Methodology and Results for Nearshore Wave Simulation in a Coupled Hydrodynamic and Wave Model System to Evaluate Storm Surge in Coastal Louisiana

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1. Introduction

To update and improve coastal storm surge estimates in coastal Louisiana, a modeling study (LA modeling study) was conducted that included wind modeling, Gulf of Mexico- and regional-scale wave modeling, surge modeling, and nearshore wave modeling (including one-way and, for nearshore waves and surge, two-way interactions). The modeling effort required relatively high-resolution nearshore wave modeling with STWAVE (Smith et al. 2001; Smith 2007) to define the coastal features and accurately resolve the nearshore wave setup. The spatial extent of the grids captured the inundation limits of the simulated storms and allowed grid manipulation to evaluate coastal protection, restoration, and management alternatives.

The variability and intensity of the storm forcing required a robust system to develop the offshore waves as input to the STWAVE grids and to couple the nearshore waves and the circulation model (ADCIRC; Luettich and Westerink 2004). Nesting from a regional offshore wave model (WAM; Komen et al. 1994), multiple STWAVE grids with 200-m (656-ft) resolution simulated nearshore waves. At each of 93 time-steps, STWAVE simulated the nearshore waves with input from WAM (offshore waves) and ADCIRC (wind and surge). Interpolation of the gradients of radiation stress from STWAVE onto the ADCIRC mesh forced spatial and temporal variation of wave setup and wave-driven currents in the circulation model.

Challenges faced during the study included several technical aspects and logistic constraints. The storm forcing conditions — extreme wind speeds, evolving wind directions, and large surge levels — required robust coupling between the offshore wave model (WAM), the nearshore wave model (STWAVE), and the circulation model (ADCIRC). The study domain presented challenges to the nearshore wave modeling with a large region comprised of low-lying coastal marshes, complex nearshore features, levees, and Mississippi River-related features. In addition, the study timeline, size of the study domain, and model resolution required execution on parallel-computing platforms with parallel processing capability. Each simulation resulted in enormous file sizes that required efficient data management and post-processing.

To overcome the study challenges listed above, the study team developed several advancements to the STWAVE model. These advancements include a new bottom-friction algorithm, variable surge and wind input capability, efficient model codes suitable for parallel computing application, and several pre- and post-processing applications.

2. Nearshore Wave Model STWAVE Model

The LA modeling study applied the numerical model STWAVE to generate and transform waves to the shore for each storm simulated. STWAVE numerically solves the steady-state conservation of spectral action balance along backward-traced wave rays:

$$(C_{ga})_x \frac{\partial}{\partial x} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} + (C_{ga})_y \frac{\partial}{\partial y} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} = \sum \frac{S}{\omega_r} \qquad (1)$$

where
$C_{g\,a}$ = absolute wave group celerity
x,y = spatial coordinates, subscripts indicate x and y components
C_a = absolute wave celerity
μ = current direction
α = propagation direction of spectral component
E = spectral energy density
f = frequency of spectral component
ω_r = relative angular frequency (frequency relative to the current)
S = energy source/sink terms

The source terms include wind input, nonlinear wave-wave interactions, dissipation within the wave field, and surf-zone breaking. The terms on the left-hand side of Equation 1 represent wave propagation (refraction and shoaling), and the source terms on the right-hand side of the equation represent energy growth and decay in the spectrum. The assumptions made in STWAVE include mild bottom slope and negligible wave reflection; steady waves, currents, and winds; linear refraction and shoaling; and depth-uniform current.

STWAVE can execute as either a half-plane model, meaning the model only represents waves propagating toward the coast, or a full-plane model that allows generation and propagation in all directions. Wave breaking in the surf zone limits the maximum wave height based on the local water depth and wave steepness:

$$H_{mo_{max}} = 0.1L \tanh kd \qquad (2)$$

where H_{momax} = maximum zero-moment wave height
L = wavelength
k = wave number
d = water depth

The study applied two alternatives for the wave energy dissipation induced by bottom friction. A Manning formulation of bottom roughness was selected for application to be consistent with the bottom roughness specified in the circulation model. The bottom friction source term is specified from Holthuijsen (2007), modified to include a Manning friction coefficient:

$$S_{bf} = \frac{-1}{g}\left(\frac{gn^2}{d^{1/3}}\right)\frac{\sigma^2}{\sinh^2 kd}E(f,\alpha)u_{rms} \qquad (3)$$

where S_{bf} = the energy term related to bottom friction
g = gravity
n = Manning's coefficient
u_{rms} = the root-mean-square wave orbital velocity at the bottom

The Manning's n coefficients were obtained from GAP land use data (U.S. Geological Survey, National Wetlands Research Center). The GAP data were interpolated to the STWAVE cells from the ADCIRC mesh, for consistency. Table 1 contains the Manning-n values assigned for the Louisiana GAP classes.

Table 1. Manning-n Values Assigned to Louisiana GAP classes

Land Cover	Manning-n
fresh marsh	0.055
intermediate marsh	0.05
brackish marsh	0.045
saline marsh	0.035
wetland forest - mixed	0.15
upland forest - mixed	0.17
dense pine thicket	0.18
open water	0.02

STWAVE is a finite-difference model and calculates wave spectra on a rectangular grid. The inputs required to execute STWAVE include the bathymetry grid (including shoreline position and grid size and resolution); incident frequency-direction wave spectra on the offshore grid boundary; current field (optional); surge and/or tide fields; wind speed and wind direction (optional); and bottom friction coefficients (optional). The outputs generated by STWAVE include fields of energy-based, zero-moment wave height, peak spectral wave period (T_p) and mean direction; wave spectra at selected locations; and fields of radiation stress gradients for input to ADCIRC (to calculate wave setup).

The study domain, storm forcing, study goals, and study schedule resulted in upgrades to the STWAVE model. The upgrades improved the model's capability to simulate waves in areas with spatially varying vegetation and for spatially and temporally varying storm forcing. This paper will not detail the model improvements that include: variable storm surge levels, variable wind forcing, development of formulations to account for bottom friction-induced wave dissipation, application of interpolation algorithms to develop coarse grid offshore spectra to nearshore grid, parallel processing capability, and calculation and output of low-frequency weighted mean wave period for design.

3. Nearshore Wave Modeling Methodology

The LA modeling effort applied STWAVE on five grids for the southern Louisiana area: Lake Pontchartrain, Louisiana West, Louisiana Southeast, Louisiana South, and Mississippi/Alabama (Figure 1). Figure 1 includes the locations of raised elevation features (e.g., levees and roads) included in the model domain. The study applied five grids to take advantage of the efficient half-plane version of STWAVE for the four outer grids (which must approximately align with the shoreline) and to concentrate grid coverage in the areas of interest. Table 2 contains the specifications of the five grids applied in the study. The Lake Pontchartrain grid applied the full-plane version of STWAVE to allow wind-wave development and propagation in all directions. The input for each grid includes the bathymetry (interpolated from the ADCIRC domain), surge fields (interpolated from ADCIRC surge fields), and wind (interpolated from the ADCIRC wind fields, which apply land effects to the Oceanweather, Inc. wind fields). The surge and wind applied in STWAVE varied spatially and temporally for all domains. STWAVE was run at 30-min intervals for 93 quasi-time steps (46.5 hrs).

To maximize efficiency on the parallel-computing platform, the modeling system divided the STWAVE simulations among multiple processors. The system executed the STWAVE grids in series with each simulation (93 time snaps) assigned to a different processor. STWAVE simulation time approached 1.5 hours for the simulations with five grids. For comparison, execution of the ADCIRC model, spread over 256 processors, lasted approximately three hours. Notably, inclusion of the wave stresses in the modeling system required a second ADCIRC simulation to develop the wave-induced water level and current changes. The first ADCIRC simulation developed the surge and wind field required as input conditions into STWAVE and provides the without wave surge estimate.

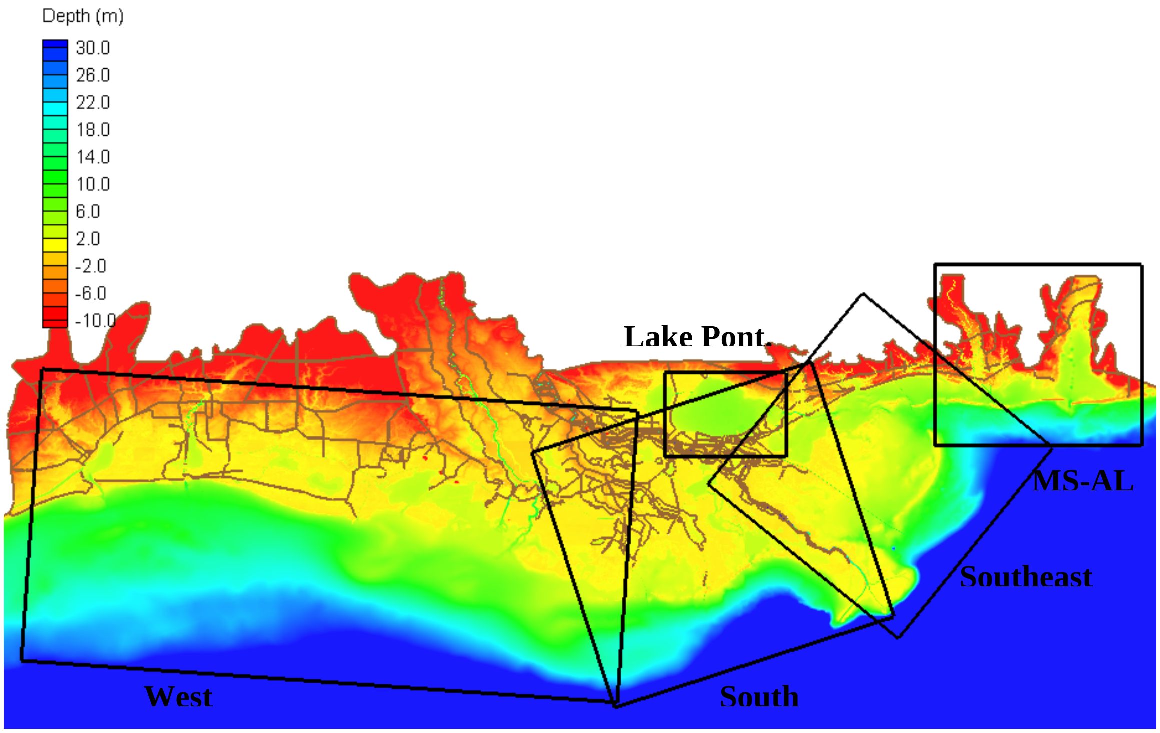

Figure 1. STWAVE Grids Applied in the LA Modeling Study

Table 2. Details of STWAVE Grids Applied in the LA Modeling Study

Grid	State Plane	Xo (ft)	Yo (ft)	dX (ft)	dY (ft)	Azimuth (deg)	# X Cells	# Y Cells
Lake Pont.	LA South	3,553,894	702,944	656	656	270	284	352
West	LA Off.	3,473,678	1,077,709	656	656	86	980	1740
South	LA Off.	3,997,077	1,264,880	656	656	108	825	839
Southeast	LA Off.	4,294,534	1,639,472	656	656	141	683	744
MS-AL	LA Off.	4,463,922	1,653,930	656	656	90	563	605

4. Nearshore Wave Modeling Results

The study applied 304 (152 “east” and 152 “west”) storm simulations to develop the 100-year water levels throughout coastal Louisiana. The storms were selected through a joint probability, optimal sampling technique. Each simulated storm involved STWAVE simulations for each of 93 time steps centered on the storm’s landfall. The 152 “west” storms applied all five STWAVE grids; however, the “east” storms did not apply the West grid. Each of the STWAVE simulations was reviewed with the quality control (QA/QC) procedures enacted for the study. The following figures present representative STWAVE model results from selected storms. In addition to the 304 storms run to establish the 100-year water levels for FEMA, many additional simulation were run (using a subset of the same storms) to evaluate sea level rise impacts, marsh restoration and degradation, barrier island restoration, and levee and barrier construction.

4.1 Wave Height Analysis

Animations of the wave height and period fields indicate the spatial and temporal changes to the wave field throughout a specific grid for each storm. Coupling with the hydrodynamic model provides the time-varying surge field that allows wave propagation over inland areas. Figure 2 shows the wave height in the Southeast grid for Storm 026. A relatively large and strong storm, Storm 026 made landfall to the west of the Mississippi River delta with a track similar to Hurricane Katrina (central pressure of 900 mb, radius of maximum winds of 14.9 nm, and forward speed of 11 kts). The plot shows the wave height and direction vectors just prior to landfall with offshore wave heights approaching 40 ft. Land areas not inundated by the storm surge are white in the figure. At this time (time step 43) significant inundation resulting in complete submergence has occurred in the nearshore marshes. Despite being inundated by the storm surge, the Chandelier Islands continue to induce wave breaking and limit the amount of wave energy that propagates past the islands to the northwest.

Figure 3 shows the wave height in the Lake Pontchartrain grid at time step 48 for Storm 026. At this time step, the wave heights along the south shore of Lake Pontchartrain approach 12 ft. The plot shows the wind-wave growth that occurs from the north shore to the south shore. After the hurricane makes landfall — approximately time step 62 — the winds come from the southwest and waves propagate to the northeast. The waves reach the north shore with wave heights near 7 ft.

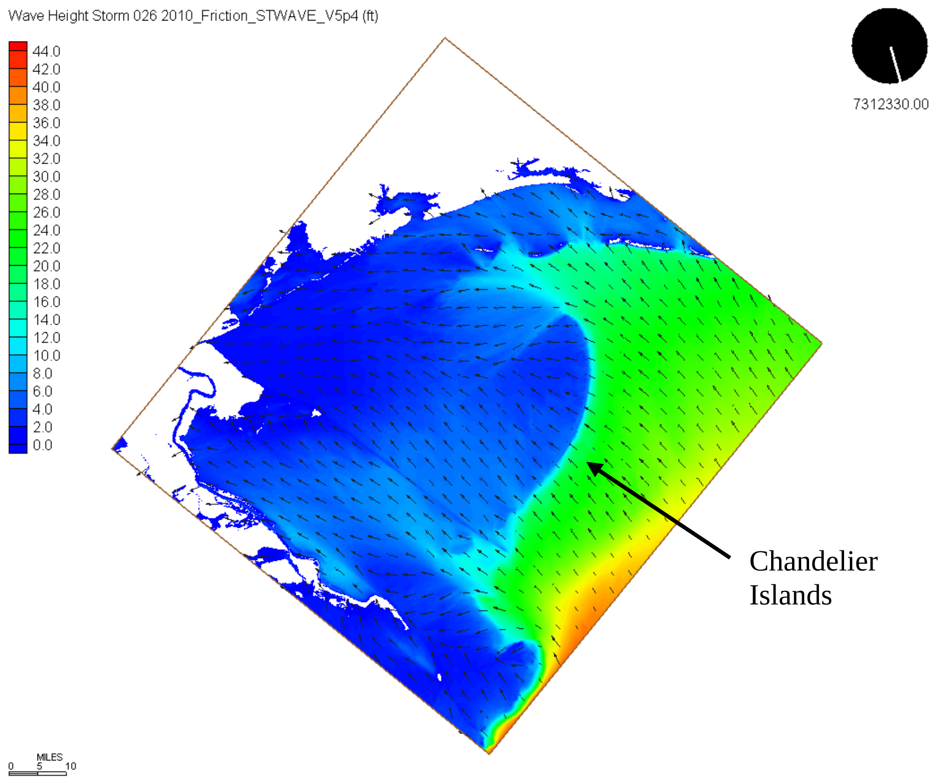

Figure 2. Wave Height and Direction Vectors during Storm 026 in the Southeast Grid

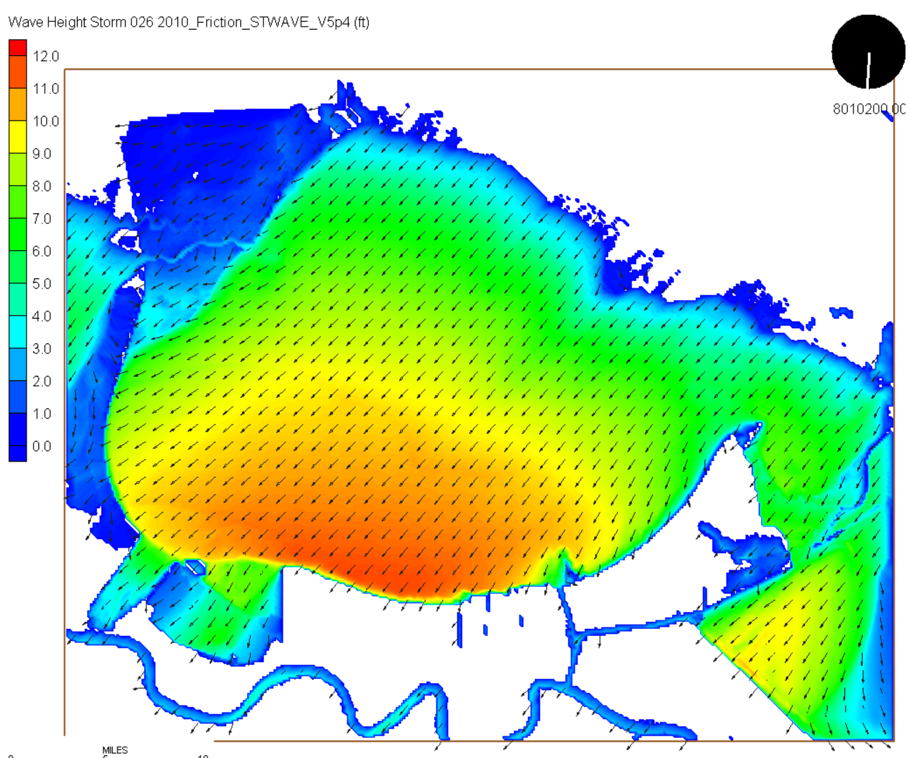

Figure 3. Wave Height and Direction Vectors during Storm 026 in the Lake Pontchartrain Grid

Development of wave results at individual grid points allows the creation of time history plots of wave parameters. Figure 4 shows the location of 12 analysis points developed for the Southeast grid. The spatial distribution of locations allowed analysis of wave conditions at offshore, nearshore, and inland points. White areas in the plot indicate locations initially above water prior to the storm surge. Figure 5 shows the variation of wave height with time for Storm 026 in the Southeast grid at the 12 output points. The figure shows the increase in wave height that occurs prior to landfall in offshore areas (Points 1, 3, and 4). Several inland points remain dry (have zero wave height) leading up to landfall and then experience wave growth as the storm surge moves inland. Although initially dry, Points 9 and 10 have maximum wave heights that exceed 5 ft. The storm surge does not inundate the area near Point 12 and no waves develop at this location. Similar analysis of selected output point locations occurred for each of the STWAVE grids.

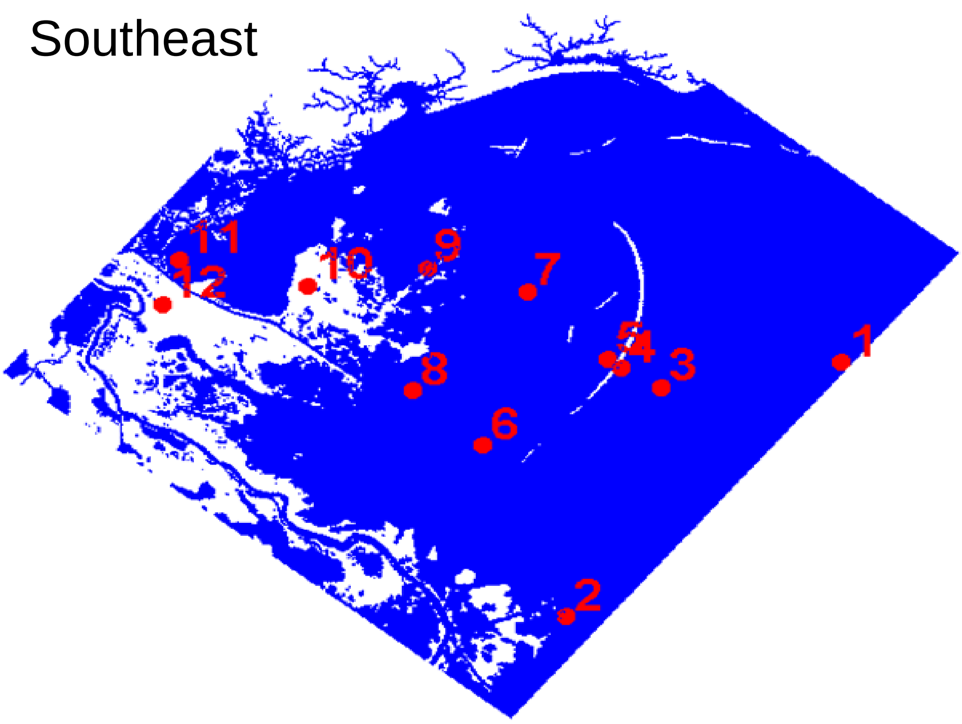

Figure 4. Output Point Locations for the Southeast Grid

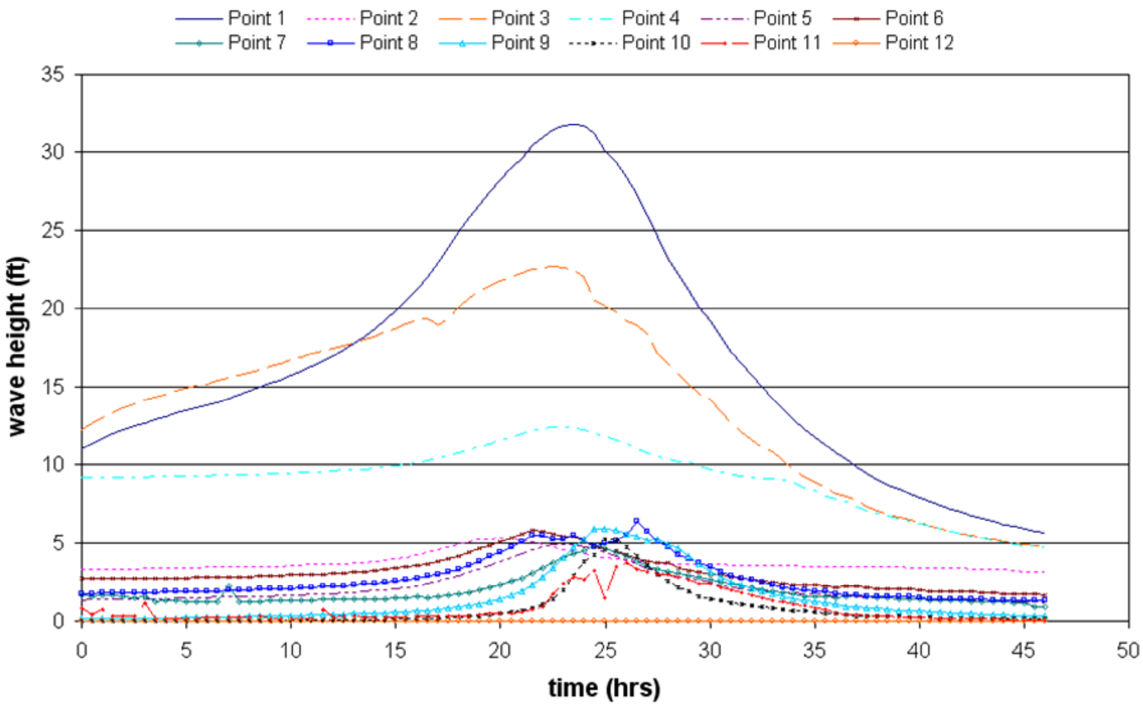

Figure 5. Wave Height at Selected Output Point Locations for the Southeast Grid (Storm 026)

4.2 Wave Setup Analysis

Analysis of the ADCIRC results with and without application of the STWAVE-developed radiation stress gradients reveals the effects of the nearshore waves on the water level. The difference between the surge field with and without waves represents the wave-induced change to the water level — the wave setup. Wave setup results from the transfer of the momentum from waves to the water column as waves dissipate (wave setup) or grow (wave setdown). Defining storm surge elevations was the ultimate goal of the LA modeling study, so the effects of the waves on the water level represent a key process not robustly modeled in most previous storm surge estimates for the region.

Figure 6 presents the wave setup at time step 29 in the Southeast grid for Storm 045. This data comes from a sensitivity study where the barrier islands were raised and given larger friction coefficients to study the effects of the barrier islands on water levels and waves. Storm 045 makes landfall along the Mississippi coast and produces significant storm surge in the area defined by the Southeast grid. The plot shows wave setup values in excess of 2 ft near the Chandelier Islands and near the Mississippi River delta in the lower portion of the grid. The white areas near the offshore boundary indicate areas of wave growth where the presence of the waves reduces the water level (setdown).

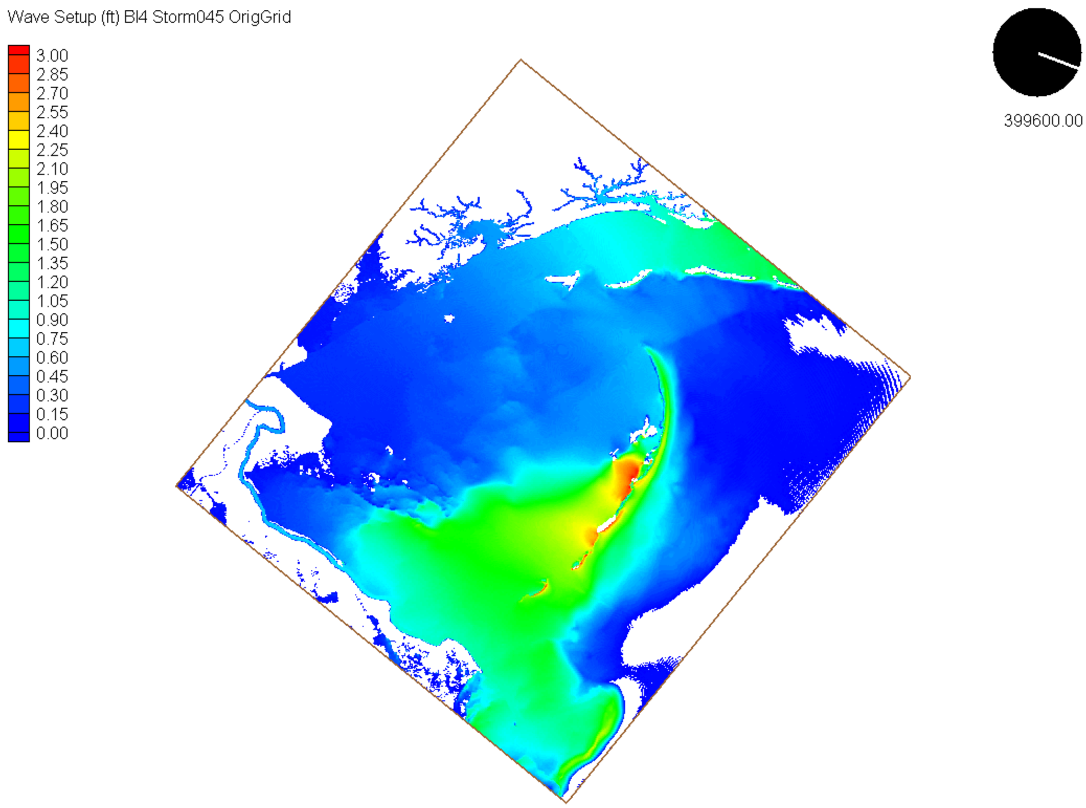

Figure 6. Wave Setup at Time Step 29 of Storm 045 in the Southeast Grid

Extracting the wave and surge information at the selected output points allows temporal evaluation of the wave setup as the storm progresses. Figure 7 presents the time series of the wave height and surge (with and without waves) for Storm 045 at Point 2 near the Mississippi River delta in the Southeast grid. Notably, time zero in the plot represents conditions approximately 24 hours prior to landfall when wave forcing commences; the hydrodynamic model indicates over 2 ft of surge at Point 2 at this time. The plot indicates wave setup of 0.8 ft after 30 minutes of forcing ADCIRC with radiation stresses from time zero of the STWAVE simulation. The plot shows the effect of the waves on the surge field with wave setup values near 2 ft at time step 26. Notably, the location of Point 2 — not at the shoreline — and the three-dimensionality of the bathymetry complicate comparison of the setup magnitude at Point 2 to the setup at a longshore homogenous beach. The timing of the maximum wave setup nearly coincides with the maximum wave height. The wave setup goes to zero as the storm moves inland and the wave height gradients diminish.

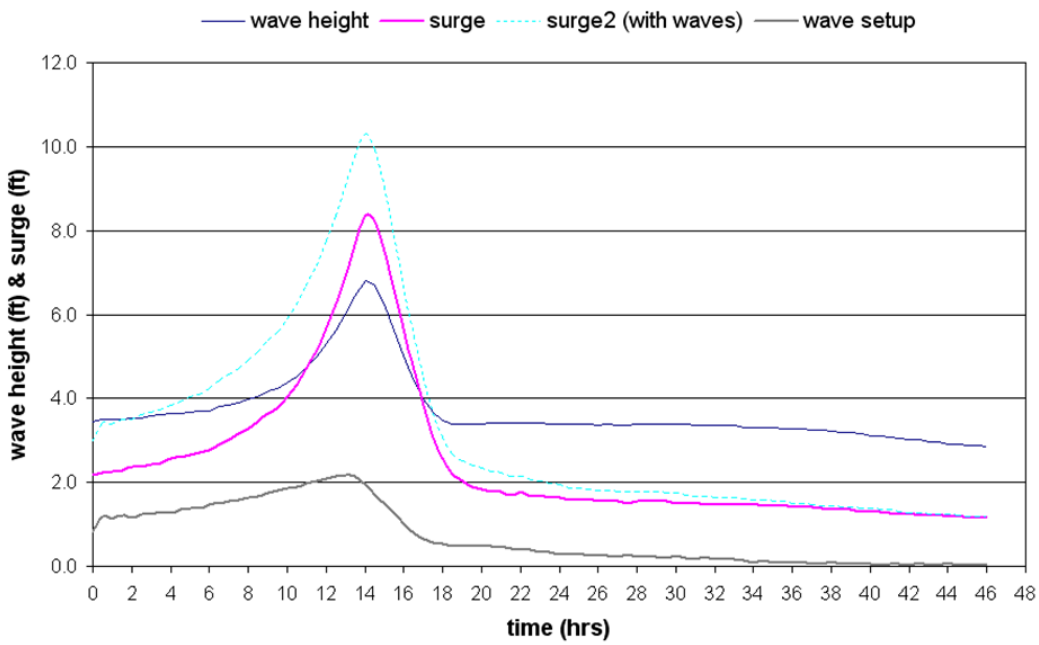

Figure 7. Time Series of Wave Height and Setup at Point 2 in the Southeast Grid (Storm 045)

Figure 8 presents the time series of the wave height and surge (with and without waves) for Storm 045 at Point 6 located landward of the Chandelier Islands in the Southeast grid. The wave setup at Point 6 grows from near zero to over 2 ft at time step 32. The time of maximum setup occurs after the maximum wave height and before the maximum surge. The wave setup trends towards zero as the storm passes and the gradients in wave height diminish.

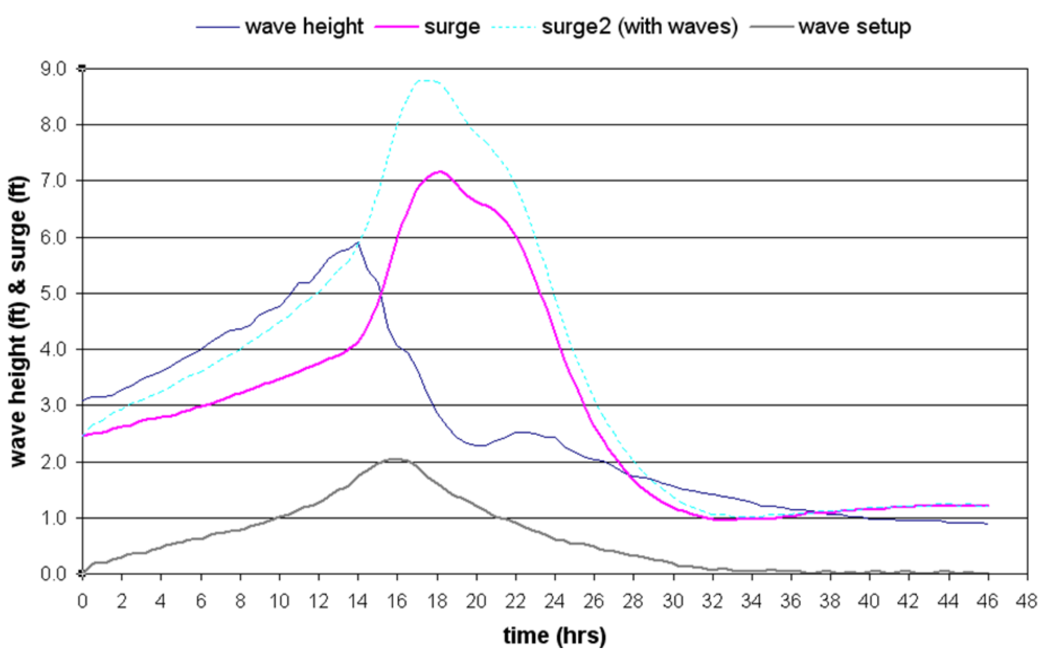

Figure 8. Time Series of Wave Height and Setup at Point 6 in the Southeast Grid (Storm 045)

5. Applications and Future Work

The previous section presents representative results from the coupled STWAVE and ADCIRC system applied in the LA modeling study. Wave height gradients developed in the STWAVE models provide the temporal variation of momentum flux (through radiation stress gradients) necessary for ADCIRC to simulate wave-induced water level effects. The coupling between STWAVE and ADCIRC allows the two-dimensional estimation of wave setup that varies with time for each simulated storm. This dynamic coupling produces storm surge estimates that account for the two-dimensional effects of waves — a process neglected by most previous large scale studies or added to the final results with limited spatial and temporal resolution.

Statistical analysis tools developed to calculate the 100-year water level also allow calculation of wave parameters versus return period. The statistical analysis of the wave heights applies the assigned probability of occurrence to each of the 304 simulated storms and the STWAVE results for each storm. The 100-year wave parameters have many applications to design levels for nearshore structures, coastal planning, and risk analysis.

The lack of field data for waves in lowland marsh areas during storm events limited the ability to verify the STWAVE results developed in this study. The upgrades to STWAVE and the coupling mechanism between ADCIRC and STWAVE applied in the study provide a modeling system ready for calibration to surge, vegetation, and bottom friction effects when field data become available.

Ongoing tests and analyses continue to apply the coupled modeling system to evaluate the sensitivity of model results to individual factors and evaluate alternative restoration and design scenarios. Sensitivity tests include the role and importance of coastal barrier islands, coastal marshes, sea level rise, and inland waterway and navigation features.

The system applied in the LA modeling study represents a new standard and a significant step forward in the Federal Emergency Management Agency (FEMA) coastal flood mapping methodology through a robust, high-fidelity method to calculate waves for contribution to storm surge. Application of technology and methodology from the USACE’s MORPHOS program will continue to develop the modeling system with improved resolution, additional source terms, and increased linkages to ADCIRC.

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