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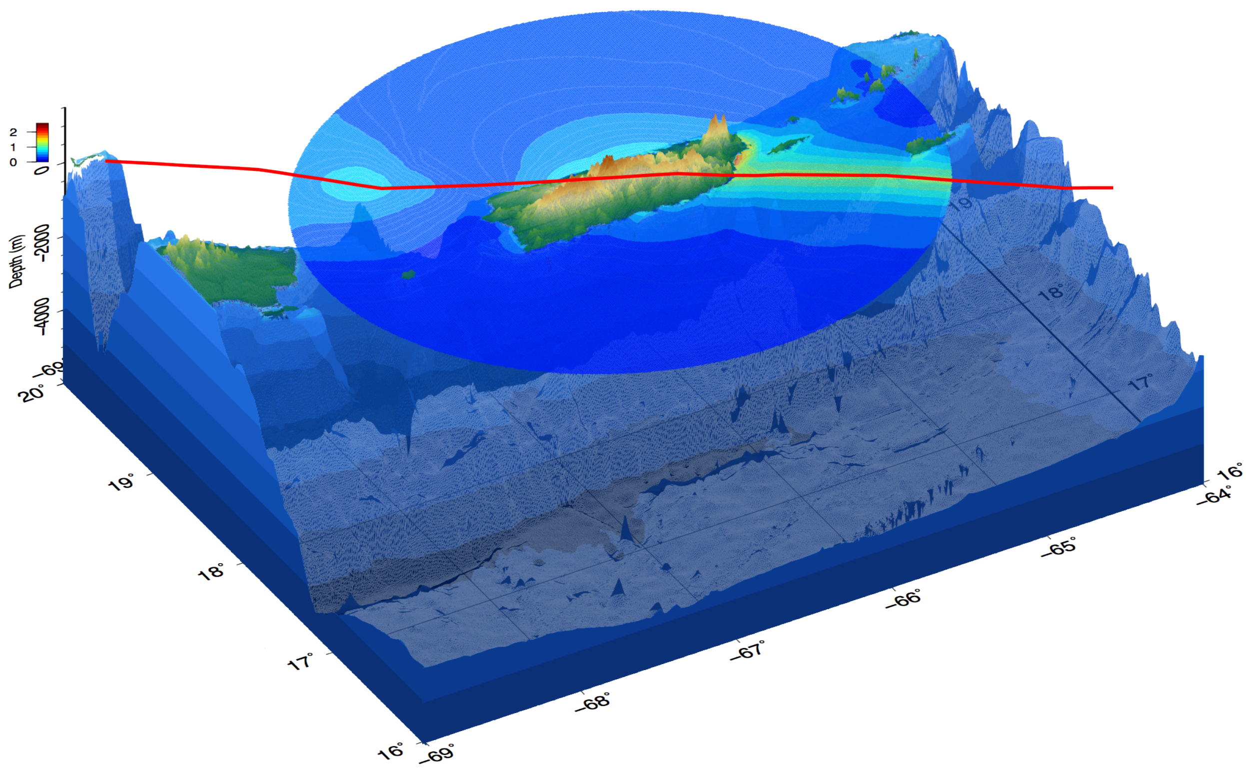
Validation of Storm Surge and Wind for High Intensity Hurricanes during the 2017 Season



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1. Introduction

Multiple major, high-intensity tropical cyclones made landfall during the 2017 hurricane season, producing massive destruction along the Gulf of Mexico, the southeast US, the Bahamas and the Caribbean Sea.

In order to assess the impact from storm surge, hindcast simulations were run using the US National Weather Service SLOSH (Sea Land Overland Surges from Hurricanes) storm surge prediction model (Jelesnianski et al. 1992) for hurricanes Harvey (al092107), Irma (al112017), Maria (al152017) and Nate (al162017, not shown).

Extensive validations were conducted by comparing observed measurements of water levels, waves and winds against model results to evaluate the performance of the model.

Model hindcast validations are an essential component in the assessment of any numerical forecast system. They help determine inherent errors in the model's dynamics, physics and input parameters (forcing, grids), help qualify and quantify these errors (Forbes et al. 2010a, Forbes et al. 2010b, Forbes et al. 2012, Forbes et al. 2014), identify biases and deficiencies that can be corrected, and establish confidence in the model's capabilities.

Comparisons of the simulation results against observations and derived statistical metrics were used to determine which enhancements were most needed to achieve more accurate numerical simulations of storm surge and winds.

Improvements in the accuracy of the water levels were assessed with two modeling systems: SLOSH coupled with 1) the SWAN (Simulating Waves Nearshore) wave model (Forbes et al. 2015, Van der Westhuysen et al. 2014, Luettich et al. 2012) which is loosely coupled, with exchanges of input/output fields every 30 minutes of model simulation time for Hurricane Maria (Section 3.1), and 2) the GWAVA (Gradient Wind Asymmetric Vortex Algorithm) wind model (Mattocks and Forbes 2008, Mattocks et al. 2010, Mattocks et al. 2018) used in simulations of hurricanes Harvey (Section 3.2) and Irma (Section 3.3) which is tightly coupled by being embedded in SLOSH, so the wind forcing is computed at every time step and grid point.

2. Methodology

The SLOSH storm surge prediction model (Jelesnianski et al. 1992, Taylor and Gahn 2008) was used to generate the hurricane hindcast simulations, as described in Forbes et al. (2012) for Hurricane Irene and in Forbes et al. (2014) for Hurricane Sandy.

The input wind parameters for SLOSH were extracted from the NHC's Best Track so the ensuing forcing was consistent with the SLOSH wind formulation.

The grid basins were determined by the landfall location of each storm. The closest point of approach was estimated from the selected basins' coastline coverage and the tropical cyclone track. A cubic spline interpolation algorithm was applied to the storm track to provide the temporal resolution required to run SLOSH.

The SLOSH model generated a maximum envelope of water and a temporal evolution of surge (plus tides) and winds in areas that were impacted by the storm. These model results were compared with observations from NOAA tide gauges and USGS pressure sensors, USGS high water marks (not shown), NDBC buoys and the Jason-3 altimeter.

Throughout this study, the maximum envelope of water is specified above ground level (AGL) - subtracting the land elevation from the total water level in the basin's vertical datum over land grid cells - and as surge plus tides over water grid cells.

3. Hindcast Simulations

The most impactful hurricanes of 2017 were simulated with the SLOSH model forced by the Best Tracks for hurricanes Maria, Harvey and Irma, as described in Section 2.

As part of the storm validation procedure, the model results were then compared against observational measurements.

3.1 Hurricane Maria

Hurricane Maria (Pasch et al. 2018) was the 10th most intense Atlantic hurricane on record and the deadliest storm of the 2017 hurricane season with maximum sustained winds of 175 mph (152 kts) and a central pressure of 908 mb at 0300 UTC on September 20, 2017. An eyewall replacement cycle took place shortly thereafter, weakening Maria to a Category 4 storm before it struck Puerto Rico. Interaction with land weakened it further.

As part of the post-storm analysis, Hurricane Maria simulations were conducted (per the methodology described in Section 2) over the SLOSH high resolution Puerto Rico hsj5 basin.

The maximum simulated water elevation using the Best Track, were 2.38 m with waves and 2.29 m without waves, located in different areas. The maximum envelope of water is shown in Fig. 1, left panel, and cover page. Note the maximum to the right of the landfall location.

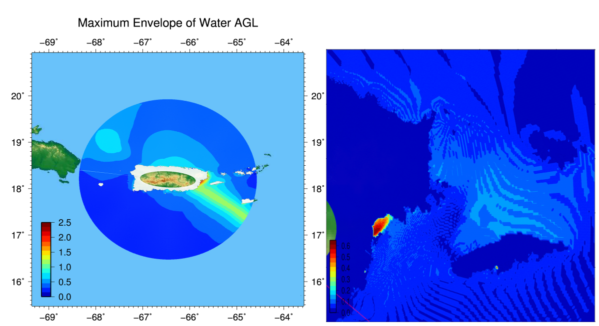

FIG. 1. Maximum envelope of water (m) with waves (AGL on land and surge+tides over water, left panel) and the wave contribution (m, right panel) along the eastern coast of Puerto Rico.

The wave contribution (difference between the SLOSH surge+tides simulation and the SLOSH+SWAN surge+tides+waves simulation at each grid location) was 0.64 m (2.1 ft) (Fig. 1, right panel).

The NOAA and USGS time series vs. the model water levels (Fig. 2) show the high surges located in the northeast and southeast (top panels) of the island. However, the model overpredicted the inundation in those areas (bottom panels).

It is worth noting that there was a higher tidal contribution in the northern part of the island (Fig 2, top left panel) than in the southern part of the island (Fig 2, top right panel).

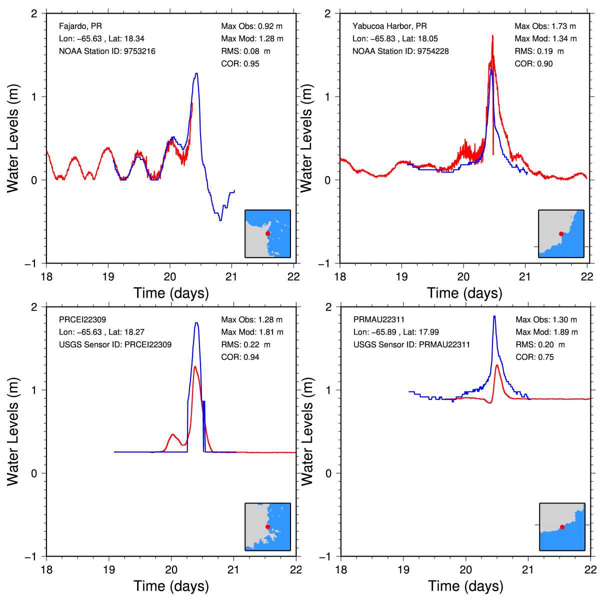

FIG. 2. NOAA (top) and USGS (bottom) time series (red) vs. the SLOSH (blue) model water levels (m).

SWAN significant wave heights (SWH), forced by the SLOSH winds and initialized with temporally varying water levels from SLOSH, were compared with the observed SWH from four NDBC buoys (two had incomplete or no time records, not shown) and from two Jason-3 passes.

The sea surface height anomaly (SSA) from the Jason-3 altimeter was also compared with the SLOSH model water levels. Since the passes occurred before and after the storm, the correlations (timing of the signal) are low but, because the ocean is a slowly evolving environment, the RMS errors are low as well.

A summary of the model results and all analyzed observations are shown in Table 1.

TYPE OF DATA	Total Analyzed Obs	Max Obs (m)	Max Mod (m)	RMSE (m)	CORR	Notes
NOAA Tide Stations (SURGE)	9	0.57-1.73	0.37-1.34	0.06-0.24	0.67-0.93	Total = 17 (no or incomplete data = 8)
USGS SSS (SURGE)	10	0.99-1.30	0.85-1.89	0.08-0.38	0.67-0.94	Total = 11 (1 @ seawall not represented in SLOSH)
JASON 3 Altimeter (SSA)	2 passes	0.62-0.72	0.30-0.52	0.13-0.23	0.35-0.20	(before and after the storm, not at the exact model time)
NDBC Buoys (SWH)	4	6.0-7.9	4.8-8.2	1.04-1.50	0.94-0.98	6 (incomplete = 2)
JASON 3 Altimeter (SWH)	2 passes	2.76 12.17	3.75-5.35	0.88-1.95	0.53-0.65	(before and after the storm, not @ exact model time and buoy location)

TABLE 1. Summary of statistics of model results vs. observations during Hurricane Maria.

3.2 Hurricane Harvey

Hurricane Harvey (Blake and Zelinsky 2018) is the second-most costly hurricane in US history behind Katrina (2005). It was a catastrophic flooding event with unprecedented rainfall (60.58 inches near Nederland, Texas). It was the wettest tropical cyclone on record in the US. Its first landfall was in Barbados; second Landfall in St Vincent; third landfall at San Jose Island, Texas, east of Rockport, with a peak intensity 113 mph (98 kts) and 937 mb as a Cat 4 storm; fourth landfall at San Holiday Beach as a Cat 3 storm; fifth landfall in Louisiana.

As part of the post-storm analysis, Hurricane Harvey simulations were conducted (per the methodology described in Section 2) over the SLOSH Corpus Christi cr3 basin in Texas where the third landfall occurred.

The maximum simulated water level was 3.54 m using the Best Track parameters (Fig. 3).

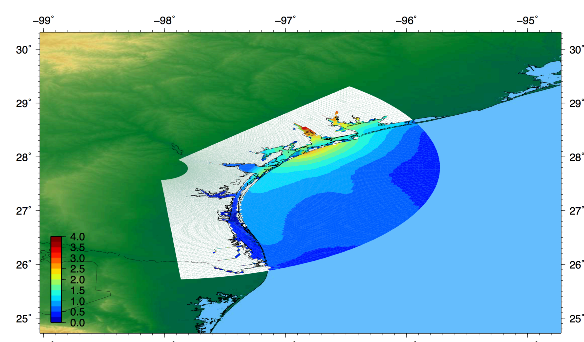

FIG. 3. Maximum envelope of water (m) AGL on land and surge+tides in the Gulf of Mexico.

Examples of the NOAA and USGS time series vs. the model water levels at locations to the left and right of the track are shown in Fig. 4.

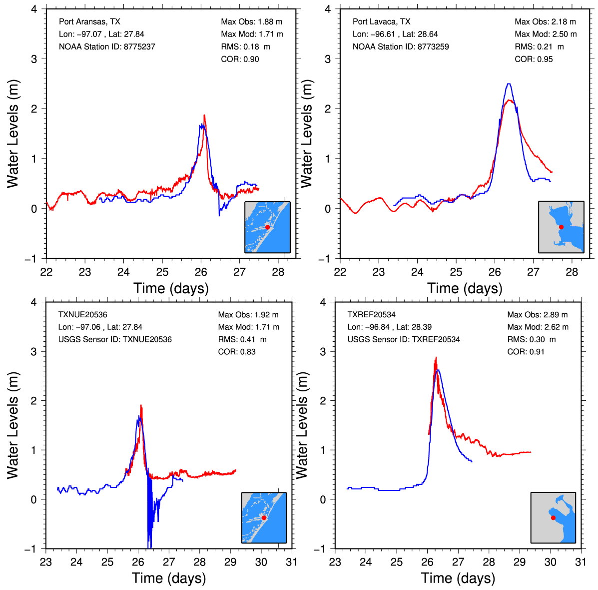

FIG. 4. NOAA (top) and USGS (bottom) time series (red) vs. the SLOSH (blue) model water levels (m).

The model water levels are in good agreement with the observations. The bottom left panel in Fig. 4 shows a visible drawdown in the model water levels that was not captured in the observations due to the placement of the USGS sensor high above the ground.

Two Jason-3 altimeter passes, before and after the storm (not shown), have SSA measurements that are in good agreement with the SLOSH model results. As seen in Section 3.1 with Hurricane Maria, RMS errors are low but the correlations are also low due to the timing of the passes before and after the storm.

Table 2 shows a summary of the statistics of model results and analyzed observations.

TYPE OF DATA	Total Analyzed Obs	Max Obs (m)	Max Mod (m)	RMSE (m)	CORR	Notes
NOAA Tide Stations (SURGE)	15	0.51-2.18	0.58-2.50	0.12-0.42	0.65-0.90	Total = 39 in TX (inside SLOSH grid = 15, 2 incomplete obs records, one with wall not resolved by grid)
USGS SSS (SURGE)	11	0.94-2.79	1.19-2.69	0.18-0.64	0.57-0.96	1 inside harbor not resolved by model grid and 1 behind a bridge.
JASON 3 Altimeter (SSA)	2 passes	0.22-0.52	0.18-0.52	0.12-0.21	0.26-0.39	(before and after the storm, not at the exact model time)

TABLE 2. Summary of statistics of model results vs. observations during Hurricane Harvey.

3.2 Hurricane Irma

Hurricane Irma (Cangialosi et al. 2018) began as a tropical wave near Cape Verde on August 30, 2017, rapidly intensified to a Cat 3 hurricane on August 31, reached Cat 5 intensity on September 5, 2017 and attained a peak intensity of 180 mph (156 kts), 914 mb on September 6. It went through multiple eyewall replacement cycles and later weakened due to land interactions over Cuba. It re-intensified to a Cat 4 storm over the warm water in the Florida Straits, making landfall near Cudjoe Key with winds reaching 130 mph (113 kts), and it produced a 10 ft storm surge. Its next landfall was close to Marco Island, Florida with winds of 112 mph (97 kts). Thousands of homes were damaged or destroyed in the Florida Keys.

Hurricane Irma simulations were conducted (per the methodology described in Section 2) over the eke2 (Key West), hmi3 (Miami) and efm2 (Ft. Myers) SLOSH basins.

3.2.1 Key West (eke2 Basin) Simulations

The maximum simulated water level in the eke2 basin was 3.93 m, using the Hurricane Irma Best Track parameters, as shown in Fig. 5.

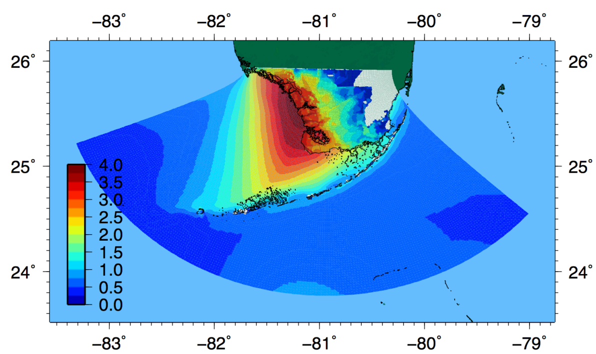

FIG. 5. Maximum envelope of water (m) AGL on land and surge+tides in the Florida Bay and adjacent open waters.

Comparisons of time series of water levels at NOAA tide stations and USGS pressure sensors with their model counterparts were conducted to assess the model performance. Examples are shown in Fig 6.

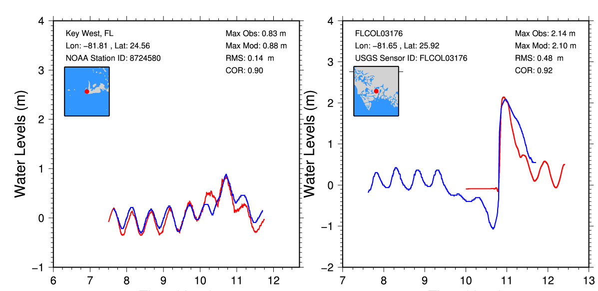

FIG. 6. NOAA (left) and USGS (right) time series (red) vs. the SLOSH (blue) model water levels (m).

Table 3 in Section 3.2.4 shows a summary of statistics for all stations analyzed in this basin.

3.2.2 Miami (hmi3 Basin) Simulations

The maximum simulated water level in the hmi3 basin was 1.74 m, using the Hurricane Irma Best Track wind parameters. The maximum envelope of water is shown in Fig. 7.

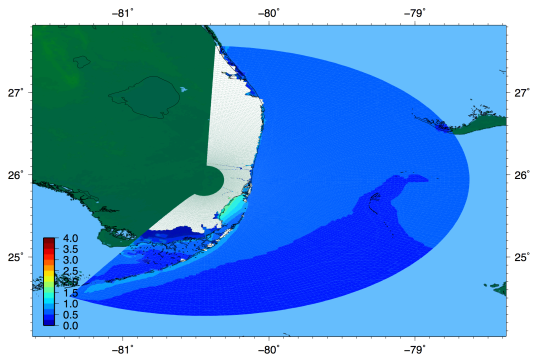

FIG. 7. Maximum envelope of water (m) AGL on land and surge+tides offshore.

Examples of time series of water levels at NOAA tide stations and USGS pressure sensors compared with their model counterparts are shown in Fig. 8. The simulated water levels are in good agreement with the observations.

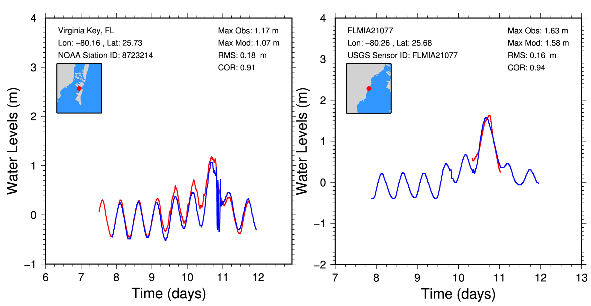

FIG. 8. NOAA (left) and USGS (right) time series vs. the SLOSH model water levels (m).

Table 3 in Section 3.2.4 shows a summary of statistics for all stations analyzed in the hmi3 basin.

3.2.3 Fort Myers (efm2 Basin) Simulations

The maximum simulated water level, using the Best Track, in the efm2 basin was 3.78 m. The maximum envelope of water is shown in Fig. 9.

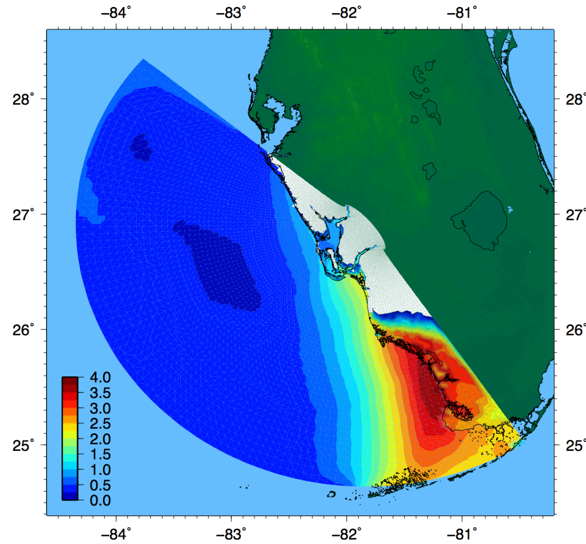

FIG. 9. Maximum envelope of water (m) AGL on land and surge+tides in Florida Bay and the Gulf of Mexico.

Examples of time series of water levels at NOAA tide stations and USGS pressure sensors and their model counterparts are shown in Fig. 10.

In this case, the SLOSH model overpredicted the water levels near the landfall location. For measurements further north of landfall, where offshore winds drove the waters away from the coast, the model water levels are in good agreement with the peak observed values.

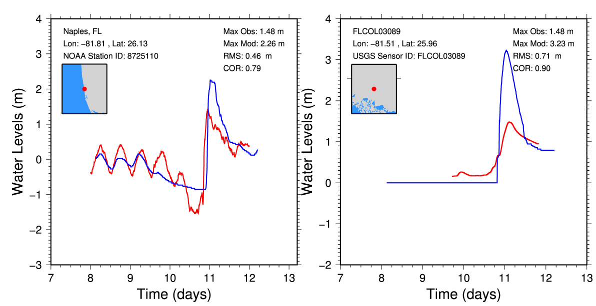

FIG. 10. NOAA (left) and USGS (right) time series vs. the SLOSH model water levels (m).

3.2.4 Summary of Hurricane Irma Simulations

Table 3 shows the summary of statistics for all stations analyzed in this basin.

The summary of the statistical analyses at some NOAA stations and USGS pressure sensors shows that SLOSH overpredicted the maximum water levels at those locations at landfall by 1 m (3 ft), in the emf2 basin.

The correlations are high, which show the timing of the model-simulated water level signals are in phase with their observed counterparts.

The RMS water level fluctuations at the coast are lower than 0.25 m in the eke2 and hmi3 basins and less than 0.5 in the efm2 basin, while the RMS errors for inland measurements in the eke2 and hmi3 basins are less than 0.9 m but reach values higher than 1 m in the efm2 basin.

TYPE OF DATA	SLOSH Basin	Total Obs Analyzed	Max Obs (m)	Max Mod (m)	RMSE (m)	CORR
NOAA Tide Stations	eke2	2	0.67-0.83	0.88-0.94	0.14-0.25	0.60-0.90
	hmi3	2	0.77-1.17	0.79-1.07	0.14-0.22	0.91-0.93
	efm2	2	1.02-1.48	1.49-2.26	0.32-0.46	0.79-0.95
USGS SSS	eke2	9	1.24-2.53	0.98-3.29	0.14-0.89	0.84-0.96
	hmi3	17	0.77-1.75	0.67-1.58	0.15-0.79	0.52-0.98
	efm2	19	0.48-2.53	0.67-3.54	0.41-1.34	0.31-0.94
TOTAL	ALL	51	0.48-2.53	0.67-3.54	0.14-1.34	0.52-0.98

TABLE 3. Summary of statistics of model results vs. observations during Hurricane Irma.

4. Improvements to the Accuracy of Simulated Water Levels

Improvements to the accuracy of the simulated water levels were achieved by coupling the SLOSH model with: 1) a wave model (SWAN) in regions of steep bathymetry, and 2) an asymmetric wind model (GWAVA).

4.1. Coupled SLOSH+SWAN Wave Model

As described in Section 3.1, simulations of Hurricane Maria were conducted using the coupled SLOSH+SWAN model. The SWAN model was loosely coupled with SLOSH (Forbes et al. 2015, Van der Westhuysen et al. 2014, Luettich et al. 2012). This was achieved by: 1) running a SLOSH simulation, 2) running SWAN with winds and water levels provided by SLOSH every 30 minutes, and 3) forcing SLOSH with the output (e.g., radiation stresses) computed by the SWAN wave model.

The coupled system was run over the SLOSH high-resolution Puerto Rico grid (hsj5). The contribution from waves for this particular storm was 0.64 m.

4.1.2. Coupled SLOSH+GWAVA Wind Model

Anomalously high surge was produced by the SLOSH model in some areas, particularly during Hurricane Irma. One of the possible causes is the simplicity of the SLOSH parametric wind model in depicting the wind field due to its storm-relative azimuthal symmetry.

To test this hypothesis, improvements to the wind forcing were achieved by incorporating the GWAVA asymmetric parametric wind model (Mattocks and Forbes 2008) into SLOSH at every time step and every grid point (tight coupling mode).

An overview of the features of GWAVA and wind model validations for Hurricane Irma are described in a separate paper (Mattocks et al. 2018).

Preliminary results of the GWAVA implementation in SLOSH during hurricanes Irma and Harvey show significant improvements in the accuracy of the simulated water levels (Fig. 11).

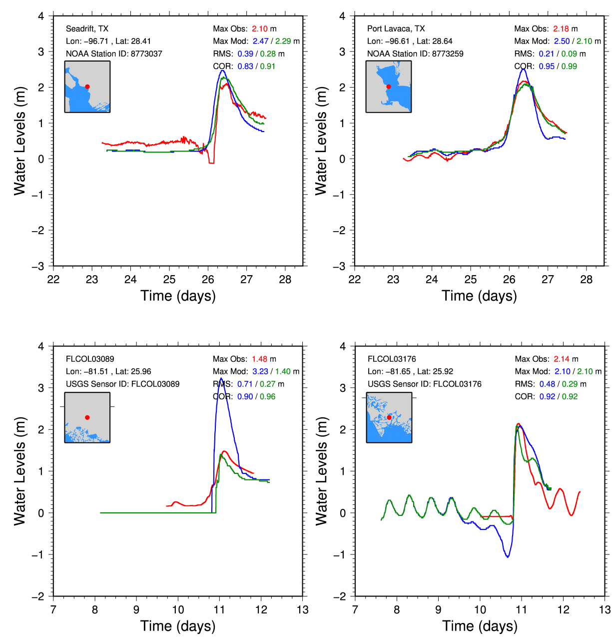

FIG. 11. Evolution of the water levels generated by GWAVA (green), SLOSH (blue) and observed winds (red) during Hurricanes Harvey at NOAA stations (top) and Hurricane Irma at USGS pressure sensor locations (bottom).

The GWAVA wind model corrects excessive peaks and drawdowns in water levels at the coast and inland during both Hurricane Harvey and Irma.

Besides the improvement in the water level peak and drawdown, the RMS error is much lower and correlations are much higher with the GWAVA wind model than with the SLOSH wind model forcing.

5. Conclusions

Extensive validations of water levels, wind speed and wind direction were performed during hurricanes Harvey in Texas, Irma in Florida and Maria in Puerto Rico.

Simulated water levels improved in regions of steep bathymetry by coupling SLOSH with the SWAN wave model. In the case of Hurricane Maria in Puerto Rico, waves contributed an additional 0.64 m (2.1 ft) to the water levels forced by winds only.

Incorporating GWAVA winds at every grid point and every time step (tight coupling) in SLOSH provides more accurate predictions of storm surge (peaks and drawdowns were cut by half in some cases) and timing (peak arrival and departure) both at the coast and inland.

Even though these were catastrophic events that affected large populations, the loss of life and damage due to coastal inundation from salt water (storm surge plus tides) was not as severe as in the cases of Hurricane Sandy (2012) and Katrina (2005). The most serious loss of life and property for these three storms during 2017 were caused by high wind and heavy rainfall.

More testing will be conducted with the updated NHC Best Tracks, which have just recently been finalized and released.

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