Coupling of Tides and Storm Surge for Operational Modeling on the Florida Coast

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Abstract

The National Oceanic and Atmospheric Administration's (NOAA) Coast Survey Development Laboratory (CSDL) and Meteorological Development Laboratory (MDL) are coupling tidal and storm surge models for operational use along the Florida coast.

The Sea Lake and Overland Surges from Hurricanes (SLOSH) model, developed by MDL, is used for climatological, deterministic, and probabilistic prediction of storm surge induced by hurricanes making landfall. The SLOSH model uses a parametric wind model based on forecast track, radius of maximum winds, and change in pressure from ambient to center of storm. SLOSH currently does not model tides. One solution is to choose a constant to approximate high tide by selecting a single reasonable answer from all the tide gauges covered. This is used in the climatological predictions as an estimate of potential surge over high tide for an area. At the request of NWS forecasters, SLOSH does not include this tidal constant for deterministic and probabilistic predictions. Improvements in the timing of hurricanes making landfall made it practical to add a time varying tidal component to SLOSH. Doing so will provide forecasters with a more realistic surge and tide forecast in their area. SLOSH is also used as the basis for NOAA's ExtraTropical Storm Surge (ETSS) model, which currently lacks a time varying tidal component as well.

In this project, predicted tidal water levels calculated with harmonic constants from tide simulations are superimposed with storm surge modeling results to provide a more accurate prediction of potential inundation. This approach will have a strong impact on all types of SLOSH and ETSS predictions. In the future, tidal forcing will be introduced into the open boundary condition of the SLOSH model, which will facilitate simulating dynamic interactions between the tide and the storm surge.

To obtain the harmonic constants required for the tidal predictions for SLOSH, a high-resolution ADvanced CIRCulation (ADCIRC) model has been run. While this has initially been done along the Florida coast, the plan is to do so in all regions covered by SLOSH. The harmonic constants will be adjusted to improve results by applying the Tidal Constituent And Residual Interpolation (TCARI) method, developed by CSDL. This adjustment is based on the difference between the model results and the tide gauge observations in the study area.

1. Introduction

Early prediction and notification of storm surge is vital for communities to prepare for the extent of damage of which tropical storms are capable. For this reason, the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model was created by C.P. Jelesnianski, J. Chen, and W.A. Shaffer (Jelesnianski et al. 1992) to predict storm surge from tropical storms. This finite differencing numerical model calculates water level and flow based on the governing equations of motion derived by Platzman (1963) who used coefficients for surface drag, vertical eddy viscosity, bottom slip, and wind friction in both the tangential and radial directions. The bottom slip coefficient was developed by Jelesnianski (1967). The SLOSH model is forced by a parametric wind model of which the inputs are storm track, radius of maximum winds, and the difference in pressure between ambient and the center of the storm (Jelesnianski and Taylor 1973). Grids for the SLOSH model are structured with higher resolutions near shore and coarser resolutions in deep waters offshore. A SLOSH grid combined with bathymetry, elevation, and sub-grid features such as levees, barrier islands, and 1-D flow for rivers, forms a SLOSH basin (Glahn et al. 2009, Jelesnianski et al. 1992). Tropical basins typically extend up to a few hundred kilometers off shore, whereas, extratropical basins extend more than a thousand kilometers off shore.

The previous version of the SLOSH model did not calculate the tides. It was possible, however, to set an initial water level equivalent to the maximum tide for the region based on predictions at tide gauges within the basin. The SLOSH model was run with this initial water level to create surge values representative of a combined storm surge and tide (aka storm tide). Ambiguity was created when several gauges were available and more so when no tide predictions were available. Errors in the forecast were also introduced, particularly when a hurricane made landfall during low tide and an initial high tide value was selected. Alternatively, the SLOSH display program and ExtraTropical Surge (ET-Surge) website have the ability to calculate predicted tide values as a post-processing step at specific predefined locations where tidal constituents are available from Center for Operational Oceanographic Products and Services (CO-OPS) tidal gauges (Taylor 2011, Glahn et al. 2009).

Adding tides to the SLOSH model is the goal of this project. To accomplish this goal, gridded, as opposed to station based, tidal harmonic constituents are needed to provide the tidal signal. One source for the Western North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico is a model-based tidal constituent database (Mukai et al. 2002), referenced in this paper as the EC2001 tidal database. The ADvanced CIRCulation (ADCIRC) coastal hydrodynamic circulation model (Luettich et al. 1992), was run to compute tidal harmonic constants for water surface elevation and depth-averaged velocity on a finite element unstructured grid containing 254,629 nodes with a minimum resolution of 1 to 2 km at the coast and maximum resolution of 25 km offshore. The domain of this grid contains an open boundary along 60° W meridian and extends west to the coastline (Fig. 1). Recently, an updated version of the EC2001 tidal database containing tidal constants for the National Ocean Service's

(NOS) primary suite of 37 tidal constituents was created based on a 410-day simulation forced by the harmonic constituents from the OSU TPXO 6.2 global tide model at the open boundary. (J. Feyen, personal comm., April 27, 2011).

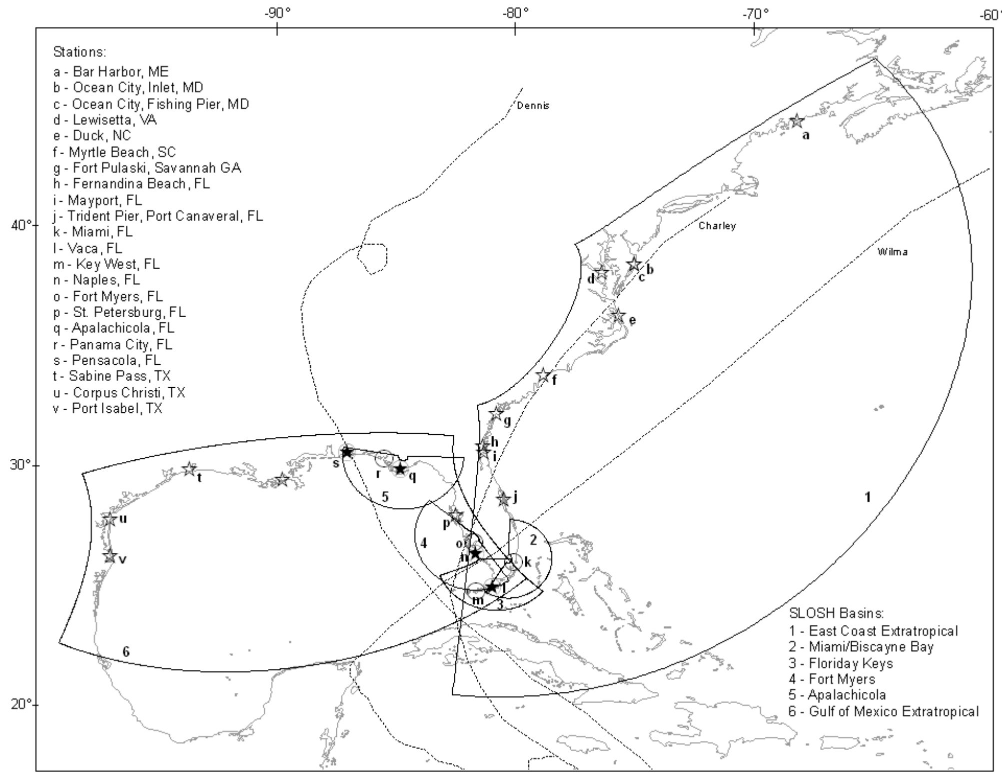

Figure 1. Map of U.S.'s East Coast and Gulf of Mexico coastlines with Caribbean Islands are overlaid with selected SLOSH basins, hurricane tracks for Charley (2004), Dennis (2005), and Wilma (2005), and NOS tide gauge station locations. Nineteen stations were tested with water levels from January 2011 (open stars). Seven stations were used with hurricanes (circles). Four stations were tested with both (closed stars with circles surrounding). Dimensions of the map represent the EC2001 tidal database grid.

2. Methods

Four Florida SLOSH basins were selected for the initial phase of this project, Miami (hmi3), Florida Keys (eke2), Fort Myers (efm2), and Apalachicola (ap2), as well as two extratropical basins encompassing the Gulf of Mexico (egm3) and the East Coast of the U.S. (eex2) (Fig. 1). All of these basins were updated since 2009. This project was extended to include all operational SLOSH basins, discussion of which is beyond the scope of this paper.

For each basin, amplitudes and phases for tidal constituents were extracted from the EC2001 tidal database. A FORTRAN program was used for extracting tidal constants at designated latitude and longitude points. Center points of the SLOSH grid cells were converted from native coordinates to the required format of latitude and longitude points.

The tide calculation code for the ET-Surge website (www.nws.noaa.gov/mdl/et-surge), which calculates tides at a given tide gauge as part of post-processing the Extra-Tropical Storm Surge (ETSS) model, was adapted to calculate tides at a given latitude and longitude point. The tide calculation code is based on Schureman's (1958) tide calculation equation and harmonic constants:

$$h = H_o + \Sigma \left[f * H \cos(a * t + (V_o + u) - k) \right] \qquad \text{Eq (1)}$$

for tidal constituents $A \in \{A_1, \ldots A_{37}\}$ where

- h = height of the predicted tide at time t
- H_o = initial water level above a datum
- H = mean amplitude of the constituent A
- f = tidal nodal factor for reducing H to the year of prediction
- a = velocity of the constituent A
- t = time relative to the beginning of the year of the desired prediction
- (V_o+u) = value of the equilibrium argument of the constituent A at $t = 0$
- k = epoch of the constituent A

Adapting the ET-Surge website tide calculation code to a gridded time series consisted of changing the existing source for a couple of the harmonic constants. Location specific constants, such as amplitude and phase which previously came from the Center for Operational Oceanographic Products and Services (CO-OPS) website (http://tidesandcurrents.noaa.gov), now come from the extraction program. The source for ingesting time specific constants remained unchanged.

The gridded tide code was tested at nineteen tide gauges along the East Coast and the Gulf of Mexico (Fig. 1). Statistical comparisons, such as Reduction of Variance (RV), were calculated between three sources: (1) the NOS predicted tidal time series, (2) the ET-surge website tidal time series, and (3) the new basin-wide tidal prediction. Hourly predicted water levels for a 24-h period in early January 2011 were selected for these comparisons. Locations of tide gauges used for comparisons and resulting RV can be found in Table 1.

Next, the gridded tide was added to the gridded storm surge creating a gridded storm tide product for the SLOSH model. This storm tide product was then tested on all of the basins selected for this project. The SLOSH display program (Taylor 2011) was used to extract time series of predicted water levels from the storm tide product for the same 24-h period previously mentioned. As expected, minimal differences (less than hundredths of meters), likely due to rounding errors, were found between station predictions and basin-wide predictions.

The storm tide product was then tested for three land-falling hurricanes (Charley 2004, Dennis 2005, and Wilma 2005). Time series water levels were collected from tide gauges which met the following criteria: (1) fell within the SLOSH basin of interest, (2) collected data during the time of the hurricane, and (3) were located nearest the peak of the storm surge predicted by the SLOSH model (Fig. 1 and Table 2). These time series were compared statistically by calculating RV, and Mean Absolute Error (MAE) for model to observation comparisons, or Mean Absolute Difference (MAD) for model to model comparisons. The time period available for model output was up to 100 hours surrounding landfall based on the strength of tropical storm winds in the basin. Model performance for Hurricanes Charley 2004, Dennis 2005, and Wilma 2005 are discussed in the Results section.

Motivated by the constraints of operational storm surge forecasting, a few optimizations were applied to expedite the production of a storm tide prediction. The extraction program output file was rewritten from ASCII to binary reducing the time required to read the harmonic constants. Additionally, by applying a trigonometry identity for adding cosines: $\cos(\alpha + \beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$, the tide calculation equation was rewritten. By doing so, the trigonometric calculation could be removed from a double-nested loop over time and space. These optimizations reduced the computational time ten-fold.

3. Results

The SLOSH tide code performed well at predicting water levels at NOS tide gauge stations. RV for nineteen tide gauge stations along the East Coast and Gulf of Mexico show good agreement at most stations (Table 1). Ten of the RV produced values of 0.87 or greater. Most of these stations are located in areas with a tide range greater than 0.3 m (one foot) such as stations in the Northeast and Mid-Atlantic regions. Stations with poor RV (i.e., < 0.6) typically had tide ranges less than 0.3 m, such as stations in southern Florida or the Gulf of Mexico.

The new storm tide product improved the prediction of water levels resulting from surge and tides for all hurricanes tested in this project. An example of this improvement is Hurricane Wilma which made landfall at low tide with an observed maximum water level of 1.12 m. The previous version of the SLOSH model predicted a maximum surge of 1.43 m whereas the new storm tide product predicted a maximum storm tide of 1.16 m. By adding gridded tides to the surge prediction, the over-estimated storm tide prediction was reduced and nearly equaled the observed water levels at Miami, FL (Fig. 2). In other cases, the storm tide product improved upon under-estimates of maximum water levels (not shown). The MAE was reduced in all cases by a few hundredths of a meter, and most of the RV increased (Table 2). RV were near or above 0.9 for Hurricane Dennis.

Table 1. RV and tidal ranges for nineteen tide gauge stations along the East Coast and Gulf of Mexico. Tidal ranges are in meters above mean sea level.

Name	Latitude	Longitude	NOS Gauge No.	RV	Tidal Range
Bar Harbor, ME	44° 23.5' N	68° 12.3' W	8413320	0.98	2.94
Ocean City, Inlet, MD	38° 19.7' N	75° 5.5' W	8570283	0.96	0.60
Ocean City, MD	38° 19.6' N	75° 5' W	8570280	0.96	0.60
Lewisetta, VA	37° 59.7' N	76° 27.8' W	8635750	0.87	0.33
Duck, NC	36° 11' N	75° 44.8' W	8651370	1.00	0.88
Myrtle Beach, SC	33° 39.3' N	78° 55.1' W	8661070	0.99	1.33
Fort Pulaski, GA	32° 2' N	80° 54.1' W	8670870	0.94	1.80
Fernandina Beach, FL	30° 40.3' N	81° 27.9' W	8720030	0.89	1.61
Mayport, FL	30° 23.8' N	81° 25.8' W	8720218	0.96	1.20
Port Canaveral, FL	28° 24.9' N	80° 35.5' W	8721604	1.00	0.94
Vaca Key, FL	24° 42.7' N	81° 6.3' W	8723970	0.34	0.22
Naples, FL	26° 7.9' N	81° 48.4' W	8725110	0.88	0.64
St. Petersburg, FL	27° 45.6' N	82° 37.6' W	8726520	0.86	0.48
Apalachicola, FL	29° 43.6' N	84° 58.9' W	8728690	1.00	0.35
Pensacola, FL	30° 24.2' N	87° 12.6' W	8729840	0.48	0.20
Grand Isle, LA	29° 15.8' N	89° 57.4' W	8761724	0.76	0.13
Sabine Pass, TX	29° 43.7' N	93° 52.2' W	8770570	0.46	0.26
Corpus Christi, TX	27° 34.8' N	97° 13' W	8775870	0.85	0.24
Port Isabel, TX	26° 3.6' N	97° 12.9' W	8779770	0.53	0.19

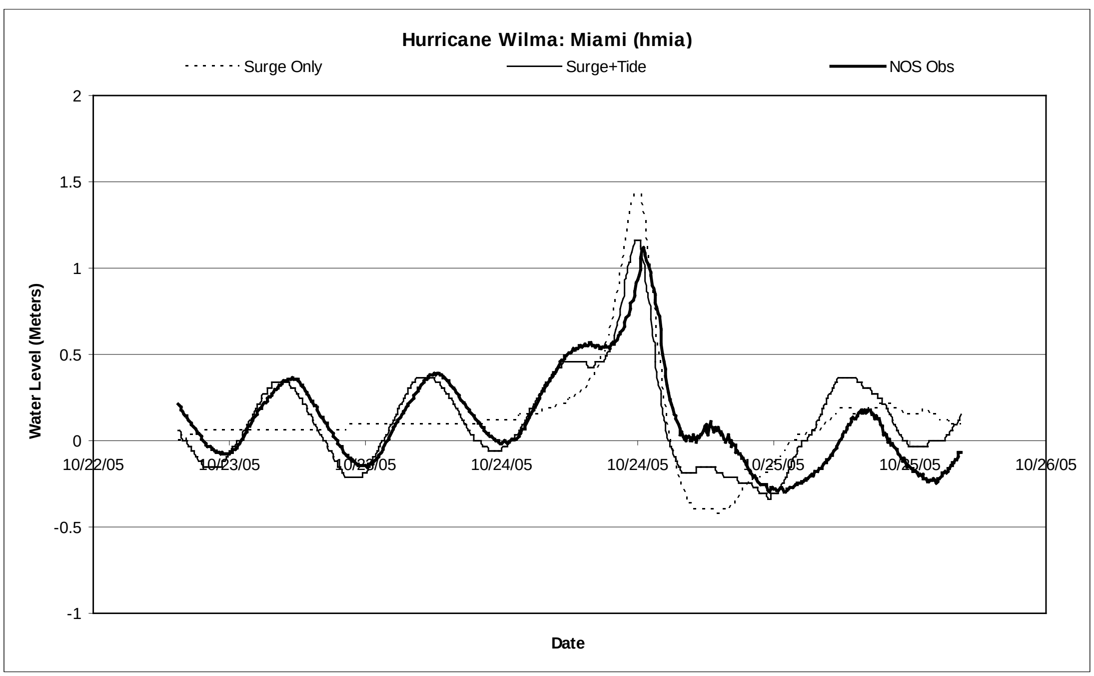

Figure 2. Time series plot of water levels for Hurricane Wilma at Miami.

There are a few locations where the storm tide product did not improve the total water level prediction. Hurricane Charley near Fort Myers, FL is an example of this. The storm tide product was not able to reproduce the NOS tidal prediction or the observed tides; therefore the correlations decreased. Additionally, both the new storm tide product and SLOSH surge predictions did not correlate well with water levels observed at Fort Myers or the Florida Keys during Hurricane Wilma. RV were equal to or less than 0.5. The gridded tide product for SLOSH was, however, able to predict NOS tides in Naples, FL which is 56 km south of Fort Myers (RV = 0.954, Table 2).

Table 2. Tidal ranges and RV from the NOS predictions during the time period data were collected. RV are presented for comparisons of SLOSH gridded tide prediction to NOS tide prediction (R^2 SGT-NOST), storm tide product to NOS observed water levels (R^2 ST-NOS Obs), and SLOSH surge only predictions to the NOS observed water levels (R^2 S-Obs). MAE of storm tide product (MAE ST) and SLOSH surge only prediction (MAE S) are also presented. Water levels are in meters above mean sea level. X represent missing observations.

Basin	Station	Tidal Range	R^2 SGT-NOST	R^2 ST-NOS Obs	R^2 S-Obs	MAE ST	MAE S	Diff MAE
Hurricane Charley 2004								
Fort Myers (efm2)	Fort Myers	0.488	0.066	0.742	0.889	0.691	0.743	0.051
Fort Myers (efm2)	Naples	1.027	0.954	x	x	x	x	x
E.T. GOM (egm3)	Fort Myers	0.488	0.066	0.469	0.768	0.482	0.486	0.004
Hurricane Dennis 2005								
Apalachicola (ap2)	Apalachicola	0.576	0.816	0.908	0.903	0.238	0.304	0.066
Apalachicola (ap2)	Panama City	0.564	0.849	0.859	0.857	0.174	0.195	0.021
Apalachicola (ap2)	Pensacola	0.631	0.704	0.913	0.789	0.142	0.185	0.043
E.T. GOM (egm3)	Apalachicola	0.576	0.804	0.933	0.929	0.192	0.247	0.055
E.T. GOM (egm3)	Panama City	0.564	0.849	0.894	0.790	0.212	0.248	0.036
Hurricane Wilma 2005								
Fort Myers (efm2)	Naples	0.887	0.896	0.264	0.147	0.204	0.228	0.024
Fort Myers (efm2)	Vaca Key	0.387	0.730	0.508	0.473	0.289	0.305	0.017
FL Keys (eke2)	Vaca Key	0.387	0.765	0.258	0.356	0.213	0.221	0.008
FL Keys (eke2)	Key West	0.597	0.986	0.336	0.095	0.215	0.273	0.058
Miami (hmia)	Miami	0.613	0.094	0.713	0.467	0.125	0.195	0.070
Miami V3 (hmi3)	Miami	0.613	0.841	0.733	0.482	0.122	0.194	0.071

4. Conclusions and Discussion

Overall, this project improved the storm tide predictions. The MAE was reduced and RV increased. Occasions where the correlations were poor could be due to inaccuracies predicting tides, timing errors in either the forcing from the parametric wind model, or delays in the predicted storm surge. Predicted peak surges led or lagged the observed peak surges by up to a few hours. Further investigation of this timing issue will be left to future work.

This project is not complete as there are a few other nuances to be worked out. Tidal prediction at stations with tidal ranges less than 0.3 m in this study tended to be inaccurate. Unfortunately, many tide gauges in Florida and the Gulf of Mexico report ranges less than 0.3 m. Attempts have been made to resolve these inaccuracies with improved harmonic constituents from the Tidal Constituent and Residual Interpolation (TCARI) method (Hess et al. 1999), developed by CSDL. Harmonic constants are adjusted on the basin-scale based on the difference between model predictions and tidal gauge observations. Resolving issues with the TCARI method will continue. Until these nuances can be resolved, caution should be exercised when predicting storm tides in regions with small tide ranges (< 0.3 m). Conversely, this does not reciprocate into large errors since these values are less than 0.3 m, which is within the prediction ability of the SLOSH model (Glahn et al. 2009).

Future work will include better methods for inundating grid cells because the current method of superimposing the tide grid on the surge grid does not allow the model to inundate cells with the combined surge and tide. We will pursue an enhanced method for adding the tide grid to the surge grid to address this. A final step will be to discontinue superimposing tides and move to tidal forcing along an open boundary, which is anticipated to improve on predicting storm tide in bays and estuaries. The three methods for creating a storm tide product will be compared, and the best method will be suggested for implementation into operations. The improvements from the progress thus far can better inform the public when a tropical storm is forecast to impact a region.

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