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4.2 A WAVE, SURGE AND INUNDATION MODELING TESTBED FOR PUERTO RICO AND THE U.S. VIRGIN ISLANDS: YEAR 1 PROGRESS

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1. INTRODUCTION

U.S. island regions in the Caribbean and Pacific pose many challenges to the accurate modeling and prediction of hazardous wave-dominated storm surge inundation events. The relative importance of physical processes causing inundation in reef-fringed island environments differs from those in milder-sloped mainland environments such as discussed by Kerr et al. (2013). Relatively little research has been done in these island environments, constituting a significant knowledge gap. To compound this uncertainty, little observational data of landfalling hurricane events are available in island environments. As a result, the National Weather Service (NWS) currently lacks operational surge and inundation guidance for island regions.

An exception to this data sparseness is Puerto Rico and the U.S. Virgin Islands (USVI), which frequently experience strong tropical and extra-tropical storms resulting in high waves, storm surge, and river flooding (Figure 1, top). Furthermore, since 2011 the IOOS Regional Association CariCOOS has deployed a large number of observational instruments in this region (Figure 1, bottom). These elements enable the evaluation and advancement of operational inundation models in U.S. island regions, via a close collaboration between federal operational, model development, and data management partners.

This project is one of five components of the second round of the IOOS Coastal and Ocean Modeling Testbed (COMT), which aims to improve the research to operations transition at the National Oceanic and Atmospheric Agency (NOAA), and its line offices such as NWS (Luettich et al. 2013). The goal of the current project is to extend the present wave/surge operational forecasting capability from mild-sloped coastal areas such as the U.S. East and Gulf of Mexico coasts to steep-sloped areas such as the Caribbean and Pacific Islands and transition this capability to NOAA's National Hurricane Center (NHC) and Weather Forecast Office San Juan. The specific project objectives are to: (1) compile a data set of observations taken around Puerto Rico and the USVI; (2) evaluate multiple, coupled wave/surge/inundation models against this data; (3) recommend the most suitable model (or methods) for transition to operations; (4) create a publically accessible archive of the project results (input data and model output) for future research; and (5) undertake local education and outreach activities.

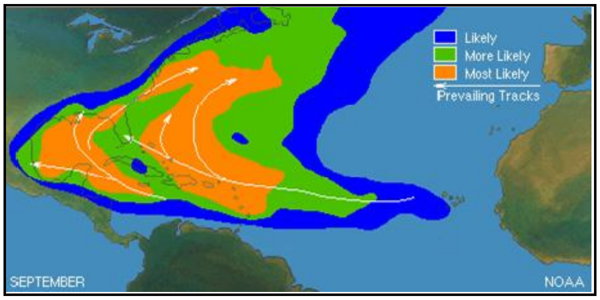

Figure 1: Top: Hurricane occurance over the U.S. Atlantic Basin showing the position of Puerto Rico and the Virgin Islands (Credit: NOAA/NHC). Bottom: Extensive CariCOOS observational network in Puerto Rico and the U.S. Virgin Islands (Credit: CariCOOS).

This paper discusses the project structure and the progress made during the first year, including: the planned project activities, model and storm case selection (Section 2), model setup including inputs and meshes (Section 3), intial results of tide and surge modeling (Section 4). Section 5 closes the paper with conclusions.

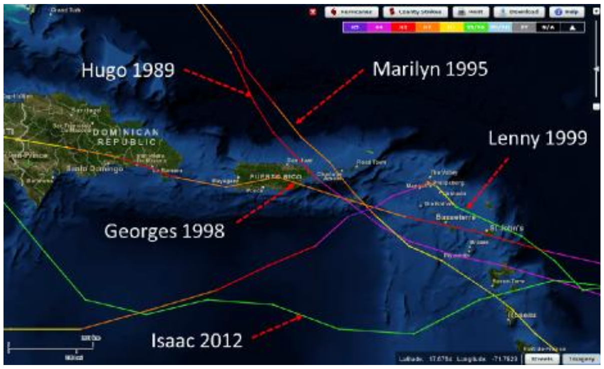

Figure 2: Collection of tropical cyclones that passed over or near Puerto Rico and the U.S. Virgin Islands in recent years. Of these, the selected storms are Goerges (1998), Isaac (2012) and Sandy (2012, not in view).

2. OPERATIONAL REQUIREMENTS AND PLANNED PROJECT ACTIVITES

2.1 Operational requirements

The starting point for this component of the COMT project was to establish the operational requirements for surge forecasting at NWS. These are ultimately set by the National Hurricane Program, and the central question to be answered is which evacuation zones to activate. Operational requirements include: (i) model data (forecast guidance) has to flow through NOAA/NWS's Advanced Weather Interactive Prediction System (AWIPS) in order to be usable in an operational setting, (ii) models need to be numerically efficient, because time (and timeliness) is critical – order of minutes to tens of minutes, (iii) numerical stability is essential. Physics requirements include (e.g. Kerr et al. 2013): (i) probabilistic approaches for all forecasts before landfall due to uncertainties in the atmospheric forcing; (ii) coarse-grained output grids in operational applications because evacuation zones are typically coarse-grained; (iii) improved parametric wind model in the operational model SLOSH (Jelesnianski, 1992); (iv) incorporate the influence of wind waves in SLOSH (essential for steep island topography and over reef systems); (v) resolve uncertainties in various model settings in reef environments (e.g. grid resolution and physical parameterization of friction over reefs).

2.2 Project phases

The present project comprises four phases, including (i) model and test cases selection, (ii) model comparisons for regional and field cases, (iii) model simulations for detailed reef-transect cases, and (iv) formulation of recommendations for operational application. In the first project phase, the requirements for operational modeling improvements discussed above were used to select the coupled models to be included it the testbed:

Figure 3: Suggested pre-selection locations for event-based deployment of USGS's HOBO sensors.

- SLOSH+SWAN (Jelesnianski et al. 1992, coupled wave and surge model on high-resolution curvilinear grid)
- ADCIRC+SWAN (Dietrich et al. 2011, coupled wave and surge model on unstructured grid)
- ADCIRC+WAVEWATCH III (under development at NOAA/National Centers for Environmental Prediction, NCEP)
- Delft3D+SWAN (Lesser et al. 2004)

In addition, the following phase-resolving models are included to investigate the details of nearshore, cross-reef wave transformation and infragravity wave generation: FUNWAVE (Chen et al. 2000), BOUSS-2D (Nwogu and Demirbilek 2001) and potentially XBeach (Roelvink et al. 2009).

Next, regional-scale field cases and nearshore, cross reef field cases were selected. A shortlist of storms that passed over or near Puerto Rico and the U.S. Virgin Islands was made (Figure 2). In the final selection, preference was given to major events that made direct landfall, but also time periods over which the extensive CariCOOS network was present (mostly after 2011). Based on these criteria, the final three regional-scale storms were selected:

- Hurricane George (1998, tropical)
- Hurricane Issac (2012, tropical)
- Superstorm Sandy (2012, extra-tropical impacts at Puerto Rico)

In addition to these cases, two nearshore field campaigns were identified, which provide detailed cross-reef wave and surge information:

- Tres Palmas, Rincon, PR: Jan-Feb 2013
- St. Croix, USVI: 2008/09/28, 2008/10/14

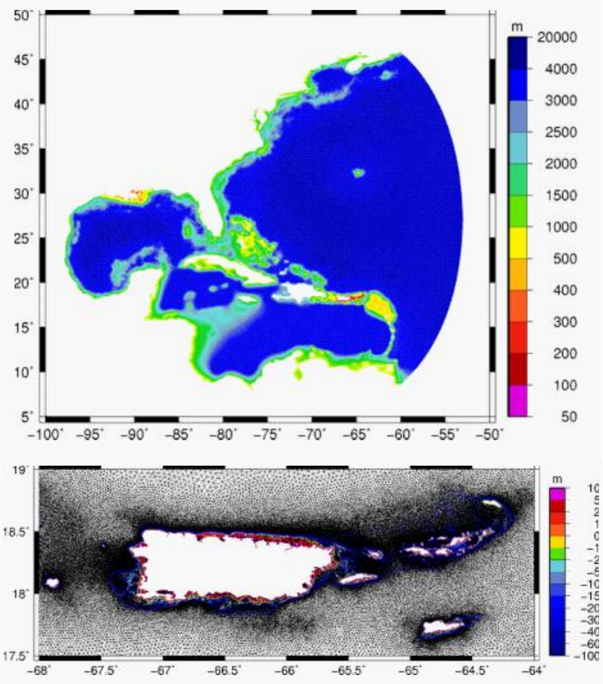

Figure 4: Computational mesh developed for ADCIRC-based models. Top: large-scale unstructured mesh, designed to accurately capture tidal motion within the basin. Bottom: detail of Puerto Rico and its surroundig islands. Scale indicates the variable mesh cell size.

The project team is also partnering with U.S. Geological Survey (USGS) Puerto Rico to collect water level data during hurricane events using re-deployable HOBO pressure sensors. These will be deployed at a sub-set of pre-selected locations around the island, where mounting brackets will be installed at fixed structures such as piers and bridges ahead of the 2015 hurricane season (Figure 3). In this way, additional nearshore observations of total surge levels, infragravity waves, and possibly wind waves will be captured during future tropical cyclone events.

In the second (present) project phase, model comparisons are being carried out over the above-mentioned three regional-scale field cases. The results are compared in terms of accuracy and computational cost. In the third project phase, model comparisons are to be carried out over the nearshore, cross-reef transects of the two above-mentioned field campaigns. In the fourth and final project phase, conclusions on the relative advantages and disadvantages of various modeling approaches for operations are to be drawn, and recommendations made regarding the most suitable models or techniques for future operational implementation made.

3. MODEL SETUP

Various data sources have been used to compile the input fields and model meshes. These include:

- Automated Tropical Cyclone Forecasting (ATCF) hurricane wind data from NHC: ATCF hurricane wind data for Hurricane Georges (1998), Isaac and Sandy (2012) was obtained and converted to the appropriate asymmetrical parametric wind model format to be used by ADCIRC-based models.

- Gridded wind and pressure fields: The Advanced Research WRF (WRF-ARW) Version 3.4 has been used to create hourly gridded fields of wind speed and surface pressure for Hurricane Georges and Superstorm Sandy. The preliminary resolution of these WRF runs is around 12.7 km. Either the NCEP Climate Forecast System Reanalysis (CFSR) or the NCEP Final Analysis (FNL) have been assimilated as boundary conditions for the WRF-ARW runs, depending on availability. Subsequently, simulations over a nested domain of 2-3 km over the Puerto Rico and the U.S. Virgin Islands region will be carried out, as well as runs for Tropical Storm Isaac.

- Bathymetry fields: The NGDC ⅓ arc-second Digital Elevation Maps for Puerto Rico and U.S. Virgin Islands were used to build a series of ADCIRC model meshes on the coastal areas of the region, at various nearshore resolutions. For deeper waters the GEBCO and SRTM30 bathymetry databases were used.

- Bed type fields: To map the reefs in the domain, the Global Distribution of Coral Reefs dataset (UNEP-WCMC et al. 2010) and the NOAA NCCOS Benthic Habitats of Puerto Rico and the U.S. Virgin Islands dataset were used. These data sets show the global and regional distribution of coral reefs in the tropical and sub-tropical regions, and combined are the most comprehensive global datasets of coral reefs to date. The mangroves were mapped from the Giri et al. (2011a,b), which shows the global distribution of mangrove forests, derived from earth observation satellite imagery. From these, the distribution of Manning's *n* bed friction values were derived for the ADCIRC-based models.

- Land cover fields: USGS land cover databases were used to create nodal attribute fields of land cover and wind reduction factors to be used in the ADCIRC-based models.

The bathymetry, bed type and land cover fields were used to construct a detailed unstructured mesh to be used in the ADCIRC-based models (Figure 4). This unstructured mesh has a spatial resolution of 50-100 m along all the coastlines of Puerto Rico and the U.S. Virgin Islands, with an emphasis on the details of reef structures. The SLOSH-based models, by contrast, use a curvilinear otrthogonal computational grid for the

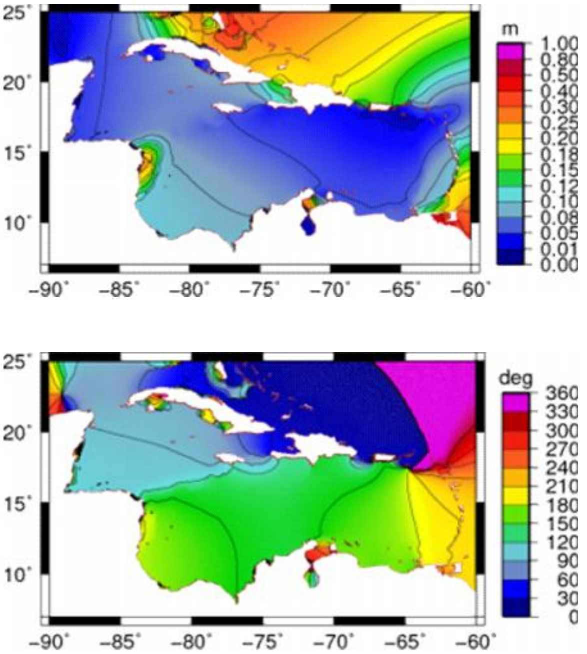

Figure 5: Lunar semidiurnal (M_2) tidal amplitude and phase (top and bottom, respectively) over the Caribbean Sea computed by the ADCIRC model.

island of Puerto Rico, which is currently under development and testing.

4. RESULTS

This section discusses some initial modeling results of this project, including tidal simulaitons and combined tidal and wind-driven surge runs with ADCIRC.

4.1 Tidal simulations

To evaluate the stability and accuracy of the unstructured mesh developed for the ADCIRC model, a tidal validation was conducted. Eight tidal constituents (M_2, K_2, S_2, N_2, O_1, K_1, P_1, Q_1) were used to force the open ocean boundary as well as the tide generating potential (refer Figure 4). The amplitudes and phases for each tidal constituent at the boundary nodes were obtained from the TPXO8-atlas global tidal inversion solution. A lest-squares harmonic decomposition was computed over a period of 140 days at all mesh nodes to evaluate and describe the geographical behavior of the various tidal constituents, as well as to validate the amplitudes and phases with the observations at the available tidal gauges.

Results for the dominant semidiurnal (M_2) and diurnal (O_1) constituents are shown in Figures 5 to 7. The M_2 constituent (Figure 5) is partly blocked by the Lesser Antilles and the northern shelf of Puerto Rico and the U.S. Virgin Islands as it moves from the Atlantic Ocean into the Caribbean Sea. Inside the Caribbean basin, the M_2 amplitude diminishes almost to zero in an area extending up to Jamaica. Figure 6 shows the M_2 amplitude and phase for the Puerto Rico and U.S. Virgin Islands. At this scale, it can be better appreciated how

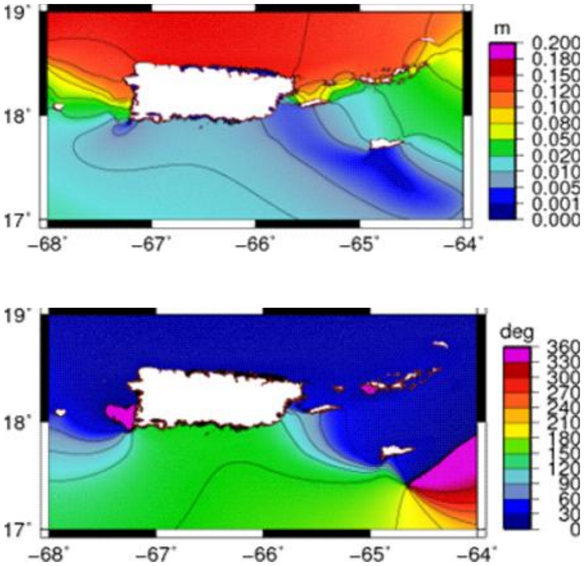

Figure 6: Lunar semidiurnal (M_2) tidal amplitude and phase (top and bottom, respectively) over Puerto Rico and the U.S. Virgin Islands computed by the ADCIRC model.

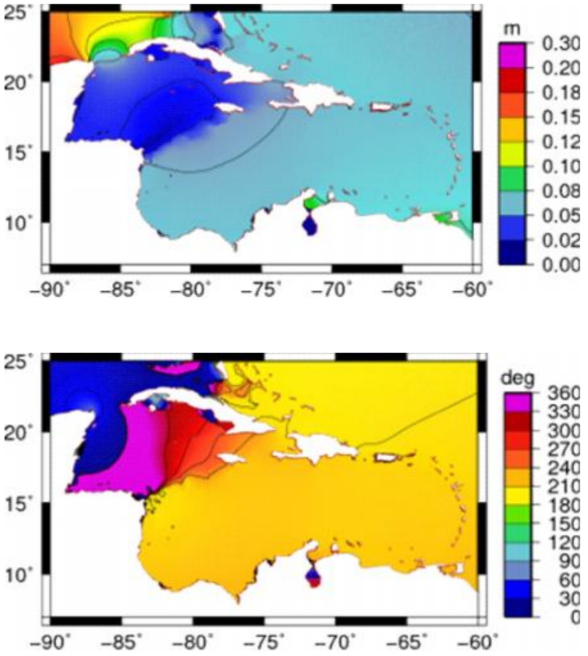

Figure 7: Lunar diurnal (O_1) tidal amplitude and phase (top and bottom, respectively) over the Caribbean Sea computed by the ADCIRC model.

the M_2 amplitude rapidly decreases as it encounters the northern shelf of the region. In addition two amphidromes are visible in the region, a main one southeast of St. Croix and a smaller one right next to the southwestern shelf edge of Puerto Rico.

In the case of the diurnal constituent (Figure 7), both the amplitude and phase are almost constant throughout the Atlantic Ocean and the Caribbean Sea, changing only inside and in the vicinity of the Gulf of Mexico. Contrary to what is observed with the M_2 constituent, the O_1 constituent is not affected by the Lesser Antilles or the Puerto Rico and U.S. Virgin Islands shelf. The results of the M_2 and O_1 amplitudes and phases is in good agreement with the description of Kjerfve (1981), which has been the most detailed description of the tides in the Caribbean Sea to date.

4.2 Tide and wind-driven surge simulations

As an example featuring both tides and atmospheric foring, we will discuss an initial simulation of Hurricane Georges (1998) with ADCIRC, using ATCF atmospheric input. The Hurricane Georges wind fields were computed using an asymmetrical parametric Holland wind model. This wind model allows for different radius of maximum winds for each hurricane wind field quadrant. The resulting structure and spatial distribution of the wind field is based on the NHC ATCF data, incorporating the best track data as well as the reported minimum central pressure and radius of maximum winds for each quadrant. Figure 8 shows the wind field on September 21, 00:00 GMT as Hurricane Georges approached Puerto Rico and the U.S. Virgin Islands. The asymmetry of the field is noticeable in this figure, as the center of the hurricane is not circular in shape as it would be with a symmetrical Holland model. This asymmetry is also noticeable at a distance away from the hurricane center, as winds do not have the same speed at all quadrants for a given distance from the center.

Water levels at the eastern coast of Puerto Rico during the same time snapshot are shown in the bottom panel of Figure 8. At this time, the ADCIRC water levels were highest at the area were winds were blowing perpendicular to the coast, in the Ceiba region. On the northwestern coast of Vieques Island (lower right of figure) there is a shallow sand bank that extends about 6 km away from the coast. It can be seen how this bank blocks the water at this location and results in increasing the water levels in the area to the east of the sand bank.

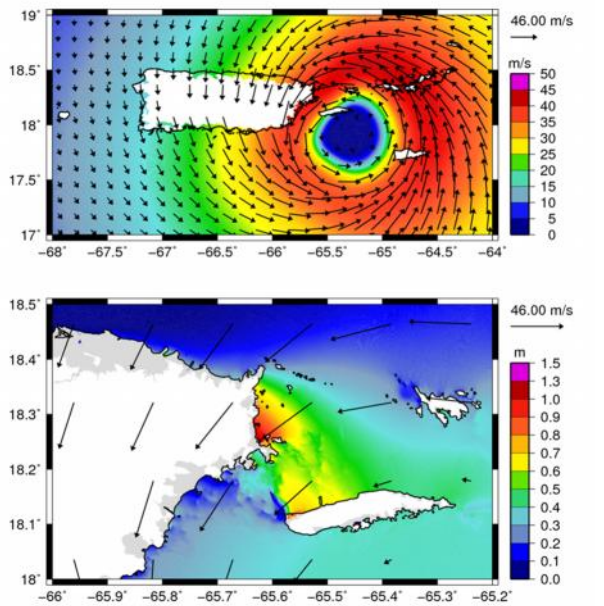

Figure 8: Results of the Hurricane Georges ADCIRC simulation (tides and atmospheric forcing) with an asymmetrical vortex model using NHC's ATCF data. Top: Parameterized wind field on September 21, 1998 at 00:00 GMT (Category 3 hurricane). Bottom: wind-induced surge levels overlayed by wind velocity vectors over northeastern Puerto Rico. Vieques Island is visible on the lower right of the figure.

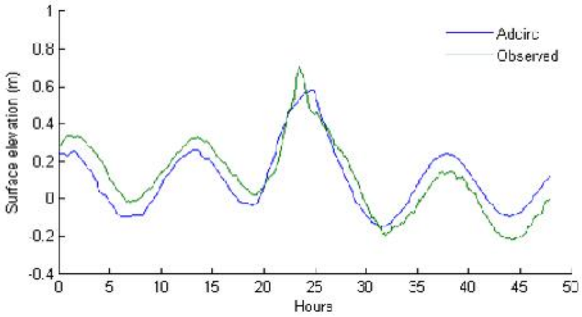

Figure 9: Time series results of the Hurricane George event at San Juan, PR, compared to observations at CO-OPS Station 9755371. Period shown is 1998/09/21 00:00 GMT to 1998/09/22 23:59 GMT.

A comparison of the time series from ADCIRC and the observed water levels at San Juan is shown in Figure 9. Even though this simulation still does not include coupling with the SWAN wave model, the results show a very good agreement with the observations. Especially the phase agreement of both time series at this location agree very well, which indicates that the wind forcing and the friction parameterization in the San Juan location are correctly simulating the conditions during this hurricane.

5. CONCLUSIONS

The work presented here, being one of five components of the current IOOS Coastal and Ocean Modeling Testbed (COMT), aims to improve the research to operations transition at NOAA of wave/surge operational models for reef-fringed island regions such as the Caribbean and Pacific islands. It contains a range of widely-used coupled wave and surge models, a diverse set of field cases (both regional and nearshore) and broad participation from academia and the operational community. From the initial results of this study, the following can be concluded:

- The tidal simulations of the ADCIRC model are able to capture the complex spatial variablitity of tides around the Puerto Rico and U.S. Virgin Islands, which are in good agreement with earlier findings. In particular, the dominant lunar semidiurnal (M_2) tide shows significant variability around these islands, with a strong amplitude gradient between the north and south coasts and amphidromes close to Puerto Rico and St. Croix. This argues the need for a large-scale model domain to capture these dynamics accurately.
- Initial ADCIRC simulations for Hurricane Georges (1998), with only tidal forcing and atmospheric forcing taken from ATCF data, shows a promising comparison against observations at San Juan on the northeast coast of Puerto Rico. The model furthermore indicates significant surge levels in the Ceiba region (northeastern tip of island) and on the north coast of Vieques Island just before the time of landfall.

6. ACKNOWLEDGEMENT

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