Development and Validation of a Coastal Surge and Inundation Prediction System

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Abstract — **The development and validation of a coastal storm surge and inundation prediction system for operational use by the United States Navy is detailed. The system consists of the Delft3D-FLOW hydrodynamic model coupled with the Delft3D-WAVE wave model and a graphical user interface, the Delft Dashboard. The coupled system is used to model storm surge and inundation produced by Hurricane Ike along the Gulf of Mexico coast in September 2008. The hydrodynamic model is run in 2D depth averaged mode to develop a "best" simulation. The best simulation is developed after hundreds of test runs and it consists of a blended elevation dataset for use as the model bathymetry and topography, a spatially varying Manning's N coefficient, multiple nests, atmospheric forcing from re-analysis wind and pressure fields with directional land masking, an initial water level of 0.11 m, an updated air – sea drag coefficient, and dynamically coupled flow and wave fields. The simulation results compare very favorably with observed water level. To assess the system in an operational forecast environment, the system's sensitivity to the elevation dataset, bottom roughness, domain resolution, atmospheric forcing, drag coefficient, initial water level, and wave coupling was investigated and found to vary widely depending on the component.**

Storm surge; Inundation; Hydrodynamic modeling; Delft3D; Forecasting

I. Introduction

Coastal regions are vital to naval operations and have rapidly growing populations making them increasingly vulnerable to storm surge and inundation. It is estimated that 10% of the world population lives in the 2% of the total landmass of the earth that comprises the low elevation coastal zone (LECZ, land area contiguous with the coast that is 10 m or less in elevation, [1]). Nearly two-thirds of coastal megacities (populations greater than 5 million) are located in the LECZ [1] and population densities within 100 km of the coast are three times higher than the global average density [2]. Many military facilities including most US naval bases are situated within the LECZ as well. These low-lying regions are most at risk from storm surge and coastal inundation as demonstrated by recent natural disasters such as Hurricanes Katrina (2005), Ike (2008), and Irene (2011) along the US Gulf and East Coasts, Cyclone Nargis (2008) along the coast of Myanmar, and the strong storm in December 2008 which affected Papua New Guinea, Wake Island and Kwajalein Atoll. Not only are many of these coastal regions key to naval operations, but the Navy's humanitarian assistance and disaster response teams play an important role in bringing aid to these affected areas [3], making it is critical to provide accurate and timely forecasts of coastal inundation.

The US Navy currently uses Delft3D for prediction of nearshore circulation when inundation is not the primary concern and uses PC-Tides [4] for worldwide coastal surge and inundation. However, PC-Tides does not include waves or other global ocean circulation and is also limited to a maximum resolution of approximately 500m, which is insufficient for inundation predictions. The Delft3D modeling system (Delft3D-FLOW and Delft3D-WAVE) uses multiple nests to capture large, basin-scale circulation as well as coastal circulation and tightly couples waves and circulation at all scales [5] [6]. A number of storm surge modeling systems exist with similar features such as: ADCIRC [7] [8], CH3D-SSMS [9] [10], CMEPS [11] [12], ELCIRC [13] [14], FVCOM [15] and POM [16]. However each of these systems has the weakness of requiring specifically trained individuals who possess a thorough understanding of storm surge and inundation physics, to perform the model set-up and data/file management manually. In using Delft3D, the Delft Dashboard, a graphical user interface (GUI) product, can be used to simplify the set-up of Delft3D features such as the grid, elevation data, boundary forcing, and nesting. In this way less man-hours and training will be needed to perform inundation forecasts without any loss in accuracy that may accompany more simplified modeling systems.

This paper will detail the validation of the new Coastal Surge and Inundation Prediction System (CSIPS) which is in development for operational use by the US Navy. Section 2 will briefly describe the modeling system and graphical user interface. Section 3 provides details of the hindcast simulation of Hurricane Ike using the best available resources. Section 4 assesses the sensitivity of the Ike results to various components of the modeling system that may be affected when the system is in an operational forecasting environment. The final section will provide a summary and conclusions of the work.

II. The Coastal Surge and Inundation Prediction System (CSIPS)

The Coastal Surge and Inundation Prediction System (CSIPS) is currently in development and undergoing validation studies before it can be transitioned into

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operational forecasting use. The core of the system consists of three parts, Delft3D-FLOW, Delft3D-WAVE, and the Delft Dashboard. FLOW solves the shallow water equations with a finite difference scheme in 2 (depth averaged) or 3 dimensions. It computes the non-steady flow resulting from tidal forcing along the open boundaries, wind stress and atmospheric pressure along the free surface, and forcing from pressure (barotropic) or density (baroclinic) gradients [5]. The model has been used in previous storm surge and inundation studies [17] [18] [19]. FLOW is dynamically coupled to WAVE by passing water level, currents, winds, and bed level to WAVE. The WAVE results are computed and passed back to FLOW at a user defined interval. Delft3D-WAVE is based on SWAN, a third generation wave model [20]. SWAN computes the full wave spectrum by considering a number of processes including: wave refraction; generation by wind; depth and current induced shoaling; dissipation due to whitecapping, bottom friction, and breaking; nonlinear interactions; transmission and blocking by flow and obstacles; and diffraction [6].

The third component of CSIPS, the Delft Dashboard, is the graphical user interface (GUI) which allows for easy set up of model simulations. Dashboard allows for rapid generation of the model grid, bathymetry, tidal and atmospheric forcing, along with any other input files. In addition Dashboard makes nesting of multiple domains a simple task. Combined the system meets the Navy's goals of including wave forcing in inundation studies, while simplifying the setup of the simulation and in effect reducing the man-hours and training needed to perform inundation forecasts. To assess the performance and sensitivity of CSIPS a test case storm surge event was simulated and various parameters altered to determine the ideal configuration.

III. VALIDATION THROUGH HINDCAST OF HURRICANE IKE

Hurricane Ike made landfall along the Texas coast near Galveston on September 13, 2008 as a category 2 hurricane. Ike was a very large and intense storm, reaching major hurricane strength for part of its track through the Gulf of Mexico. To validate CSIPS, a "best" simulation was established. The simulation consists of multiple nests, a 0.1° basin wide domain (GoM domain), and multiple 0.004° coastal domains (Fig. 1). The elevation dataset consisted of bathymetry and topography data from multiple datasets including: the SURA inundation testbed, the NOAA NGDC Coastal Relief Model, SRTM topography data, and GEBCO data to fill in any gaps in the higher resolution datasets. Tidal constituents were obtained from the OSU global model of ocean tides based on TOPEX7.2 satellite altimeter data [21]. An analysis of mean water levels in the Gulf of Mexico during September indicated a basin wide average elevation increase of 0.11 m which was applied throughout the domain as a constant value in the tidal forcing. Riemann, or weakly reflective, boundary conditions were used along the open boundaries. The atmospheric forcing was in the form of Oceanweather, Inc. (OWI) reanalysis wind and pressure fields on a 0.02° grid provided every 15 minutes. The air-sea drag formulation of [22] was used to convert wind velocity to wind stress. A directional land-masking technique following [23] was applied to account for the reduction of the wind due to changes in the land roughness in the coastal zone. Based on the same land roughness values, a spatially varying Manning's N coefficient was developed with an offshore value of 0.02. Wave simulations are performed in the same domain in the case of the GoM domain, and with 0.016° resolution in the coastal domains. SWAN is run in non-stationary mode with a 20 minute time-step and coupling with the hydrodynamics every hour. Simulated water level for the best run and all sensitivity studies was compared to five NOAA water level stations (Fig. 1) and FEMA high water mark (HWM) data along the Texas and Louisiana coasts.

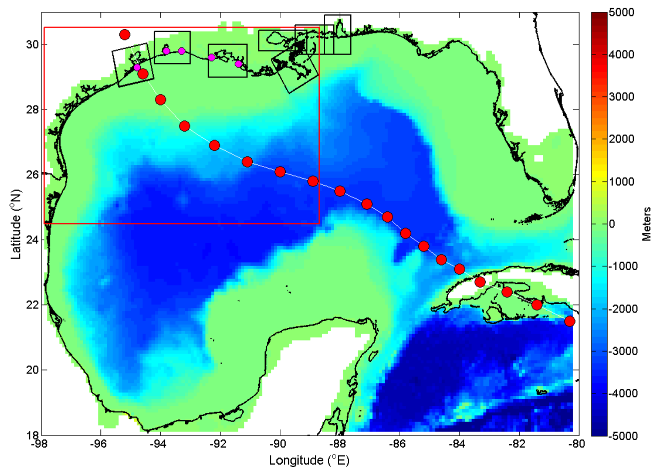

Figure 1. Gulf of Mexico, nearshore (red) and coastal domains (black) for Hurricane Ike simulations (track shown). Magenta circles are water level station locations, left to right: Galveston Pleasure Pier, Sabine Pass North, Calcasieu Pass, Freshwater Canal Locks, and Lawma

The best simulation was run in the Gulf of Mexico basin wide domain for ten days, beginning September 5, 2008 through September 15, 2008. Fig. 2 shows water levels comparisons at the five NOAA stations and a HWM comparison. CSIPS does a very good job capturing the peak water level, even at this coarse resolution, however the inundation results showed a mean absolute percent error (MAPE) of 23.72%. To reduce this error, the higher resolution nests were used. Nesting between the domains was accomplished through Dashboard with water level time series being passed from the GoM domain to the open boundaries of the coastal domains. With the nesting the MAPE for the HWM comparison is reduced to about 18.5%. Further reduction in error is expected with finer grid resolution; however this will come at an increased computational cost. A coupled simulation in the GoM domain takes approximately 30 minutes of wall clock time for each day of simulation with a 10 minute time-step and run on Intel Xeon X5570 2.93GHz processors (one per model). Simulations in the coastal domains also take approximately 30 minutes for a day of simulation with a 1 minute time-step. Future work will address increasing the resolution to improve overland flooding and inundation results.

IV. SENSITIVITY STUDIES

To obtain the best results, hundreds of simulations were performed before settling on the above configuration. In a forecast environment where time is crucial and tropical cyclones can affect naval operations worldwide, many of the above parameters will not be known or available. To determine the capabilities of CSIPS in a forecasting environment a number of sensitivity studies to various components were investigated. Specifically the sensitivity of the results to the elevation dataset, bottom roughness, domain resolution, wave coupling, initial water level, and atmospheric forcing and drag coefficient was studied in the GoM domain.

The elevation dataset used in the best simulation was obtained by comparing the simulation results from a number of combinations of available datasets along with comparison between model depth and recorded station depth at the observation stations. In a forecast environment, these options are not available. Furthermore, for many areas of the world high resolution elevation datasets do not exist. There is global coverage of both the GEBCO and SRTM datasets. Two simulations were performed to see how the use of these datasets affects the model results. Fig. 3 shows the water level comparison and HWM analysis from using the GEBCO dataset only and using the topography data in the SRTM dataset along with the GEBCO bathymetry data as compared to the best simulation. The water level values do not seem to be significantly affected, but the inundation is. The MAPE increases for use of GEBCO only and increases significantly for the combined GEBCO and SRTM dataset. This is expected since these datasets have more coarse resolution than that used in the best simulation. Additionally the combined dataset of GEBCO bathymetry and SRTM topography data may not match up perfectly at the 0 meter contour.

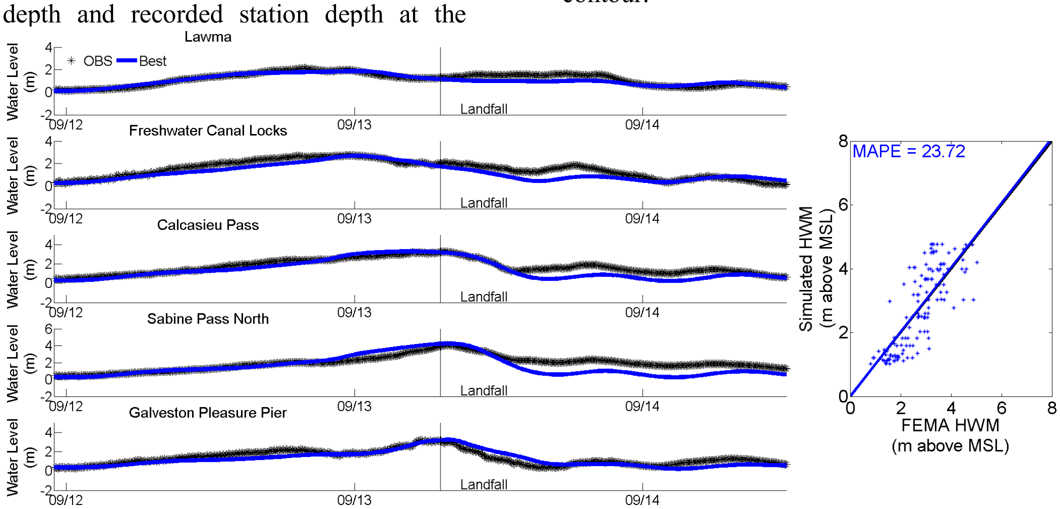

Figure 2. Water level comparisons at five NOAA stations and HWM analysis for best Ike simulation

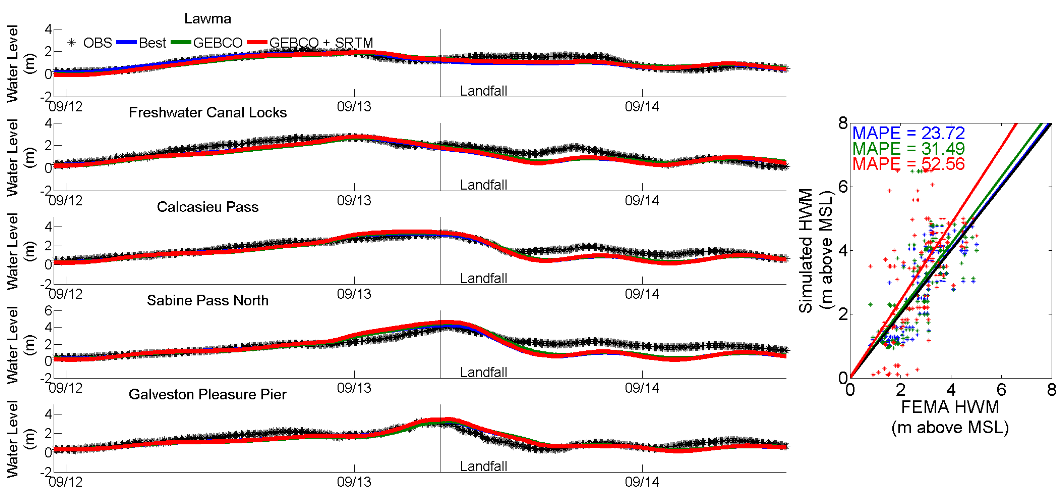

Figure 3. Comparison of water level and inundation results for different bathymetry datasets, the multi-component best set, the GEBCO only set and the combined GEBCO and SRTM dataset

In the 2D (depth-averaged) simulations the bottom roughness is given by the Manning's N coefficient. For the best simulations the spatially varying coefficient was determined based on land use data and the relations in [23]. With land use data not readily available worldwide or variations in land use classifications existing in the available data, sensitivity studies with a constant Manning's N were performed. The plots in Fig. 4 show that the water level is not really influenced when the Manning's N value is held at a constant value of 0.015, 0.02, and 0.025. This is expected since the spatially varying Manning's N of the best simulation has an offshore value of 0.02 for open water. However the HWM comparison shows that the inundation results are affected by this change. The constant values of 0.015 and 0.02 tend to lead to an overestimation of the inundation, since the land surface is rougher than this typically offshore value. The simulation with a constant value of 0.025 gives results closest to those obtained with the spatially varying simulation. While this value works well for this region, it may not always be the case and some local knowledge of the region being forecasted will be necessary to choose and appropriate value.

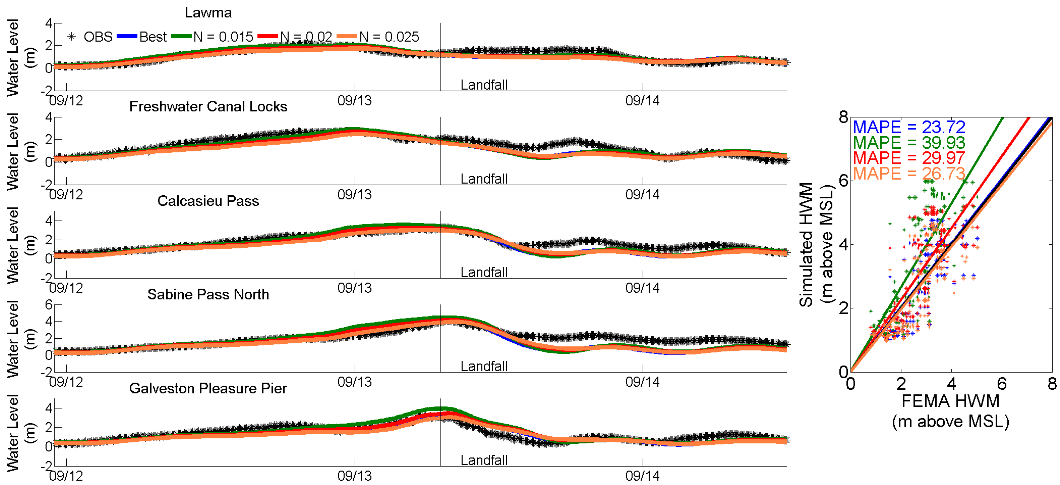

Figure 4. Comparison of water level and inundation results for different Manning's N coefficients, spatially varying for the best, and constant values of 0.015, 0.02 and 0.025

Water levels in the Gulf of Mexico undergo seasonal variations which can influence the simulation results. Analysis of average seasonal mean sea level across the Gulf shows variations of greater than 20 cm depending on the time of year, with maximums occurring during the summer months and minimums in the winter. These fluctuations are primarily caused by changes in temperature, but also do to change in salinity, atmospheric pressure, winds, and ocean currents. To account for this fluctuation a basin wide average of September mean sea level was determined to be +0.11 m and applied in the best simulation. With the Riemann boundary conditions it is necessary to not only start with the initial water level, but to apply it as a constant tidal forcing along the boundary, otherwise the initial conditions will simply "spill out" of the domain. Fig. 5 shows the comparison between the best simulation and one without accounting for the seasonal sea level fluctuation. There is a slight difference at all stations and in the HWMs. However considering the magnitude of the surge compared to that of the seasonal variation, it is not a surprise that this component has only a slight effect on the results.

The resolution of the domain can also have an influence on the results and the timing of the simulation. For the GoM domain a simulation with double the resolution (0.05°) was performed but showed little improvement and increased computational cost (MAPE of 20.97% as opposed to 23.72% in HWM analysis). The number of nests may also have an influence on the simulation. To attempt to improve the inundation results another domain was included. A nearshore 0.02° domain encompassing the Texas and Louisiana coasts (Fig. 1, red) was added. By including this extra nesting step the MAPE of the inundation in the coastal domains improves to only 17.99%, from 18.54% without it. Nesting from the 0.05° Gulf of Mexico domain produces a combined MAPE of 17.84%. These small gains come with an additional wall clock time of approximately 1 hour per day of simulation.

The most time consuming part of the storm surge simulations is the computation of the wave fields and associated coupling between the hydrodynamic and wave models. For example, a one day simulation in the GoM domain can be reduced from 30 minutes to 5 minutes if wave effects are ignored. A simulation without wave coupling and many with various communication times, ranging from 20 minutes up to 6 hours, between the two models were performed. The results on the peak water level comparisons and HWM are summarized in Table 1 and show that the inclusion of waves is needed for accurate simulations; however the frequency of the communication between the flow and wave fields is not as pertinent as initially thought. In general there is a decrease in accuracy with an increase in the communication frequency. However, even at 6 hour coupling, there is a large improvement over not including waves at all. In terms of wall clock time for a day long simulation, the 20 minute coupling adds approximately 15 minutes over the best simulation, while the 6 hour coupling saves about 6 minutes compared to the best simulation.

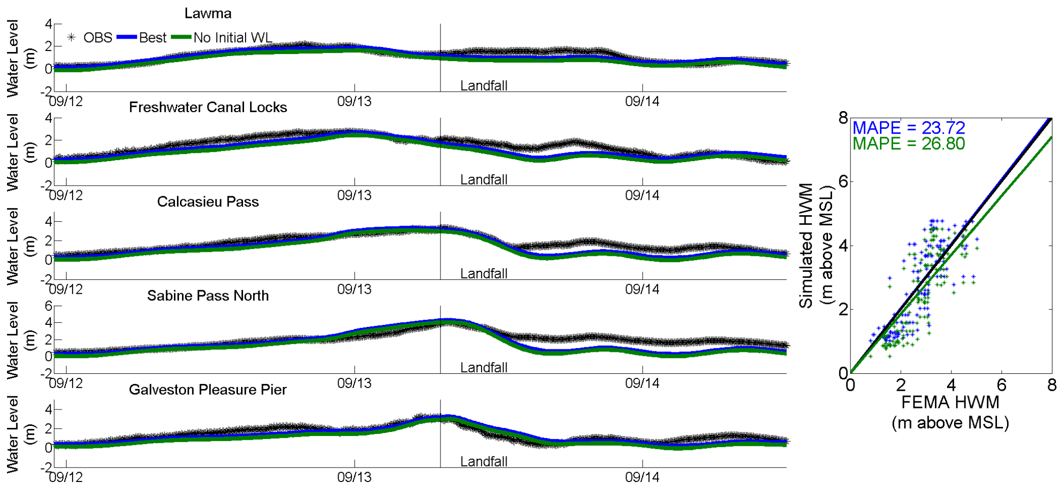

Figure 5. Comparison of water level and inundation results with and without initial water level conditions

TABLE I. WATER LEVEL AND INUNDATION ERROR FOR VARIOUS FLOW-WAVE COMBINATIONS

Run	**Water Level – Percent Error of Peak**					**HWM MAPE**
	Lawma	***Freshwater Canal Locks***	***Calcasieu Pass***	***Sabine Pass North***	***Galveston Pleasure Pier***	
Best (60 Min Coupling)	12.34	0.59	0.79	4.49	1.72	23.72
No Waves	48.77	46.25	37.33	32.76	25.81	32.94
20 Min Coupling	9.00	4.06	3.55	4.50	3.43	23.37
30 Min Coupling	8.98	4.04	0.52	4.36	1.40	23.97
120 Min Coupling	13.86	5.09	3.27	6.51	3.25	23.92
180 Min Coupling	10.67	3.69	2.67	6.66	2.51	23.89
360 Min Coupling	16.06	15.69	3.33	4.44	0.74	22.93

The driving force in the simulation of storm surge and inundation is the atmospheric forcing. Two key components were investigated. The first was the influence of the air-sea drag coefficient on the simulation results. The drag coefficient is used to parameterize the momentum exchange at the sea surface. There are a number of formulations of which 12 commonly used ones were investigated [22] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] and are shown in Fig. 6. A scorecard approach was used which ranked the simulations based on peak water level at the coastal stations, percent of the simulated hydrograph within a given tolerance of the observations, and HWM metrics including MAPE, correlation coefficient, root mean square, and mean percent error. In general the more recently published formulations, which show a plateau or decrease in drag coefficient at the highest winds speeds, showed the best overall results. The formulation of [22] had the highest overall score and was used in all other sensitivity studies. In general this formulation shows reduced values of the drag coefficient for similar wind speeds compared to the other formulations investigated.

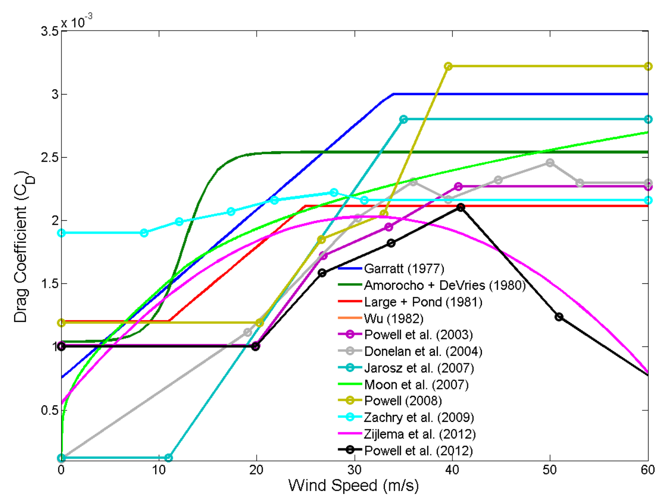

Figure 6. Twelve different drag coefficient formulations tested in sensitivity runs

The final sensitivity test of CSIPS involved the simulation of the wind field. The best simulation used reanalysis winds from OWI that combine NOAA HRD surface analysis winds with background observations to create detailed hindcast wind fields. In a forecasting environment this information is not available so analytic wind models are needed in place of it. Five wind models were tested. One based on a simple gradient wind profile (ANA1), the analytic model of Holland [35] (ANA2), two asymmetric Holland-type models [36] [23] (ANA3, ANA4), and a new model we developed for this study which combines Holland type profiles with multidimensional interpolation of radii information (ANA5). All models are run in MATLAB to create a wind field on the Delft3D computational grid with any desired temporal resolution. The creation of the wind fields can be accomplished within five minutes when given storm forecast characteristics (latitude and longitude location and track, maximum wind speed intensity, 64, 50, 34 knot wind radii information, central pressure estimate, and radius to maximum winds). A snapshot of the wind speed from reanalysis wind fields (OWI) and each of the models for September 12, 20:00 UTC; a few hours prior to landfall, is shown in Fig. 7. There is quite a bit of variance amongst the models. The ANA3, ANA4, and ANA5 models all do a good job of capturing the asymmetric shape of Ike; however each tends to overestimate the peak wind speed and the spatial distribution of the peak size. These wind fields do not have the effects of land roughness nor background winds incorporated in them. By not including background winds, the spatial extent of the atmospheric forcing is less than that in the best simulation which is evident in the HWM comparison in Fig. 8. ANA3, ANA4, and ANA5 all underestimate the inundation, although ANA5 does a comparable job to the OWI wind field in terms of correlation coefficient, RMSE, and MAPE. The simpler models, ANA1 and ANA2, both overestimate the inundation. ANA5 also does the best overall job of modeling the water level. ANA5 generates peak water level values within 7 percent of the observations for four of the five stations. The error at the Lawma station is 20 percent, but this is the second lowest of the analytic models and only 8 percent higher than that obtained with the OWI wind field.

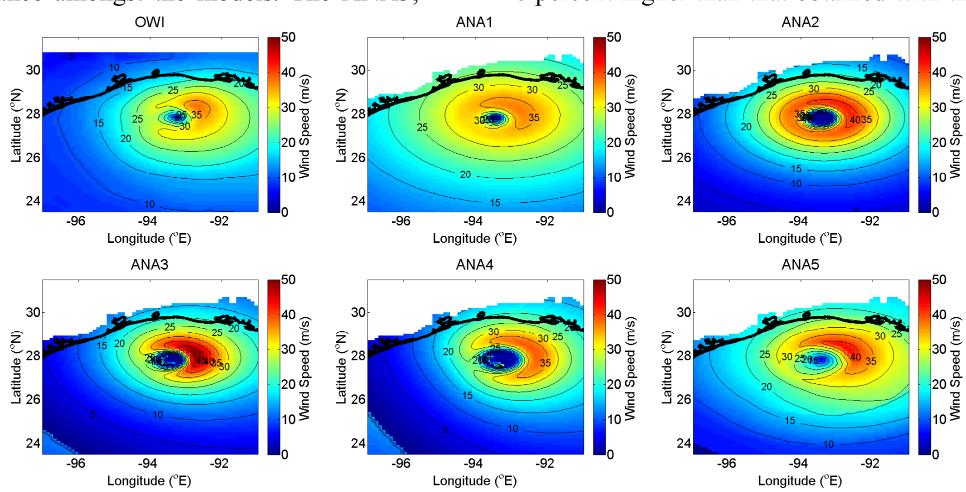

Figure 7. Wind contours for OWI winds and 5 analytic models tested on September 12, 2008 20:00 UTC

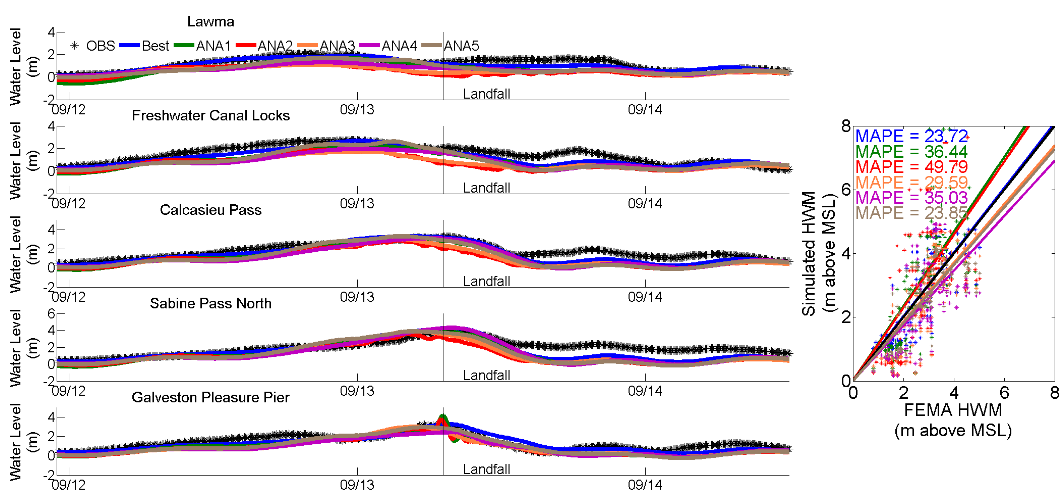

Figure 8. Water level and inundation comparison for different wind models

V. Conclusions

The Coastal Surge and Inundation Prediction System is undergoing evaluation before use by the US Navy for worldwide prediction of surge and inundation. The system has been shown to accurately simulate surge in hindcast mode for Hurricane Ike. Inundation simulation is improved with higher resolution and further tests to improve these results are ongoing. The best simulation results were obtained with a variety of parameters that may not be available in a forecast environment, specifically high resolution bathymetry and topography data, land use data and the corresponding Manning's N to parameterize bottom roughness, seasonal water level fluctuations, and a detailed wind analysis. Additionally, in a forecasting environment where time is of essence, the importance of including the time consuming dynamic wave coupling needed to be quantified. A number of tests using CSIPS were performed to look into how these parameters affect the simulation results. The elevation dataset had a little effect on the water levels, but a large effect on the inundation results. Similar to how the inundation results improve with increased resolution in the model grid, they also improve with increased resolution in the elevation dataset. The use of only GEBCO data actually showed some improvement over combined GEBCO and SRTM data, likely due to inconsistencies in the overlap of the two datasets. The variable bottom roughness produces the best results. Using a constant value did not affect water levels much; mostly the inundation results were affected. These results are likely region specific as the coastal characteristics will vary worldwide. In this case the highest Manning's N value tested, 0.025, produced reasonable water level predictions and similar inundation predictions to the variable value. The seasonal fluctuations in water level were not too significant. By not including the effects of the summertime heating, both water level and inundation were slightly under predicted. The wind forcing is a very significant component. The more detailed asymmetric models such as [36] and the newly developed model used in this study produced the best results. These models preserve the shape of the hurricane wind field for accurate simulation. Future work to include the background wind and the effects of land roughness should only help to improve these models and the simulation results. The inclusion of waves is necessary to accurately simulate the surge and inundation. This has been the driving force in developing a new forecast model for the US Navy and has been shown here. In general the more frequent the coupling between the hydrodynamic and wave model, the better the simulation results. However the loss in accuracy is relatively small at coupling frequencies of up to 3 hours.

Sensitivity studies have shown that a number of factors can have ranging effects on the accuracy of the water level and inundation results predicted by CSIPS. Initial tests are encouraging that the system is performing well and will do so in the future. Future work will focus on improving inundation results with higher resolution domains, inclusion of background winds in the wind forcing, and validating the system in different regions for different storms.

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