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Improving the accuracy of hurricane wave modeling in Gulf of Mexico with dynamically-coupled SWAN and ADCIRC

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ABSTRACT

Dynamically-coupled SWAN and ADCIRC models have been applied to enhance the predictions of extreme waves and storm surges induced by hurricanes and sea level rise (SLR) in the Gulf of Mexico. The model performance was evaluated using Hurricane Michael, a Category-5 hurricane, as a case study. Modeled wave heights were compared to the observations. Results indicate that the dynamically-coupled SWAN-ADCIRC models substantially enhance the modeling accuracy. By comparing to the maximum observed 2.69 m of wave height near the hurricane landing site, the error is 0.04 m by the SWAN-ADCIRC models in comparison to the 0.39 m by the SWAN stand-alone simulation. Effects of sea level rise on hurricane wave heights were investigated under four SLR scenarios of 0.2m, 0.5m, 1m, and 1.5m. Results indicate that, as sea level rises, wave heights increase non-linearly in shallow waters near the hurricane landing site. At the wave observation station near the hurricane landing site, the ratio of the wave-height change to SLR increases to 117% and the ratio of the combined wave-surge change to SLR increases to 265%. Analysis indicates that this is due to the substantial percentage changes in water depth occurring in shallow water compared to deep water caused by SLR.

1. Introduction

Coastal areas around the world are frequently affected by weather related hazards like tropical cyclones, resulting in significant loss of life and other assets. Among coastal hazards, hurricanes and tropical storms take the largest share of the economic burden in the USA. Both coastal development and an increase in the frequency of hurricanes exacerbate the damage costs (Dinan, 2017). Damages due to hurricanes and tropical storms are attributed to high winds and surging of water on-shore and further, called wind and water damage, respectively (Baradaranshoraka et al., 2017). Water damage is due mainly to storm surge, an abnormal rise in water level as hurricane winds push more and more ocean water on shore. A spectrum of water waves generated by the highly turbulent winds also contributes to the damaging effects of storm surge. More importantly, long term factors such as sea-level rise (SLR) affect the storm surge along coastal zones nonlinearly (Wang and Yang, 2018). Accurate quantification of storm surge and high-frequency waves, either for forecasting or hindcasting, is necessary to effectively minimize the cost of a hurricane (Martinez, 2020). An accurate forecast helps coastal communities to plan and execute mitigation actions against an impending storm while post-storm analyses enable a better understanding of the characteristics of coastal inundation and manage future disasters effectively.

Numerical models are extensively used in forecasts, hindcasts and long term analyses (Yang et al., 2015); (Bilskie et al., 2020). Disaster management agencies at federal and state levels use numerical models to delineate hazard zones depending on the possible extent of damage due to a hurricane. For example, FEMA uses results from numerical models to draw flood zones based on the return period of storms. A 100-year flood zone has a 1% probability of being flooded every year (Horn and Brown, 2018). The flood zones are divided into zones AE and zones VE (E stands for Elevation) which provide information about the probable floodwater elevation as well (Fig. 1). Zone AE corresponds to areas with a 1% chance of flooding every year with base flood elevations estimated by hydraulic analysis. In Zone VE, there is a 1% chance of occurrence of waves with significant wave heights of 3 ft or more in a given year in addition to the base flood elevations. In other words, high-risk zones such as VE and AE are delineated based on significant

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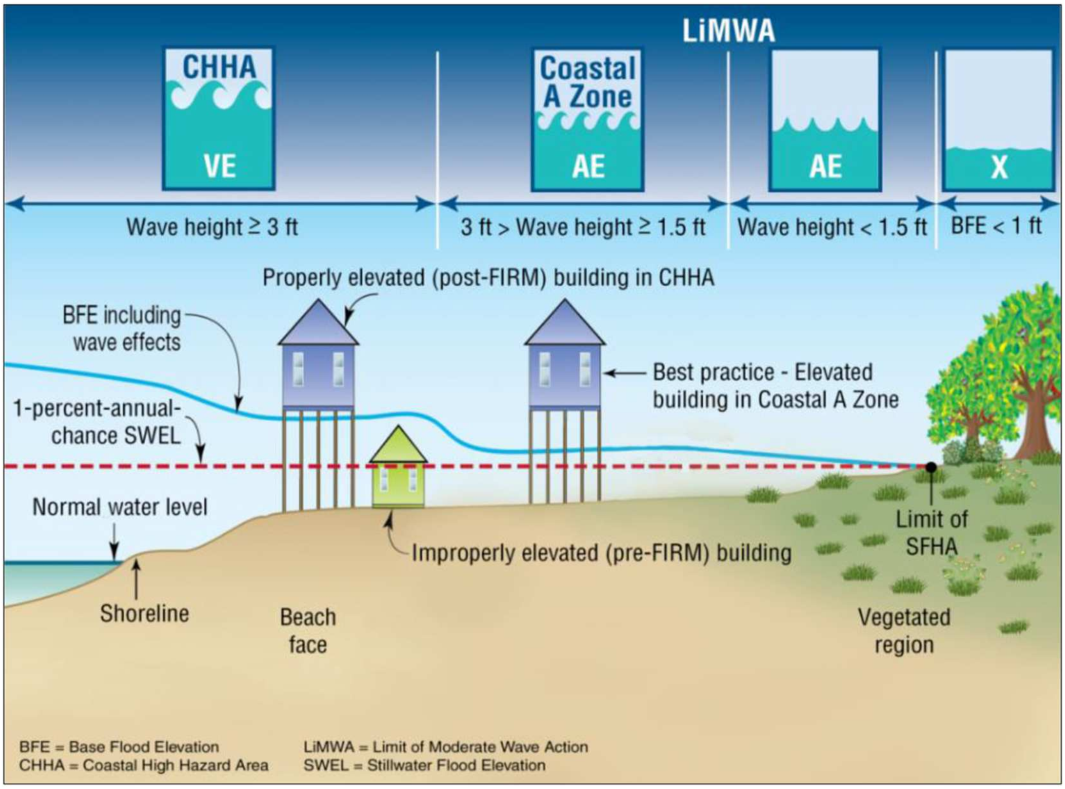

Fig. 1. Wave height used as an important factor by FEMA to determine flood hazard zones (Horn and Brown, 2018).

wave height, in addition to the probable storm surge water level, both estimated from models. The significant wave height (Hs) defined as the average amplitude of the highest 1/3 waves of a spectrum(Horn and Brown, 2018), significantly contributes to the water damage during storms.

Hurricane winds create waves of varying spatial scales and frequencies in the ocean. Storm surge and tidal waves are of long period (or low frequency), whereas surface gravity waves, like swells, are of high frequency (Cavaleri et al., 2012). There are many studies on storm surges (e.g. (Wang and Shen, 2011); Park et al., 2014; Vijayan et al., 2021). **ADCIRC** (ADvanced CIRCulation), is a popularly used storm surge model (Luettich et al., 1992), which solves discrete differential equations of momentum and continuity for a physical domain. Many studies have proved the reliability of ADCIRC in modeling storm surge, both in terms of performance and accuracy (Marsooli and Wang, 2020) (Reffitt et al., 2020).

Hurricane-induced waves change their characteristics such as amplitude, speed, and direction as they propagate from the open ocean to shallow waters near shore (Guisado-Pintado, 2020). In other words, they reflect, refract or break depending on the near shore topography and slope. Additionally, waves interact with each other and with currents non-linearly. **SWAN** (Simulating WAves Near shore) is a spectral wave action model that can simulate such near shore dynamics of the waves (Booij et al., 1999). Under non-hurricane conditions, SWAN wave models have been applied to many studies for ocean wave modeling (Sebastian et al., 2014; Umesh et al., 2021; Yang et al., 2015). However, during a hurricane, storm surge can cause changes in currents and water depth, which can in-turn cause the changes in significant wave heights. Wang and Shen (2011) have demonstrated the enhancement in accuracy of a dynamically coupled wave-current model for wave predictions.

Traditionally, ADCIRC and SWAN are two separate models and are not dynamically coupled. FEMA has used significant wave height to delineate coastal flood zones, which requires more accurate predictions of extreme waves during hurricanes. A recent FEMA report indicated that simulated wave heights by traditional wave models alone have large errors, which show the need for coupling wave and storm surge modeling to improve wave prediction (FEMA, 2020). A coupled model of ADCIRC and SWAN can give both storm surge water elevations and wave action parameters. When ADCIRC and SWAN are dynamically coupled, both models can use the output from the other for dynamic model calculations. Additionally, model derived hazard zones used by disaster management agencies do not change with track changes of a hurricane, resulting in complications in evacuation efforts within a short time frame (Senkbeil et al., 2020), as it happened during hurricane Irma of 2017 in Florida as given in the Mitigation Assessment Team Report ("Mitigation Assessment Team Report: Hurricane Irma in Florida," n.d.). In short, the effects of water waves of higher frequency are not properly accounted for in delineating hazard zones due to a hurricane, which are derived from models. The first aim of this study is to validate the SWAN part of the coupled ADCIRC + SWAN model by comparing the modeled significant wave heights and the observations, during Hurricane Mitigation Assessment Team Report: Hurricane Irma in Florida as a case study.

The model study by (Wang and Yang, 2018)), showed that sea level rise can amplify the storm surge height non-linearly, as much as 100%. There are not many studies assessing the response of significant wave heights to SLR. Therefore, the effect of increase in sea level on storm surge water levels and significant wave heights modeled using ADCIRC + SWAN is investigated here. Four SLR scenarios were used to understand the response of storm surge water levels and significant wave heights induced by a hurricane like Michael. As the impacts of SLR are more pronounced in the coastal areas, the SLR scenario study is focused on stations located in zones AE and VE of the region close to the landfall location of Hurricane Michael.

In the coupled ADCIRC + SWAN model, a single shared executable program runs both models (Santiago-Collazo et al., 2019). The modeled data is dynamically interchanged between ADCIRC and SWAN (Dietrich et al., 2011). There has been an increasing number of studies using the

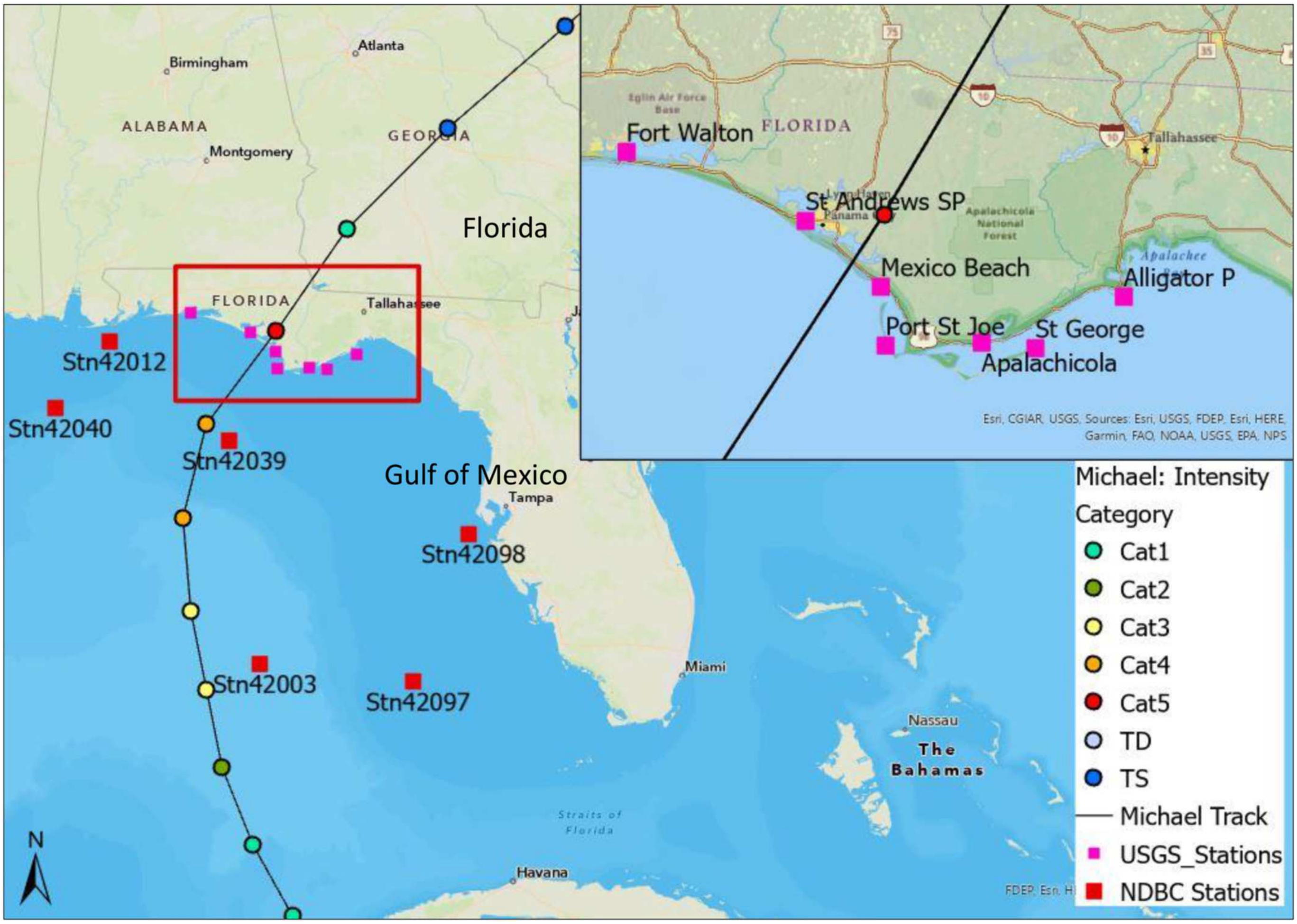

Fig. 2. Path of Hurricane Michael in 2018 in Gulf of Mexico and Florida coast. NDBC offshore and USGS on shore sensor stations in the Gulf of Mexico.

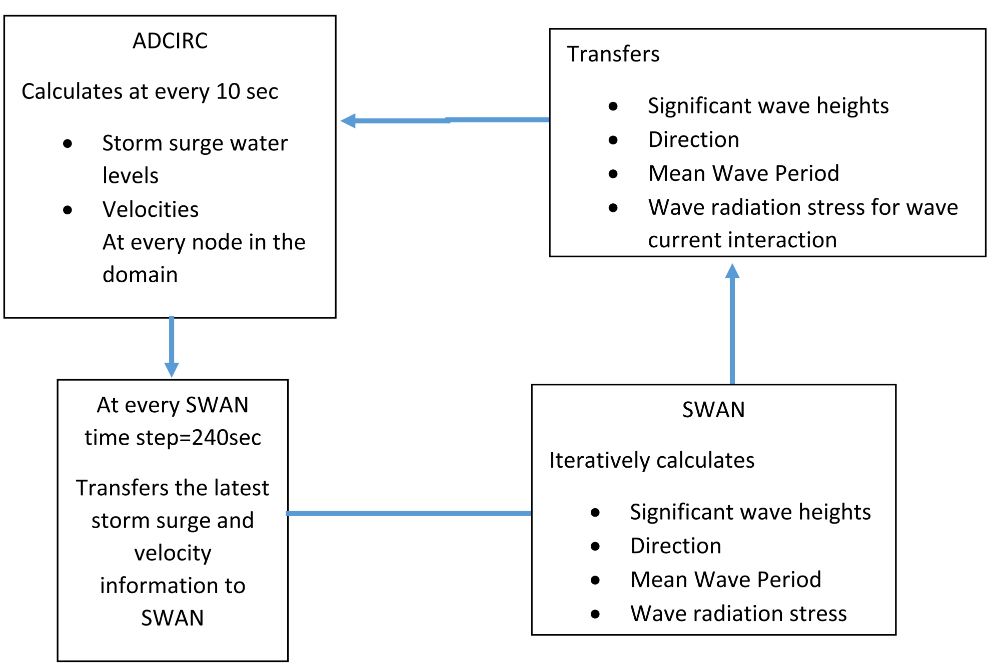

Fig. 3. Schematic of the data exchange between the dynamically coupled ADCIRC and SWAN models based on Dietrich et al. (2011).

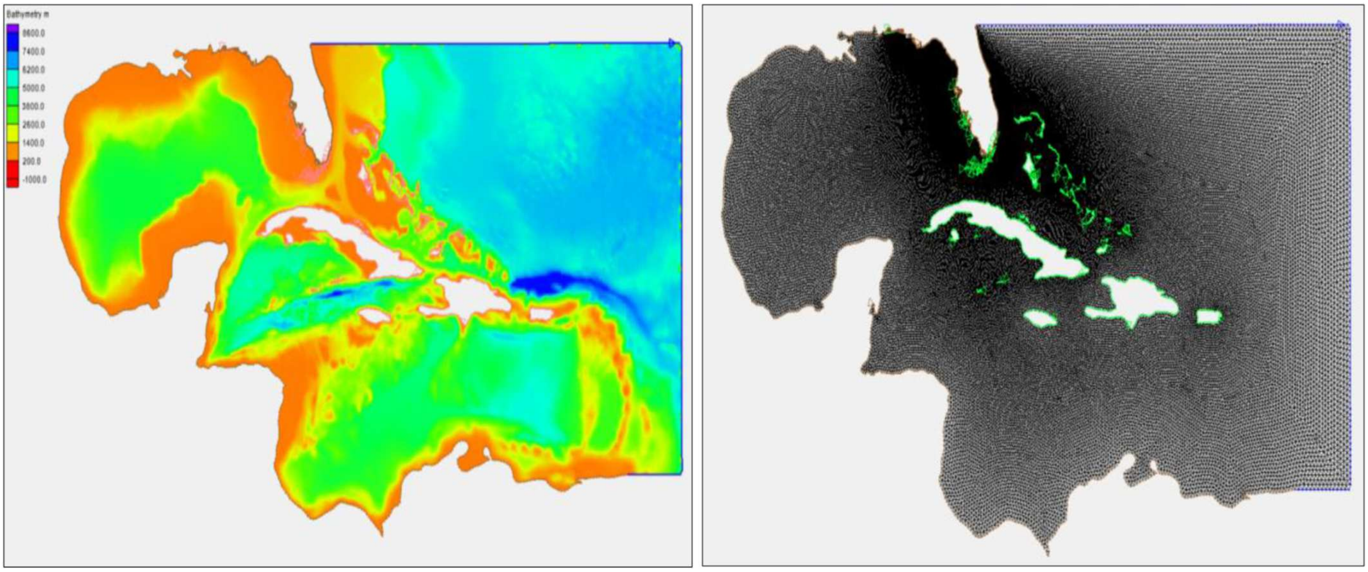

Fig. 4. Bathymetry (left) and triangular model mesh (right) for model computational domain.

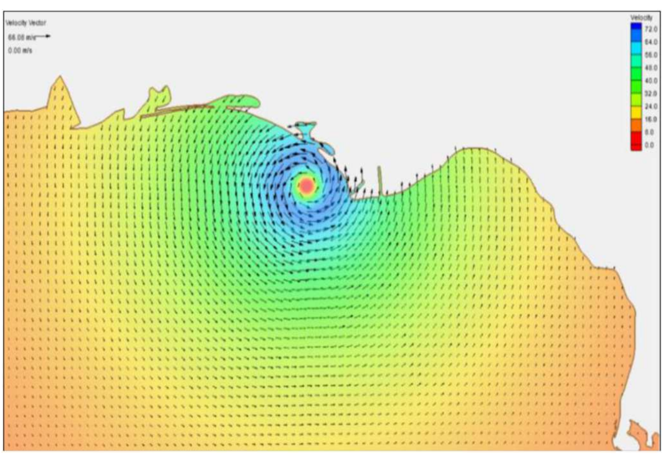

Fig. 5. Symmetric wind field based on Holland (1980), using 64 kt wind radius for parameter estimation at 5pm UTC October 10, 2018.

coupled ADCIRC + SWAN such as (Dietrich et al., 2012; Sebastian et al., 2014). Recent studies used the coupled model to study the long term effects of sea level rise (Bilskie et al., 2016) and sedimentation (Siverd et al., 2019) on storm surge inundation. A long term hazard analysis using an ensemble of synthetic storms were conducted by (Wang et al., 2018a) and a study in the South China Sea analyzed the effect of typhoon intensity and size on inundation zones (Li et al., 2020). Zou and Xie (2016) used the coupled ADCIRC SWAN model to study the interaction between tides surge and wave during a post-tropical storm in the Gulf of Maine. Since the tidal variation in the Gulf of Mexico is small, it is expected that the interaction is limited in the domain of the present study. Most of the studies used the coupled model for post storm analysis, as it is computationally intensive and slower than the individual uncoupled models. In short, there are not many studies using the coupled storm surge and wave model ADCIRC + SWAN, that explicitly validates the wave part of a model using observed significant wave height values during a storm. Therefore, in this study, the accuracy in computing the significant wave height by the coupled ADCIRC + SWAN is compared with that of the uncoupled model (stand-alone SWAN) using observations of wave heights during Hurricane Mitigation Assessment Team Report: Hurricane Irma in Florida, and subsequently

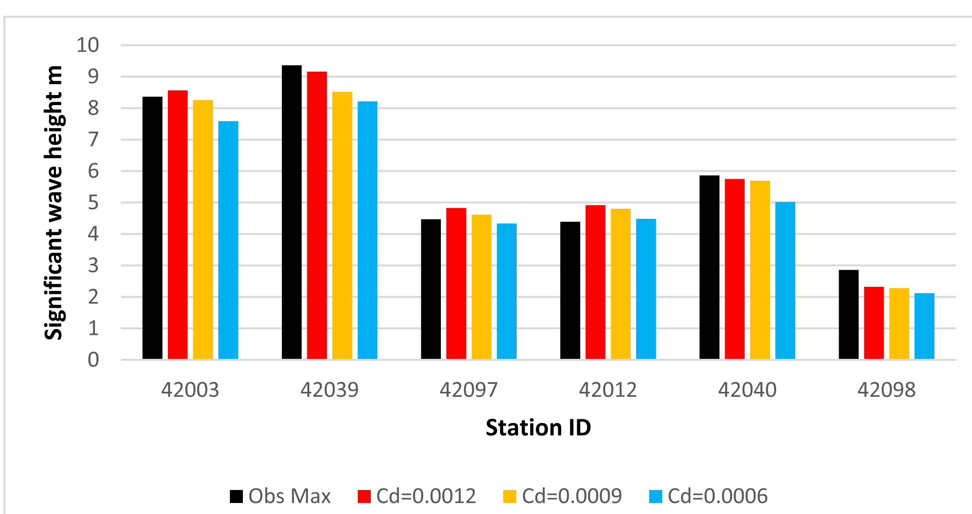

Fig. 6. Comparison of Maximum significant wave heights at offshore buoy locations.

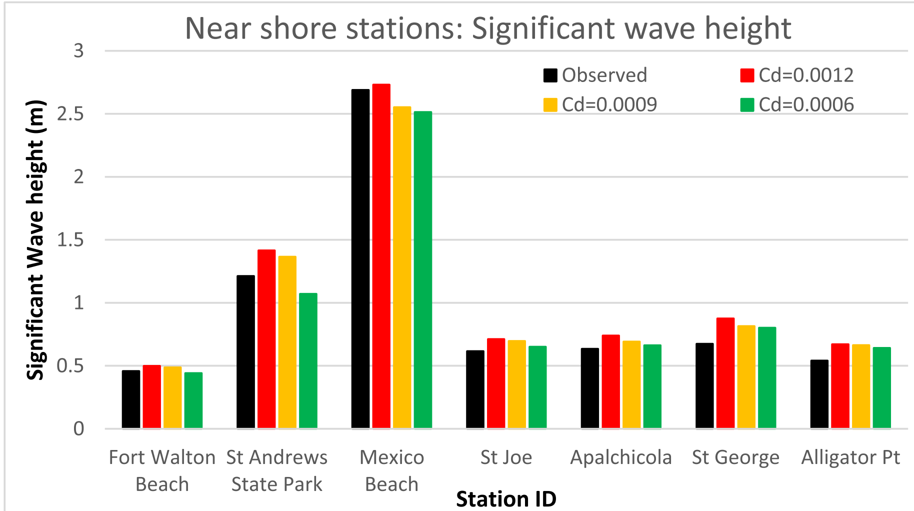

Fig. 7. Maximum significant wave heights at USGS on-shore stations.

Table 1
Comparison to observations of maximum significant wave height (Hs) by two different wave modeling approaches: a) dynamically coupled wave-surge model ADCIRC + SWAN; b) stand-alone wave model SWAN.

Station Name	Obs. Hs (m)	Coupled ADCIRC + SWAN Hs m	Stand Alone SWAN Hs m	Abs Error (m) ADCIRC + SWAN	Abs Error (m) Stand-alone SWAN
Fort Walton Beach	0.46	0.50	0.22	0.04	0.24
St Andrews	1.21	1.42	1.02	0.20	0.19
Mexico Beach (Hurricane landing)	**2.69**	**2.73**	**2.30**	**0.04**	**0.39**
St Joseph Bay	0.62	0.71	0.52	0.10	0.1
Apalachicola	0.63	0.74	0.22	0.11	0.41
St George Isl.	0.67	0.86	0.49	0.19	0.18
Alligator Pt	0.54	0.67	0.25	0.13	0.29
Stn42003	8.36	8.56	8.12	0.20	0.24
Stn42039	9.36	9.16	8.98	0.20	0.38
Stn42097	4.47	4.83	4.31	0.36	0.16
Stn42012	4.39	4.92	4.21	0.53	0.18
Stn42040	5.86	5.75	5.51	0.11	0.35
Stn42098	2.86	2.32	2.20	0.54	0.66
Root-mean-square error (RMSE) for all 13 stations				**0.26**	**0.32**

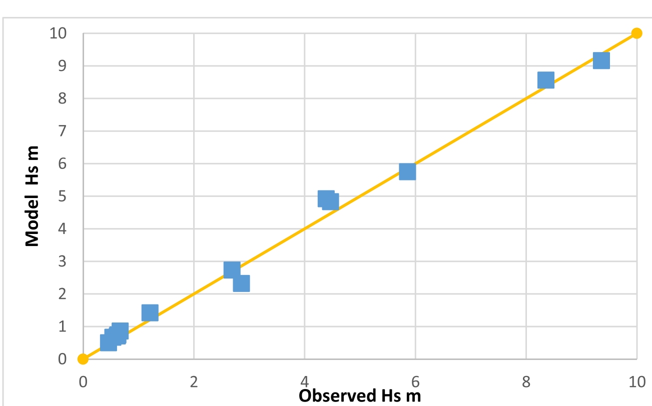

Fig. 8. Scatter plot of Observed and Modeled Hs at various stations.

assess the benefits of coupling the two models.

An important factor influencing the modeling of storm surge and wave heights is the wind field. SWAN model is sensitive to wind forcing and showed most accurate significant wave heights when observed winds were used compared to other reanalysis products (Wang et al., 2018b). Therefore, a symmetric hurricane wind-field parametrization is used in this study to force the coupled model.

There are many numerical wind field parametrization methods used to represent hurricane wind forcing (Akbar et al., 2017). Two simple symmetric wind field models frequently in use are (Holland, 1980; Holland et al., 2010). Both Holland models define wind field using two parameters namely radius of maximum wind (R_{max}) and the exponential shape parameter B to determine the radial profile of hurricane winds. The shape parameter B depends solely on the maximum wind velocity of a hurricane in the first method (Holland, 1980). On the other hand, the second model uses an empirical formula with a radial pressure gradient of the hurricane, a temporal change in the center pressure, latitude of the center, translation speed of the hurricane, sea surface temperature and the air temperature close to the sea level surface (Holland et al., 2010). Holland wind field parametrizations assume that the hurricane wind field is symmetric and therefore better suited for forecasts (Garzon et al., 2018; Murty et al., 2020; Torres et al., 2019).

The primary objective of this study is to evaluate the enhancement of wave modeling by the dynamically coupled SWAN-ADCIRC model. In a previous study of storm surge modeling of Hurricane Michael using ADCIRC (Vijayan et al., 2021), the Holland wind field parametrizations has been validated with observations during the Hurricane Michael event of 2018. The two parameters R_{max} and B are calculated using maximum velocity (V_{max}) and the radii where 64 kt wind speed is measured within the hurricane. The same wind field parametrization is used to assess the significant wave heights simulated by the coupled ADCIRC + SWAN and the stand-alone SWAN. The numerical model and its validation using observed significant wave heights during Hurricane Michael is introduced, followed by the effects of SLR on the increase of significant wave heights.

2. Numerical modeling method

2.1. Observation data

Waves are formed in the ocean due to the action of winds, the drag force being proportional to the square of wind velocity. The momentum transfer from wind to the ocean surface is a highly turbulent process and therefore, generates ocean waves that fall into a spectrum of wave-

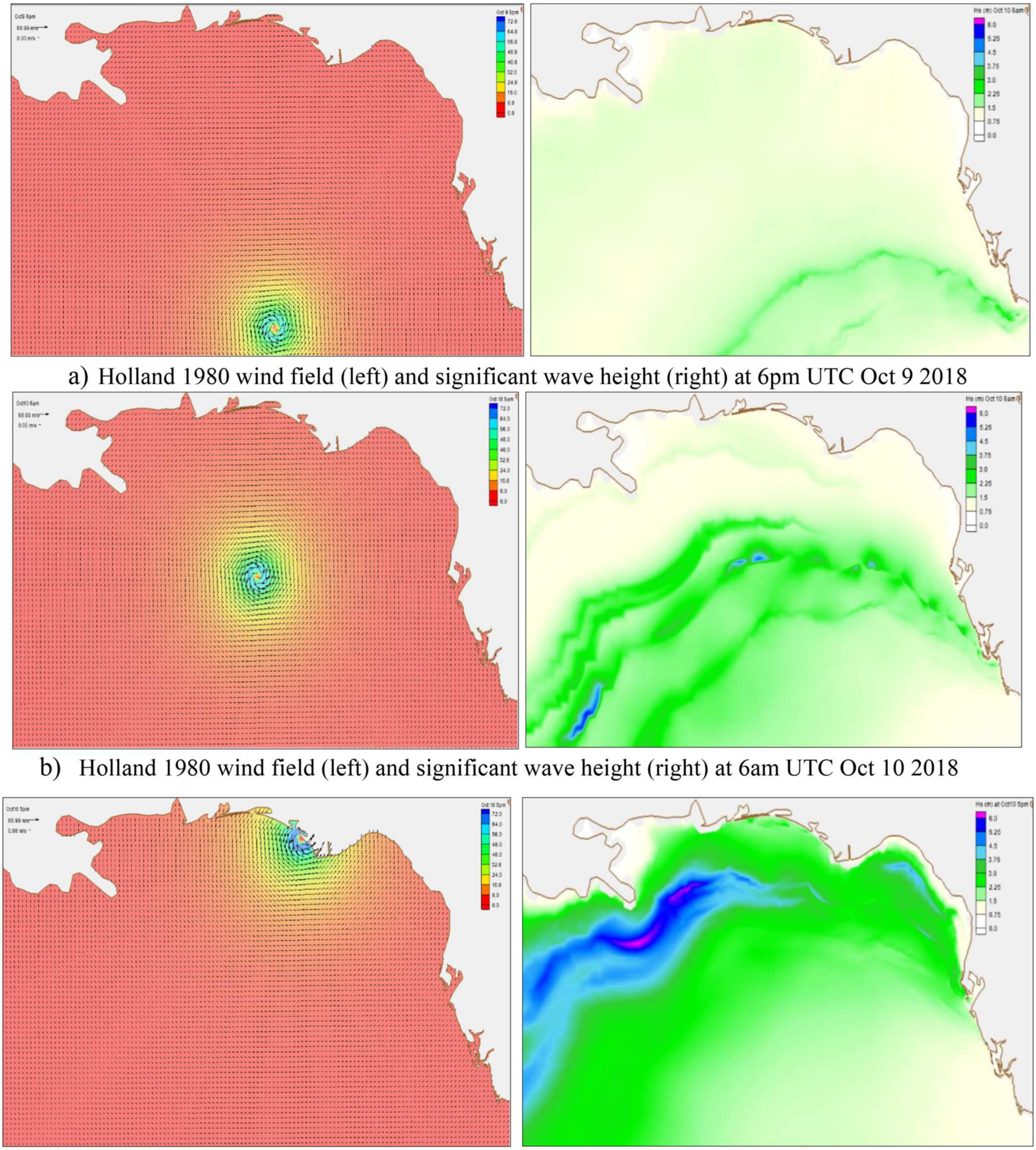

Fig. 9. Wind field and significant wave heights from coupled ADCIRC + SWAN modeling.

lengths. Wave's characteristics change when they propagate to the shore and enter shallow waters, such as an increase in wave heights. On shore, the low frequency waves contribute to storm surge water levels referred to as the Base Flood Elevation (BFE), as shown in Fig. 1. Higher frequency waves on shore enhance the effective water level due to the storm. A good way to estimate this fluctuating water level is using the significant wave height (H_S), which is defined as the average wave height of the highest one third of the waves in the wave spectrum. The wave spectrum approximately follows a Raleigh distribution (Park et al., 2014). Hs is determined by the formula

$$Hs = 4\sqrt{\sigma^2} \tag{1}$$

where σ^2 is the variance of the wave height spectrum for a given time

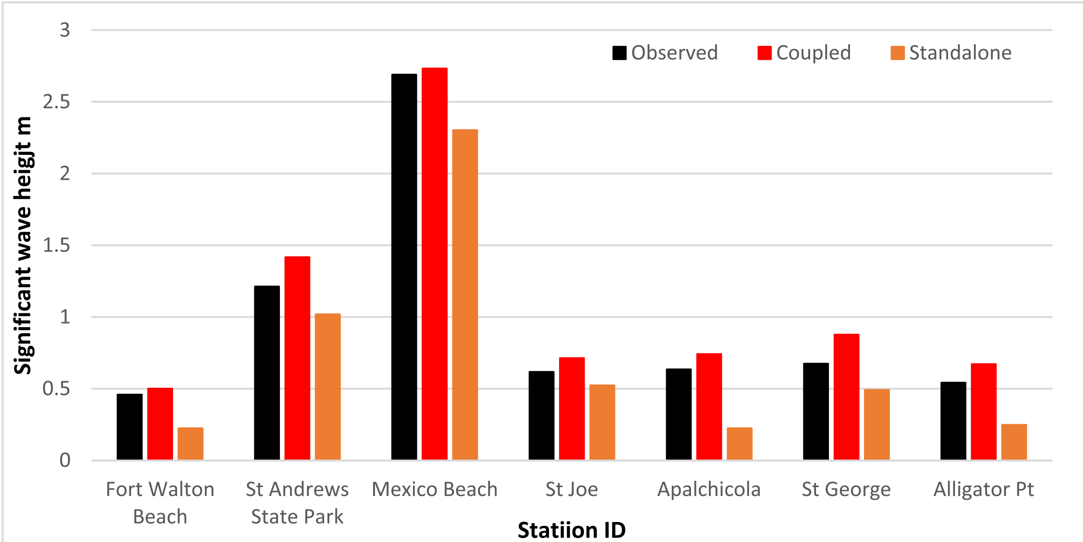

Fig. 10. Comparison with observations to show the enhancement of hurricane wave modeling by dynamical coupling of ADCIRC + SWAN.

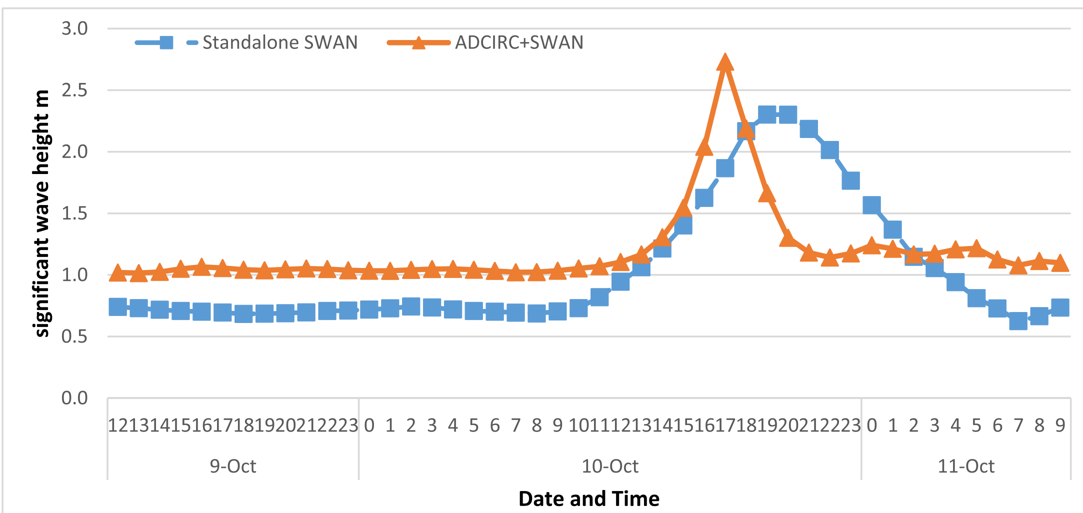

Fig. 11. Time series comparison of significant wave heights at Mexico Beach from Coupled ADCIRC + SWAN and SWAN stand-alone models.

period.

$$\sigma^2 = \sum_{f_l}^{f_u} S(f) * d(f) \tag{2}$$

where S(f) is the spectral density of a given frequency band of width d(f), f_l and f_u are the lowest and highest frequencies of the full spectrum.

Significant wave height and other wave characteristics due to a storm are difficult to measure directly, and as a result, the availability of data is limited. The National Data Buoy Center (NDBC) maintains a data center that provides time series observations and spectral data of various oceanographic measurements mainly in the US coastal waters. Fig. 2 shows the position and labels of the buoys in the Gulf of Mexico. Many buoys in the area do not provide significant wave height measurements and some others failed to work during Hurricane Michael due to the severity of the storm. Only six buoys highlighted in Fig. 2 have significant wave height data for offshore buoys during the period of October 7–12, 2018, near Hurricane Michael's track.

Because NDBC buoys along Florida Panhandle coast that are close to the shore, did not have significant wave height or spectral wave density data during Michael, data from United States Geological Survey (USGS) water level sensor stations very close to the shoreline were also used in this study. Fig. 2 also shows the sensor locations that provide unfiltered time series of water levels. Significant wave heights are calculated multiplying standard deviation (σ) of time series water level data using a modified formula $Hs = 1.62 * 4\sqrt{\sigma^2}$ (Park et al., 2014). In short, offshore data are from three NDBC buoys and onshore data extracted from USGS water level sensors are used as observations in this study. Inset in Fig. 2 shows the focus area of Mexico Beach, where Hurricane Michael caused maximum destruction and the locations of USGS water level sensors in the area.

2.2. Model setup

SWAN is a near-shore spectral wave model that numerically solves the wave action equation and calculates wave characteristics due to the wind action. SWAN employs an implicit time stepping scheme and calculates the wave parameters such as significant wave height, wave period and direction, iteratively. Wave radiation stress and gradients are also computed. ADCIRC on the other hand, is a hydrodynamic model that uses an explicit time-stepping scheme making it conditionally

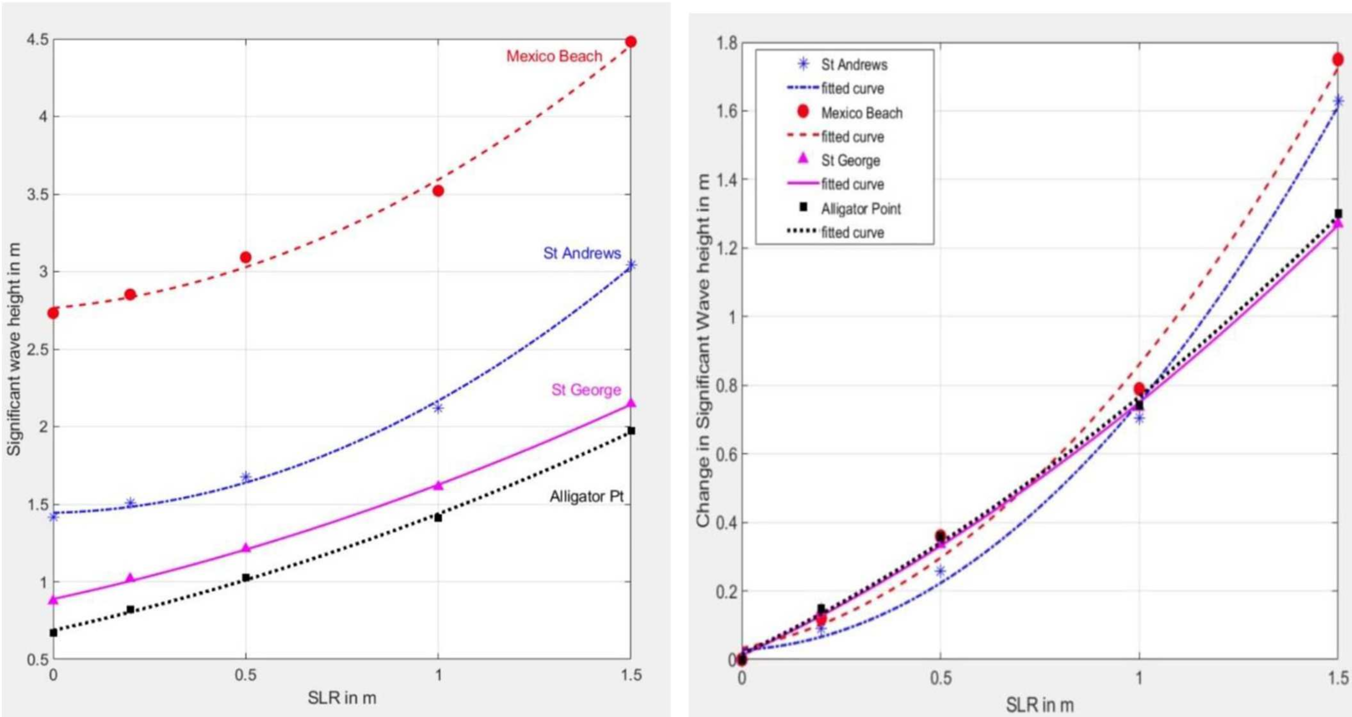

Fig. 12. a) Maximum Hs vs SLR, b) Change in Maximum Hs vs SLR.

Table 2
Regression equations of significant wave height and SLR under Hurricane Michael.

Station		Significant wave height Hs (m)	
		Abs	Change
St Andrews	Polynomial	$0.66x^2+0.05x+1.45$	$0.66x^2+0.05x+0.02$
	R	0.994	0.994
Mexico Beach	Polynomial	$0.6x^2+0.22x+2.76$	$0.6x^2+0.22x+0.03$
	R	0.988	0.988
St George	Polynomial	$0.2x^2+0.54x+0.89$	$0.2x^2+0.54x+0.01$
	R	0.998	0.998
Alligator Point	Polynomial	$0.20x^2+0.55x+0.68$	$0.2x^2+0.55x+0.01$
	R	0.997	0.997

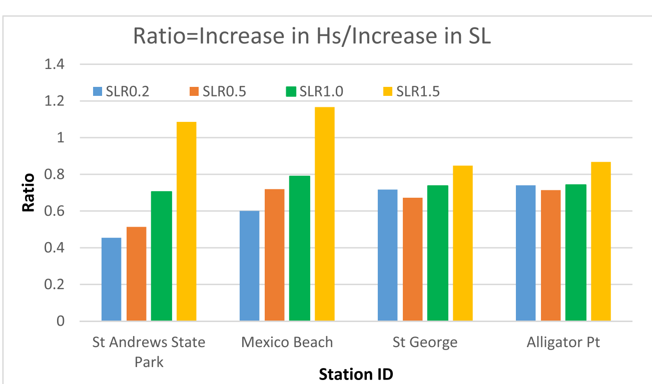

Fig. 13. Ratio of increase in Hs to increase in sea level.

stable. This sets a limitation to the time step size: higher resolution mesh needs lower time step size.

Hurricane wind fields for the 5 days are prepared using the symmetric Holland parametrization (1980). Wind fields are generated using the 64 kt wind radii and maximum wind speed obtained from NOAA HURDAT2 data archive. Calibration and validation of the wind field due to hurricane Michael is described in (Vijayan et al., 2021). Storm surge heights were the most accurate using this wind parametrization and therefore the same wind field is used here as well. First, sensitivity of the SWAN model in calculating significant wave heights applying the same wind field to a coupled ADCIRC + SWAN model is assessed. The parameters for ADCIRC are not modified here with the intention of minimum effect on the storm surge calculations. The maximum significant wave height recorded on these stations during Hurricane Michael are compared with the model simulations.

2.3. SWAN model description

SWAN is a spectral wave model working on the wave action balance equation. The wave action density is defined as $N=\frac{E}{\sigma}$ where E is the spectral energy which is a function of σ the frequency and θ, the propagation direction. The wave action balance is

$$\frac{\partial N}{\partial t}+\nabla.\left[\left(C_g+U\right)N\right]+\frac{\partial C_\sigma N}{\partial \sigma}+\frac{\partial C_\theta N}{\partial \theta}=\frac{S_{tot}}{\sigma} \tag{3}$$

S_{tot} on the RHS of equation (3) is the source/sink term, representing wave energy generation, dissipation and modification of wave energy. SWAN estimates S_{tot} using the formula $S_{tot}=S_{in}+S_{NL}+S_{wc}+S_{br}+S_{fr}$ where S_{in} is the wave growth by wind, S_{NL} is the transfer of energy due to non-linear interactions. The last three terms represent energy dissipation due to white capping, breaking and bottom friction respectively. S_{in} due to wind is calculated based on equation (4).

$$S_{in}=A+BE(\sigma,\theta) \tag{4}$$

where A is a linear growth term and B is an exponential factor, both functions of the friction velocity of the wind U_*

The wind field input to the model is given as U_{10}, the velocity at a height of 10m from the sea surface. But $U_*^2=C_dU_{10}^2$ where C_d is the coefficient of drag. In this study, three values of Cd are applied to evaluate the sensitivity of significant wave height to C_d. In short, maximum significant wave heights obtained by changing various

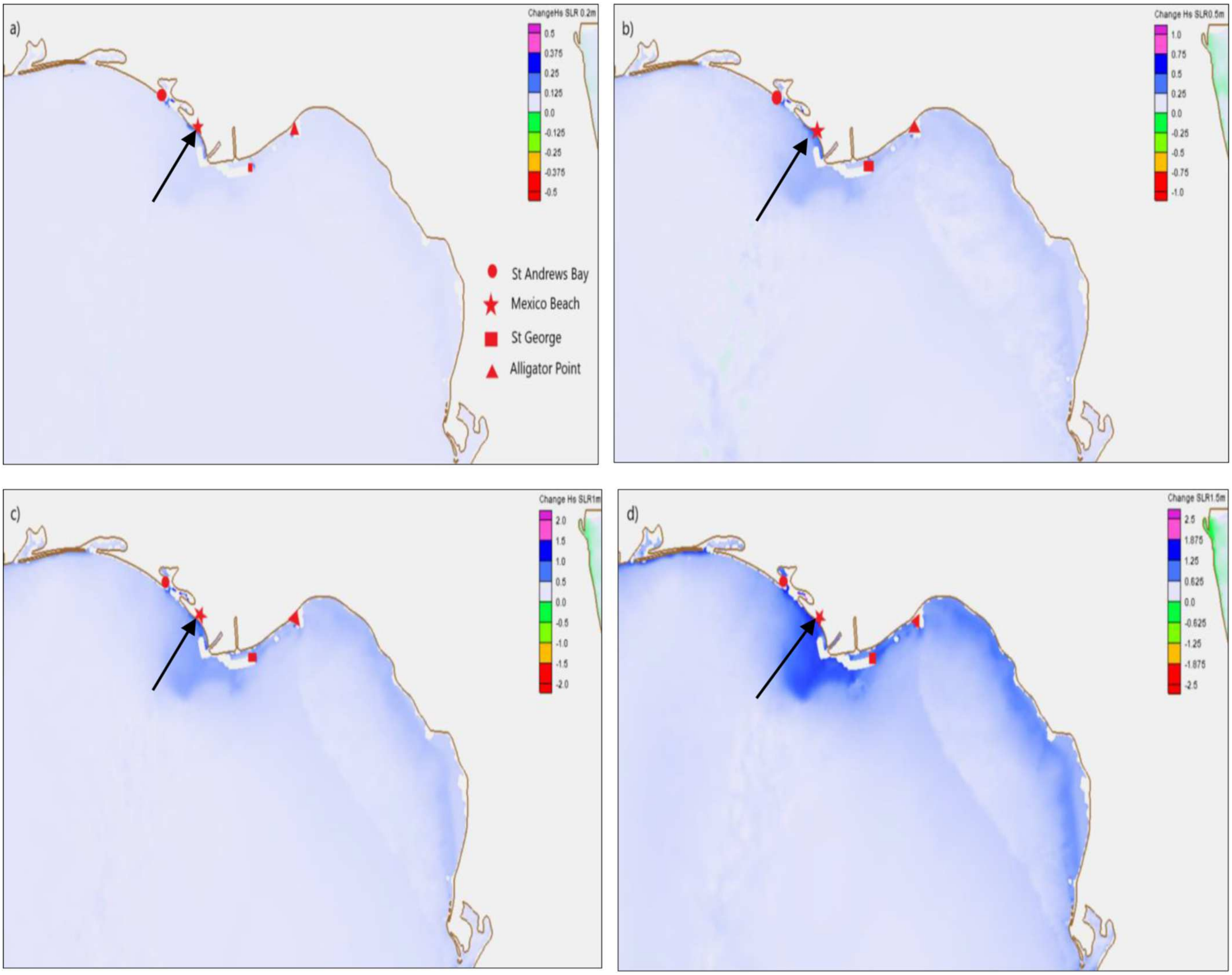

Fig. 14. Increase in Hs (m) from the baseline Hurricane Michael condition under different sea level rise scenarios: a) SLR = 0.2 m; b) SLR = 0.5 m, c) SLR = 1.0 m, and d) SLR = 1.5 m.

parameters in the wave action balance equation are compared with the observed values of the three offshore buoys and 6 nearshore stations, particularly the station in Mexico Beach.

2.4. Dynamically coupled ADCIRC + SWAN model description

The dynamic coupling of storm surge model (ADCIRC) and wave model (SWAN) works by transferring data between the two computational cores of individual models (Dietrich et al., 2011; Santiago-Collazo et al., 2019), as illustrated in Fig. 3. ADCIRC computes water surface elevations and currents at all nodes in the domain, at every ADCIRC time step, which was 10s in our model simulations. Details of ADCIRC model equations can be found in Luettich et al. (1992). The step size is determined by the grid resolution to ensure computational stability. The hurricane wind field, and air pressure data is input to the ADCIRC and SWAN computational cores.

SWAN model employs an implicit time stepping scheme and is unconditionally stable. We use 240s time stepping for SWAN. Water levels and velocities computed by ADCIRC is transferred to the SWAN computing core after every SWAN time-step. SWAN iteratively calculates the wave heights, direction and mean wave periods and transfers the data to ADCRC core, where the new surge heights and currents are calculated using the SWAN data, along with the input wind field data.

The large-scale domain used in the coupled ADCIRC + SWAN simulation is shown in Fig. 4 The unstructured triangular finite element grid has a minimum resolution of 1.2 km near the coast. The coupled model is computationally more expensive than the individual models run separately. A standalone SWAN model using the same wind field forcing as the coupled model is run and compared to the coupled model for accuracy, in the second part of the article. Both coupled and standalone SWAN models run on the same grid domain, with the same runtime parameters and boundary conditions.

The coupled model simulates storm tide water levels (from ADCIRC) and significant wave height values (from SWAN). But to include the effect of waves on inland floodwater pathways, the total water surface elevation (Park et al., 2014) in the coast is calculated using equation (5)

$$H_{Total} = \xi_{ADCIRC} + 0.5\, H_{max} = \xi_{ADCIRC} + 0.5 * 2 * \ H_s = \xi_{ADCIRC} + H_s \qquad (5)$$

The output from the nested land-based inundation model is incorporated into a GIS database so that inundation of coastal infrastructure such as coastal roadways and hurricane shelters can be estimated. Conversion of this output into shape files helps determine inundation zones, which can be subsequently used to guide evacuation efforts. The storm tides simulated by the ADCIRC include the combined effects of wind, tides, and hurricane winds.

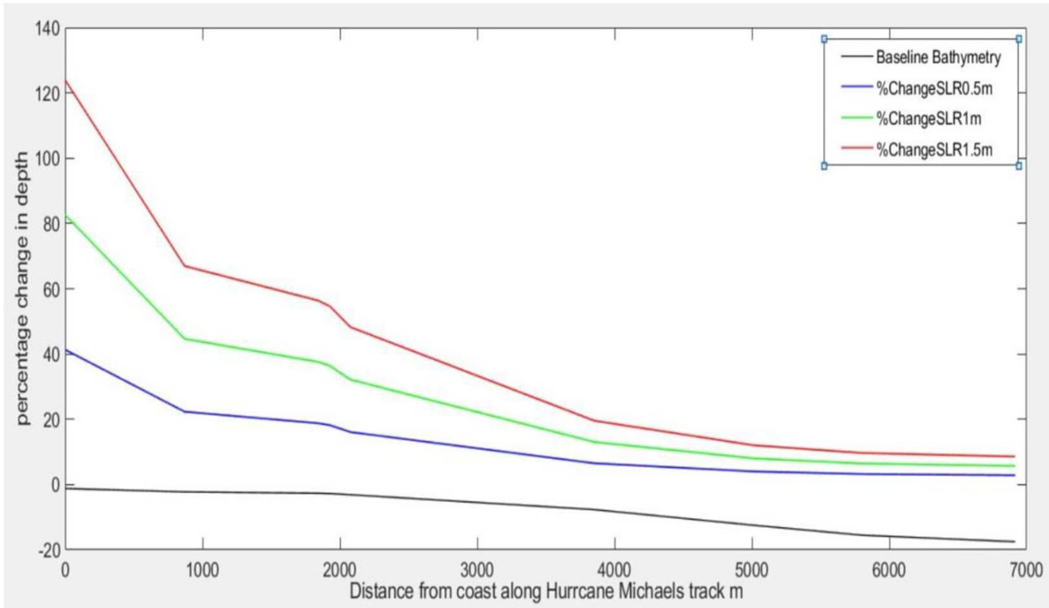

Fig. 15. Percentage change in water depth along the hurricane's track, moving away from coastline from the hurricane landing site.

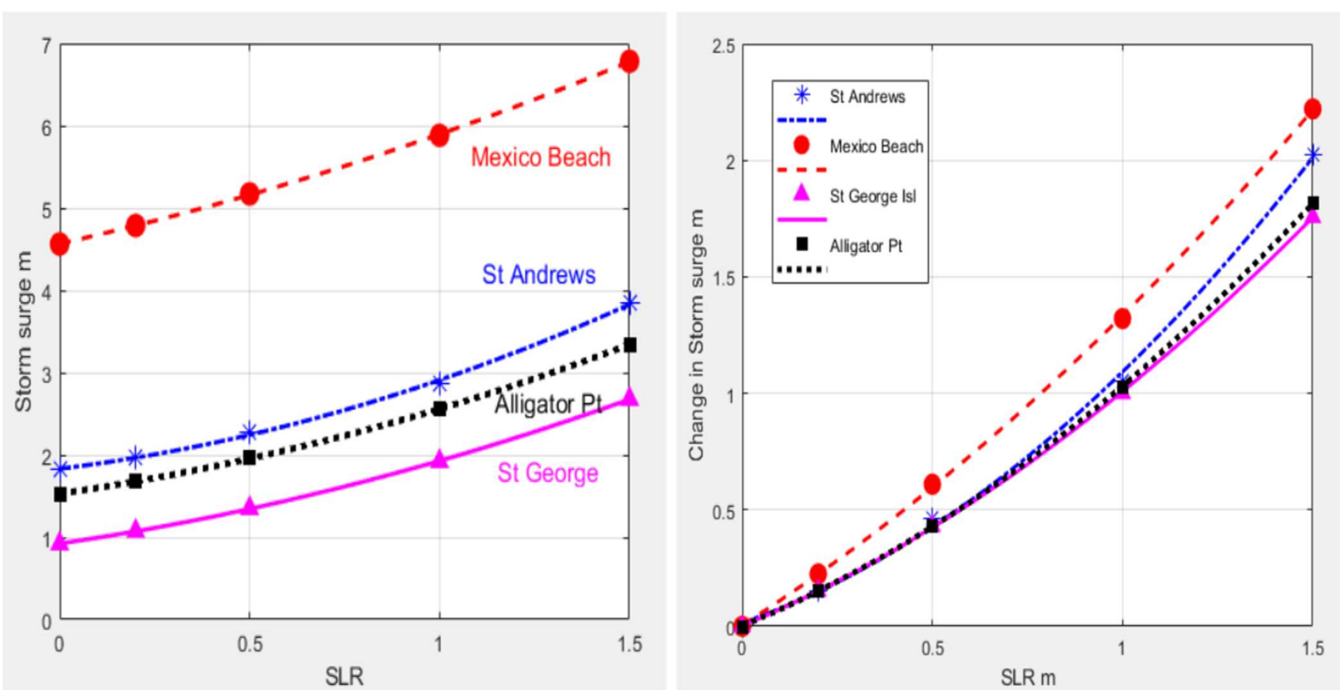

Fig. 16. a) Maximum Storm surge vs SLR b) Change in Maximum Storm surge vs SLR.

2.5. Sea level rise scenarios

Four SLR scenarios were run on the coupled ADCIRC + SWAN model, namely 0.2m, 0.5m, 1m and 1.5m by specifying the increase in sea levels above geoid. Hurricane Michael's track and intensity were not changed. The ratio of change in modeled surge and significant wave heights in each scenario to the increase in sea level is used to measure their responses respectively. A ratio value greater or less than one indicates a non-linear response while a value equal to one shows a linear increase. Positive values less than 1 indicate an increase in significant wave heights and surge less than the rise in sea levels, and conversely negative values indicate a decreasing trend with respect to SLR.

3. SWAN model calibration

As mentioned before, the model validations are carried out using observations during Hurricane Mitigation Assessment Team Report: Hurricane Irma in Florida. It made landfall on October 10, 2018, around 6PM UTC near Mexico Beach in the Florida panhandle. The maximum water damage occurred around this area as the hurricane wind speed attained a maximum before landfall. The hourly symmetric wind field (for the model duration of 5 days) input to the coupled model is based on Holland (1980) parametrizations. Fig. 5 shows the symmetric wind field forcing the model ocean surface just before landfall. It is noted that the same wind field is applied to different model runs, only the C_d is changed

Table 3
Regression equations of storm surge and SLR under Hurricane Michael condition.

Station		Storm Surge (m)	
		Abs	Change
St Andrews	Polynomial	$0.51x^2+0.57x+1.83$	$0.51x^2+0.57x+0.01$
	R	0.98	0.99
Mexico Beach	Polynomial	$0.3x^2+1.04x+4.57$	$0.3x^2+1.04x$
	R	0.994	0.99
St George	Polynomial	$0.33x^2+0.68x+0.92$	$0.33x^2+0.68x$
	R	0.99	0.998
Alligator Point	Polynomial	$0.36x^2+0.67x+1.53$	$0.36x^2+0.67x$
	R	0.99	0.99

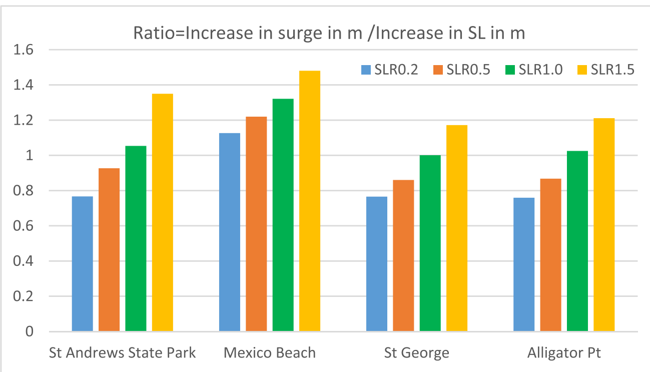

Fig. 17. Ratio of increase in Storm surge to increase in sea level rise.

for sensitivity analysis. The coupled ADCIRC + SWAN model provides the hourly significant wave height (Hs) output for the duration of the model run (5 days), and a maximum value output of Hs at the end of the model run. The model is calibrated using significant wave heights observed at various stations close to the track of Hurricane Michael. Due to the limited spatial accuracy of the parametric wind field, a more reasonable validation of the wave part of the model is by comparison of the significant wave heights with observations that are closer to the hurricane's track, especially the landfall location of Mexico Beach. This is described next.

3.1. Off-shore buoys

The comparison of model results with observations at the three offshore stations is shown in Fig. 6. The model was run with three different values of C_d, in order to test the sensitivity of the modeled significant wave height to the drag coefficient. The NDBC station 42003 and 42039 are close to the path of Hurricane Michael and therefore recorded higher maximum Hs close to 9m. Station 42039 data is only available partially and the last data it recorded provided the maximum wave height. The third station (42097) was relatively closer to the peninsular coast of Florida and was not near Michael's track. However due to the sparsity of observations, data from this station was also used for comparison. The recorded maximum significant wave height at station 42097 was nearly 4.5m. Two additional stations far from the influence of the hurricane winds were also included in the comparison.

3.2. Near-shore stations

The maximum significant wave heights observed at the nearshore stations are shown in Fig. 7. Evidently, the values are all less than 3m, much lower than the maxima observed at offshore stations such as 42003 and 42039, which are close to the hurricane track as shown in Fig. 5. The primary reason for this is the influence of bottom friction and wave breaking, due to wave energy dissipation. In the case of nearshore stations, a consistent pattern cannot be detected. The default value of Cd = 0.0012 slightly overestimates the significant wave height at all near-shore stations as well. It is to be noted that some stations like St Andrews State Park and Mexico Beach are onshore whereas the model data is taken from the nearest node in water.

The significant wave heights of the coupled ADCIRC + SWAN model depends on the wind field forcing applied, in addition to the topography. A comparison of the mean absolute error indicates that the model simulation with the default value of C_d = 0.0012 is better than those with the other two values, and subsequent sections only describe the model run with the drag coefficient = 0.0012. The largest error encountered was 1.14m at the offshore buoy 42039, which stopped operation during the hurricane. However, the observation data may be inaccurate at this station. A comparison of errors between the offshore and near-shore stations point to the fact that errors are higher for offshore stations. In short, the model performance primarily depends on two factors, bottom topography and the applied wind forcing.

4. Spatial variations of waves during the path of Hurricane Michael

A comparison of maximum significant wave heights reveals the sensitivity on prescribed wind fields. This is especially visible for offshore stations where the magnitudes of wave heights are large. Therefore, it is critical to use the most appropriate wind field for the model. The Holland symmetric wind field is chosen to calibrate the model which is further used for real time forecasts where preprocessing is simple and fast. Maximum significant wave heights of the model correlate well with the observed values as shown in Table 1 and as in the scatter plot of observations vs model values in Fig. 8. The wind field at three instances of the model run and the corresponding significant wave heights are shown in Fig. 9. The wave heights are very high, around 10m in the deep ocean, compared to 2m the near shore shallow waters, as noted in the previous section.

Fig. 9 shows the spatial wind fields and wave fields, which shows that maximum wave heights occur after the hurricane's center passes. This is because the wind-generated waves need both time and fetch to develop into extreme waves. At the time of hurricane's landing at Mexico Beach, it generates a band of extreme waves with the significant heights ranging from 5 to 5.25 m (Fig. 9c) along a region of offshore waters where bathymetry changes from deep water to shallow water in the continental shelf of the Gulf of Mexico shown in the bathymetry map in Fig. 4. This is consistent to the theory of wave shoaling (USACE, 2015). When waves enter shallow waters, they slow down and wavelength is reduced. But,

Table 4
Ratio of change in maximum wave height Hs to SLR and ratio of change in combined wave and surge to SLR near Mexico Beach, closest station to the hurricane landfall.

SLR	Absolute change in Hs (m)	Ratio of wave-change to SLR(%)	Absolute change in Storm surge (m)	Ratio of Surge-increase to SLR(%)	Absolute change in combined wave surge (m)	Ratio of (wave + surge change) to SLR(%)
0.2m	0.12	60	0.23	113	0.35	173
0.5m	0.36	72	0.61	122	0.97	194
1.0m	0.79	79	1.32	132	2.10	211
1.5m	1.75	117	2.22	148	3.97	265

Note: Under baseline SLR = 0.0 m condition, Hs = 2.73 m and surge = 4.56 m at Mexico Beach station.

the energy flux must remain constant, and therefore, the reduction in group (transport) velocity must be compensated by an increase in wave height.

Even though the maximum winds and the 64 kt wind radii in the model are accurate compared to the observed values, hurricanes are seldom symmetric. The aim here was to prepare a simple, but accurate wind field, that could model the significant wave heights accurately particularly nearshore stations. This is because further use of the validated model would be in estimating storm surge water levels that includes the wave effects on coastal areas, The model would be subsequently used to delineate dynamic inundation zones over land, for which a symmetric wind model is more suitable. In contrast, complex, more realistic wind fields might produce better significant wave heights but will be computationally expensive and time consuming, reducing the model's further use in producing dynamically changing water hazard zones in real-time. The spatial distribution of significant wave heights indicates that the maximum occurs in deeper ocean as deep-water waves have less dissipation due to lower friction and higher energy transfer from the wind for a larger distance. Secondly, largest significant wave heights along the coast were obtained near the landfall location at Mexico Beach concurrent with hurricane landfall.

5. Comparison of coupled wave-surge modeling and stand-alone wave modeling

The sensitivity experiments on the coupled ADCIRC + SWAN model indicate that the modeled significant wave heights depend on the wind field that forces the model. In this section, a comparison is made between the coupled model and a stand-alone SWAN model. The model domain and parameters were chosen such that both coupled and standalone models are forced with the same conditions of C_d, bottom friction, wind field and tidal boundary conditions. Fig. 10 shows a comparison of the coupled and uncoupled model maximum significant wave heights at different on shore stations.

It is clear that the coupled model is noticeably more accurate than the standalone model, particularly in the Mexico Beach station. The difference is due to the data exchange between ADCIRC and SWAN during each SWAN time step. ADCIRC calculates storm surge water levels and transfers the water level data to SWAN; using which it calculates the wave heights. On the other hand, stand-alone SWAN calculations are based on the water levels of its previous time step. The coupled model is more realistic because the significant wave height is calculated above the storm surge water level or the base flood elevation experienced on shore during a storm. In other words, the water level in the coupled model is enhanced by wave heights calculated by SWAN at every time step, and storm surge calculated by ADCIRC. Due to the two-way coupling, there is an enhancement in significant wave heights in the coupled model, improving the accuracy of the wave part of the coupling. In effect, water surface elevations obtained from the coupled model are more accurate due to the addition of the wave effects from SWAN.

Significant wave heights in the open ocean are much larger than that near shore. It can be inferred that significant wave heights would be more in the case of coupled model because the effective depth of water given to SWAN at every time step is increased by the storm surge water elevation calculated by ADCIRC. It is analogous to the non-linear increase in storm surge due to sea level rise scenarios as described by (Wang and Yang, 2018). The surge water levels increased two-fold due to SLR in the above study. In this case, the enhancement in Hs at the Mexico Beach station was close to 0.6m. Additionally, the SLR and water levels in the study were non-linearly related spatially.

6. Time evolution of significant wave height at Mexico beach station

Mexico Beach and the surrounding areas experienced the maximum storm surge levels, which includes the higher frequency waves, during Hurricane Michael. The hurricane was strongest just before landfall resulting in these extreme conditions. Fig. 11 shows a comparison of the two models. The maximum significant wave height observed at the station is 2.69m. The coupled model time series of Hs quickly rises to the maximum of 2.55m, which is concurrent with the landfall. In the case of the stand-alone model, the significant wave height maximum was 2.21m, approximately half a meter lower than the observed. Additionally, it occurred 2 h after the landfall, and died down slowly. Both models showed only a small tidal influence on significant wave height before and after the hurricane passed. The critical factor for a shallow water location in addition to the wind field is the water level above which the wave model calculates significant heights. In short, improvement in modeled Hs due to the coupling is more visible close to the landfall area of Mexico Beach.

7. Response of significant wave heights to sea-level rise

Model data from the four near shore stations, for the four SLR scenarios are used for the analysis. Fig. 12 (a) shows the significant wave heights for the four scenarios and 12(b) the change of Hs from the baseline values at the four stations. All stations in all SLR scenarios showed an increase in Hs. The quadratic behavior is more visible on the change from baseline scenario plot in Fig. 12b, especially for the two stations near the location of landfall.

The overall response of significant wave heights is only slightly non-linear against the four SLR scenarios. A quadratic polynomial correlates very well with the increase in significant wave heights at each of the four stations. The quadratic fit equations along with correlation coefficients in the plots are summarized in Table 2.

A ratio of increase in Hs to the increase in sea level is calculated and plotted for the 4 stations in Fig. 13. The ratio can be used to assess the response of Hs to SLR. A value of 1 indicates purely linear response, whereas a value of 2 corresponds to a quadratic behavior. The maximum value occurred at Mexico Beach, very close to the landfall location. The response of Hs in the coupled model is only weakly non-linear, the ratio is only 1.2 around the Mexico Beach area for a rise of 1.5m in sea level. Locations farther from the storm center like St George and Alligator Point showed an almost linear response because of the protection by the barrier islands.

The change in Hs corresponding to all four scenarios are the greatest around a region close to the hurricane track near the coasts. Fig. 14 a - c show the spatial variation of change in Hs. In all scenarios of SLR, the change in Hs is larger near the shoreline. Deep-water waves are not much influenced by SLR. The maximum change in each scenario were near the landfall location of Mexico Beach. A region with larger change extends further to the ocean and to the right side of the track of the hurricane. This is especially visible for the 1m and 1.5m SLR scenarios. The significant wave heights respond slightly more to SLR on the right side of the hurricane, along its track. Additionally, changes in Hs due to SLR are more in regions where shallower depths are encountered, much farther from the storm's track to the east along the coast.

The effect of sea level rise on significant wave height is more prominent in the shallower areas, especially for 1 and 1.5m rise scenarios. For shallow bathymetric depths, such increments in sea level result in a large percentage change in bathymetry (Fig. 15). Significant wave heights tend to be larger for deeper areas as described in the previous section (Figs. 6 and 7). Therefore, larger significant wave heights compared to the baseline scenario are obtained in these locations. This results in larger changes in significant wave heights in areas where there is a large change in bathymetric depth. This is more prominent in locations close to the hurricane's track where the maximum wind speeds are experienced.

8. Response of storm surge and combined wave-surge to sea-level rise

Storm surge water levels obtained from the ADCIRC in the coupled model is described here. Similar to Hs, the storm surge water levels responded non-linearly to SLR. Fig. 16 shows a more visible quadratic behavior for the four stations. There is a marked increase of 2.25m in storm surge water levels for 1.5m SLR scenario at Mexico Beach, closest to land fall. (Fig. 16b). As before, quadratic equations fit very well with data points of the four stations, as shown in Table 3. However, for low values of SLR, the responses were larger compared to the Hs response. This can be observed in the values of change in storm surge (Fig. 16b) for 0.5m SLR as opposed to 0.3m in Fig. 12b.

The ratio of change in storm surge water levels to SLR is used to assess the degree of non-linearity, here as well (Fig. 17). The ratios are larger compared to those of Hs for all SLR scenarios of all stations and in particular, surge responses were larger for lower SLR. At the hurricane land fall location of Mexico Beach, the ratios are larger than 100% for all SLR cases, indicating a stronger non-linear behavior near hurricane center. For other stations about 30–40 km away from the hurricane landing site, the rations are above 100% only under 1–1.5 m sea level rise conditions.

A comparison of change in significant wave height Hs, change in storm surge and change in total water level at Mexico Beach is provided in Table 4 as it is nearest to the landfall location of hurricane. In all the SLR scenarios, the percentage increase in storm surge was greater than the corresponding rise in SL. An increase of 1.22 times the SLR of 0.5m can be expected at the landfall location, while the increase would be 1.48 times that of the SLR of 1.5m.

The combined response of storm surge and waves at the landfall location is highly non-linear. An increase in total water levels as high as 4m can be expected near the landfall location for a 1.5m rise in sea level, due to a category 5 hurricane in the future. For the most likely scenario of SLR of 0.5m, the increase in total water level at Mexico Beach would be approximately 1m. The increase would be 1.94 times the SLR in this case. The total water levels experienced would be 2.65 times that of the SLR in the case of a 1.5m rise in sea level.

Even though the response of Hs is not as high as storm surge for lower SLR, the effect of Hs in enhancing the total water levels cannot be ignored. In effect, VE flood zones (Fig. 1) where there is a significant wave action and consequently zone AE (wave height 1.5–3 ft) would cover areas further inlands due to SLR for the same return period of 100 years. Zones VE also specifies the expected value of storm surge and waves while AE shows the expected surge levels for a 100-year flood. These values of water levels would increase non-linearly due to SLR.

9. Conclusions

Numerical simulations have been conducted in this study to evaluate the enhancement of wave simulations by the dynamically coupled ADCIRC + SWAN model through the case study of Hurricane Michael. By comparing observations, simulations of significant wave heights by the dynamically coupled ADCIRC-SWAN model are more accurate compared to the standalone SWAN model, with the error of 0.04 m nearshore at the hurricane landing site of Mexico Beach and 0.26 m RMSE for all stations. By comparison, the wave simulation by stand-alone wave model SWAN results in an error of 0.30 m near Mexico Beach and 0.39 m RMS error over all 13 stations. The substantial reduction of error in significant wave height near the hurricane's landing site will provide more accurate information to support coastal hazard evacuation and mitigations. The validated ADCIRC-SWAN model has been used to investigate the effects of SLR on the increase of significant wave height under the same Hurricane Michael conditions. Results indicate that, near the hurricane landing site, significant wave height non-linearly increase as the SLR increases. For the case study of Hurricane Michael, a SLR of 1.5 m would cause an increase in wave height of 1.17 times SLR near Mexico Beach. The response of storm surge water levels was more non-linear than significant wave heights for all coastal locations. For a SLR of 1.5 m near the Mexico Beach location, the increase of wave and storm surge would be 1.17 times and 1.48 times, respectively, under the condition of Hurricane Michael. Total water levels (combined wave and surge) would substantially increase 2.65 times for a 1.5m SLR. The most likely scenario of 0.5m shows a change in total water level of 0.97m (1.94 times that of SLR) near the land fall location. In short, model results indicate a strong non-linear response of storm surge and Hs in a region close to the landfall of a hurricane to SLR. It can be expected that an increase in the coverage area of FEMA flood zones VE (influenced by the change in Hs and surge) and AE (influenced by the change in storm surge alone) would result due to SLR. In addition, the expected water levels specified in such zones would increase non-linearly due to SLR. Because the study is limited to the case study of Hurricane Michael, the regression equations of significant wave heights and SLR are limited to a few stations in Hurricane Michael impact areas. For other coastal areas, similar approach may be conducted by selecting representative hurricanes for study coastal waves under different SLR scenarios by using the dynamically-coupled ADCIRC and SWAN.

CRediT authorship contribution statement

Linoj Vijayan: conducted coupled SWAN-ADCIRC simulations. **Wenrui Huang:** developed the concept and supervised the research. **Mengdi Ma:** conduct stand-alone SWAN model simulation. **Eren Ozguven:** linked the modeling results to hurricane evacuations. **Mahyar Ghorbanzadeh:** linked the modeling results to hurricane evacuations. **Jieya Yang:** processed and analyzed observation data. **Zhaoqing Yang:** contributed ideas for manuscript revisons.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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