Development of a Two-Dimensional Overland Wave Modeling System for Franklin & Wakulla Counties, Florida

Final Report

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Summary

The University of Florida has worked cooperatively with the Northwest Florida Water Management District to develop and test a new, two-dimensional (2-D) Overland Wave model as part of an effort to improve wave analysis and associated Flood Hazard analysis along northwest Florida's coast. Ultimately the 2-D model approach summarized in this report will be tested in a production mode and compared to the traditional one-dimensional (1-D) overland wave modeling approach employed by District contractors to prepare flood hazard maps for FEMA. The wave model SWAN (Simulating Waves Nearshore) which has become an industry standard for coastal wave forecasting was adapted for overland wave analysis. Model adaptation was straight forward and demonstrated this is possible at a very reasonable cost. The 2-D model approach is also well suited for hurricane studies being used by FEMA to predict wave setup with good success. The current technology for Overland Wave Modeling (OWM) was developed in 1978 following the recommendations of an NRC panel utilizing a one-dimensional "line by line" approach. Computational capabilities have dramatically increased in the past 30 years and a more advanced "integrated two-dimensional" approach is now feasible.

The basic approach is to simulate the hurricane waves during the time period of landfall of the storm on a fine resolution grid (using a grid spacing of approximately 80 meters) for 3 to 6 hours when the flood and waves are largest. The waves are calculated on the high resolution overland wave grids using the SWAN model. Modifications to SWAN were made that make it appropriate for predicting the wave heights over flooded inland territories, including a variety of overland obstacles, such as forests, railroad tracks, buildings, and various types of vegetation.

The chief virtues of this approach are that:

1) the waves from each storm are strongly coupled to the wind fields and the water levels from each of the approximately 150 calculated low frequency storms in the same way that they are in nature and in the same way that they are used in calculating the 100 and 500 year flood levels;
2) essential, order-one, wave physics are included in the wave predictions, including: wave refraction around bathymetry, wave diffraction through irregular coastal features, wind-wave growth, wave breaking for a wave spectrum, wave-current interactions; and,
3) subjective judgment may be reduced to produce final FEMA maps, since the calculations are done at every grid location and no subsequent interpolation between transects is required.

Model Development

SWAN model software development has been prepared so that it is operational and ready to be used in production along the eastern coast of NWFWMD. It was prepared to be operating with SWAN model coastal grid resolutions at approximately 80 meters. Discrete model grids (see Figure 1) were developed to extend from about 2 km offshore to approximately 8 km onshore, depending on where the 6 meter topography level is located onshore and cover developed barrier islands. It is unlikely that the 500 year flood levels exceed 6 meters, and the only need is to accurately calculate the wave statistics where the land will be flooded. This roughly works out to area coverage of 100 km long by 10 km wide, or approximately 1000 square km. At grid resolutions of 80 m, this requires approximately 3000 x 500 grid points for the overland grids, which, have been set up as 6 overlapping coastal grids. The number of grid points (and approximate dimensions in kilometers) in each of the six grids shown below in Figure 1 are respectively:

(1) 201 x 889 points or 16 x 71 km
(2) 286 x 672 points or 23 x 54 km
(3) 255 x 672 points or 20 x 54 km
(4) 271 x 505 points or 22 x 40 km
(5) 271 x 637 points or 22 x 51 km
(6) 430 x 481 points or 34 x 38 km

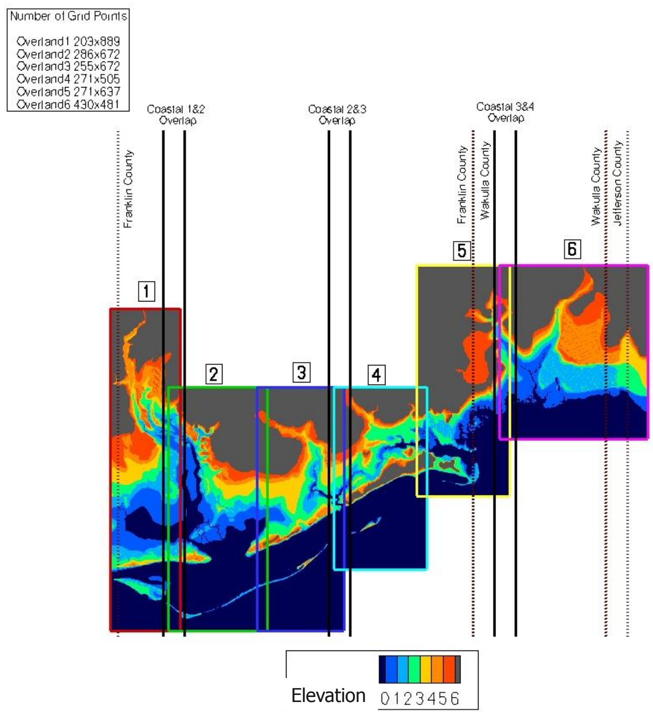


Figure 1. Layout of overland grids. Each is nested inside of the Coastal grids described in the wave setup report. The contours of the topographic height are shown. The layout of the grids was designed to go up to the 7 meter contour of topography (approximately 22 feet of land elevation) so that the 100 year and 500 year flood plains would probably be captured).

Overland Wave Grid Development

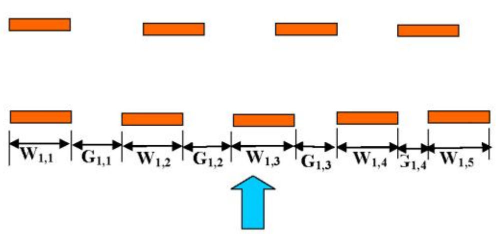
Setting up the grids with information appropriate to approximate the overland wave physics required a similar amount of effort as is usually the case for 1D overland wave modeling. In fact, many of the same model factors could be extracted from similar 1D overland wave modeling efforts as well as efforts to develop the 2D ADCIRC storm surge models. An important recognition was the 2D overland modeling approach was actually very efficient in terms of assembly and processing of input data because similar efforts (1D overland and 2D ADCIRC and SWAN modeling) were coordinated in the beginning.

Factors and data assembled at this stage included:

1) integration of the best available topography into the SWAN grids (see Figure 2).
2) integration of land use information, especially as represented by variable bottom friction coefficients, similar to the approach done for ADCIRC (see Figure 3)
3) integration of linear features such as railroad tracks, levies, and roadways into the SWAN model subgrid weir fields.
4) integration of the coastal dunes into the grid following FEMA regulations using the 540 square foot rule
5) integration of coastal development (buildings) and forests as obstacles represented by subgrid elements into the SWAN grids (see Figure 4). This is distinct from the physical principle of spatially variable bottom friction coefficients due to different types of vegetation.
7) Multi-directional wind stress factors. Figure 5 provides stress factors for one of the twelve different directions.
6) Blockage of waves is different from frictional dissipation of wave energy and was represented separately. The basic concepts and methodology of the blockage approach taken is explained as follows:

Wave Height Reduction by a Series of Baffles

Consider a series of baffles as shown below.



The transmission coefficient for the first row is $\kappa_{T,1} = \sqrt{\dfrac{\sum_{n=1}^{N} G_{1,n}}{\sum_{n=1}^{N}\left(G_{1,n} + W_{1,n}\right)}}$

The overall transmission coefficient, $\kappa_{T,TOTAL}$, is

$\kappa_{T,TOTAL} = \kappa_{T,1}\kappa_{T,2}\kappa_{T,3}\ldots\kappa_{T,J}$ or $\kappa_{T,TOTAL} = \prod_{j=1}^{J}\kappa_{j,TOTAL}$

where J is the total number of rows.

Figure 2. Wave height reduction by buildings is handled by wave attenuation and transmission as a series of baffles within a control volume. The wave transmission coefficient is converted to an equivalent sub grid scale coefficient.

Blockage of buildings was not a significant factor for much of the area studied because of its rural nature and that most coastal buildings were elevated on piers. However for areas in the more western panhandle, areas with greater building size and density blockage and sensitivity to blockage size may require further investigation.

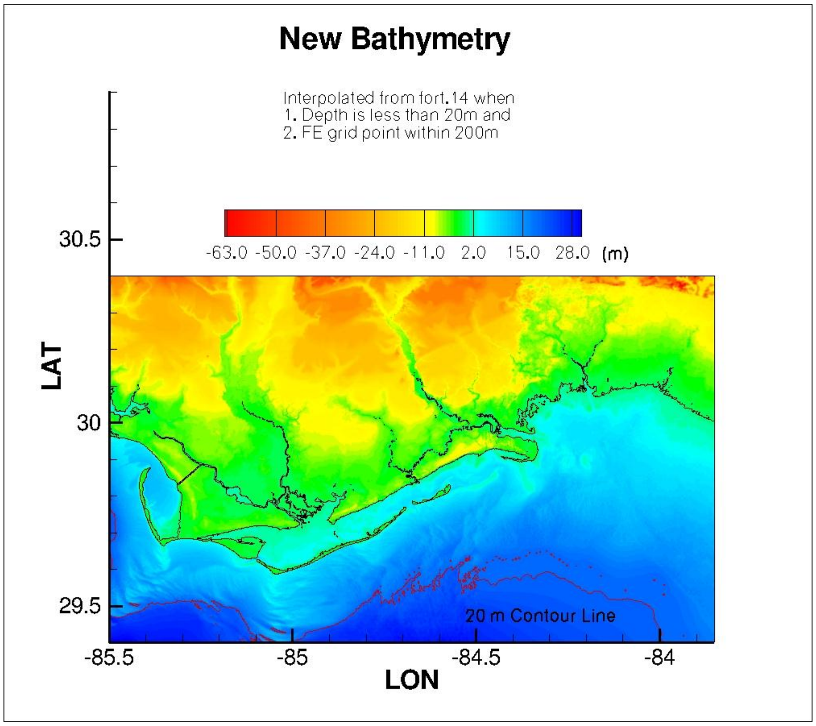


Figure 3. Image of Seamless Topography and Bathymetry Used

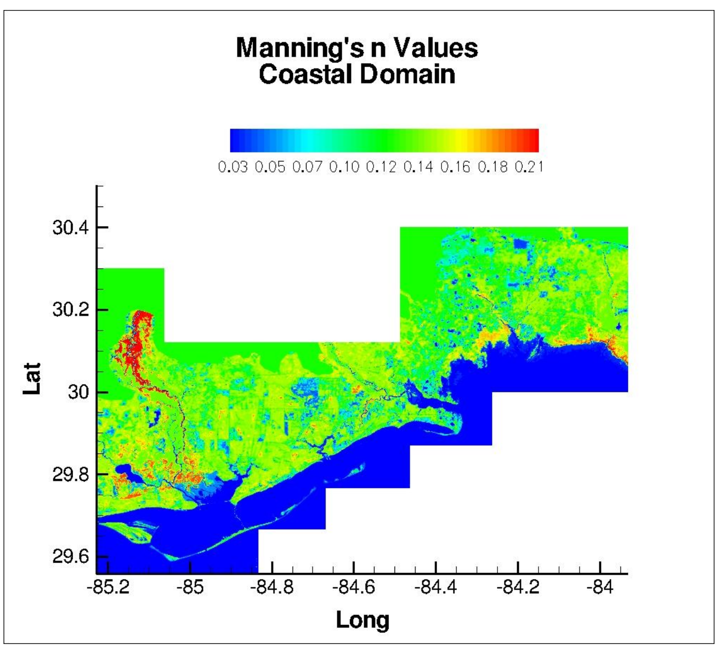


Figure 4. Depiction of Manning's N Bottom Friction Distribution, reduces wave heights in areas of high bottom friction over land, values taken from ADCIRC grids.

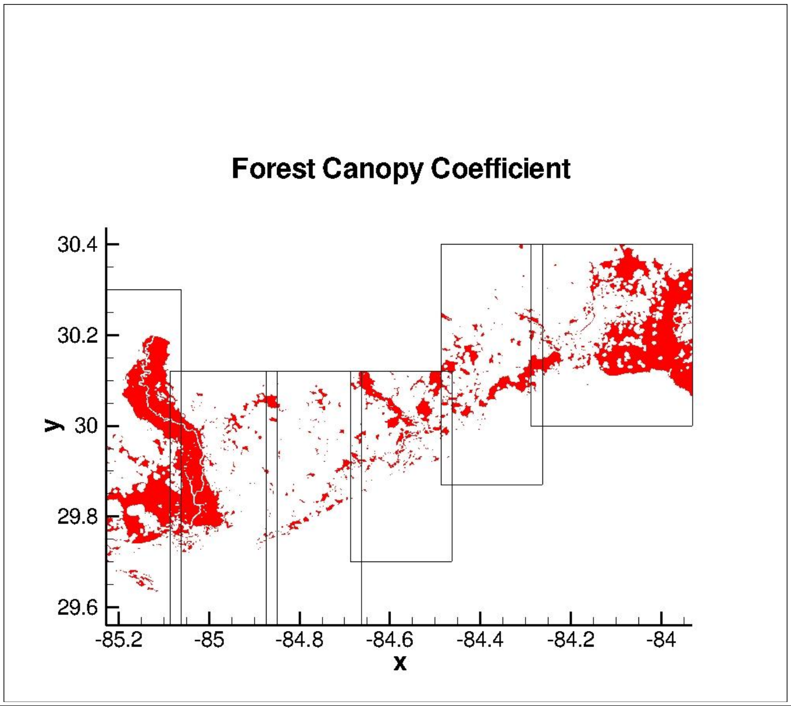


Figure 5. Forest Canopy Coeficients Distribution

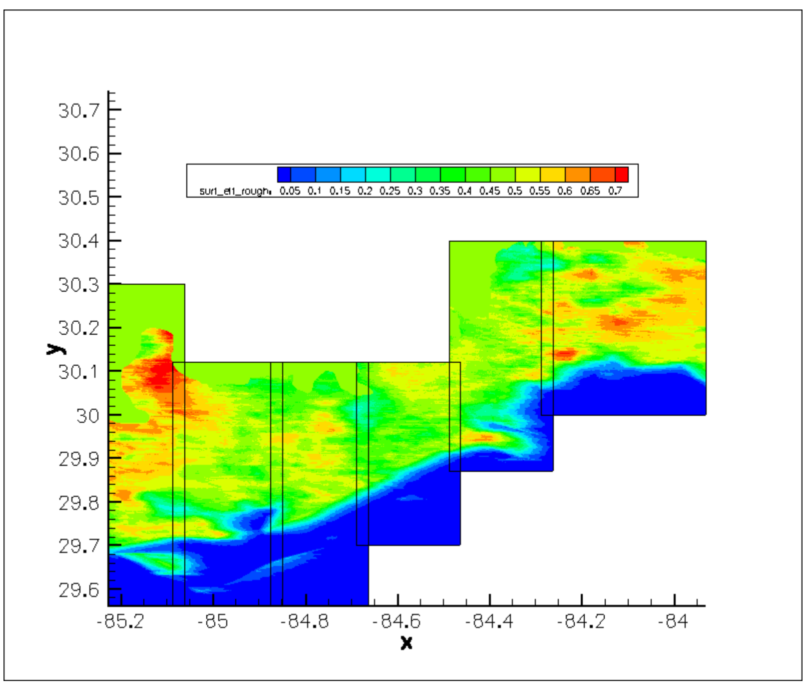


Figure 6. Example of Multi-directional Wind Shear Resistance Factor when wind comes from different direction, the Canopy reduces the local wind stress on the wave field, these are calculated from 12 different directions, as done in ADCIRC.

Model Set-up and Simulation Approach

The basic procedure was to automate the entire process by writing shell scripts for the computing platform. This allows all of the directory structures and input-output files to be handled automatically. Once the procedure worked on a single run, it was expected to work on all future runs. SWAN model testing indicated it is very robust and is not expected to ever crash. Once the system worked on a single storm, a large portion of the work was accomplished. It is expected that post-processing and QA/QC methods for each storm will also be automated and may only require a human to look at a set of five or so plots from each run.

The following summarize the steps taken to develop and set up the model:

1) A beta-testing version of the system has been setup and run for hurricane Dennis.

2) The system was designed based upon written shell scripts to simulate a hurricane wave field over land and is setup to run over the chosen grids. Most of the time was spent improving the physical parameterization on the grids, including variable bottom friction coefficients and blockage coefficients as required to improve model resolution.

3) In order to put the model into production, basic data interfaces were developed to automatically download data from others who were involved with the District coastal study. This included computation the water levels, wind fields, current fields, and wave boundary conditions, over other's model domains.

4) The main effort of this study was focused on completing the details that make the basic open ocean wave model (SWAN) into an appropriate overland wave model, and testing the response of the system to our approximations.

5) An automated system has been set up and tested on Hurricane Dennis and is ready to do production and test the model against the 1D model being developed for the region by others as well as to be run to test the model sensitivities to different parameterizations.

6) We developed software to find the 6 hour period of time during the peak of landfall when at least 98% of all of the waves were at their peak in the overland model domain. It is not necessary to run the overland wave simulations for the entire 5 days of the approaching hurricane, just during landfall. This makes the 2-D overland modeling approach very efficient. On our modeling system, with about 32 computer processors, it is possible to run about 30 simulations per day, or complete a 160 storm surge study in approximately 2 weeks, accounting for data storage, and model initialization and setup times. In addition, a restudy of one area is even more efficient, since all the water levels and currents and winds are stored for each of the 6 overland domains, so that a LOMAR would be possible for a single subdivision or area in about 1 day of CPU time, because each storm only has to be recalculated on one of the 6 overland domains. This could be helpful in the future if the 2-D approach was adopted.

7) tests were done on overland grids varying between 80 meter grid resolution and 10 meter grid resolution to determine the differences in the results. It was found that the results changed by less than 5% at the finer grid resolution and yet the time to calculate the solutions took approximately 20 to 60 times longer, so it was decided that there were significant advantages to using the 80 meter grid resolution. This included the issues that individual wave lengths are usually about 30 to 80 meters and the model is a statistical representation of waves, not a individual, wave by wave model. When the grid is refined beyond about 80 meters, then individual houses are no longer sub-grid scale elements that simply block a percentage of the area, they eventually fill the entire grid cell (houses are approximately 20 meters by 20 meters, which would be about a 3000 square foot house). When individual houses would be resolved on the grid instead of representing them as a sub-grid scale coefficient, it would be necessary to decide if they were sturdy and would remain intact during a hurricane flood, or if they were break away, because it would change the local ground elevation. This was beyond the scope of what we were trying to accomplish here.

Results

Two Dimensional overland wave simulations were done with Hurricane Dennis that included the time dependent currents and water levels from high resolution ADCIRC simulations done by Scott Hagen at UCF test. The UCF - NWFWMD team provided Figures 7 to 9 shows model tests for Hurricane Dennis.

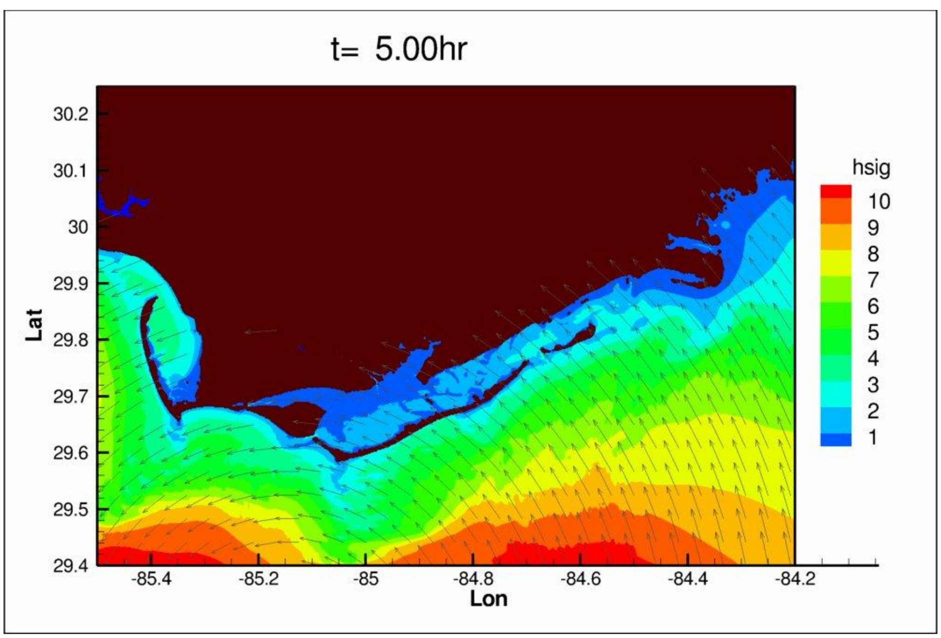


Figure 7. Franklin County wave simulation for the offshore wave, the arrows show the direction of the wind field.

Figure 7 shows the Franklin County Coastal Grid (at 160 meter grid resolution) that has been developed for SWAN setup model simulations under previous NWFWMD funding. The set of high resolution overland wave grids were nested inside of this grid. The Franklin County grid passes the offshore boundary conditions to the overland wave grids that contain the more detailed physics for overland wave analyses.

The bathymetry and topography data for the wave grid was originally from the National Geophysical Data Center (80 meter horizontal resolution) but later it was improved to agree with the same more detailed resolutions for the bathymetry and LiDAR topography data used by others responsible for performing other elements of the coastal study for the NWFWMD.

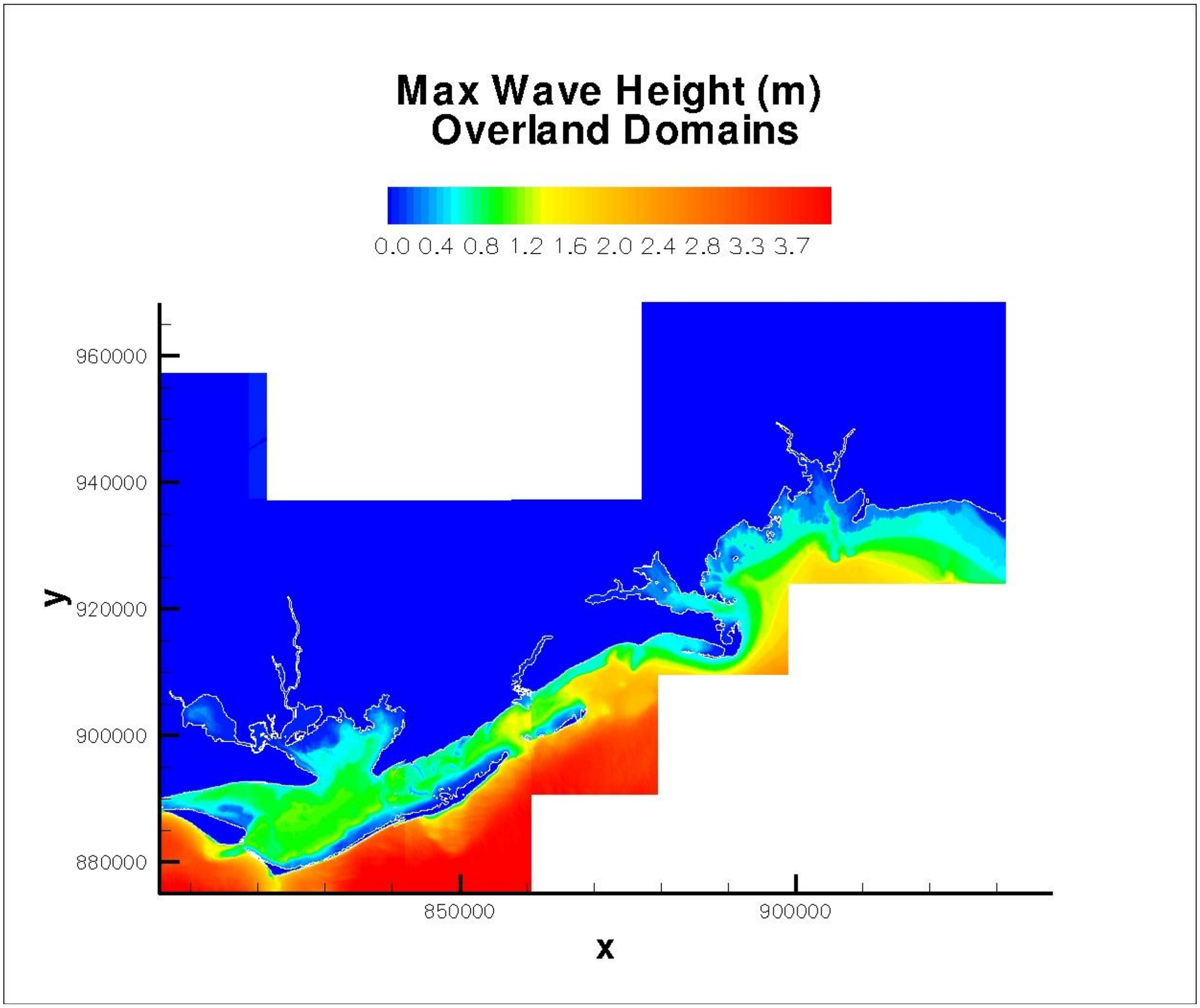


Figure 8. Maximum wave heights (in meters) in the overland wave domains during the simulation of Hurricane Dennis. In this figure, the results from each domain is simply plotted overtop of each other, in a final implementation, in the overlapping areas, the results are blended together in the overlap region. The wave heights are riding on top of the surge levels.

Model results for of the Maximum Envelope of Waves (MEOW) for Hurricane Dennis are shown in Figure 8 from the overland wave simulation. It is noted that not a great deal of inland flooding occurred at this location since Dennis made landfall farther to the west. In Figure 9 the differences in the results are show between when SWAN is used as an open coastal wave model, and when the additional overland wave dynamics are included (wind stress reduction, currents, and spatially varying bottom friction). These results are from simulations conducted on the exact same grids with the exact same winds and boundary conditions. Because a lot of flooding did not occur here, the additional physics usually changes the wave heights by less than a meter. The red areas show regions where waves are smaller with the overland approach, the blue areas show areas where the waves are actually larger. These are possible, of course, because the more sophisticated overland wave model includes wave refraction by currents. During the peak flood conditions, the currents in the coastal areas are quite strong and they can focus waves into different areas. For example when the waves and currents are in the same direction then the waves ride on the currents with less resistance and can be larger before breaking. This effect generally is less than 30 centimeters but showed the importance of including wave refraction from currents in the wave modeling approach. In addition, when using spatially varying bottom friction (Collins friction approach) as opposed to a constant value of the bottom friction (Jonswap friction approach) variations in the offshore wave field result for waves of different periods.

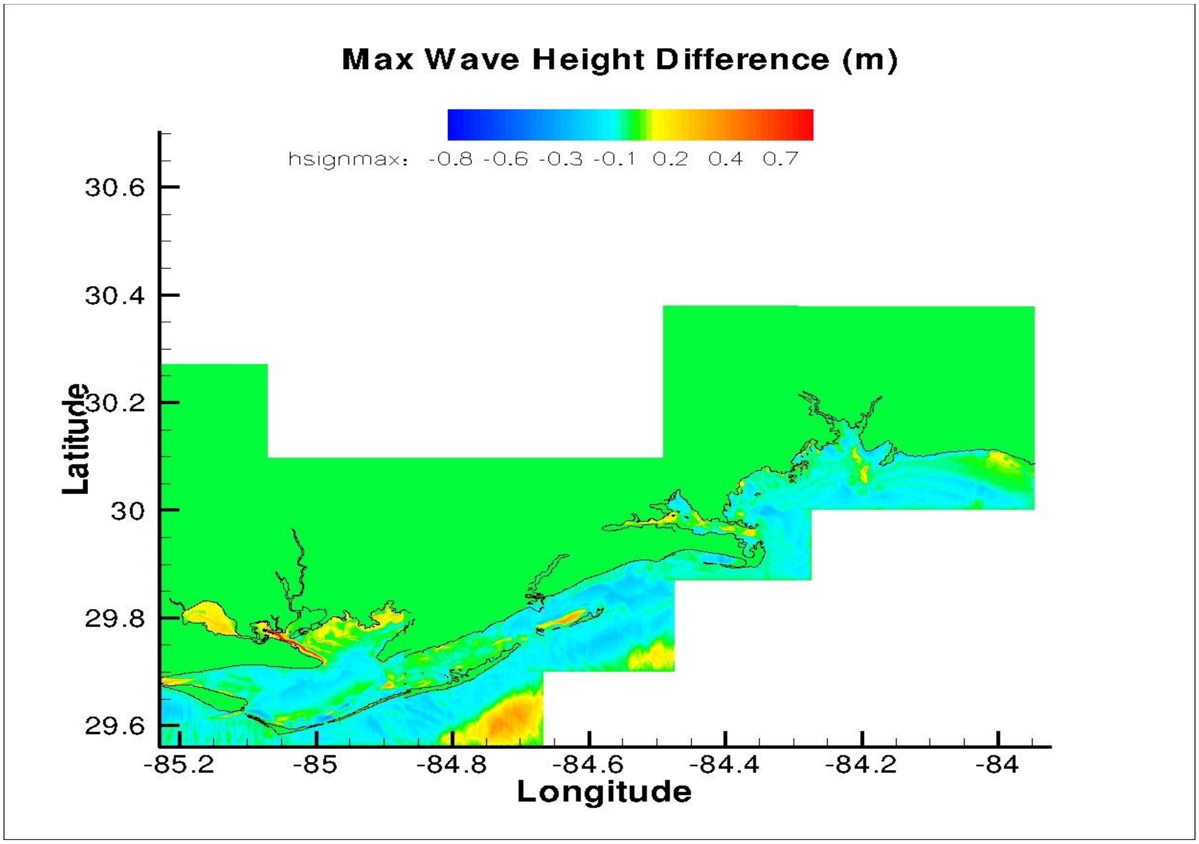


Figure 9. Difference in using SWAN in Overland mode with all the extra model physics included, compared to using SWAN on the same grids and for the same boundary conditions, topography, and wind fields for Hurricane Dennis, in the normal, open ocean mode.

Discussion and recommendations for future work

- One of the hardest parts was the preparation of grids with buildings where many of the buildings are elevated. As LiDAR and other remote sensing technologies improve or street level elevation conditions are mapped this task may be improved and automated.
- Full scale production of the 2D model is recommended to derive appropriate statistics consistent with storm stage statistics.
- We determine significant wave heights H_s, not Maximum (or Design) wave heights, H_{max}, – typically $H_s = 0.43$ D vs $H_{max} = 0.78$ D, where D is the local water Depth, simple statistical conversions based on Rayleigh wave height distribution can convert from one standard wave definition to another and may be utilized to compare our 2D model results with 1D model results.
- The 2D model should also be simulated given the same assumptions as the 1D model to make direct comparisons and confirm the validity or lack thereof of the 1D approach currently employed by FEMA for flood hazard mapping.
- Transportability of the models to future map changes on the FEMA map amendment process (i.e., LOMAR's) needs to be demonstrated and tested to a NWFWMD district engineer. This can be easily done by making minor land usage changes to a single region of the grid and then recalculating the statistics for that single region by rerunning just that single coastal domain over for the 160 production runs using the original offshore boundary conditions and winds and flood levels that have all been archived. Estimates are that this could be completed in a day or two of computing time once the process is automated, since only a small portion of the domain needs to be recalculated and only for the peak hours of landfall of the storms.

Deliverables

The deliverables for this project include this final report which indicates that the system is operational and summarizes the details of the methods used. Digital data and the model developed have been provided to the NWFWMD and are available for both NWFWMD and FEMA for future use. This report will also be posted on the web site NWFWMDfloodmaps.com. Funding for this project was provided by FEMA and NWFWMD under contract to the University of Florida Contract number: NWFWMD G000670 – UF # 0080684.

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