# NUMERICAL MODELING OF OBSERVED HURRICANE WAVES IN DEEP AND SHALLOW WATERS

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Extensive field measurements of wind waves in deep and shallow waters during Hurricane Gustav (2008) in the Gulf of Mexico have been simulated by the spectral wave prediction model, SWAN. First, a parametric asymmetric hurricane wind model with three major improvements is used to generate hurricane wind fields for the wave model. The changes of water level near the coast are taken into account by using a storm surge model. Forced by the verified hurricane winds and hindcasted water levels, the wave model performs fairly well in comparison to the observed wave heights and periods in both deep and shallow waters except a few locations with complex bathymetry and landscape. In addition to the hurricane wind field that controls the accuracy of wave modeling in deep water, wave-surge interaction plays an important role in the wave growth and transformation in shallow water. Wave spectral comparisons show that the white-capping formulation of Westhuysen et al. (2007) generally outperforms the default formulation of Komen et al. (1984) in SWAN under hurricane conditions. The model result indicates that the asymmetry of hurricane winds and the hurricane translation result in the maximum wind waves occurring on the right side of the hurricane track and propagating in the direction parallel to the hurricane translation direction, consistent with field observations.

*Keywords: asymmetric wind; spectral wave model; hurricane waves; wave-surge interaction*

## INTRODUCTION

The northern Gulf of Mexico (GOM) is extremely susceptible to the impacts of frequent tropical storms and hurricanes. In deep water, the offshore oil drilling industry, a major contributor to domestic U.S. oil and gas supplies, is vulnerable to the impacts of extreme waves generated by hurricanes in the GOM. In shallow water, severe coastal flooding, enormous property damage, and loss of life are ubiquitously associated with tropical cyclone landfalls on the north Gulf coast, and this devastation was no more evident than during Hurricanes Katrina and Rita in 2005 and Gustav and Ike in 2008. Over 1600 people lost their lives and several major coastal populations were crippled for months after the hurricanes passed. Obviously, mitigating the impacts of hurricanes requires an accurate prediction of hurricane-induced waves in deep and shallow waters, including the interaction of wave and surge in coastal regions.

Significant advances in numerical modeling of hurricane-generated waves have been made in the past two decades. Third-generation spectral wave prediction models, such as WAM and WAVEWATCH, are routinely used for wave forecasts and hindcasts in oceans, which provide offshore boundary conditions for coastal wave models, including SWAN and STWAVE. Efforts are being devoted to unifying both types of wave model by incorporating shallow water physics and variable spatial resolutions into basin-scale, deep-water wave models. Recent rapid development of computing technology also enables coastal wave models that have included both shallow and deep water physics to predict hurricane waves from deep to shallow water simultaneously if coupled with a basin-scale storm surge model. One of such examples is the development of the unstructured SWAN wave model that can employ the same computational mesh of the finite-element storm surge model, ADCIRC.

In-situ wave observations are extremely important for validating and improving numerical wave models. The National Oceanic and Atmospheric Administration (NOAA) has maintained a wave buoy network, including 12 buoys in the Gulf of Mexico. There are however very limited permanent wave monitoring stations in shallow water, especially along the hurricane-prone north Gulf coast. The recent successful deployment of 20 short-term wave gages along Louisiana coast during the passage of Hurricane Gustav (Kennedy et al. 2010) provides a comprehensive dataset of waves and surge in water depths shallower than 10 m near a landfalling hurricane for testing hurricane wave prediction models. The objective of this study is to simulate wind waves generated by Hurricane Gustav in the entire Gulf of Mexico, including Louisiana coastal waters, using the spectral wave prediction model SWAN coupled with a basin-scale storm surge model, and to compare the model results with the comprehensive wave measurements in both deep and shallow waters. First, an improved asymmetric hurricane wind model is introduced and applied to generate the wind fields of Hurricane Gustav.

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Second, the SWAN wave model is setup to model hurricane waves in the GOM from deep to shallow waters, focusing on the Louisiana coast. Comparisons with the observations are made and model results are analyzed. Emphasis is given to the influence of white-capping on the modeled spectral shapes in comparison to the measurements. Conclusions are presented finally.

## AN IMPROVED ASYMMETRIC HURRICANE WIND MODEL

### Model Description

The computational domain of the spectral wave model covers the Gulf of Mexico with high spatial resolution on the Louisiana coast. Simulations of hurricane-generated waves over the entire hurricane event and in a vast area require an accurate wind field that not only has sufficient temporal and spatial resolution of the tropical cyclone, but also includes the basin-scale background winds, as the time series of surface waves at a given location consists of both swell and locally generated seas. Therefore, we have improved a parametric analytical wind model for asymmetric hurricanes and merged it with the large-scale background wind field provided by the National Center for Environmental Prediction (NCEP). The improved asymmetric hurricane wind model is developed from the asymmetric Holland-type vortex model (Mattocks and Forbes 2008). The model creates a two-dimensional surface wind field based on the National Hurricane Center (NHC) forecast (or observed) hurricane wind point values, namely the maximum wind, radius of maximum wind, the specified (34, 50, and 64-knot) wind intensities and their radii in 4 quadrants.

Three major improvements are made to ensure the consistency between the input parameters and the model output. First, the Coriolis parameter is taken into account in the determination of the shape parameter B and the range limitation of B is released to eliminate the potential error in the modeled maximum wind speed. Second, the effect of the translational velocity of a hurricane is excluded from the input wind intensities provided by the NHC before applying the Holland-type vortex to avoid exaggeration of the wind asymmetry. Third, a new method is introduced to develop a weighted composite wind field that makes full use of all wind parameters, not just the largest available specified wind intensity and its 4-qudrant radii. The reader is referred to Hu et al. (2010) for detailed formulas and procedures of this improved parametric hurricane wind model.

### Hurricane Gustav (2008)

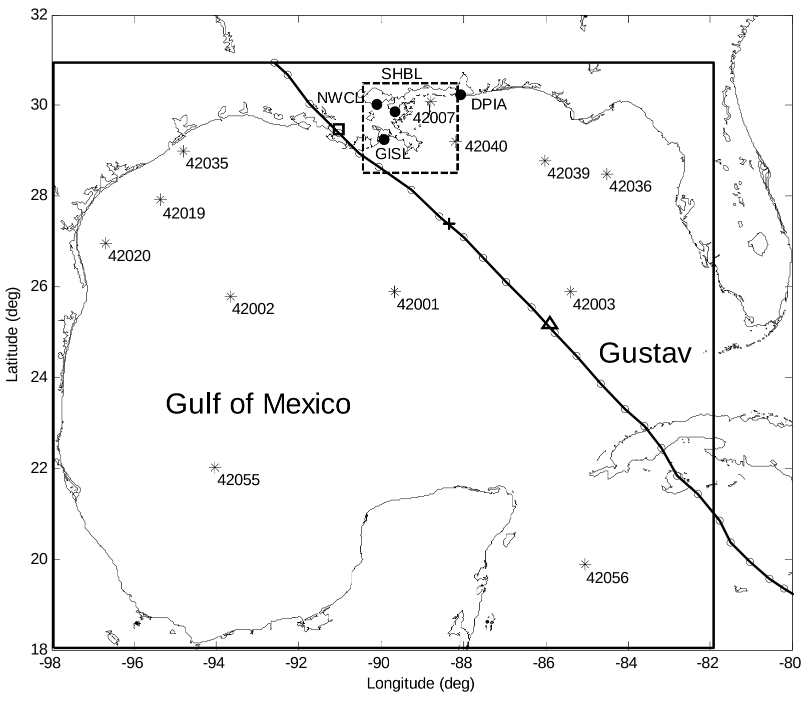


**Figure 1. Hurricane track of Gustav (2008) and observation stations (star symbols for offshore buoys and solid dots for coastal stations) in the Gulf of Mexico. Solid and dashed rectangles respectively denote gulf-scale and local domains for wave modeling. Symbols of triangle, cross and square along the hurricane track denote the hurricane center at times 14:00 UTC 08/31, 03:00 UTC 09/01 and 16:00 UTC 09/01, respectively.**

In the forecast mode, the hurricane parameters are given every 6 hours in the National Hurricane Center's hurricane advisory. In the present hindcast study of Hurricane Gustav, such information is extracted from NOAA's H*wind data (Powell et al. 1998). The only exception is the central pressure which comes from the NCEP Automated Tropical Cyclone Forecasting best track data. The track of Hurricane Gustav is shown in Fig. 1. Gustav moved erratically through the Greater Antilles into the Gulf of Mexico, eventually making landfall on the coast of Louisiana. Time series comparisons of wind speed and wind direction at four buoys and four coastal stations are shown in Fig. 2. An experimental result without the improvements described above was included for comparison. The experimental case uses the highest available wind intensity (34-, 50-, or 64-knot) and its 4-quadrant radii to generate the asymmetric hurricane wind, and the effect of the translational velocity is not excluded from those specified wind intensities. The modeled wind with and without the improvements will be called the 'improved' wind and the 'experimental' wind, respectively, in this paper hereafter.

It can be seen that the agreement between the improved winds and observed data is better than that of the experimental winds, especially for large wind speeds. The experimental winds show some underestimation on the left side of hurricane track (e.g. buoy 42001) and overestimation on the right side of hurricane track (e.g. buoys 42003 and 42040), which means that the asymmetry of the wind structure will be exaggerated if the effect of the translational velocity is not excluded from the input wind intensities but still added back in the end. In contrast, the improved asymmetric wind model is capable of producing hurricane winds with higher accuracy than the model without modifications.

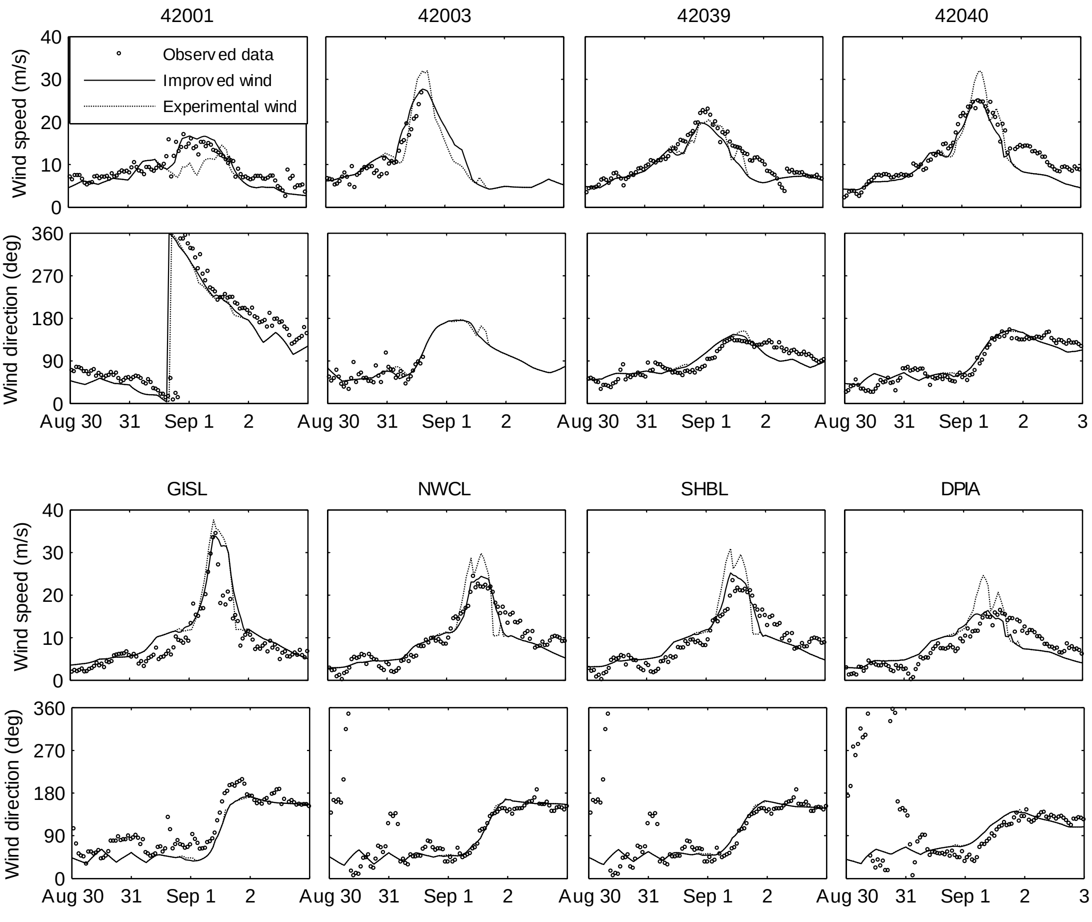


**Figure 2. Comparisons of wind speed and wind direction with observed data for Hurricane Gustav. Circles, solid lines and dashed lines denote observation, improved wind and experimental wind, respectively.**

Fig. 3 depicts the comparison of the wind swaths generated from the H*wind, the improved winds, and the experimental winds. The H*wind swath is obtained by both temporal (every half an hour) and spatial interpolations of the wind data using an accurate interpolation scheme (Chen et al. 2008). The other swaths are calculated based on half-hour outputs from the parametric wind models. The modeled swath based on the improved winds agrees fairly well with the H*wind swath of maximum winds, while the swath based on the experimental winds shows some obvious discrepancies. In Fig. 3c, the maximum wind band on the right side of the hurricane track appears to be 'broader' than that in Fig. 3a, and on the left side, the result seems 'narrower', which is consistent with the discrepancies at buoy 42001 (left side) and buoys 42003 and 42040 (right side) in Fig. 2. The improved wind model gives better results overall.

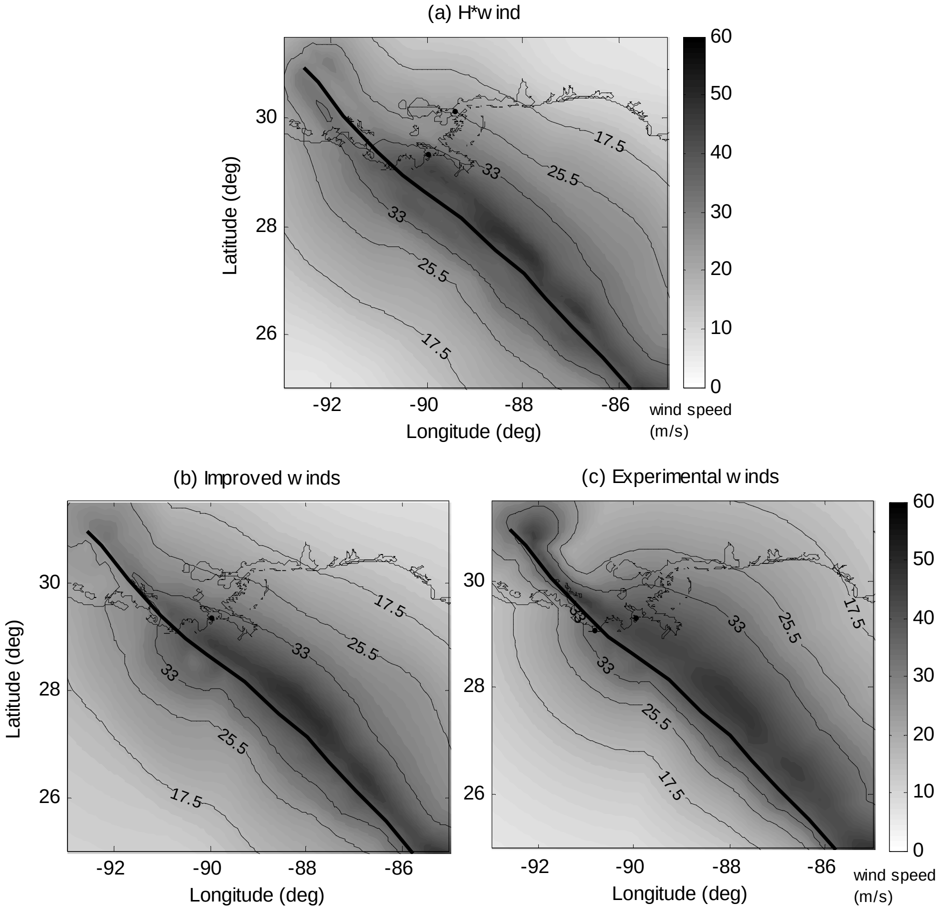


**Figure 3. Wind swaths of (a) H*wind, (b) improved winds and (c) experimental winds during Hurricane Gustav. Thick solid line denotes hurricane track.**

## HURRICANE WAVE MODELLING

A third-generation spectral wave model, SWAN (Booij et al. 1999) is employed to hindcast the resultant wave fields as Hurricane Gustav passed over the GOM. SWAN solves the spectral action balance equation without any a priori restrictions on the spectrum for the evolution of the wave field. This equation represents the effects of spatial propagation, refraction, shoaling, wave generation, wave dissipation and nonlinear wave-wave interactions. The reader is referred to the SWAN User Manual and Scientific and Technical Documentation (http://www.swan.tudelft.nl) for details of the model.

### Model Setup

In order to improve the resolution near the Louisiana coast, two computational domains (see Fig. 1) are setup for nested modeling. The rectangular gulf-scale domain (593×477) which covers the whole GOM has a resolution of $0.0271^0$ (about 3 km). The grid spacing for the local domain (575×500) is 400 m. The boundary conditions of the local domain are wave spectra interpolated from the gulf-scale domain. The non-stationary mode of SWAN in spherical coordinates is used. Thirty nine exponentially spaced frequencies from 0.024304 Hz to 1 Hz with 36 evenly spaced directions (10° resolution) for a time step of 15 min are utilized for both domains. The nonlinear saturation-based white-capping method (Westhuysen et al. 2007) combined with the wind input of Yan (1987), instead of the default white-capping formulation (Komen et al. 1984), is chosen. The differences between these two formulations in 1-D spectra will be discussed later in this paper. Other parameters use default values in the model. The water lever change is considered by a storm surge model, ADCIRC (Luettich et al., 1992). Both wave and surge models are driven by the verified hurricane wind field merged with the background winds. The simulation time is 5 days from August 29 to September 3, 2008. The program runs parallel on a supercomputer from the Louisiana Optical Network Initiative (LONI), Queenbee, which has 668 nodes and each node has two 2.33 GHz Quad Core Xeon 64-bit Processors and 8 GB Ram. By using 40 nodes (320 cores), the simulations for both domains can be finished within one hour.

**Model Results**

Comparisons of modeled and measured waves at four offshore buoys are shown in Fig. 4. It is seen that the modeled wave heights agree well with the observations, except for small discrepancies at buoys 42001 and 42036. For large wave heights (greater than 5m at buoys 42003 and 42004), which were generated by Hurricane Gustav, the model reproduces the measurements very well. In term of dominant wave direction and peak wave period, the agreement is also quite good. These indicate that the wave model performs well in deep waters with the validated wind input.

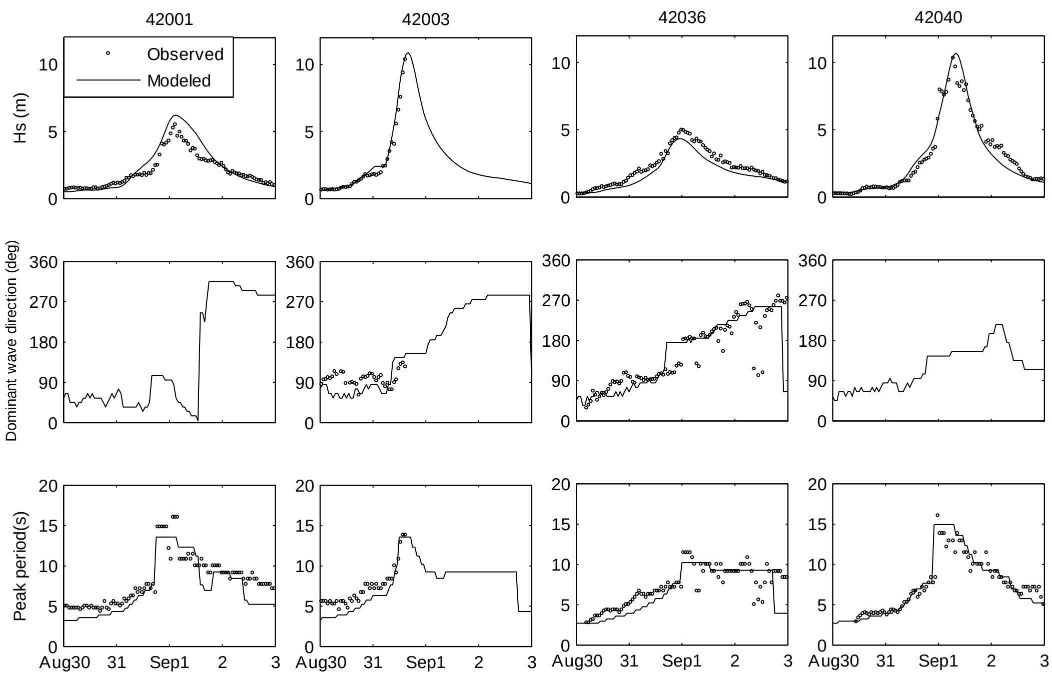


**Figure 4. Comparisons of modeled significant wave height (Hs), dominant wave direction and peak wave period with measurements at four offshore buoys for Hurricane Gustav. Circles and solid lines denote observed data and model results, respectively.**

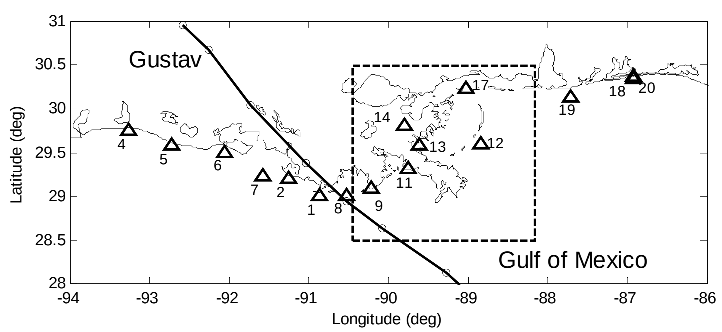


**Figure 5. Rapidly-deployed wave gages (triangles) along the Louisiana and adjacent coast during Hurricane Gustav. Thick solid line denotes the hurricane track. Dashed rectangle shows the nested local domain.**

Modeling hurricane-generated waves in shallow water are more complicated than in deep water because not only the hurricane winds, but also coastal landscapes and wave-surge interactions affect the model results. Observations are crucial to test the wave model. During Hurricane Gustav, 20 short-term wave gages were deployed along the Louisiana and adjacent coast to measure waves and surge (Kennedy et al. 2010). The data were successfully recovered at 16 gages (see Fig. 5). The comparisons of modeled surface elevation and significant wave height with the measurements at four wave gages are shown in Fig. 6. It is seen that the storm surge at those nearshore locations ranged 2~3.5 m and the ADCIRC results agrees with the measurements except for an underestimation at Station 13. Using the output of water levels from ADCIRC as an input to SWAN, the modeled significant wave heights agree fairly well with the observation. The maximum wave height at Station 9 is higher than those at other three stations because Station 9 is very close to the hurricane center. The results with no water level changes show that storm surge has a considerable effect on the development of waves in shallow water. The modeled wave heights diminished at all four stations, especially at Stations 11 and 13, if no surge was included. The accuracy of the modeled water level change caused by a hurricane influences the accuracy of hurricane wave modeling in shallow water.

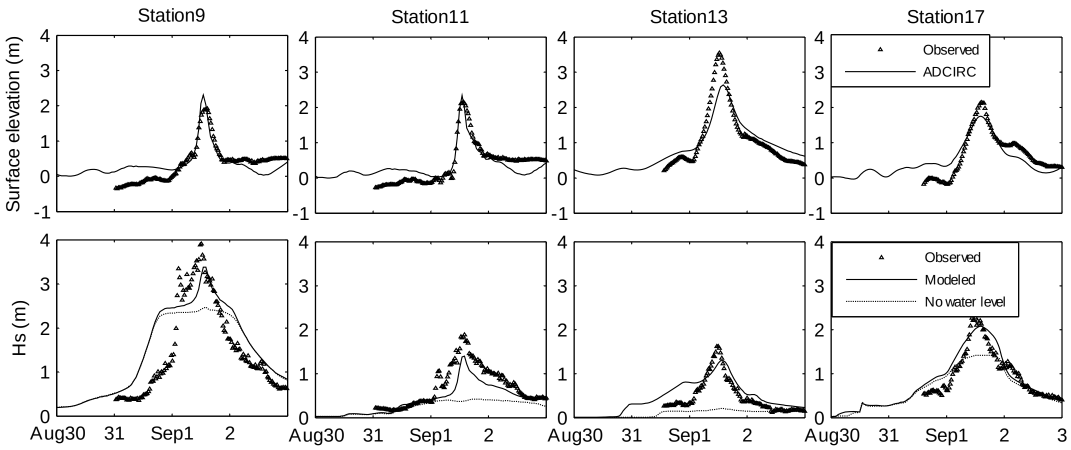


**Figure 6. Comparisons of modeled and observed surface elevations and significant wave heights at four nearshore wave gages during Hurricane Gustav. Triangles: observed; Solid lines: modeled; Dashed lines: modeled without storm surge.**

Comparisons of the modeled and measured wave spectra at offshore buoys are shown in Fig. 7. The model results of two different white-capping formulas, namely the nonlinear saturation-based (NSB) method (Westhuysen et al. 2007) and the default formulation in SWAN (Komen et al. 1984), are also presented for comparison. The location of hurricane center at different times is shown in Fig. 1.

At 14:00 UTC on August 31, 2008, Hurricane Gustav was located close to buoy 42003, which resulted in very high waves near the buoy station. The peak frequency was lower than 0.1 Hz and the spectrum was dominated by hurricane-generated seas with an inverse wave age of 1.25. The NSB result agrees well with the observation, while the default white-capping underestimates the spectrum peak. The spectrum at buoy 42007 was local wind-sea dominated because the hurricane center was still far away at that time. Both NSB and default methods give similar results at buoy 42007. The measured spectrum at buoy 42039 shows that the peak frequency was between 0.1 Hz and 0.2 Hz, and the inverse wave age was 1.41. The NSB result significantly overestimates the low frequency waves. For buoy 42056, the hurricane had already passed by. The spectrum there shows bimodal with mixed large swell and small wind sea. Both results show good agreement with the observation of swell energy, but the NSB method underestimates the wind sea while the default white-capping overestimates.

At 03:00 UTC on September 1, 2008, as the hurricane moved closer to buoys 42001, 42007, 42039 and 43040, the spectra at buoys 42001 and 42007 were swell-dominated while the other two were hurricane wind seas. Overall, the NSB method gives better results than does the default method. The default white-capping tends to understate the low frequency waves and overestimate the wind seas, which is consistent with the conclusion in Westhuysen et al. (2007). Fig. 7c shows the results after Hurricane Gustav made landfall. The spectra at buoys 42001, 42039 and 42040 are similar to those in Fig. 7b but with smaller energy. The observed spectrum at buoy 42035 was bi-modal with two distinct peaks of swell and wind sea. The NSB result agrees well with the measured swell energy but underestimates the wind sea, which could be caused by errors in the background winds. By contrast, the default method reproduces the observed wind sea very well but underestimates the observed swell.

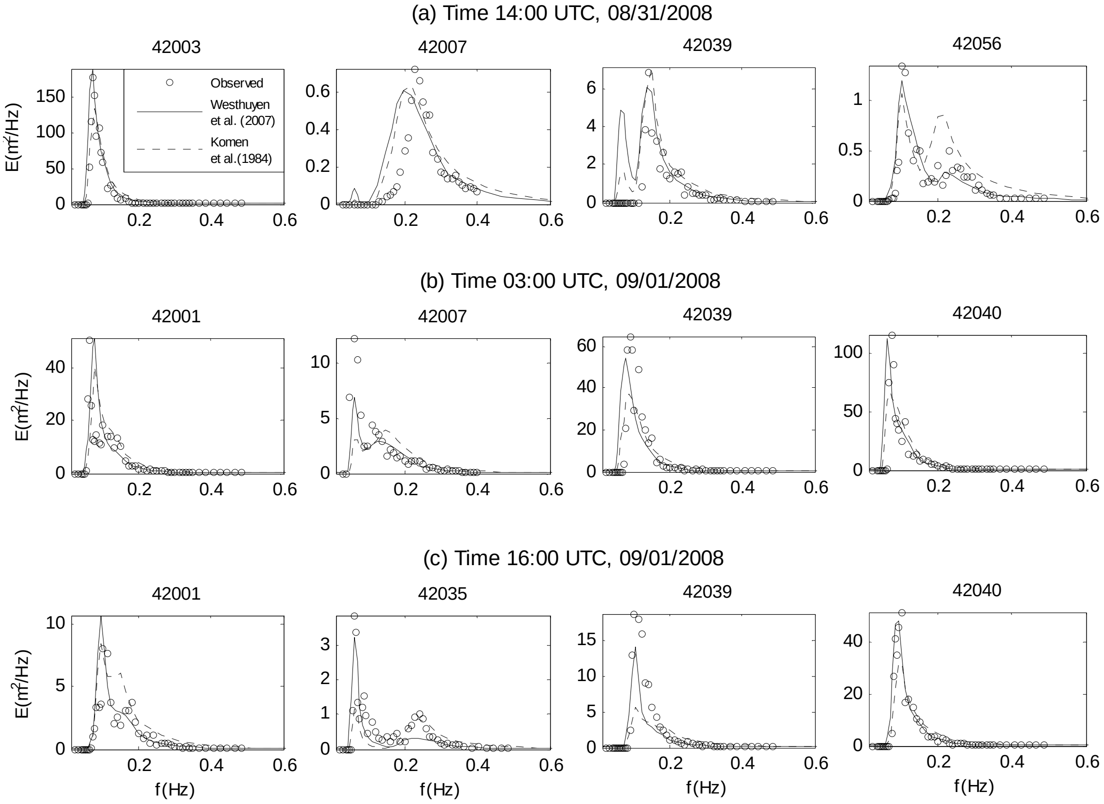


**Figure 7. Comparisons of modeled and measured energy density spectra at three instants during Hurricane Gustav. Circles: observations; Solid lines: results using Westhuysen et al.'s (2007) white-capping; Dashed lines: results using Koman et al.'s (1984) white-capping.**

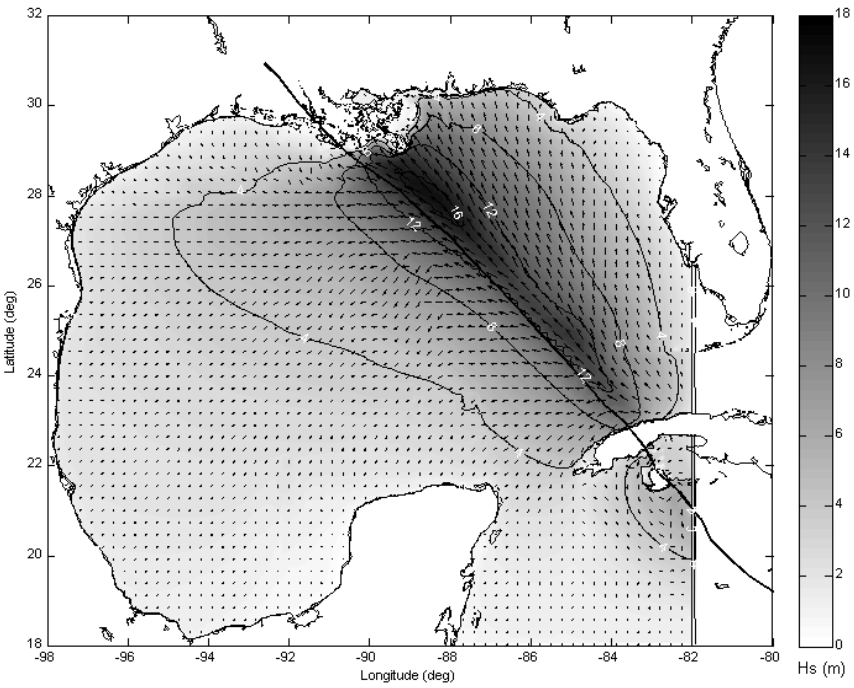


**Figure 8. Distributions of modeled maximum significant wave height (contours) and corresponding dominant wave direction (arrows) in GOM during Hurricane Gustav. Thick solid line denotes the hurricane track.**

Figure 8 depicts the spatial distributions of the modeled maximum significant wave height and the corresponding dominant wave direction in the GOM. It can be seen that due to the asymmetry of the hurricane winds and the forward translation of the hurricane center, near the hurricane track, wave heights on the right side of the track were larger than those on the left side. The maximum wave height in the GOM generated by Hurricane Gustav was about 16 m. In deep water, hurricane-generated waves diminish with the increase of distance from the track. In shallow water, such as the Louisiana coast, the continental shelf and barrier islands dissipate the majority of wave energy due to wave breaking and bottom friction. Along the track, the dominant wave direction on the right side where the maximum hurricane wind speed occurs is parallel to the moving direction of the hurricane center. The wave direction deviates gradually from the hurricane moving direction as the distance from the track increases.

## CONCLUSIONS

An improved parametric hurricane wind model has been developed and used to force wind wave and storm surge models with high resolution. Three improvements have been made to ensure the consistency between the input parameters from the hurricane forecast and the wind model output. The good agreement with observed winds at offshore buoys and coastal stations shows that the improved wind model produces reliable hurricane winds. The results without those improvements overestimate the maximum wind speeds and exaggerate the asymmetry of a tropical cyclone.

The spectral wave prediction model, SWAN, was applied to the entire Gulf of Mexico with a 3km resolution to model hurricane-generated waves. Nesting computation is used to increase the resolution near the Louisiana coast to 400m. The use of a high-performance computer with several hundred processors significantly speeds up the simulations. Forced by the verified hurricane winds and hindcasted water level changes from the storm surge model, ADCIRC, the SWAN wave model performs fairly well in comparison to the measured wave heights and periods in both deep and shallow waters except a few locations with complex bathymetry and landscape.

In addition to the hurricane wind field that controls the accuracy of wave modeling in deep water, wave-surge interaction also plays an important role in wave modeling in shallow water. The wave spectral comparisons show that the white-capping formulation of Westhuysen et al. (2007) generally outperforms the default formulation of Komen et al. (1984) in SWAN under hurricane conditions. An exception at buoy 42039 (Fig. 7b), however, warrants further testing. The model result indicates that the asymmetry of hurricane winds and the hurricane translation result in the maximum wind waves occurring on the right side of the hurricane track and propagating in the direction parallel to the hurricane translation direction, consistent with field observations.

## ACKNOWLEDGMENTS

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