Charleston Peninsula Coastal Storm Risk Management Feasibility Study – Summary Report

by Gregory Slusarczyk, S.C. Dillon, Mary Anderson Bryant, Norberto Nadal-Caraballo, Rusty Permenter, Bradley Johnson

ABSTRACT: The U.S. Army Corps of Engineers (USACE), Wilmington (SAW) and Charleston (SAC) Districts are currently engaged in the Charleston Peninsula Coastal Storm Risk Management (CSRM) Feasibility Study. The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Lab (CHL) conducted a numerical modeling study to evaluate the effectiveness of structural solutions to increase resilience and reduce risk from future storms and impacts from sea level change as a part of coastal flood risk management. The numerical modeling study includes the computation of water levels and wave heights for Existing Conditions (EC), Future Without Project (FWOP) and With Project (WP – breakwater) scenarios. Results from that numerical study are presented herein and provide the engineering inputs for the economics model, G2CRM.

INTRODUCTION: The Charleston Peninsula (**Figure 1**) is approximately 8 square miles, located between the Ashley and Cooper Rivers. The two rivers join at the Battery in Charleston to form Charleston Harbor before discharging into the Atlantic Ocean. Charleston Harbor is a natural tidal estuary sheltered by barrier islands. The first European settlers arrived in Charleston around 1670. Since that time, the peninsula city has undergone dramatic shoreline changes, predominantly by landfilling of the intertidal zone. Early maps show that over one-third of the peninsula has been "reclaimed." Much of the landfilling occurred on the southern tip and the western side of Charleston (predominant flooding is on the western side due to lower elevations), behind a seawall and promenade, known as the Battery. The Charleston Peninsula is the historic core and urban center of the City of Charleston and is home to 38,000 people.

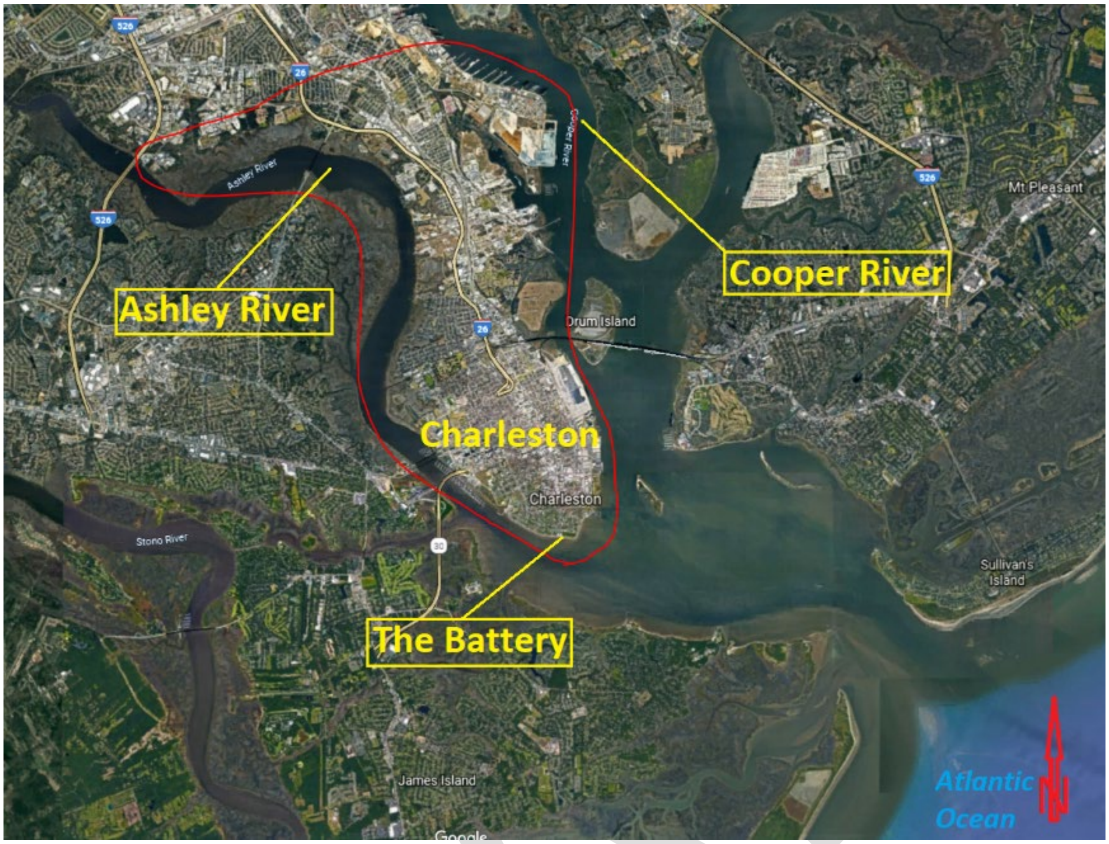

Figure 1: Charleston Peninsula study area encircled by the red line.

PROJECT OBJECTIVES: The Charleston Peninsula CSRM Study is a feasibility level study being conducted by SAC, with technical support by SAW, with the objective of reducing damages from coastal flooding that affects population, critical infrastructure, property, and ecosystems in the Charleston Peninsula area. Therefore the numerical modeling aspect of the Charleston Peninsula Study (CPS) is to provide estimates of waves and water levels for Existing Conditions (EC), Future Without Project (FWOP), and With-Project (WP - breakwater) scenarios to be evaluated by SAC. These project scenarios reflect only physical changes in the study and not changes to sea level. In order to meet these objectives the following steps were taken:

- Selection of 25 tropical synthetic storms from the set of 122 synthetic and 3 historical tropical cyclones that were designed and simulated in a previous South Carolina Storm Surge Study conducted by FEMA (Federal Emergency Management Agency), 2013
- Modification to the FEMA ADCIRC grid to reflect without/with project conditions and development of corresponding STWAVE grids
- Simulation of waves and water levels. The simulations are in support of G2CRM and do not include tides or sea level changes since these are already included in G2CRM model
- Production of maximum water surface elevations, time series of water surface elevations at specified save point locations, maximum wave heights and time series, and data files (.h5) as part of post-processing of simulation results for the economics model, G2CRM.

STORM SELECTION METHODOLOGY: As part of the 2012 South Carolina Storm Surge Project (SCSSP) a joint probability method (JPM) storm suite of 122 synthetic tropical cyclones was developed by URS for SCDNR and FEMA (FEMA 2012, 2013). SAC obtained the SCSSP storm suite from AECOM, a FEMA contractor. The intent of this 122-storm suite was the generation of water levels corresponding to 2%, 1%, and 0.2% annual exceedance probability (AEP) for FEMA's flood hazard mapping program.

For the Charleston Peninsula Study (CPS), an initial reduced storm set of 20 synthetic tropical cyclones (TCs) was selected from the original SCSSP 122-storm suite (i.e., full storm set (FSS)). The number of storms to be selected was driven by schedule and budget constraints, and by knowledge gathered from other previous and ongoing USACE feasibility studies about the minimum number of storms required to adequately capture the storm surge hazard. The goal of storm selection was to find the optimal combination of storms given a predetermined number of storms to be sampled (e.g., 20 TCs), referred to as reduced storm set (RSS). In the process of selecting 20 TCs, it was determined that a RSS of this size adequately captured the storm surge hazard for the range of probabilities covered by the FSS (122 TCs).

The storm selection process was performed using the design of experiments (DoE) approach described in detail in Jia et al. (2015) and, more recently, Taflanidis et al. (2017) and Zhang et al. (2018). The DoE compares still water level (SWL), further in the text referenced as water elevation, hazard curves derived from the RSS to "benchmark" hazard curves corresponding to the FSS at a given number of save points within the study area. The difference between the RSS hazard curves and FSS benchmark curves is minimized in an iterative process considering multiple subsets of 20 TCs.

In summary, the general steps in this DoE approach for selecting a subset of storms are:

1. Identify a set of save points critical to a project or study area, where optimization will be performed.
2. Develop hazard curves for the FSS.
3. Select number of storms to be sampled.
4. Develop hazard curves for the RSS.
5. Choose the range of probabilities for which hazard curves will be compared. RSS versus FSS differences can be computed along the entire hazard curve, or by prioritizing a specific segment of the curves, e.g., 50 to 500 years.
6. Compute differences between RSS and FSS hazard curves.
7. An iterative sensitivity analysis is performed to determine the optimal combination of storms constituting the RSS.
8. Once the optimal combination of storms is determined, an optional analysis can be performed to evaluate the benefits of increasing storm subset size; finalize storm selection.

REDUCED STORM SET FOR CPS: For the CPS, a metamodel with recursive iterative implementation was used to select an optimal subsample of the 122 SCSSP storms. The method is based on the Gaussian process metamodeling described by Taflanidis et al. (2017)

and Zhang et al. (2018). In this approach, an initial sample of 20 storms (i.e., RSS) is recursively obtained in the 122 storm FSS. A metamodel is produced for each of the 89 save points within the CPS area (**Figure 2**) based on these 20 events with hurricane JPM parameters as inputs and ADCIRC storm surge as output. Each metamodel is then used to predict the SWL hazard curves for each of the 89 save point locations. The metamodels of each 20-sample surrogate are trained, and hazard curves are produced at the 89 save point locations. The best 20-storm sample is determined by minimizing the error across the parameter space using a genetic algorithm where the error is between the reduced sample and the full 122 storm set. Many permutations of 20 events are sampled using a Monte Carlo sampling of the entire parameter space. This process is repeated until an optimal 20-event sample is defined that minimizes the error between the target (FSS) hazard curve and the sample (RSS).

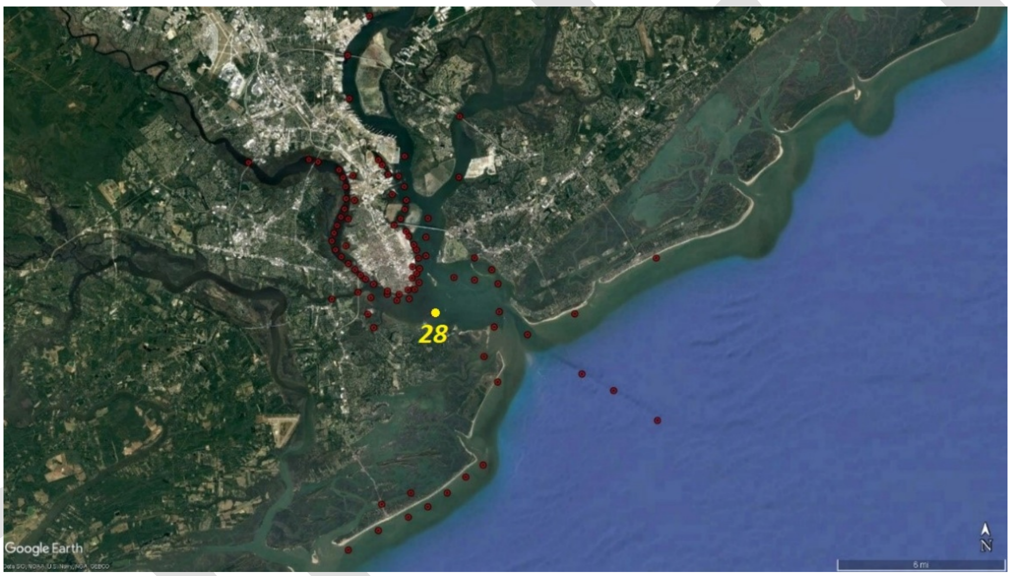

Figure 2: Location of the 89 save points (88 save points indicated by red dots, save point #28 shown as the yellow dot) within the CPS domain used for storm selection.

Figure 3 shows the results of the optimization process, from the initial random guess hazard curve (red) to the optimal 20-storm (RSS) hazard curve (black) matching the "benchmark" or full storm set (FSS) hazard curve. The figure illustrates that a sample of 20 storms converges and ultimately results in a hazard-curve error very close to zero for the intended range of AEPs of the full storm set (i.e., 2%, 1%, and 0.2%; or 50, 100, and 500 years).

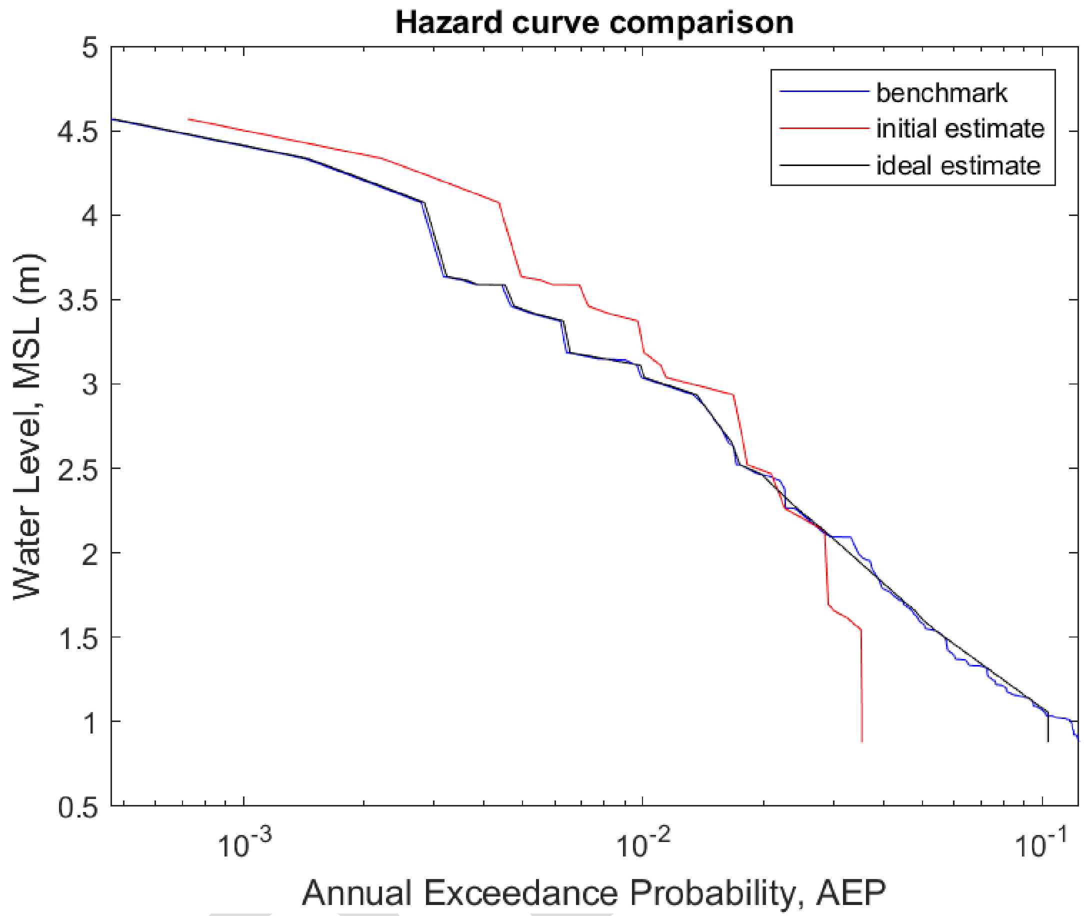

Figure 3: Optimization process for selection of initial 20-storm set.

The tracks and storm number for each of the 20 storms in the RSS are shown in **Figure 4**. As expected, a majority of the selected storms have paths to the left of the study area, since higher storm surge and flooding impacts are caused by the right side of the hurricanes due to their counterclockwise vorticity.

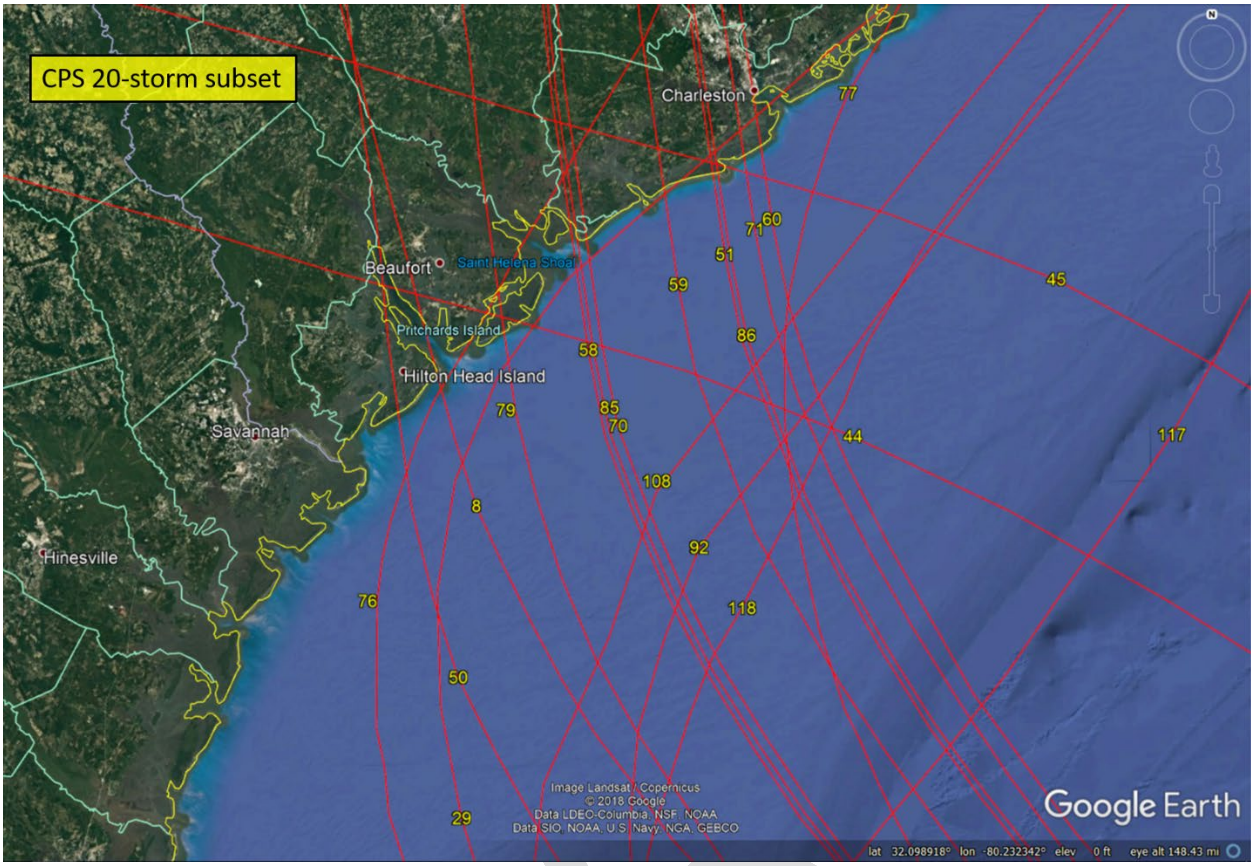

Figure 4: Zoomed in map of tracks of the 20-storm subset.

The FEMA SWL hazard curve for CPS save point no. 28 is shown in **Figure 5.** Also illustrated in this plot are the 20-storm subset and corresponding AEFs (x-axis) and SWL (y-axis).

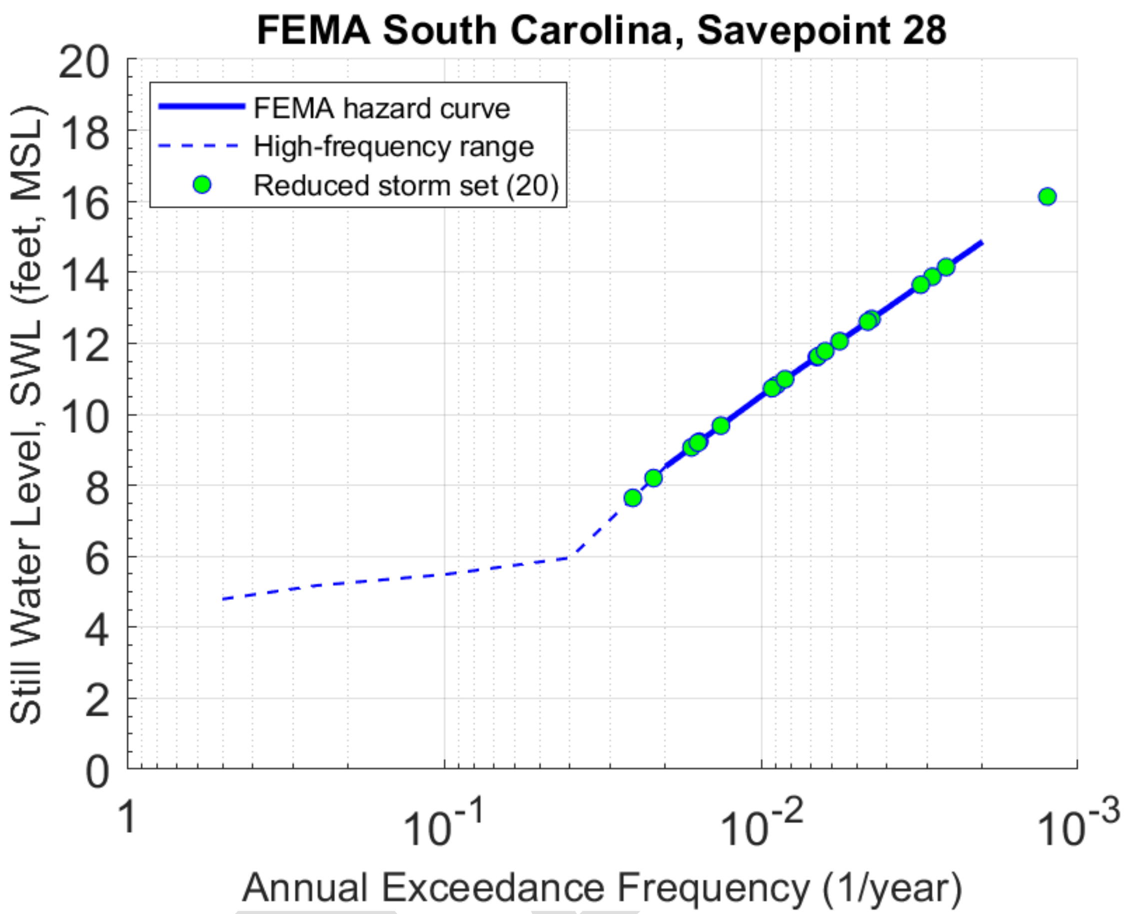

Figure 5: SWL hazard curve (AEF) for CPS save point no. 28 along with the 20-storm subset (green).

In CPS, the need for storms representing the high-frequency range of the SWL hazard was later identified; this is, storms outside the range of regulatory FEMA SWL corresponding 2%, 1%, and 0.2% AEP. As discussed in the SCSSP report, although not required by FEMA, water levels corresponding to 50%, 20%, 10%, and 4% AEP were determined through extreme value analysis (EVA) of water levels recorded at tidal gages. Therefore, five (5) additional storms were selected from the range of probabilities determined from EVA of water level measurements.

The tracks and storm number for each of the additional five storms, and for the updated 25-storm subset are shown in **Figure 6** and **Figure 7**, respectively. As previously stated the additional five storms are intended to represent the high-frequency range of the SWL hazard. Although the FEMA SCSSP storms were not designed for this purpose, the five selected storms can serve as proxies for low-magnitude SWL responses due to a combination of relatively low intensities and/or long distances from the study area.

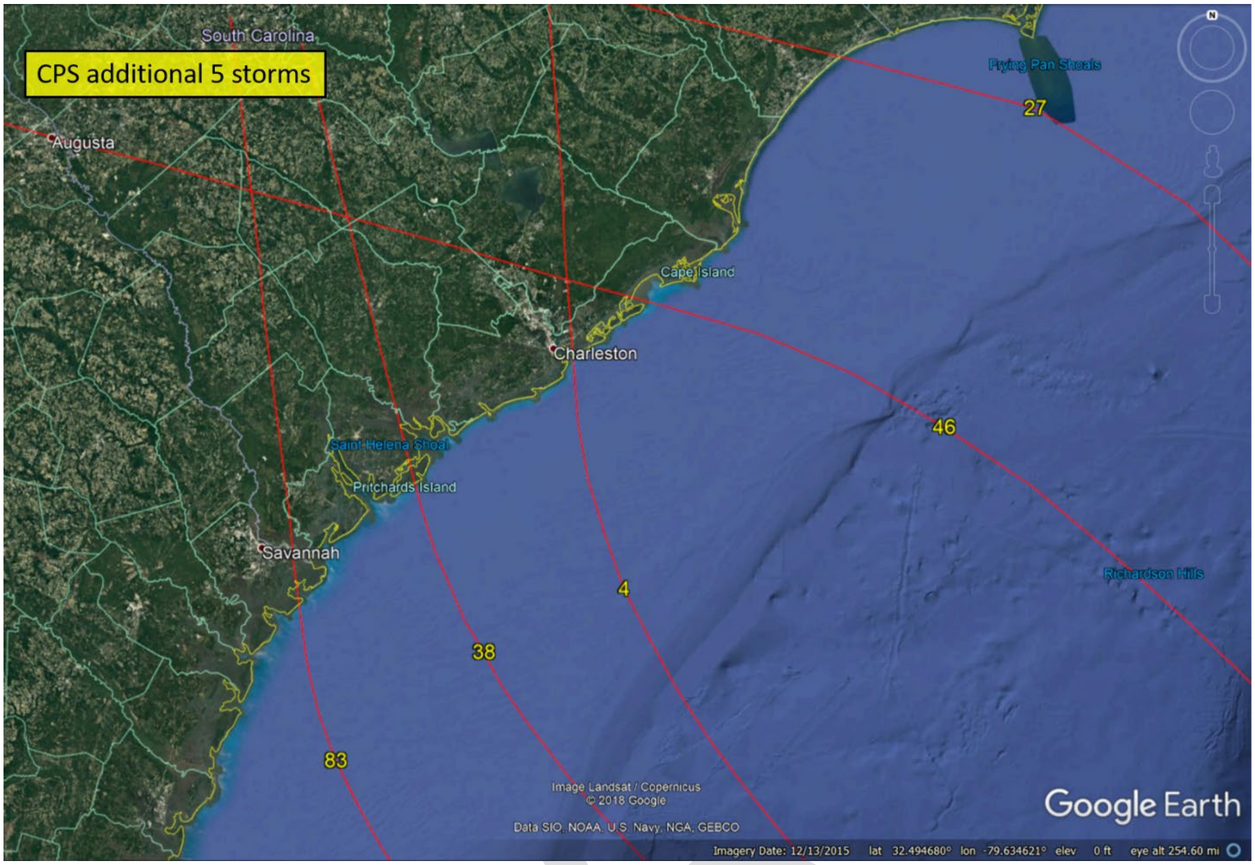

Figure 6: Zoomed in map of tracks of the additional 5 storms.

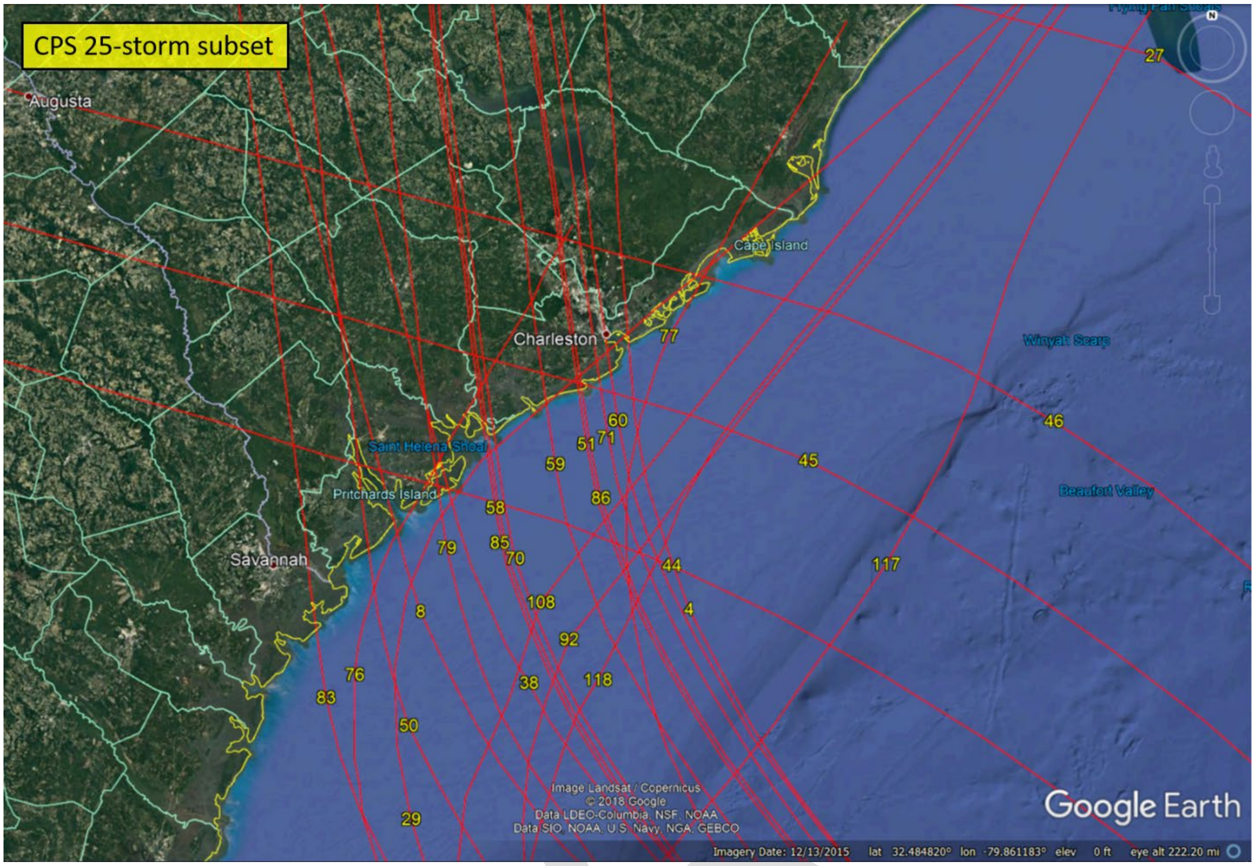

Figure 7: Zoomed in map of tracks of the final 25-storm subset.

The FEMA SWL hazard curve for CPS save point no. 28, along with the 20-storm subset (red circles) and the additional 5 storms (red circles) are shown in **Figure 8**. The same information is depicted in **Figure 9** with the x-axis modified to show AEPs instead of AEFs.

Figure 9 seems to show an additional green circle not seen in **Figure 8**. This green circle corresponds to synthetic TC no. 117. At station no. 28 the water level produced by this storm has an AEP of 99.4%, as seen in **Figure 9**. The AEF of the water level associated with this storm is 5.12 year-1, which is outside the range of the x-axis in **Figure 8**.

Storm recurrence rates for each of the 25 storms were estimated for Monte Carlo sampling purposes within G2CRM based on:

i) the parameterization of hurricane climatology, as described in the SCSSP JPM-OS report (URS 2012) for the FSS and adjusted for the RSS following Zhang et al. 2018; and

ii) the interpolation of ADCIRC-simulated water level responses from the SCSSP hazard curves reproduced by AECOM and provided to SAC.

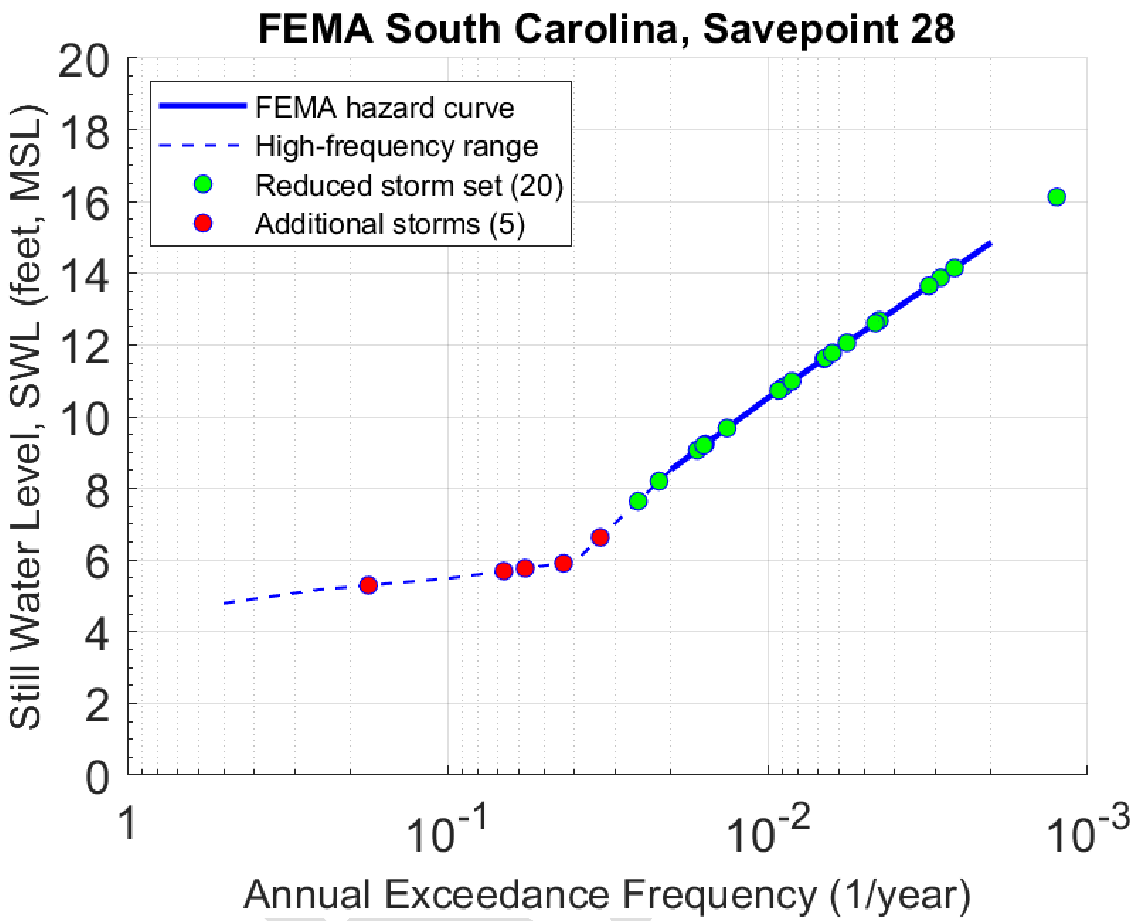

Figure 8: SWL hazard curve (AEF) for CPS save point no. 28 along with the 20 storm subset (green) and additional 5 storms (red).

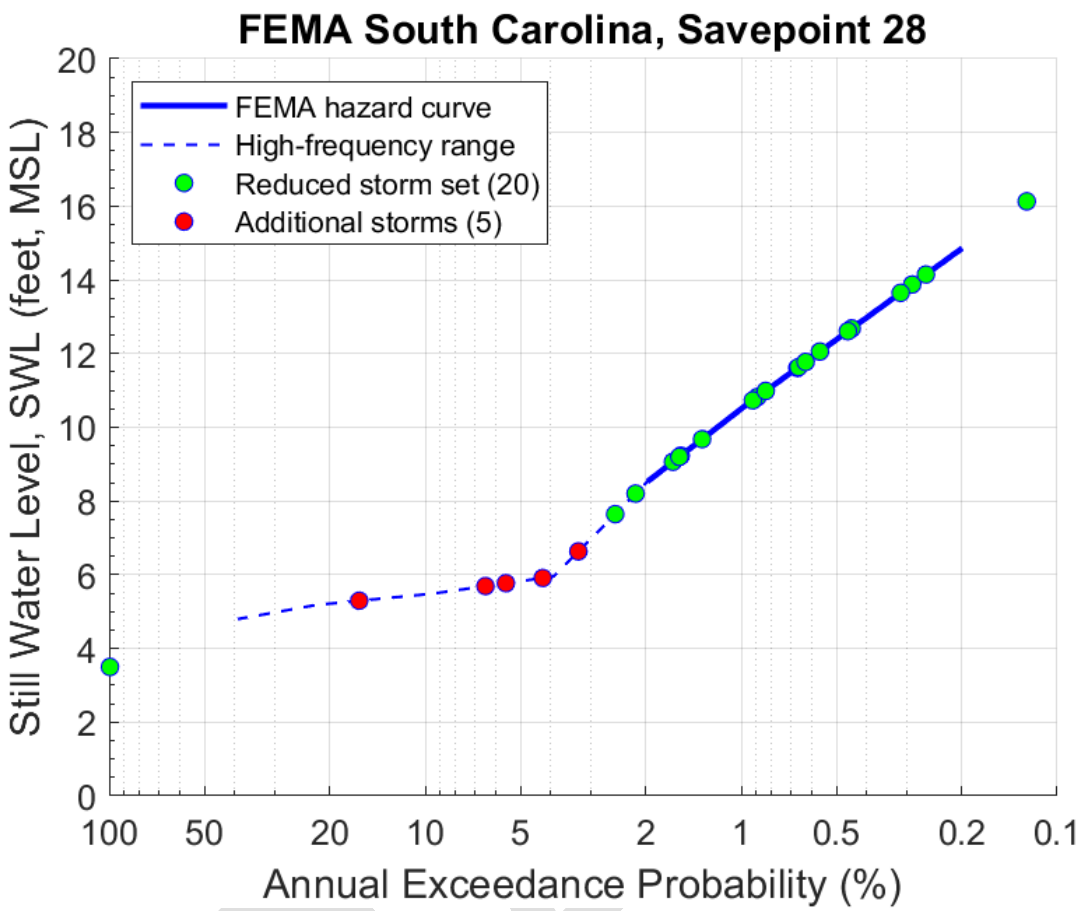

Figure 9: SWL hazard curve (AEP) for CPS save point no. 28 along with the 20 storm subset (green) and additional 5 storms (red).

ADCIRC MESH DETAILS AND MODEL PARAMETERS: The computational domain for CPS, shown in **Figure 10**, was derived from South Carolina Storm Surge Study grid (FEMA 2013). While the original ADCIRC mesh boundary was maintained, the grid elements in the vicinity of the study area were refined by increasing the resolution of the mesh in order to provide more details in the region of interested. **Figure 11** shows the target area for the grid refinement.

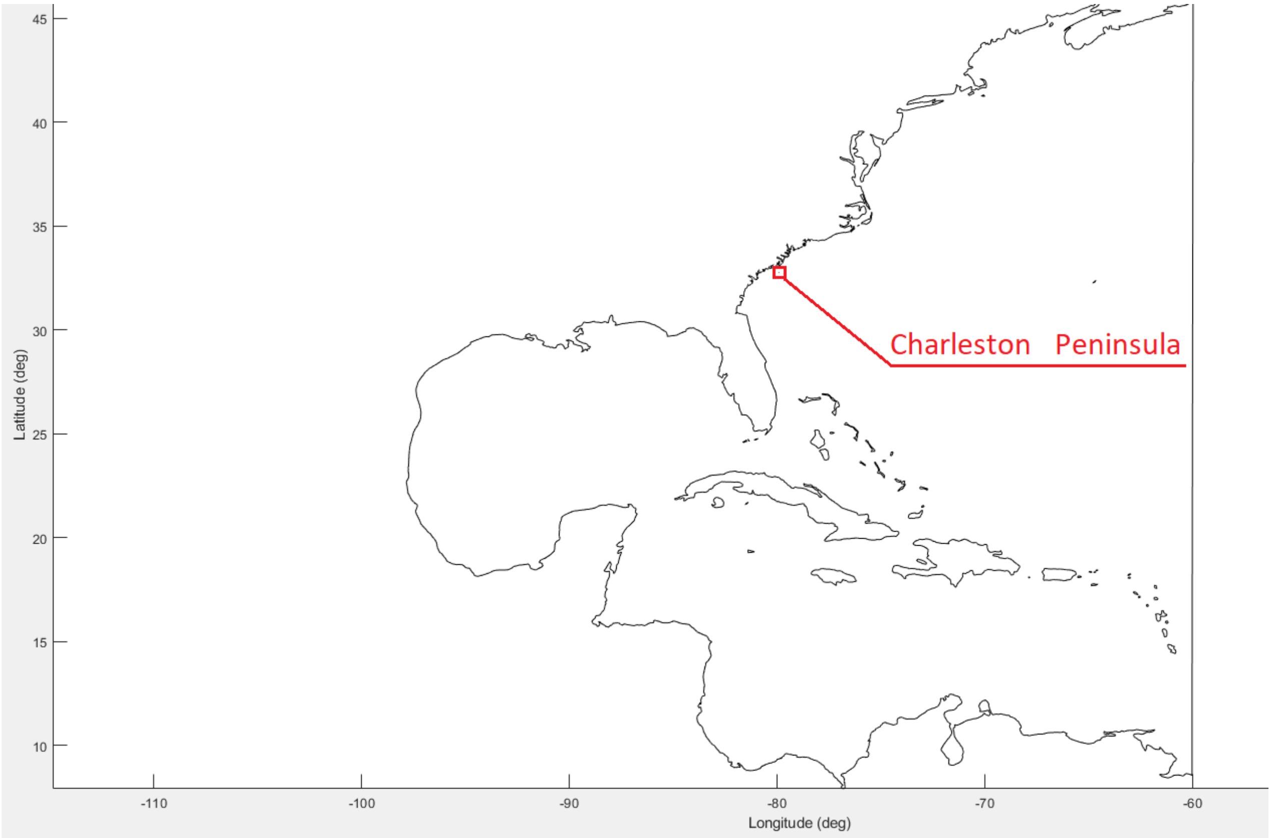

Figure 10: Outline plot showing the boundary of the ADCIRC mesh.

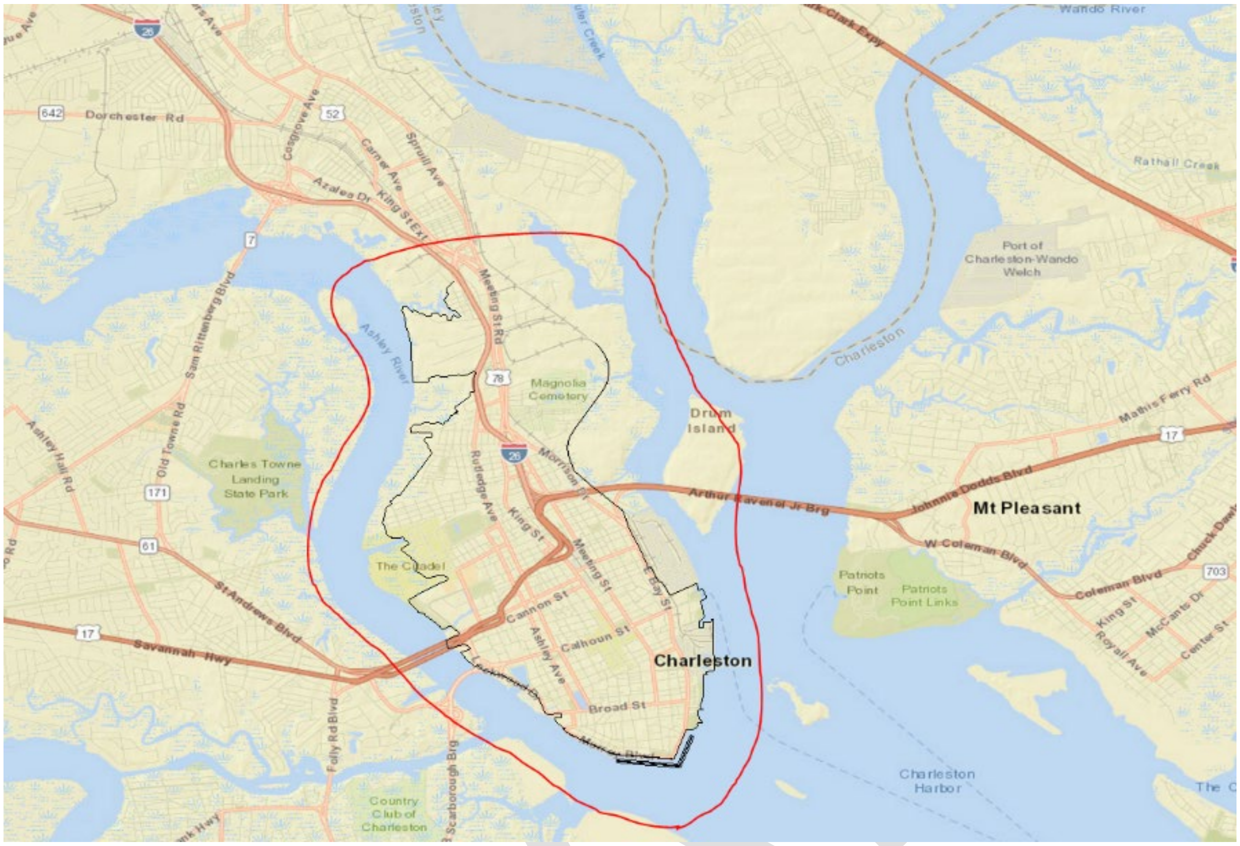

Figure 11: The area of the grid (encircled by red line) that was subject to the grid refinement procedure.

However due to grid instabilities caused by rapid change from element size of 150-200 m to 15-25 m, a buffer zone had to be created around the grid refinement target area (**Figure 12** and **Figure 13** show the CPS area before and after the grid refinement, respectively**). Figure 14, Figure 15,** and **Figure 16** show successive magnifications of the refined area to better illustrate the transition of the element size. This zone enabled gradual transition from the coarse grid to the refined grid inside the target area. Moreover to achieve additional grid stability, the element sizes in the target area were set to 25-35 m.

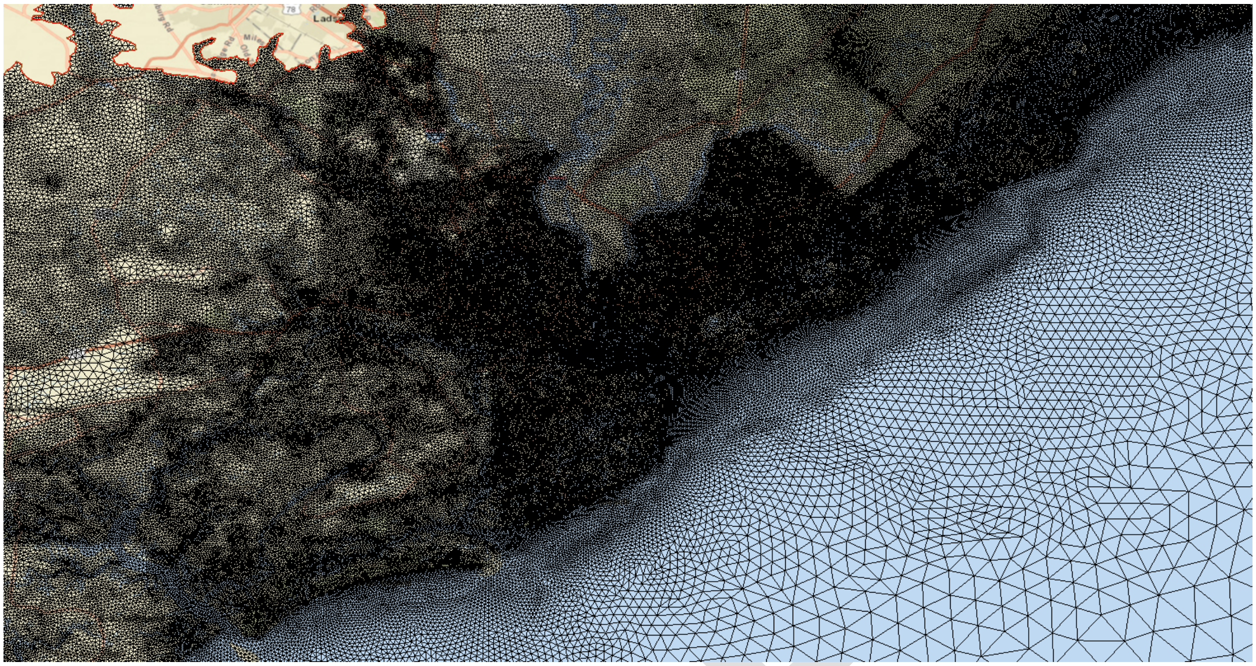

Figure 12: CPS before the grid refinement.

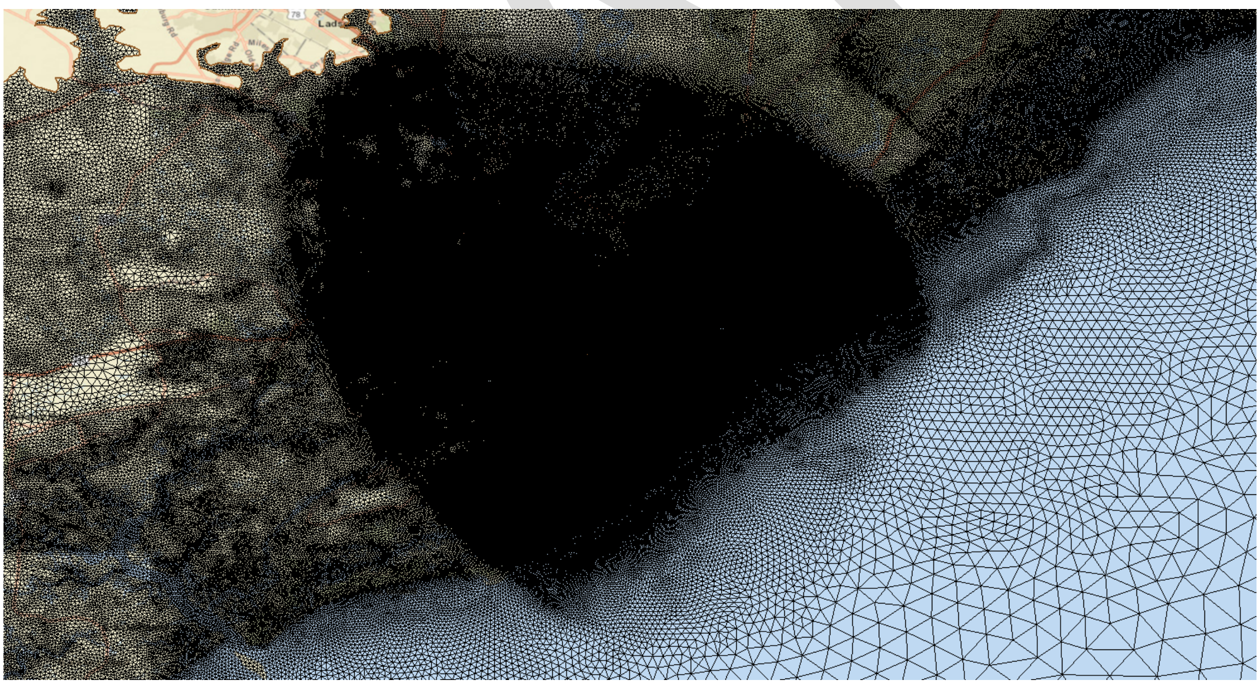

Figure 13: CPS after the grid refinement (with the buffer zone).

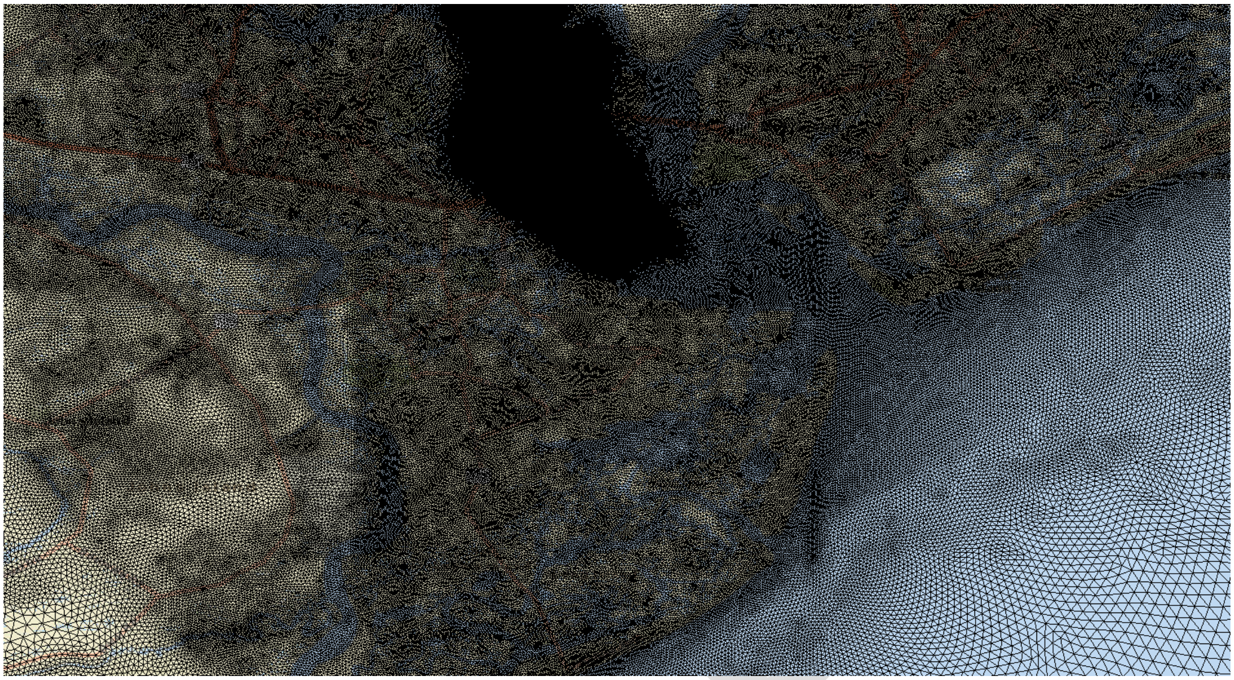

Figure 14: ADCIRC mesh after refining - zoom in (1).

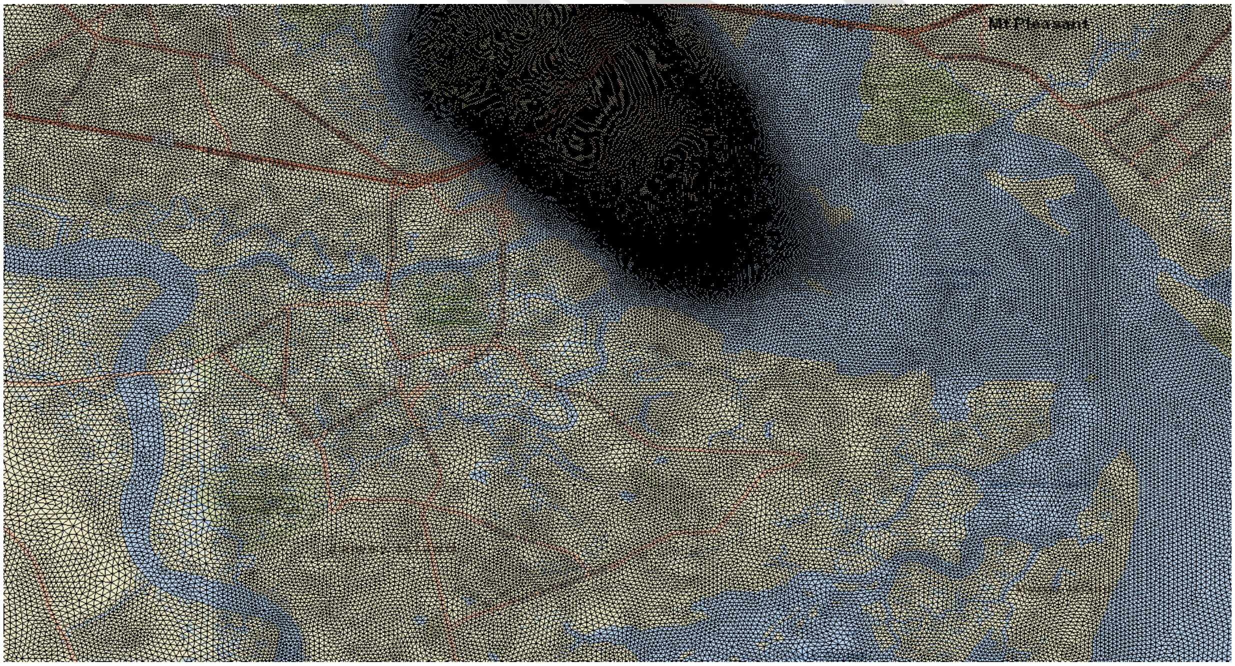

Figure 15: ADCIRC mesh after refining - zoom in (2).

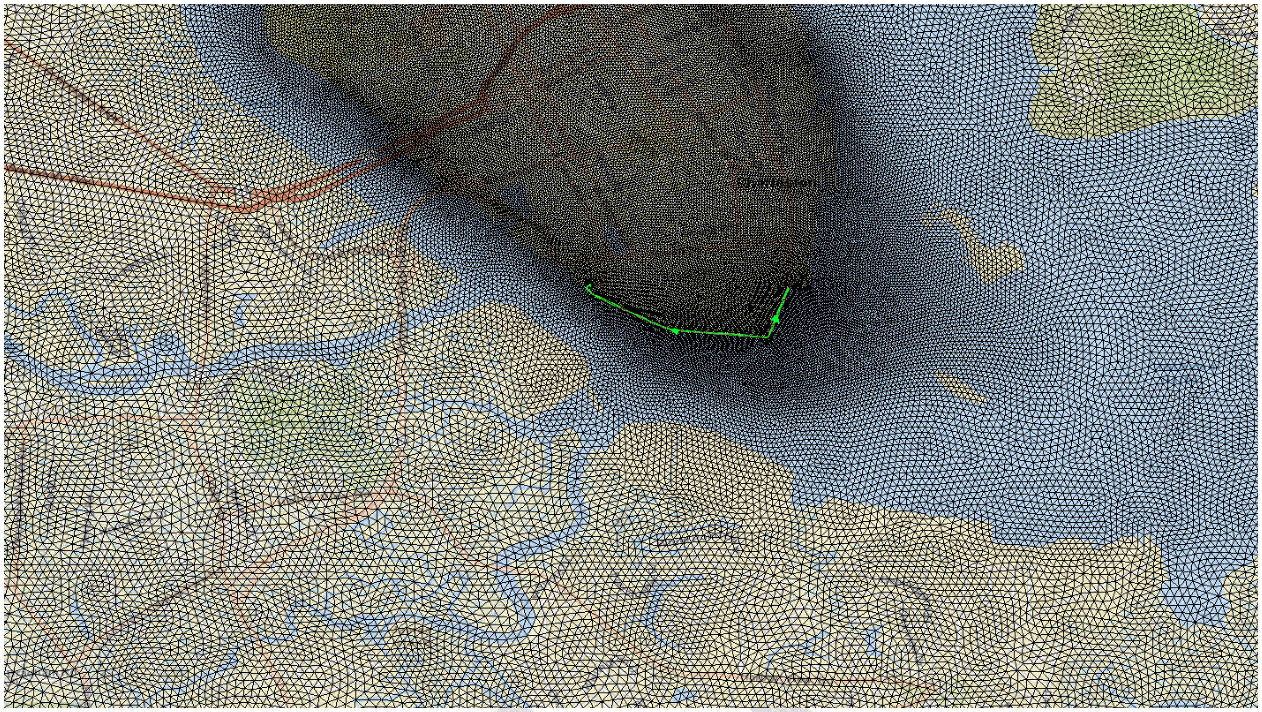

Figure 16: ADCIRC mesh after refining - zoom in (3).

Figure 17 and **Figure 18** illustrate the difference in the mesh resolution before and after the refining procedure. The number of nodes increased from 542809 (South Carolina Storm Surge Study grid) to 793975 (Charleston Peninsula Study – EC grid). The green line in **Figure 18** indicates the Battery implemented as a weir-pair subgrid feature according to the specifications provided by SAC. The Battery in the original South Carolina Storm Surge Study FEMA grid was represented by topographic values.

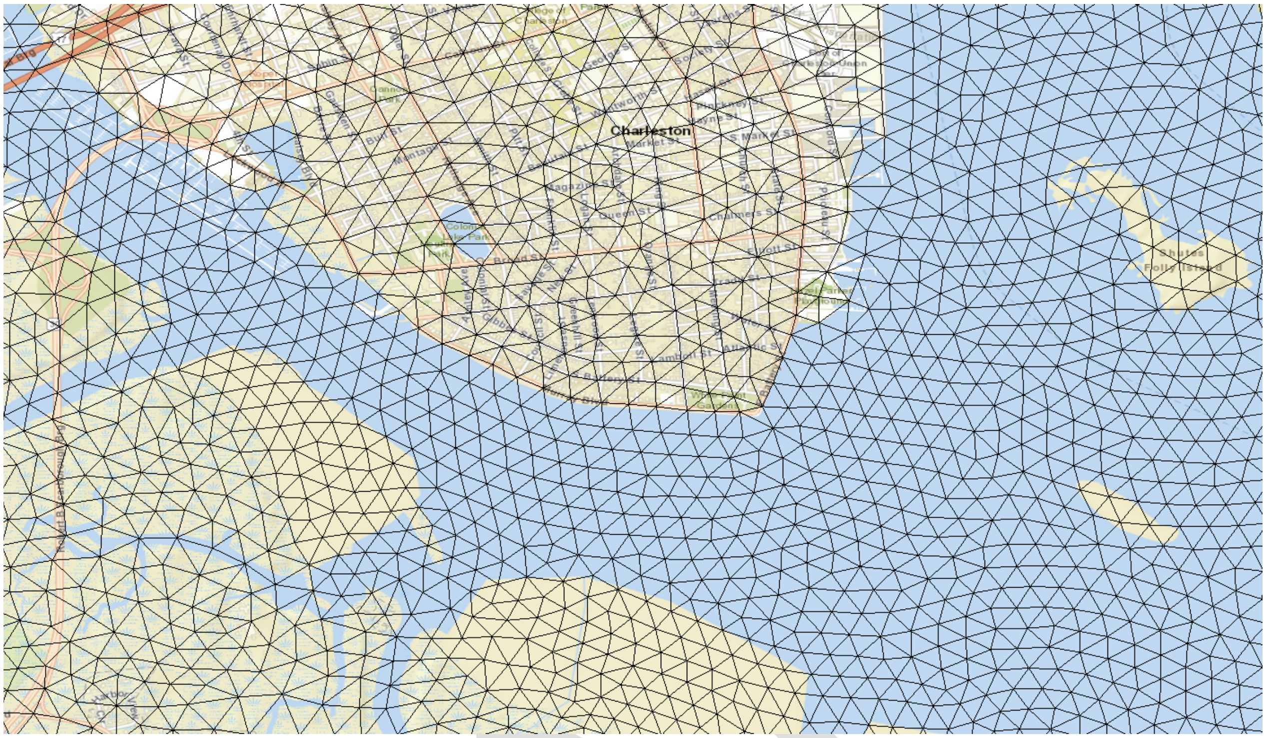

Figure 17: Zoom in to the Charleston Peninsula (before the grid refinement).

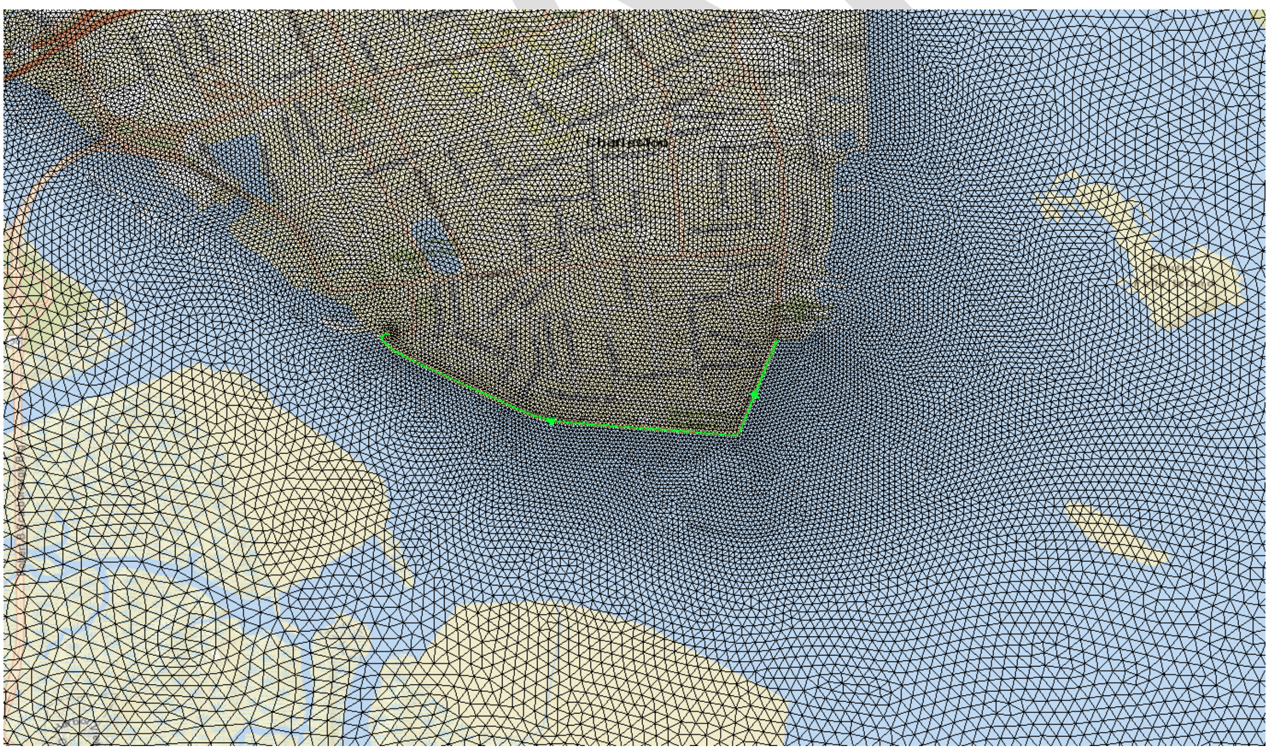

Figure 18: Zoom in (4) to Charleston Peninsula (after the grid refinement).

Finally, the grid topography/bathymetry (South Carolina Storm Surge Study – FEMA) had to be updated in the region distant and hydraulically independent from the study area shown in **Figure**

19 in order to maintain model stability. Because of the stability issue, smoothing (elimination of narrow creek and channels away from the area of study) and a slope limiter (selective limiting of the maximum water elevation within a mesh element) were applied and are also shown in **Figure 19**. Smoothing and implementation of the slope limiter did not contaminate the results of the study since they were applied 60 km away from Charleston Peninsula to the area that is hydraulically independent from the study area. The source of the updated bathymetry was the Northeast Florida Georgia Surge Study conducted by FEMA.

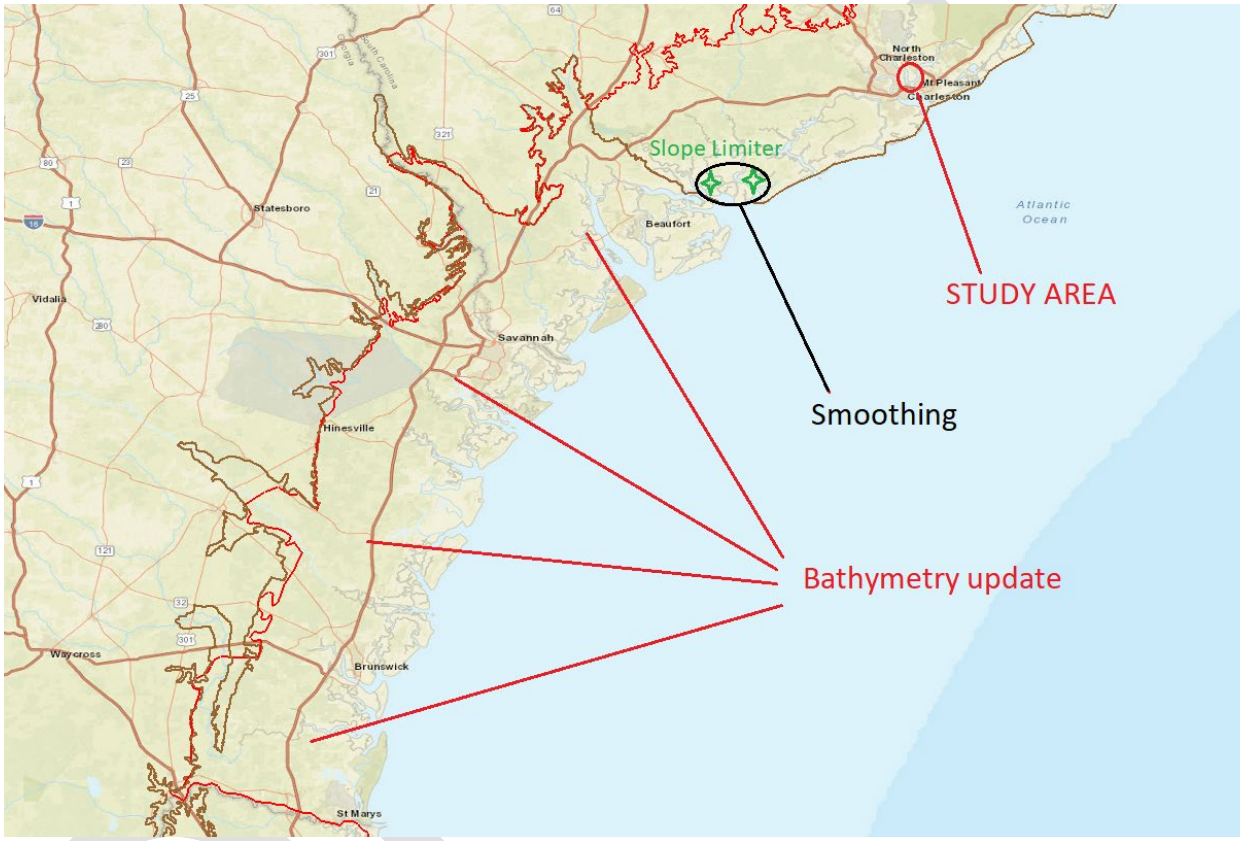

Figure 19: South Carolina Storm Surge Study FEMA grid with locations where bathymetry update, smoothing, and slope limiter were applied.

The resulting grid with the above modifications and the implemented Battery (shown in **Figure 20 -** red/black line) as a weir-pair subgrid feature served as Existing Condition (EC) grid. The elevation of the Battery (EC) was set to 9.1 ft., NAVD88 for the higher wall and 6.8 ft., NAVD88 for the existing low battery wall. Then the elevation of the Battery was modified according to the guideline provided by SAC (the higher and the existing low battery wall was set to 9.0 ft., NAVD88) to generate the Future WithOut Project (FWOP) conditions mesh. This mesh, in turn, served as the base for developing the final grid configuration which contained a breakwater. The breakwater (shown in **Figure 20** – magenta line), also implemented as a weir-pair subgrid feature, was set to 16.2 ft., NAVD88 (elevation of the crest). This grid is referred as the With Project condition (WP01).

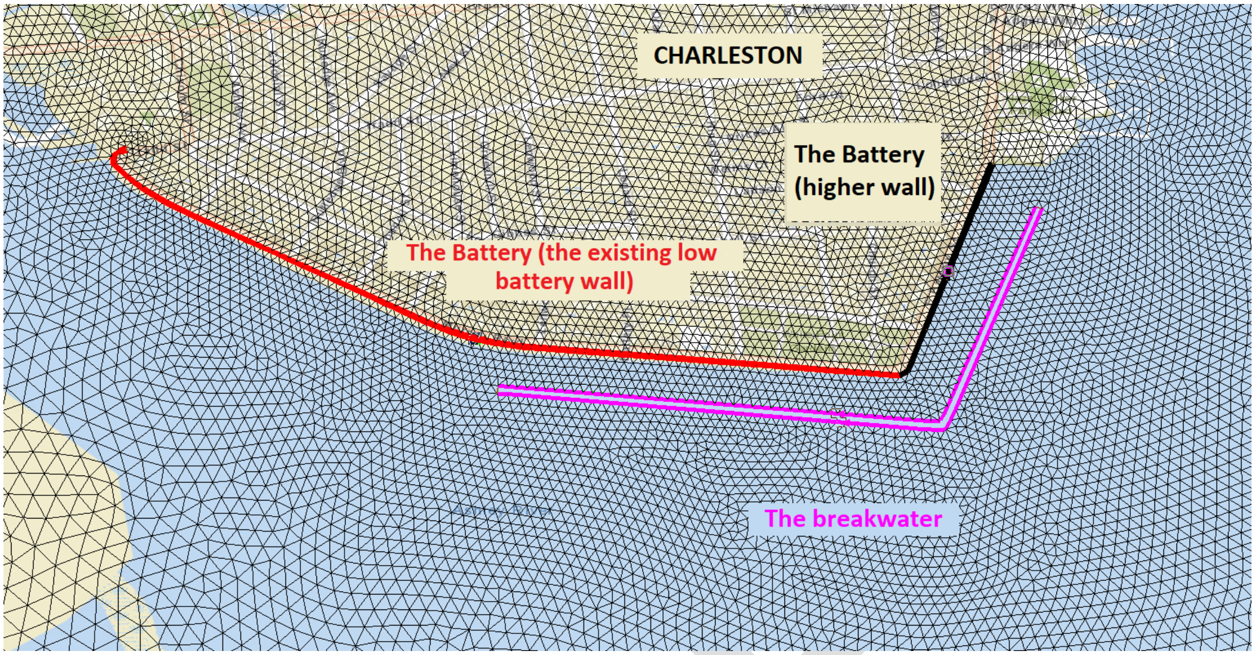

Figure 20: Charleston Peninsula with the Battery (the existing low battery wall: red, the higher wall: black) and the breakwater (magenta).

ADCIRC OUTPUT FILES - MAXIMUM WATER ELEVATION AND TIME-SERIES OF WATER ELEVATION: The maximum water elevation and water elevation time-series plots presented in this section are based on a single storm event (Synthetic Tropical Storm #27) for the brevity of the document. All model output is referenced to MSL, meters, however at the request of SAC plots shown in this section are converted to NAVD88, feet. Note that water levels do not include tide or sea level change per the requirement of G2CRM. The water elevation time-series illustrate results for save points preselected by SAC/SAW (Stations: 180, 598, 329, 699, and 976; shown **Figure 21**) that were also used for generation of the G2CRM .h5 files. The plots of maximum water elevation for the other four storm events (Storms: 4, 38, 46, and 83) are found in **Appendix A** of this document. The characteristics of all five storms are in **Appendix D**. Storm characteristics detailed in Appendix D include Rmax (the radius of maximum wind for a tropical cyclone), storm track, landfall location, Cp (Central pressure of a tropical cyclone), RAD1 (the scale pressure radius related to the radius of maximum winds), B1 (the peakedness of the primary wind maxima), and wind speed. Characteristics for all other storms can be found in the Appendix B of the FEMA document (FEMA 2012). **Figure 22, Figure 23,** and **Figure 24** show that the modification to the Battery elevation for the FWOP grid as well as the implementation of the breakwater had an insignificant effect on maximum storm surge water levels. That is, the three maximum surge envelopes show identical patterns of maximum water elevation. This observation is confirmed by hydrographs in figures:

- **Figure 25, Figure 26, and Figure 27** – time-series plots recorded at Station 976
- **Figure 28, Figure 29, and Figure 30** – time-series plots recorded at Station 699
- **Figure 31, Figure 32, and Figure 33** – time-series plots recorded at Station 598

- **Figure 34, Figure 35, and Figure 36** – time-series plots recorded at Station 329
- **Figure 37, Figure 38, and Figure 39** – time-series plots recorded at Station 180

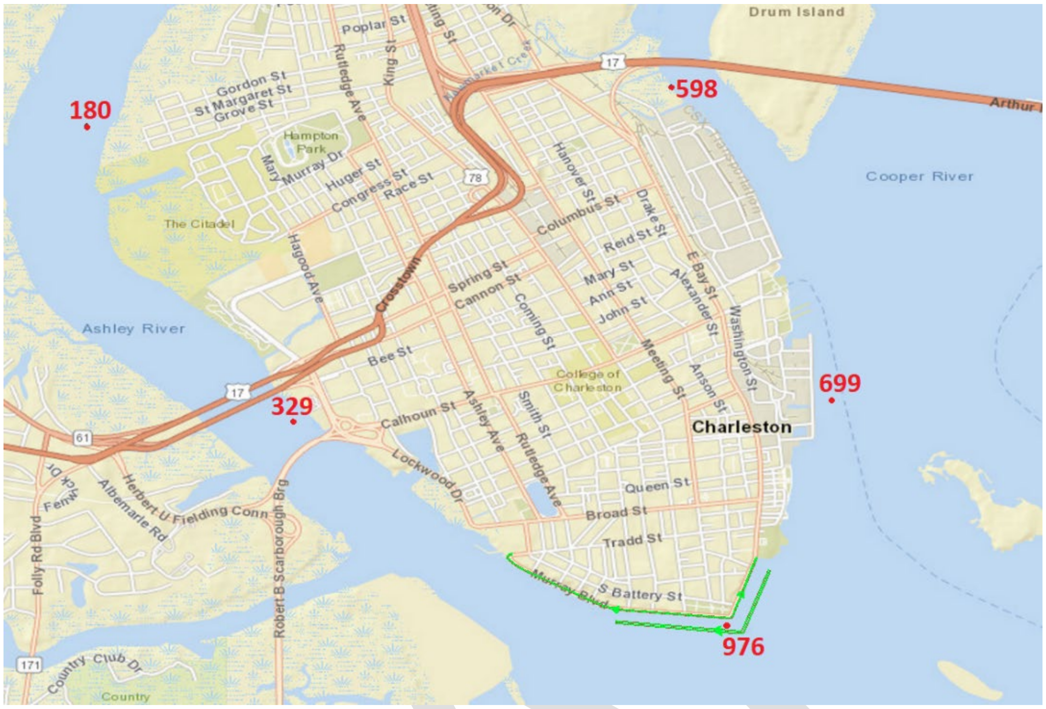

Figure 21: The locations of the save points: 976, 699, 598, 329, and 180.

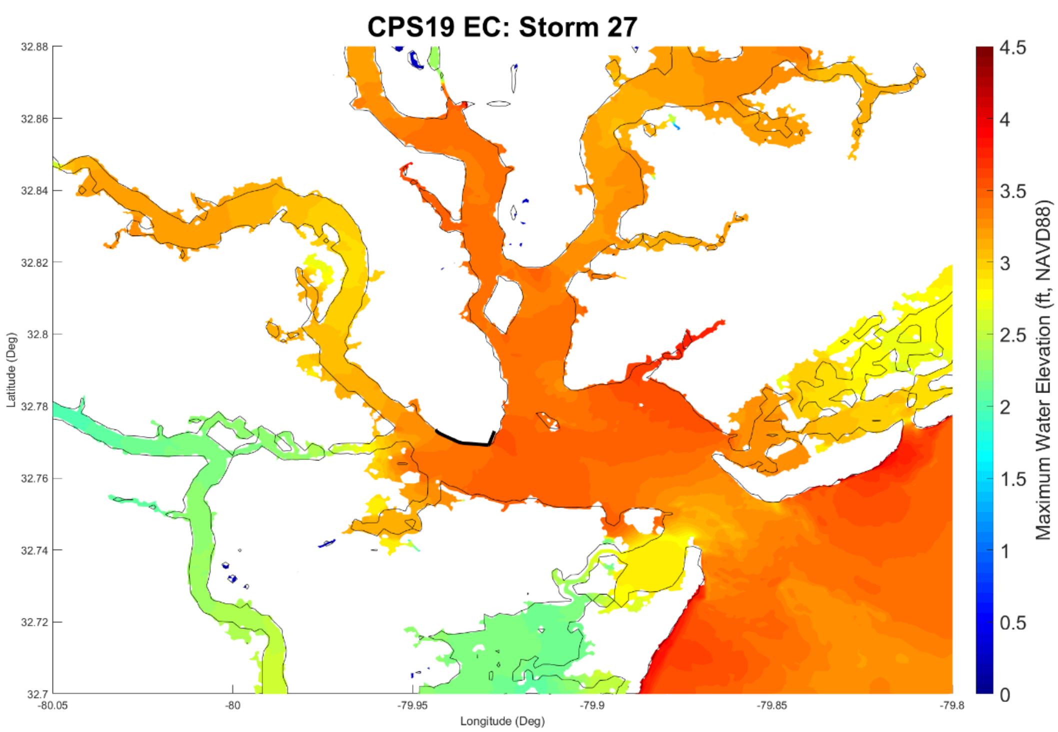

Figure 22: CPS EC grid, Storm 27.

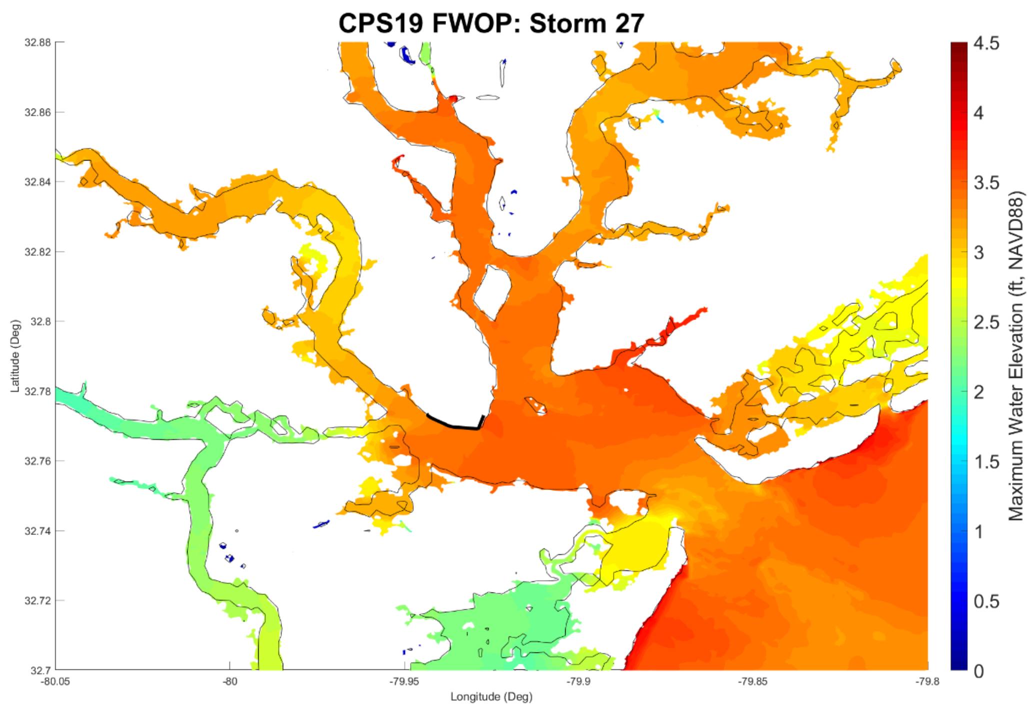

Figure 23: CPS FWOP grid, Storm 27.

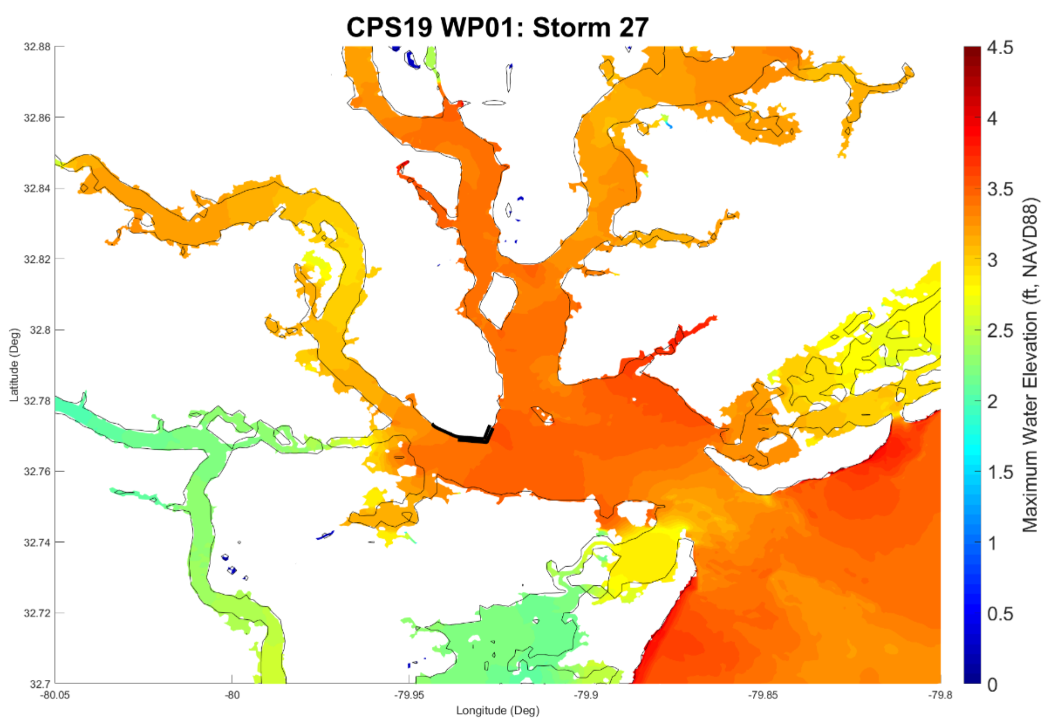

Figure 24: CPS WP01 grid, Storm 27.

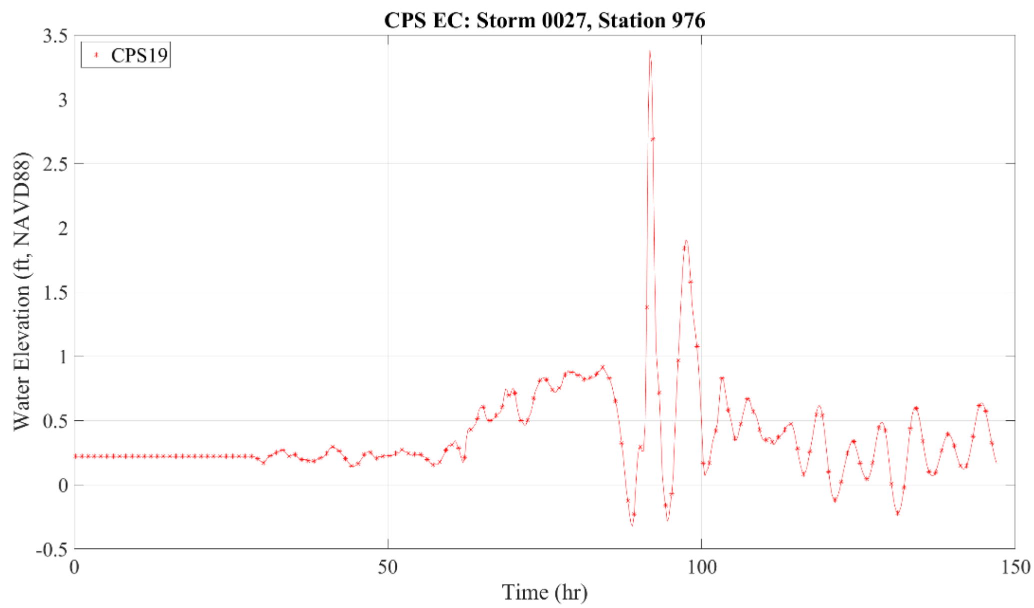

Figure 25: CPS EC grid, Storm 27, Station 976.

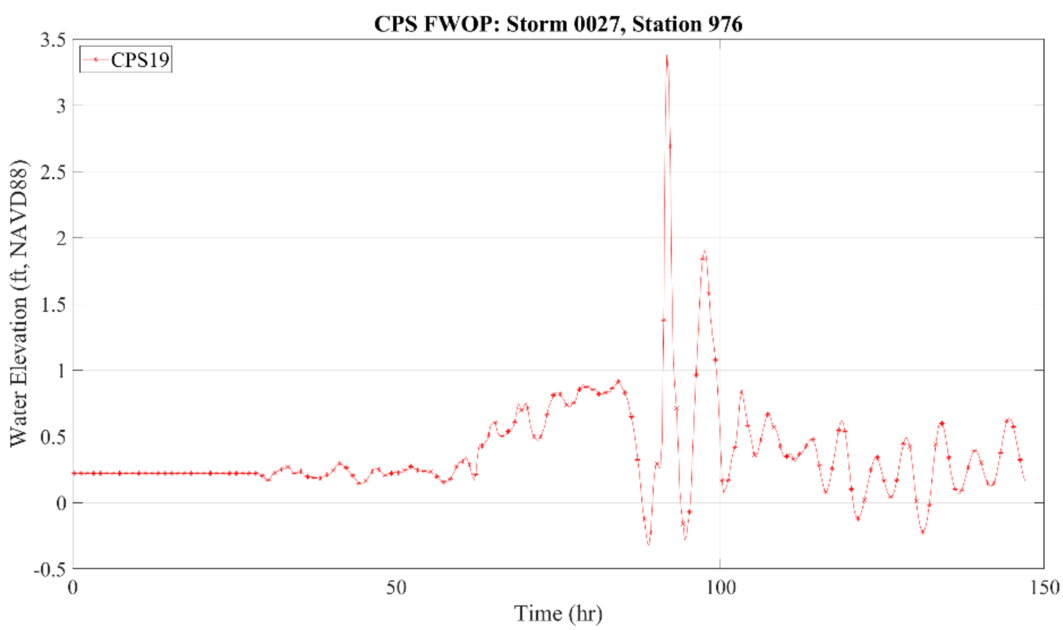

Figure 26: CPS FWOP grid, Storm 27, Station 976.

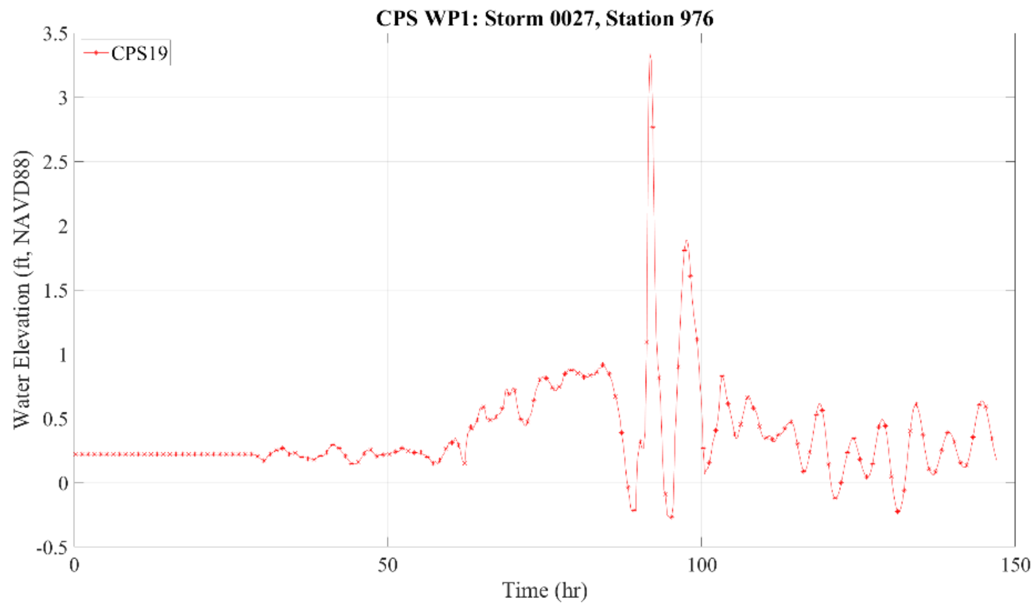

Figure 27: CPS WP01 grid, Storm 27, Station 976.

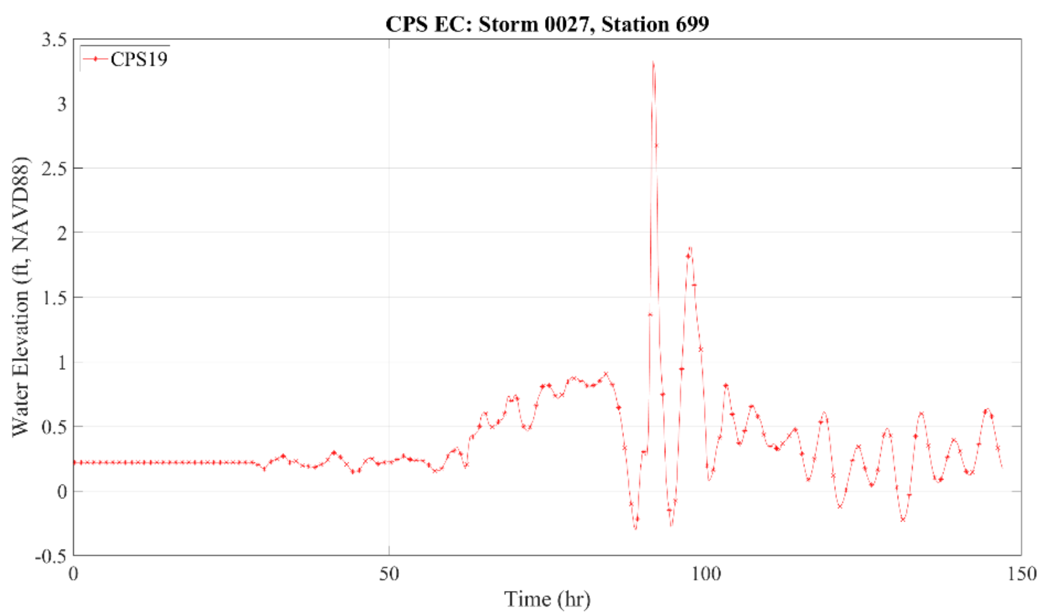

Figure 28: CPS EC grid, Storm 27, Station 699.

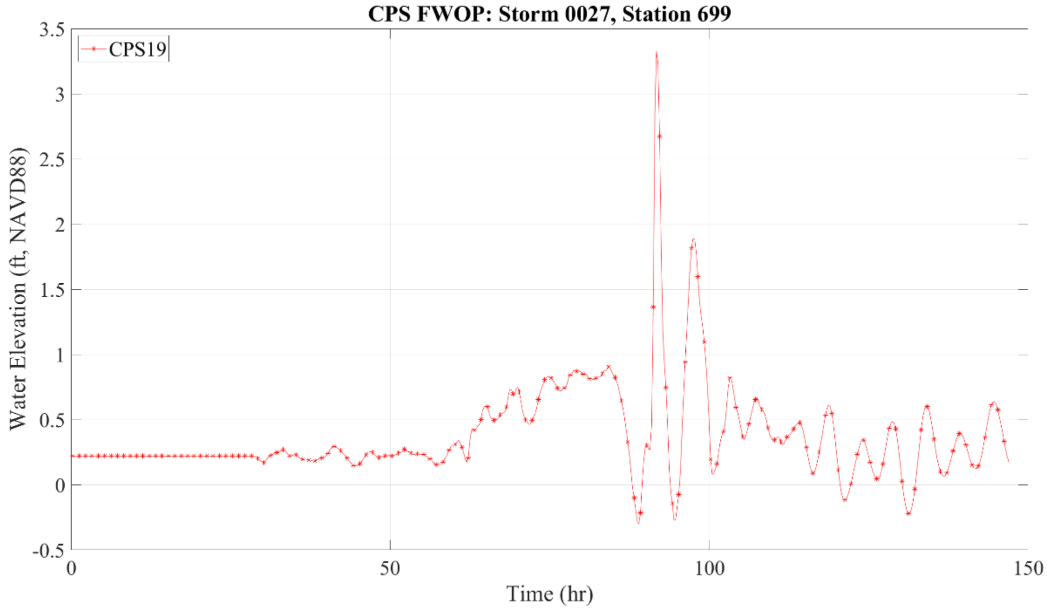

Figure 29: CPS FWOP grid, Storm 27, Station 699.

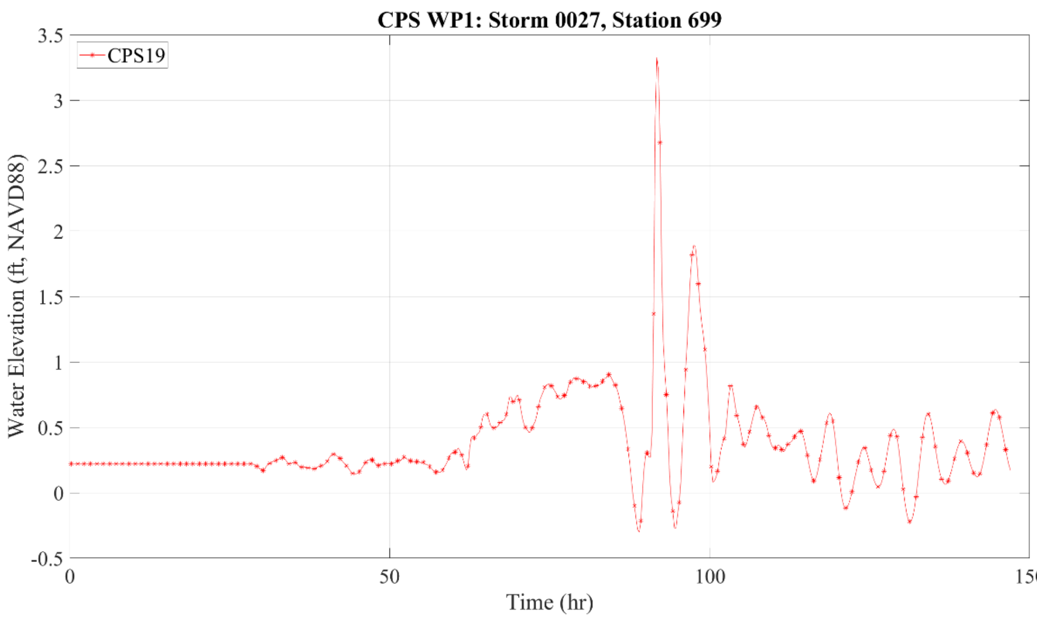

Figure 30: CPS WP01 grid, Storm 27, Station 699.

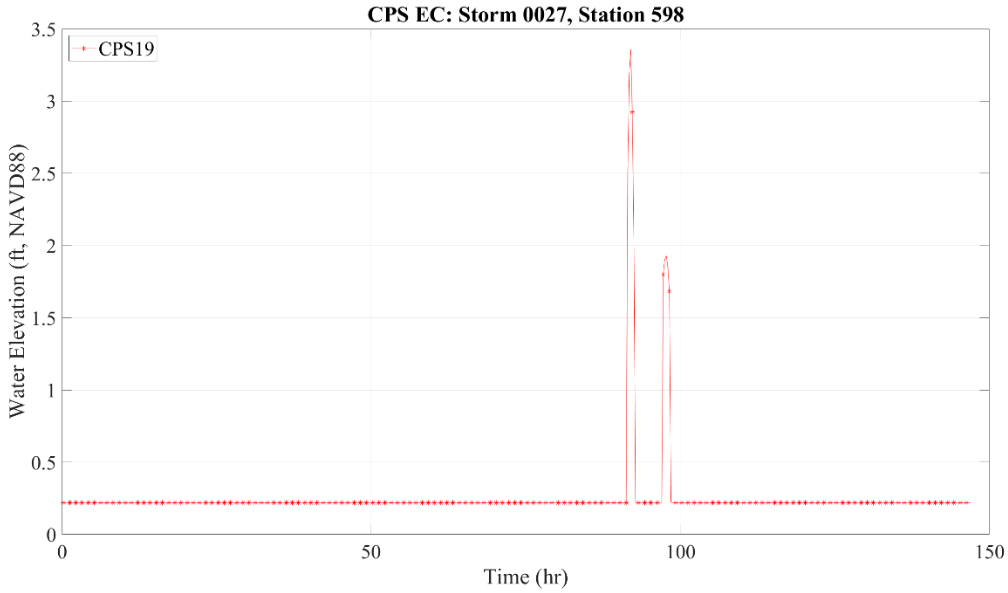

Figure 31: CPS EC grid, Storm 27, Station 598.

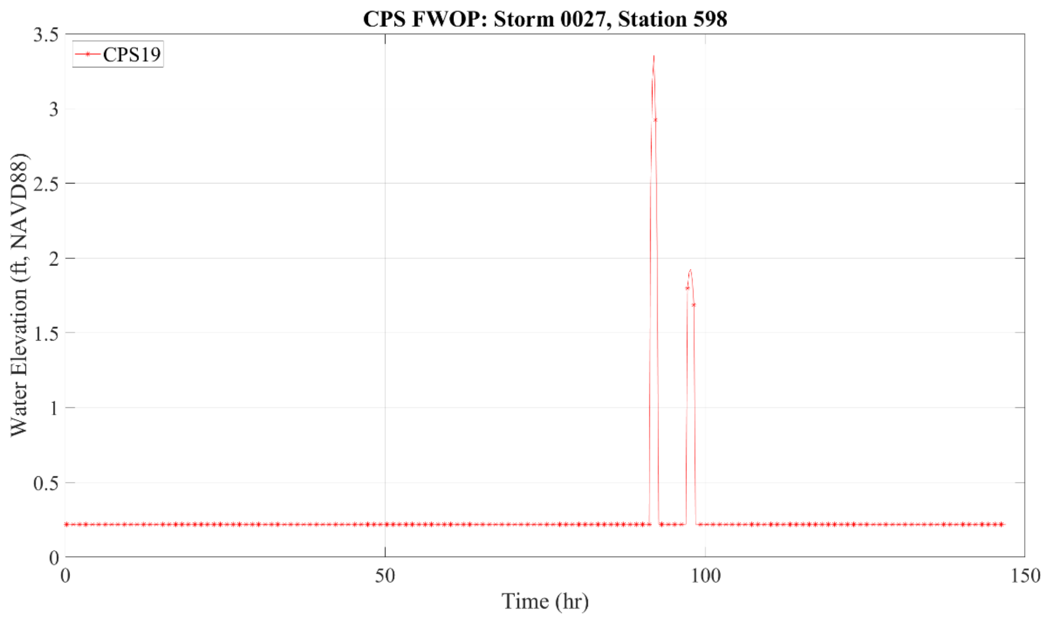

Figure 32: CPS FWOP grid, Storm 27, Station 598.

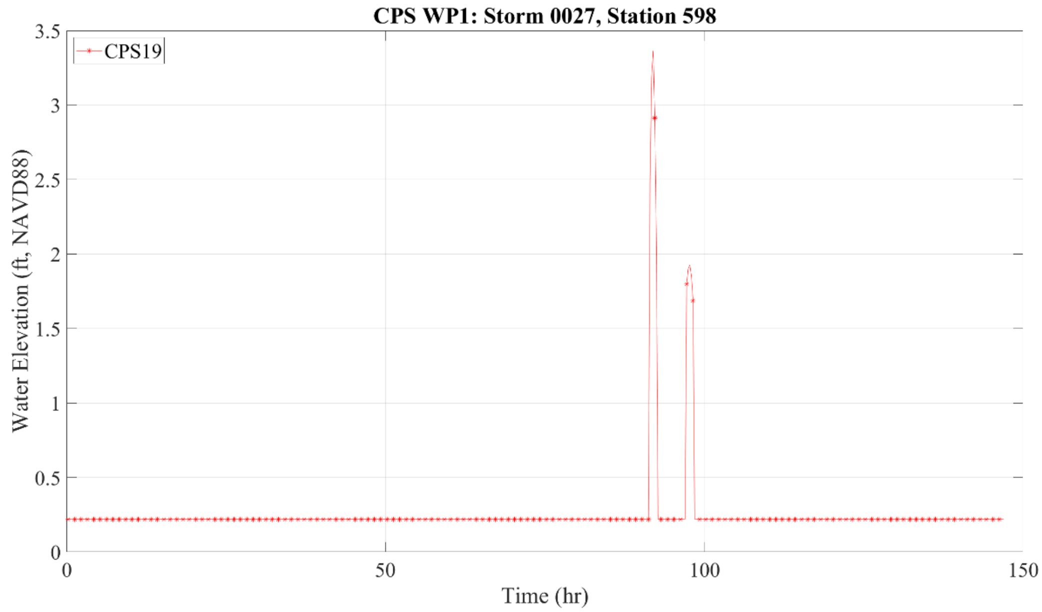

Figure 33: CPS WP01 grid, Storm 27, Station 598.

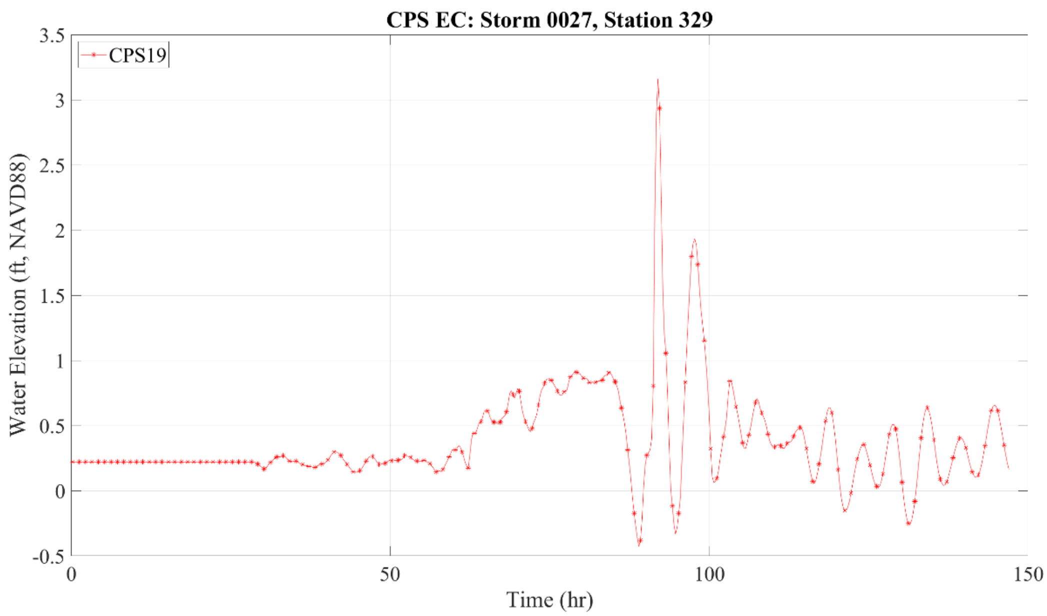

Figure 34: CPS EC grid, Storm 27, Station 329.

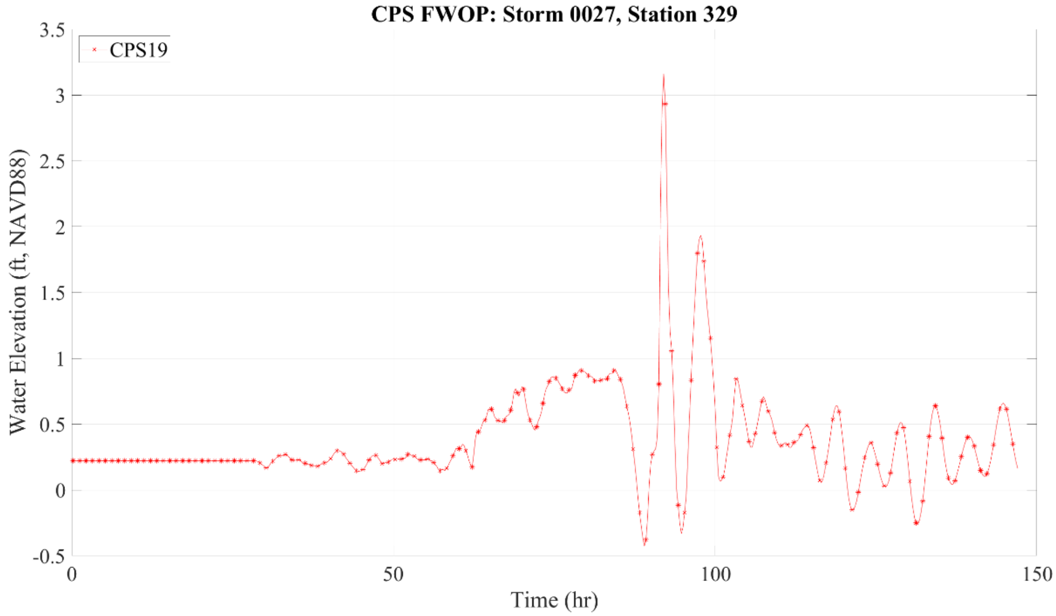

Figure 35: CPS FWOP grid, Storm 27, Station 329.

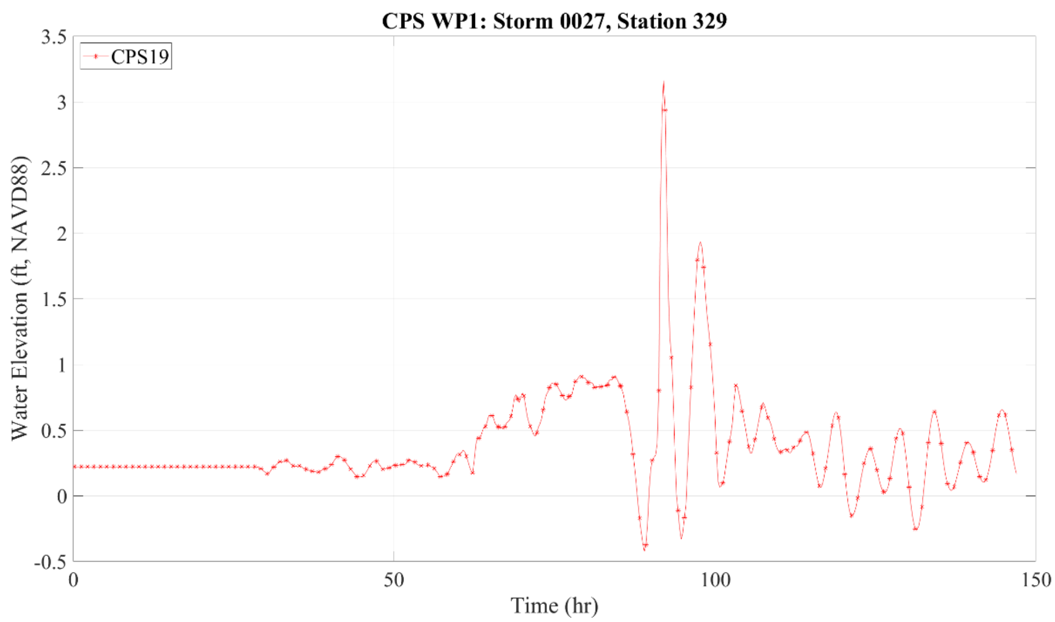

Figure 36: CPS WP01 grid, Storm 27, Station 329.

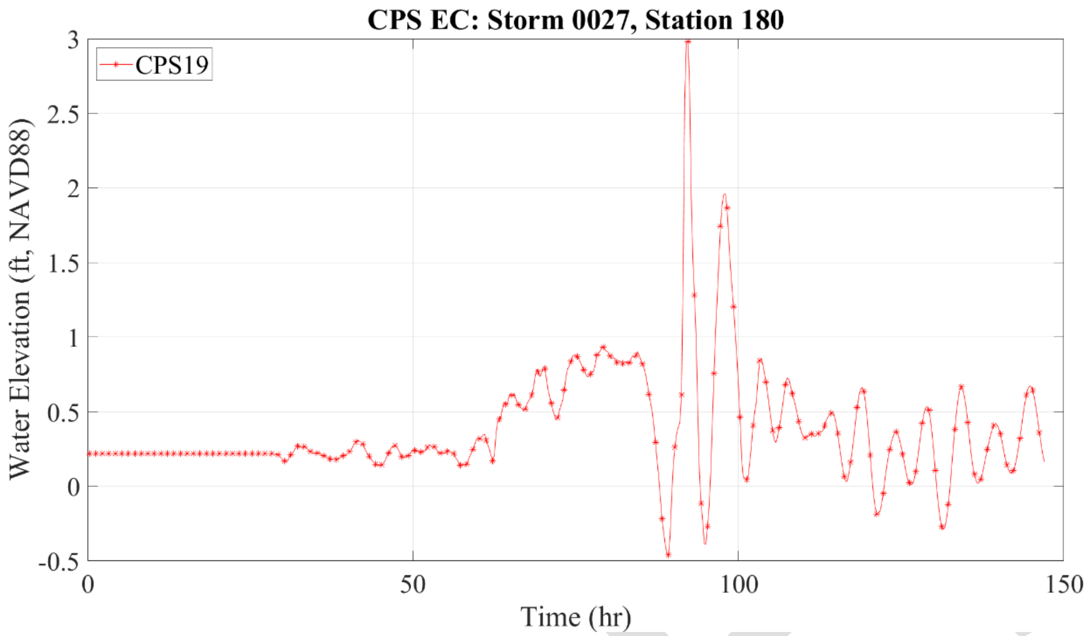

Figure 37: CPS EC grid, Storm 27, Station 180.

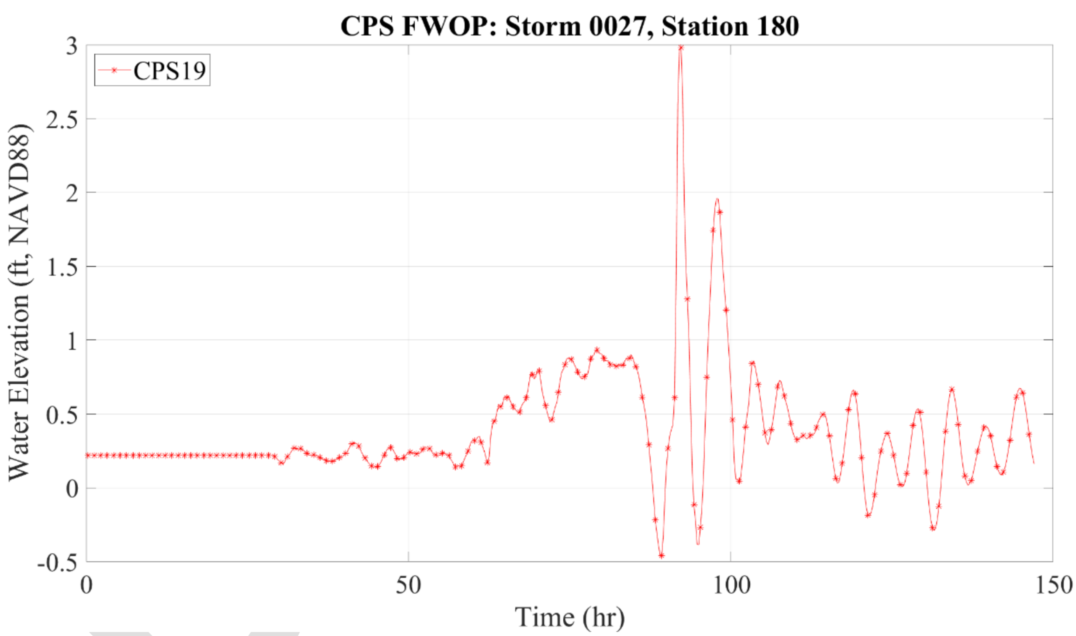

Figure 38: CPS FWOP grid, Storm 27, Station 180.

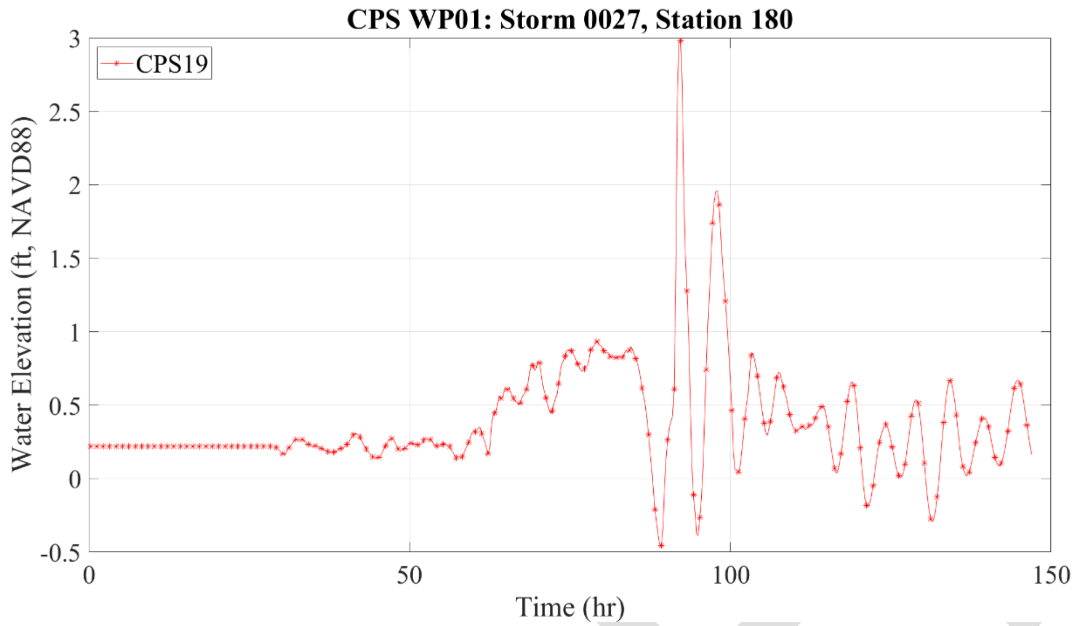

Figure 39: CPS WP01 grid, Storm 27, Station 180.

STWAVE: To incorporate the effects of waves for each storm, the steady state spectral wave model, STWAVE, was used to simulate nearshore wave generation, propagation, transformation, and dissipation (Smith et al. 2001, Smith 2007, Massey et al. 2011). STWAVE numerically solves the steady-state conservation of spectral wave action along backward-traced wave rays:

$$(C_g)_i \frac{\partial}{\partial x_i} \frac{CC_g \cos \alpha E(\sigma,\theta)}{\sigma} = \sum \frac{S}{\sigma} \qquad (1)$$

where i is tensor notation for x- and y- components, C_g is group celerity, θ is wave direction, C is wave celerity, σ is wave angular frequency, E is wave energy density, and S is energy source and sink terms. Source and sink mechanisms included surf-zone wave breaking, wind input, wave-wave interaction, whitecapping, and bottom friction. STWAVE is formulated on a Cartesian grid, with the x-axis oriented in the cross shore direction (I) and the y-axis oriented alongshore (J), generally parallel with the shoreline. Angles are measured counterclockwise from the grid x-axis.

GRID DEVELOPMENT: The STWAVE grid extended alongshore from Folly Beach, SC to the south to Dewees Island, SC to the north, and seaward to a depth of approximately 82 ft (25 m) to allow for transformation of waves from the offshore boundary into the nearshore. The Cartesian grid was approximately 49 ft (15 m) in resolution and was comprised of 3386 cells in the cross-shore direction (I) and 2383 cells in the alongshore direction (J). The projection of the grid was State Plane Coordinate System, South Carolina (FIPS 3900). **Table 1** provides the properties of the STWAVE domain.

Table 1. STWAVE Grid Properties.

Horizontal Projection	Grid Origin (x,y) [m]	Azimuth [deg]	Δx/Δy [ft]	Number of Cells	
				I	J
South Carolina (FIPS 3900)	(754814.787125, 88860.170325)	134.43	49	3386	2383

The bathymetry, topography, and bottom friction Manning's *n* values to populate the STWAVE domain were interpolated from the ADCIRC mesh. The final STWAVE domain overlaid on aerial imagery is shown in **Figure 40**. Although the area of interest for this study was a smaller area near the Charleston Peninsula, the STWAVE domain extents were designed to capture wave transformation from the offshore to the nearshore and limit boundary effects in the area of interest.

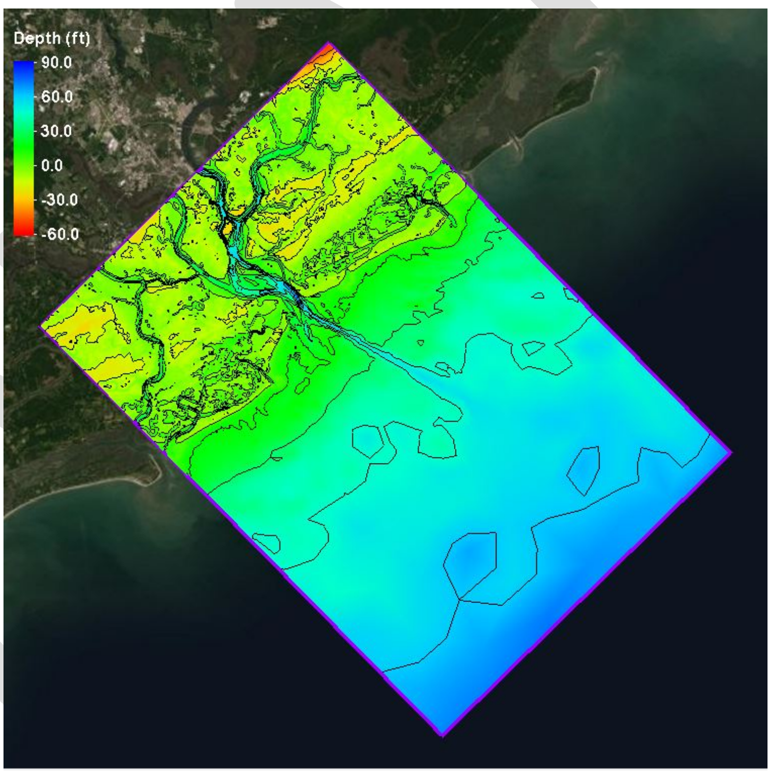

Figure 40: STWAVE domain extents.

In the area of interest, two different structural features were implemented under three conditions. The STWAVE domain was updated for the three conditions, existing condition (EC), future without project (FWOP) and with project (WP01), by interpolating from the ADCIRC mesh with the added features. **Figure 41** depicts the bathymetry of the area of interest, with the locations of the implemented features circled in black.

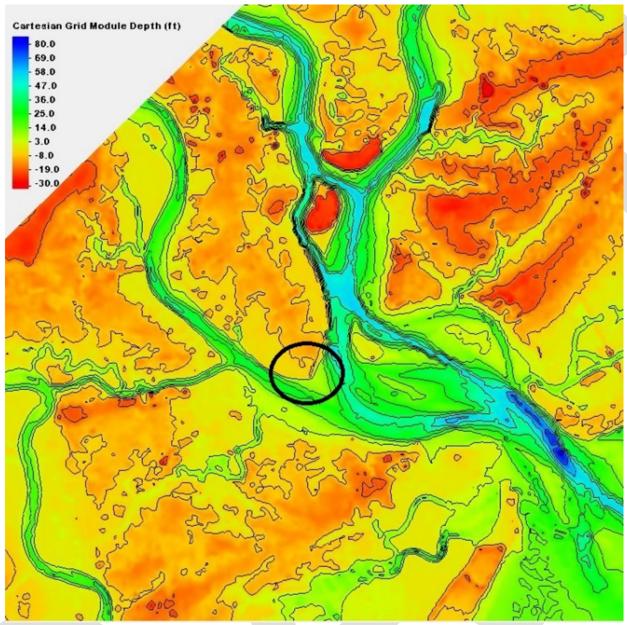

Figure 41: Bathymetry around the area of interest. The locations of the implemented features are located at the seaward tip of the peninsula (circled in black).

As stated in the ADCIRC section, the Existing Condition (EC) featured a battery wall with a height of 6.8 ft NAVD88 (existing low battery wall) which transitioned to a height of 9.1 ft NAVD88 (higher wall). The Future Without Project (FWOP) also included the battery wall, but with a uniform, elevated height of 9.0 ft. NAVD88. In addition to the elevated battery wall, the With Project (WP01) condition included the addition of a 16.2 ft NAVD88 breakwater located in the foreshore of the peninsula.

OFFSHORE BOUNDARY SPECTRA: Available SWAN results, obtained from the FEMA contractor, were comprised of time series of bulk scalar parameters, including wave height, period, and direction. The STWAVE model, however, required explicit specification of input spectra including variation of wave energy in frequency and direction for this application. To construct the spectral boundary forcing, it is assumed that the detailed spectra are well-represented by the established Texel-Marsen-Arsloe [TMA, Bouws *et al.* 1985] spectral shape, and overall energy conservation is prescribed as

$$H_s = 4\left\{\int P_{\eta\eta}(f)\right\}^{1/2} \tag{2}$$

where H_s is the provided SWAN model result and $P_{\eta\eta}$ is frequency-dependent power spectral density. A TMA spectrum is a JONSWAP (Joint North Sea Wave Project) spectrum modified for shallow water. Directional dependence is computed as in Goda 2000, with a symmetric distribution around the peak angle

$$P_{\eta\eta}(f,\alpha) = G(\alpha)P_{\eta\eta} = G_0 \cos^{2s}(\frac{\alpha - \alpha_p}{2})P_{\eta\eta}(f) \tag{3}$$

where the scalar G_0 is numerically determined to normalize the directional function G, and s is a user-defined empirical parameter as provided in Goda 2000. The outputs of FEMA SWAN node 16763 served as the time series from which the spectra was constructed.

The resulting resolved spectra were represented by 35 frequency bands, ranging from 0.029 Hz (34.4 sec) to 0.32 Hz (3.1 sec), and 72 angle bands, from an angle of 0 degrees to 355 degrees with respect to the grid azimuth. Frequency and angular resolution were 0.00881 Hz and 5 degrees, respectively. To match the FEMA ADCIRC/SWAN modeling effort, the time interval for STWAVE spanned the last two days of the simulation, from 7-13-2000 12:00:00 to 7-15-2000 12:00:00, with regularly spaced intervals of 20 minutes. For coupling in CSTORM, STWAVE must start on a whole hour. Since the first output from the FEMA modeling effort began 20 minutes after the hour, the first spectra was duplicated for the STWAVE modeling, resulting in a total of 145 time steps per storm.

MODEL EXECUTION: Tight two-way coupling between ADCIRC and STWAVE was facilitated with the CSTORM-MS, a physics-based modeling capability for simulating tropical and extratropical storm, wind, wave, and water level response. During the two-way coupling process, a single instance of ADCIRC passes water elevations and wind fields to STWAVE. Upon completion, STWAVE passes wave radiation stress gradients to ADCIRC to drive wave-induced water level changes (e.g., wave set-up and setdown). Each STWAVE simulation conducted used the full-plane mode of STWAVE to allow for wave generation and transformation in a 360-degree plane. The full-plane version of STWAVE uses an iterative solution process that requires user-defined convergence criteria to signal a suitable solution. Boundary spectra information is propagated from the boundary throughout the domain during the initial iterations. Once this stage converges, winds and surges are added to the forcing, and this final stage iteratively executes until it also reaches a convergent state. The convergence criteria for both stages include the maximum number of iterations to perform per time-step, the relative difference in significant wave height between iterations, and the minimum percent of cells that must satisfy the convergence criteria (i.e., have values less than the relative difference.) Convergence parameters were selected based on a previous study by Massey et al. (2011) in which the sensitivity of the solution to the final convergence criteria was examined. The relative difference and minimum percent of cells were set as (0.1, 100.0) and (0.05, 99.8) for the initial and final iterations, respectively. STWAVE was set up with parallel in-space execution whereby each computational grid was divided into different partitions (in both the x- and y-direction), with each partition executing on a different computer processor. The number of partitions in the x direction was 60 and the number of partitions in the y direction was 41. The maximum number of initial and final iterations was set to a value of 74 iterations, higher than the largest partition size.

Additionally, 921 station locations, or save points, were identified within the STWAVE domain from the ADCIRC station list. During the simulations, these stations recorded the significant wave height, mean wave period, mean wave direction, peak wave period, wind magnitude, wind direction, and water elevation for each time step. Out of the 921 stations, five stations were identified to be of particular interest and were used for input into the G2CRM input .h5 files. The locations of these stations are included in **Table 2** and in **Figure 42.**

Table 2: Locations of the STWAVE stations of interest.

FID	STWAVE Station Number	Longitude	Latitude	X coordinate (FIPS 3900, m)	Y coordinate (FIPS 3900, m)
180	818	-79.9704403374	32.8008995586	706020.67461907	107784.70541894
329	690	-79.9571539187	32.7818545302	707286.24719876	105685.37069113
598	425	-79.9327239290	32.8034032096	709549.91419664	108098.15509148
699	324	-79.9224045444	32.7832094125	710539.63362569	105868.99971441
976	47	-79.9291526483	32.7687239390	709924.19701562	104256.20754288

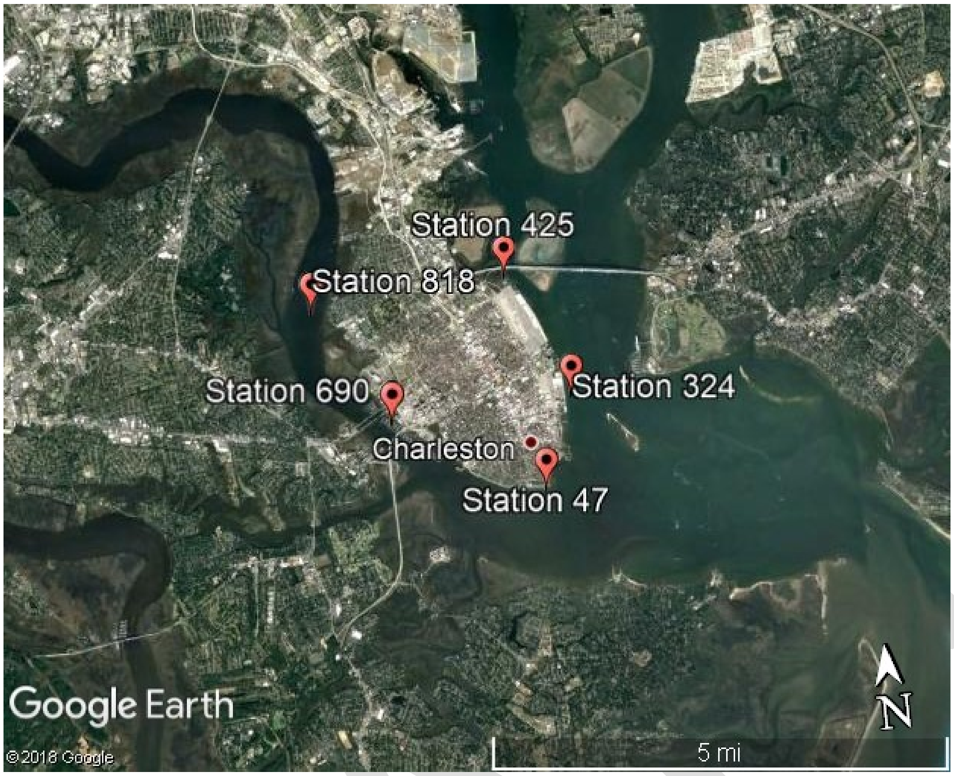

Figure 42: Location of the five stations of interest within the study area. The points are labeled with their correlating STWAVE station number.

RESULTS: Two types of figures were generated for each storm, a plot of maximum significant wave height and time series plots at the five stations of interest. For discussion, the plots and results from Storm 27 are highlighted in **Figure 43** - **Figure 45**, with the plots for the other four high-frequency storms events provided in **Appendix B** and **Appendix C**. Although not evident in Storm 27, some of the other storms, such as Storm 4 in the Appendix, saw 'blocking' in the maximum significant wave height solutions. This behavior is a well documented behavior of the parallel STWAVE model, as noted in Massey et al. (2011). Additionally, the way these maximum wave height plots are computed tend to exaggerate the differences between grid partitions – e.g., the maximum significant wave height is the largest wave that occurred during the entire simulation at that particular grid cell and could occur at different times during the simulation.

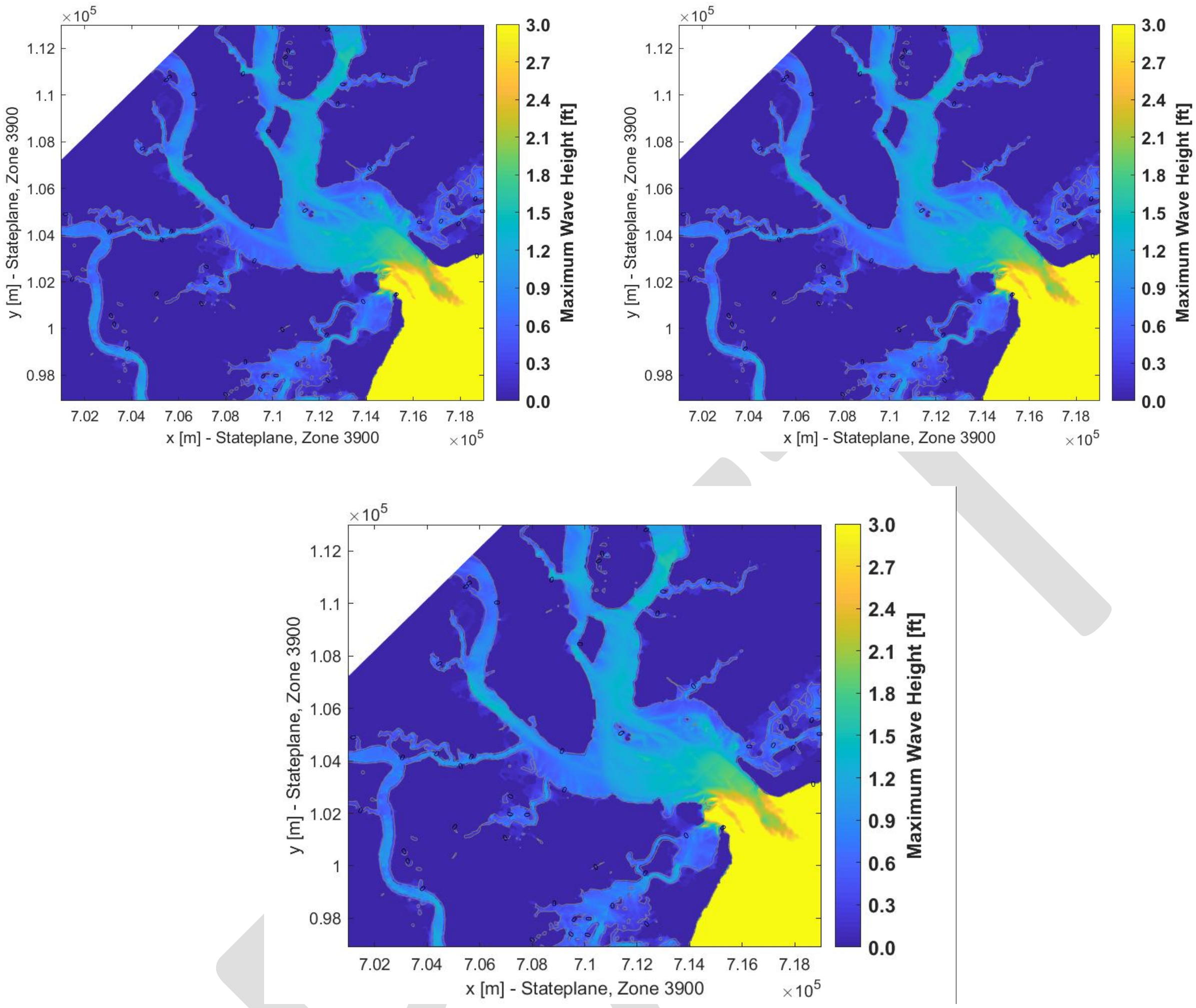

Figure 43: Maximum wave height (ft) of Storm 27 for EC (upper left), FWOP (upper right), WP01 (bottom).

For all three conditions, the maximum wave heights were greater than 3 ft at the opening of the inlet and along the open coast boundaries. These waves reduce to heights between 1 to 2 feet as they propagate into Charleston Harbor. Little difference is observed between the EC and the FWOP condition, which is expected as elevating the battery wall (the only change included in FWOP compared to EC) would have little impact on the waves around the peninsula. However, the addition of the breakwater in WP01 results in slight changes in the maximum wave height field in the immediate vicinity of the breakwater. Wave heights are slightly increased offshore of breakwater but are smaller lee of the breakwater. The difference in maximum wave height between WP01 and EC is shown in **Figure 44** for the area of interest. Smaller wave heights immediately behind the breakwater are expected. Additionally, differences in wave height in the vicinity of the breakwater are also anticipated given the breakwater changed the local bathymetry of the domain. For Storm 27, the increase in the maximum wave height due to the breakwater is marginal, on the order of 0.2 ft or 2-3 inches.

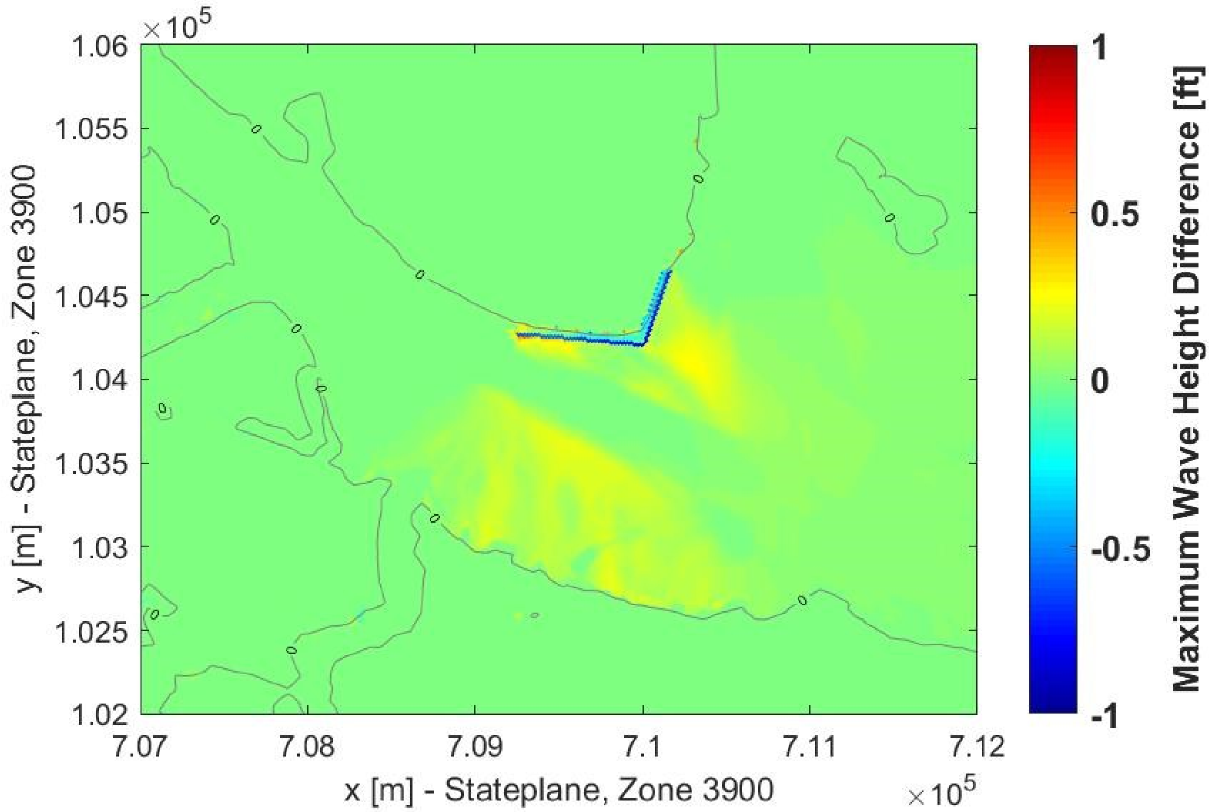

Figure 44: Difference between WP01 and EC [WP01-EC] maximum wave heights in feet, where warm colors indicated increases in wave height and cool colors indicate decreases in wave height. The breakwater is shown in dark blue.

The time series plots, such as that shown in **Figure 45**, show the growth and decay of wave heights through the simulated storm event at each of the selected locations. Here, we see that the highest waves grow to a little over 1 ft tall at the points of interest, with the highest wave heights occurring at STWAVE stations 818, 690, and 324. These stations are located at the upper western side, the central western side, and the central eastern side of the peninsula, respectively. Whereas there is little difference between the wave heights experienced at these sites between the EC and the FWOP, the wave heights at Station 47 are slightly smaller for WP01 than EC due to the presence of the breakwater. The wave heights at the other stations, which are further from the breakwater, are similar between EC and WP01.

It is important to note that the maximum wave height plots are useful for assessing overall conditions during a storm, but not necessarily for assessing wave climate as a factor of time, such as determining greatest reductions in wave height by condition. For instance, at station 47, the maximum wave heights for EC and FWOP, which would be included in the maximum wave height plot, occur during the beginning of the simulation while the maximum wave height for WP01 occurs more towards the end of the simulation. These differences in the time of occurrence for the maximum wave height are shown in **Figure 45** in the black boxes. The greatest difference in wave heights between the EC/FWOP and WP01 (0.6 ft. EC/FWOP to 0.1 ft. WP01) occurred at the time circled in red. As shown, the time of this greatest difference does not correlate with any of the occurrences of the maximum wave heights and, therefore, will not be evident in the maximum wave height plots. In summary, the greatest reduction in wave height between conditions may not be captured in a direct comparison between the maximum wave heights because these values are independent of time. Rather, a comparison of the time series will better show the effect of each condition on the wave climate through the entire simulation.

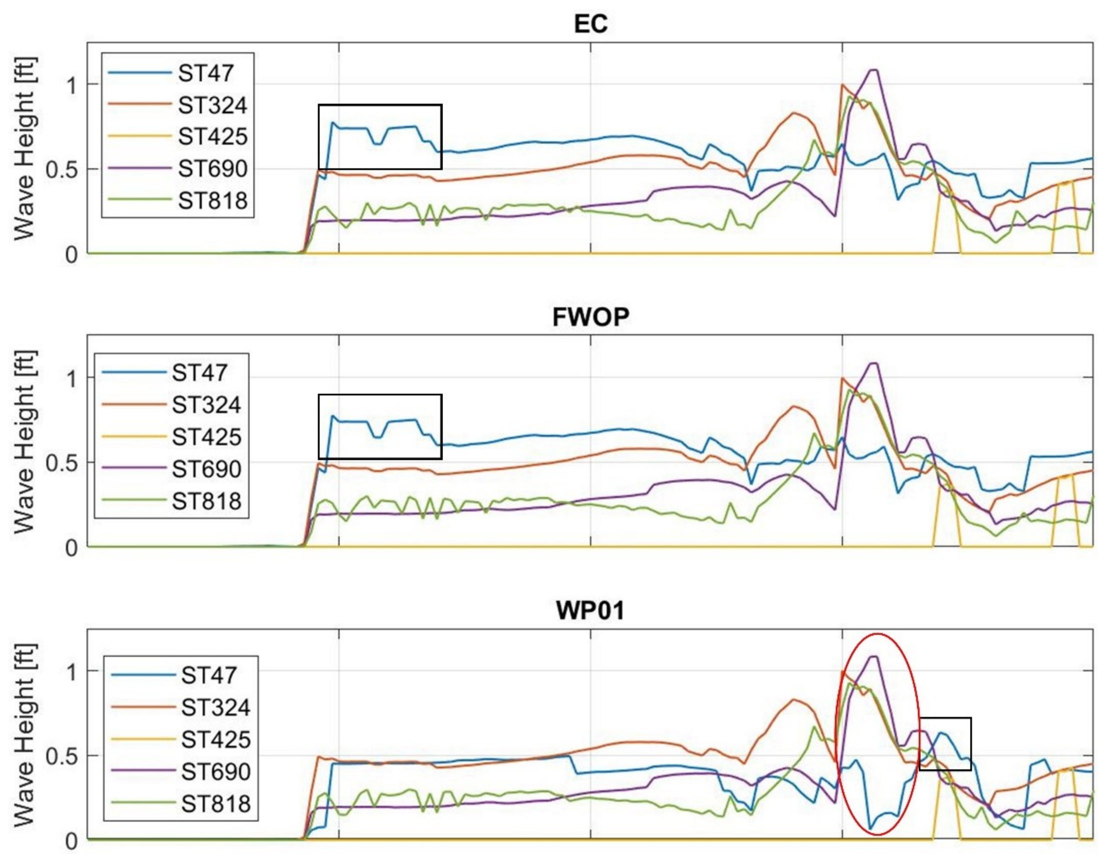

Figure 45. Time series of significant wave height at the five selected stations for Storm 27.

G2CRM: G2CRM is a Probabilistic Life Cycle Analysis model that applies a suite of storm surges and wave conditions to a study area to quantify the damages expected during a 50-year life cycle. Capturing the whole range of possible life cycles requires multiple iterations of the 50-year life cycle with randomly selected storms determined by the likelihood of the storms. G2CRM uses the selected storm surges to calculate the damages/life loss suffered by each modeled area. These damages can be calculated with and without a protective element, and allow stakeholders to determine the value added by constructing different scenarios.

Save Point Selection: For the purposes of this study, Charleston Peninsula was divided into five separate modeled areas. The modeled area is the region over which G2CRM aggregates damages and reports overall statistics. These regions are divided for either geographic or political reasons. Each modeled area is driven by an individual set of modeled data containing the surge data and wave data for each storm in the study. Multiple save stations account for variations in the hydraulic conditions in the areas being inundated by the storms. In this case the save stations selected were the stations immediately adjacent to the shoreline of the modeled area with the lowest lying area. Each save station was exported from the detailed modeling performed with ADCIRC and converted into an .h5 format. Each .h5 file contains the metadata required to identify the time step and modeled area associated with the storm suite. The .h5 data is supplemented with an input file containing the details needed for G2CRM to apply the correct interpretation of the files given. The excel file contains the columns listed in **Table 3**.

Table 3: Inputs for H5 Metadata Excel File.

Column	Description
IsStwaveFormat	Format of the H5 file (1= STWAVE, 0 = ADCIRC)
ModeledStormSetTextId	Unique (within the representation) text identifier for the storm set
ModeledStormSetDescription	Description of the modeled storm set
StormDatumToAssetInventoryDatumConversion	Vertical conversion from storm datum to asset inventory datum (conversion from MSL to NAVD88)
MllwToStormDatumConversion	Vertical conversion from MLLW to MSL storm datum
UseWaveDataAsIs	1 = Use wave data from H5, 0 = auto-generate wave data in model

H5 METADATA AND .h5 FILE: The ModeledStormSetTextId is the unique identifier for a particular storm set. It needs to match the names internal to G2CRM. ModeledStormSetDescription describes the particular data set and serves as a tool to indicate any changes to the modeling. The StormDatumToAssetInventoryDatumConversion and MllwtoStormDatumConversion columns are critical in that they allow for G2CRM to convert from the various datums to NAVD88. This conversion is necessitated by the use of MSL in the ADCIRC modeling used as forcing for G2CRM. UseWaveDataAsIs indicates when G2CRM should search for wave data within the .h5 file. If the wave data is being used (UseWaveDataAsIs of 1), G2CRM will add 0.7 of the given wave height to the overall inundation level. If UseWaveDataAsIs is zero G2CRM will calculate the maximum possible depth limited wave height for each storm condition and then apply 0.7 of the resulting wave height to the total inundation level. If no waves are desired the user can input zero wave heights into the .h5 file and indicate that the zero wave heights are to be used as input. For the Charleston study, the waves from Stwave were applied so the IsStwaveFormat and UseWaveDataAsIs columns were both set to 1. The ModeledStormSetTextID was set from 1 to 5 depending on the modeled area for each set of data. The H5 Metadata excel file also requires the storms to keep tab. This tab is an artifact of the intended application of Coastal Hazards System (https://chs.erdc.dren.mil) (Nadal-Caraballo et al. 2020) data for G2CRM studies. The Coastal Hazards System provides a full suite of synthetic storms that capture the full probability space for locations across the United States' coastline. The storm names on the tab match the names in the .h5 file. For the specific case in Charleston, the datum conversions from the storm to inventory was set to 0.22 ft, and the mllw to storm datum conversion was -2.92 ft. The .h5 files contain the water elevations and wave heights for all selected storms. For simplicity, the save points were renamed to 1-5 as shown in the **Table 4**.

Table 3: Save point correspondence.

Save Point Correspondence	
Original	ERDC
976	1
699	2
598	3
329	4
180	5

SEASONS: The seasons excel file for G2CRM delineates the given seasons for each type of storm given. Typically, this would include both tropical and extratropical storms. In the Charleston case the storms were all synthetic tropical storms. The seasons are usually broken down by months, and a probability of storm occurrence for each season/storm type condition is provided by the user. The maximum storms per season gives an upper extreme for the number of storms in a simulation. For Charleston, a value of 100 was applied.

STORMS: The storms excel spreadsheet lays out the relative probability of each storm, the time of year possible for each storm, and the basis year for the storm. The recurrence probability for each tropical cyclone was calculated by URS (2012), and the basis year gives the year that was used to calculate water levels. Sea level change is calculated based on the three Corps curves, and the net change from the storm basis year and the year of storm occurrence in an iteration is added to the water levels from the .h5 file. The Charleston study applies the present day water levels.

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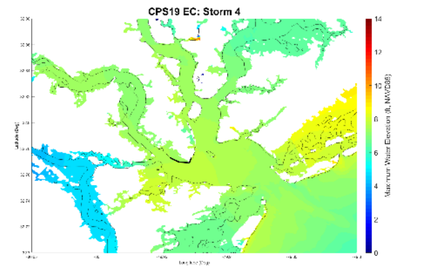
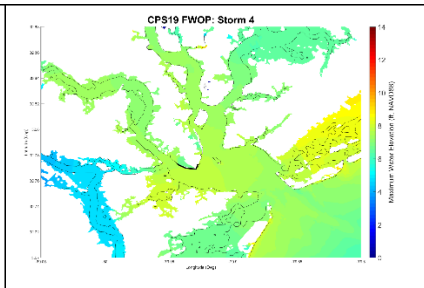
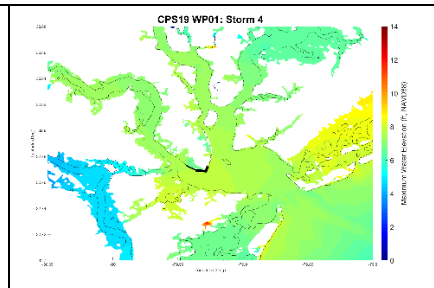
APPENDIX A: Maximum Water Elevation Plots



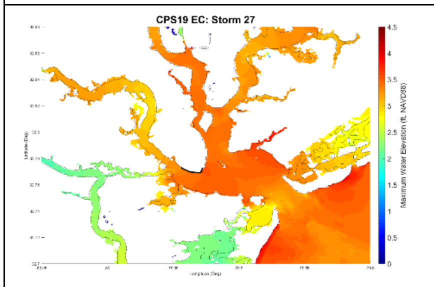
EC Storm 4



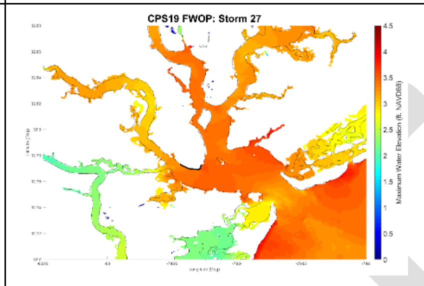
FWOP Storm 4



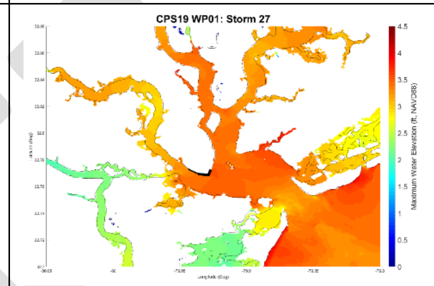
WP01 Storm 4



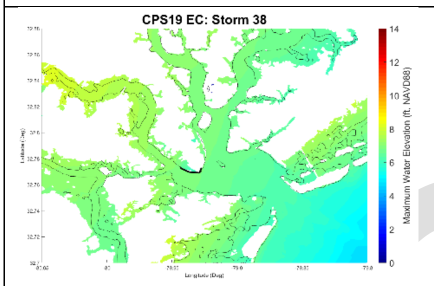
EC Storm 27



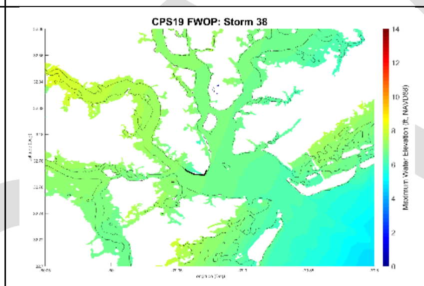
FWOP Storm 27



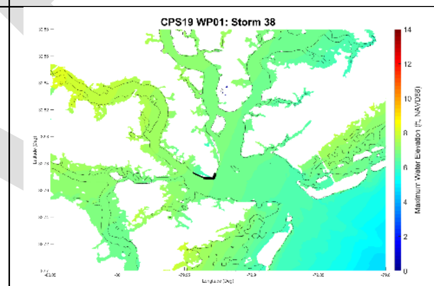
WP01 Storm 27



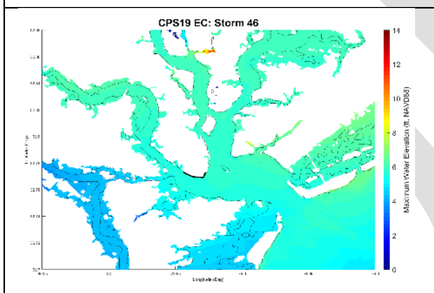
EC Storm 38



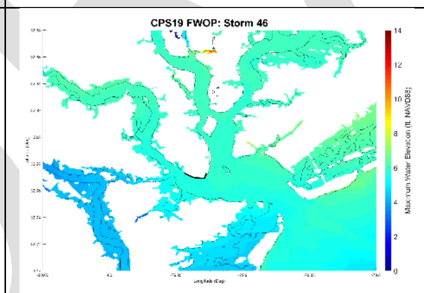
FWOP Storm 38



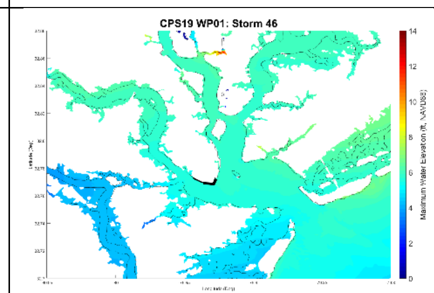
WP01 Storm 38



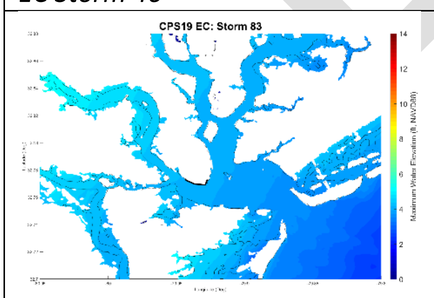
EC Storm 46



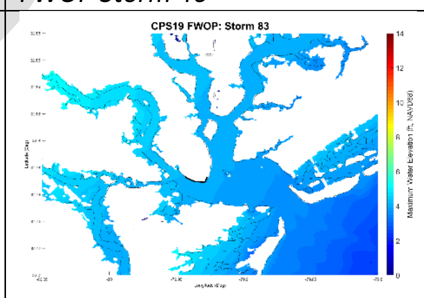
FWOP Storm 46



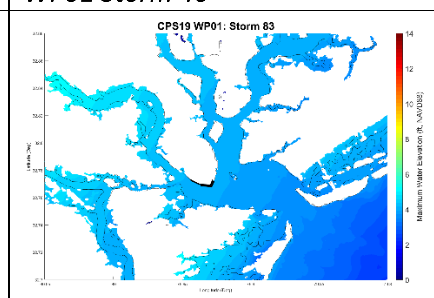
WP01 Storm 46



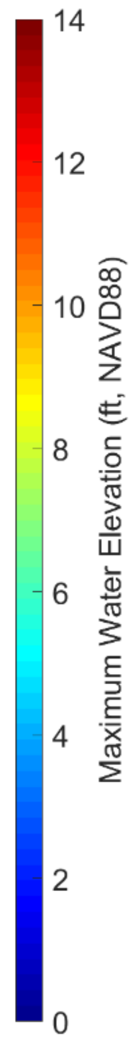
EC Storm 83



FWOP Storm 83



WP01 Storm 83



APPENDIX B: Maximum Wave Plots

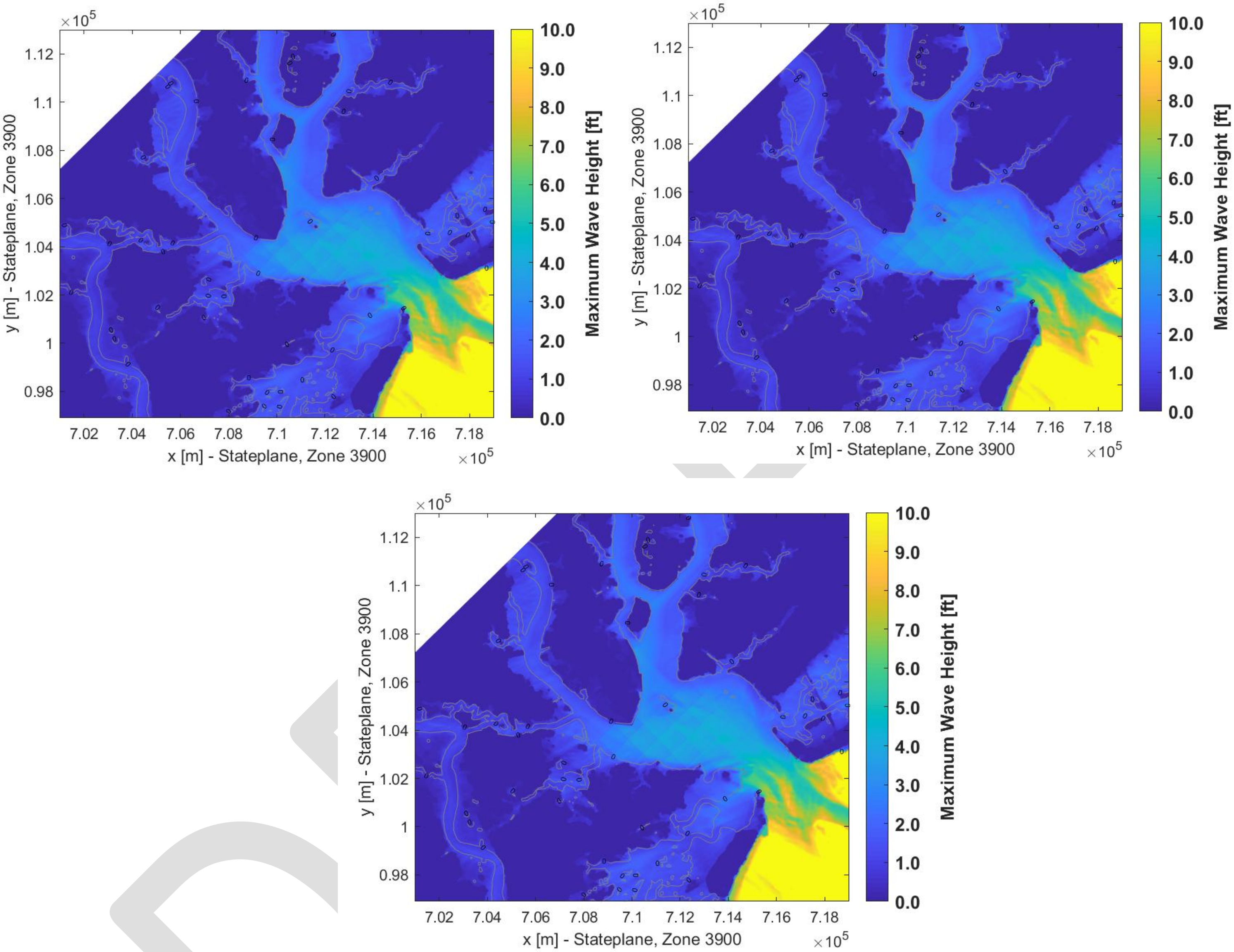


Figure 46. EC (upper left), FWOP (upper right), and WP01 (bottom) for Storm 4.

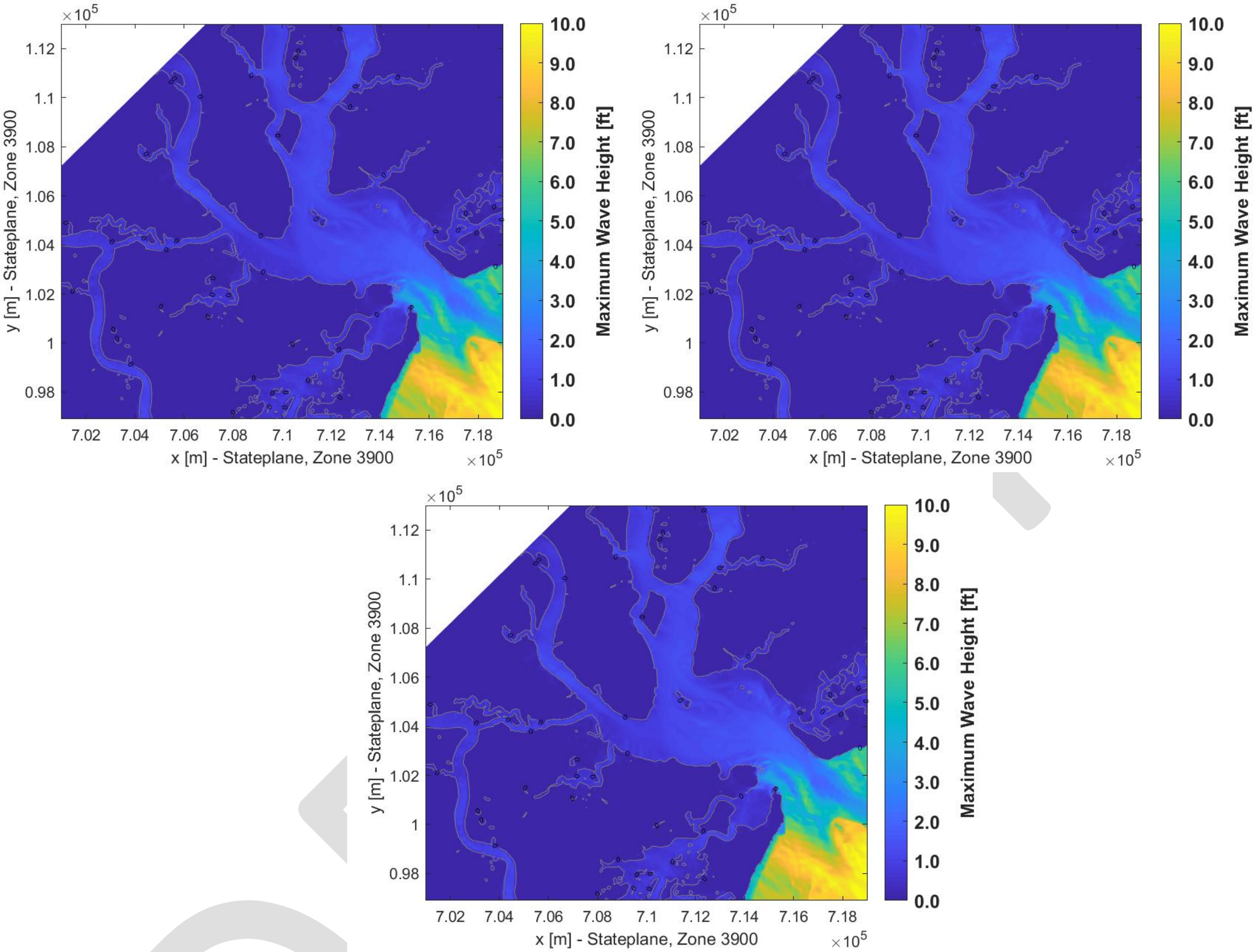


Figure 47. EC (upper left), FWOP (upper right), and WP01 (bottom) for Storm 27.

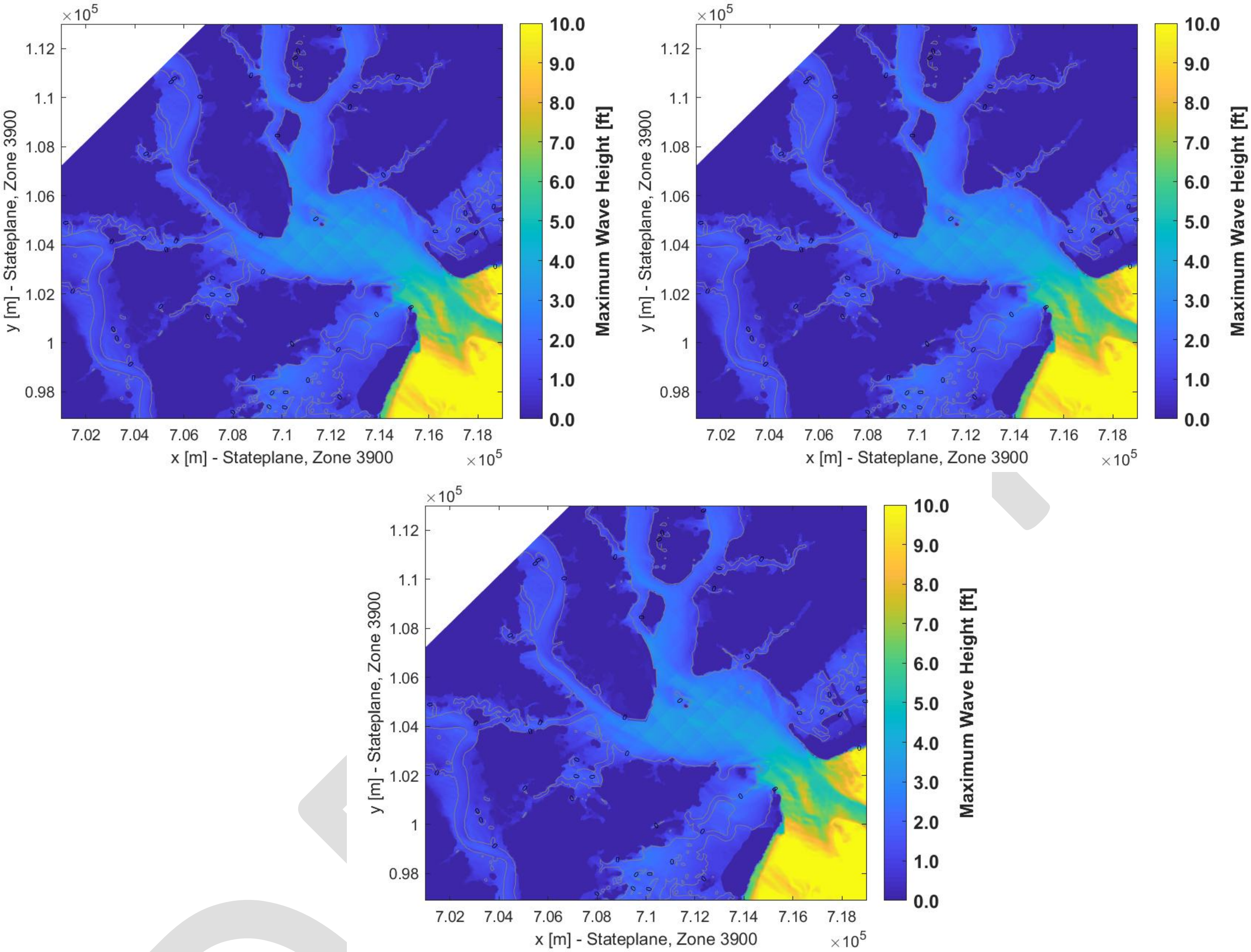


Figure 48. EC (upper left), FWOP (upper right), and WP01 (bottom) for Storm 38.

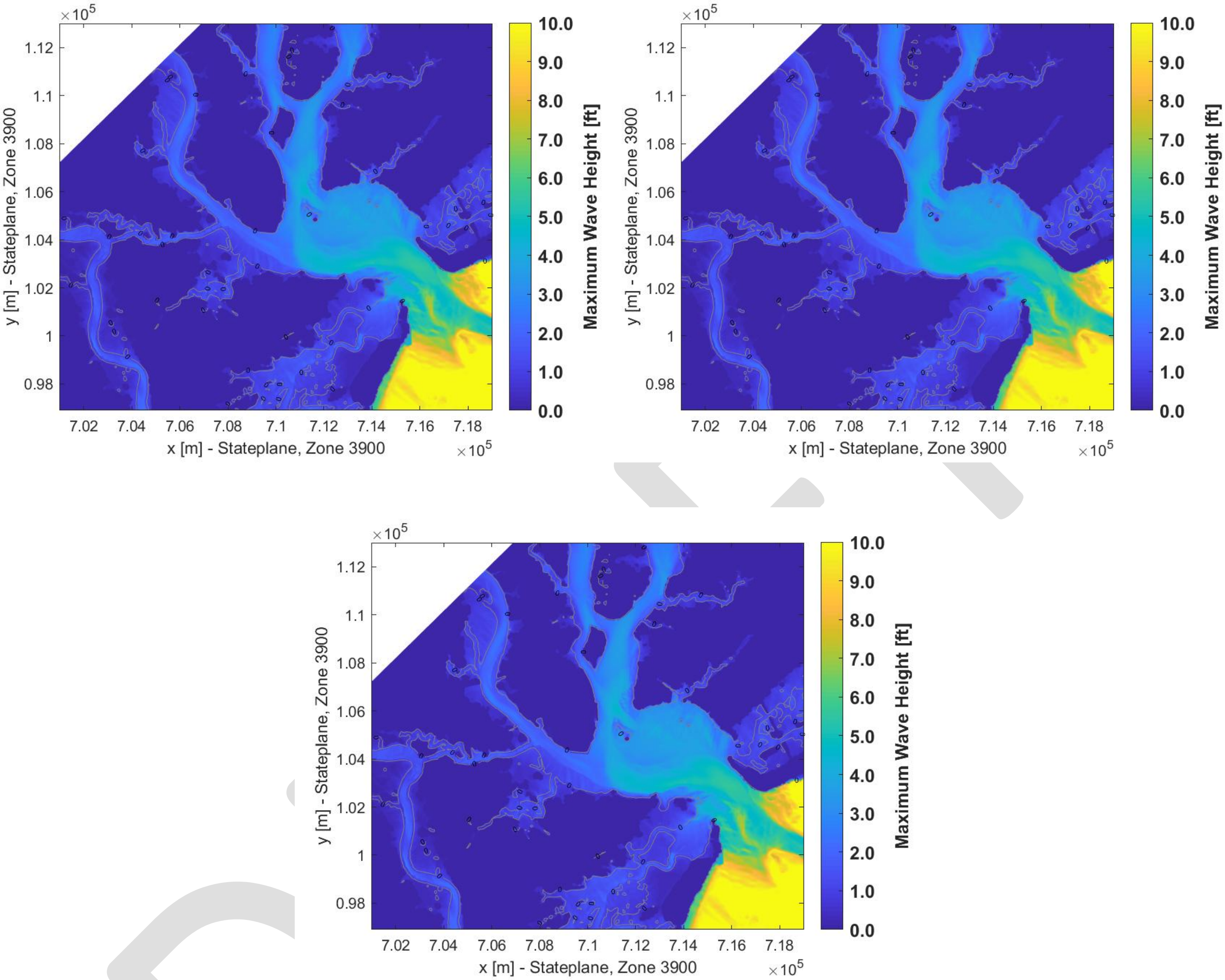


Figure 49. EC (upper left), FWOP (upper right), and WP01 (bottom) for Storm 46.

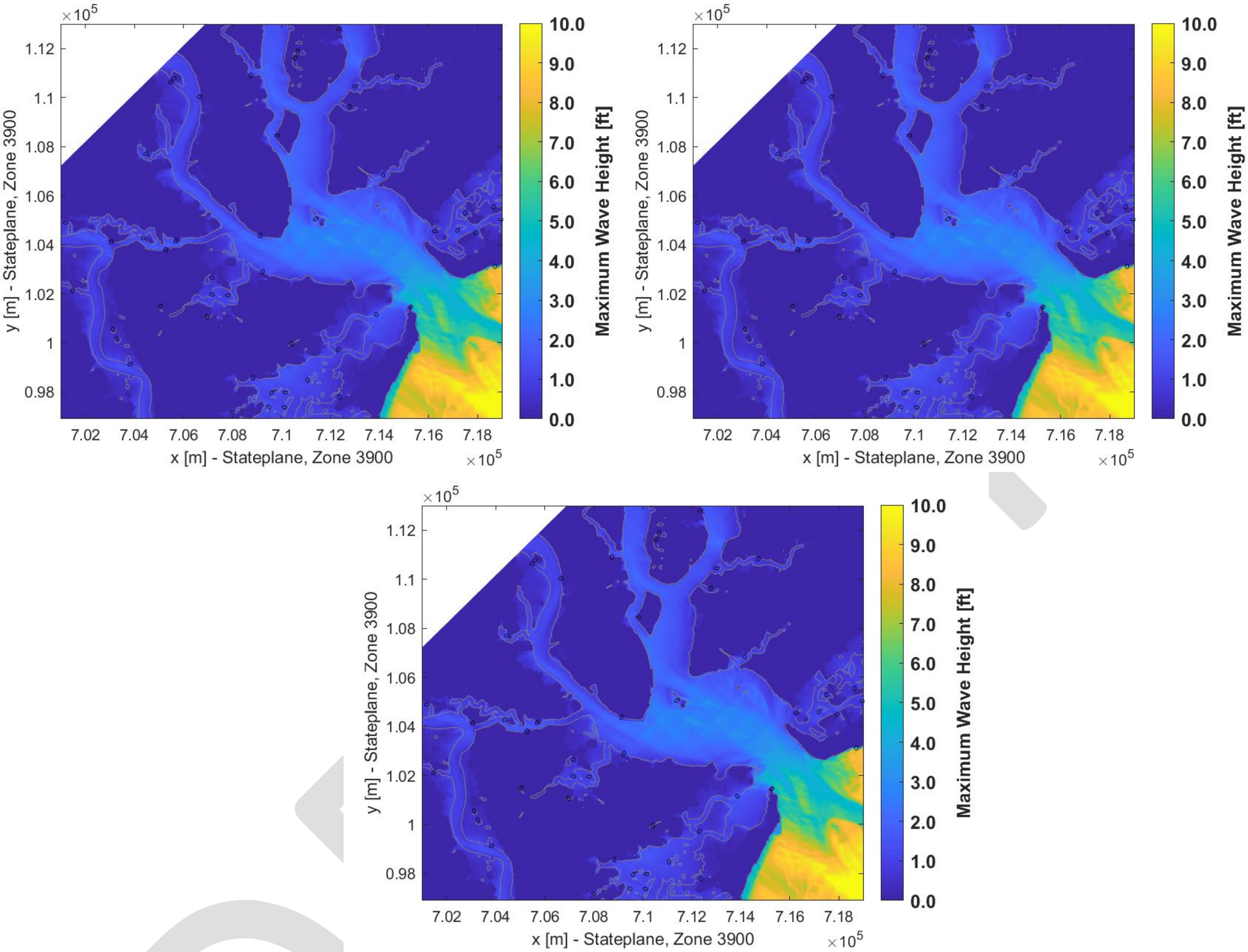


Figure 50. EC (upper left), FWOP (upper right), and WP01 (bottom) for Storm 83.

Appendix C: Time Series Plots

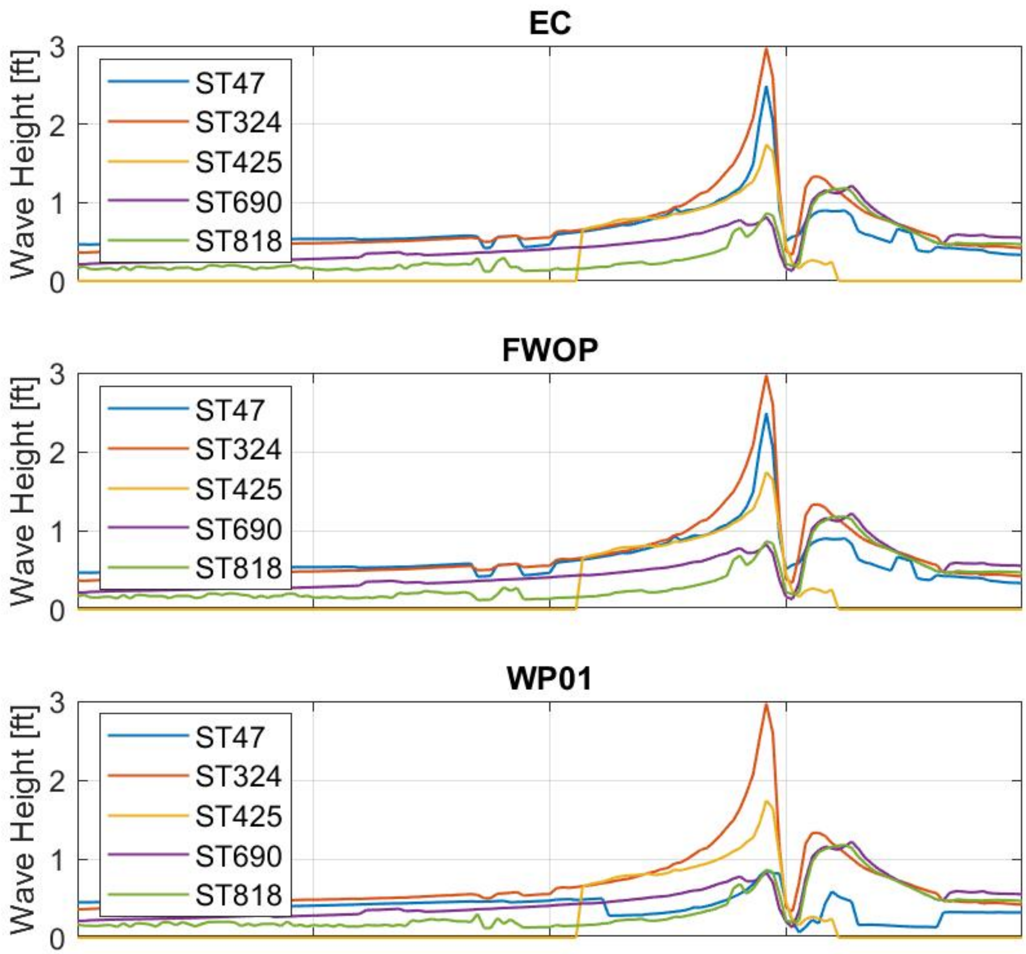


Figure 51. EC (upper), FWOP (middle), and WP01 (bottom) for Storm 4.

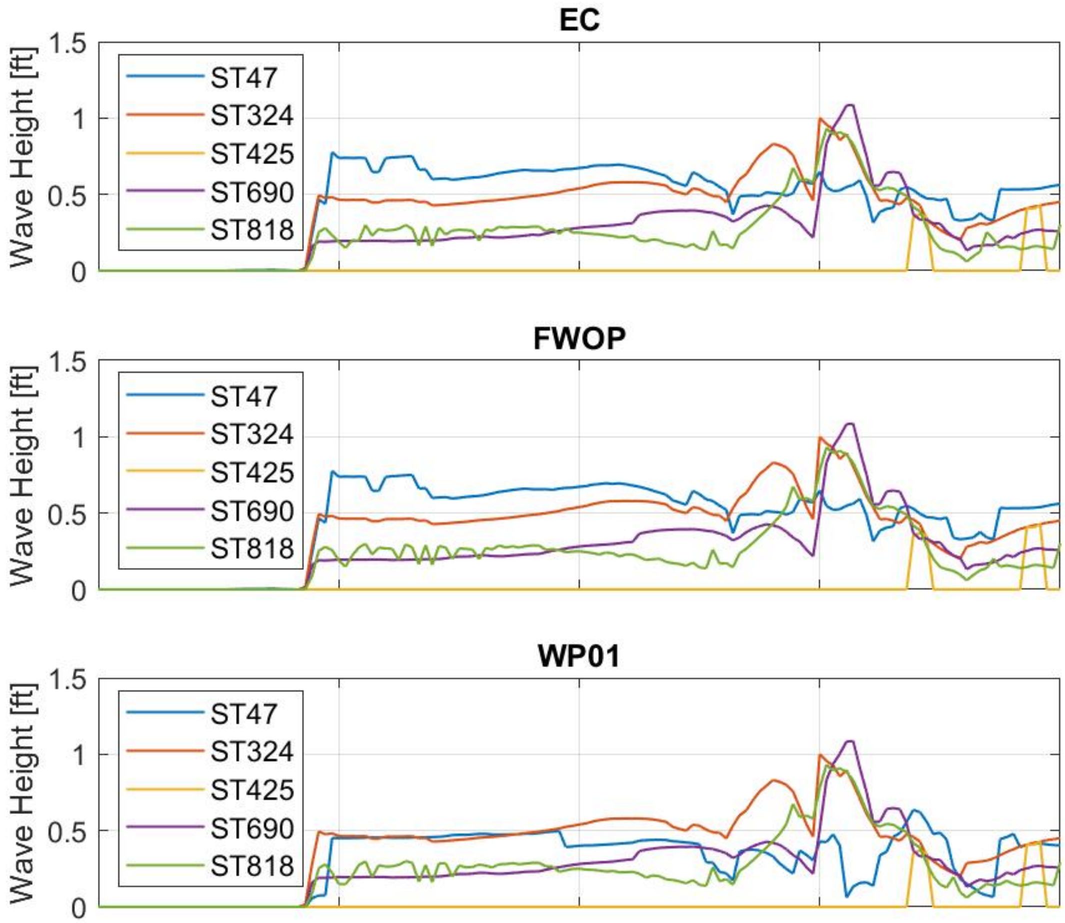


Figure 52. EC (upper), FWOP (middle), and WP01 (bottom) for Storm 27.

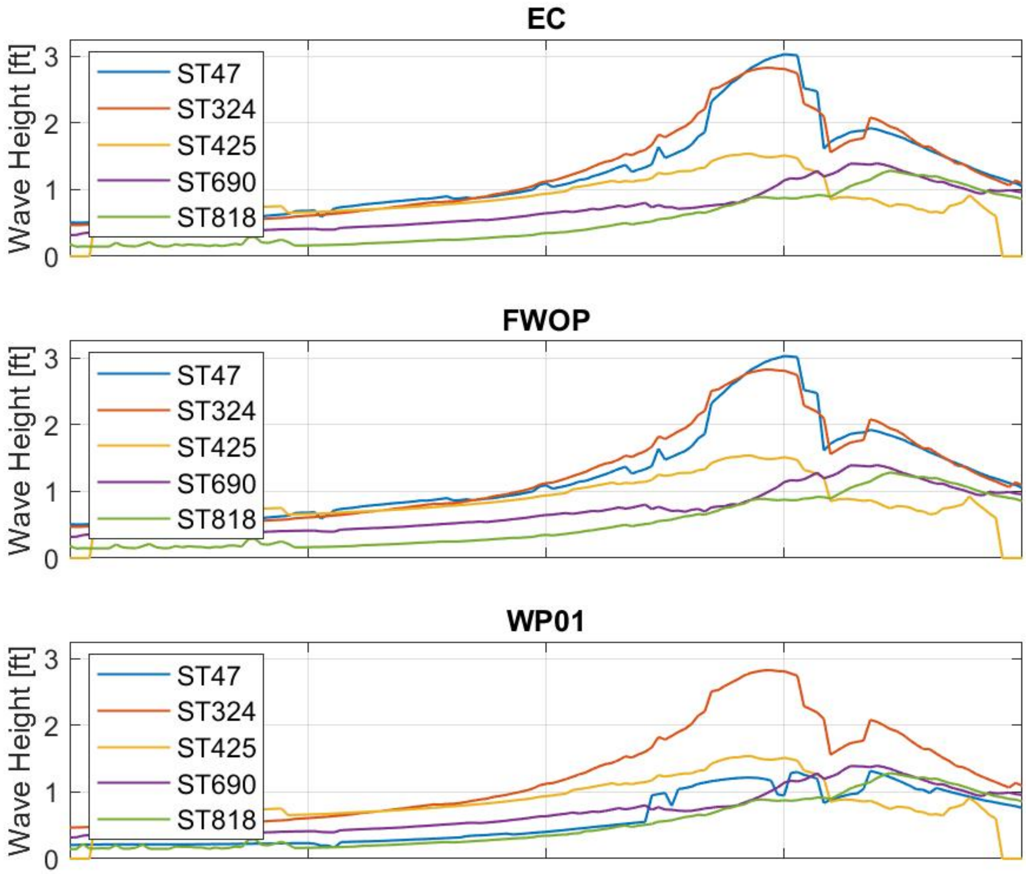


Figure 53. EC (upper), FWOP (middle), and WP01 (bottom) for Storm 38.

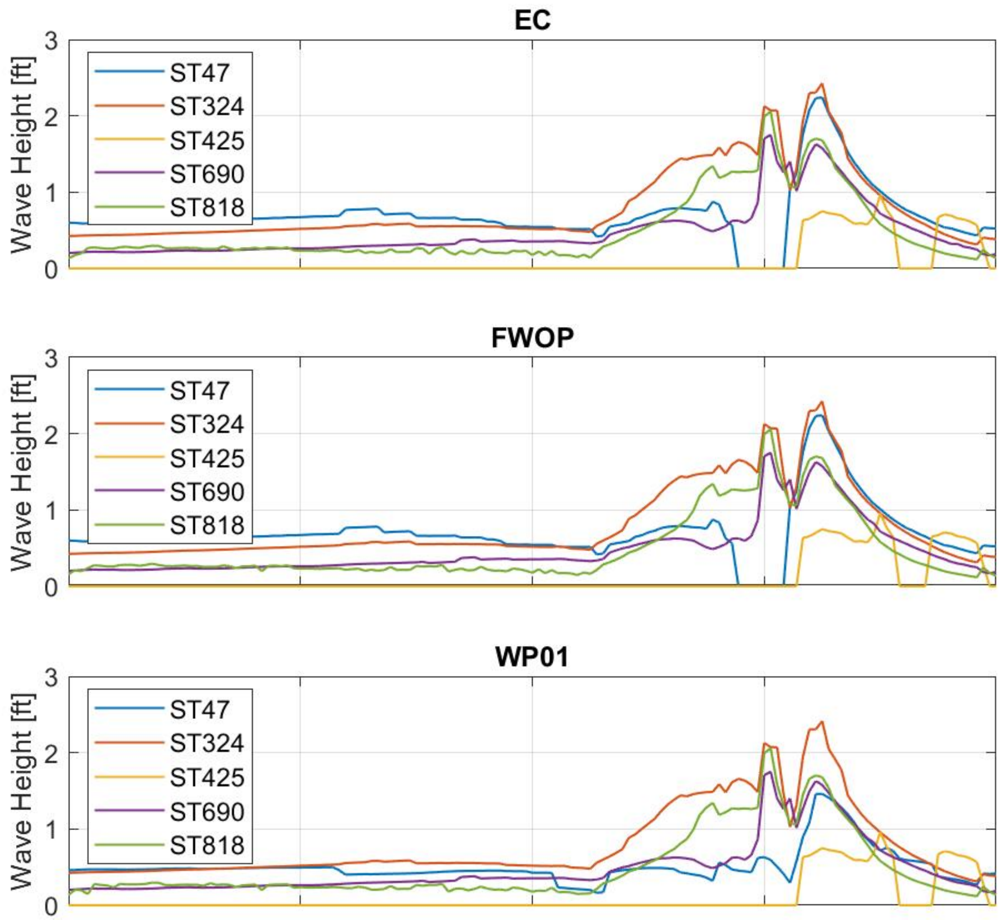


Figure 54. EC (upper), FWOP (middle), and WP01 (bottom) for Storm 46.

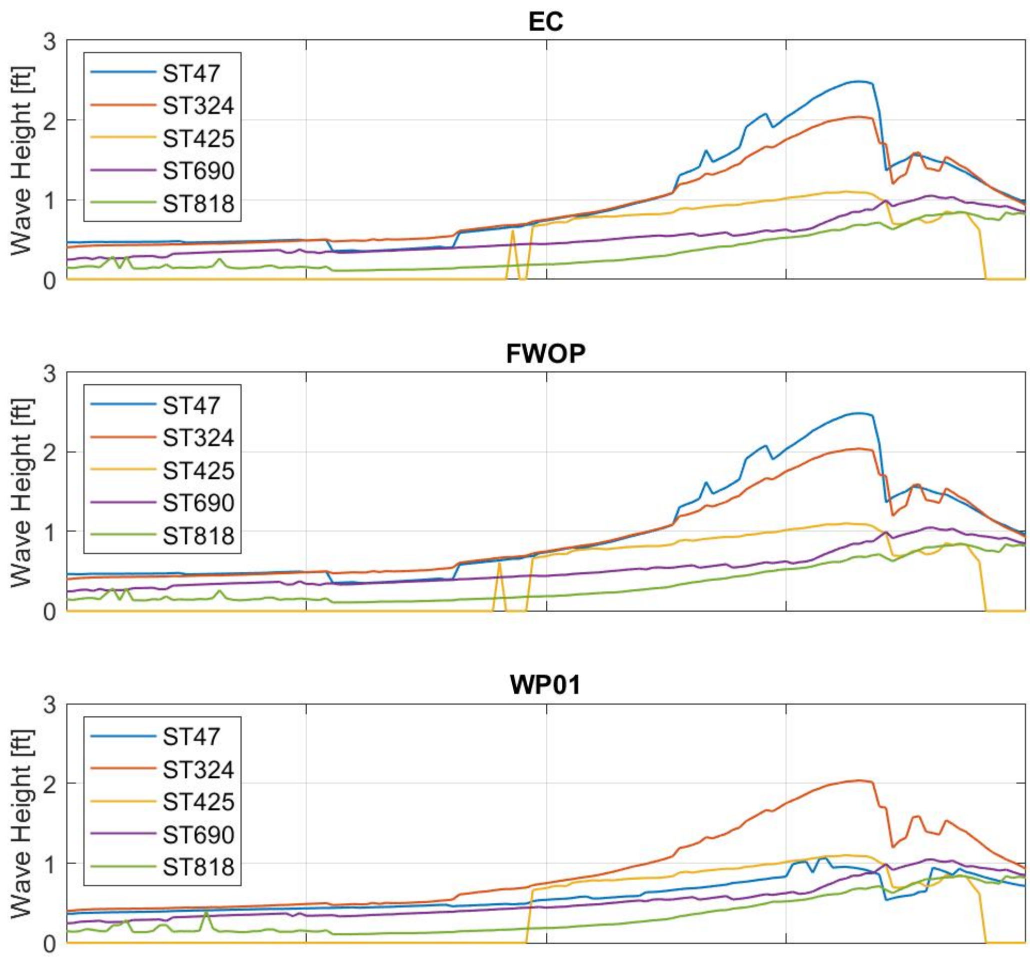


Figure 55: EC (upper), FWOP (middle), and WP01 (bottom) for Storm 83

Appendix D: Characteristics of the Synthetic Tropical Storms - Appendix B (FEMA 2012)

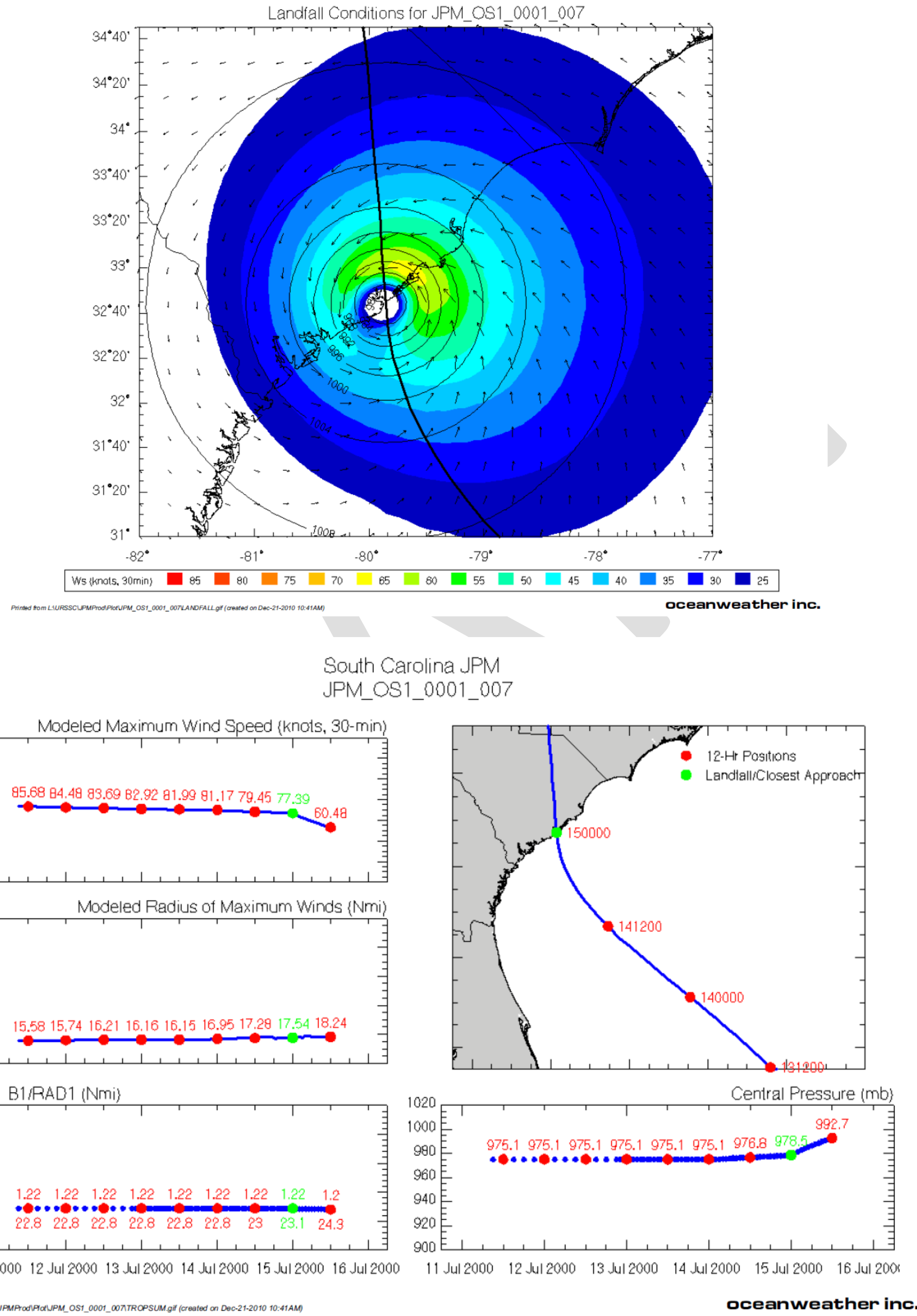
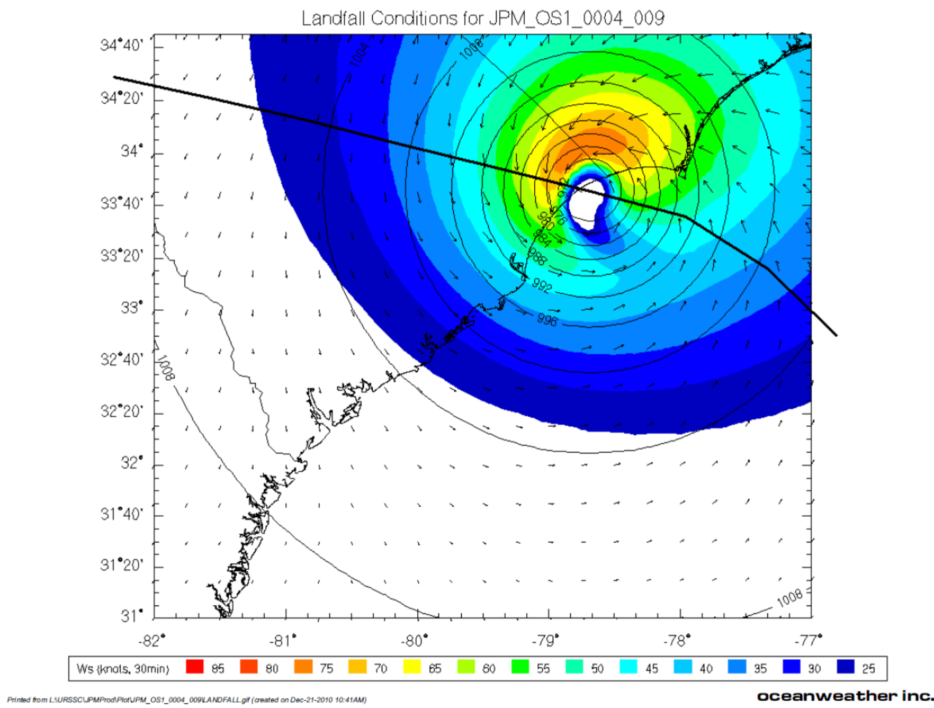


Figure 56: Storm # 4 (JPM_OS1_0001_007).



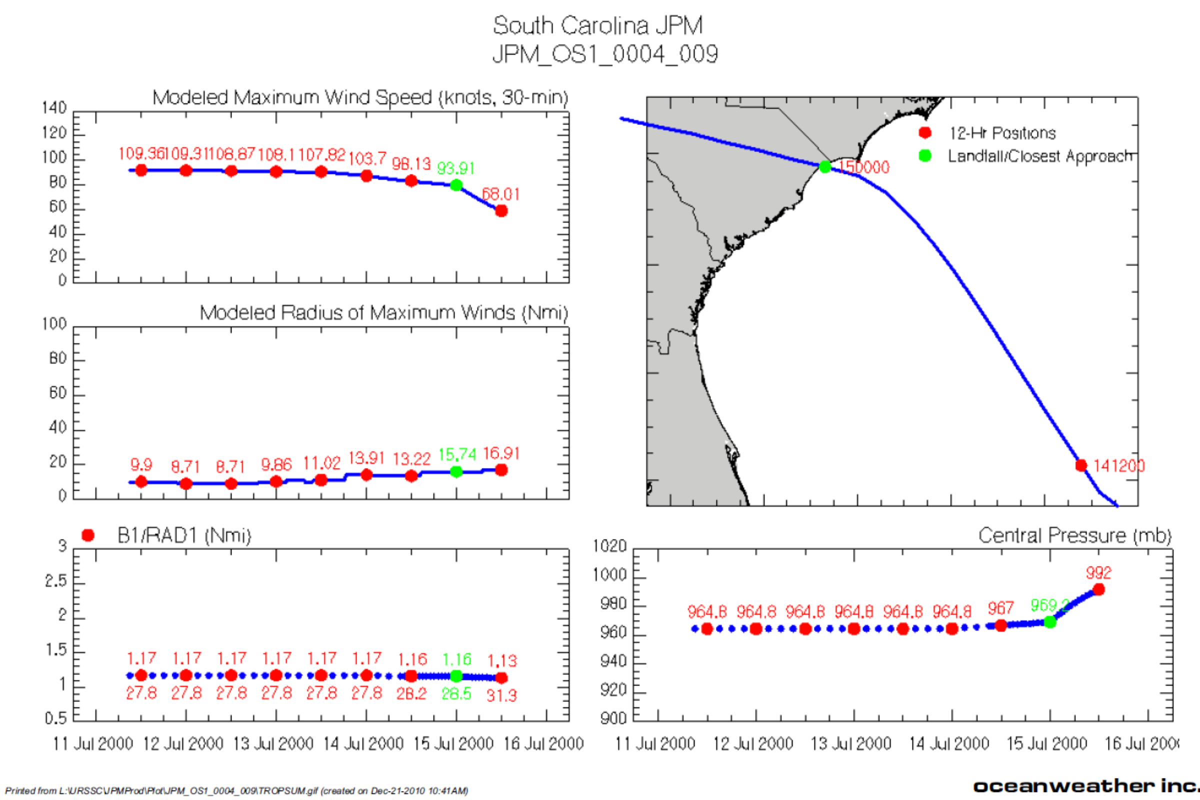


Figure 57: Storm # 27 (JPM_OS1_0004_009).

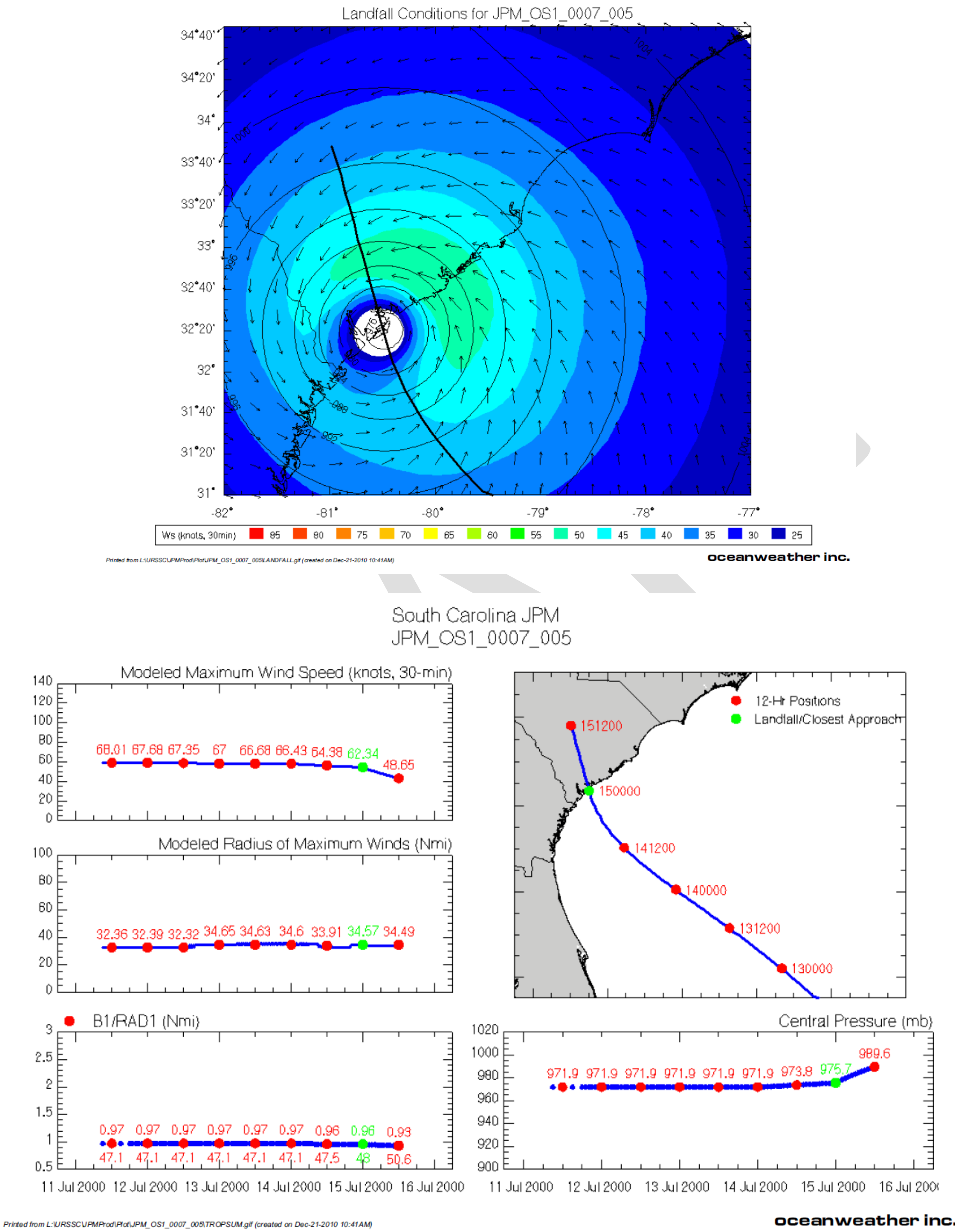
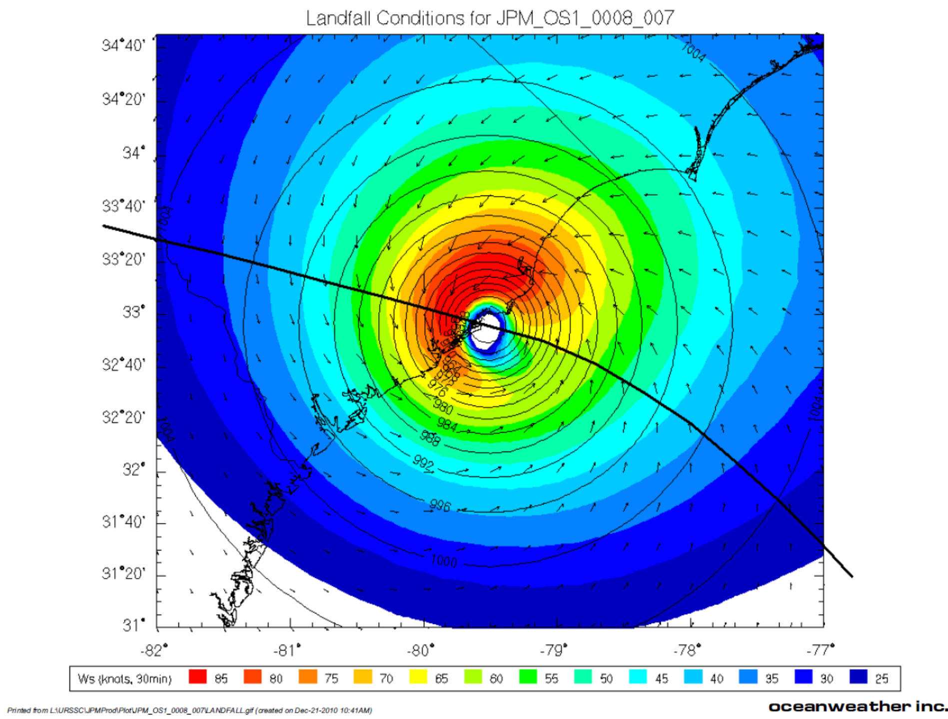


Figure 58: Storm # 38 (JPM_OS1_0007_005).



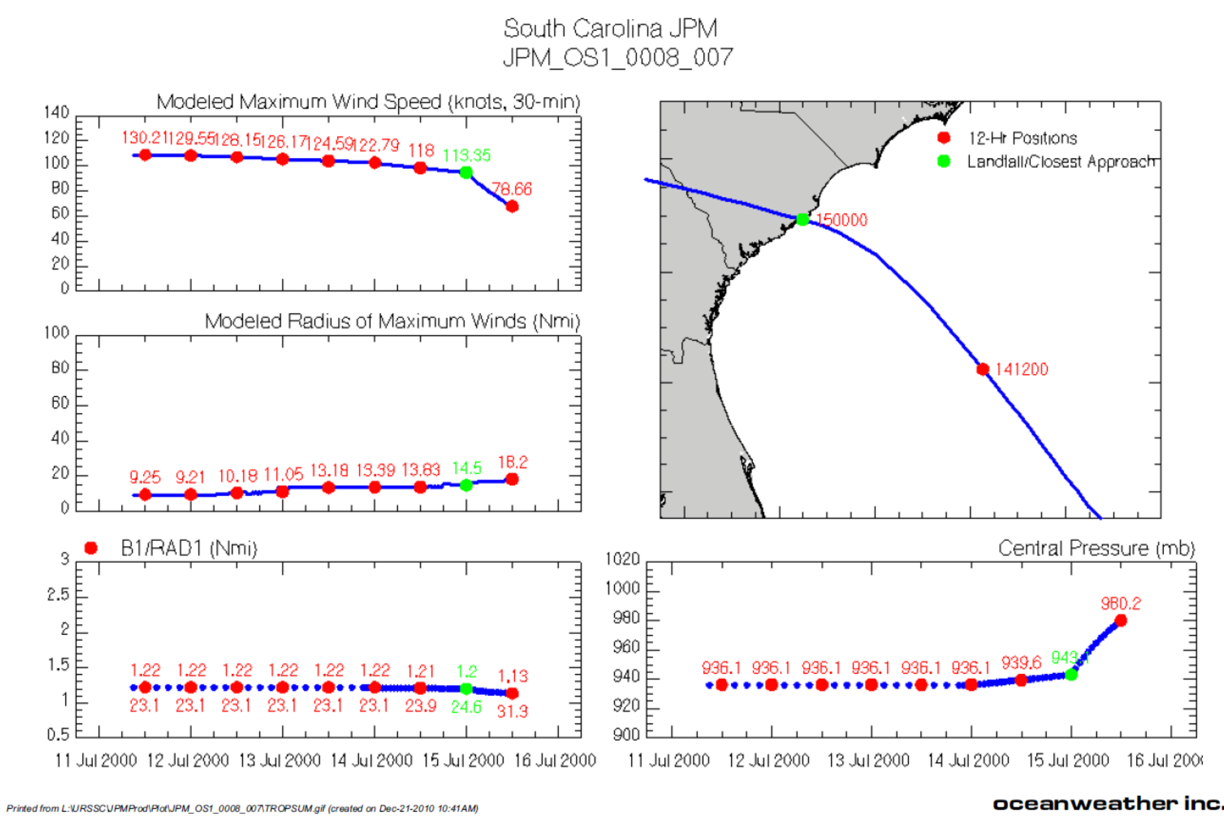
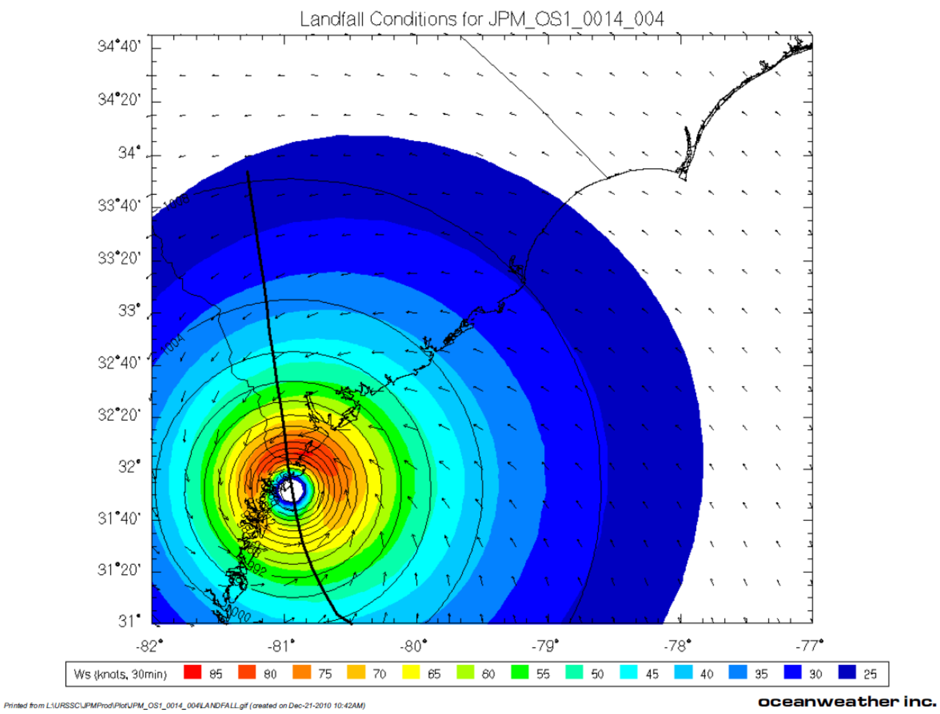


Figure 59: Storm # 46 (JPM_OS1_0008_007).



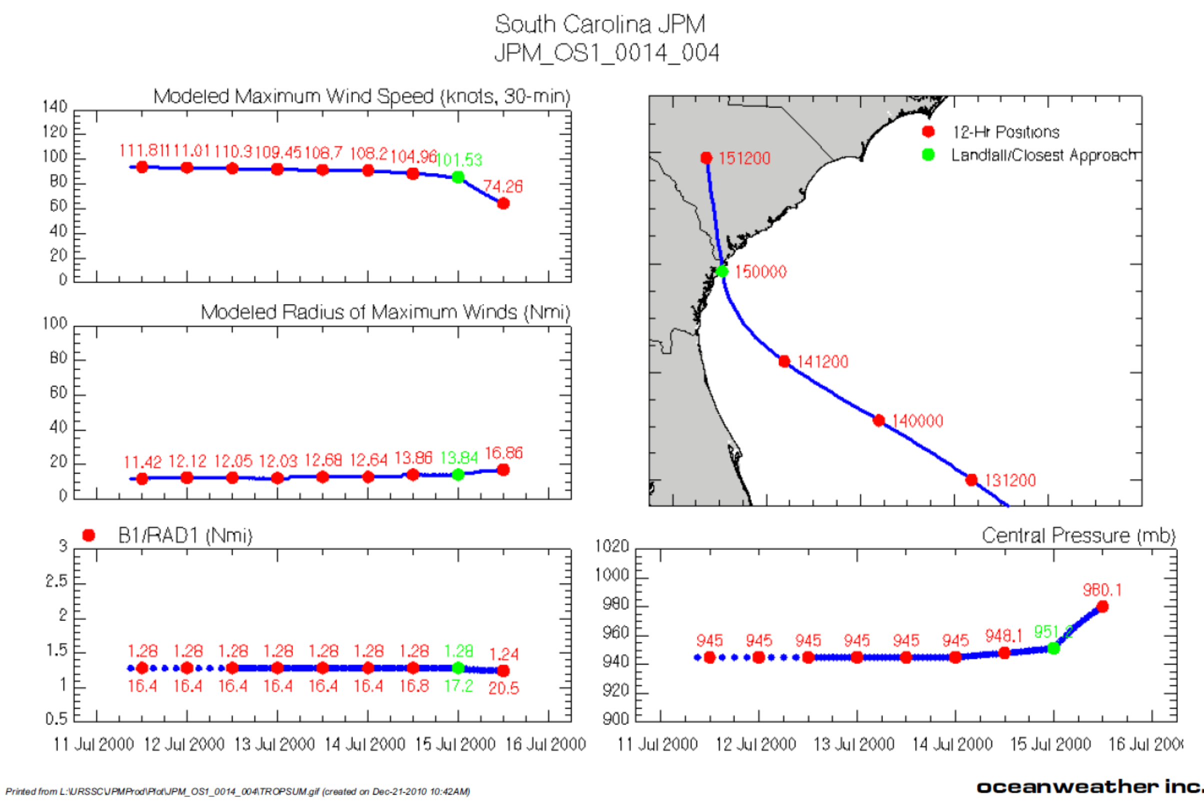


Figure 60: Storm # 83 (JPM_OS1_0014_004).