# THE ROLE OF THE SLOSH MODEL IN NATIONAL WEATHER SERVICE STORM SURGE FORECASTING

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## *Abstract*

The storm surge model, Sea, Lake, and Overland Surges from Hurricanes (SLOSH), is used by the National Weather Service (NWS) in producing storm surge guidance in several ways. SLOSH is run by the National Hurricane Center (NHC) to forecast storm surge in real-time when a hurricane is threatening. The model is applied to 38 specific coastal areas, called basins, along the Atlantic and Gulf of Mexico coasts of the U.S.; Oahu, Hawaii; Puerto Rico; and the Virgin Islands. SLOSH is also used to create simulation studies to assist in the "hazards analysis" portion of hurricane evacuation planning by the Federal Emergency Management Administration (FEMA), the U.S. Army Corps of Engineers, and state and local emergency managers. Two composite products, Maximum Envelopes of Water (MEOW) and Maximum of the MEOWs (MOM), are created to provide manageable datasets for planning. The Probabilistic Storm Surge model (P-surge) overcomes the limitations of a single deterministic SLOSH storm surge forecast by being comprised of an ensemble of SLOSH forecasts. The members of the ensemble vary in speed, direction, intensity, and size, based on NHC's forecast and past errors associated with NHC's forecasts. P-surge is prompted to run when NHC issues a hurricane watch for the Atlantic or Gulf coasts. The Extratropical storm surge (ET surge) model uses SLOSH to forecast storm surge from extratropcial cyclones. The ET surge model uses surface wind and pressures that are generated by NWS's Global Forecast System (GFS) model as driving forces.

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## 1. Introduction

Storm surge caused by hurricanes is one of the most devastating natural phenomena affecting the coastal communities of the United States and of some other countries. Almost every year, one or more hurricanes slam into the Gulf of Mexico or Atlantic coasts. Much of the devastation to structures and ecosystems is caused by the wind-driven surge of water. The damage is exacerbated if the major surge occurs at high tide. The high water and wave action may level entire communities, as occurred with Hurricane Katrina in 2005 (Rosenfeld 2005; NWS 2006). Obviously, the accurate prediction of such flooding is of great benefit to the public, and the potential flooding from different intensities, tracks, and sizes of storms is very useful in long range evacuation and land use planning, the setting of insurance rates, etc.

The Meteorological Development Laboratory (MDL) of the National Weather Service (NWS) has been providing guidance forecasts for storm surges for over three decades. The NWS storm surge model, named SLOSH for Sea, Lake, and Overland Surges from Hurricanes, evolved from earlier models developed in the late 1960's and early 1970's (e.g., Jelesnianski 1972). Chester Jelesnianski realized the potential benefit of such a model, and the culmination of his and his small team's efforts was published in a comprehensive National Oceanographic and Atmospheric Administration (NOAA) Technical Report in 1992 (Jelesnianski et al. 1992, to be called CJ hereafter).[1] According to CJ, "Output from the SLOSH model was originally intended to aid forecasters at the National Weather Services's (NWS) National Hurricane Center (NHC) in preparing their forecast bulletins. More recently, the model has been used to delineate coastal areas susceptible to hurricane storm surge flooding."

It soon became apparent during development of the model that the major errors in forecasting storm surge were in the storm parameters–track, size, and intensity–rather than in the error of the model itself. Communities need many hours, even days, to prepare for a hurricane and/or to evacuate. Although NHC's forecasts are used as input parameters for the SLOSH model for real time forecasting, the model has also been used to predict *potential* flooding for the U. S. Gulf and East coasts for different combinations of storm track, size, and intensity. This output has proven to be very useful at NHC and at NWS Weather Forecast Offices (WFO), and is the basis for comprehensive hurricane evacuation planning studies conducted by the Federal Emergency Management Administration (FEMA), the U.S. Army Corps of Engineers, and state and local emergency managers.

SLOSH is also being used in a probabilistic framework, and more recently to provide data to establish design criteria for structures. The same basic model, called the ET surge model, also forms the basis of extratropical guidance forecasts. These forecasts are useful for forecasters in areas where major extratropical storms are a threat.

## 2. The Model

CJ took a very pragmatic approach; his model had to be used operationally, so the various necessary inputs had to either be available, assumed, or parameterized. Of prime importance, of course, is the wind to drive the surge, so a "wind model" was needed. Such winds could come from a large-scale dynamic atmospheric model, but they would represent that model's forecast of the hurricane, not the NHC's. So, CJ chose to use a simplified parametric wind model that could be driven with forecasts routinely made by NHC. The input parameters for the wind model are storm track, radius of maximum winds, and the pressure difference between the storm's central pressure and the ambient (or peripheral) pressure. Storm track and intensity are obtained from the official NHC advisory. The initial radius of maximum winds is estimated from observations available, including aircraft, ships, buoys, satellites, and radar. The initial pressure difference is derived from the wind information provided in the official NHC advisory. Forecast pressure differences and radii of maximum winds are estimated by NHC's storm surge specialists. The resulting model wind field produces surface stresses, which act as driving forces on the water beneath the hurricane. Houston et al. (1999) compared wind observations analyzed by the Hurricane Research Division (HRD) and found, "The SLOSH wind fields were very similar to the HRD observation-based wind fields in the region of highest winds for six out of seven of the cases studied."

The transport equations used in SLOSH were derived by Platzman (1963) and modified with a bottom slip coefficient by Jelesnianski (1967). The equations are integrated from the sea floor to the surface. The advection terms in the hydrodynamic equations used by SLOSH are ignored, and the Coriolis term is generally omitted for lakes and inland inundation but is retained for large amplitude surges or if inundation covers a large area. As a result of the difficulty of forecasting winds surrounding a hurricane, a constant drag coefficient in air and a constant eddy stress coefficient in the water are used.

For best results, the finite difference solution of the equations of motion on a grid used for SLOSH requires

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[1] On a personal note, the lead author remembers Chester punching and feeding cards into the IBM 1620 in the annex to the Weather Bureau Headquarters at 24th and M Streets in Washington D. C. in the 1960's. I remember thinking, "He'll never make that work." How wrong I was.

fine resolution near the coastline, and especially where the water may be funneled into a bay or estuary. The grid also needs to extend some distance away from the coast, and if the grid resolution is the same everywhere, enormous amounts of computer time would be required. This would have been prohibitive when the model was being developed. Even with the computers of today, it is important that the resolution need not be the same over the whole grid. The model is applied to specific coastal areas, called basins. Depending on the basin, either a polar or elliptical/hyperbolic grid type is chosen. CJ chose the grid spacing to balance the requirement for fine resolution near the area of interest with the computational time requirement of having fewer cells. The result was a grid which was fine near the area of interest, and monotonically increased toward the open ocean. This allows for high resolution in bays and near coastlines and a decreasing resolution in the deepwater where detail is not as important. For example, the grid used for New Orleans is shown in Fig. 1.

To model a specific area of vulnerable coastline, SLOSH requires accurate bathymetric and topographic data. Topographic data are obtained from the U.S. Geological Survey (USGS) and are augmented with Light Detection and Ranging (LiDAR) elevations when available; bathymetric data are obtained from NOAA's National Geophysical Data Center (NGDC). These detailed data must be at the same datum plane.[2] The data are then averaged to obtain one value per grid cell. Next, sub-grid scale features such as barriers (representing smaller than a grid cell width) are added. Finally, surface types are added which inhibit the strength of the surface winds based on the average type of terrain in the cell.

The routing of the water over land is modeled by the grid of boxes or cells. If water floods into a cell, it then has the potential of filling an adjoining cell. In some sense, this is a gross simplification, because the cells are of the order of kilometers in size, and of course the actual land is much more variable than can be represented by a grid of almost any contemplated size. However, special treatment is given to major barriers and narrow, by grid

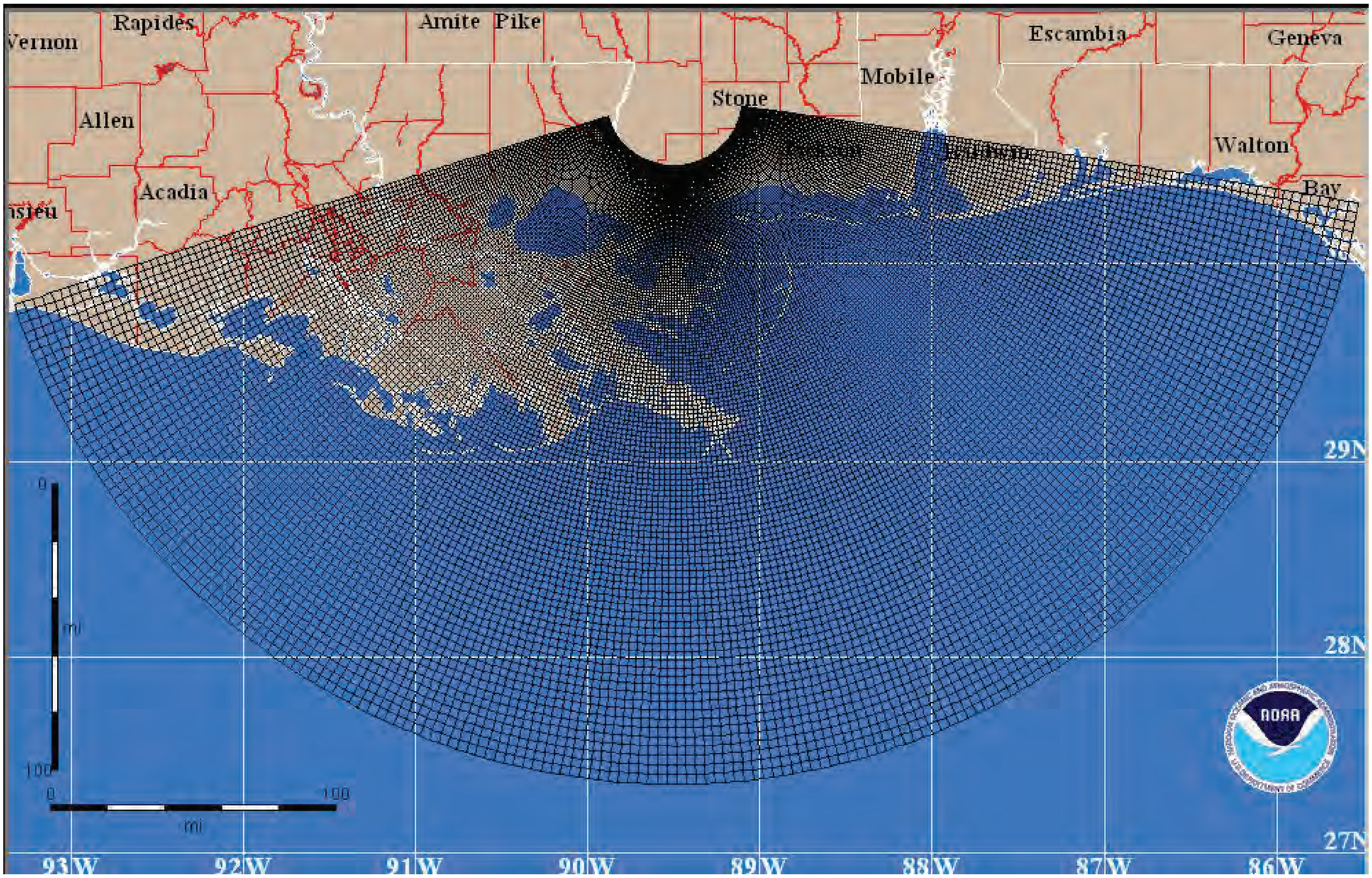

Fig. 1. The polar coordinate system used for the New Orleans basin.

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[2] The SLOSH model references all elevations, depths, and surge heights to National Geodetic Vertical Datum 1929 (NGVD-29). However, as basins are being updated, North American Vertical Datum 1988 (NAVD-88) is being used.

size standards, cuts (or gaps), such as canals and rivers. Modeling with good results very near the land/air/sea interfaces is very difficult, as atmospheric modelers are well aware.

Currently there are 38 SLOSH basins, shown in Fig. 2, which encompass the Atlantic and Gulf of Mexico coasts of the United States; Oahu, Hawaii; Puerto Rico; and the Virgin Islands. The model has also been applied to parts of Guam, China, and India. Since their inception, most basins have been updated, several times in some cases, with refined and newer bathymetric and topographic data (e.g., to depict changes in levees) and to increase resolution of the grids.

## 3. Model Accuracy

Establishing a surge model's accuracy is not without difficulty. First, the number of situations in which there is a hurricane and the driving parameters are available is severely limited. Even in those instances, the water measurements are very sparse and tend to be clustered in areas of higher water, so low or moderate flooding is not usually measured adequately. Also, the available high water mark measurements are prone to various errors and uncertainties. SLOSH does not predict tides or waves but water marks are many times affected by both.[3] High water marks often vary by 20 percent for two locations that are less than a mile apart (Jelesnianski et al. 1984). Forecasters in the NWS preferred to not include tides in the model so that they could add the tide, depending on their assessment of when the hurricane was likely to make landfall. Additionally, the model does not include flooding by rainfall or fresh water river flow; in general, storm surge peaks well before riverine flooding does.

CJ found that SLOSH was correct to within about 20 percent, when the driving parameters were estimated as well as possible (Fig. 3). For such determination, the "best track" was plotted according to known data, along with the size and intensity for 13 hurricanes in nine different locations. Of course, these parameters are not necessarily known to that accuracy before the fact. Recent work has supported this error estimate (Fig. 4). For surge forecasts over 12 ft, Jarvinen and Lawrence (1985) found that model errors were less than 2 ft 79 percent of the time when best tracks were used. Even so, there are cases when model error is considerably greater than this.

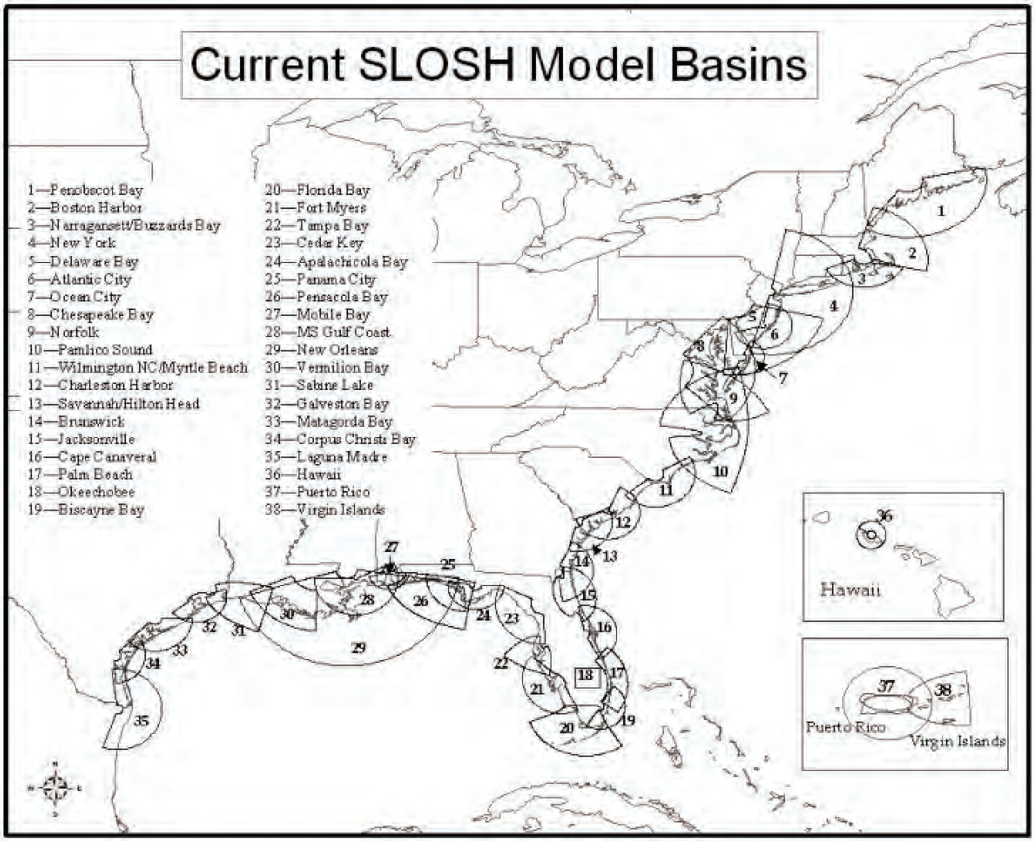

**Fig. 2.** Map showing the 38 SLOSH basins which encompass the Atlantic and Gulf of Mexico coasts of the United States; Puerto Rico; Oahu, Hawaii; and the Virgin Islands.

## 4. SLOSH in Real-Time Forecasting

When a hurricane is threatening the coast, NHC runs SLOSH with parameters provided by hurricane forecasters. As stated previously, the specific parameters needed are (1) storm position as a function of time, (2) the radius of maximum winds, and (3) the pressure difference between the central pressure and the peripheral pressure. The forecast track is used to determine which basin or basins for which SLOSH will be run. However, due to significant average track and intensity errors, the storm has to be within a day or two of forecast landfall for there to be high confidence in the SLOSH output. Nevertheless, it provides potentially useful

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[3] Because the timing of peak storm surge is not predictable with high accuracy, forecasters have preferred to use SLOSH output without tides and to add a tidal component themselves. Waves are very difficult to model accurately and are not included in SLOSH. However, there is some work contemplated whereby a wave component would be added depending on accuracy of results.

guidance to the forecasters at NHC, as well as emergency managers and other government officials in the affected areas.

Products from these operational runs are made available to the forecast and emergency management communities by means of a file transfer protocol (ftp) site. These products include the maximum the forecast storm surge attained in every grid cell [in Geographic Information System (GIS) format] and an animation of the storm surge. The SLOSH runs are then used by NHC in their advisories and by the WFOs in greater detail through their hurricane local statements and briefings to emergency managers and the media. As hurricane Katrina approached land, operational SLOSH runs prompted NHC to

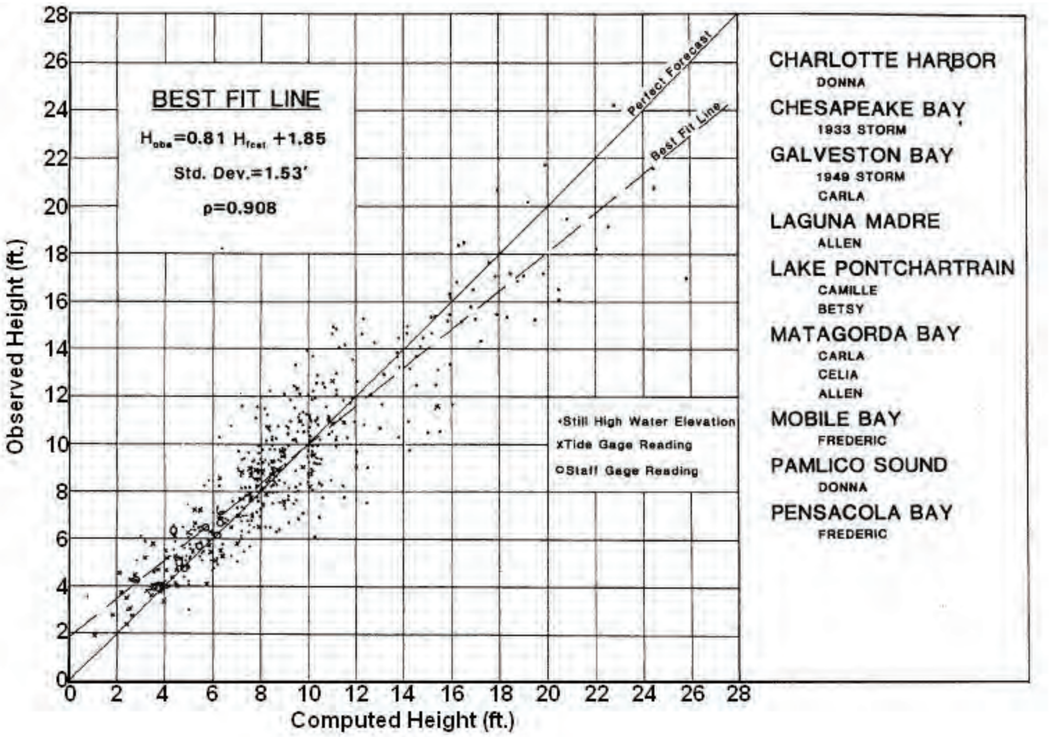

**Fig. 3.** Observed surge heights versus surge heights forecast by the SLOSH model for thirteen storms in nine basins. A total of 570 tide gage, staff gage, and high water mark observations are shown with the corresponding SLOSH forecast. Generally, the model is within ± 20% for significant surge heights (from Jelesnianski et al. 1992).

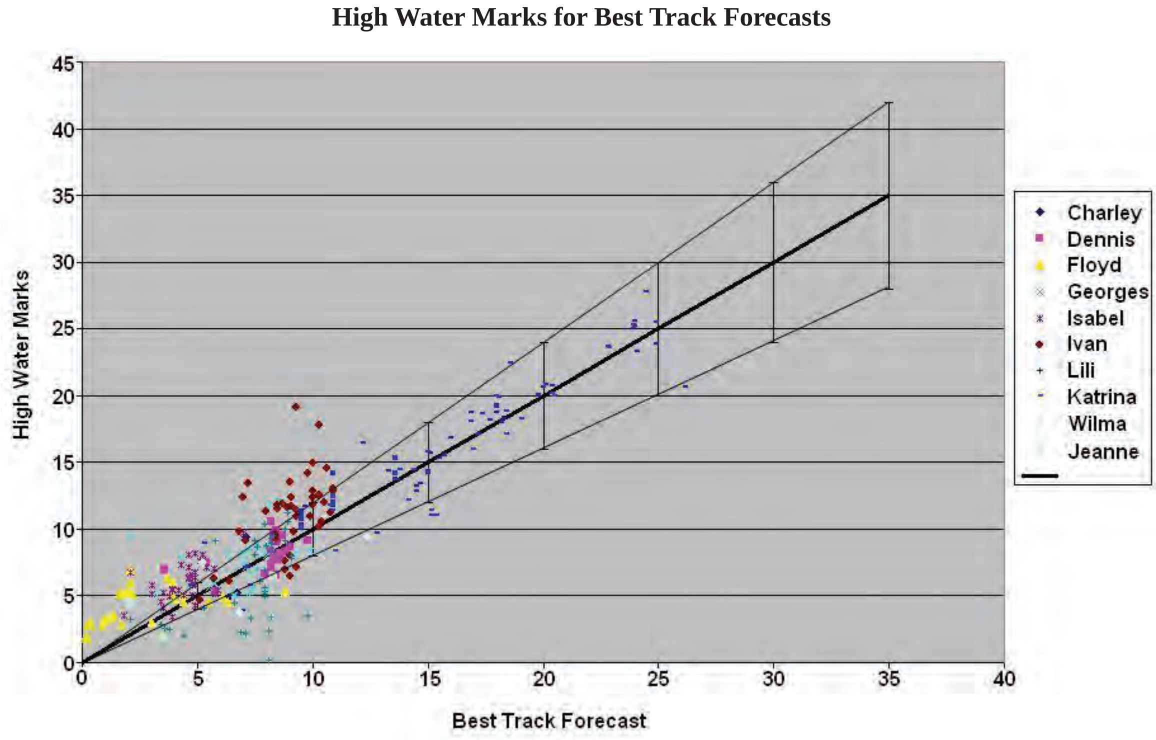

**Fig. 4.** High-water marks versus the surge heights forecast by SLOSH for 10 storms. The perfect forecast line is shown along with 20% error lines. All surge forecasts over 12 ft are for Katrina and verified within a few percent. There is considerable scatter for forecasts of lower surge.

include the statement beginning with Advisory 24 issued approximately 16 hours before landfall, that surges "... OF 18 TO 22 FEET ABOVE NORMAL TIDE LEVELS...LOCALLY AS HIGH AS 28 FEET ... CAN BE EXPECTED NEAR AND TO THE EAST OF WHERE THE CENTER MAKES LANDFALL. SOME LEVEES IN THE GREATER NEW ORLEANS AREA COULD BE OVERTOPPED." Surges of 26 to 28 ft occurred (NWS 2006). A hindcast run of SLOSH made with observed hurricane parameters showed surges as high as 28 ft in that area. These SLOSH forecasts likely aided the excellent NWS forecasting performance for Katrina (NWS 2006).[4] Post Katrina runs with best track input showed "more than 70% of the SLOSH calculated values were within 1.5 ft of observations; the correlation coefficient was 0.94."[5]

## 5. SLOSH Simulation Runs

The SLOSH model is used by the NWS to create simulation studies to assist in the "hazards analysis" portion of hurricane evacuation planning by FEMA, the U.S. Army Corps of Engineers, and state and local emergency managers. Thousands of hurricanes with various combinations of categories [according to the Saffir-Simpson scale (Simpson and Saffir 2007)], forward speeds, track directions, and landfall locations are simulated to compute storm surge for each basin. Two composite products, Maximum Envelope of Water (MEOW) and Maximum of the MEOWs (MOM), are created in order to provide a manageable dataset for hurricane evacuation planners to access and display; these are also used in real-time operations to partially overcome the difficulty with using a single deterministic run.

An envelope refers to the maximum height of the surge at every grid cell in the SLOSH basin for a hypothetical storm. SLOSH is run for many hypothetical hurricanes through a basin with parallel tracks and otherwise the same input parameters to create envelopes. A MEOW is formed from the composite of these SLOSH model runs. It is the set of the highest surge values at each grid location for a given storm category, forward speed, and direction of motion, regardless of which individual storm simulation produced the value. NHC generates one MEOW for each storm category, storm direction, forward speed, and tide level. An example of a MEOW is shown in Fig. 5. This product, then, displays the potential flooding for a hurricane of a given category, tide level, and general track direction and speed. Because forecasters are unable to forecast the exact location of landfall, the MEOWs are relied on to indicate potential flooding. Estimates of storm surge that are included in NHC tropical cyclone advisories and WFO hurricane local statements are based partly on the SLOSH MEOWs.

A MOM is a composite of the maximum storm surge heights for all simulated hurricanes of a given category. There are typically five MOMs per basin (one per storm category), as results for forward speed, direction, and landfall location are aggregated; see Fig. 6 for an example. Thus, the MOM depicts the potential flooding for a given hurricane category, regardless of landfall approach direction and speed. This product can be used by evacuation planners to designate evacuation routes and emergency managers to make early decisions. MOMs and MEOWs are created with the best topographic and bathymetric data available, including levee heights and waterways.

## 6. SLOSH for Design Criteria

Design criteria are needed for structures that consider the influence of factors associated with hurricanes, such as wind, surge, and waves. The National Institute of Standards and Technology (NIST) and NOAA are collaborating to develop a methodology for dealing with this issue. The methodology involves the selection of a stochastic set of hurricane storm tracks affecting the region of interest, the hydrodynamic simulation of the time histories of wind speed and surge, the generation of probabilistic information on joint wind speed and surge, and risk-consistent structural design methods. NOAA's Hurricane Research Division (HRD) has simulated hurricanes over a period of 55,000 years that would affect Florida (Powell et al. 2005), and MDL has applied SLOSH to those hurricanes. These data were processed by NIST to develop a procedure for developing design criteria as a function of wind and surge (NIST 2007). This process could be used to develop design criteria for all coastal areas.

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[4] Quoted from the Service Assessment (NWS 2006), " 'The Mobile office used IM (Instant Messenger) to get the SLOSH out to the TV stations. I think that saved a lot of lives. They do a tremendous job. I can't say enough good things about them'–David Glenn, WPMI-TV NBC 15, Mobile, AL."

Quoted from the same publication, " 'The forecast for Katrina was outstanding and very accurate. We moved heavy equipment out of the risk area, and evacuated people based on the Weather Service forecasts. The Weather Service has been proactive with the Southeast Louisiana Hurricane Task Force.'– Jesse St. Amant, Director, Emergency Management and President of the Southeast Louisiana Hurricane Task Force, Plaquemines Parish, LA."

[5] Private communication from Dr. Stephen Baig, from a draft National Hurricane Center document.

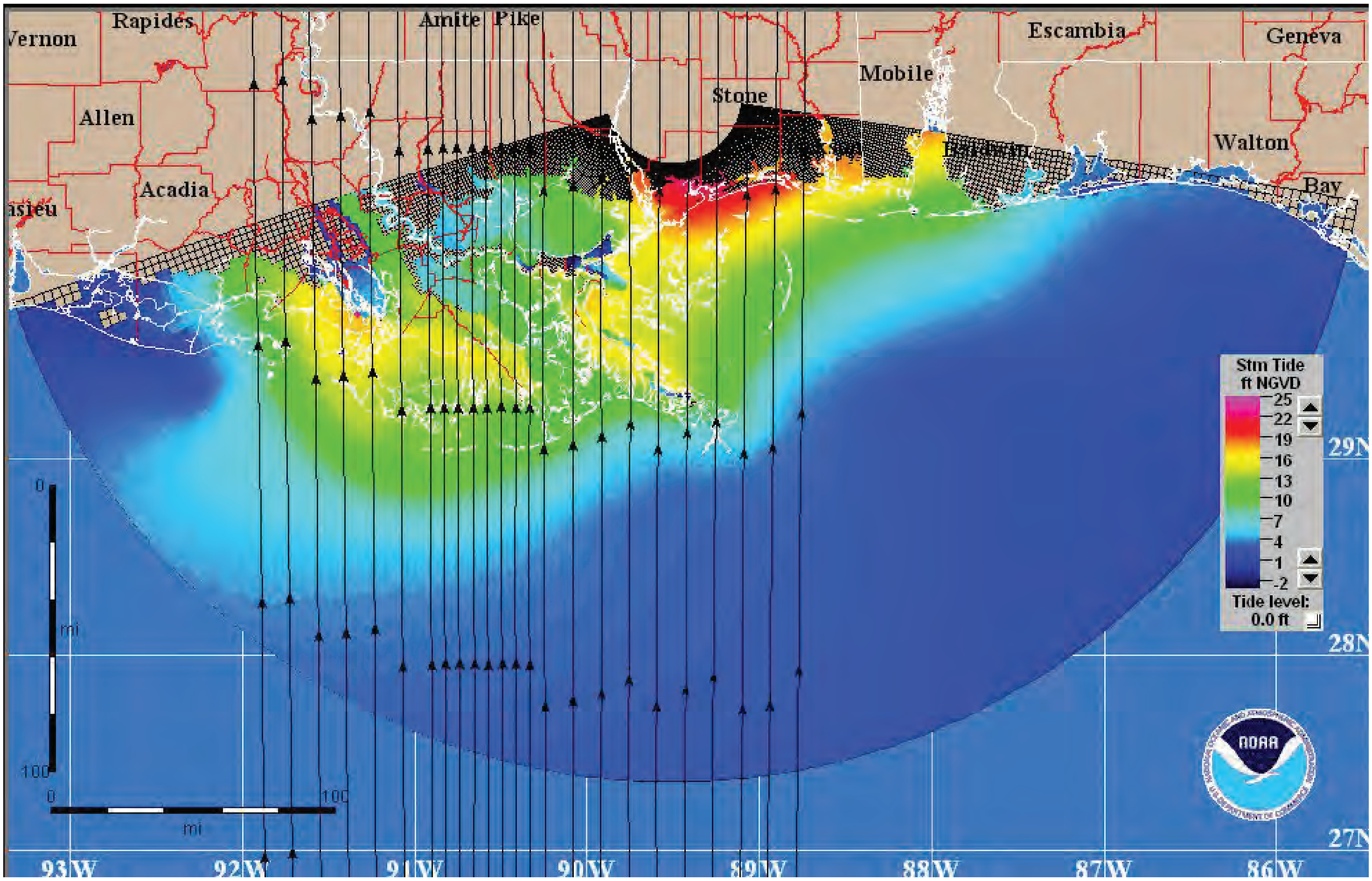

**Fig. 5**. A sample Maximum Envelope of Water (MEOW) forecast for a Category 4 hurricane in the New Orleans basin at mean tide moving northward at 15 miles per hour.

## 7. Probabilistic Storm Surge Forecasts

The track, intensity, and size of a tropical cyclone are not always forecast accurately. The NHC forecast landfall location, for example, can be in error by tens of miles even during the final 12 to 24 hours before the center reaches the coast. These limitations can make the single, deterministic SLOSH surge forecasts incorrect. To help overcome these limitations by quantifying them, probabilistic storm surge (P-surge) forecasts are being produced. This is in accordance with the National Research Council (NRC) report "Completing the Forecast" encouraging probabilistic products (NRC 2006). Instead of forecasting storm surge from only a single SLOSH run, an ensemble of SLOSH forecasts is made, with each member based on NHC's forecast and on past errors associated with NHC's forecasts. The input parameters needed are the same as those needed for a single run, along with knowledge of the past errors. The average along- and across-track, and maximum wind speed (or intensity) errors of NHC's predictions over the past few years are either known or can be inferred. Combining the average errors with an assumption of a normal distribution, we can establish along-track, across-track, and maximum wind speed error distributions. Since the radius of maximum winds and the forecast pressure are not in the NHC forecast, we use the SLOSH parametric wind model and assume the pressure is constant, to estimate a radius of maximum winds error distribution. For each of the along-track, maximum wind speed, and radius of maximum winds parameters, we choose three representative storms from the error distributions by sampling the 0.15, 0.5 and 0.85 sigma values, thus creating 27 storms. The cross track variation of the storms is modeled in more detail and is a function of the forecast radius of maximum winds 48 hours before forecast landfall. Each of the combinations is used for a SLOSH model run; this may result in several thousand simulated storms for a particular basin. For each cell in every SLOSH run, if the water level exceeds a specified height, a weight determined from the likelihood of that specific combination of storm parameters is summed. The sum of the weights divided by the number of ensembles gives the probability of exceeding the specific height for that basin, storm, and cell. For each basin, every hurricane in the recent past is simulated with a distribution of

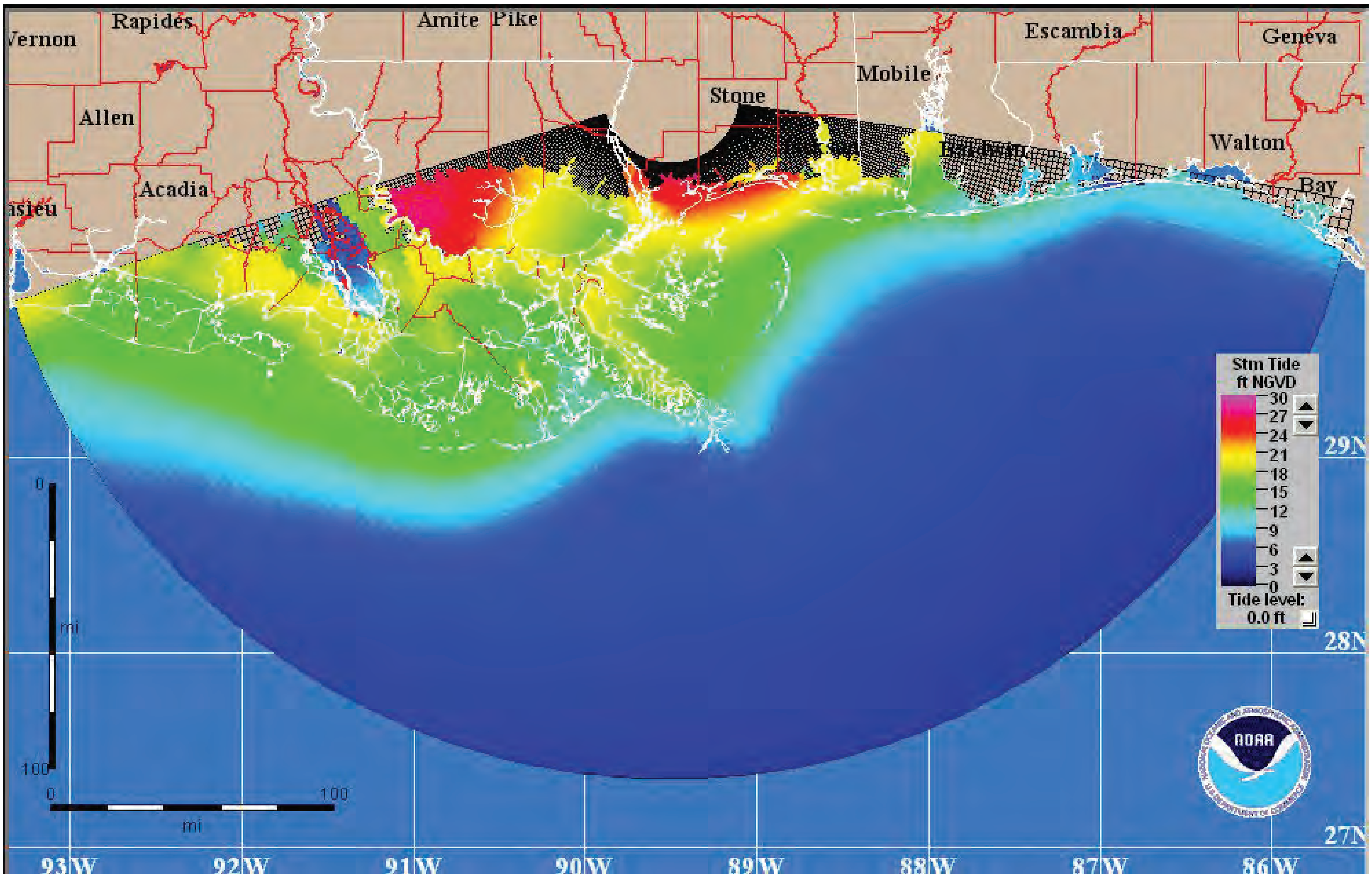

**Fig. 6.** A sample forecast of Maximum of the MEOWs (MOM) in the New Orleans basin for a Category 4 storm at mean tide level.

runs. Finally, the results for all hurricanes and all basins are averaged, and the resulting relative frequencies are matched with observed surge heights for verification purposes.

The P-surge model ran in an experimental mode during the 2007 hurricane season and was made operational in 2008; it is prompted to run when NHC has issued a hurricane watch or warning (roughly 48 hours before landfall) for the Atlantic or Gulf coasts. The operational product, the probability of storm surge greater than 5 feet, is available to NHC and WFO forecasters. NHC is providing images of the operational P-surge on their web site (http://www.nhc.noaa.gov). Meanwhile WFOs are experimenting with the combined use of these data with SLOSH real-time runs (when available) to make threat assessments and potential impact graphics products available through their websites (see Sharp et al. 2008). In addition, the probabilities of storm surge exceeding 2 through 10 feet at increments of one foot are also being created but are considered experimental (except the 5-foot value, which is operational). Those results are displayed on an experimental webpage (http://www.nws.noaa.gov/mdl/psurge), which links to NHC's website for the operational 5-foot product. Also on this website is the experimental product: the storm surge above normal tide level, which has a 10 percent chance of being exceeded. Obviously, the P-surge model can be run at times other than 36 hours before forecast landfall.

A major difficulty is in verifying the reliability of the probabilistic forecasts. While data are barely adequate to draw conclusions concerning single value forecasts (e.g., Figs. 3 and 4), about an order of magnitude more data are required for an accurate assessment of the reliability of probabilistic forecasts. Our calibration, and what we will always have to rely heavily on, is based on comparing the probabilistic forecasts with the SLOSH output made from the best track (hindcast) provided by NHC, where "best track" includes all the parameters needed for SLOSH. While this check on calibration of a probabilistic system based on SLOSH with a run of SLOSH itself is not ideal, it does provide adequate data to determine whether the output needs to be calibrated. Rather than having a few observations that are inadequate not only in number but also are extremely biased as to location within a storm area, we have a simulated observation at every grid cell. As stated previously, a single SLOSH forecast is accurate to about 20% for large surge values. Even here, the larger surges are rare and verification is problematic.

## 8. Extratropical Storm Surge Forecasts

The surge caused by extratropical storms, although not as serious a threat in hurricane prone regions as hurricane storm surge, is of considerable importance to other coastal areas where extratropical storms are frequent. The NWS warns coastal residents of threatening conditions due to such storms, and the forecasting of surge heights is prerequisite to the preparation for the impact. The model is useful for forecasting storm surge associated with Nor'easters which are prevalent between fall and spring (e.g., see Dolan and Davis 1992) and in western Alaska where storm surge associated with intense extratropical cyclones can devastate low-lying coastal communities.

The Extratropical storm surge (ET surge) model, based on the same depth-integrated shallow water equations used by the SLOSH model (Kim et al. 1996), is run operationally four times daily (at 0000, 0600, 1200, and 1800 UTC) to forecast storm surge resulting from extratropical cyclones. Extratropical storms have larger time and length scales than tropical storms. So, instead of using the SLOSH model's parametric wind model, the ET surge model uses the 10-m surface winds and pressures reduced to mean sea level generated by the NWS's Global Forecast System (GFS) at 3-h projection intervals. The model starts from a water level of zero feet, executes a 48-h runup period, and generates hourly forecasts out to 96 hours. Operationally, the resulting storm surge values are distributed in a numerical text format for locations throughout the five regions covered–the east, west, and Gulf coasts of the conterminous United States and the Bering Sea and arctic regions of Alaska (see Fig. 7). An associated Web site (www.nws.noaa.gov/mdl/etsurge) shows the total water level from astronomical

**Fig. 7.** The five basins used for the Extratropical storm surge model.

tides, observed water levels (when available), and the forecasted storm surge values (Fig. 8). This allows the forecasting community to view the numerical results graphically to assist in decision making. In late August 2008, the operational products were expanded to include two gridded forecasts, one covering Alaska, and the other the conterminous United States.

Model experiments conducted in the region of western Alaska for three storms displayed the model's strength for simulating high positive and negative surge events (a negative surge occurs when the winds are strong offshore, and the water level is below the normal level at that time). Forecasts for two of the storms were quite good (Blier et al. 1997). However, one of the three storms was of quite short duration, and was not well simulated. This was undoubtedly caused in part by the relatively low resolution input wind field being used. At the time of the study, the model was using 2.5 degree latitude by 2.5 degree longitude wind and sea level pressure at 12-h intervals. The model has been updated to use 1 degree latitude by 1 degree longitude data from the GFS model at 3-h intervals. Better predictions should result for smaller scale events because of this upgrade.

## 9. Summary

The SLOSH model has proven to be a dependable and valuable tool for forecasters and emergency management officials in predicting storm surge in real-time and for assessing the potential storm surge flooding when the future track is in considerable doubt. When used for real-time forecasting, it assists NHC and WFOs in fine-tuning their storm surge forecasts. It provided quite accurate data to NHC and WFOs for their forecasts of Katrina. The MEOWs and MOMs that result from the SLOSH model simulations are used extensively by FEMA, the U.S. Army Corps of Engineers, and state and local emergency managers, and provide a thorough, yet manageable, dataset to assist in the "hazards analysis" portion of hurricane evacuation planning. SLOSH is now being used for developing methods for establishing structure design criteria related to hurricane winds and surge.

More recently, a probabilistic component has been added to the SLOSH family in keeping with the NRC report "Completing the Forecast" (NRC 2006). The P-surge forecasts will potentially be useful to emergency managers to assist in coordinating evacuation efforts. A

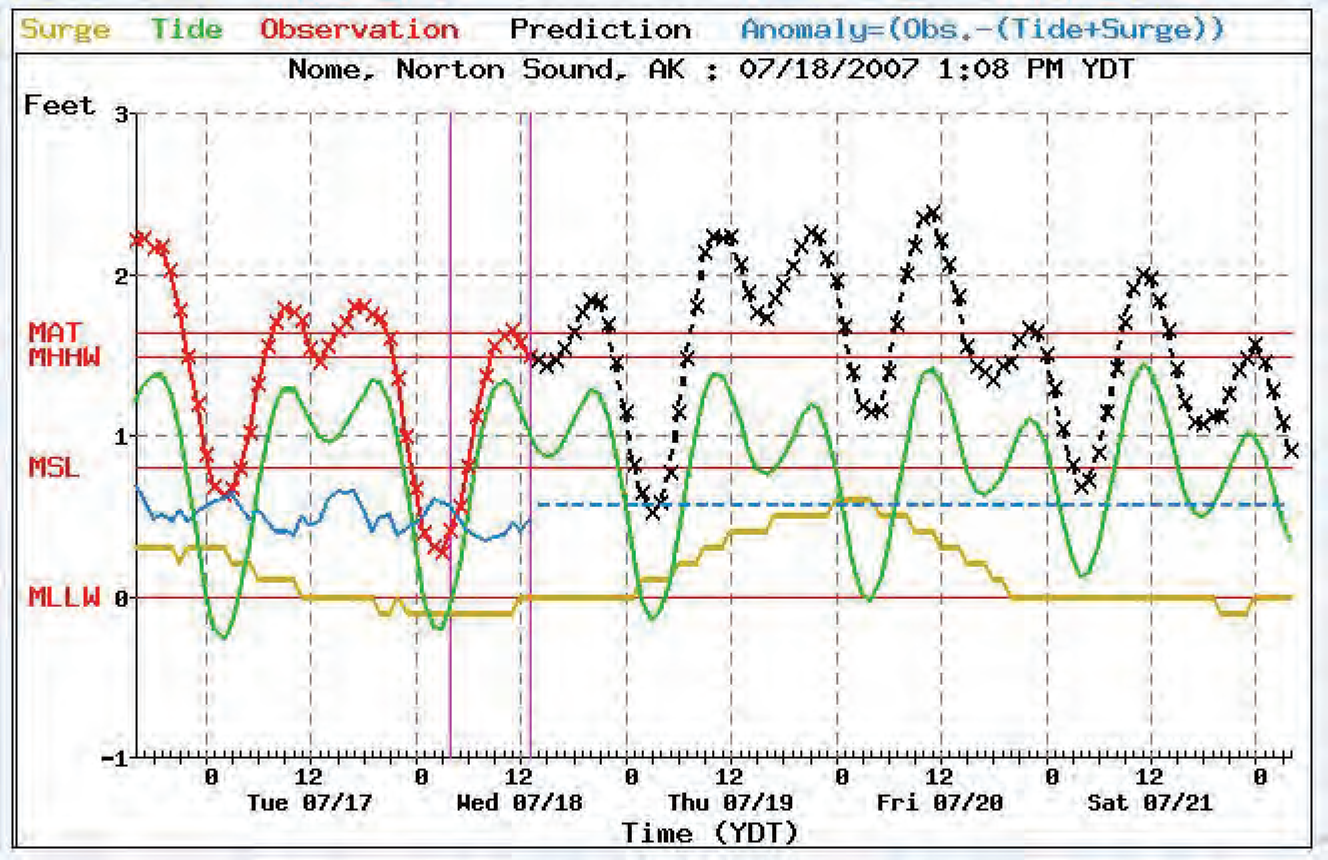

**Fig. 8.** Graphical representation of the extratropical storm surge model forecasts (gold line), astronomical tides (green line), and observed water levels (red line) to predict the total water level (black line). The anomaly (blue line) is the difference between the observed water level and the sum of the tide and storm surge. The most recent five day average of the anomaly is added to the storm surge and tide predictions to create the total water level prediction. MAT, MHHW, MSL, and MLLW are Maximum Astronomical Tide, Mean Higher High Water, Mean Sea Level, and Mean Lower Low Water, respectively.

concern of the emergency managers is that if they always assume the potential flooding depicted by the MEOWs and MOMs, and the resulting forecasts consistently exceed the actual flooding, the public and elected officials may tend to disregard future forecasts. By taking the probabilistic forecasts into account, they may improve their ability to communicate the uncertainty inherent in storm surge forecasts. The reliability of the probabilistic forecasts has not been well established due to the paucity of verifying data, but they are well calibrated according to a single best-track run of the model. To the extent that observations from a single storm can be an indication of reliability, SLOSH performed well for Katrina (see Fig. 4).

An extension to the original SLOSH model, the ET surge model provides storm surge forecasts for extratropical cyclones. This model utilizes the basic SLOSH, but replaces its parametric winds with winds and pressures that are generated from the NWS's GFS. The model performs well for both high positive and negative surge events. The model is particularly useful for forecasting storm surge associated with Nor'easters and in western Alaska where storm surge associated with extratropical cyclones can devastate low-lying coastal communities.

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