PAPER

Water Level Observations for Storm Surge

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ABSTRACT

Issues affecting the utility and accuracy of water level measurements for storm surge are addressed. Vertical datum control (including land elevation measurements), water level sensor survivability, and sensor placement are critical to obtaining useful information on storm surge. Hurricane Dennis in 2005 provides an example of how water level measurements are used to evaluate and improve storm surge prediction models. A water level gauge operated by the University of South Florida Coastal Ocean Monitoring and Prediction System (COMPS) was the only site to capture time history of the maximum surge that occurred in Apalachee Bay, Florida, leading to improvements in the storm surge prediction model. A more dense network of water level gauges, as a component of the U.S. Integrated Ocean Observing System, will enable a more efficient response to and mitigation of future storm surge events.

Introduction

Coastal inundation from storm surge is the most destructive aspect of land-falling hurricanes (NOAA, 2006). Water level measurements of storm surge are needed both in real-time for emergency responders and post-storm (delayed mode) for evaluation of storm surge model predictions, for damage assessment, for assessing changes in vulnerability, and for managing and mitigating impacts. Present methods of water level data collection provide inconsistent measurement of surge heights, often not meeting the needs of the NOAA National Hurricane Center (NHC) and other storm surge modelers. After a storm surge, the Federal Emergency Management Agency (FEMA) issues a contract for surveys of high water marks. Only a portion of high water as estimated from these surveys is a result of surge. It is fortunate to get a few pure surge values from each of those surveys. Recent 2004-2005 storm surge heights from hurricanes along the Northern Gulf of Mexico yielded minimal surge height data. Issues concerning accuracy, timeliness, and dependability of such measurements continue to hamper analysis of hurricane surge heights. An expanded water level observation network as part of a U.S. Integrated Ocean Observing System can address many of these issues (Malone and Hemsley, 2007).

This paper provides an overview of issues affecting the utility and accuracy of water level measurements for storm surge. For such measurements to be useful to emergency responders, data must be available in real-time throughout the storm and must be related to a consistent vertical reference (datum). For surge model evaluation, water level data must capture the highest point of the surge, free of wave influence, again relative to a consistent datum. All of the above presume that accurate land elevations and water depths also are available relative to the same vertical datum (Stockdon et al., 2007). Issues of differing vertical datums, water level gauge range and placement, data telemetry, and alternative methods of data collection are discussed. An example of water level data from Hurricane Dennis is presented to illustrate the use of water level measurements in evaluation of storm surge predictions.

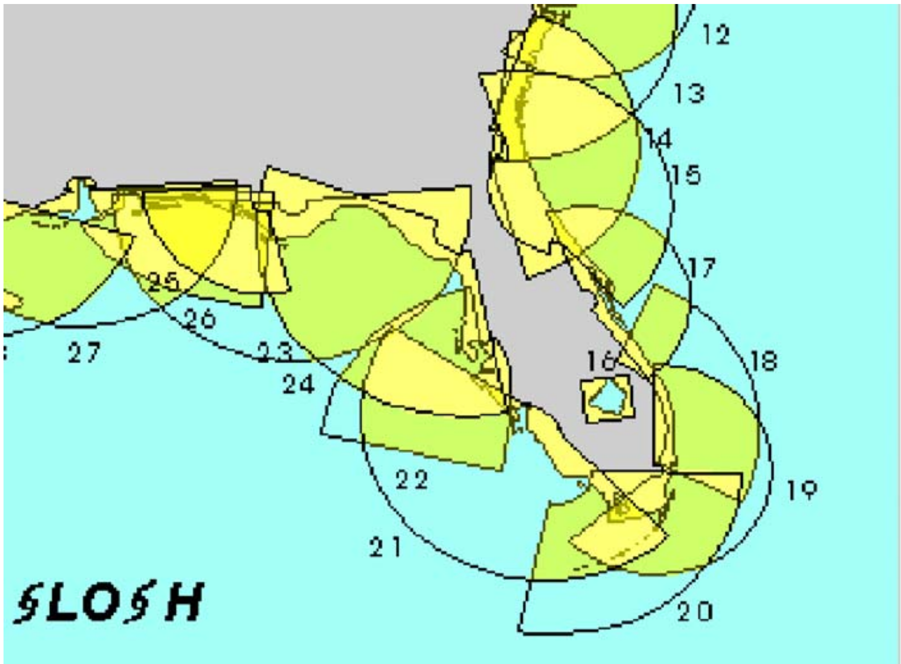
Storm Surge Data and Models

Storm surge is measured as the total water elevation (storm tide) minus the astronomical (predicted) tidal elevation. Storm surge does not include wind-generated surface gravity waves and wave runup (NOAA-NOS, 2000). Surface wave effects can lead to an erroneously high estimation of storm surge from coastal high water marks on buildings or other fixed structures. Other measurements of storm surge from instrumental observations of water level suffer from problems of inconsistent vertical reference levels (datums), inappropriate instrumental range or placement, or destruction of the observing site.

The standard storm surge model used by the National Weather Service is the SLOSH model (Sea, Lake and Overland Surges from Hurricanes) (Jarvinen, 1985; Jelesnianski et al., 1992). The SLOSH model is a numerical storm surge model that computes water elevations generated by the wind and pressure forces in a tropical cyclone. Part of the model is a grid, covering the area of interest, which contains land elevations, water depths, channels, and vertical barriers which can impede storm tide flooding. The grid is termed a basin and given a name. For example, there are 14 SLOSH basins that cover the state of Florida (Figure 1). The computational part of the SLOSH model accepts a tropical cyclone track, intensity—parameterized as the difference in pressure between the storm's center and the surrounding undisturbed atmosphere—represented as delta-P, and Radius of Maximum Winds (RMW) as input and creates a wind and pressure field which is passed through the grid. This in turn numerically moves the water in the grid and creates a storm surge

FIGURE 1

SLOSH model basins for Florida.



flooding pattern and is termed a SLOSH model run. The history of the water elevation is saved in each grid cell and the maximum for each grid cell is displayed in what is termed the Envelope Of High Water (EOHW).

SLOSH is run in two modes—in a planning scenario mode and in a real-time predictive mode. In the planning mode, multiple storms of different magnitudes along different tracks are simulated to produce Maximum of Maximum (MOM) surge maps for each SLOSH basin. When landfall of a hurricane is forecast within the next 24 hours, SLOSH is run in a predictive mode using the best consensus forecast of track, delta-P, and RMW to generate wind and pressure fields. The predicted surge is displayed as a time series of water level elevation maps in a GIS format and made available to emergency management officials. SLOSH model surge simulations are run after a storm to evaluate the model performance against available water level observations.

Datum Issues—NAVD88, NGVD29, and Tidal Datums

There often is confusion regarding the vertical datum, or base elevation used as a reference, for water level and land elevation measurements. Water level measurements and water depth (bathymetric) measurements most often are referenced to a tidal datum, determined relative to a particular phase of the astronomical tide that is unique to each water level gauge. In the U.S., water level observations, tide predictions and bathymetric measurements are referenced to NOAA Nautical Chart Datum of Mean Lower Low Water (MLLW), the average of all lower water levels during each lunar day over a 19-year National Tidal Datum Epoch (NOAA-NOS, 2000). Land elevations are referenced to the North American Vertical Datum of 1988 (NAVD88), a geodetic datum determined from a least-squares fit to leveling networks and constrained by mean sea level observed at Father Point/Rimouski, Canada. NAVD88 supersedes the National Geodetic Vertical Datum of 1929 (NGVD29). Also originally known as the Sea-level Datum of 1929, NGVD29 was determined from geodetic leveling to correspond to local mean sea level (MSL) observed at 26 long-term tide stations. NGVD29 should no longer be used as equivalent to local MSL for any application (NGS, 1973).

The relationship between tidal datums and geodetic datums may be highly variable in space and time (in geodesy, "datums" is used as the plural for "datum"). Ocean currents, density patterns, river flow and tidal hydrodynamics affect mean sea level from place to place and can change over time. Geodetic datums are fixed relative to benchmarks on land, leading to variable relationships among tidal and geodetic datums, as shown in Table 1.

These tidal datums are relative to the National Tidal Datum Epoch (NTDE) (1983 to 2001) and have changed from the previous NTDE (NOAA-NOS, 2006) due to relative sea level change. Linear trends in MSL from NOAA tide stations range geographically from 2.4 mm/yr at Mayport and St. Petersburg, FL to 3.4 mm/yr at Padre Island, TX. Local maxima in sea level trends due to regional land subsidence are 9.9 mm/yr at Grand Isle, LA and 6.5 mm/yr at Galveston (Zervas, 2001).

Storm surge models require a consistent vertical datum for water level, bathymetry, and land elevations (topography) to be most useful for storm response. SLOSH presently uses NGVD29 as its vertical datum, although efforts are underway to change to NAVD88. This choice of datum leads to problems in relating SLOSH computations to bathymetry and water level observations relative to MLLW and land elevations relative to NAVD88. Other storm surge models suffer from similar datum issues and employ various schemes to convert from MSL to NAVD88 or other geodetic datums.

TABLE 1

Regional variations in the relationship of elevation of tidal datums and geodetic datums.

	8720218 Mayport		**8726520 St. Petersburg**		**8775870 Corpus Christi**	
NAVD88	0.934	NAVD88	0.433			
MSL	0.752	MSL	0.366	MSL	0.292	
NGVD29	0.598	NGVD29	0.172	NAVD88	0.136	
MLLW	0.000	MLLW	0.000	MLLW	0.000	
				NGVD29	**-0.146**	

The NOS VDatum tool (Myers, 2005; http://nauticalcharts.noaa.gov/csdl/vdatum.htm) was developed jointly by NOAA's Office of Coast Survey and National Geodetic Survey to transform coastal elevations between 28 different tidal and geodetic vertical datums. VDatum uses tidal models to interpolate and extrapolate observed tidal datums but is available only for limited geographic regions. This tool is extremely useful where it is available, allowing comparison of elevations measured or estimated relative to differing datums. The northern Gulf of Mexico is an area for which VDatum is currently being developed by NOS.

Water Level Measurements

Routine water level measurements are provided by the NOAA National Ocean Service Center for Operational Oceanographic Products and Services (CO-OPS) through the National Water Level Program (NWLP; http://tidesandcurrents.noaa.gov/nwlon.html). The NWLP consists of networks of long-term and short-term water level stations and is an "end-to-end" system of data collection, quality control, data management and product delivery and provides the tidal datum reference system for the U.S. At present, the NWLP operates 196 long-term, real-time telemetered water level sites distributed around the coastal waters of the U.S., including the Great Lakes and island territories that form the National Water Level Observation Network (NWLON). In addition to providing tidal information, these sites provide storm surge warning and monitoring and many are part of the NOAA Tsunami Warning System network. Data are telemetered via a combination of satellite, wireless data modem, and land-line phone service. Most long term sites have a primary water level sensor based on a self-calibrating acoustic transducer, the Aquatrak, and a back-up sensor based on a bubbler pressure gauge (Edwing, 1991). The reference point of the water level sensors are leveled annually to multiple bench marks to ensure vertical stability of the observed tidal datums and to connect the tidal datums to geodetic datums. To be useful for storm surge measurements, water level sensors need to be connected to NAVD88 so that water level observations can

FIGURE 2

COMPS water level sites. (a) Shell Point (b) New Port Ritchey, and (c) Cape Sable sites. Aquatrak sensor (white pipe) is placed as high as possible to capture maximum surge.

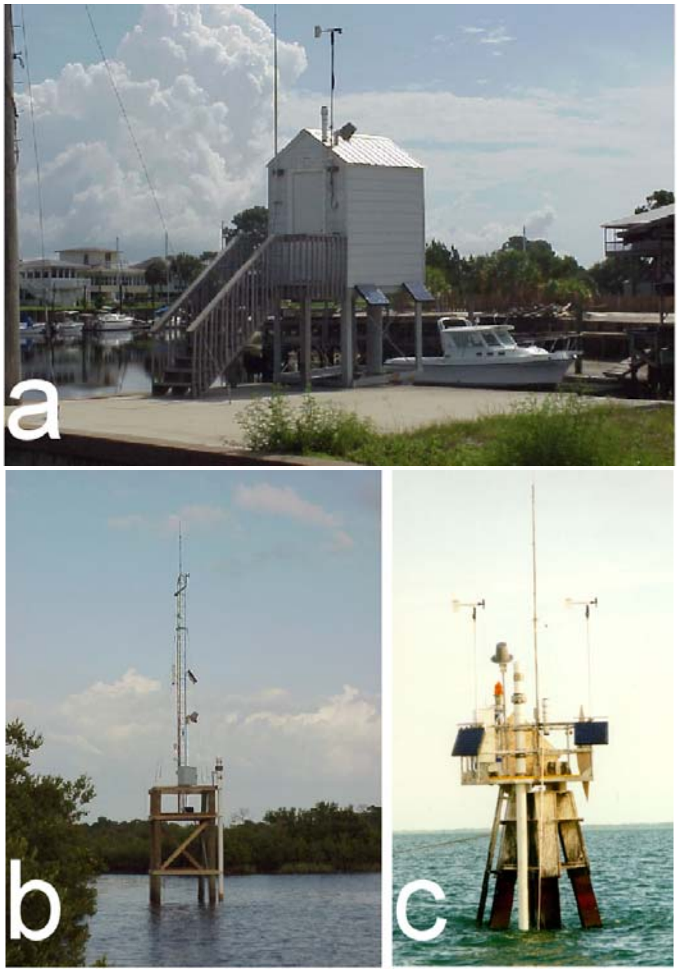
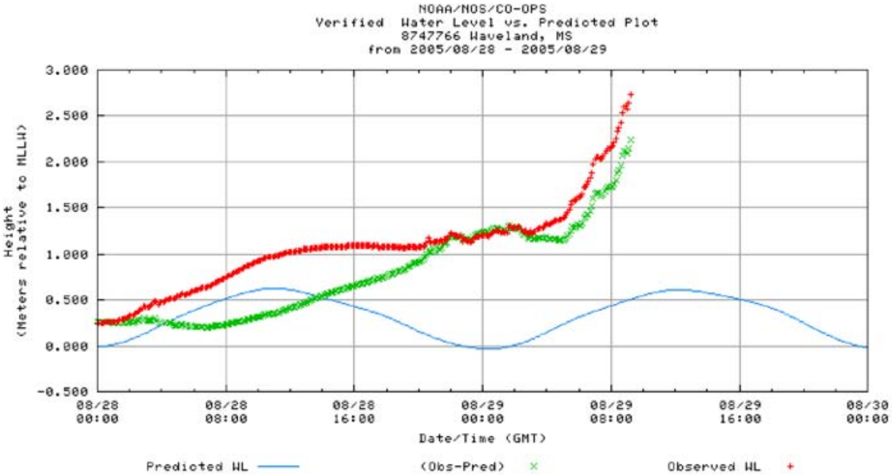


FIGURE 3

Water level record for the NWLON site at Waveland (Station ID 874776) during Hurricane Katrina. The site stopped collecting data when the water level reached the upper end of the sensor range or when supporting structures on which it was established were destroyed by surge, waves, and wind.



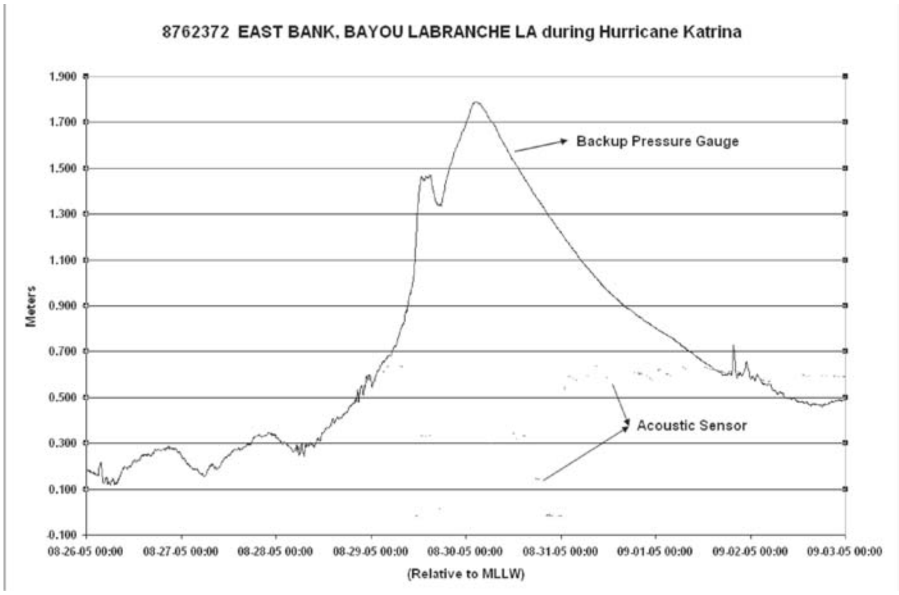


FIGURE 4

Water level record for acoustic and backup pressure sensors during Hurricane Katrina at the NOAA tide station at Bayou LaBranche (Station ID 8762372) on Lake Pontchartrain. The acoustic water level sensor failed at a level of approximately 0.75 m, while the back-up sensor continued to collect data through the storm.

be related to topographic elevations. NOS publishes NAVD88 relative to tidal datums only when two or more reference benchmarks have consistent NAVD88 elevations but not all NWLON stations meet this requirement. Some non-NOAA water level observing networks, like the University of South Florida's Coastal Ocean Monitoring and Prediction System (COMPS; see http://comps.marine.usf.edu) do meet this requirement, while others do not.

To measure the history of a storm surge, a water level sensor must be positioned so that it captures the entire range of the surge. The acoustic transducer has a calibration hole in the sounding tube positioned one meter below the transducer head. If this hole is inundated, the sensor no longer functions. The acoustic transducer head therefore must be positioned at least one meter above the maximum anticipated storm surge level. In addition, the water level sensor and its data collection/telemetry system must survive the storm. These two requirements sometimes are at odds with each other, as elevating the acoustic transducer and its protective well to a height above the anticipated surge makes it more susceptible to damage from wind and waves (Figure 2).

In the recent storms to strike the Gulf coast, both these problems were encountered where there was widespread destruction near the path of the eyewall of hurricanes. Water level gauges in the northern Gulf first were inundated beyond their operating range and in many cases were destroyed during recent events. Figure 3 shows the water level record from NWLON sites in Waveland, MS, near the maximum estimated storm surge for Hurricane Katrina. The Waveland sensor (8747766) stopped reporting at 09:12 UTC on August 29, 2005 at an observed water level of 2.737 m when the predicted astronomical water level was 0.504 m. The site subsequently was destroyed completely.

Pressure gauges used as back-up water level sensors on NWLON sites or on other real-time telemetered observing sites do not have a problem with a maximum range; however, the DCP and associated electronics still must survive the storm. The backup pressure gauge at Waveland also was destroyed during Katrina. Figure 4 is an example of the backup pressure gauge recording correctly through the storm. At the NOAA station at Bayou LaBranche located to the west of New Orleans on Lake Pontchartrain, the acoustic sensor reached its maximum tolerance while the pressure sensor provided the only continuous water level record in the vicinity. The data collection platforms were mounted high enough such that they were not inundated.

Exceedance probability analyses are now being used to design new NWLON stations. Replacement NWLON and new NWLON stations being established in the wake of Katrina and Rita are being built on independent four-pile hardened structures with raised platforms at elevations near the estimated 100-year event elevation (Zervas, 2006).

Internally recording pressure gauges deployed ahead of a storm can yield very useful information on surge levels. Because the pressure gauges are self-contained, they can be deployed quickly and efficiently but because data are not telemetered in real-time, they are not useful for emergency response during and immediately after the storm. A recent example is provided by McGee et al. (2006), who deployed a network of 47 Hobo U20 pressure transducers at 33 sites in southwestern Louisiana just before the landfall of Hurricane Rita in September 2005. All pressure gauges were connected to NAVD88 using GPS and differential leveling. Data from the pressure gauges were consistent with high-quality water level marks on fixed structures and indicated storm surge water levels over 14 feet above NAVD 88 and rates of water level rise greater than 5 feet per hour at three locations near the Louisiana coast. These gauges are extremely important for development and evaluation of storm surge modeling of the finer scale structure of the phasing and elevations of the storm surge.

Coastal High Water Mark Surveys

After storm surges have struck, the Federal Emergency Management Agency (FEMA) sends contractors into the affected area during the days and weeks following a hurricane to determine the elevation of coastal high water marks (HWM). Many HWM's are collected by the Army Corps of Engineers and the U.S. Geological Survey and then assembled by private contractors for FEMA. These HWM surveys are the primary source of post-hurricane high-water level data now available to NHC for evaluation of storm surge models. The HWM surveys provide FEMA a standardized method for collection of high water data used for budget allocation purposes and for upgrading flood maps.

Usually, but not always, these HWMs are leveled to NAVD88. The high water marks include "inside high water marks" inside of structures which generally reflect the storm tide elevation without the effect of waves as well as "outside high water marks" which usually reflect the combined effect of storm tide and wave set up and runup. Outside high water mark elevations are generally higher than inside high water marks because of the added wave effects. On the outer coastline of the Gulf of Mexico the additional breaking wave effects that are produced on top of the storm surge can increase the observed water elevations at shoreline structures by a factor of 100 to 200%. For example, if the storm tide was observed to be 10 feet above NGVD29 at a tide gauge just offshore, then values ranging from 10 to 30 feet above NGVD29 could be measured at structures along the shoreline. Outside high water marks also may be affected by water disturbed by deflection from other structures or topography. Inside high water marks are protected from wave influence but may underreport water elevation because water could not enter the building space fast enough for water levels to equilibrate inside and outside the structure. The quality of HWM surveys depends greatly on the experience of the crews who "flag" the HWMs. Using the *in situ* photos and the surveyors' descriptions of the surveyed coastal high water marks, one can assess the quality of each HWM elevation.

Storm surge modelers face a dilemma in that only a few of such HWM's are pure storm surge. Many, if not most, are some combination of tide, surge, wave, wave run-up and other anomalies. In 2006, NHC received additional surge data from the U.S. Army Corps of Engineers for Hurricane Katrina. A committee of storm surge experts established by the U.S. Army Corps of Engineers reviewed more than 500 CHWM reports, from various sources, but was able to validate only 100 HWMs as "excellent" representations of storm surge.

Self-recording Tide Staffs

Self-recording tide staffs use floats or other material that remain fixed at the highest water level, providing a record of surge height. A tube or well filters surge height data from extraneous wave and wave runup that can bias conventional post-hurricane data collection methods. The tide staff can have a very simple design and requires no power, acquiring high water marks in a controlled and calibrated manner. Tide staffs are referenced to NAVD88 at time of installation so that surge height can be determined immediately after a storm event. Raw storm surge heights can be collected, cross-checked for accuracy, and field-transmitted to a central database for data ingestion, management, and dissemination to end-users. Repeatability of hurricane surge height is impossible; therefore, accuracy and redundancy are important at each of the data collection stations.Routine maintenance of the tide staffs is required to assure connection to vertical datum.

Optimal Placement of Gages/Tide Staffs Using SLOSH Output

When siting new water level sensors, whether real-time telemetered or self recording, care should be taken to place them in areas where the information they provide is of maximum utility. Output from storm surge models like SLOSH can be used to guide sensor placement. The MOM maps can be used to site water level sensors to ensure that they capture the maximum surge anticipated.

Actual location of water level sensors usually involves tradeoffs among several factors. For water level sensors that also make tidal observations, the site should be on a body of water that has some protection but that also has good communication with open water. For maximum survivability, the sensor system should be mounted on a sturdy structure that is unlikely to be destroyed in a storm (Figure 5). Significant engineering costs may be incurred to strengthen the observing site to ensure its survivability. Even the most well-engineered and constructed system can't be guaranteed of surviving a severe storm. As comedian Ron White says, "it's not *that* the wind is blowing, it's *what* the wind is blowing." If a barge or other large object is blown into the system, there is little that can be done to protect it from destruction. In the case of an acoustic water level sensor or self-recording tide staff, placing the sensor so that it will observe the highest anticipated storm tide makes it more vulnerable to damage from wind and wave action, as stated above.

FIGURE 5

New NWLON site at New Canal, LA (Station ID 8761927).

Real-time Telemetry Options

For use in emergency response, water level data must be telemetered in real-time to emergency operations centers. Dedicated line-of-sight radio systems or satellite telemetry systems have an advantage over land-line or cellular phone based systems as they are less susceptible to interruption due to destruction of land-based communications infrastructure (Clark, 2007). An additional advantage of real-time data telemetry is that data will be collected and archived at least up until the point when the system is destroyed or inundated for post-storm analysis, as was the case in the recent Gulf of Mexico storms (Figure 3). NWLON stations use a combination of GOES satellite telemetry and land-line telephone connections. The COMPS water level sites use a combination of GOES and line-of-sight radio telemetry, with direct radio links to the nearest emergency operations center. GOES telemetry is one-way and low bandwidth (100 to 1200 bits/sec with 6 min to hourly transmissions), while other telemetry options provide continuous two-way communications and relatively higher bandwidth (9600 to 100,000 bits/sec). Under normal operating conditions, GOES telemetry is adequate; however, two-way communications are required if data are needed from the system more frequently or sampling parameters need to be changed or diagnostics need to be performed.

Real-time Water Level for Emergency Response

A primary use for real-time water level data is for operational response during and immediately after an inundation event. Emergency responders need real-time observations of water level tied to NAVD88 in order to assess the present state of inundation for routing emergency vehicles, for guiding search and rescue efforts, and for responding to hazardous material spills. Real-time water level observations allow monitoring the length of time required for the flood waters to recede (post-storm) and aid Emergency Management personnel in deciding when emergency response personnel can begin rescue operations. Many roads in the coastal regions have very low elevation and when floodwaters are present, firefighters, police, and medical teams cannot traverse them to rescue victims. Availability of real-time water level observations allows Emergency Management coordinators to predict when emergency teams can be sent into the field. The data will also be useful for tracking trajectories of hazardous materials incidents, and for modeling and forecasting in general. A partnership program between NOAA and the St. Charles Parish, LA, is an example of the focused product delivery for local emergency managers (NOAA, 2006). The Bayou LaBranche tide station (Figure 4), which survived Hurricane Katrina, was installed for this partnership.

Sometimes storm surges are not predicted accurately due to inaccurate forecasts of storm intensity and detailed structure of the wind field. In such cases, real-time water level observations are critical for emergency response. After recent storms, NOAA began issuing High Water Alerts whenever data from NWLON gauges registered water levels of 1.5 ft (0.45 m) above predicted tide. In the March 1993 extratropical storm that struck the west coast of Florida with an unanticipated 14 ft. storm tide, people in coastal communities from Crystal River to Steinhatchee literally woke up with water lapping over the edge of their mattresses. After this event, emergency managers from two affected counties and forecasters from the National Weather Service local forecast office for the Tampa Bay region approached the University of South Florida College of Marine Science (USF/CMS) for assistance in providing better real-time water level information. With their assistance, USF/CMS approached the state legislature and obtained additional funding to implement the Coastal Ocean Monitoring and Prediction System in 1996 (see http://comps.marine.usf.edu). COMPS began by integrating existing water level and meteorological observations in the eastern Gulf of Mexico and supplementing those observations with new sites where needed. Since that time, COMPS has added 12 water level sites and 6 offshore buoys, along with nowcast/forecast models of ocean conditions for west Florida coastal waters.

COMPS water level sites are constructed to published NOS standards and are surveyed to NAVD88 by the Florida Department of Environmental Protection Bureau of Survey and Mapping. Water level sensors are placed as high as possible to capture potential storm surge events and are placed according to the needs of state, county, and local emergency managers. Data from all sites are relayed in real-time via a combination of line-of-sight radio and GOES satellite telemetry, both to the nearest Emergency Operations Center and to servers at USF/CMS where data are monitored for quality assurance and disseminated on the internet. Surface meteorology data are handed off to the NOAA National Data Buoy Center where they undergo additional quality control and assurance before being ingested into the NOAA gateway.

Hurricane Dennis Case Study

Hurricane Dennis struck the panhandle of Florida in July 2005, causing widespread and largely unanticipated coastal flooding. The Federal Emergency Management Agency issued a report on high water marks within a few months after the storm (FEMA, 2005). The report contains data on 222 surveyed high water marks, measured post-storm. Also contained are data from five NOAA/NOS tide gauges and one tide gauge from the University South Florida Coastal Ocean Monitoring and Prediction System, all measured during hurricane Dennis.

Quoting from the above-referenced report:

> *The overall pattern of the storm surge caused by Hurricane Dennis was rather remarkable.…[T]he storm had a small radius to maximum winds and a relatively high forward speed. These factors could be expected to limit the length of the Gulf Coast that would be subject to a significant surge. However the wind field in Dennis was skewed so that relatively high winds extended far to the east of the storm center The maximum storm surge (in relation to the NAVD88 datum) remained high from the point of the landfall at Navarre Beach (open coast surge 9 to 10½ feet) eastward to near Panama City. From Panama City eastward all the way to St. Marks, the surge remained high (approximately 8 to 10 feet). Strong winds located well east of the storm track, along with other unidentified oceanographic processes, contributed to the high storm surge reaching so far to the east. The degree to which these forces contributed to these conditions is presently not known.*

Using the *in situ* photos and the surveyors' descriptions of the surveyed coastal high water marks, and only coastal tide gauges, NOAA National Hurricane Center Storm Surge Team winnowed the number of reliable storm surge observations to 25 for comparison with the SLOSH storm surge model calculated values at the same locations.

The basin covering the northeast Gulf of Mexico where Dennis made landfall is called the Pensacola Bay basin (basin 25 in Figure 1). Dennis also excited storm surge in the Apalachicola Bay (basin 24) and Cedar Key (basin 23) SLOSH basins. A SLOSH basin that represents the entire Gulf of Mexico also was used in the post-landfall analyses of Dennis. The full-basin model has a lower spatial resolution than the three coastal grids.

The reference datum used for the high water marks in the FEMA study is NAVD88. The study contractor used VERTCON software (Milbert, 1999) to provide the high water marks in NGVD29, the native vertical datum for the SLOSH model. Prior to landfall a tidal anomaly of approximately 0.3 m (1.0 ft) was observed at all the NOS tide gauges along the northern Gulf coast. Therefore the SLOSH model was initiated at 0.3 m MSL in each of the basins. Vertical adjustments were made to the SLOSH-calculated water elevations based on the predicted astronomical tide for the NOS and COMPS water level gauges, depending on the location of the HWM observations on the affected coastline.

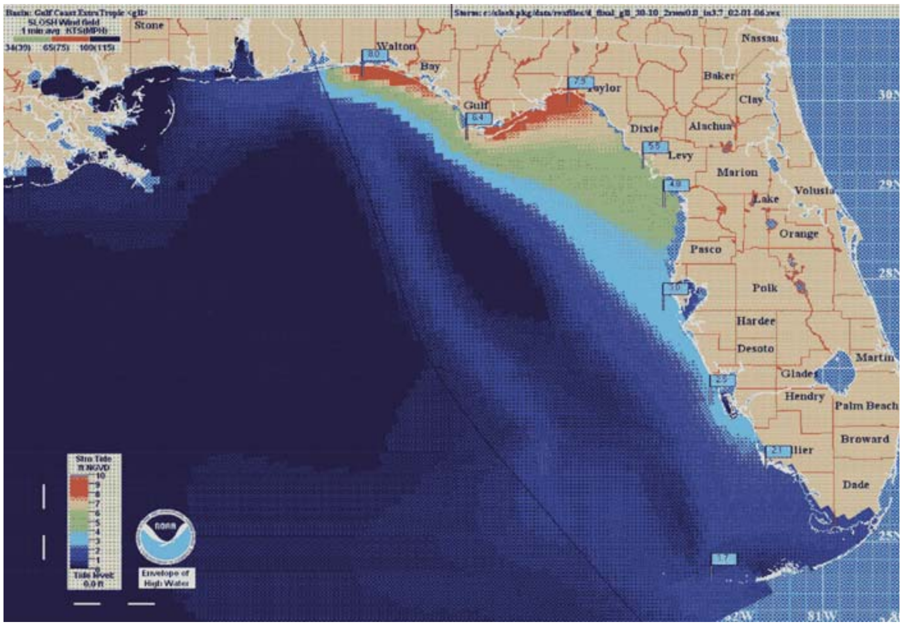
SLOSH model runs were made in each of the three coastal basins using Dennis' track and intensity data as input (Figure 6). The maximum Pensacola values are ~ 3 m (10 ft), close to the observed HWMs. SLOSH calculated maxima of ~ 1.8 m (6 ft) in the Apalachicola and Cedar Key basins. The initial observations from the Apalachee Bay coastline, made and/or confirmed by NHC staff, local Emergency Managers, the COMPS water level gauge, and, finally, by the FEMA HWM Report, were closer to 3 m (10 ft).

To address the discrepancy of about 1 m (3+ ft) between observations and SLOSH calculations in the Apalachee Bay region, Morey et al. (2006) performed a series of Gulf-wide model runs which closely replicated Dennis' observed coastal storm surge from Pensacola to Cedar Key. Those model runs used the same track as SLOSH but used a wind field derived from observations in addition to the SLOSH parametric wind field.

To replicate not only the areal extent of the other modeled water elevations but also the observed HWM data, NHC ran SLOSH in the full Gulf of Mexico basin grid. The same track was used as in the previous modeling. The RMW was adjusted from 7 miles to 30 miles. This adjustment (an "effective" RMW) produced SLOSH-modeled tropical storm force winds in Apalachee Bay, as had been observed. With these parameters the SLOSH calculation produced an entirely satisfactory storm surge result from Pensacola to Cedar Key. It also produced a feature generated by the other models and observed in the eastern Gulf of Mexico tide gauge data.

FIGURE 6

SLOSH Envelope of High Water (EOHW) for Hurricane Dennis on the full Gulf of Mexico basin.



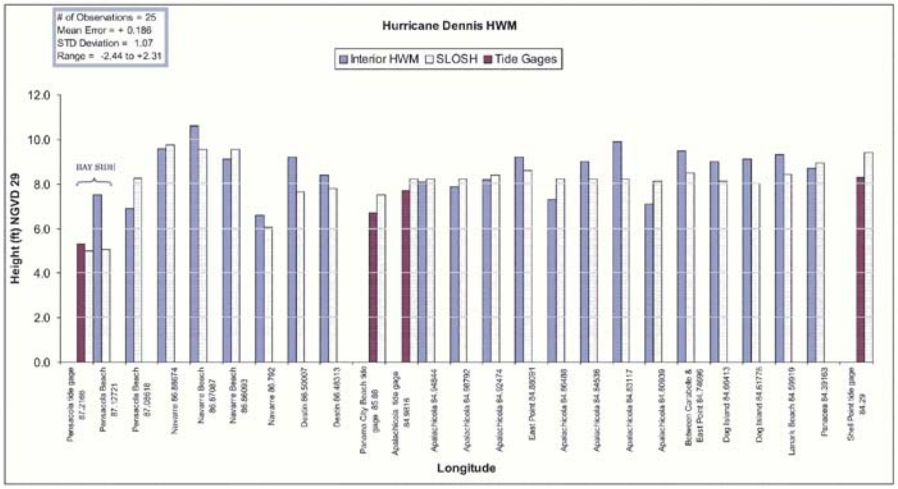
This unique feature was generated in all the numerical modeling using either observed or appropriately parameterized wind fields. In each model run, from the time Dennis passed to the west of Key West until it made landfall, a localized rise of water was generated on the West Florida Shelf. The rise traveled northward along the west Florida shoreline parallel to Dennis as a barotropic continental shelf wave (Morey et al., 2006). Observations from coastal tide gauges confirm the existence of the feature and its timing. Dennis tracked along the continental shelf break at the same speed as a shelf wave, leading to a near-resonant response in water level elevation. No other storm in HURDAT, the official "best track" hurricane archive, has traveled along the shelf break anywhere in the Gulf of Mexico. Dennis' track, coupled with the geographic extent of its tropical storm force winds, produced this unique feature.

To calculate overland flooding to compare with the HWM survey, the higher resolution local grids for the Pensacola Bay, Apalachicola Bay, and Cedar Key SLOSH basins were used. SLOSH model runs were again made in each of the three coastal basins using Dennis' track, with intensity data modified as described above. On the outer coast the SLOSH model runs calculated a large area of storm surge elevations of 8 to 10 feet. The maximum storm surge values of approximately 10 feet occurred in an area just east of Pensacola Beach, Florida, where the radius of maximum winds made landfall. Six to 8 feet of surge occurred between Panama City, FL, and Apalachicola FL. Surge values of 8 to 10 feet were calculated and observed in Apalachee Bay, FL. Figure 7 shows Hurricane Dennis high water marks and the co-located SLOSH calculated storm tide elevations.

A histogram of the differences (SLOSH minus observed) is shown in Figure 8. To be noted is the negative average bias of the results. This is due, in large part, to the effect of breaking waves, an effect that the SLOSH model does not compute. Also adding to this negative bias may be the erosion of barriers, such as sand dunes and roadways, due to the

FIGURE 7

Hurricane Dennis storm tide elevations from water level gauges, High Water Marks, and the co-located SLOSH simulations. "Bayside" in the figure differentiates water level measurements made on the bay side of Pensacola Beach from those made on the ocean side.



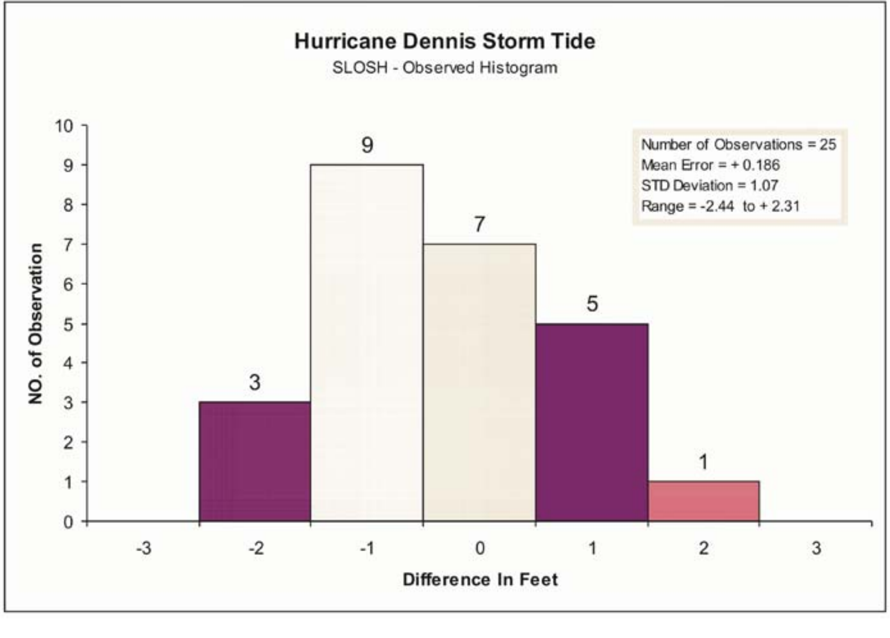
rising storm tide and breaking waves (e.g., Stockdon et al., 2007). Subsequent over-topping of these lowered barriers may lead to additional water in bays and sounds with resulting higher measured water marks. Although the SLOSH model computes over-topping of barriers, it maintains invariant barrier elevations during a simulation. The distribution of surge differences shown in Figure 8 is otherwise similar to case studies on other individual hurricanes where the SLOSH model results were compared to observed high water marks.

Observed storm surge hydrographs from a number of the water level gauges were compared to the SLOSH model-generated storm surge hydrographs for the same location based upon hurricane Dennis input parameters. As an example, Figure 9 shows the COMPS water level gauge record at Shell Point, Florida. The SLOSH model captures the rate of rise of the storm surge and the maximum storm tide but the timing of water rise in the model is approximately one hour earlier than observed. The COMPS Shell Point site was the only water level observing system in Apalachee Bay, where the maximum surge occurred.

Operational SLOSH surge calculations for storms in the Gulf of Mexico henceforth will be first run in the full-basin grid, with due accounting made for the geographical extent of storm force winds. These two steps should alert users to the potential generation of shelf trapped waves and for the sensitivity of shallow bays to even less-than-hurricane force winds.

FIGURE 8

Histogram of SLOSH Storm Tide values minus Observed High Water Marks for Hurricane Dennis.

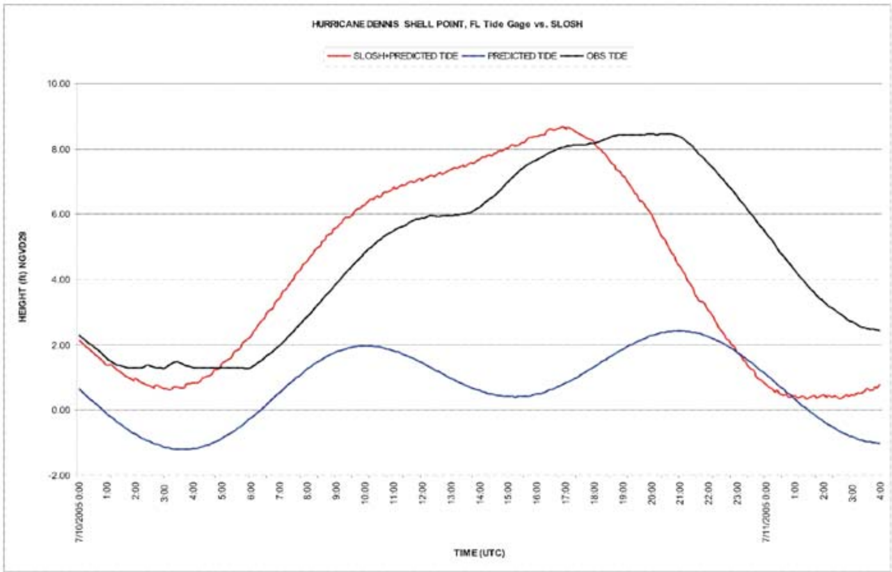


Conclusions

Water level measurements play a critical role in emergency response to storm surge and its aftermath and in evaluation of surge predictions. With proper water level sensor placement and vertical datum control, water level monitoring systems primarily intended for tidal analyses also can provide useful data on storm surge. Lessons learned from recent storm surge events have led to changes in the way storm surge model forecasts are performed and the way that NWLON real-time data are analyzed and disseminated. For example, NOAA (2006) has initiated new online products such as TidesOnline and Quicklook to provide 24/7 value-added information from tide stations. Consideration should be given to sensor height range, sensor system survivability, and consistent datum reference when developing new or upgrading existing water level observing systems as part of the U.S Integrated Ocean Observing System. While careful attention is given these issues in the National Water Level Observation Network and in the Coastal Ocean Monitoring and Prediction System, recent storm surge events have identified weaknesses that can be corrected in future installations. A more dense network of hardened permanent and short-term water level gauges, augmented by pressure gauges and self-recording tide staffs sited pre-event, will enable a more efficient response to and mitigation of future storm surge events. This combined network of permanent and dynamically located gauges must be integrated by referencing all water level measurements to common geodetic and tidal datum reference systems. This allows for meaningful transfer of water level elevations to the land and subsequent application of the observed and modeled storm surge to be applied to inundation map products.

FIGURE 9

Water level record from the USF/COMPS gauge at Shell Point, FL, compared with the SLOSH simulated record.



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References

Clark, A.M. 2007. On developing disaster-resilient communications infrastructure. Mar Technol Soc J. 40(4):27-34.

Edwing, R. 1991. Next Generation Water Level Measurement System, NOAA-NOS Report (http://tidesandcurrents.noaa.gov/publications/next_generation_water_level_measurement_system_manual.pdf)

FEMA, 2005. Hazard Mitigation Technical Assistance Program Contract No. EMW-2000-CO-0247, Task Orders 403 & 405, Hurricane Dennis Rapid Response Florida Coastal High Water Mark (CHWM) Collection, FEMA-1595-DR-FL,Final Report, December 19, 2005. Federal Emergency Management Agency, Region IV, Atlanta, GA.

Jarvinen, B.R. and Lawrence, M.B. 1985. An evaluation of the SLOSH storm-surge model. B Am Meteorol Soc. 66(11):1408-1411.

Jelesnianski, C., Chen, J. and Shaffer, W.A. SLOSH: Sea, Lake, And Overland Surges from Hurricanes, NOAA Techbnical Report NWS 48; Silver Spring, MD, April 1992.

Malone, T.C. and Hemsley, J.M. 2007. Developing the IOOS for improved management and mitigation of coastal inundation. Mar Technol Soc J. 40(4):45-55.

McGee, B.D., Goree, B.B., Tollett, R.W., Woodward, B.K. and Kress, W.H. 2006. Hurricane Rita Surge Data, Southwestern Louisiana and Southeastern Texas, September to November 2005. U.S. Geological Survey Data Series 220 (http://pubs.usgs.gov/ds/2006/220/index.htm).

Milbert, D.G., 1999. National Geodetic Survey (NGS) Height Conversion Methodology. (http://www.ngs.noaa.gov/TOOLS/Vertcon/vert_method.html)

Morey, S.L., Baig, S., Bourassa, M.A., Dukhovskoy, D.S. and O'Brien, J.J. 2006. Remote forcing contribution to storm-induced sea level rise during Hurricane Dennis, Geophys Res Lett. 33:L19603.

Myers, E.P. 2005. Review of Progress on VDatum, a Vertical Datum Transformation Tool. (http://nauticalcharts.noaa.gov/csdl/Vdatum_pubs/myersOceans05.pdf), Marine Technology Society / IEEE OCEANS Conference Proceedings, Washington, D.C., September 19-23, 2005 (7 pages, pdf).

NOAA. 2006. Storm Surge (http://www.nhc.noaa.gov/HAW2/english/storm_surge.shtml)

NOAA National Geodetic Survey (NGS). 1973. Federal Register, Vol. 38. NO 94-Wednesday, may 16, 1973. http://geodesy.noaa.gov/PUBS_LIB/FedRegister/FRdoc73-9694.pdf

NOAA-NOS. 2000. Tide and Current Glossary (http://tidesandcurrents.noaa.gov/publications/glossary2.pdf)

NOAA-NOS. 2001. Tide Datums and Their Applications. NOAA Special Publication NOS CO-OPS 1 (http://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf)

NOAA-NOS, 2006. Center for Operational Oceanographic Products and Services (http://tidesandcurrents.noaa.gov/)

NOAA-NOS, 2006. Center for Operational Oceanographic Products and Services, St. Charles Parish Water Level Monitoring System. http://tidesandcurrents.noaa.gov/st_charles.html

Stockdon, H. F., Lillycrop, W.J., Howd, P.A. and Wozencraft, J.M. 2007. The need for sustained and integrated high-resolution mapping of dynamic coastal environments. Mar Technol Soc J. 40(4):90-99.

Zervas, C. 2001. Sea Level Variations of the United States 1854 – 1999, NOAA Technical Report NOS CO-OPS 36, NOAA/NOS, Silver Spring, MD, 186 pp.

Zervas, C. 2006. Estimating Storm Tide Exceedance Probabilities from Long-Term Tide gauge Data, 13th Ocean Sciences Meeting, Honolulu, Hawaii, February 2006.