JP1.6 AN ANALYSIS OF THE IMPACT OF HURRICANE ISABEL'S FLOODING ON THE CHESAPEAKE BAY REGION AND THE ACCURACY OF THE SLOSH MODEL IN PREDICTING THIS FLOODING

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1. INTRODUCTION

Hurricanes are tropical storms that have sustained winds greater than 33 m/s. They are formed from basic complexes of thunderstorms which grow to hurricane strength through interaction between the ocean and the atmosphere.

Many factors play a role in the formation, growth, and survival of hurricanes, including temperature, moisture, winds and pressure. One of the most important contributors to hurricane formation is the ocean temperature, which must be warmer than 28 °C. The heat and moisture supplied from the warm ocean is ultimately the main energy source for hurricanes. As well as needing heat and moisture, hurricanes also require high relative humidities in the lower and middle troposphere and an absence of vertical wind shear. The pressure gradient present within the hurricane because of the extreme low pressures in the center of the storm and higher pressures in the outer bands serves to balance the centrifugal force, keeping air from being pushed away from the storm, thus preventing the storm from dissipating.

One of the most significant causes of damage due to a hurricane is storm surge. Storm surge is the sum of the effect of high wind speeds and low atmospheric pressure, in addition to the timing and strength of the tide when the storm reaches its maximum strength (Hovis and others, 2004). The rise in the water level caused by storm surge can cause severe flooding in coastal areas, particularly when the storm tide coincides with a certain time in the tidal cycle. The level of surge in a particular area is also determined by the shape of the coastal area where the hurricane made landfall. Also, confined areas such as bays or rivers which can concentrate the surge in a narrow area will see greater storm surges.

Numerical models have been developed to provide emergency management officials with storm surge predictions for hurricane-impacted areas. The SLOSH model is one such numerical model (Houston and others, 1999). The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model was developed by the National Weather Service's Technique Development Laboratory and provides the primary guidance used by emergency management officials to create and carry out coastal evacuation plans in the event of a hurricane. SLOSH is used by the Federal Emergency Management Agency (FEMA) to map the storm surge flood plain in each of 40 U.S. SLOSH basins (Houston and others, 1999). SLOSH estimates storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account pressure, size, forward speed, track and winds of the hurricane. The surge calculations are applied to specific shorelines, incorporating unique topographical configurations, bays and rivers, water depths, bridges, roads, and other physical features. The observed surge and predicted surge can be compared in order to determine the model's accuracy and possibly lead to future improvements in the program. Hurricane Isabel is an ideal storm for using the SLOSH hindcast model comparison due to the large amount of storm surge which resulted and the large area across which the hurricane impacted.

Hurricane Isabel was one of the most memorable hurricanes of a very active 2003 North Atlantic hurricane season. The storm surge levels experienced by numerous locations along the Chesapeake Bay were record-breaking (Hovis and others, 2004). Despite the fact that Hurricane Isabel was a closely watched and tracked storm by many people, the surge which resulted from the storm came as a surprise to most of the population which was, therefore, unprepared for the event (Olson, 2004). An accurate SLOSH model prediction could have helped prevent some of the destruction by giving the affected communities an idea of how bad the surge would be. Therefore, a case study investigation of the accuracy of the SLOSH model in predicting the storm surge and flooding associated with Hurricane Isabel may provide useful data for the improvement of future surge predictions and hurricane events.

2. METHODOLOGY

In order to determine the accuracy of the SLOSH model predictions for Hurricane Isabel, the observed, predicted, and SLOSH water levels during the time period in which hurricane hit the area were needed. Eight stations along the

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Chesapeake Bay belonging to the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) programs were chosen for analysis for the period18-19 September 2003, the days when Hurricane Isabel and the resulting storm surge greatly impacted the stations (see Fig. 1).

Fig.1 CO-OPS water levels stations and track of Hurricane Isabel 18-19 September, 2003. Yellow boxed stations are the eight stations chosen for storm surge analysis (adapted from Hovis and others, 2004).

The observed and predicted water levels for 18-19 September 2003 were obtained online from the CO-OPS National Ocean Service (NOS) water level observation network (http://co-ops.nos.noaa.gov/usmap.html). The observed data were the water levels which the stations experienced during the hurricane. The predicted water levels were just the normal tide, not taking into account any changes from the hurricane.

NOAA entered the following input data into the SLOSH program to produce the storm surge predictions: the latitudes and longitudes of Hurricane Isabel's track for 18-19 September, Delta P values (the standard barometric pressure is used with the initial position and then the wind speed forecast is used to estimate the other values), and the Radius of Maximum Winds (RMW) which are determined either by aircraft data or radar data correct to 10 m (correspondence with LT Pralgo, NOAA Corps). Once this was done, the observed, predicted, and SLOSH predicted water levels for each of the eight stations were graphed and compared. The differences between the three values for each station were graphed and compared to show at which stations the SLOSH model best predicted the water levels. The observed storm surge and the SLOSH predicted storm surge for each of the eight stations were graphed along with the difference between the values. The maximum observed storm surge and SLOSH predicted storm surge values were calculated as well as the date and time at which they occurred. In addition, the observed and historical water level maxima were compared to determine by how much Hurricane Isabel broke the historical water level records.

The overall goal is to determine why the SLOSH program would be more or less accurate at a certain station so that in the future, improvements can be made to the model if needed. The wind direction and strength, pressure, and location of Hurricane Isabel should help to explain why the SLOSH program predicted the values it did and, perhaps, why the observed water levels turned out to be what they were.

3. RESULTS

At the most northern of the eight CO-OPS stations, Chesapeake City, MD, the SLOSH model predicted a consistently higher water level, a larger maximum storm surge, and an earlier surge peak than was observed. These observations can be seen in **Fig**. 2 and Fig. 3, which compare the observed, predicted, and SLOSH predicted water levels and storm surge for Chesapeake City.

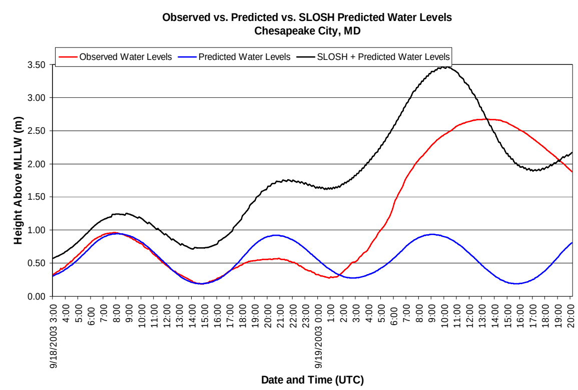

Fig. 2 Comparison of observed and predicted water levels for Chesapeake City, MD during Hurricane Isabel, 18-19 September, 2003.

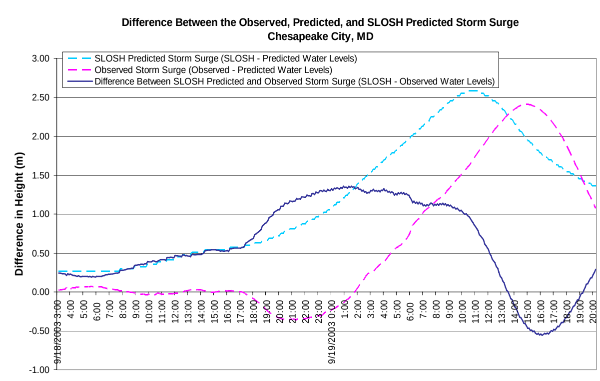

Fig. 3 Comparison of storm surge differences for Chesapeake City, MD during Hurricane Isabel, 18-19 September, 2003.

At Fort McHenry in Baltimore, MD, southwest of Chesapeake City, the SLOSH model was considerably more accurate overall in its surge prediction. The timing of both maximum surge values was exact and the maximum SLOSH predicted surge was 0.28 m larger than the observed surge. The SLOSH predicted surge stayed within 0.5 meters of the observed value all the way up until late afternoon on 19 September, when the observed surge receded quicker than the model predicted. These observations can be seen in Fig. 4 and Fig. 5, which compare the observed, predicted, and SLOSH predicted water levels and storm surge for Baltimore.

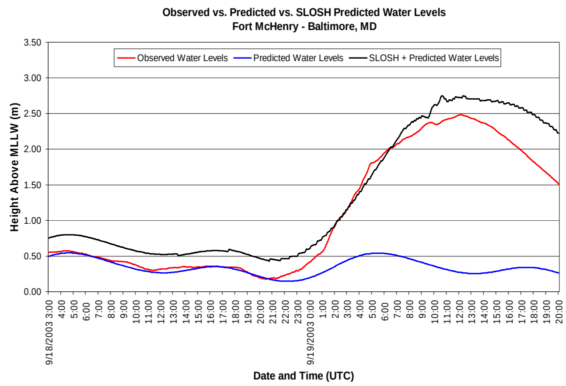

Fig. 4 Comparison of observed and predicted water levels for Baltimore, MD during Hurricane Isabel, 18-19 September, 2003.

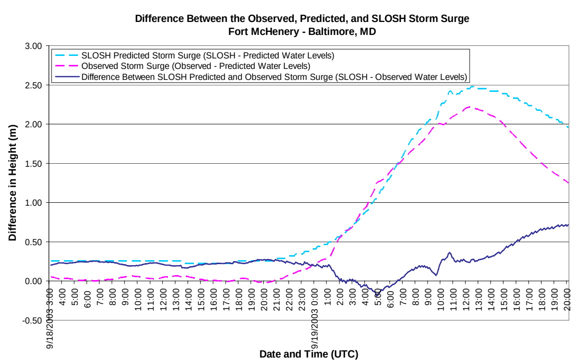

Fig. 5 Comparison of storm surge differences for Baltimore, MD during Hurricane Isabel, 18-19 September, 2003.

The SLOSH predicted and observed water levels and storm surge were closest in value at the US Naval Academy, Annapolis, MD station, south of Baltimore. Not only were the maximum SLOSH predicted and maximum observed storm surge values only 0.064 m different, but the timing was exact. The SLOSH predicted surge stayed within 0.4 meters of the observed value throughout 18 and 19 September. These observations can be seen in Fig 6 and Fig 7, which compare the observed, predicted, and SLOSH predicted water levels and storm surge for Annapolis.

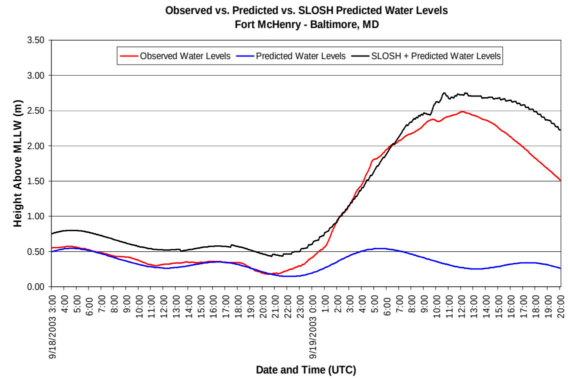

Fig. 6 Comparison of observed and predicted water levels for Annapolis, MD during Hurricane Isabel, 18-19 September, 2003.

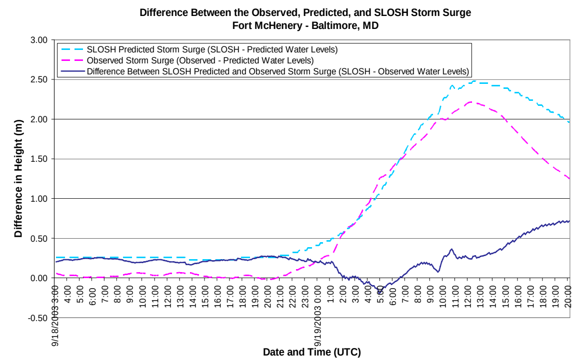

Fig.7 Comparison of storm surge differences for Annapolis, MD during Hurricane Isabel, 18-19 September, 2003.

Southwest of Annapolis in Washington DC, the SLOSH model did a poor job of predicting the timing and the maximum value of the storm surge. The observed water level and surge rose much earlier and receded faster than predicted. Whereas the SLOSH model over predicted the surge by only 0.16 m, it under predicted the timing of the maximum surge by over 5 hours. These observations can be seen in Fig. 8 and Fig. 9 which compare the observed, predicted, and SLOSH predicted water levels and storm surge for Washington, DC.

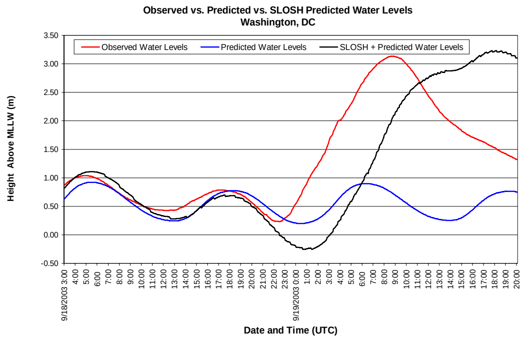

Fig. 8 Comparison of observed and predicted water levels for Washington, DC during Hurricane Isabel, 18-19 September, 2003.

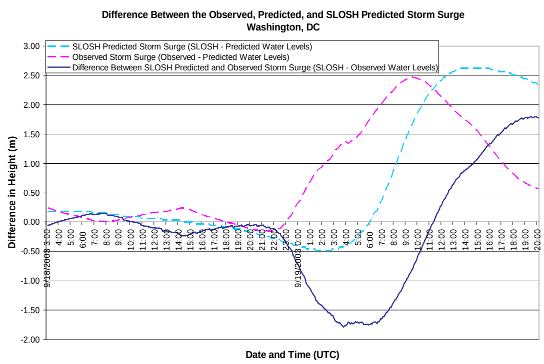

Fig. 9 Comparison of storm surge differences for Washington, DC during Hurricane Isabel, 18-19 September, 2003.

Southeast of Washington and on the eastern shore of the Chesapeake Bay in Cambridge, MD, the SLOSH model accurately predicted the maximum storm surge but was not as accurate with the timing of the surge. While the SLOSH model only under predicted the maximum surge by 0.064 m, the timing of the maximum surge was almost six hours later than the observed value. The model also underestimated the rate at which the water level rose once the surge started to move into the area and overestimated the recession rate of the surge. These observations can be seen in Figure 10 and Figure 11 which compare the observed, predicted, and SLOSH predicted water levels and storm surge for Cambridge.

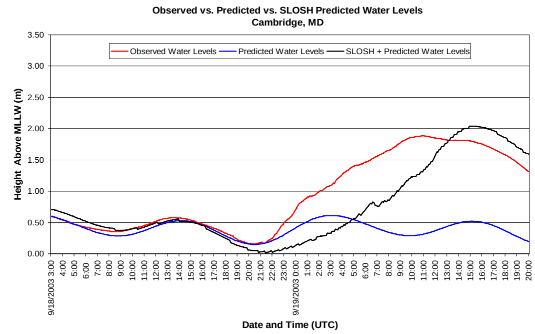

Fig. 10 Comparison of observed and predicted water levels for Cambridge, MD during Hurricane Isabel, 18-19 September, 2003.

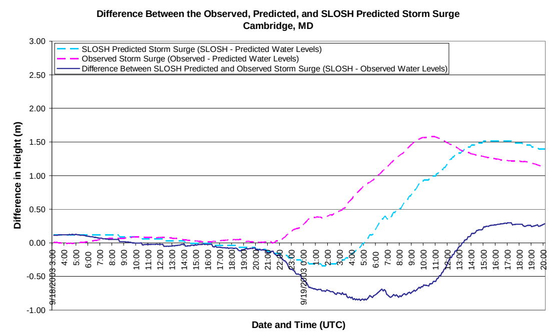

Fig. 11 Comparison of storm surge differences for Cambridge, MD during Hurricane Isabel, 18-19 September, 2003.

South of Cambridge is the Kiptopeke, VA station at the mouth of the Chesapeake, Of the eight stations being considered, the SLOSH predictions for water level and storm surge were the farthest from the observed values at Kiptopeke. The maximum storm surge was grossly overestimated, the timing of the maximum surge was much later than was observed, and the recession rate was much slower than observed. These observations can be seen in Fig.12 and Fig. 13, which compare the observed, predicted, and SLOSH predicted water levels and storm surge for Kiptopeke.

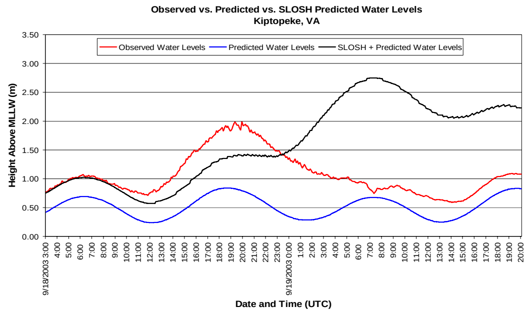

Fig. 12 Comparison of observed and predicted water levels for Kiptopeke, VA during Hurricane Isabel, 18-19 September, 2003.

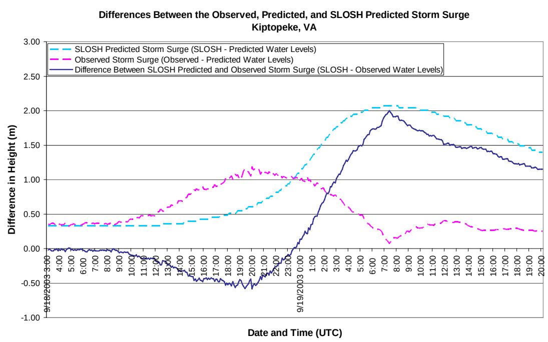

Fig. 13 Comparison of storm surge differences for Kiptopeke, VA during Hurricane Isabel, 18-19 September, 2003.

The final two stations are at the mouth of the Bay: Chesapeake Bay Bridge Tunnel (BBT) and Sewells Point, VA. They are fairly close to each other in distance and, therefore, had very similar SLOSH predicted and observed storm surge values and timing. The SLOSH model over predicted the maximum storm surge but the timing of the surge closely followed the observed surge timing. The observations for Chesapeake BBT can be seen in Fig. 14 and Fig. 15and for Sewells Point in Fig. 16 and Fig. 17. These figures compare the observed, predicted, and SLOSH predicted water levels and storm surge for the two stations.

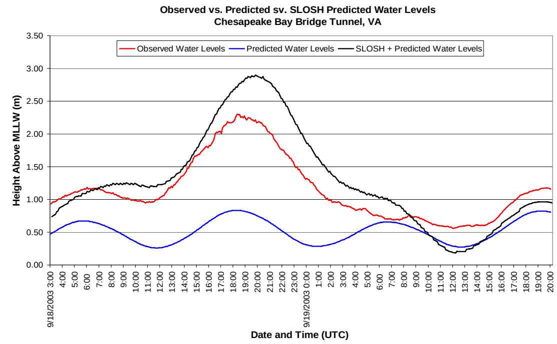

Fig. 14 Comparison of observed and predicted water levels for Chesapeake Bay Bridge Tunnel during Hurricane Isabel, 18-19 September, 2003.

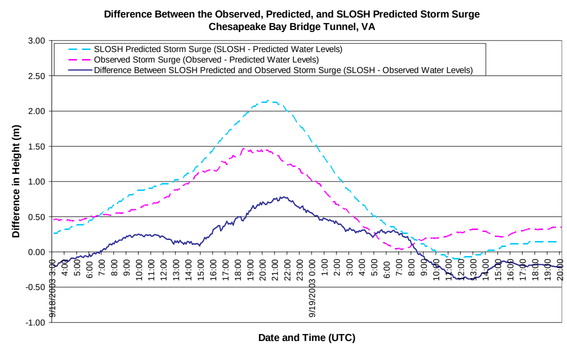

Fig.15 Comparison of storm surge differences for Chesapeake Bay Bridge Tunnel during Hurricane Isabel, 18-19 September, 2003.

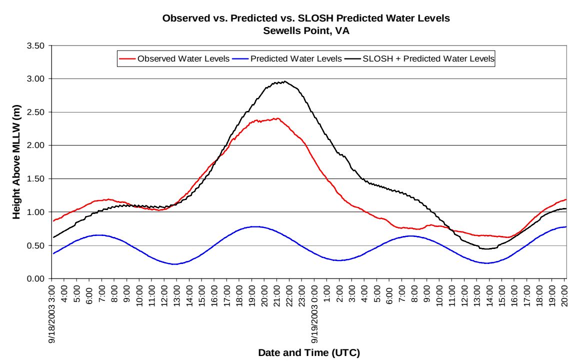

Fig. 16 Comparison of observed and predicted water levels for Sewells Point, VA during Hurricane Isabel, 18-19 September, 2003.

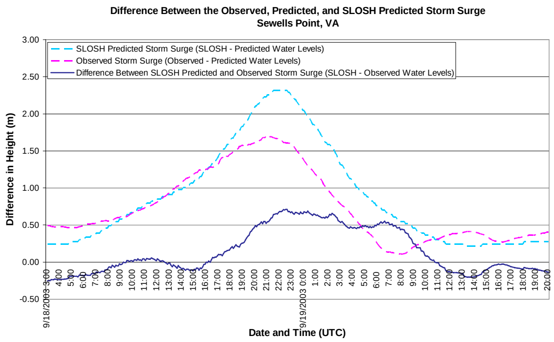

Fig. 17 Comparison of storm surge differences for Sewells Point, VA during Hurricane Isabel, 18-19 September, 2003.

The graphs of the observed storm surge for all eight stations, Fig.18, and the SLOSH Predicted storm surge for all eight stations, Fig. 19, is useful to compare in order to observe overall trends. The five stations in the northern half of the Chesapeake Bay (Chesapeake City, Baltimore, Annapolis, Washington DC, and Cambridge), in general, had higher storm surge values which peaked at a faster rates and at later times than the three southern stations towards the mouth of the Bay (Kiptopeke, Chesapeake BBT, and Sewells Point). The SLOSH model, in general, overestimated the storm surge values for all stations, but particularly for the three southern stations. For the five northern stations, the SLOSH model predicted that the surged water would recede at slower rates than were observed. The Kiptopeke station stands out in the SLOSH predicted storm surge graph as well as the graph of the difference between the predicted and observed storm surge,

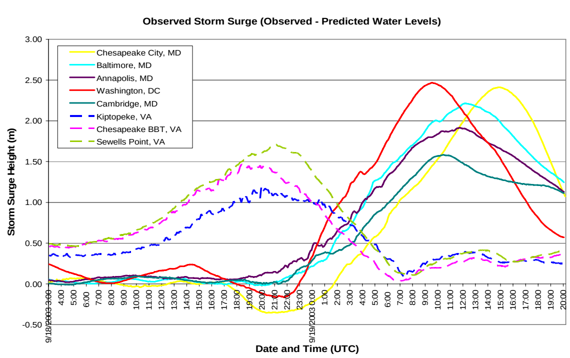

Fig. 18 Comparison of the observed storm surge at each of the eight stations for 18-19 September, 2003 (dotted lines denote three southern stations in the lower Chesapeake Bay).

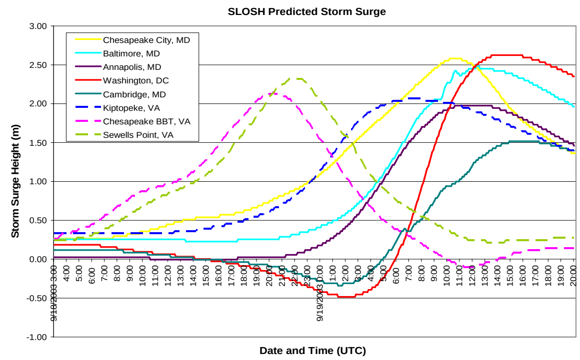

Fig. 19 Comparison of the SLOSH predicted storm surge at each of the eight stations for 18-19 September, 2003 (dotted lines denote three southern stations in the lower Chesapeake Bay).

Fig. 20, as being the station that was least accurately predicted. In general, when the two graphs are compared, it appears as though the observed surge levels at the five upper Bay stations followed a general storm surge trend of a quick rise to a high maximum peak and then a fairly quick recession, and the three lower Bay stations followed a general trend of a slow rise to a lower maximum surge peak and receded more slowly. The SLOSH predicted storm surge graph does not show such a distinct trend. Although the more southern stations generally saw an earlier maximum surge time than the northern stations, a trend in the predicted maximum storm surge values was hard to notice.

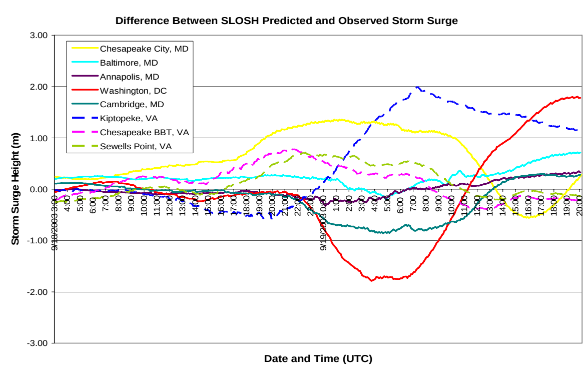

Fig. 20 Comparison of the difference between the SLOSH predicted and observed storm surge at each of the eight stations for 18-19 September, 2003 (dotted lines denote three southern stations in the lower Chesapeake Bay).

4. DISCUSSION

The shape of the Chesapeake Bay, station location, and track which Hurricane Isabel took along with the resultant wind vectors and pressures had the greatest impact on storm surge levels at the eight different stations.

The observed storm surge at the three southern stations at the mouth of the Bay (Kiptopeke, Chesapeake BBT and Sewells Point), followed a pattern of an earlier, slower rise to a lower maximum surge peak and a slower recession than the northern stations. The storm surge that occurred at these stations was more a result of the immediate and direct impact Isabel's winds and pressure had on the station, and less of the "sloshing" and pushing of built up water along the Bay, as was the case in the northern stations.

The average time of the maximum storm surge at Chesapeake BBT, Sewells Point, and Kiptopeke was around 2030 UTC on 18 September. At this time Hurricane Isabel was over halfway through North Carolina, still southwest of the three stations. As seen in

Fig. 21, the winds were highest (over 35 m/s) and the pressure was lowest (almost 990 hPa) between 2000 and 2200 EDT on the 18th, which coincides with the maximum storm surge timing.

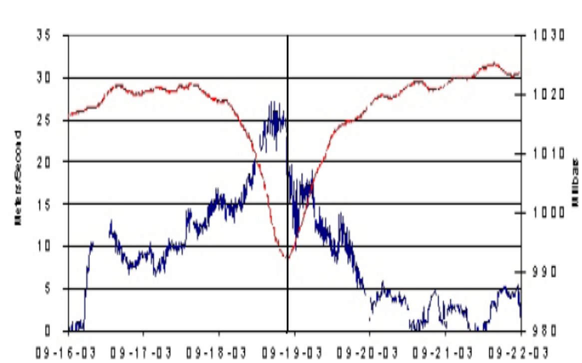

Fig. 21 Chesapeake Bay Bridge Tunnel wind speed in m/s (lower curve), and barometric pressure in millibars (upper curve) during Hurricane Isabel, 16-22 September, 2003 (adapted from Hovis and others, 2004).

The wind vectors for the area (see Fig. 22) show that not only was the wind most intense at the time of the maximum storm surge, but it was blowing in a direction that pushed the sea water up against the coastline. This was especially true at Sewells Point, which saw the largest storm surge height of the three southern stations. As Isabel continued to track northwest and pass the stations in the early hours of 19 September, taking them out of the more intense eastern side of the hurricane, the winds lost some strength and changed directions so that they were then blowing straight up the Bay.

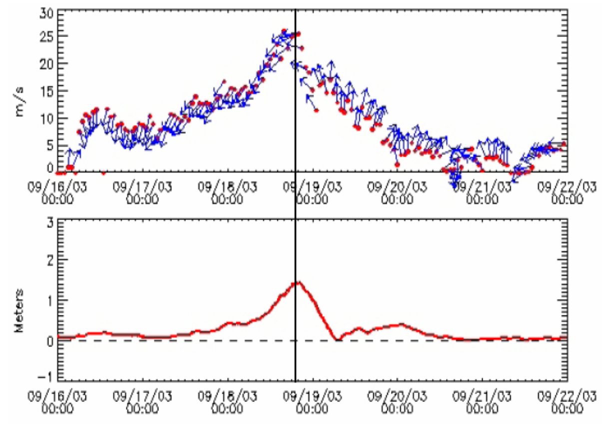

Fig. 22 Hourly wind vectors (m/s) and storm surge (m) at Chesapeake BBT for Hurricane Isabel, 16-22 September, 2003 (adapted from Hovis and others, 2004).

These constant southern winds served as a pushing force to drive the surge north along the Chesapeake.

Of the three lower-Bay stations, Kiptopeke was least accurately modeled by the SLOSH program, particularly with respect to the timing. The location of Kiptopeke on the very tip of the Maryland eastern shore, right at the mouth of the Bay, appeared to be a difficult location to model with the SLOSH program. Being exposed to the Bay on one side and the Atlantic Ocean on the other, it was difficult for the SLOSH model to predict how the surge would react at that location. The station is more exposed and vulnerable to the winds because it is a on a narrow point of land and not on a solid coastline like the BBT or Sewells Point. Whereas the maximum surge values coincided with the maximum intensity winds for BBT and Sewells Point, Kiptopeke recorded its maximum storm surge when the winds were still building and had not yet reached their peak intensity, as see in Fig. 23.

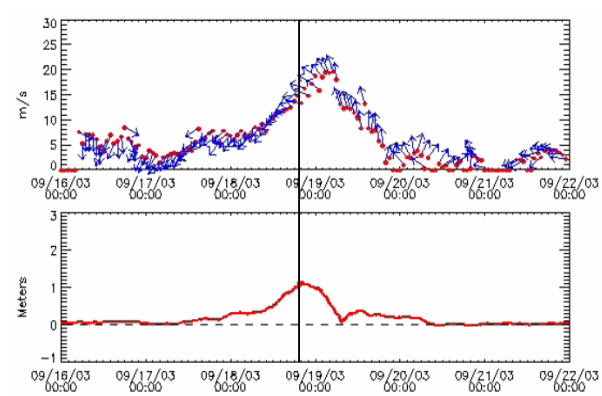

Fig. 23 Same as Fig. 22 except at Kiptopeke, VA.

Also, the winds were much more variable at Kiptopeke than the other two stations, changing direction by almost 180° from 18-19 September. The SLOSH model predicted that Kiptopeke would see its maximum surge at 0724 UTC on 19 September, which is when the station saw some of its most intense winds, so perhaps the SLOSH program depended more on the intensity of the winds rather than their direction for its predictions. However, for Kiptopeke, because of its unique location on a point, using the wind intensity to time maximum surge height was not the best technique.

As Hurricane Isabel continued to move northwest over Virginia, West Virginia, and Maryland, it lost intensity, sped up, and moved farther west of the Chesapeake Bay. However, because the stations continued to remain in the stronger right-half of the storm and the winds continued to blow towards the north, the surge of water which built up in the mouth of the Bay was pushed up the Chesapeake towards the five northern stations (Chesapeake City, Baltimore, Annapolis, Washington DC, and Cambridge), growing in height as it "sloshed" north.

The observed storm surge at the five upper Bay stations followed a general surge trend of a quicker rise to a higher maximum peak and then a quicker recession than the three lower Bay stations. These observations make sense because the storm surge resulted, not from the hurricane passing and having a direct impact on the stations like it did for the southern three stations, but from the surge of water pushed up the Bay hours after Isabel had passed. So, the water moved into the northern areas more quickly; peaked at higher values because the water gathered and built upon itself as it was forced up the Bay; and recessed quicker because once it hit the northern-most point of the Bay, it, in a sense, bounced off and sloshed back out of the Bay, just as water in a bathtub does when it is pushed towards one end.

The location of Hurricane Isabel at the average time of maximum surge for the upper five stations, 1230 UTC, was northern Pennsylvania. This location illustrates that the forcing of surge up the Bay was causing the water level rise, not the intense winds and incredibly low pressures from Isabel, since it was hundreds of miles from the Bay at the time. Whereas the time of maximum surge coincided closely with the time of maximum wind velocities in the southern Bay, the maximum surge time for the northern Bay occurred several hours after the wind velocities peaked, as seen in the wind vectors graphs for Cambridge and Tolchester, Fig. 24 and Fig.25. Although the time of peak surge did not coincide with peak wind velocities, the times did coincide with the northerly blowing winds, illustrating the importance of wind direction over wind speed for the peak surge timing in the northern Bay.

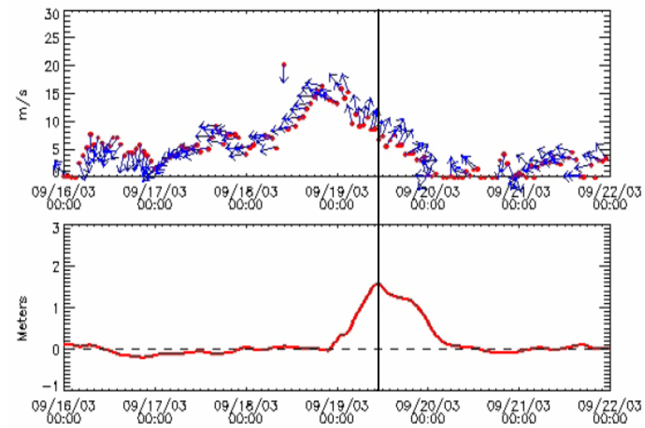

Fig. 24 Same as Fig. 22 except at Cambridge, MD.

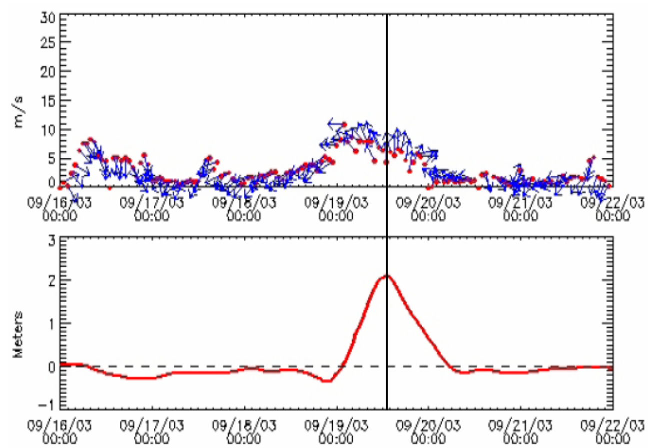

Fig. 25 Same as Fig. 22 except at Tolchester, MD.

The SLOSH model predictions for the Annapolis and Baltimore stations were the most accurate of the five stations in the upper Chesapeake Bay. Their location on the coastline of the main body of the Bay and not on a point or up a river like Kiptopeke or Washington DC made them easier to model. The prediction for Annapolis, the most accurate of all eight stations, was exact with respect to timing and was only off of the maximum storm surge height by 0.064 m.

The SLOSH model predictions for Washington DC and Chesapeake City were two of the least accurate station predictions in the upper Chesapeake Bay, particularly with respect to timing. Washington DC's location at the very tip of the Potomac River made it difficult for the SLOSH program to predict its surge values. It would be very difficult to create a SLOSH model which accurately model storm surge in rivers and bays and oceans because each differently-sized body of water behaves uniquely. The SLOSH program was accurate with respect to the maximum storm surge value, but it was over five hours late with its prediction of the time of maximum surge. While it is obvious that the SLOSH program successfully predicted that the highest storm surge would be found up the river in DC, it was quite unsuccessful in predicting the timing, considering the surge was already almost two feet high at the time when the model predicted the water level would just start to rise. DC residents would have been unprepared it they had used this SLOSH model output to plan for the storm.

Just as the location of Washington DC decreased the SLOSH prediction accuracy for that station, the same was true for Chesapeake City. Chesapeake City is located at the northern-most tip of the Bay, making it the "wall of the bathtub" off which the water sloshes.. The Bay narrows significantly as you move north, and by the time you reach Chesapeake City, you are almost in an inlet. This intricate location caused problems for the SLOSH model. Chesapeake City had the latest maximum surge peak time and the second highest maximum surge value next to DC, which makes sense because the water traveled the farthest distance from the mouth to get there. The timing of the SLOSH prediction for Chesapeake City was very in error it as was Washington DC. However, unlike for DC, it predicted the surge would reach its maximum over four hours earlier than it actually did, which is a safer way to err - on the side of caution. Chesapeake City residents would have been prepared earlier than needed if they used the SLOSH prediction because they would have expected the surge to arrive quicker than it did.

5. CONCLUSION

With the exception of a few stations in difficult-to-model locations, the SLOSH predictions for the locations near the Chesapeake Bay area during Hurricane Isabel were reasonably accurate. At the three stations in the lower Bay, the model predictions reflected the fact that the Isabel came closest to these stations, creating the highest wind speeds and lowest pressures seen at any of the more northern stations. The maximum surge values and timing coincided with these peak wind speeds and low pressures everywhere except Kiptopeke, which, because of its location on a narrow point at the mouth, the SLOSH model was unable to accurately estimate how or when the water levels would rise.

At the five stations in the upper Bay, the model predictions reflected the absence of a direct impact from Hurricane Isabel and the presence of surge being forced up the Bay by the still northerly blowing winds at the southern stations. The residual winds left from Isabel's passing were pointed in a perfectly northern direction so as to build up a "front" of water which swept up the Chesapeake the afternoon and evening of 19 September, raising the water levels in all the coastal communities and communities along any rivers and tributaries. The SLOSH model ran into problems predicting the surge timing in Washington DC because of its location at the tip of the Potomac and in Chesapeake City, because of its location at the very narrow northern end of the Bay

The least accurate SLOSH model predictions were the ones for the stations located up rivers or on points of land or in small inlets, so further research into improving modeling of those areas would be useful. A study using one of the other surge modeling techniques which are currently used in other areas, inputting Isabel's track and intensity information, and comparing the results would provide ways in which the program could be bettered. A study could be done in which Hurricane Isabel's track information is used but the intensity and size of the storm were increased and decreased. The SLOSH prediction outputs could then be compared, noting how the changes affected the different forecasts.

A model is only as good as the parameters entered in to it, so as long as hurricane forecasting continues to improve and researchers continue to make strides in ocean modeling, SLOSH model programs will become more and more accurate.

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