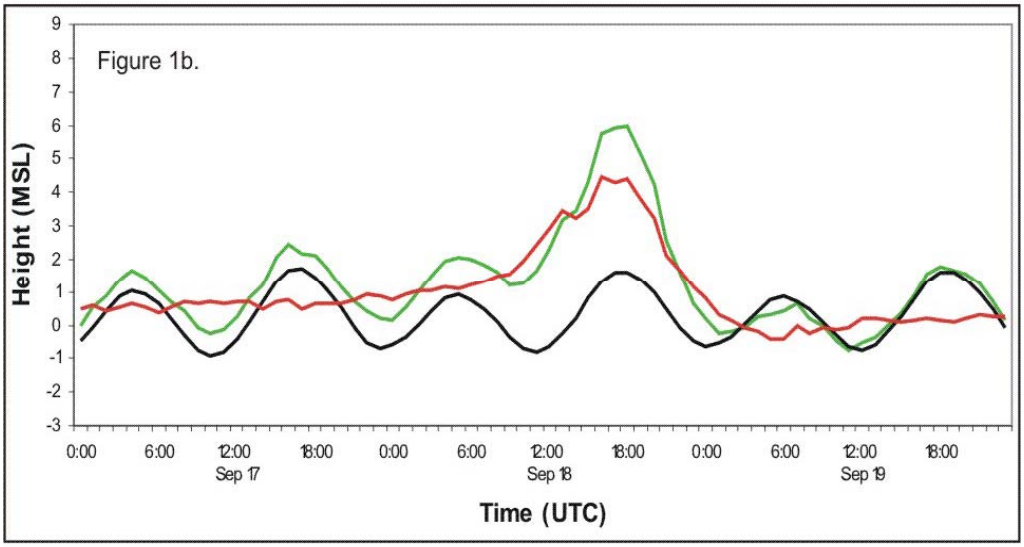


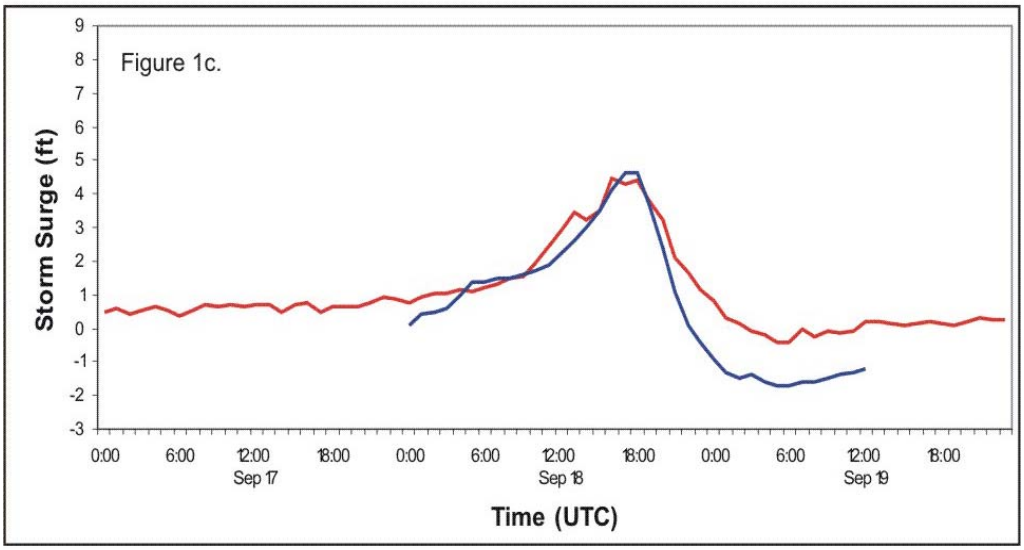
Figure 11. Observed Tide Gage Storm Surge Maximum vs. SLOSH Maximum

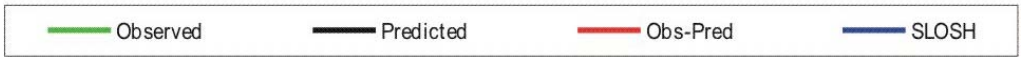
APPENDIX A

Duck USACE FRF, NC

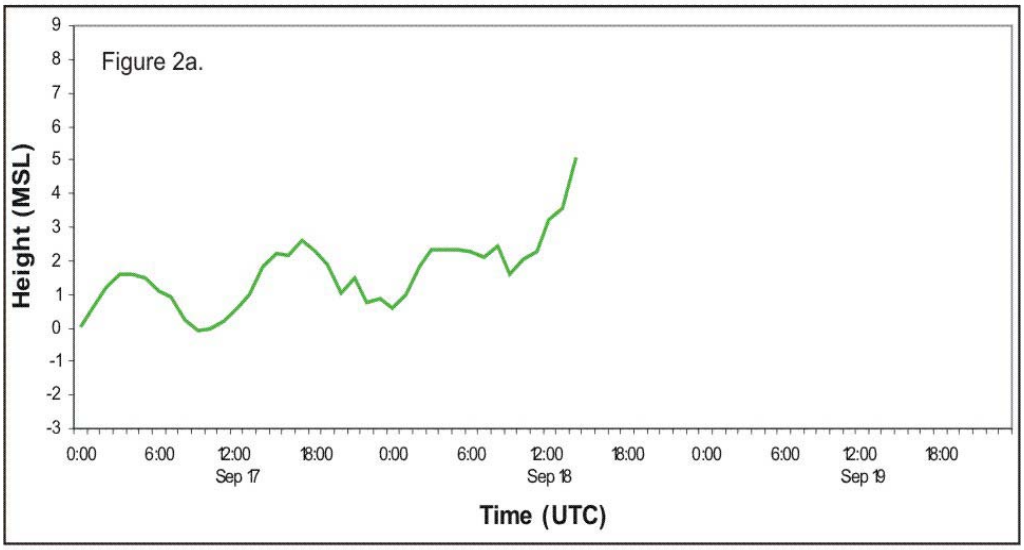


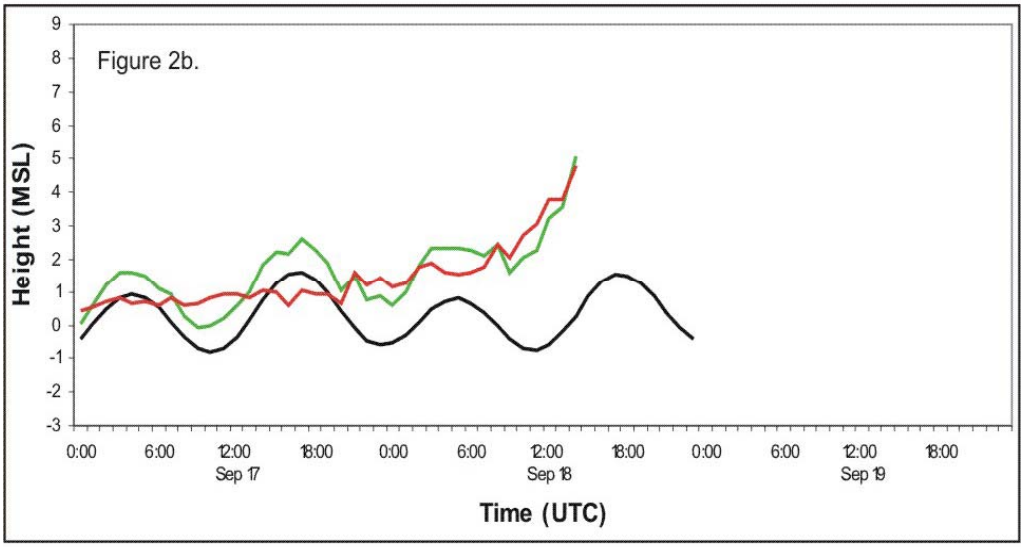


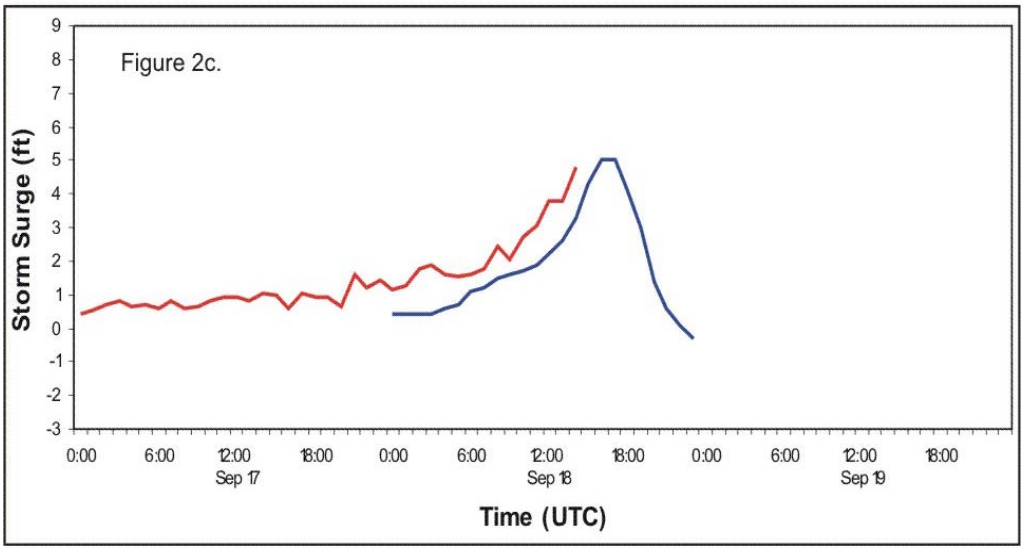




Cape Hatteras Fishing Pier

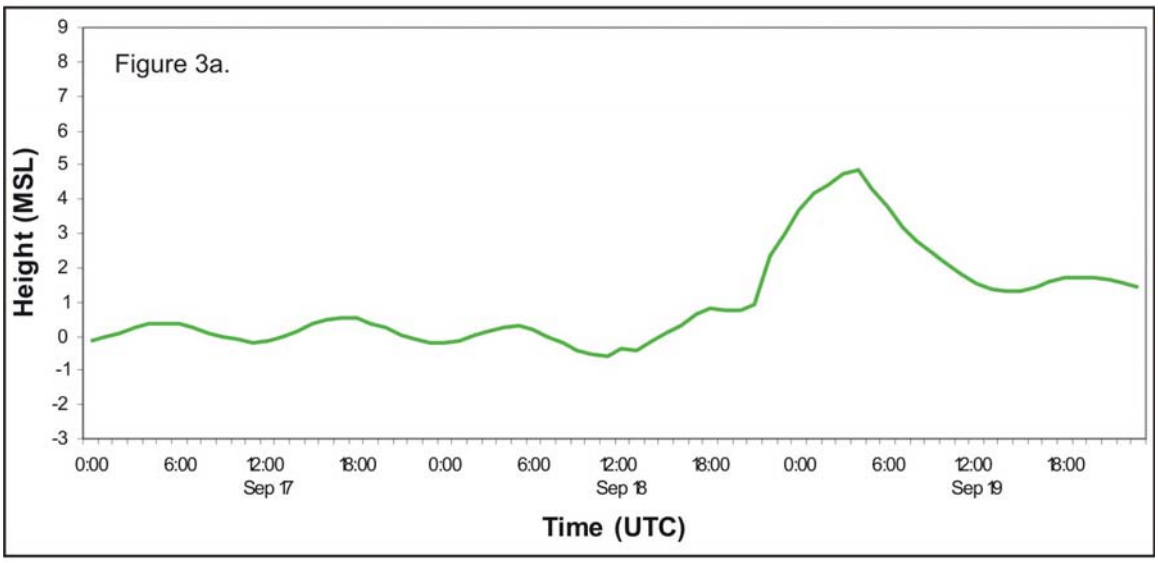


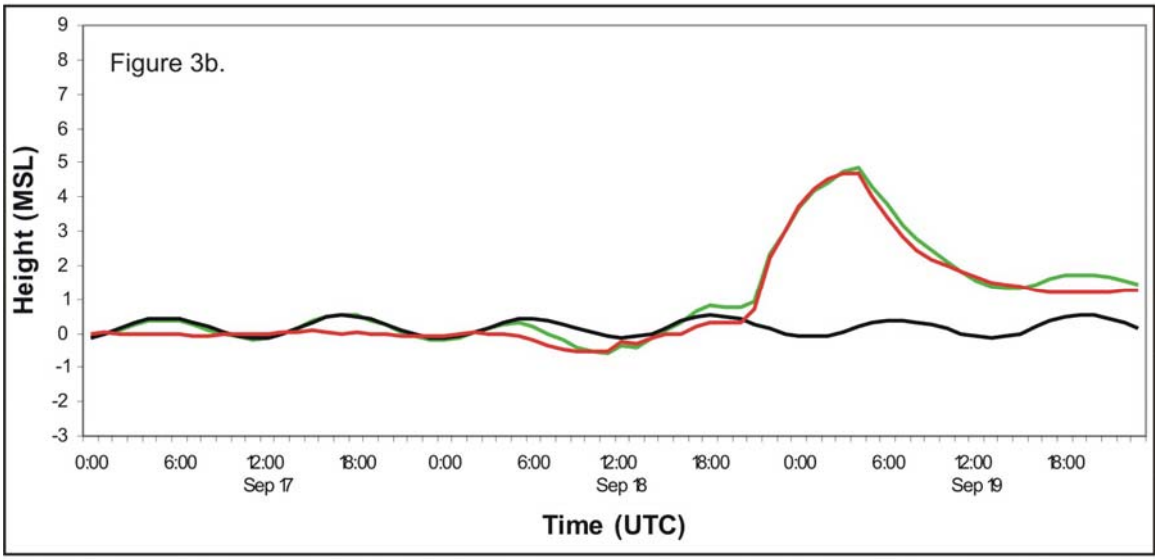


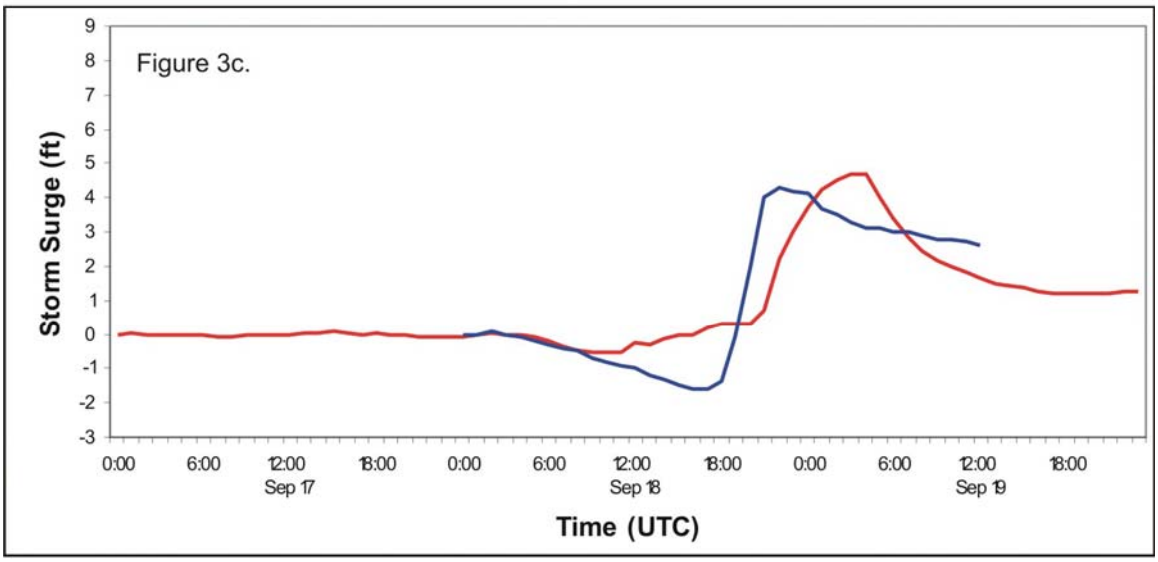


Observed Predicted Obs-Pred SLOSH

Oregon Inlet Marina, NC

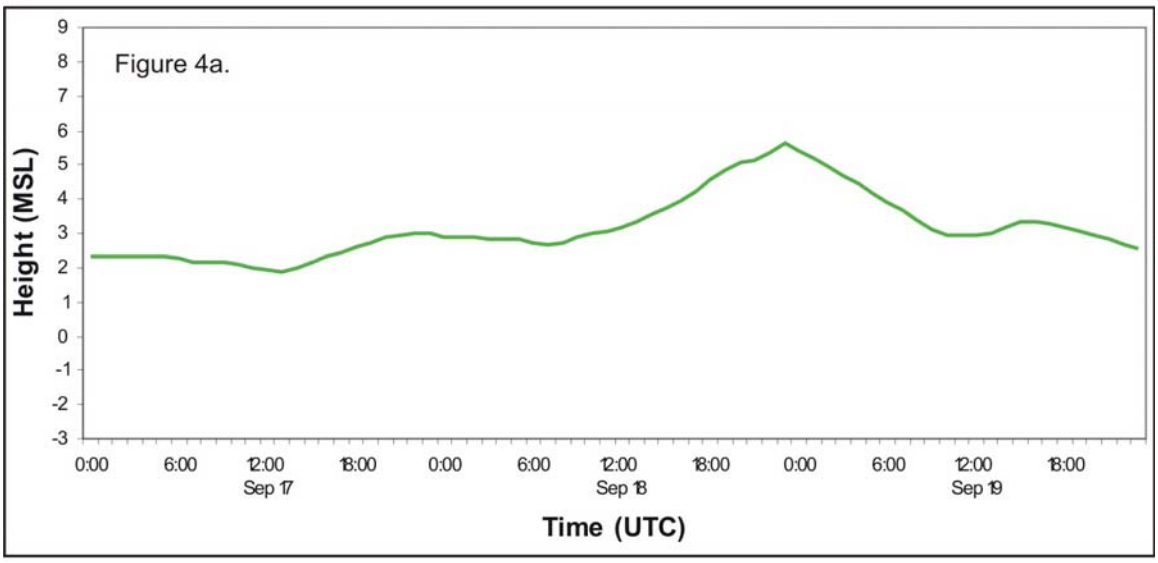


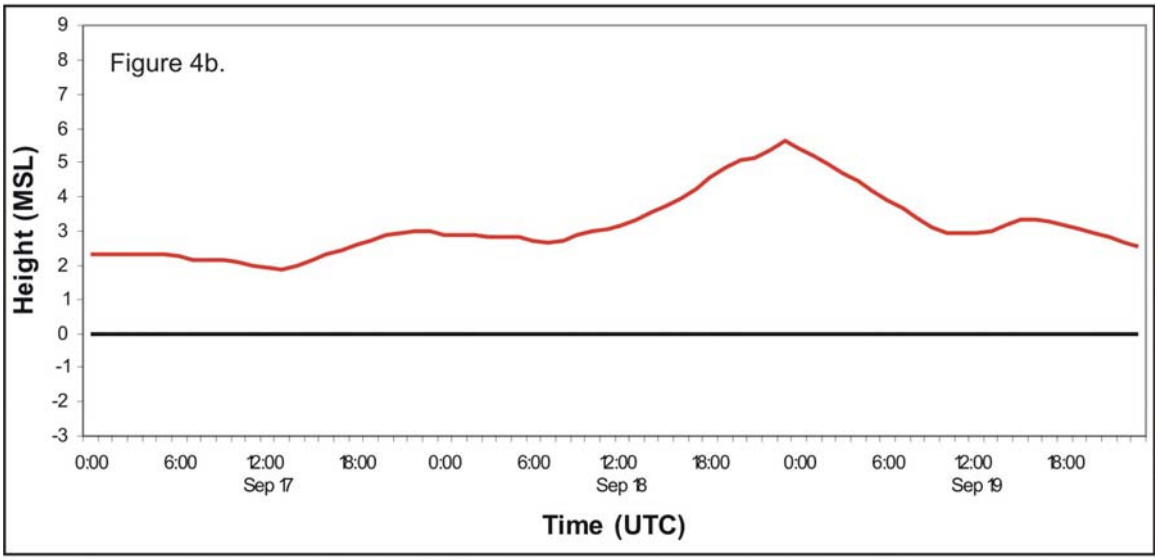


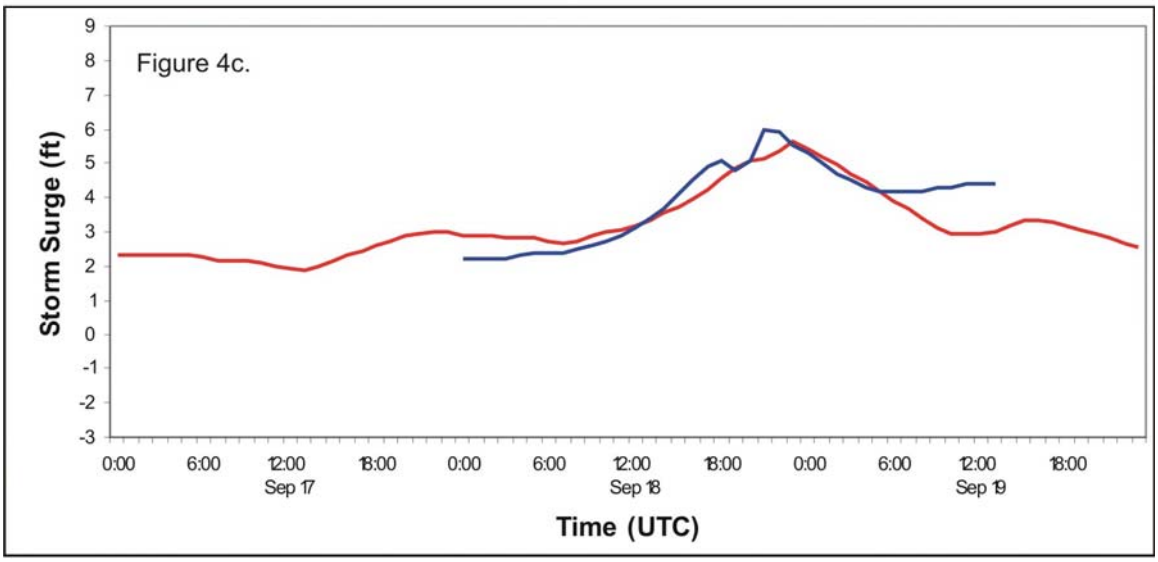


Observed Predicted Obs-Pred SLOSH

Pollockville, NC

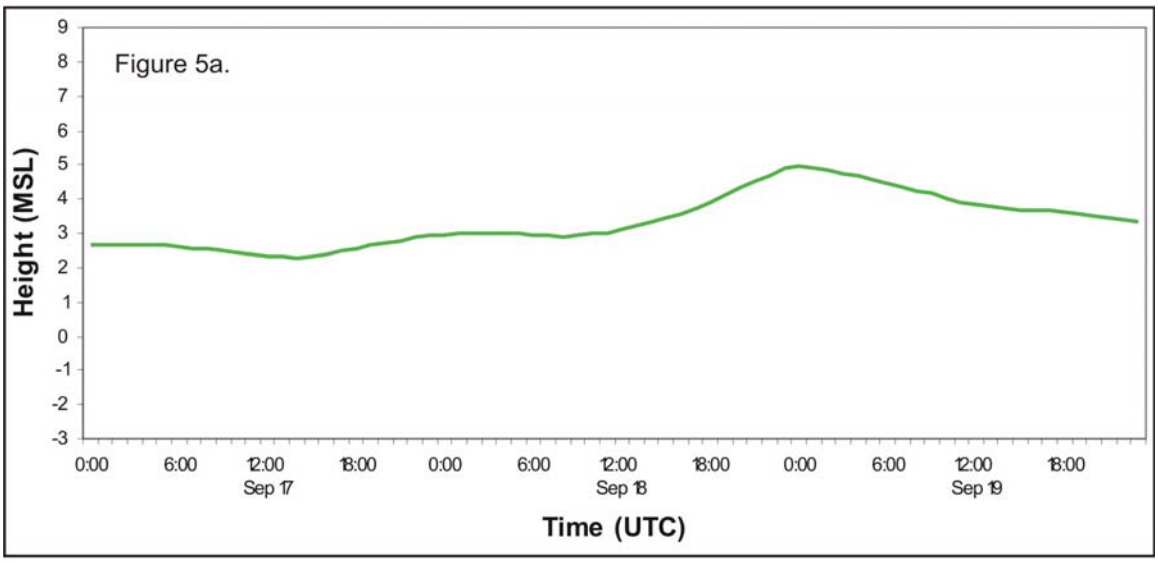


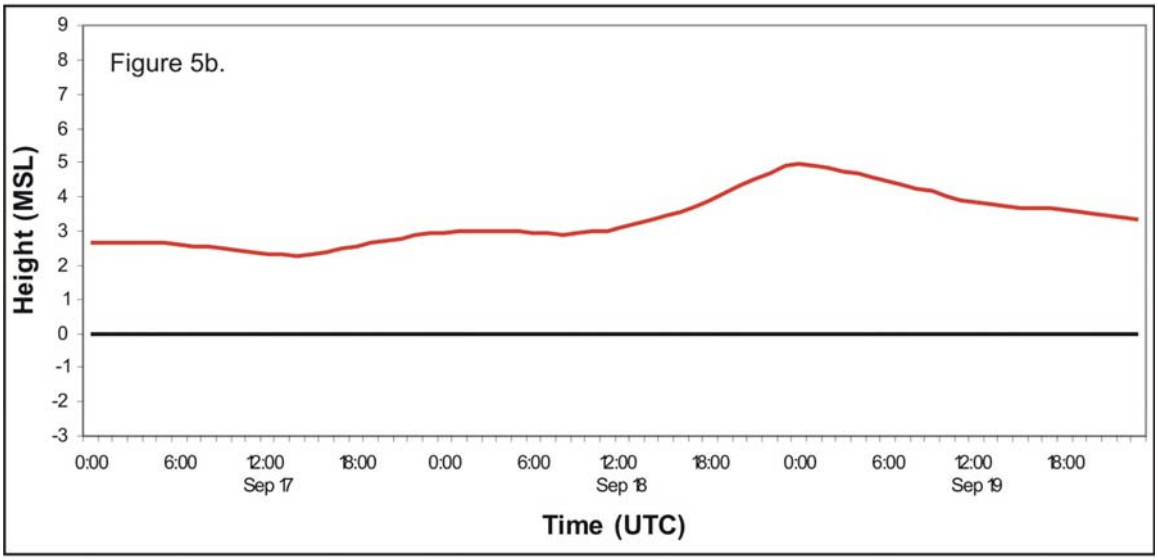


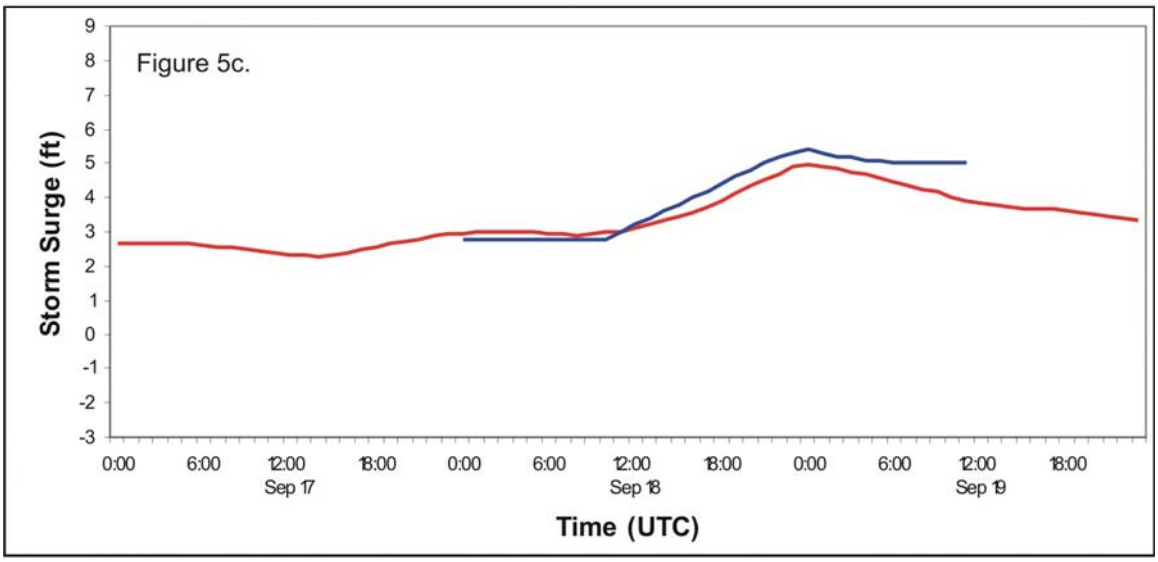


Observed Predicted Obs-Pred SLOSH

Swift Creek, NC

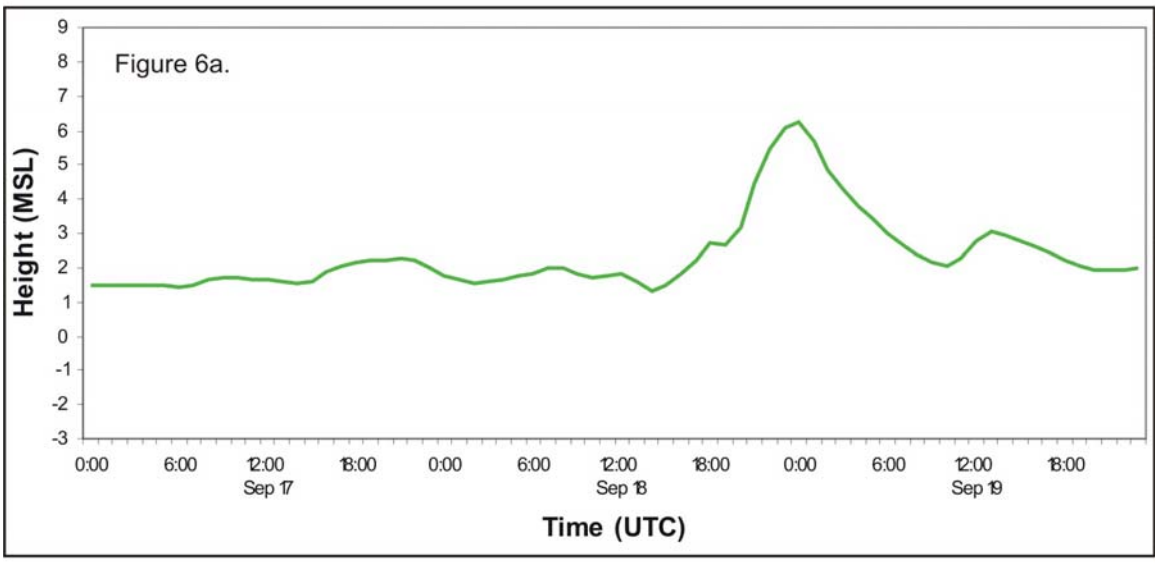


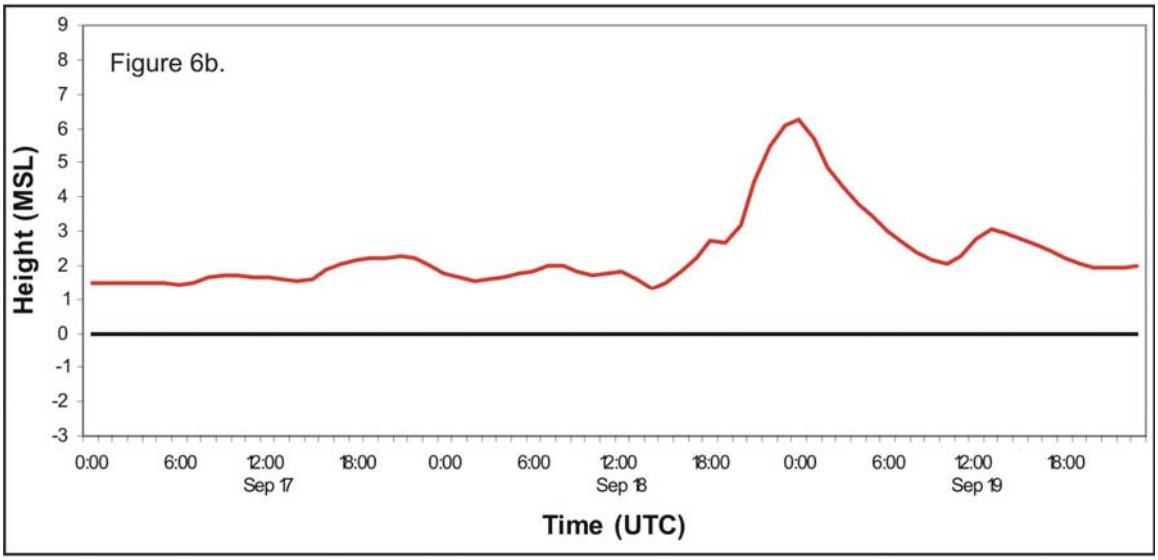


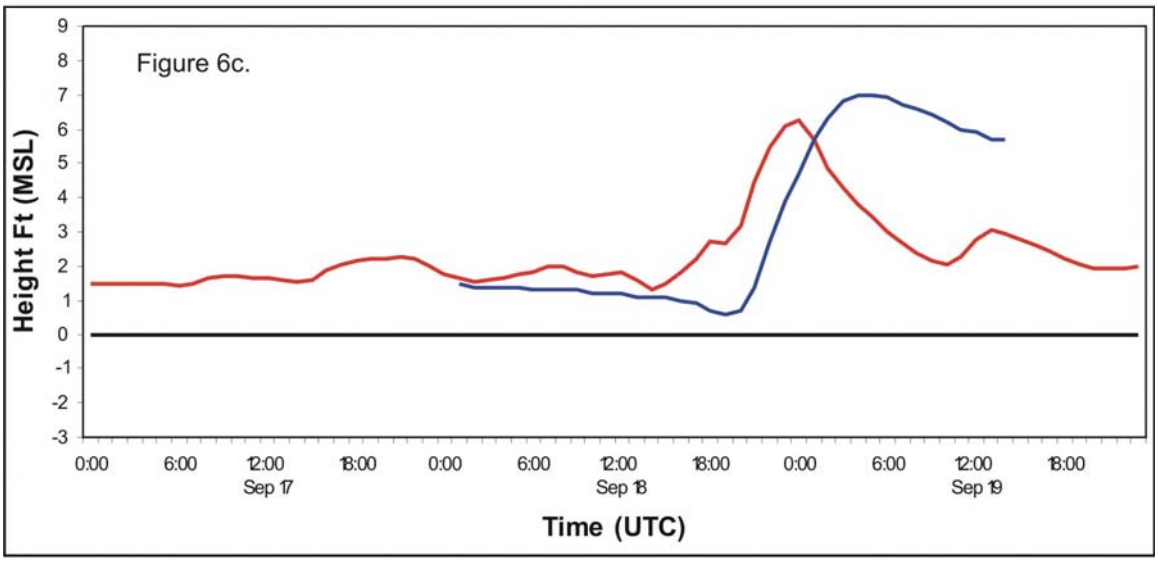


Observed Predicted Obs-Pred SLOSH

Washington, NC

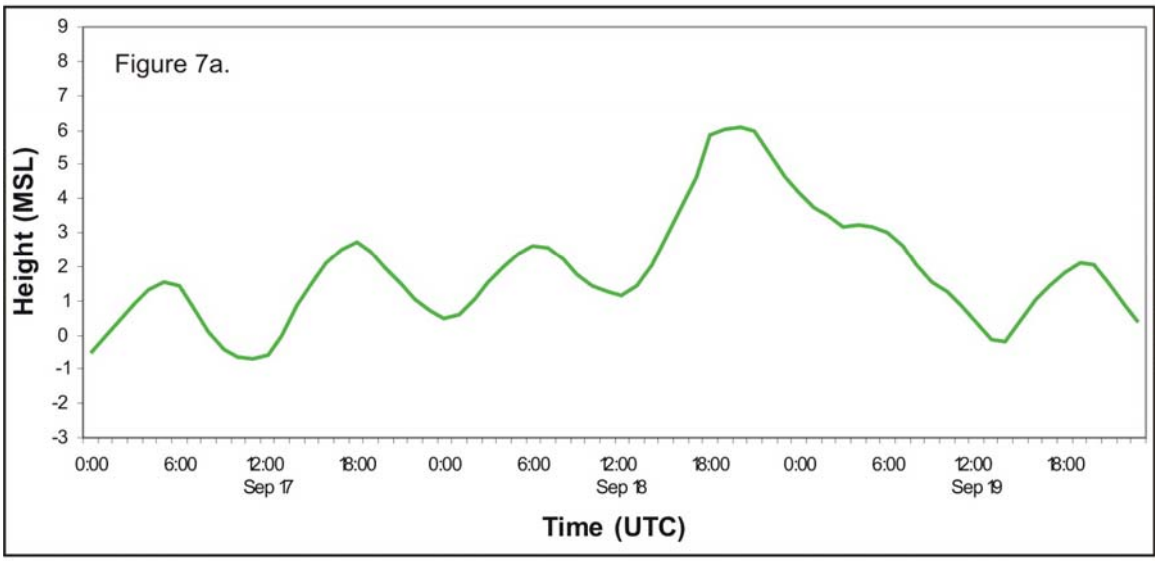


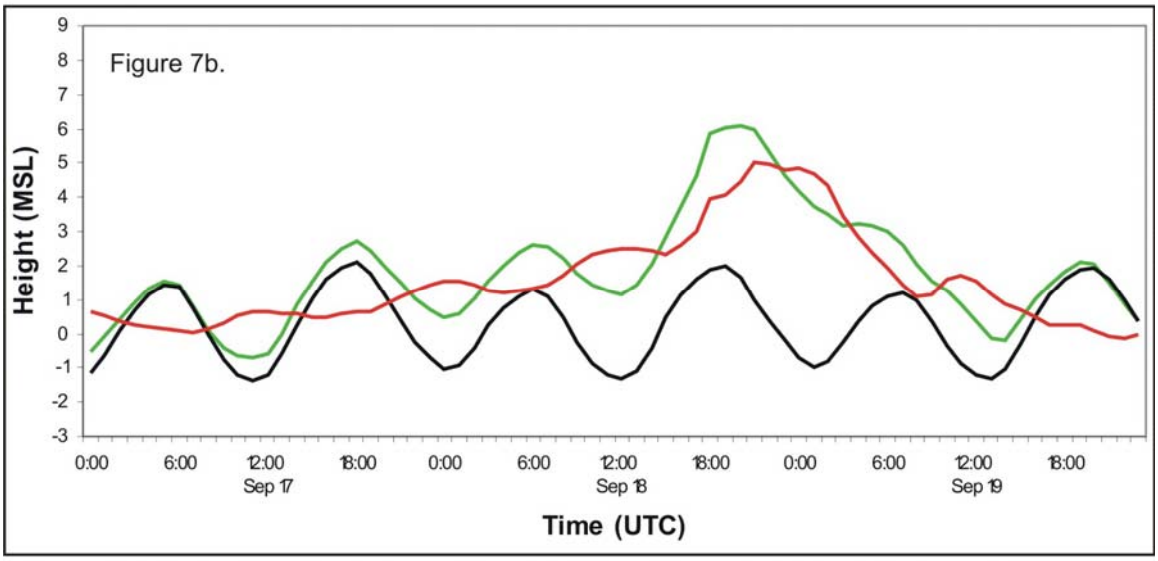


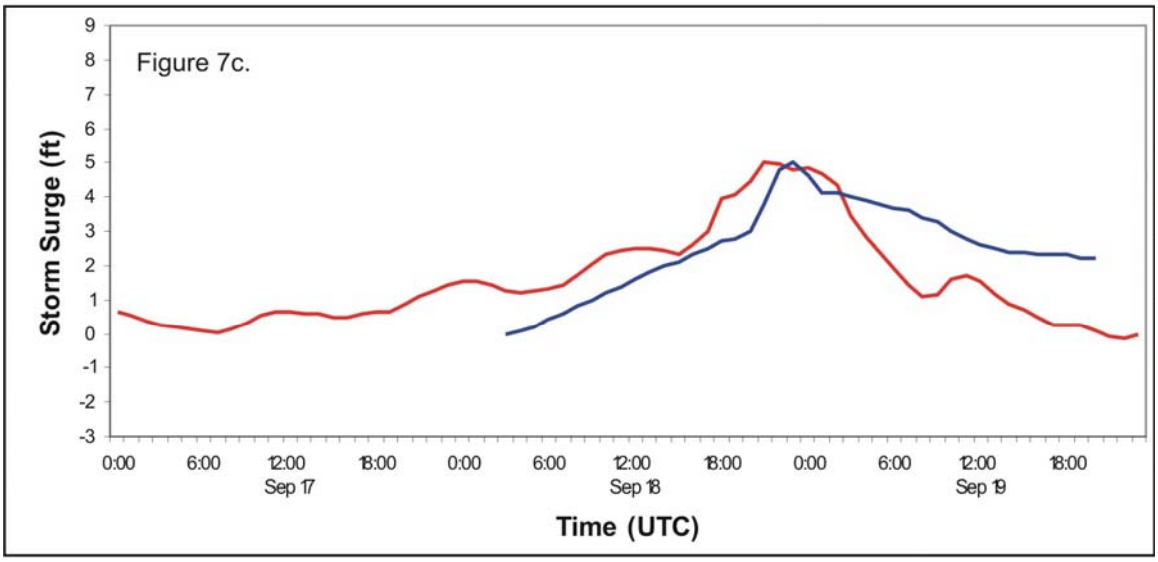


Observed Predicted Obs-Pred SLOSH

Wachapreague, VA

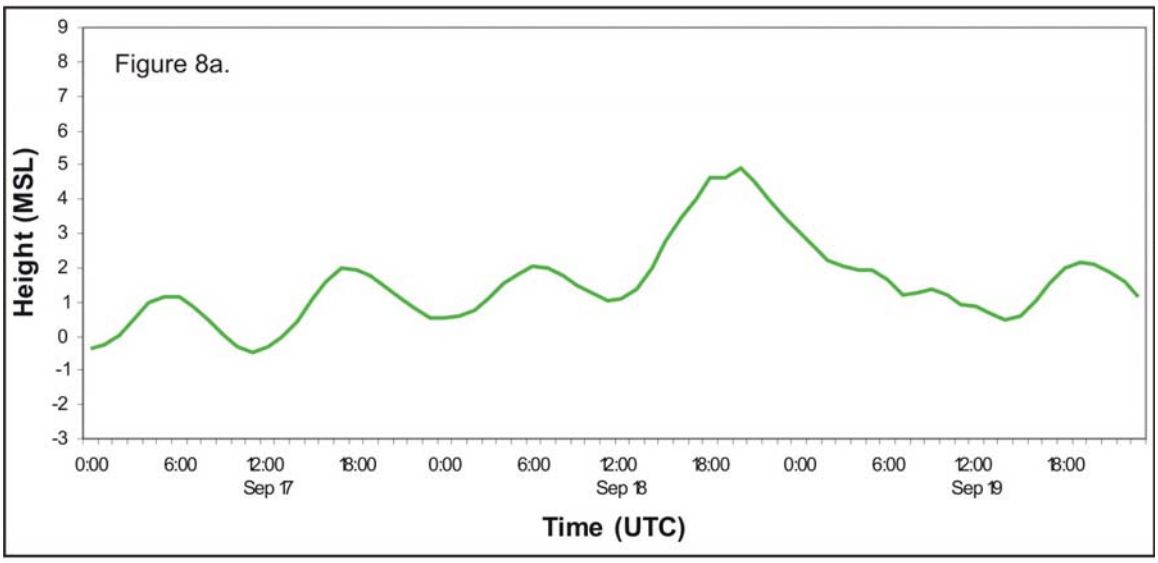


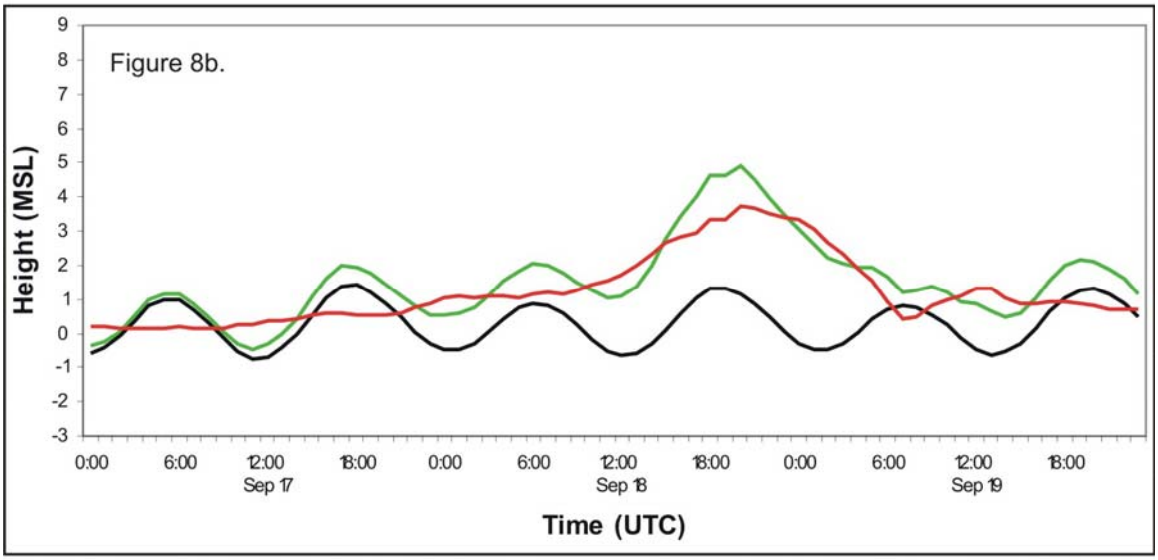


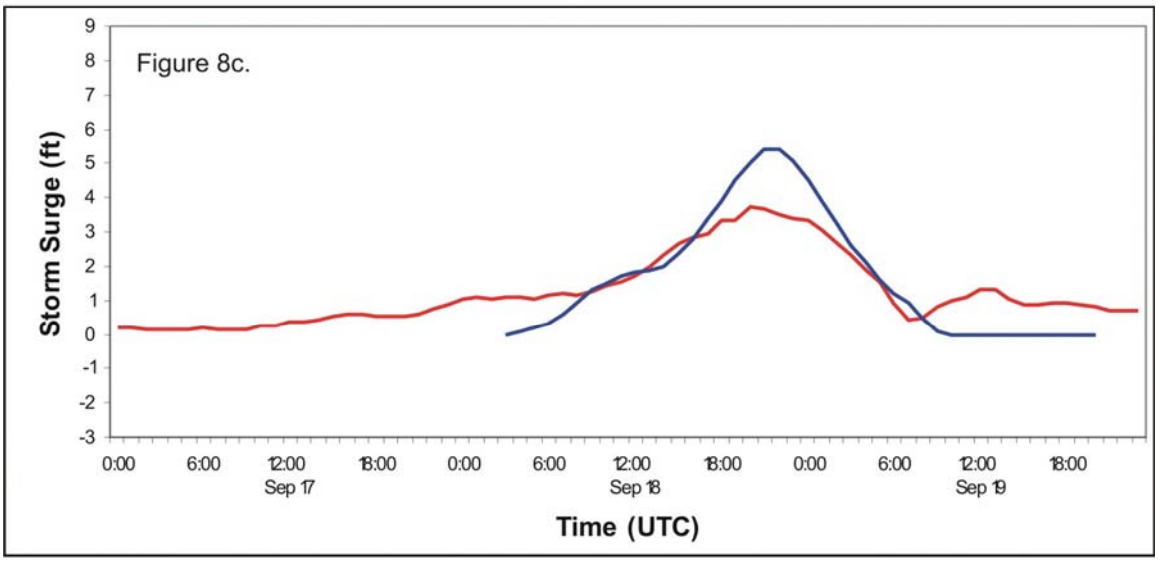


Observed Predicted Obs-Pred SLOSH

Kiptopeke, Chesapeake Bay, VA

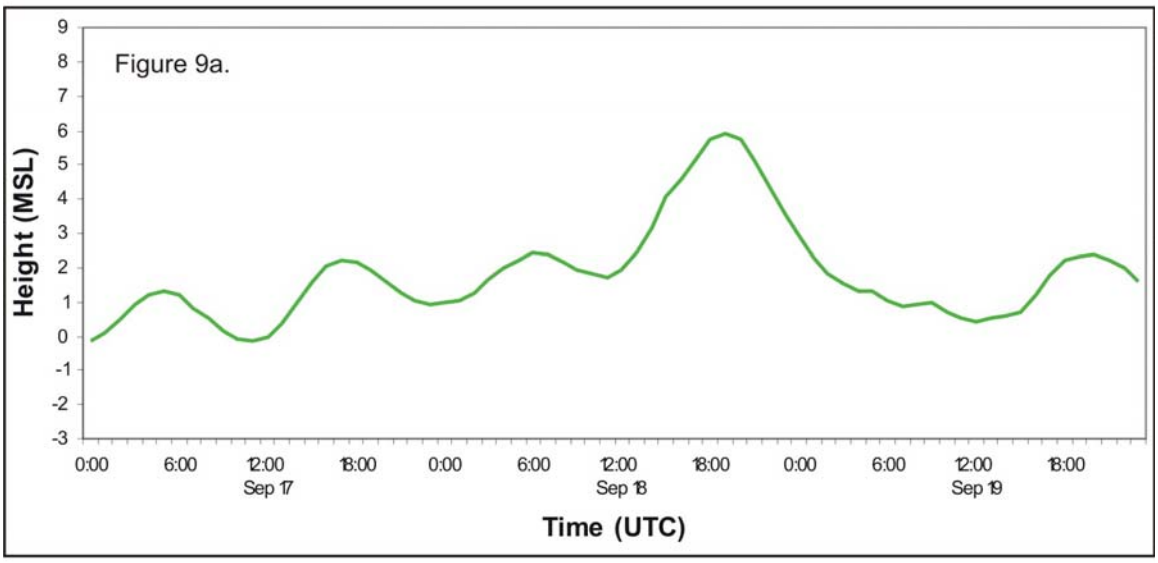


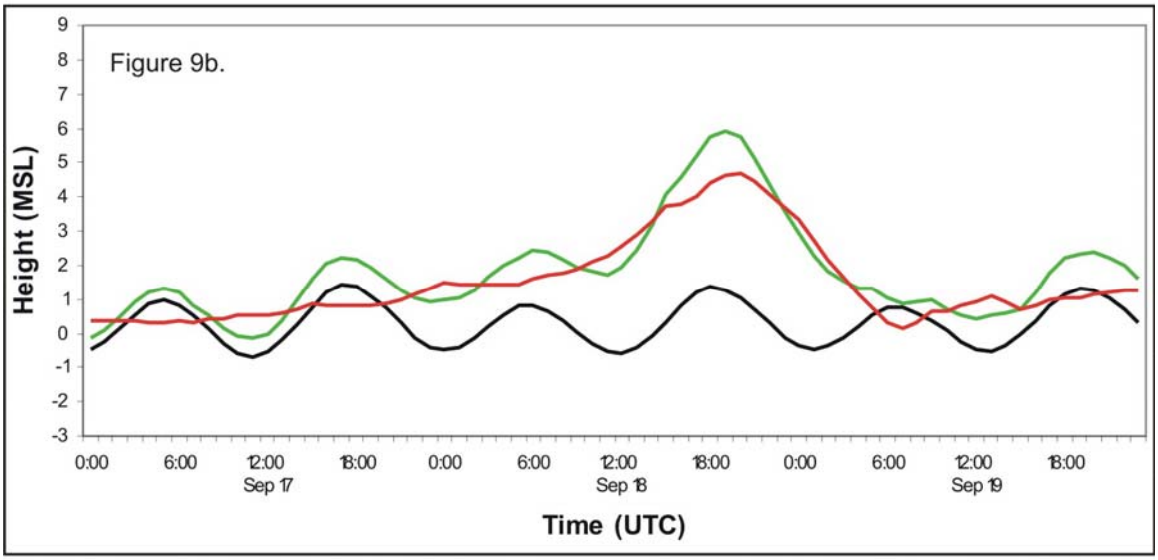


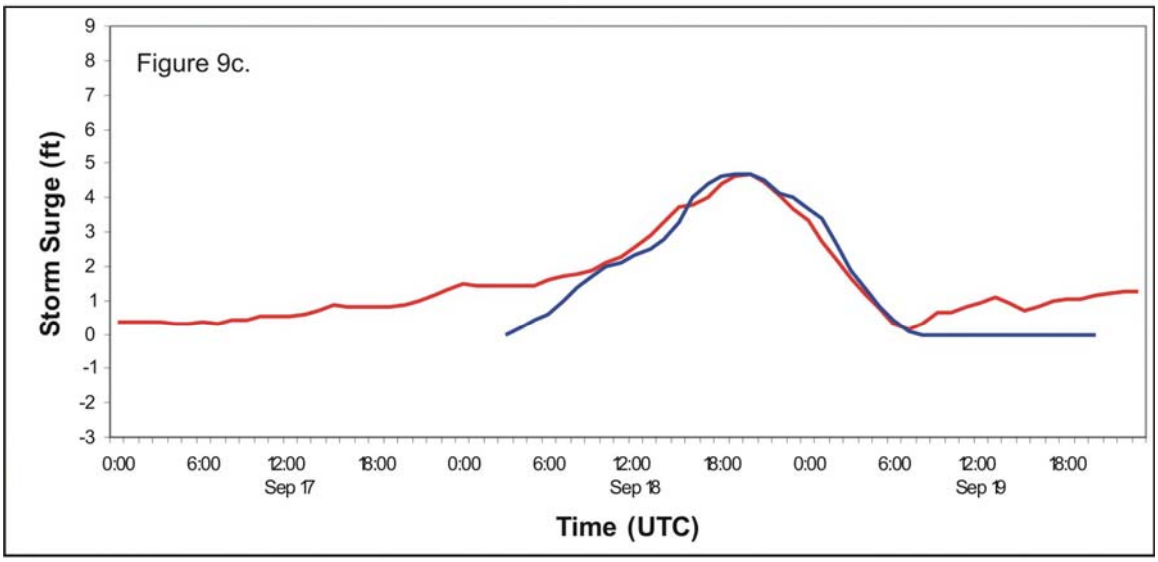


Observed Predicted Obs-Pred SLOSH

Chesapeake Bay Bridge Tunnel, VA

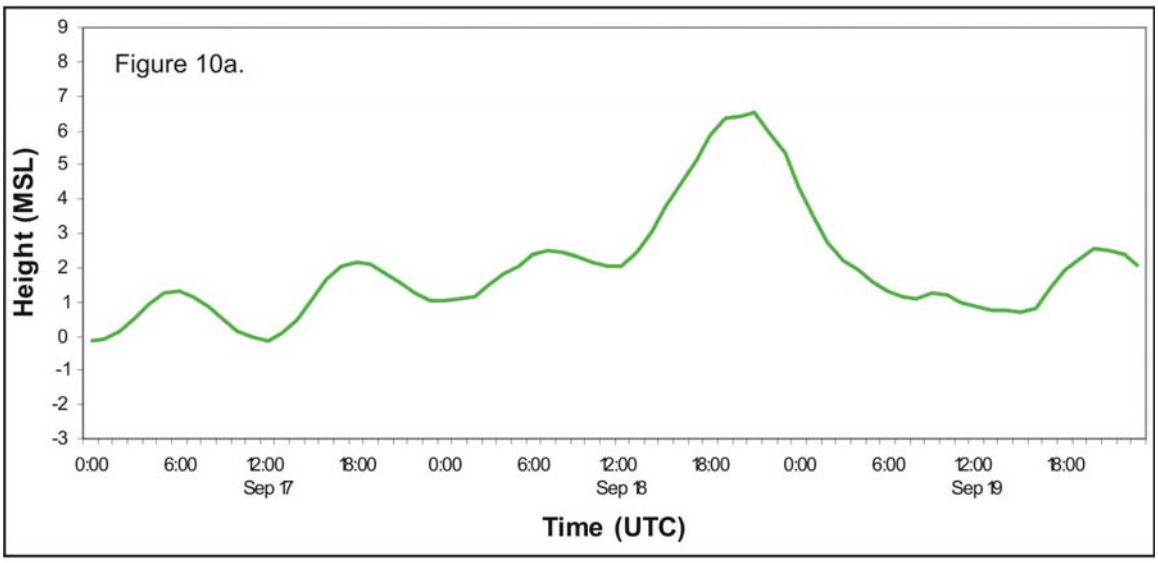


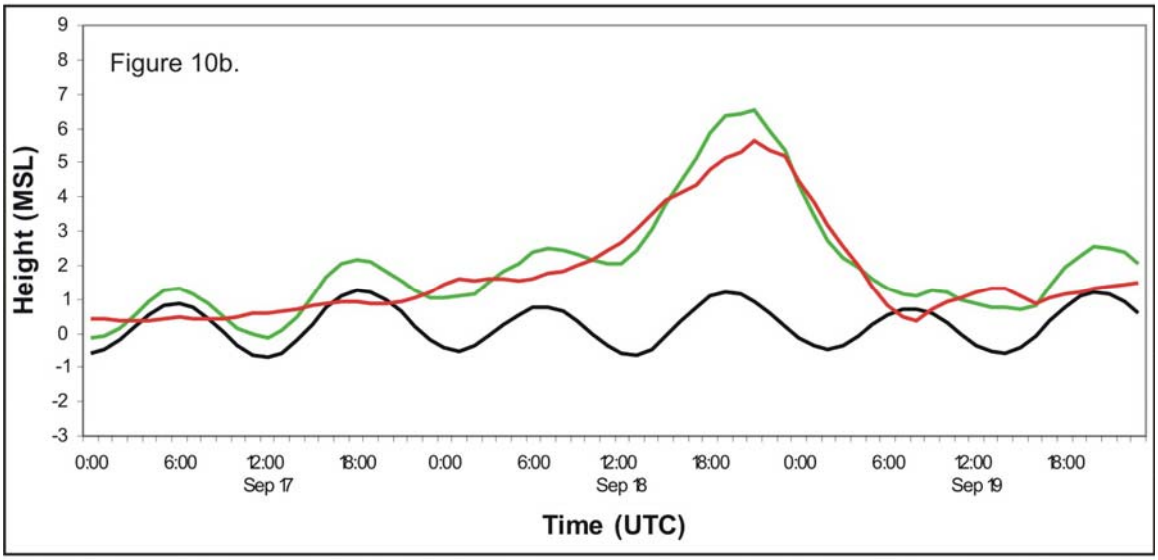


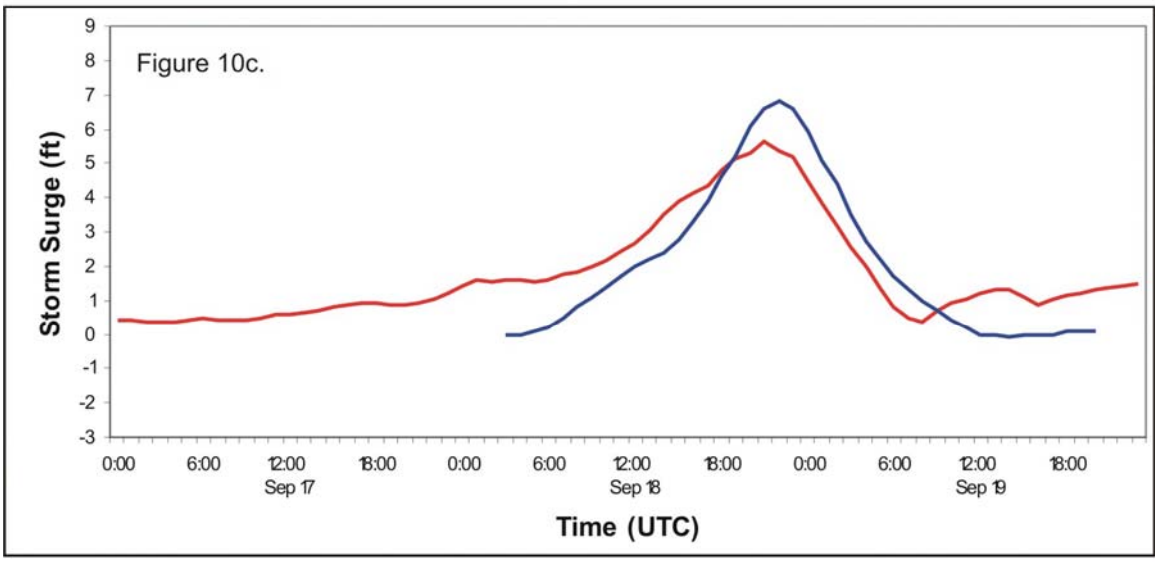


Observed Predicted Obs-Pred SLOSH

Sewells Point, VA

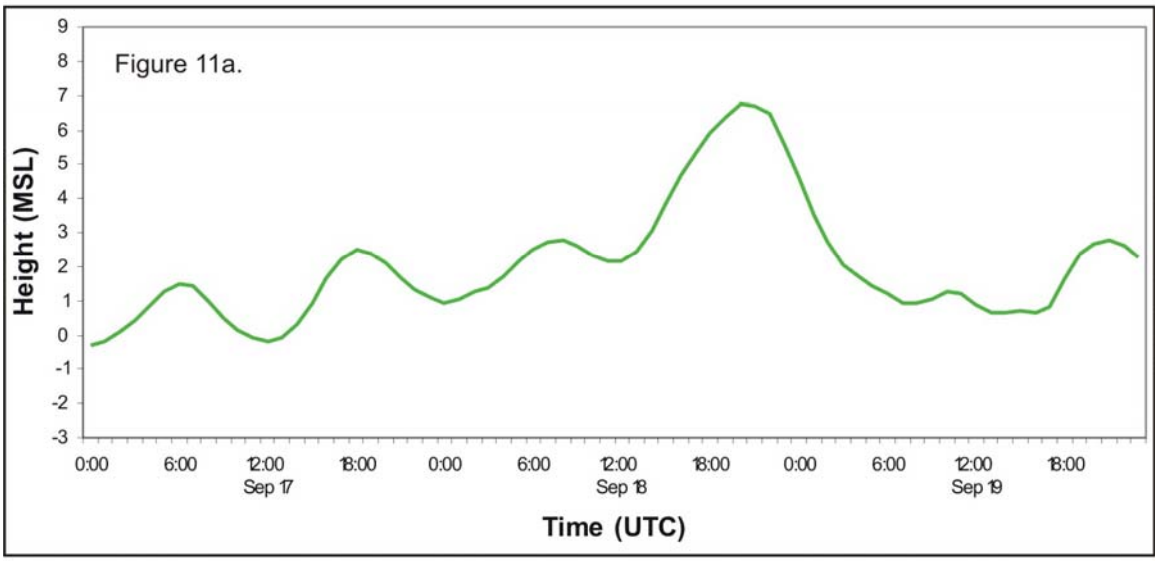


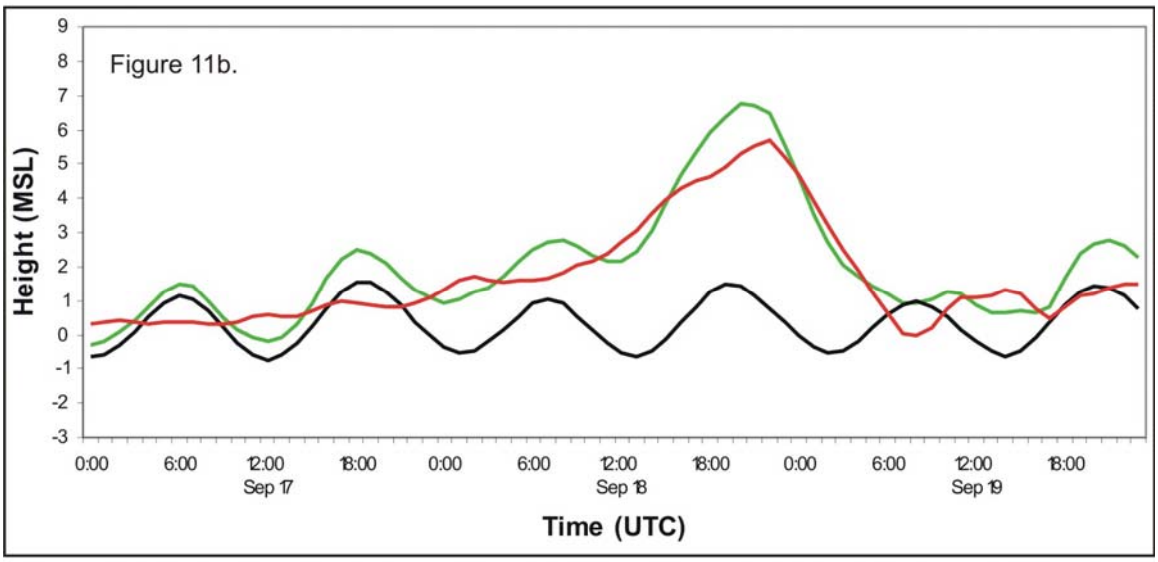


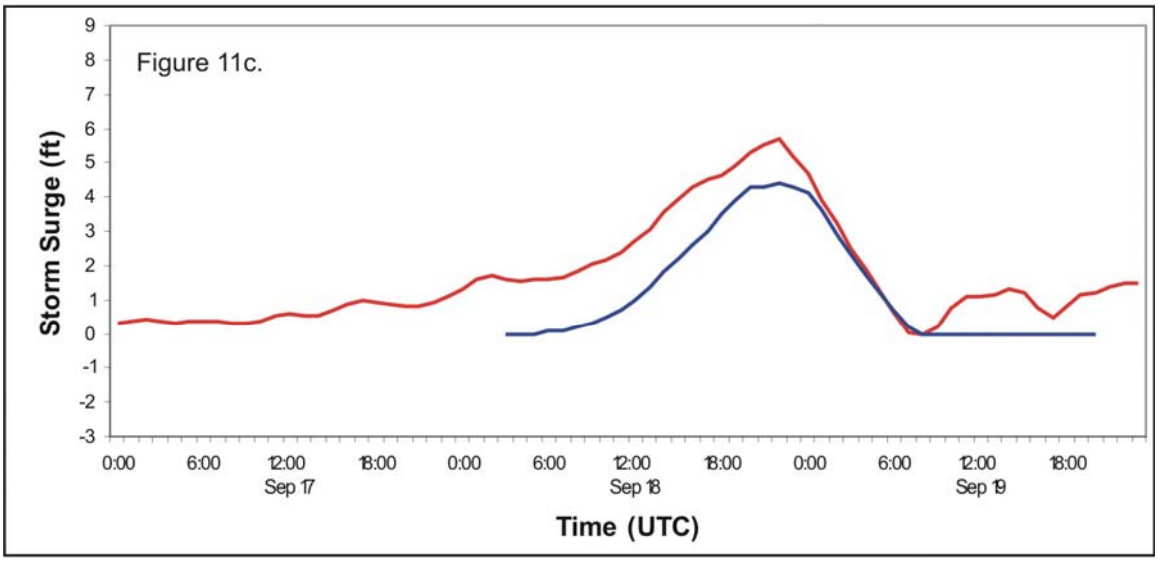


Observed Predicted Obs-Pred SLOSH

Money Point, Elizabeth River, VA







Observed Predicted Obs-Pred SLOSH

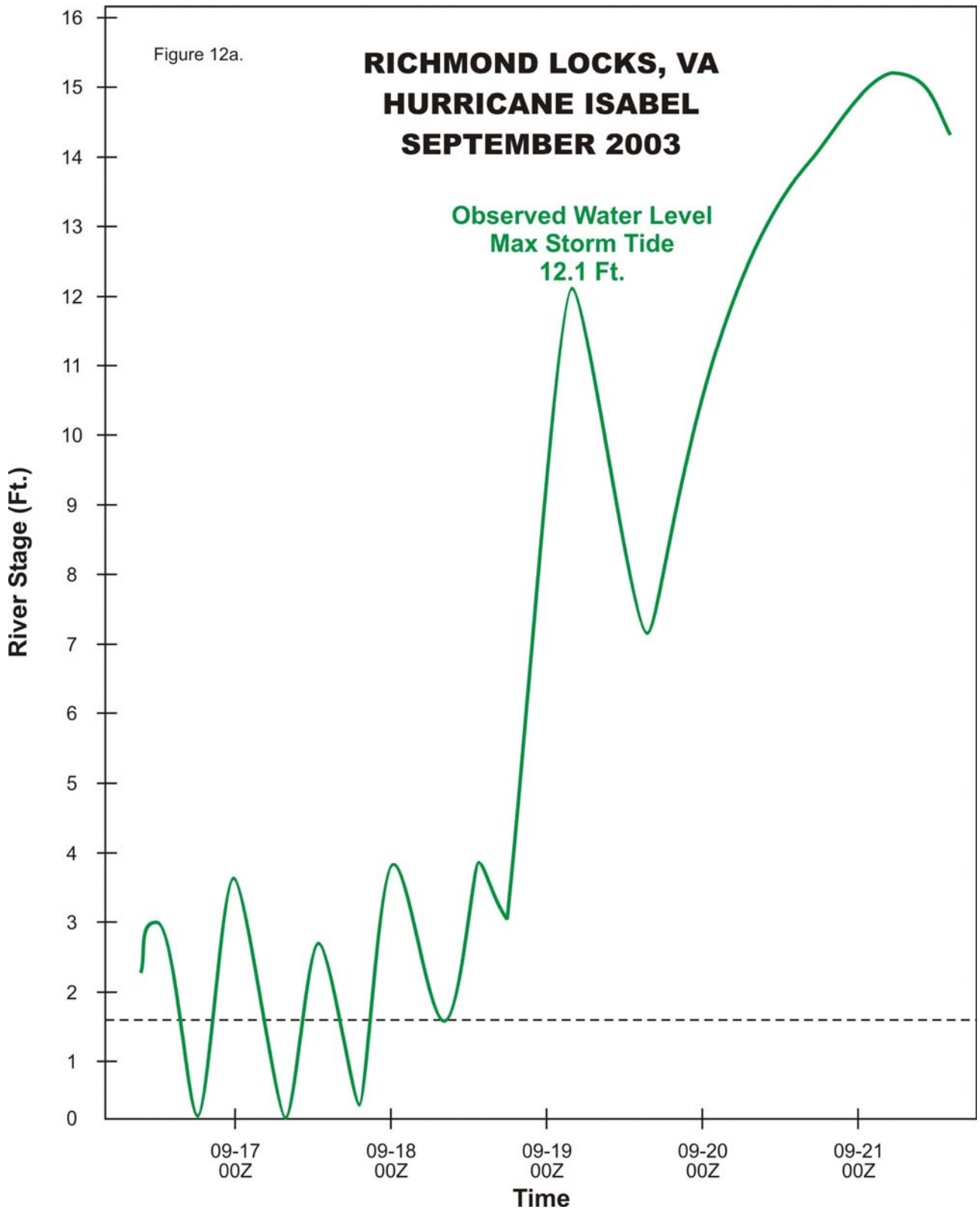


Figure 12a.
RICHMOND LOCKS, VA
HURRICANE ISABEL
SEPTEMBER 2003
Observed Water Level
Max Storm Tide
12.1 Ft.
River Stage (Ft.)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
09-17
00Z
09-18
00Z
09-19
00Z
09-20
00Z
09-21
00Z
Time

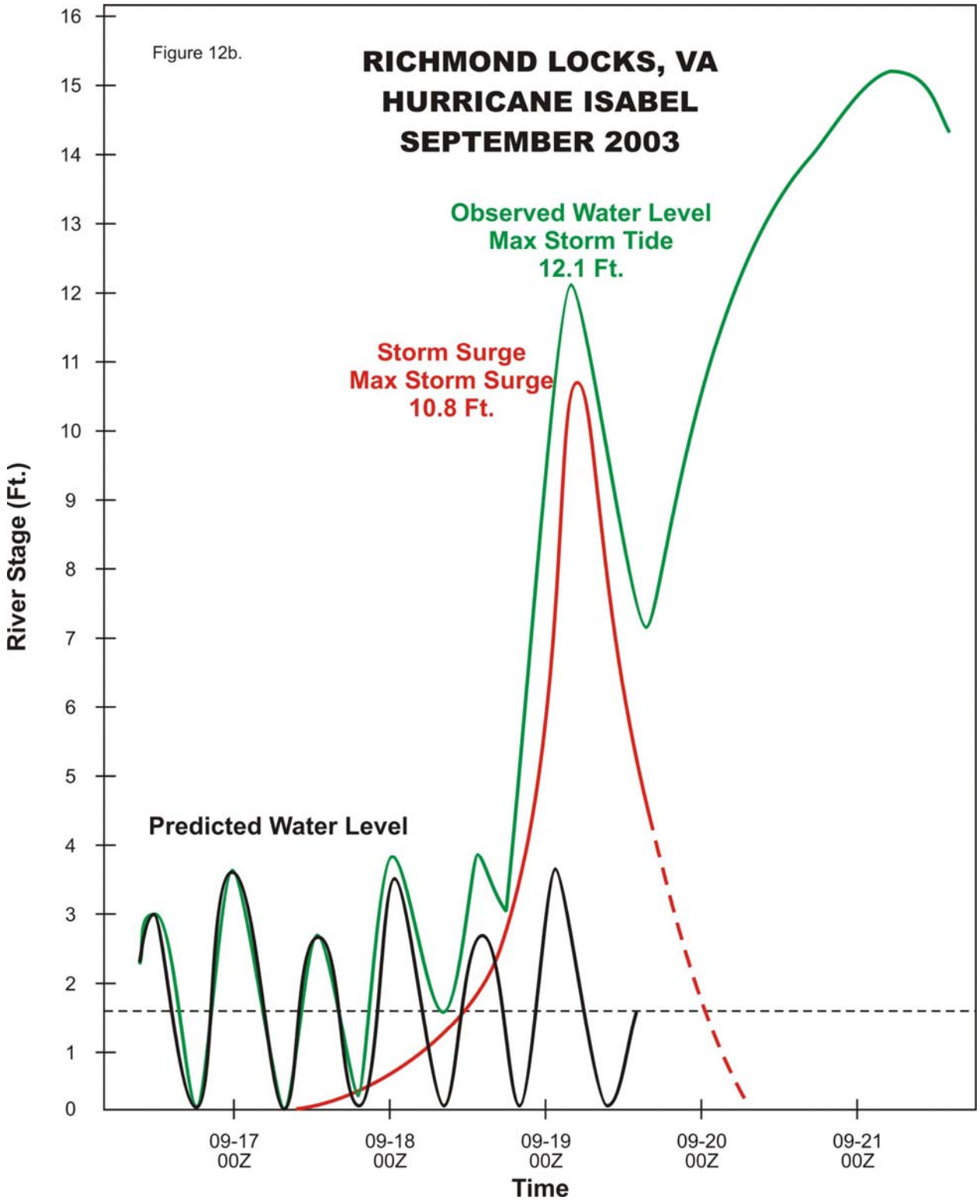


Figure 12b.
RICHMOND LOCKS, VA
HURRICANE ISABEL
SEPTEMBER 2003
Observed Water Level
Max Storm Tide
12.1 Ft.
Storm Surge
Max Storm Surge
10.8 Ft.
Predicted Water Level
River Stage (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
09-17
00Z
09-18
00Z
09-19
00Z
09-20
00Z
09-21
00Z
Time

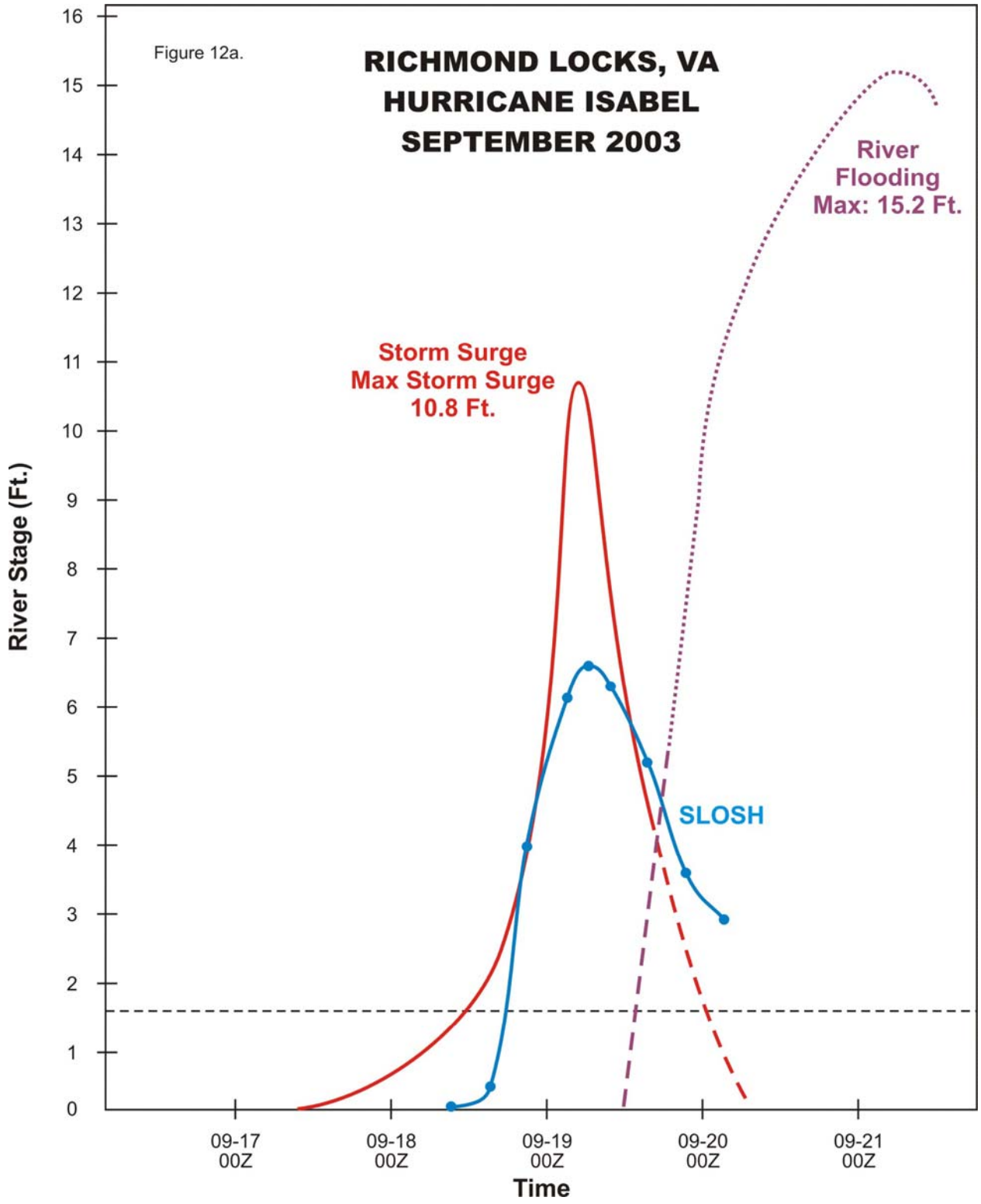
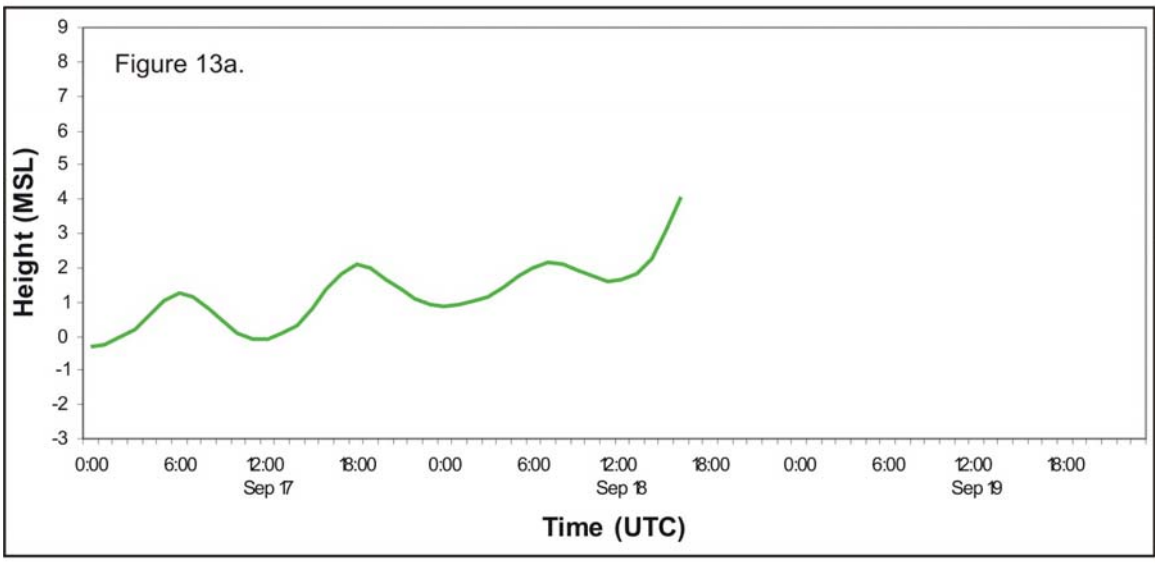
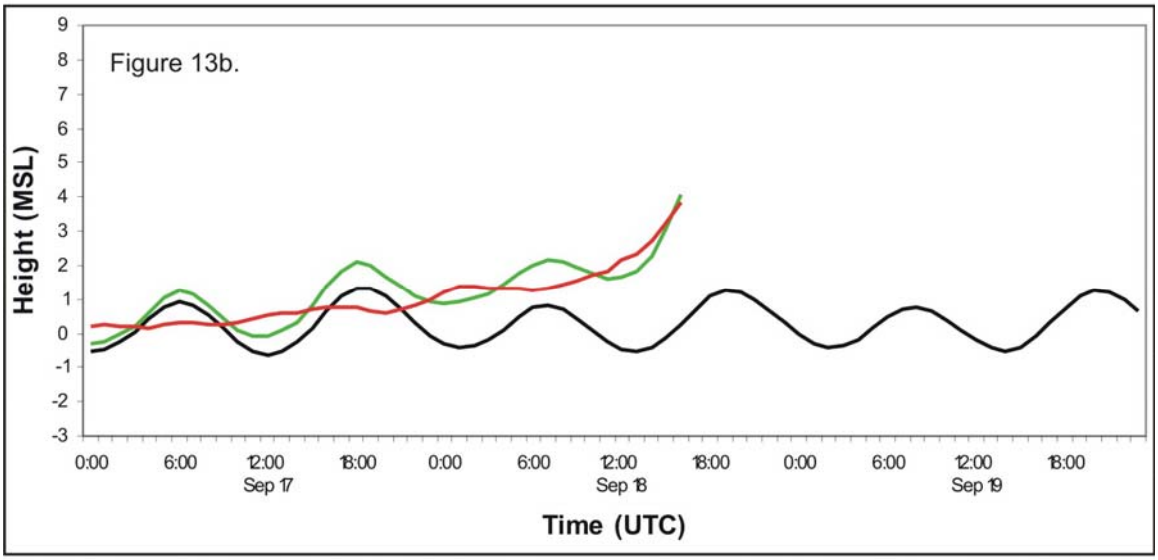
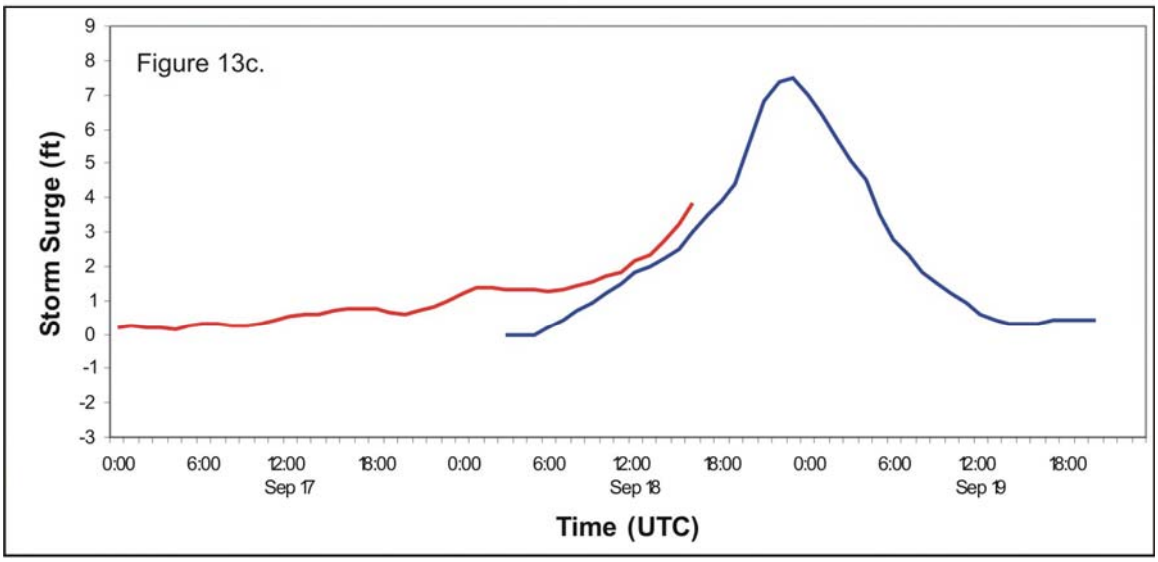


Figure 12a.
RICHMOND LOCKS, VA
HURRICANE ISABEL
SEPTEMBER 2003
River Flooding Max: 15.2 Ft.
Storm Surge Max Storm Surge 10.8 Ft.
SLOSH
River Stage (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
09-17 00Z
09-18 00Z
09-19 00Z
09-20 00Z
09-21 00Z
Time

Gloucester Point, York River, VA

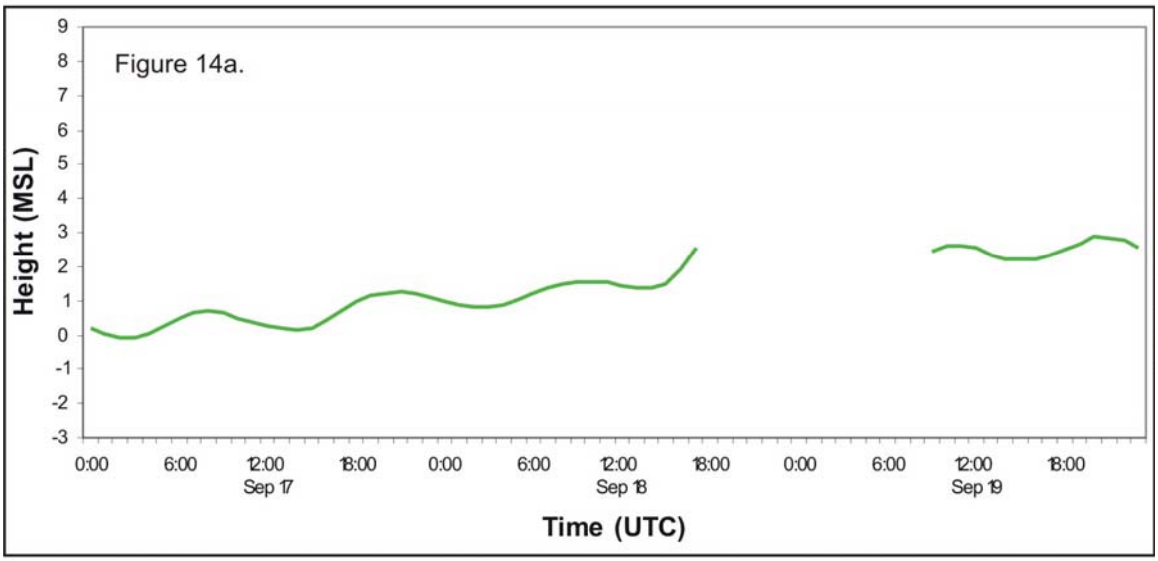


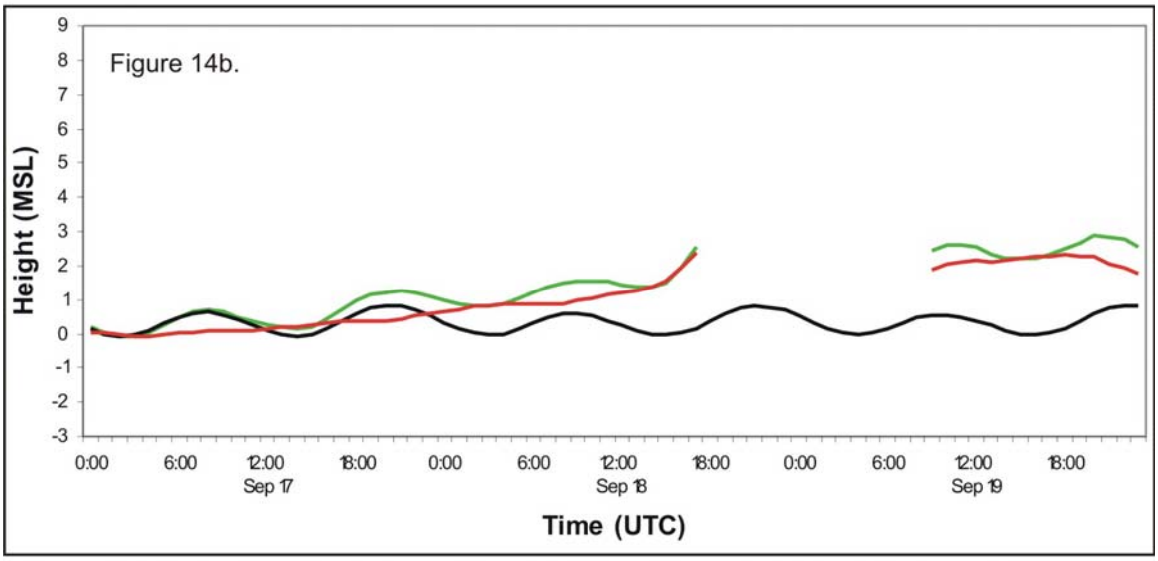


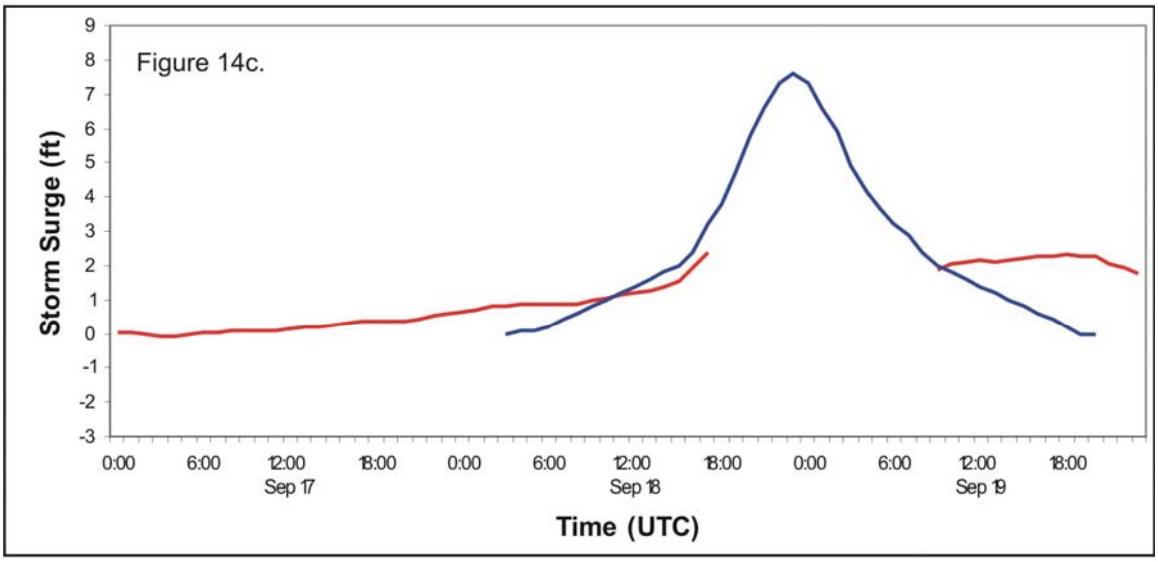


Observed Predicted Obs-Pred SLOSH

Windmill Point, VA

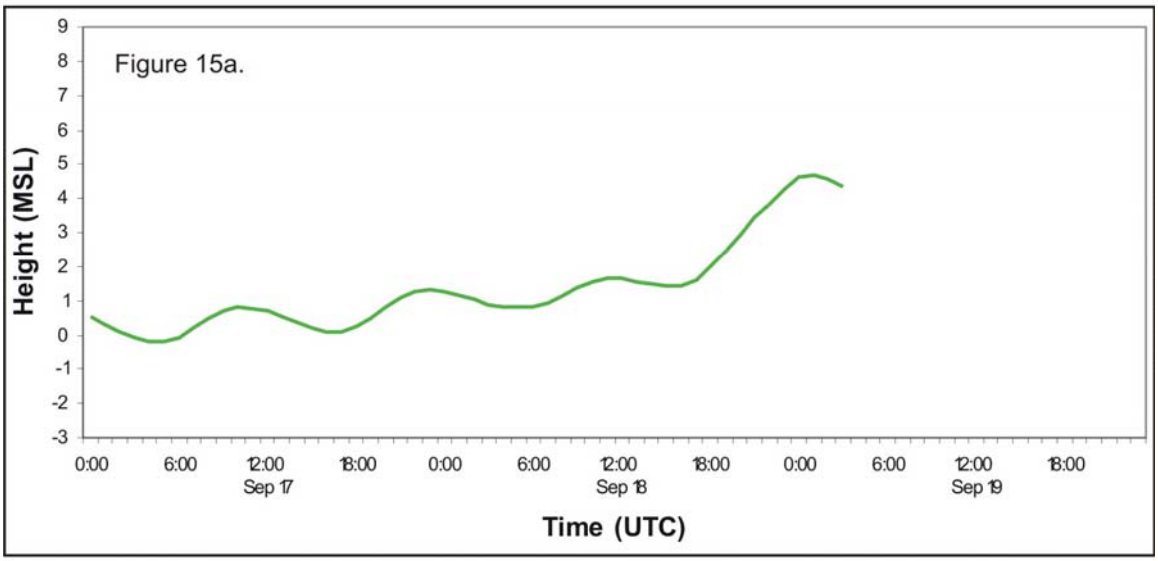


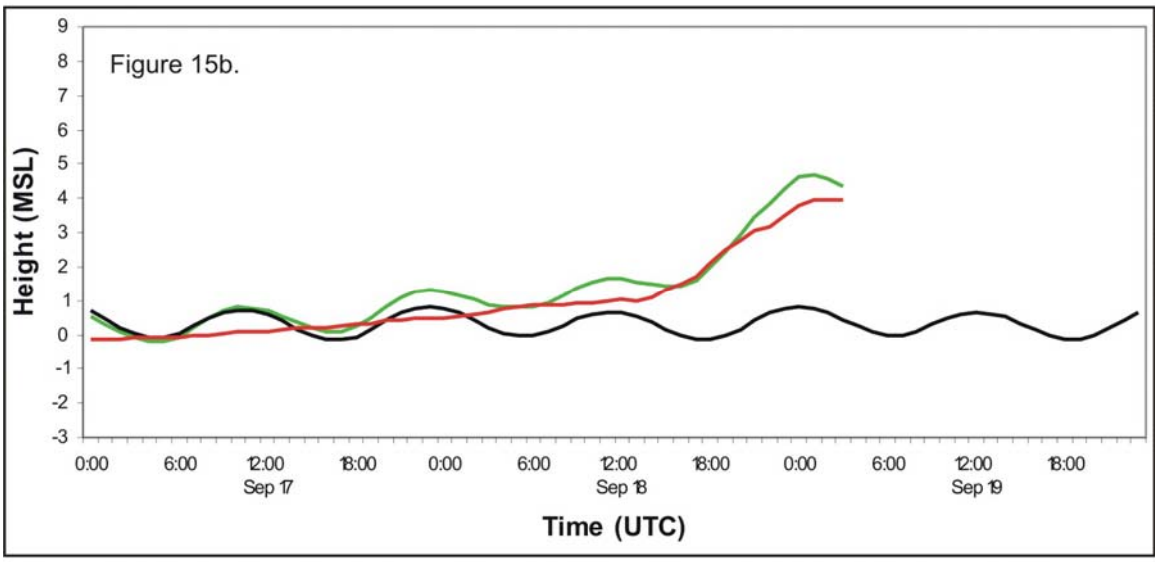


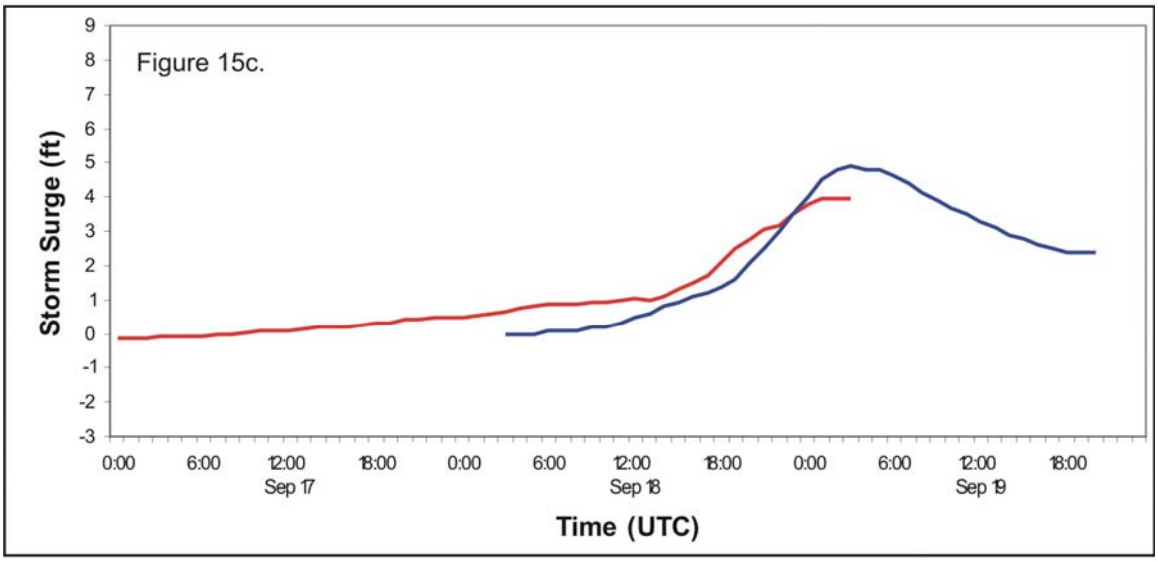


Observed Predicted Obs-Pred SLOSH

Lewisetta, Potomac River, VA

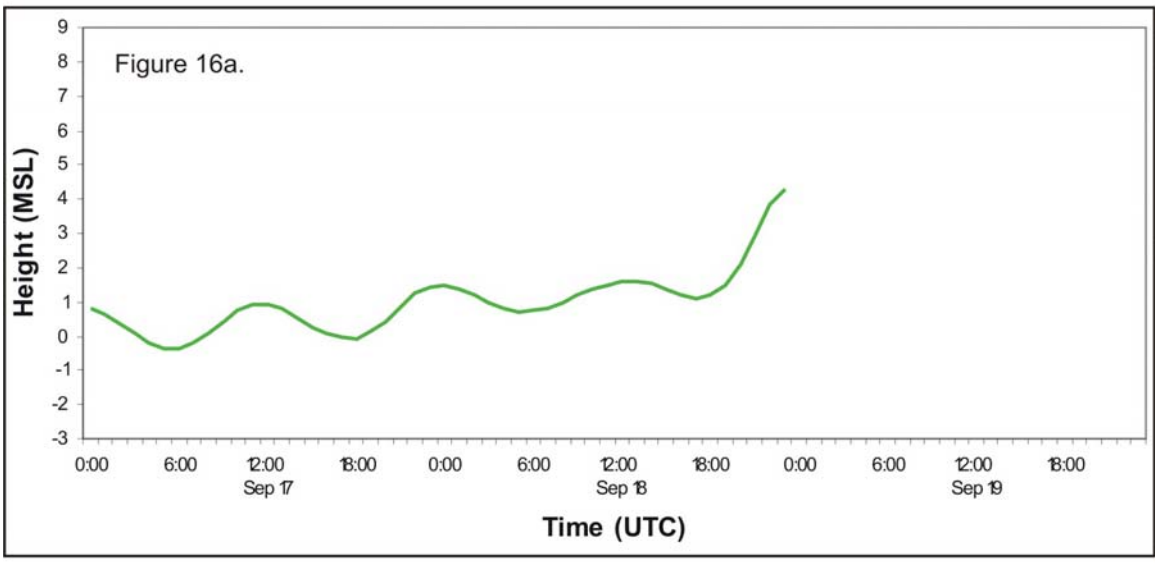


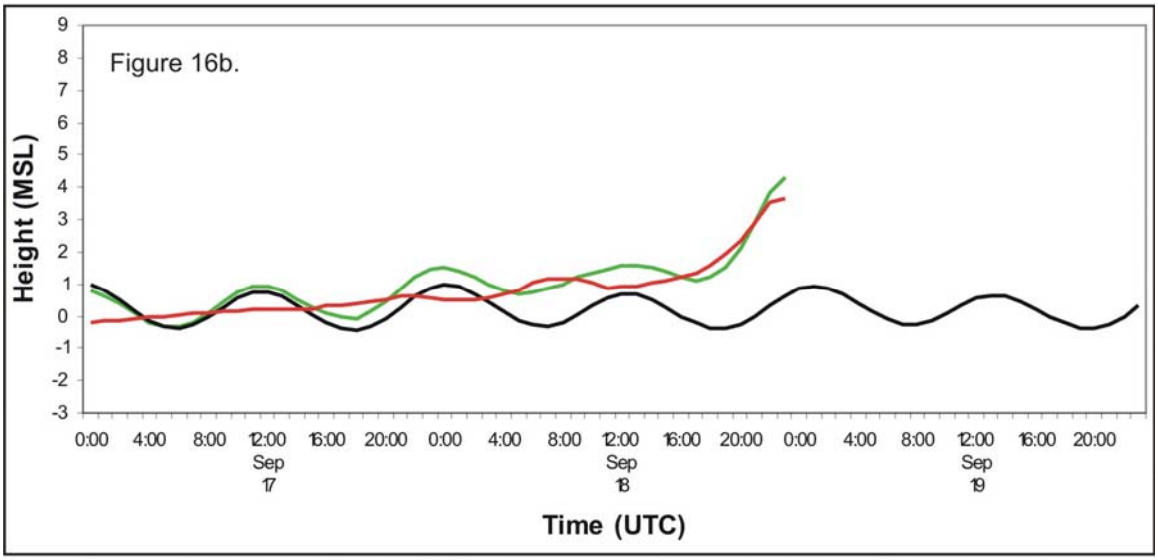


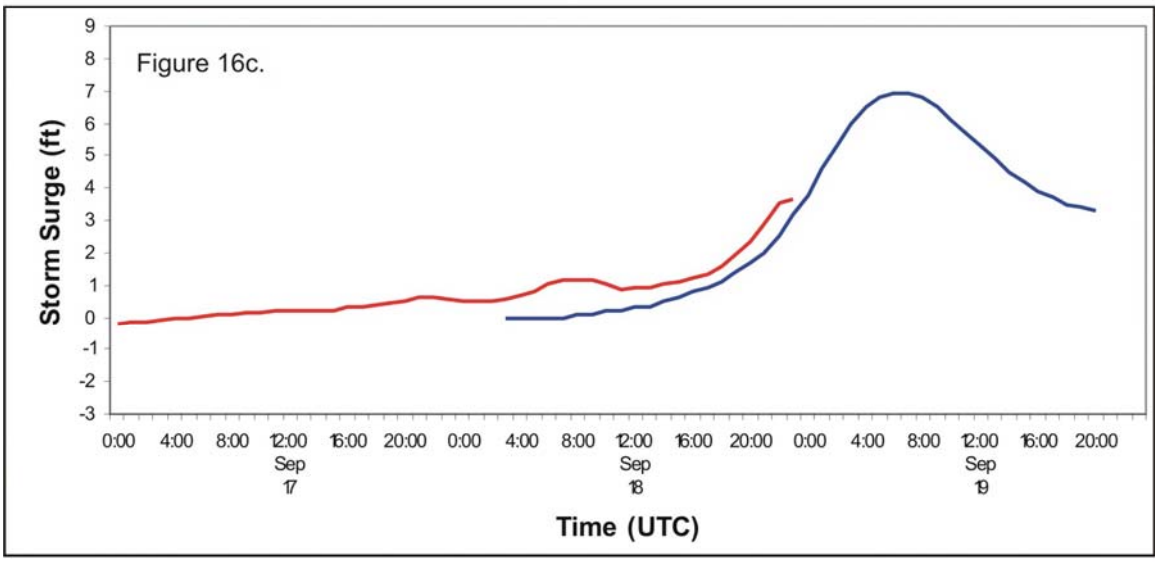


Observed Predicted Obs-Pred SLOSH

Colonial Beach, Potomac River, VA

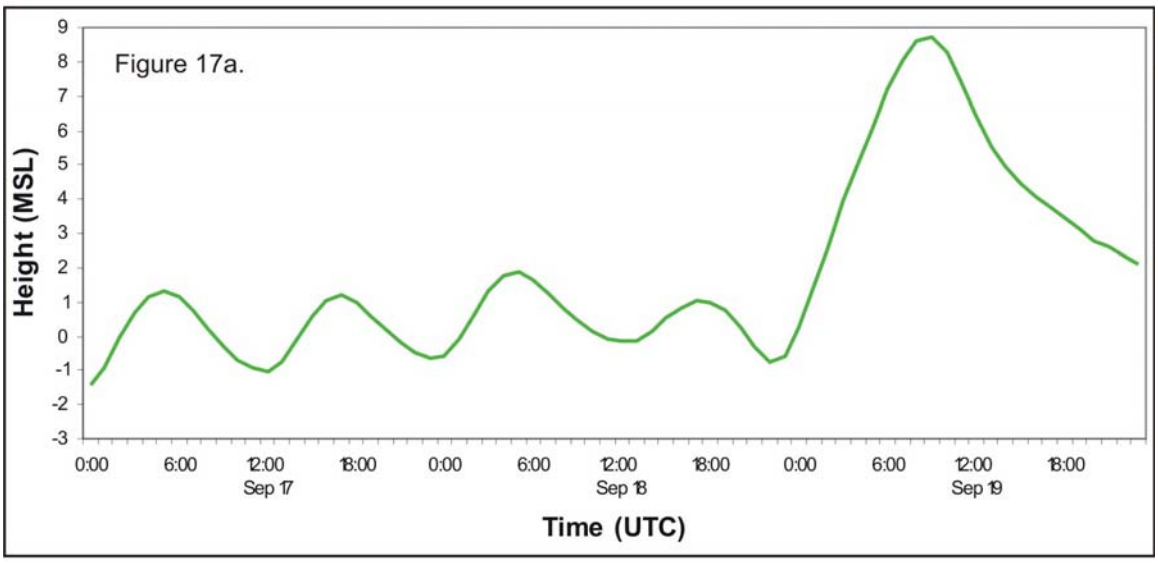


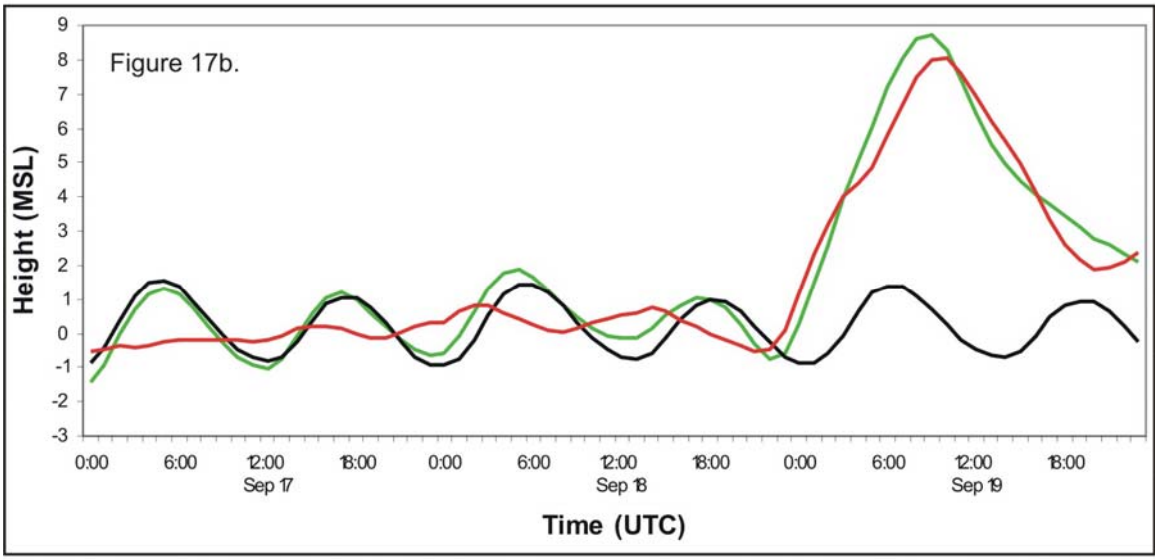


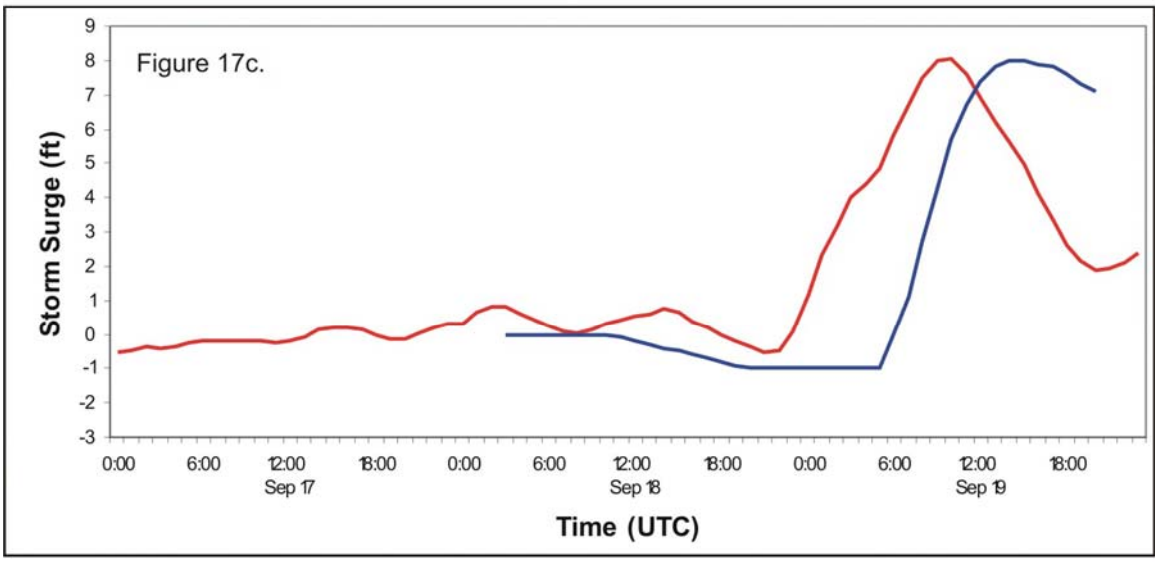


Observed Predicted Obs-Pred SLOSH

Washington, DC

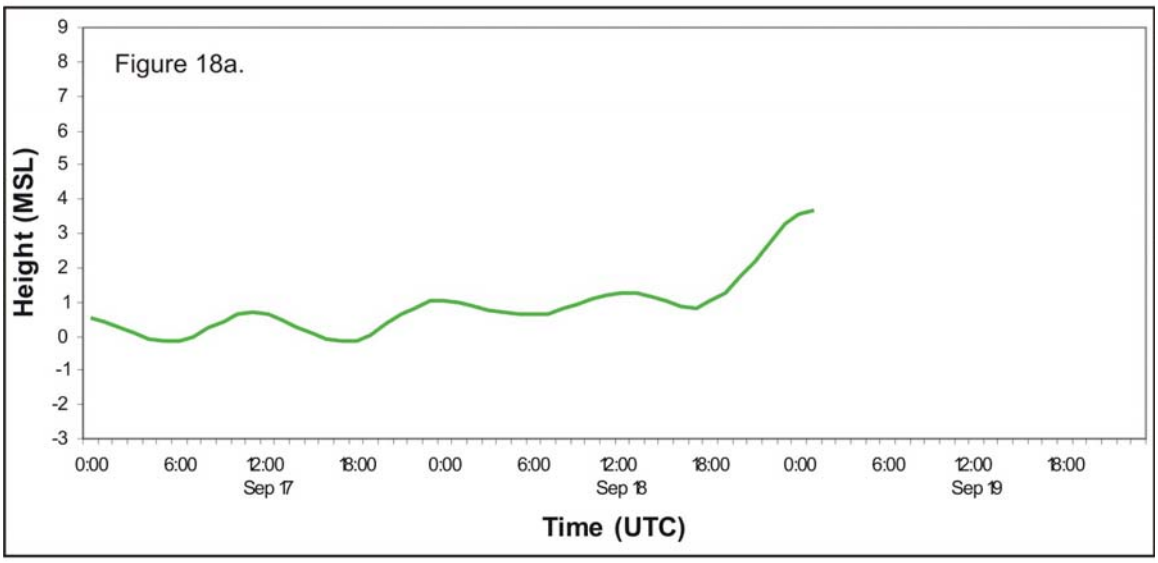


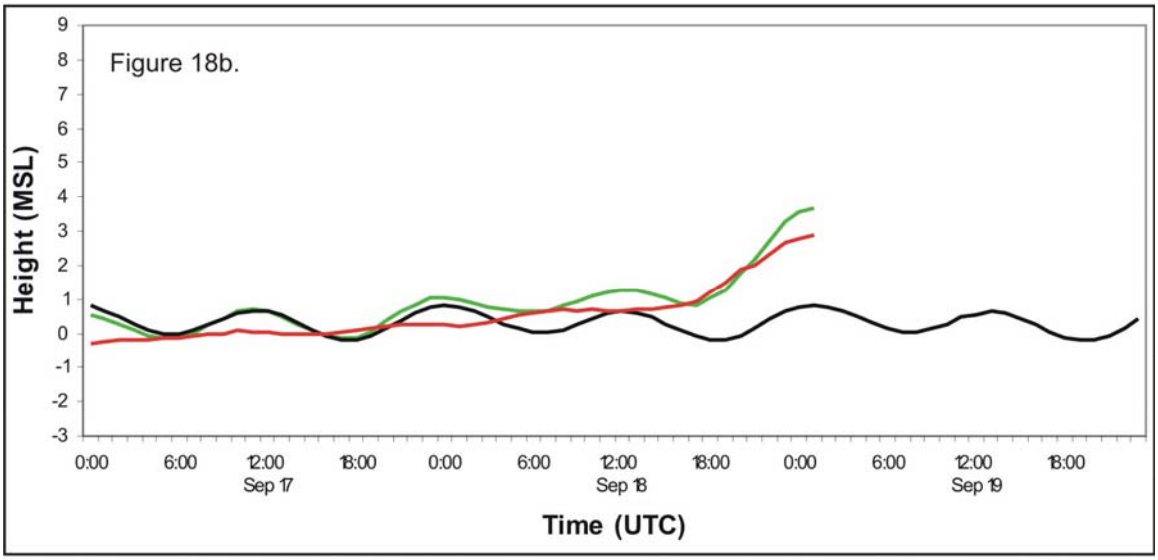


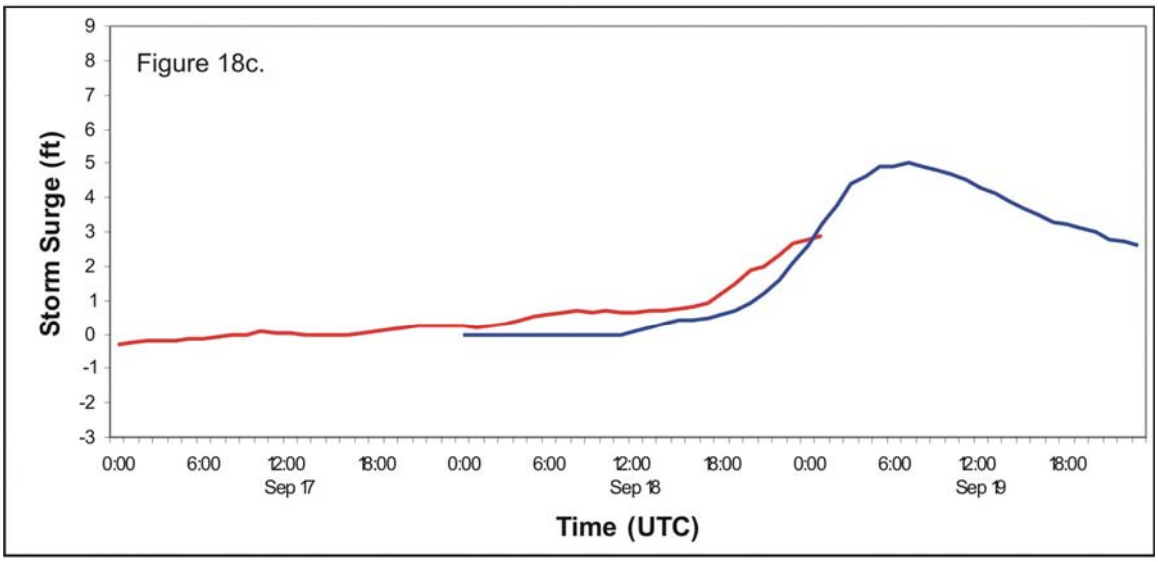


Observed Predicted Obs-Pred SLOSH

Solomon Island, MD

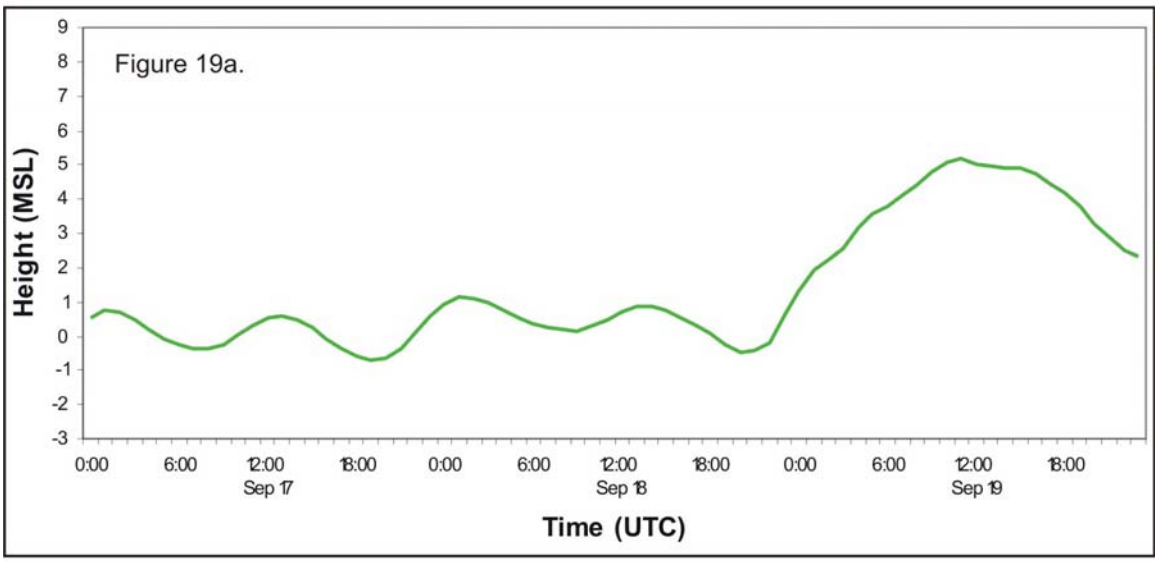


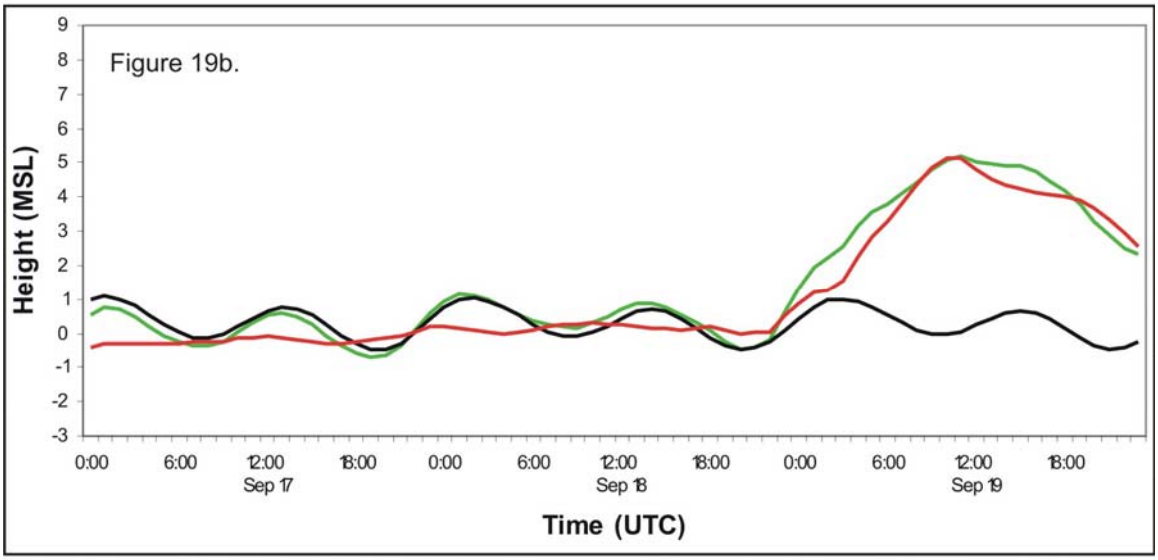


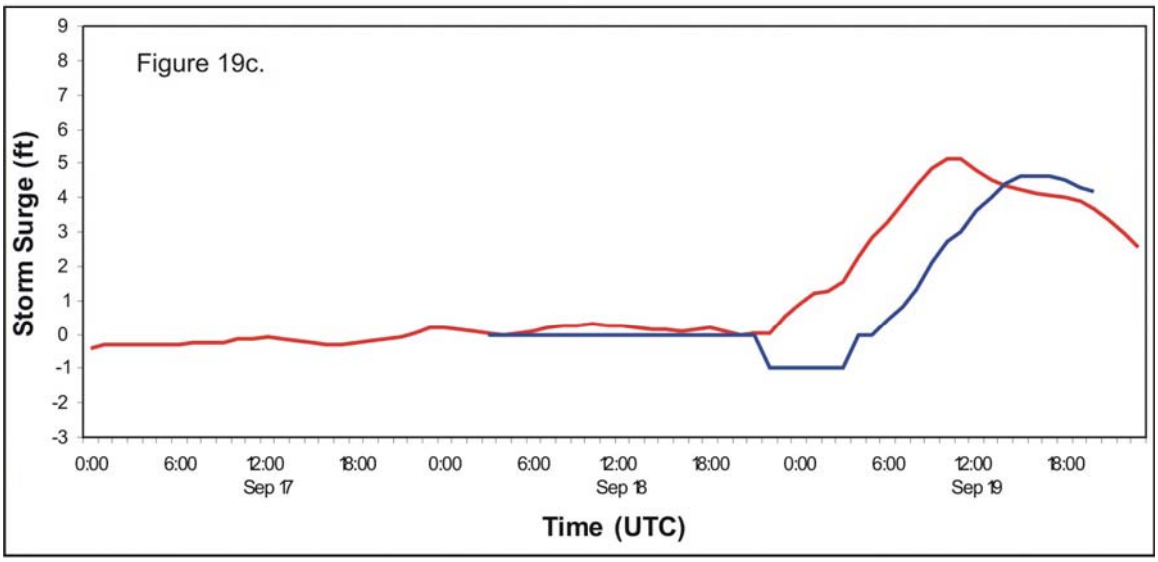


Observed Predicted Obs-Pred SLOSH

Cambridge, Choptank River, MD

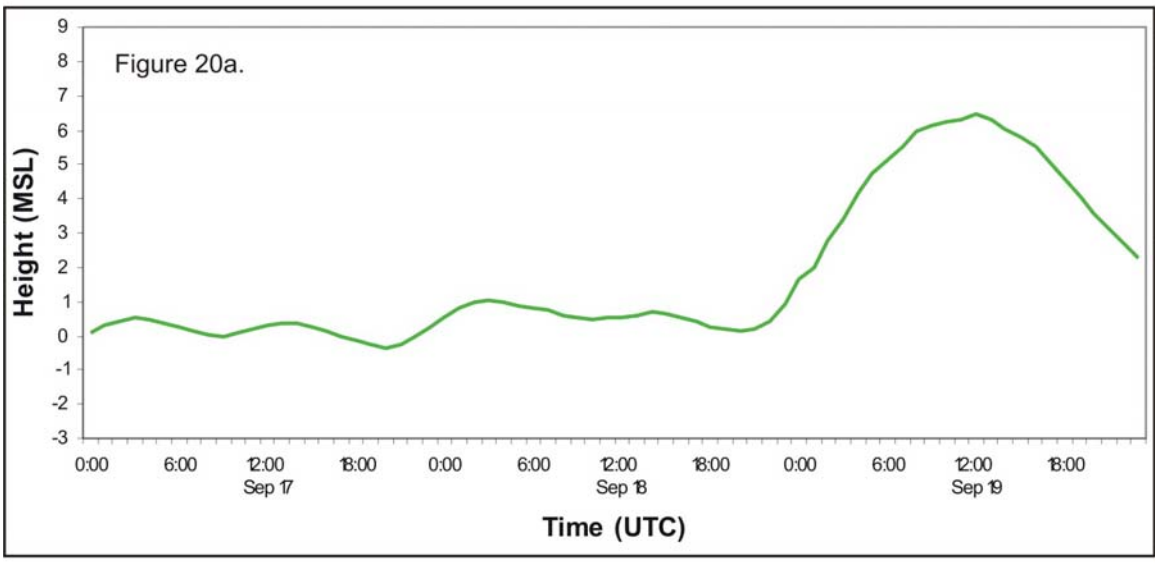


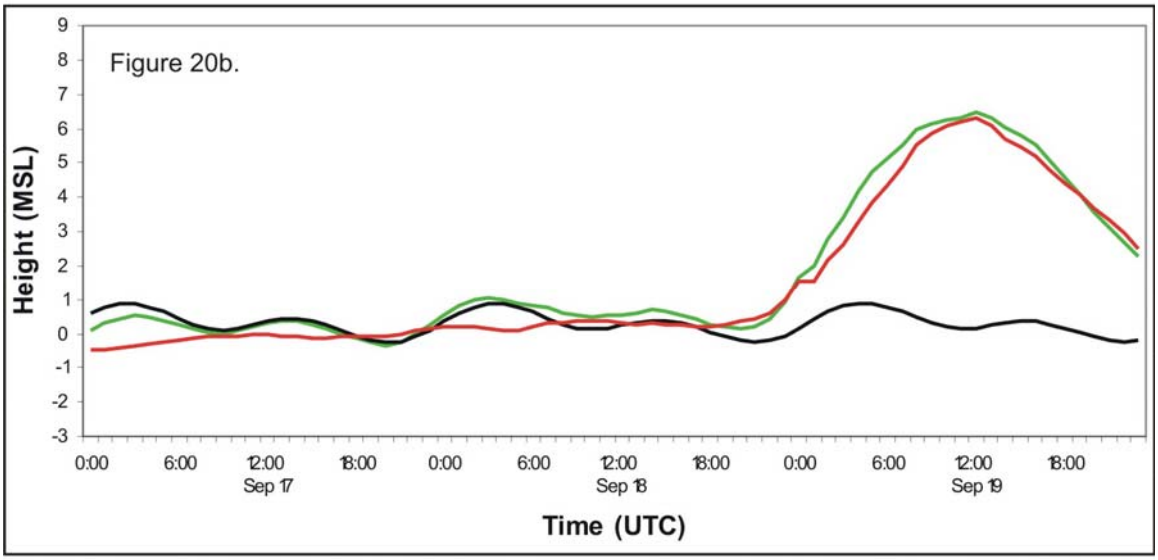


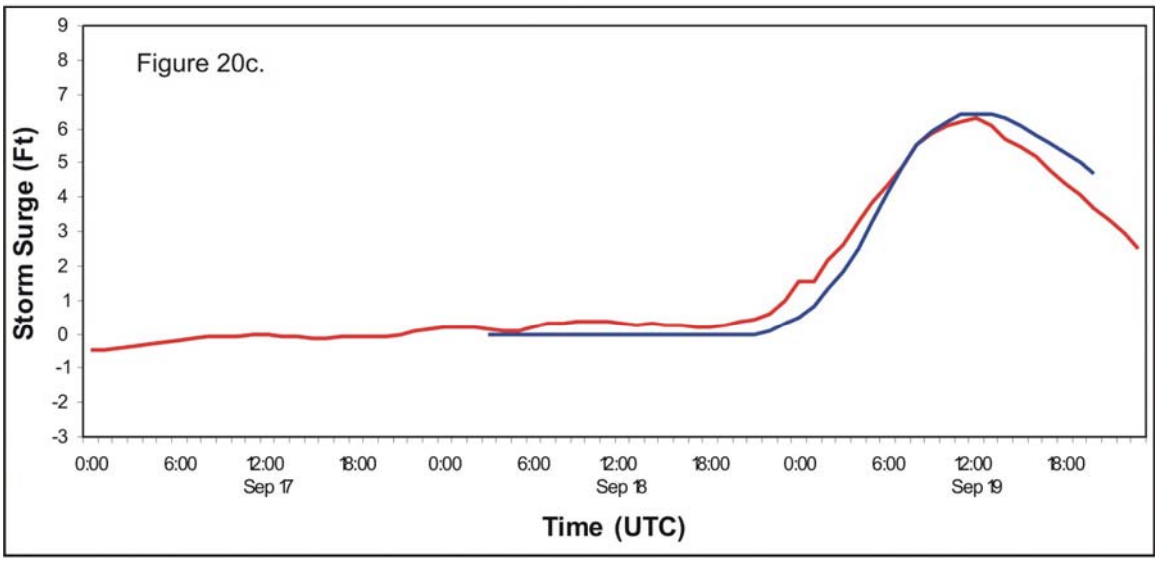


Observed Predicted Obs-Pred SLOSH

Annapolis, US Naval Academy, MD

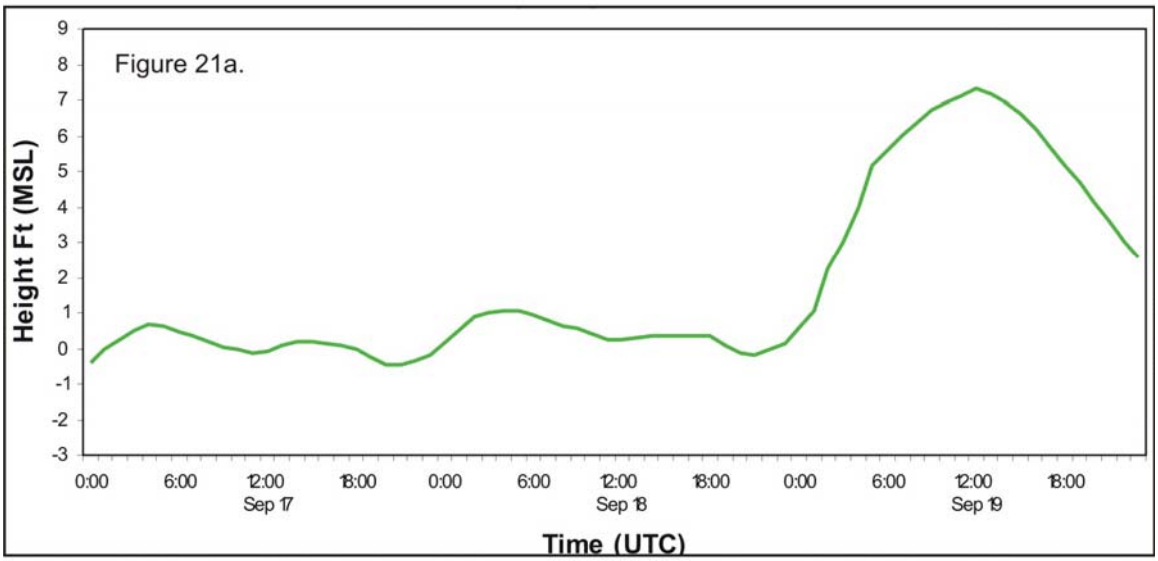


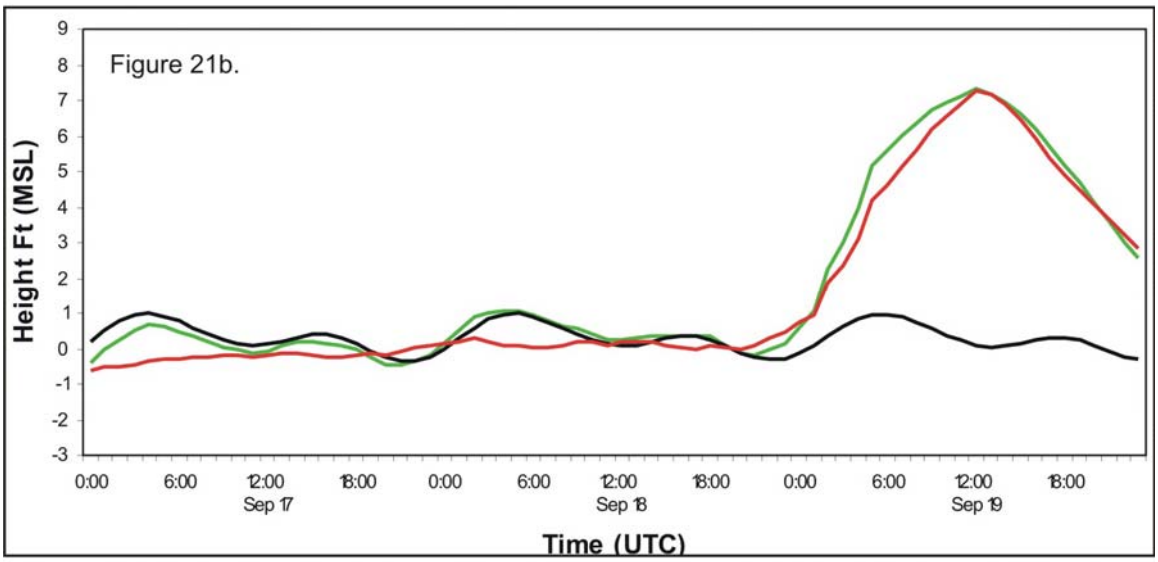


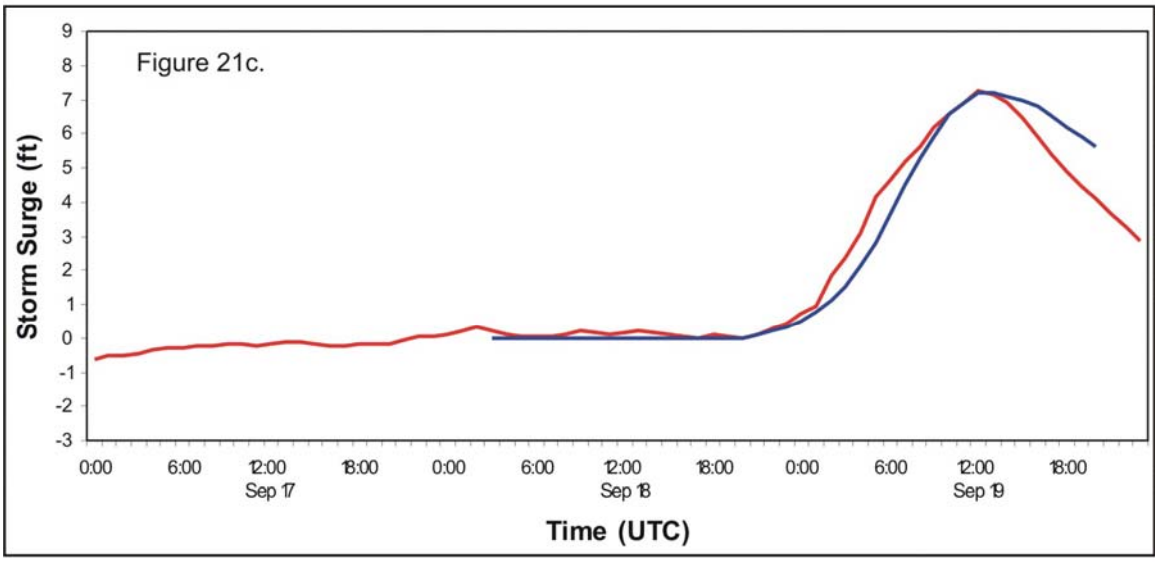


Observed Predicted Obs-Pred SLOSH

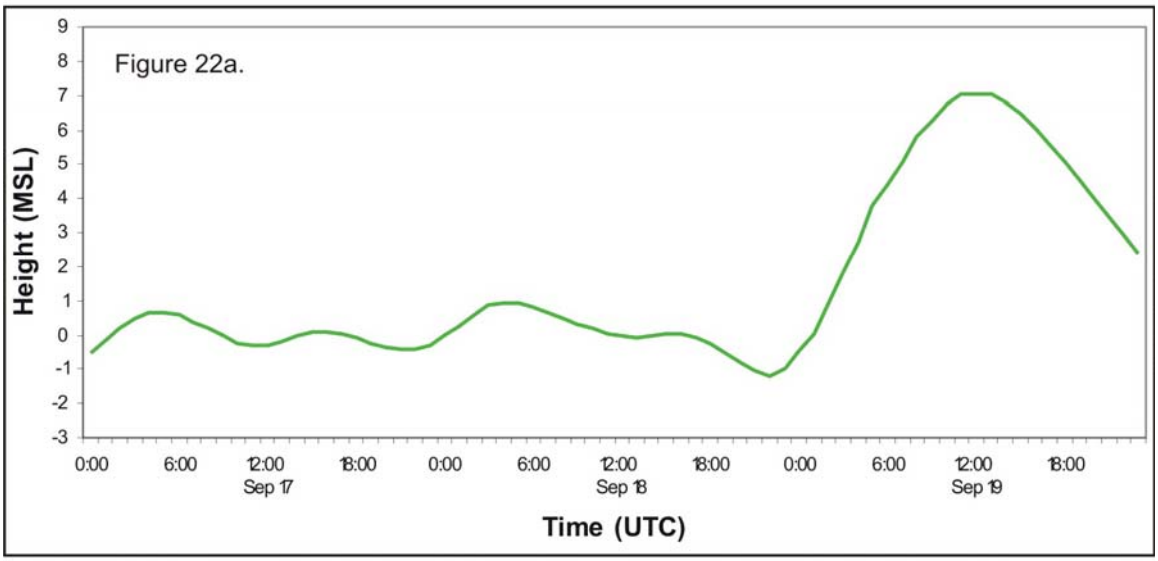
Baltimore, MD

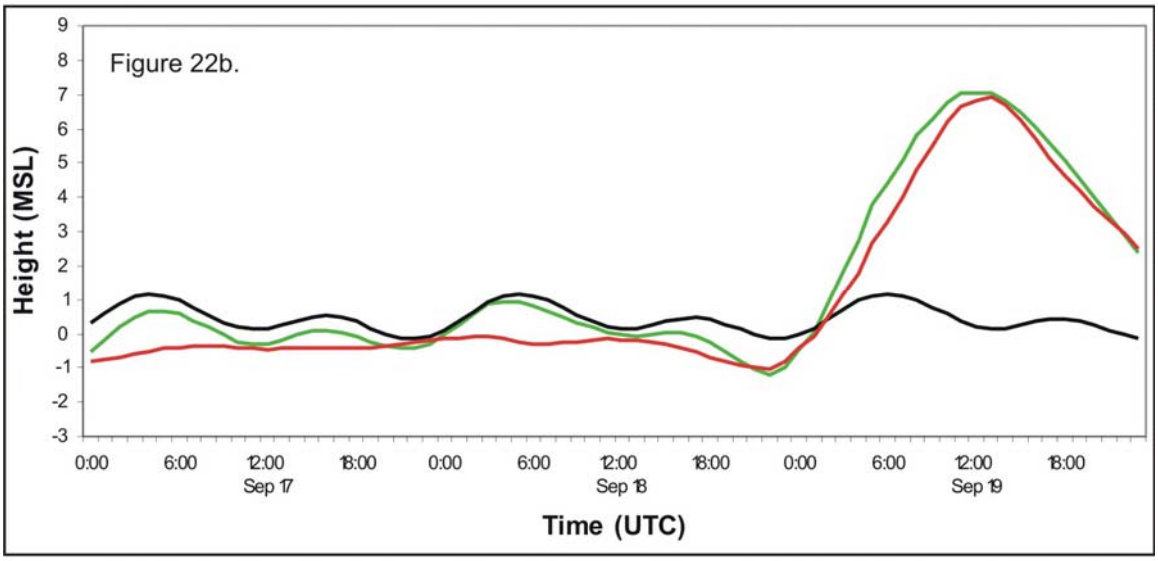


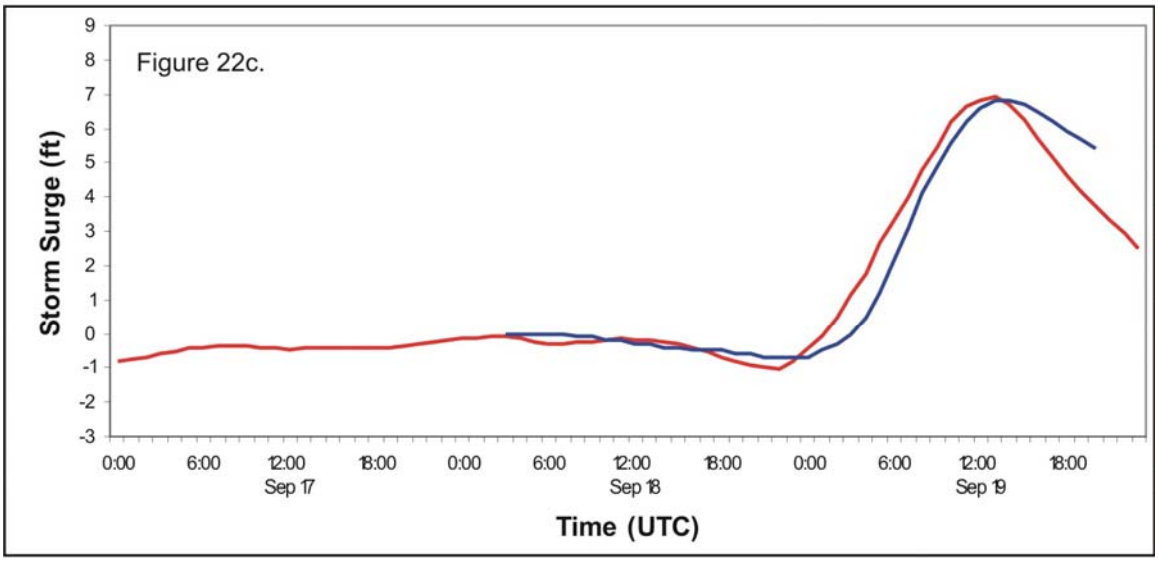




Tolchester Beach, MD

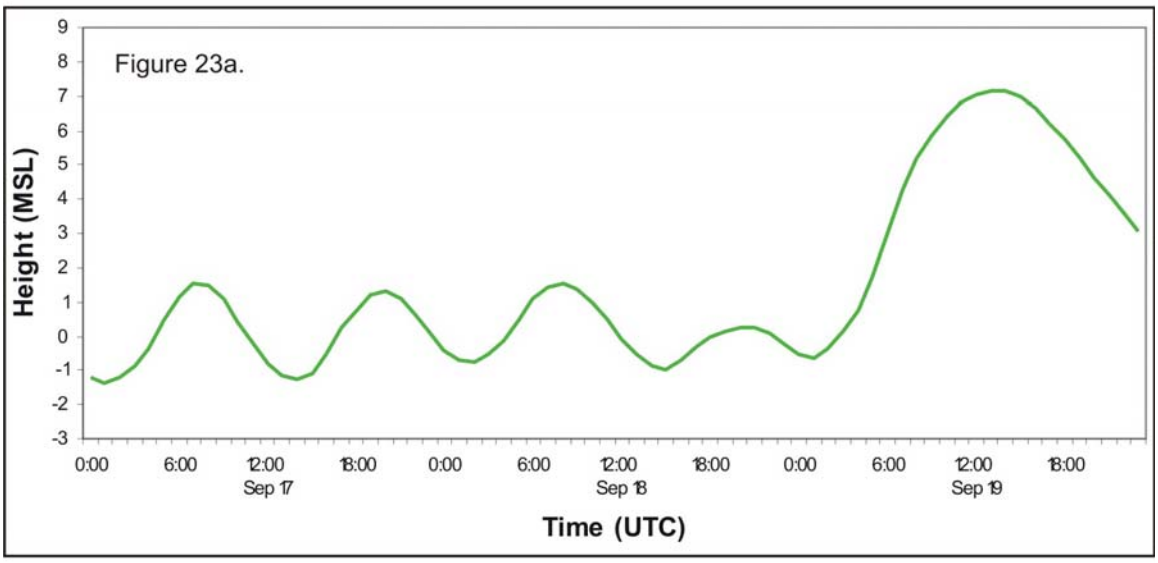


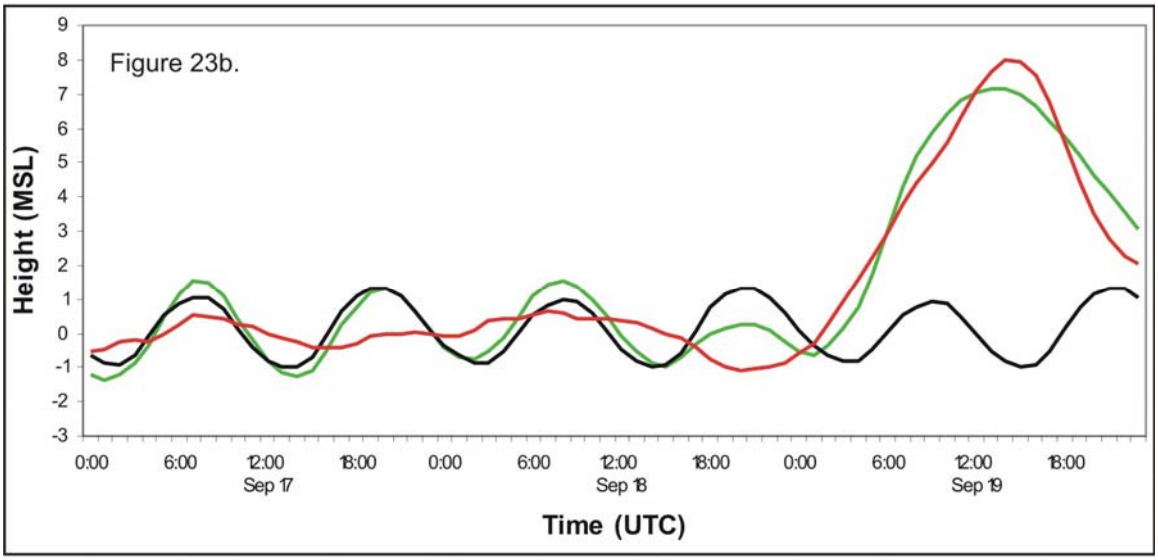


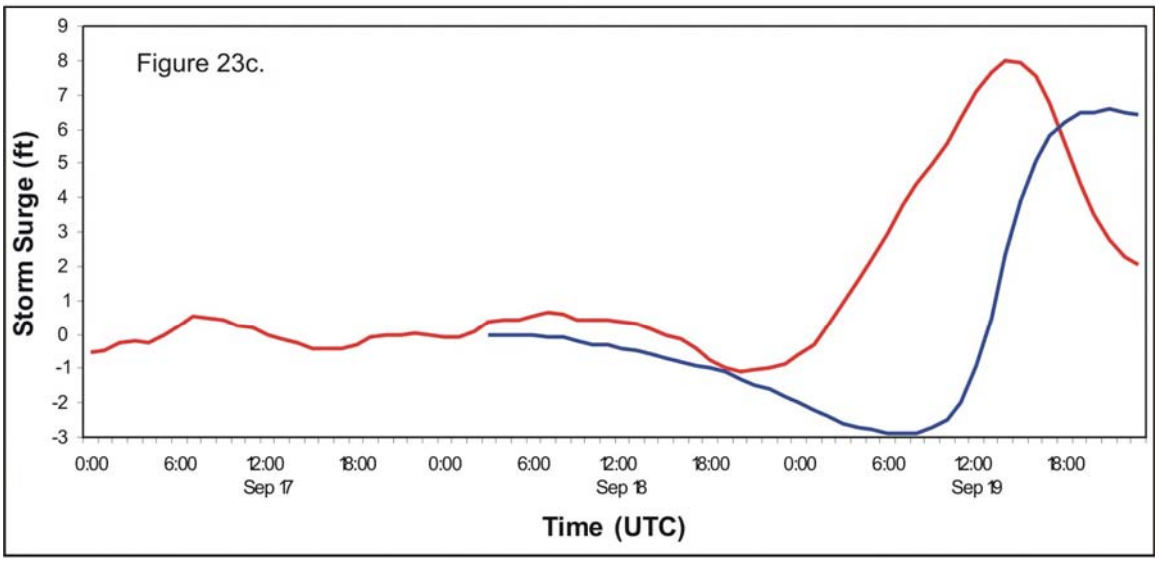


Observed Predicted Obs-Pred SLOSH

Chesapeake City, MD

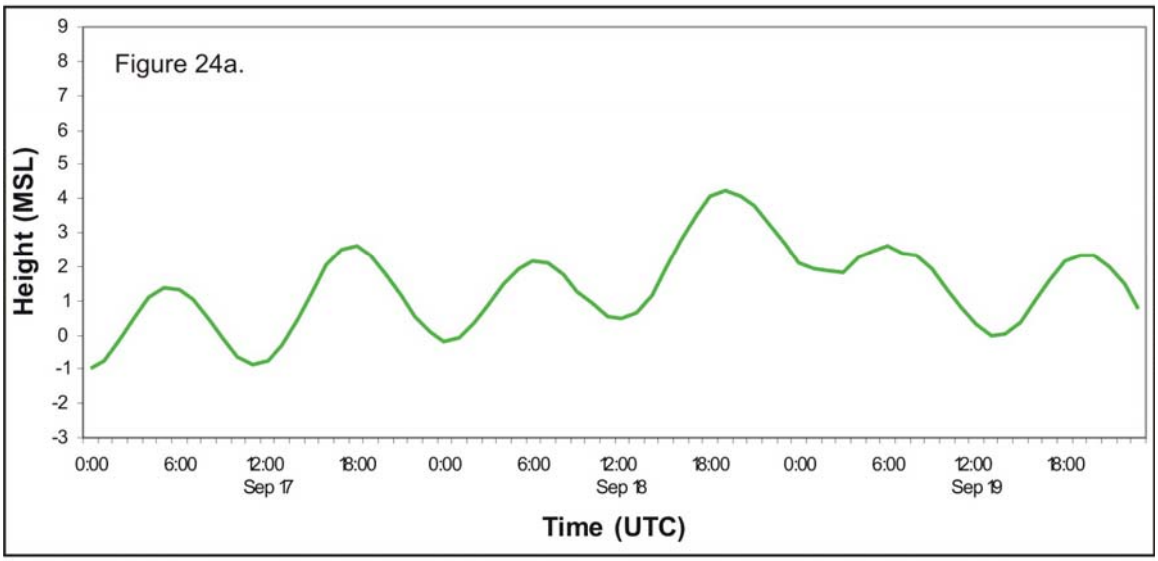


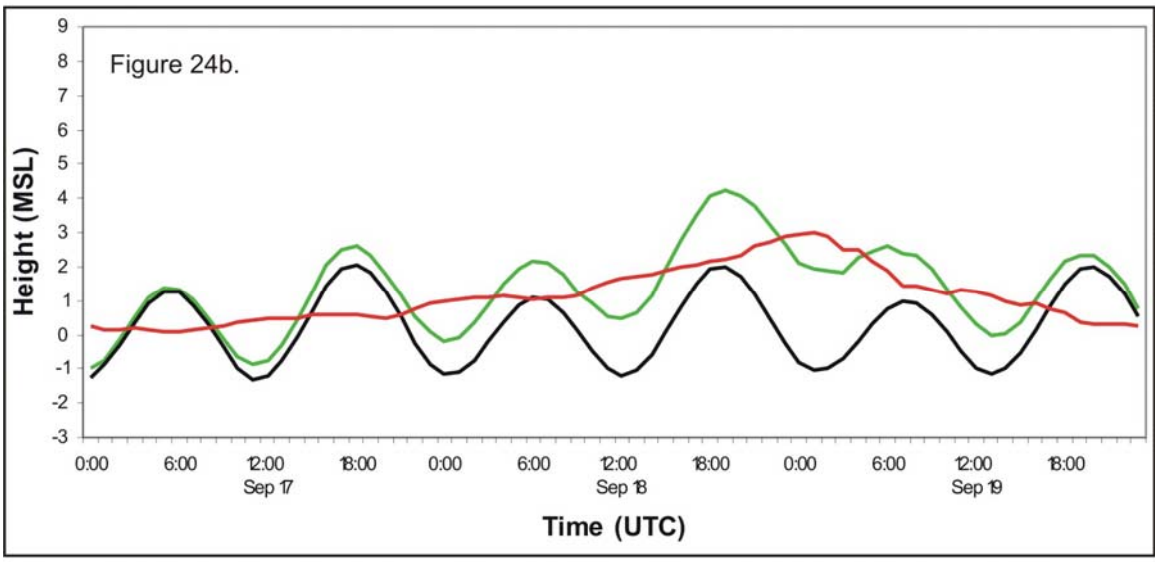


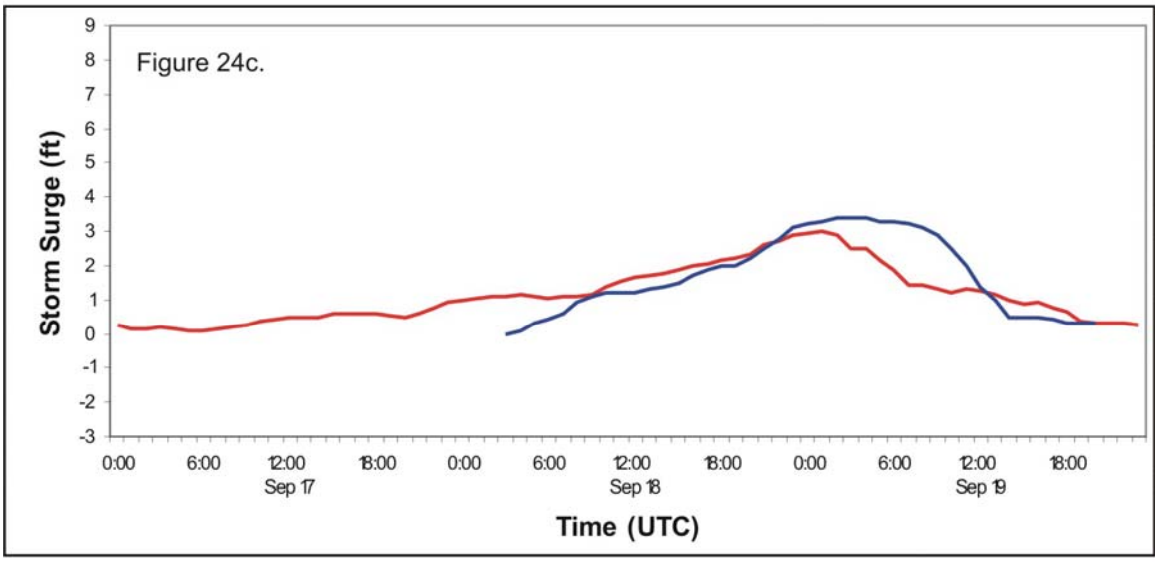


Observed Predicted Obs-Pred SLOSH

Lewes, DE

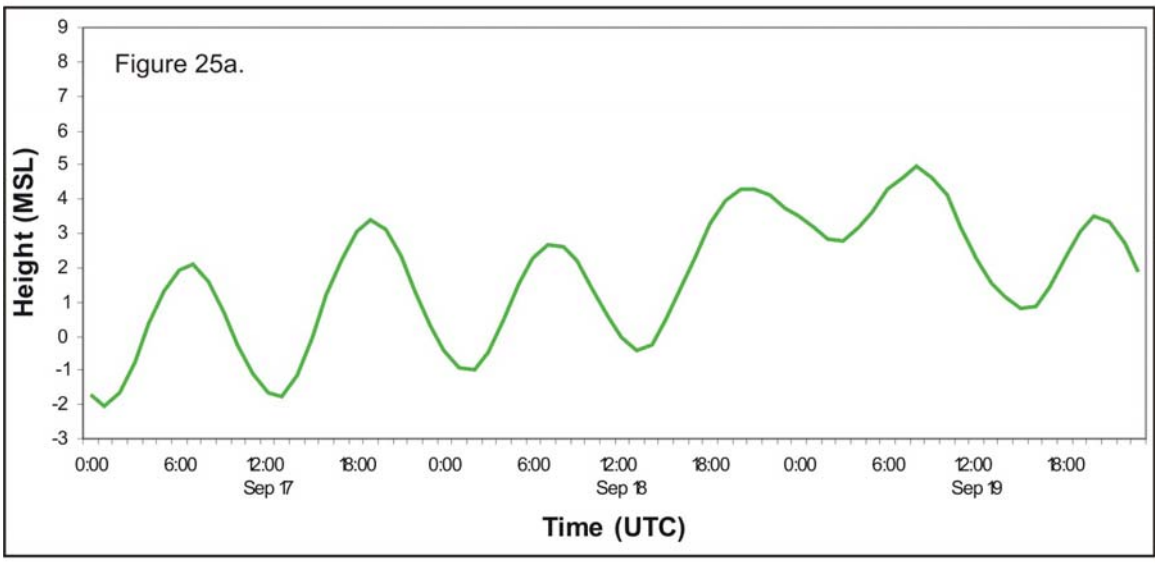


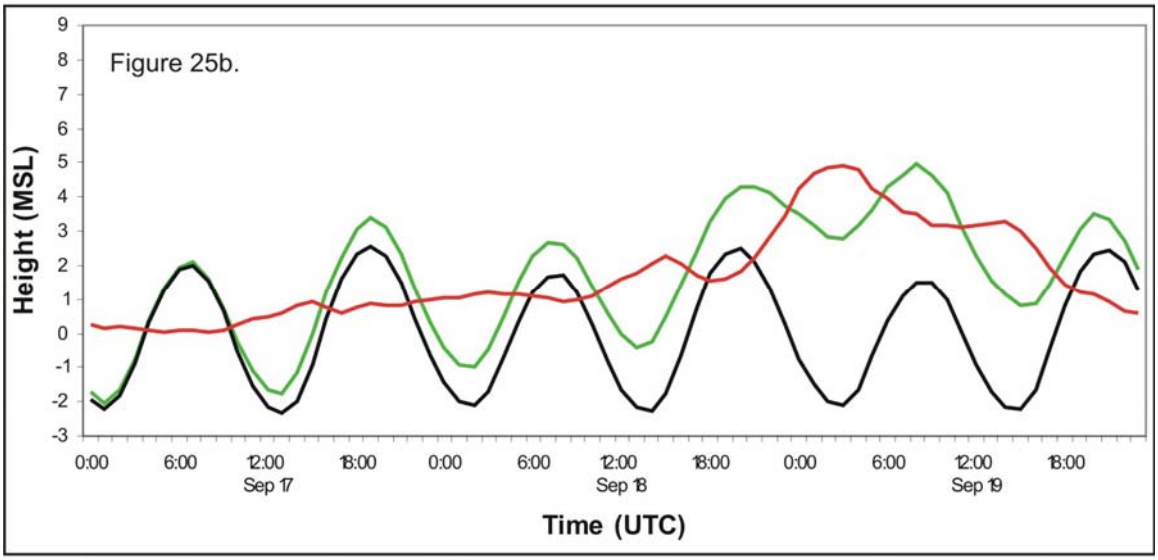


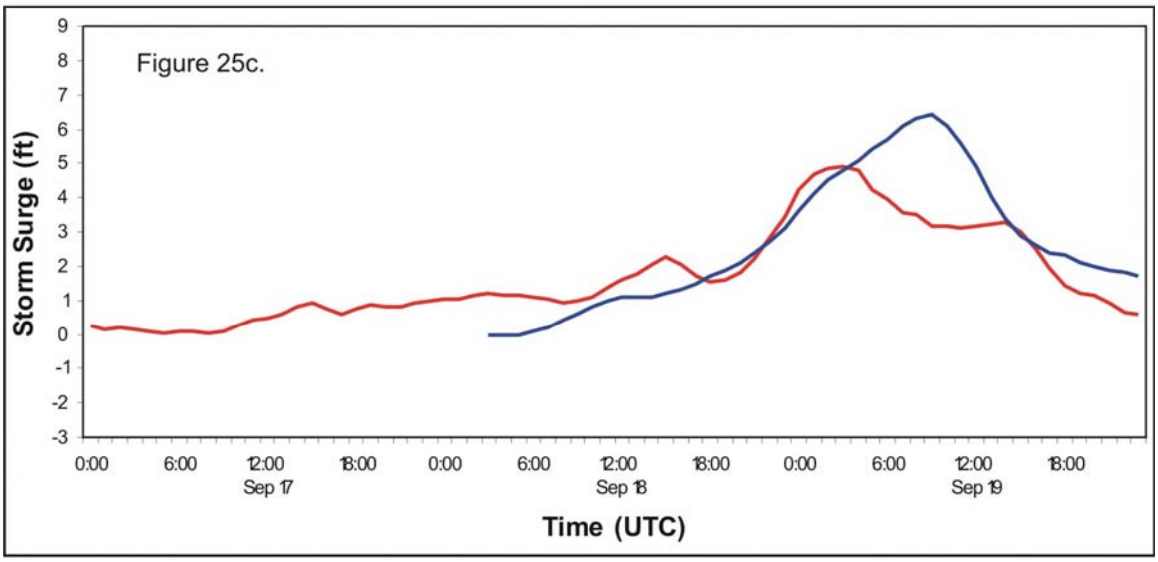


Observed Predicted Obs-Pred SLOSH

Ship John Shoal, NJ

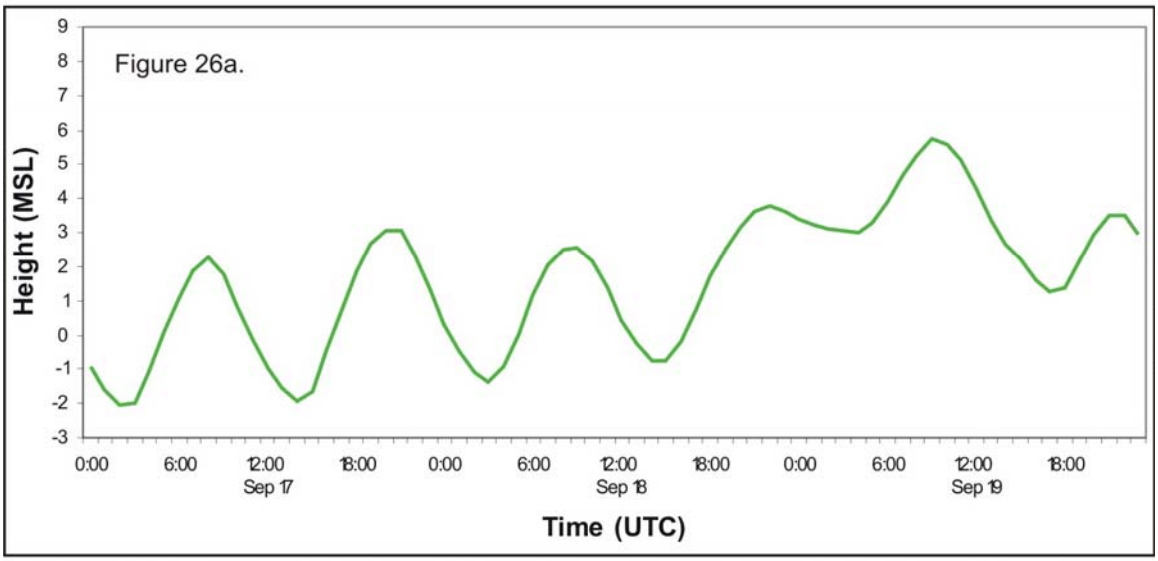


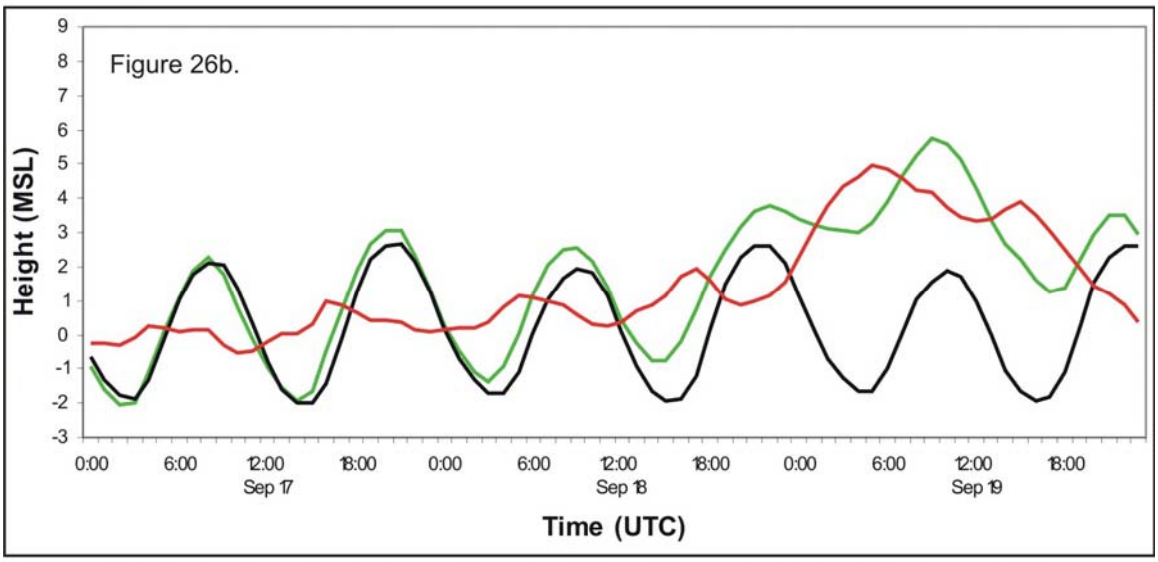


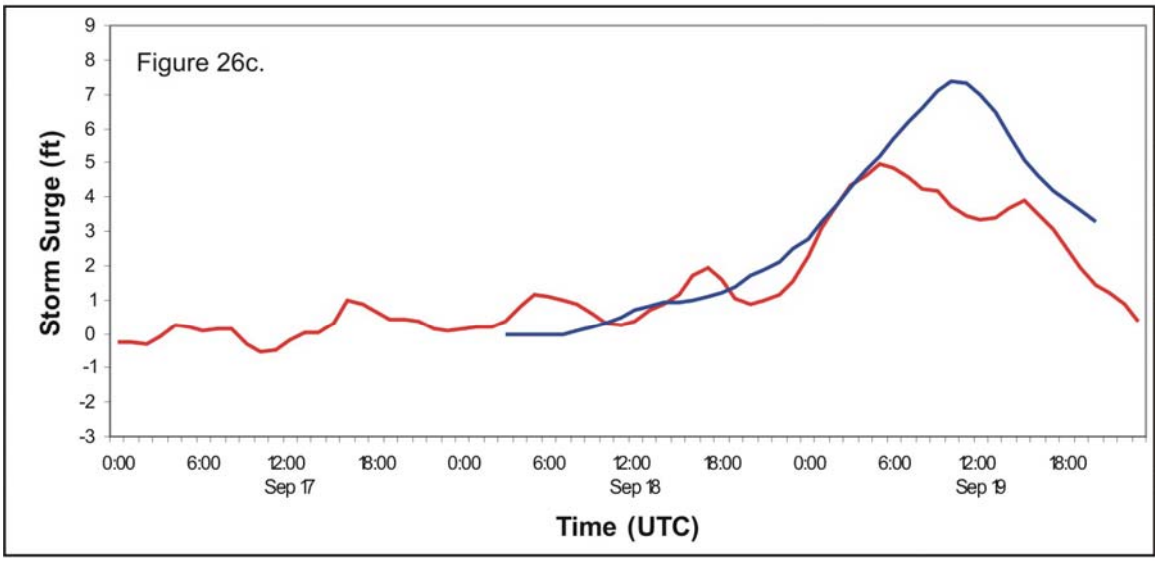


Observed Predicted Obs-Pred SLOSH

Reedy Point, DE

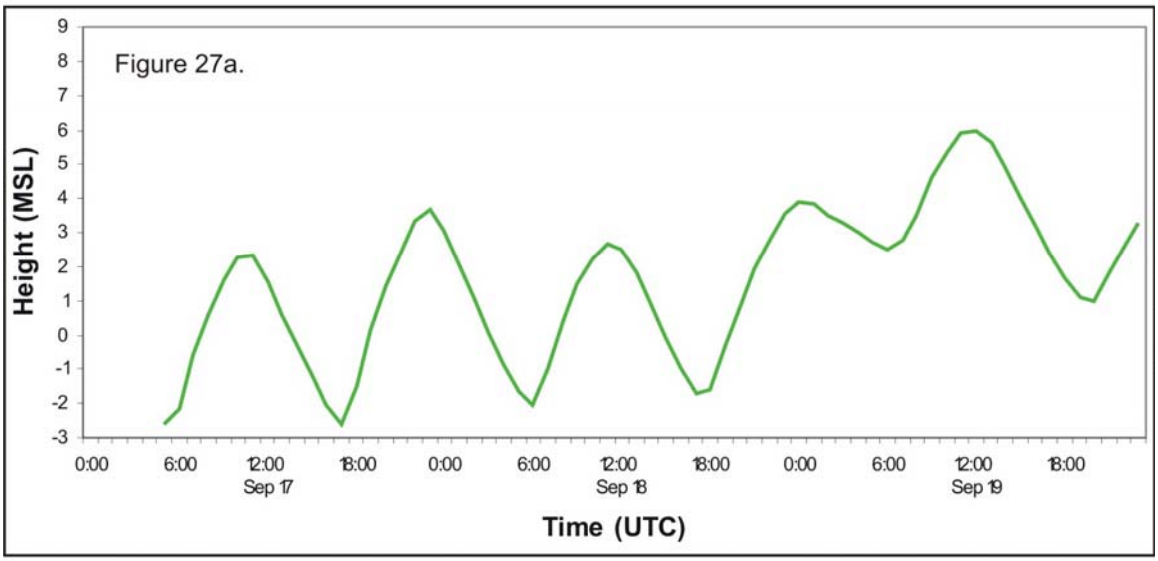


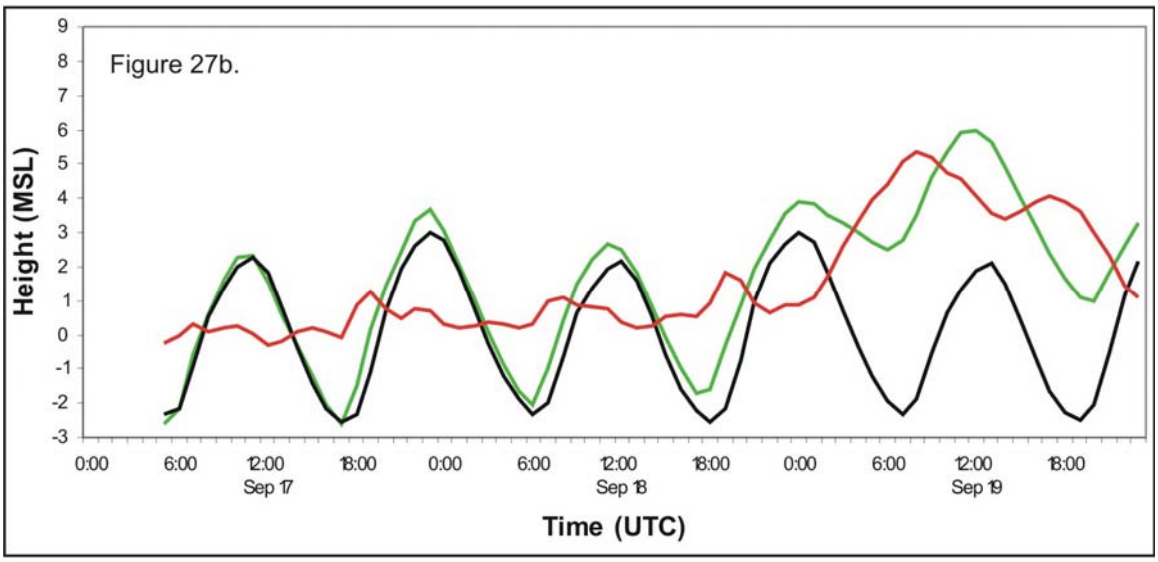


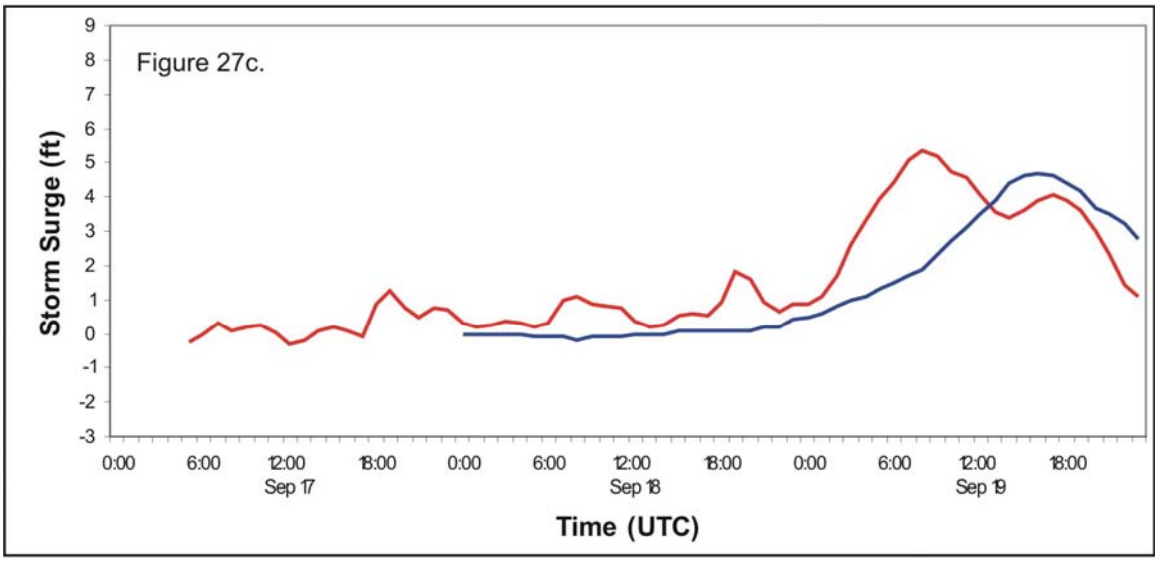


Observed Predicted Obs-Pred SLOSH

Philadelphia, PA







Observed Predicted Obs-Pred SLOSH

APPENDIX B

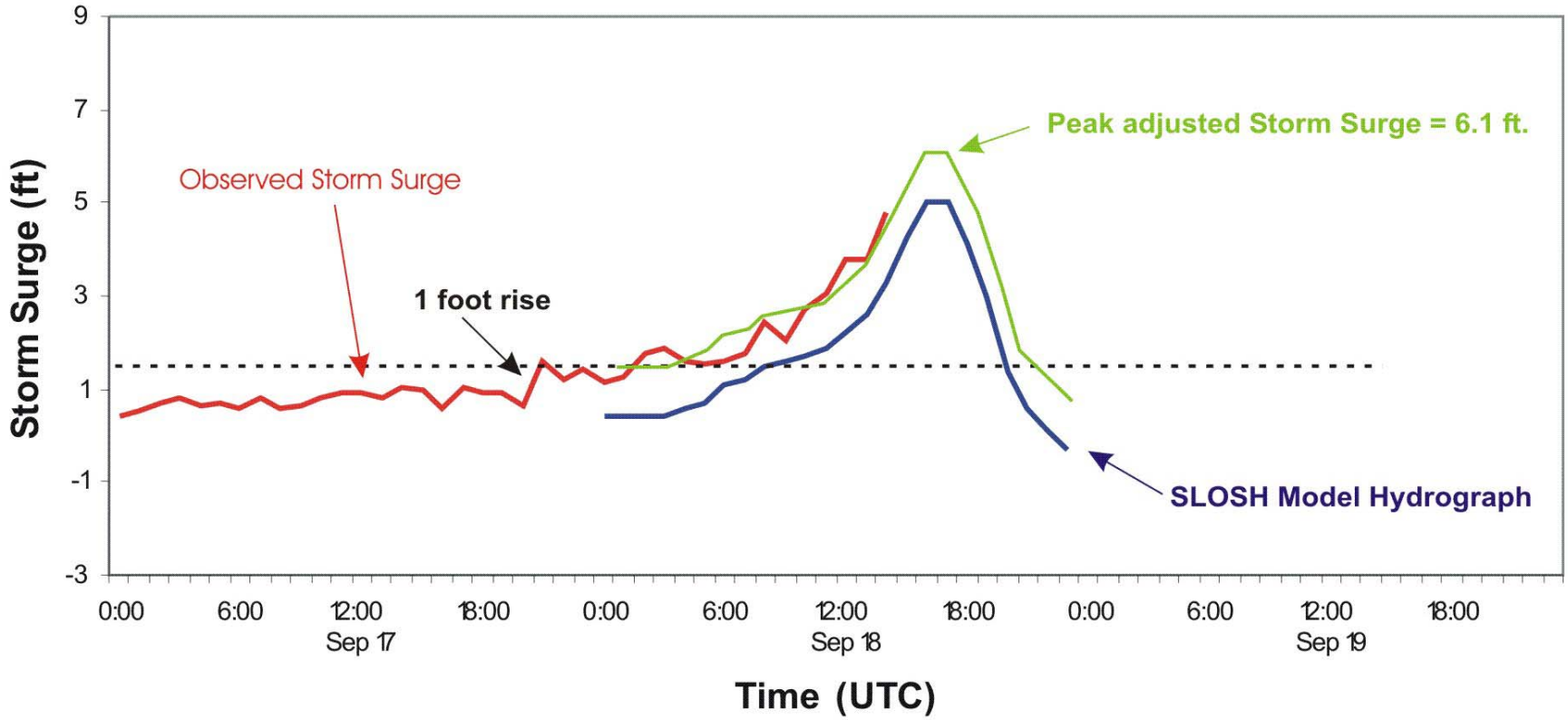


Figure 1. Cape Hatteras Fishing Pier Adjusted Storm Surge Hydrograph

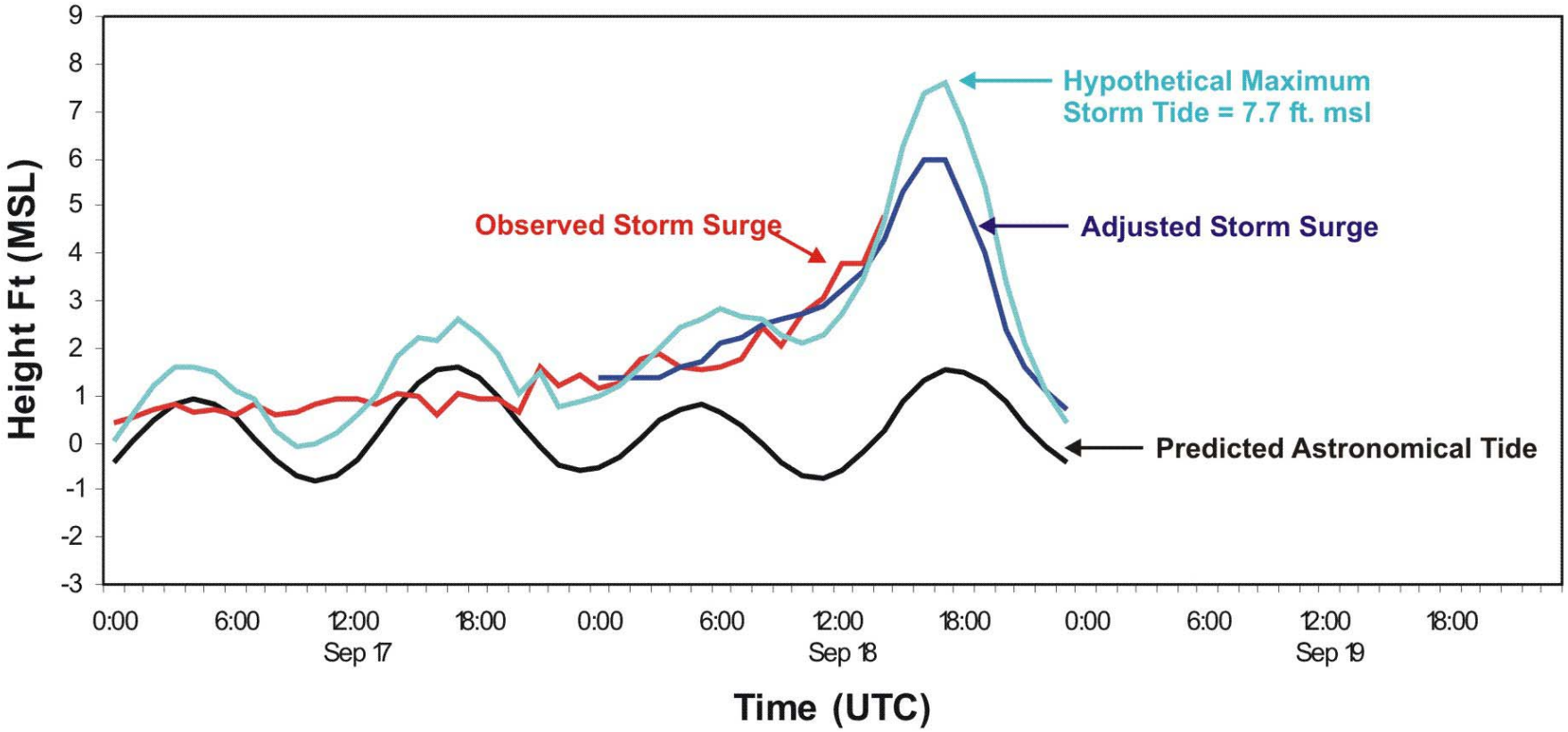


Figure 2. Cape Hatteras Fishing Pier Hypothetical Hydrograph