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Sensitivity of wind waves to hurricane wind characteristics

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Abstract

In this study, the influence of the spatial and temporal variability of hurricane winds, storm translation speed, intensity, and ambient wind field on surface wind waves are investigated by using a third-generation wave model (Simulating WAves Nearshore, or SWAN). The results show that the asymmetric structure of wind-induced wave field is sensitive not only to the asymmetric structure of the hurricane wind field, but also to the variations in the storm translation speed and intensity. The significant wave height (SWH) in the front-right quadrant of the storm rises as storm translation speed increases until it reaches a critical value, then the SWH drops. The opposite occurs in the rear-left quadrant. The total contribution of the hurricane translation speed to the asymmetric structure of the wave field also depends on the intensity of the hurricane. As the intensity of the hurricane increases, the relative significance of the influence of the translation speed on the asymmetric structure of the wave field decreases. Most parametric hurricane wind models can only model symmetric hurricanes and do not include background winds. However, actual hurricanes in nature are not only asymmetric but also imbedded in background winds. Thus, to more properly model hurricane-induced wave field, it is important to consider storm asymmetry, translation speed, intensity, as well as background winds.

Keywords: Wave; Hurricane; Numerical modeling; Ocean response; Wind forcing

1. Introduction

Waves generated by hurricanes can exceed 20 m in deep open ocean waters. Wang et al. (2005) reported that the maximum significant wave height (SWH) reached 27.7 m during the passage of Hurricane Ivan. Although SWH is lower when waves reach shallow waters, these waves can devastate the coastal zone. It is well known that hurricane-induced waves are one of the most damaging phenomena during the passages of hurricanes. Severe wave conditions are dangerous to vessels in ocean and coastal waters, and waves can also run up over the storm surge in the coastal zone to cause more severe damage along and on the coast. So the ability to predict hurricane-induced waves precisely is a very important challenge and is of great value to many

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user communities. As the wind is the principal source of energy creating and driving waves, in order to forecast hurricane-induced ocean surface waves, it is necessary to establish a thorough understanding of how the wave field manifests itself in response to the spatial and temporal variation of hurricane winds.

During the 1950s, the resonance mechanism (Phillips, 1957) and the feed-back mechanism (Miles, 1957) of how wind energy is transferred to waves were developed. Most of the present community wave models (e.g., WAM by the WAMDI, 1988; and SWAN by Booij et al., 1999) still use the concepts introduced by the pioneering works of Phillips and Miles as the mechanisms of wind energy input into ocean surface waves. These two wave models have been verified and used to forecast waves, hind-cast waves and in wave–current interaction analyses in many oceans around the world (WAMDI, 1988; Komen et al., 1994; Xie et al., 2001; Booij et al., 1999; Ris et al., 1999).

There have been a number of past studies on the response of wind waves to tropical cyclones including data analysis and numeric model studies. Wright et al. (2001) and Walsh et al. (2002) provided all quadrants of sea surface directional wave spectrum in the open water (August 24, 1998) and at landfall (August 26, 1998) during hurricane Bonnie using the NASA airborne scanning radar altimeter data. They found that the dominant waves generally propagated at significant angles to the downwind direction, and developed a simple model to predict the dominant wave propagation direction. Recently, Young (2006) studied the directional wave spectrum during the passages of several hurricanes using wave buoy observations and showed that in almost all quadrants of the storm, the dominant waves are remotely generated swells. In the meantime, Ou et al. (2002) used SWAN to simulate typhoon-induced waves in the coastal waters of Taiwan. Their results showed that waves under typhoon forcing condition can be reasonably well simulated by the SWAN wave model. Moon et al. (2003) simulated the surface wave spectra under hurricane wind forcing using a high resolution WAVEWATCH III model (Tolman, 1991). They showed that numerical simulation results agree reasonably well with observational data. Furthermore, they also analyzed the effect of hurricane translation speed on the wave spectra. However, their study focused on the analysis of a specific case. Moon et al. (2004) investigated the effect of sea surface waves on air–sea momentum flux during the passages of tropical cyclones. A remaining issue which has received little attention in the past is the sensitivity of surface wind waves to the spatial and temporal variations of tropical cyclone winds. In order to address this issue, a suite of numerical experiments are designed to quantify the influence of wind distribution, storm translation speed and intensity on ocean surface wind waves using SWAN. Additionally, two historical hurricane cases (Hurricane Bonnie, 1998 and Floyd, 1999) are studied to quantify the effects of actual hurricane structure and background wind field on waves. A brief description of the SWAN model and parameteric hurricane wind models are given in Section 2. Section 3 describes the model experiments. Results are presented in Section 4, followed by discussions and conclusions.

2. Model description

2.1. The SWAN wave model

The SWAN model is based on the wave action balance equation (or energy balance in the absence of currents) with sources and sinks. In SWAN the evolution of the wave spectrum is described by the spectral action balance equation, which for Cartesian coordinates (e.g., Hasselmann et al., 1973) is:

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}C_xN+\frac{\partial}{\partial y}C_yN+\frac{\partial}{\partial \sigma}C_\sigma N+\frac{\partial}{\partial \theta}C_\theta N=\frac{S}{\sigma} \tag{1}$$

where N is the action density ($N(\sigma,\theta)=E(\sigma,\theta)/\sigma$), E is the energy density spectrum, σ is the relative frequency and θ is wave propagation direction. X and Y are Cartesian coordinates. C_x, C_y, C_σ and C_θ are wave propagation speeds in x-, y-, σ- and θ-space, respectively. S is the source term which represents the effects of generation, dissipation and nonlinear wave–wave interactions.

2.2. Hurricane wind models

Two hurricane wind models are employed in this study to simulate hurricane winds, one is the symmetric Holland (1980) model (hereafter referred to as H1980) and the other is an asymmetric Holland–NCSU model

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(Xie et al., 2006) (referred to as HN2006 hereafter). In H1980, the wind speed as a function of radial distance from the center of the storm is described as

$$V_a = [AB(P_n - P_c)\exp(-A/r^B)/\rho_a r^B]^{1/2} \quad (2)$$

where V_a is wind speed at radius r, P_c is the central pressure, P_n is the ambient pressure (P_n is set to 1000 mb in this study), and A, B are scaling parameters ($A = (R_{max})^B$) in which R_{max} is the radius of maximum wind (RMW). Wind field parameters used in Eq. (2) were obtained from the National Hurricane Center (NHC) of the United States National Oceanic and Atmospheric Administration (NOAA).

In the comparison experiment, the hurricane wind field is obtained by combining an asymmetric hurricane wind field produced by HN2006 with the background wind field. In the asymmetric hurricane wind model, R_{max} in Eq. (2) was modified to fit a polynomial function of the azimuthal angle θ:

$$R_{max}(\theta) = P_1\theta^{n-1} + P_2\theta^{n-2} + \cdots + P_{n-1}\theta + P_n \quad (3)$$

B and R_{max} in Eq. (2) are then optimized using available observational data, wind analysis or forecast guidance. The background wind field was obtained by removing the hurricane vortexes in the eta data assimilation system (EDAS) data, which are often coarse and weak, using a cylindrical filtering operator (Kurihara et al., 1993). Then the optimized asymmetric hurricane wind field described above was imbedded into the background wind field to produce the total wind field.

3. Experimental designs

Four experiments are designed to investigate the effect of Hurricane translation speed, intensity and structure on the wave field. The experiments are listed in Table 1. Hurricane wind fields for these experiments are simulated by H1980 for symmetric wind cases and by HN2006 for the asymmetric hurricane cases as well as for Hurricane Bonnie in 1998 and Floyd in 1999. For the symmetric hurricane experiments, an idealized domain and bathymetry are assumed, which is 1500 km in the x-direction and 3000 km in the y-direction. The water depth is set to a constant 5000 m for convenience. The moving direction of the hurricanes is from south to north. In these experiments, the wind field is translated across the model domain along the storm track and after the wave model is initiated with a "cold start" from a quiescent sea state. The first 75 h of the simulation was considered as a "spin-up" and the data after 75 h are analyzed. The settings for the asymmetric hurricane experiments will be presented in Section 4.4.

In Exp. A, 15 hurricane cases are used to study the effect of the hurricane translation speed on waves. All 15 hurricanes have the same intensity (identical central pressure) but travel at different translation speeds. The effect of hurricane intensity on waves is investigated in Exp. B, as the hurricane translation speed is set to 0 and different central pressures are assumed. Next, the combined effects of hurricane intensity and translation speeds on waves are examined in Exp. C. Finally, the effects of hurricane wind structure and background wind field on waves are investigated in Exp. D, which includes real hurricane cases of Hurricane Bonnie (1998) and Floyd (1999). The observed hurricane translation speed and center pressure are used in these two cases. Hurricanes in Exps. A, B and C have the same RMW.

4. Results

4.1. The effect of hurricane translation speed on waves

The distributions of SWH, relative to the hurricane center and driven by symmetric hurricanes with different translation speeds (Exp. A) are shown in Fig. 1. Fig. 1 also displays the SWH differences between each case and the SWH generated by a static hurricane. These SWHs are plotted at locations within a distance of 300 km from the center of the hurricane. Fig. 1 shows that the SWH in the front-right quadrant of the storm track increases, while that in the rear-left quadrant decreases, with increasing hurricane translation speed. This result is consistent with the findings of Moon et al. (2004). The results indicate that hurricane translation speed can cause asymmetric distribution of waves regardless of whether the hurricane is symmetric or asymmetric.

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Table 1
Experimental designs

Exp. name		Hurricane Translation speed (m/s)	Center pressure (intensity)(hpa)	Structure
A		From 0 to 14 Interval = 1 m/s	963	Symmetric
B		0	953 963 973	Symmetric
C	C1	0	953 963 973	Symmetric
	C2	1	953 963 973	
	C3	2	953 963 973	
	C4	3	953 963 973	
	C5	4	953 963 973	
	C6	5	953 963 973	
D		Varying	Varying	Symmetric Asymmetric

It is worth noting that, initially the hurricane translation speed increases from 0 to approximately 12 m/s, the SWH in the front-right quadrant of the storm track also increases, but when the translation speed exceeds 13 m/s, the SWH begins to decrease. To illustrate this trend, the SWH values of the waves generated by hurricanes moving with different translation speeds at a location in the first quadrant and one RMW away from the storm center (Point A in Fig. 2), and a location in the third quadrant, which is also one RMW away from the storm center (Point B in Fig. 2), are plotted in Fig. 3. Note that Point A is located at 45° angle (front-right), while Point B is 235° angle (rear-left) to the storm motion. It can be seen that the SWH at Point A monotonically increases with the translation speed from 0 to 12 m/s, but begins to drop when the translation speed exceeds 13 m/s. This phenomenon can be explained by the following resonance theory proposed by King and Shemdin (1978) and elaborated by others (Young, 1988; Bowyer and MacAfee, 2000; Moon et al., 2003): "waves to the right of the hurricane track are exposed to the prolonged forcing of winds, and as the hurricane translation speed becomes comparable to the group speed of the dominant waves, those waves essentially become trapped within the hurricane and there appears to be resonance between swells produced previously by the hurricane and the locally generated wind waves." The period of the dominant wave generated by this intense hurricane is 15.89 s and the corresponding group velocity of the dominant wave is 12.3 m/s. Fig. 4 shows the one dimensional directional wave spectrum at Point A. It can also be seen from Fig. 4a–g that wave energy increases with increasing translation speed. However, it shows the presence of only one spectrum energy peak, which is located near 100°, because the direction of swells (Fig. 6) is similar to the direction of local wind-generated waves at Point A. The notion that waves in the forward quadrants of storm are being dominated by swell is also verified by observational data (Wright et al., 2001; Young, 2006). In contrast, as the hurricane translation speed becomes greater than the group speed of the dominant waves, the waves to the right of the hurricane track are less likely to be trapped within the influence of the hurricane. Hence, previously generated swells at Point A will not have the opportunity to interact with new waves generated by

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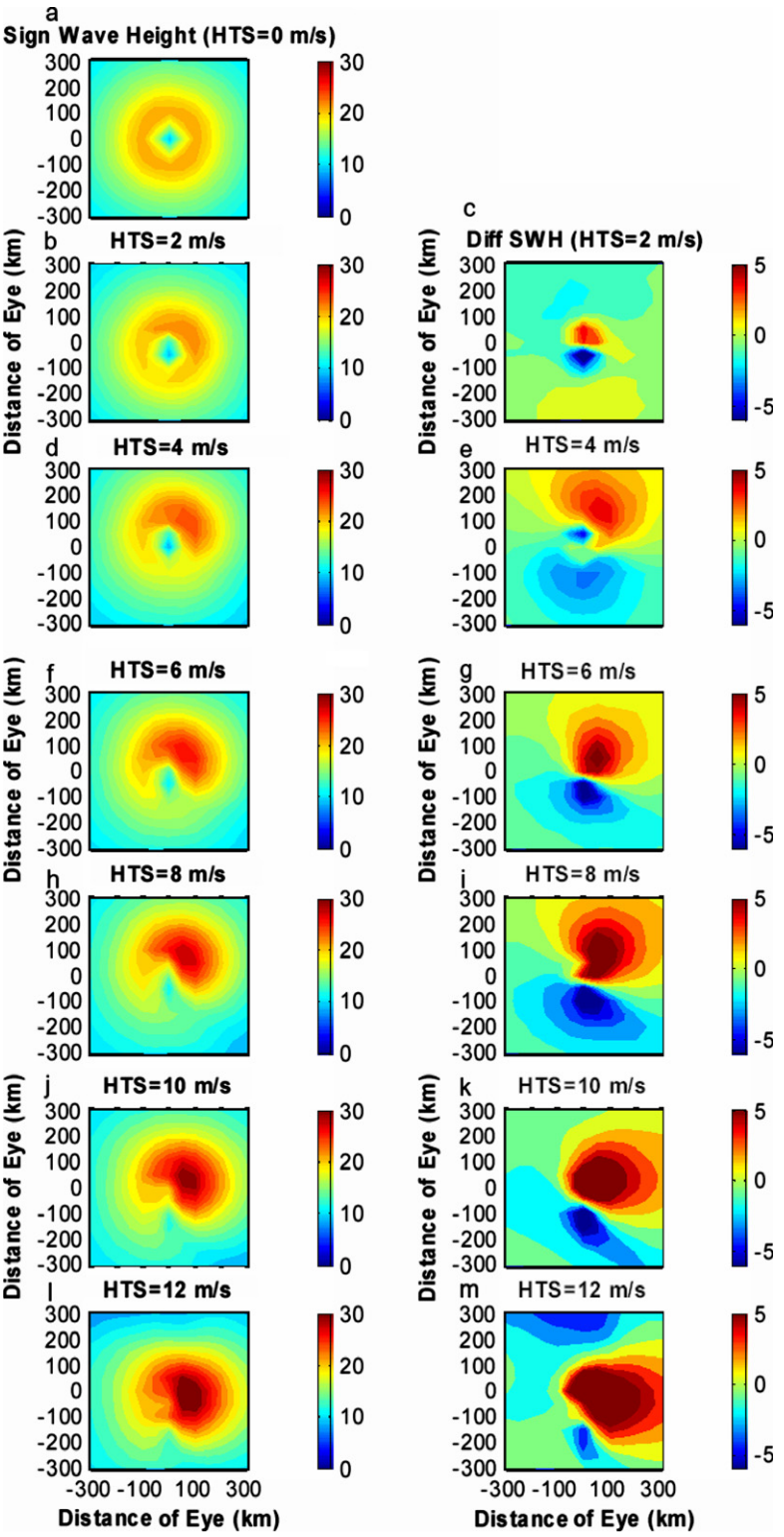

Fig. 1. The distribution of significant wave height (SWH) driven by static symmetric hurricanes (a) and symmetric hurricanes with different translation speeds (b) 2 m/s; (d) 4 m/s; (f) 6 m/s; (h) 8 m/s; (j) 10 m/s; (i) 12 m/s and different SWH differences between them and these generated by the static hurricane (c) 2 m/s; (e) 4 m/s; (g) 6 m/s; (i) 8 m/s; (l) 10 m/s; (m) 12 m/s.

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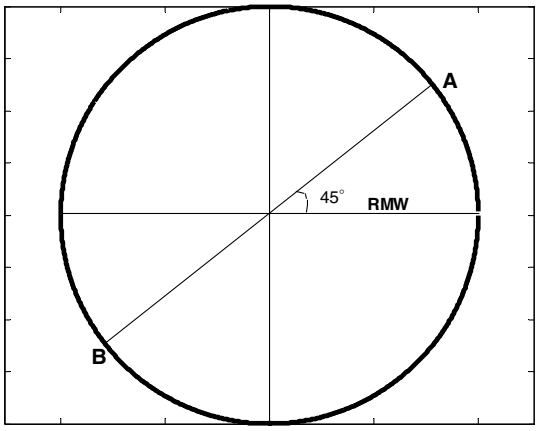

Fig. 2. The locations of two sampling points. Point 'A' locates in the first quadrant one RMW from the storm center, while point 'B' locates in the third quadrant, also one RMW away from the storm center.

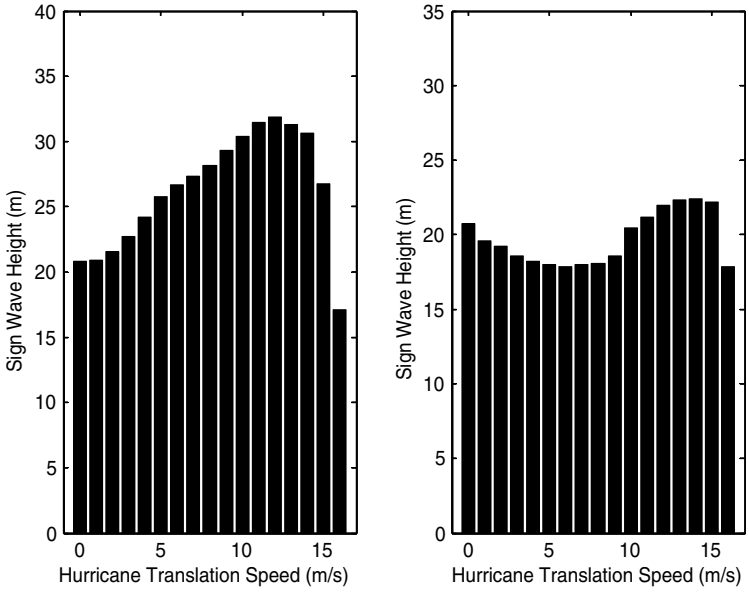

Fig. 3. SWH values of waves generated by symmetric hurricanes moving with different translation speeds of location 'A' (a) and location 'B' (b) (shown in Fig. 2) at RMWs.

the hurricane. In other words, there is no resonance effect at the front-right quadrant of the hurricane, and as a result, wave energy starts to decrease at Point A because of the reduction of the duration of wind action (Fig. 4h).

The situation at Point B is the opposite. At the beginning, the SWH at the rear-left of the hurricane decreases monotonically with increasing hurricane translation speed (Fig. 3b). However, it starts to increase when the translation speed reaches about 7 m/s and its maximum value occurs at 15 m/s. Furthermore, the SWH at Point B generated by the hurricane with a translation speed at (or in excess of) 11 m/s will be higher than that induced by a static hurricane (Fig. 3b). Fig. 5 shows the one dimensional directional wave spectrum at Point B. It can be seen from Fig. 5a–d that the major wave spectrum energy is located between 270° and 360°, which is the same as the local wind direction. In other words, SWH is mainly contributed from locally-

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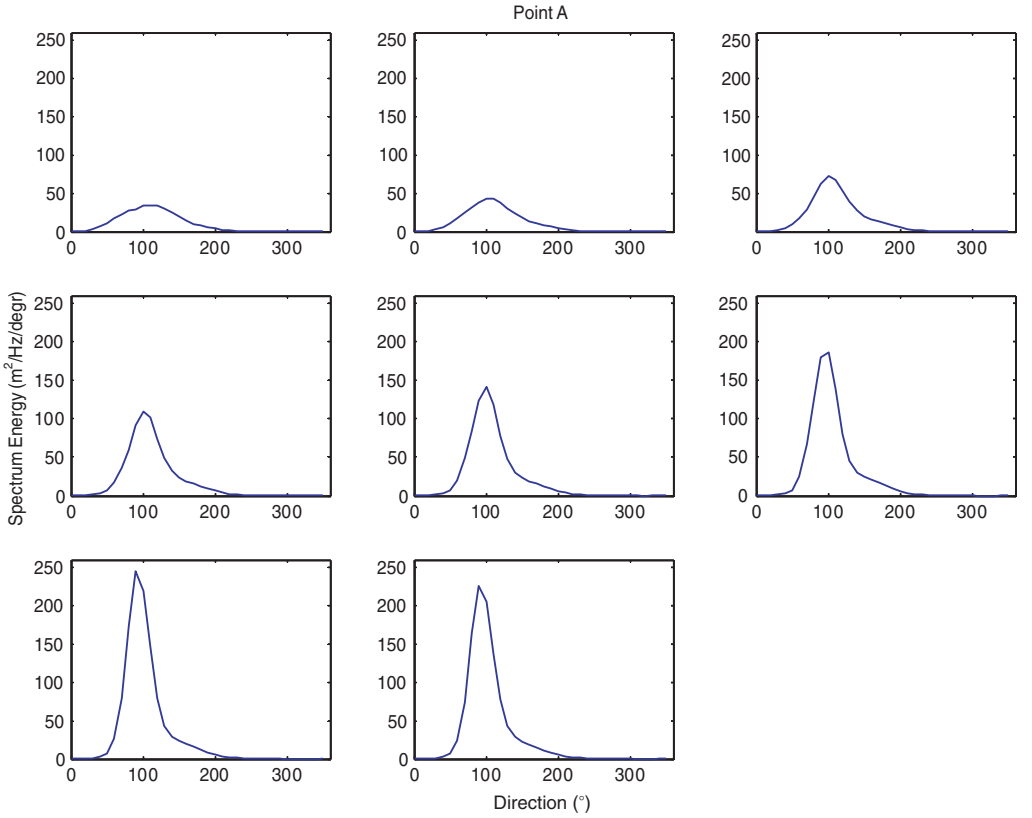

Fig. 4. One dimensional directional wave spectrum at Point A, which were generated by symmetric hurricanes moving with different translation speeds: (a) 0 m/s; (b) 2 m/s; (c) 4 m/s; (d) 6 m/s; (e) 8 m/s; (f) 10 m/s; (g) 12 m/s and (h) 14 m/s.

generated wind waves because the waves are not trapped when the storm translation speed is below the group speed of the dominant waves. Therefore, SWH of locally-generated wind waves are reduced at the beginning (Fig. 5a–d) due to reduced forcing time as the waves propagate against the hurricane moving direction. However, with increasing translation speed, it becomes possible for waves generated on the right side of the track under "near-resonance" conditions to reach Point B, as will be discussed later. This is also due to the resonance between the swells and the locally generated wind waves. It can be explained by using Fig. 5e–h. There is another peak in the spectral energy distribution located between 100° and 140°. It is obvious that this energy peak does not correspond to waves generated by local winds, but from swells transported from some distance. The SWH at Point B increases until the hurricane translation speed increases to a critical value 15 m/s in the case considered here. Same as at Point A, SWH at Point B decreases as the storm translation speed increases beyond this critical value and the duration of wind action reduces with the increase of hurricane translation speed.

The reason why the two critical values of storm translation speed at Point A and Point B are different can be explained by using Fig. 6, which shows a schematic picture of swell (of Point A and Point B) propagating in the direction tangential to the circle defined by the RMW at an earlier position of the storm. This schematic picture is based on the assumption that the swell is generated from the earlier position of the storm and the propagation direction of the swell at each point is determined by the waves propagating in the direction tangential to circle of RMW at the earlier position of the storm (Fig. 6) (Moon et al., 2003). The maximum SWH is achieved for swells that maximize their forcing time under the hurricane, which (at least approximately) corresponds to having the component of swell propagation velocity in the translation direction equal to the hurricane translation speed. Given the angle needed for waves to reach Point B, as shown in Fig. 6, this requires a greater hurricane translation speed for Point B than for Point A.

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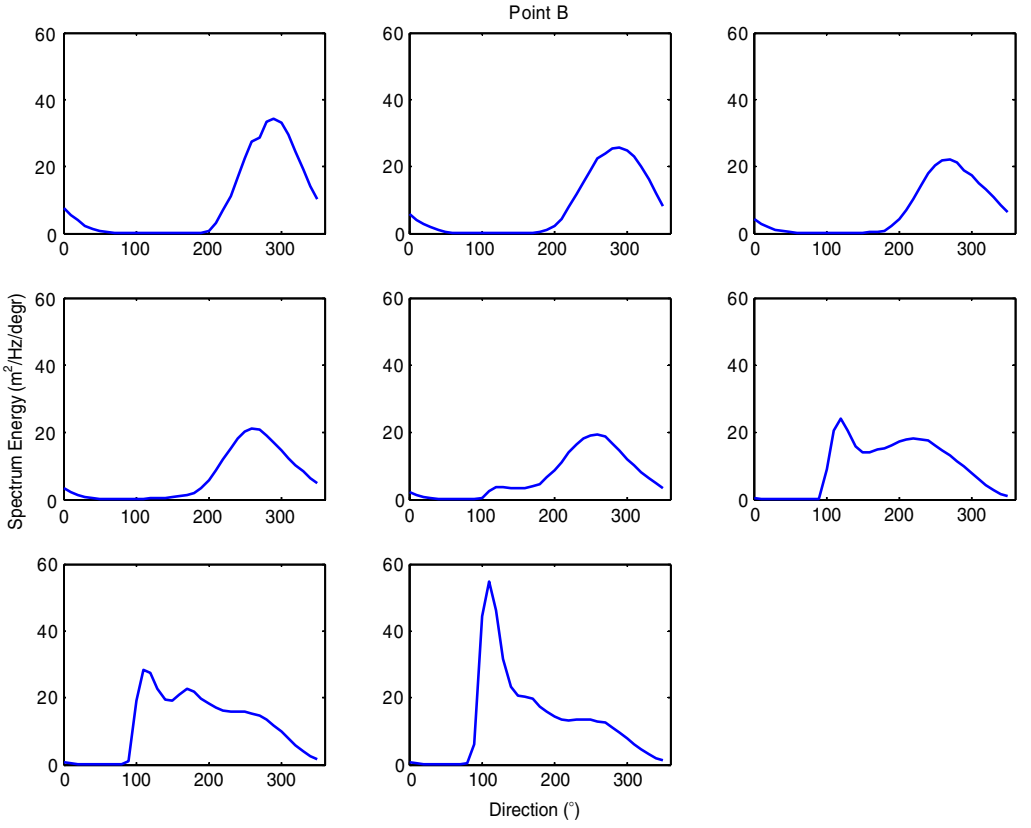

Fig. 5. Same as Fig. 4 except for Point B.

4.2. The effect of hurricane intensity on waves

In Exp. B, three static hurricanes with different center pressure (intensity) were used to investigate the effect of hurricane intensity on waves. One is a strong hurricane whose central pressure is 953 hpa (maximum wind velocity, MWV is 44 m/s), the second is a moderate hurricane whose central pressure is 963 hpa (MWV = 39 m/s) and the third is a weak hurricane whose central pressure is 973 hpa (MWV = 34 m/s). The SWH at locations A and B, as indicated in Fig. 2, is shown in Fig. 7 for the three different hurricane cases. It is obvious that the SWH at the two points indicated in Fig. 2 increases with hurricane intensity, but the intensity of the hurricane does not affect the asymmetric structure of waves.

The question is what would the combined effects of hurricane intensity and translation speed be on the SWH of the wave field? This question will be addressed in the next section.

4.3. The effect of the combined hurricane intensity and translation speed on waves

In this section, we will examine how waves vary with varying hurricane intensity and translation speed. Different hurricanes with translation speeds at 0, 1, 2, 3, 4 and 5 (m/s), each of which has different central pressures, were used in Exp. C (Table 1). We will examine whether or not the effect of the hurricane translation speed on waves depends on hurricane intensity. The normalized SWH difference (NSD) between C2 (C3, C4, C5 or C6) and C1 at locations A and B is defined as

$$\mathrm{NSD} = \frac{\mathrm{SWH}_{Ci} - \mathrm{SWH}_{C1}}{\mathrm{SWH}_{C1}} \times 100\%$$

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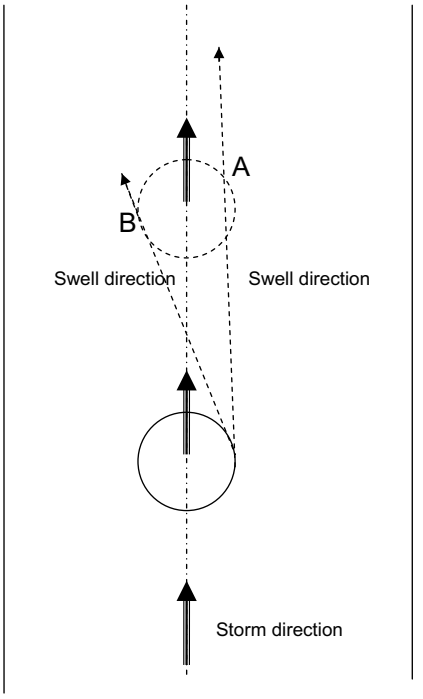

Fig. 6. Schematic picture of swell (of Point A and Point B) propagating in the direction tangential to the circle defined by the RMW at an earlier position of the storm.

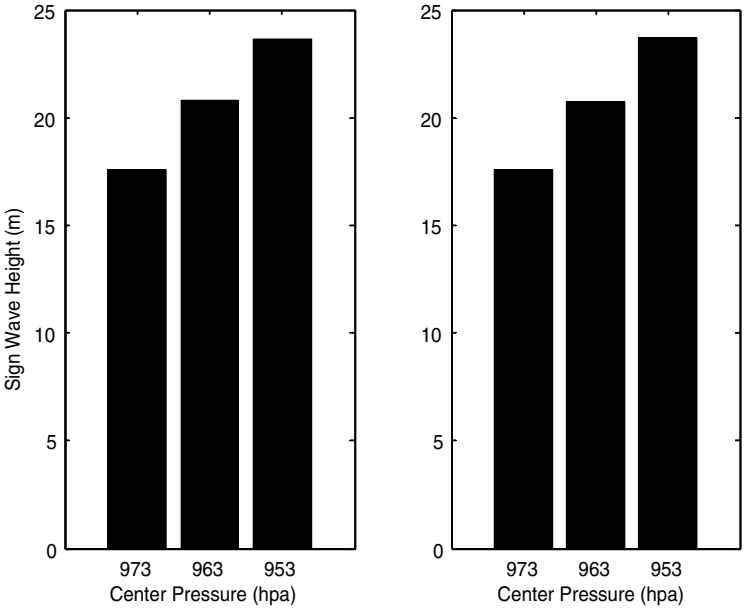

Fig. 7. SWH values of waves generated by static and symmetric hurricanes with different intensity of location 'A' (a) and location 'B' (b) (shown in Fig. 2) at RMWs.

It was used to represent the impact of hurricane translation speed on waves where SWH_{Ci} represents the SWH in Exps. C2, C3 C4, C5 or C6, and SWH_{C1} represents the SWH in Exp. C1. Fig. 8 shows that the NSD at locations A and B (as shown in Fig. 2) varies with different intensity and translation speed. It is obvi-

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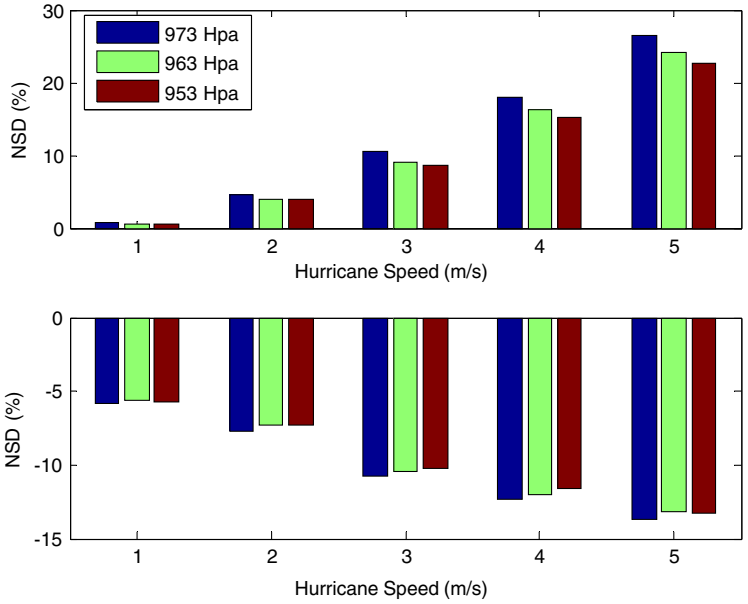

Fig. 8. Normalized SWH difference (NSD) at location 'A' (a) and location 'B' (b) (shown in Fig. 2).

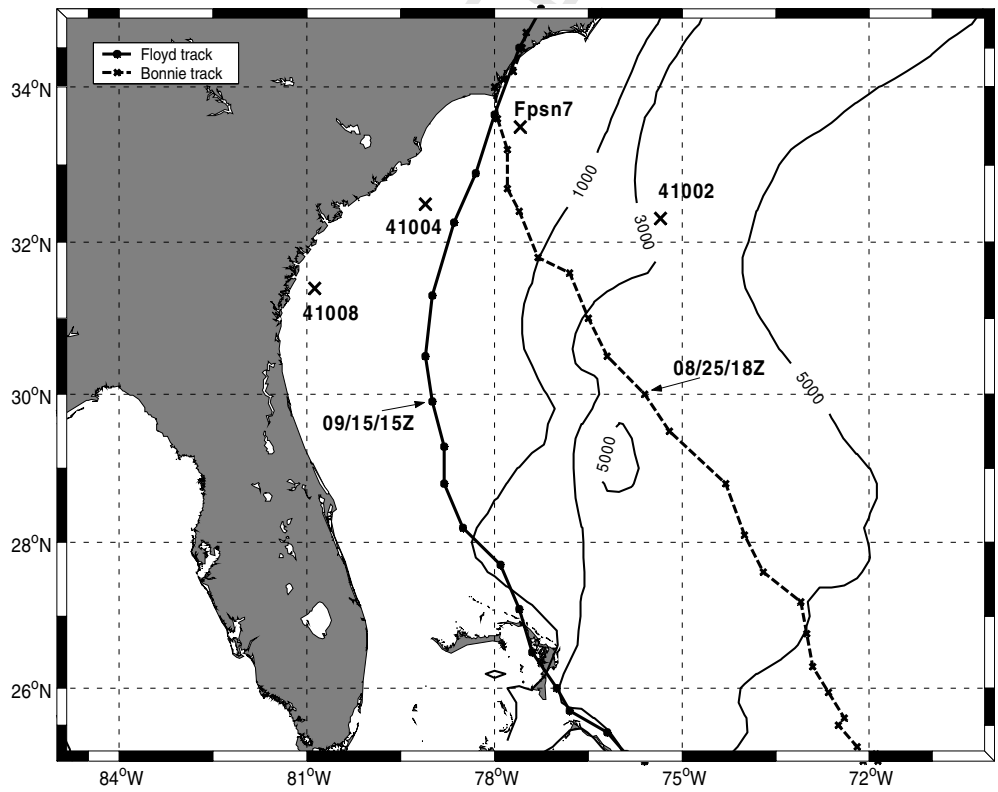

Fig. 9. The model topography and domain used in experiment D, extends latitudinally from 25° to 35° north and longitudinally from 85° to 70° west. Dashed-X line and solid-point line are the best tracks of Bonnie and Floyd respectively (time interval is 3 h). The X-mark is the distribution of the buoy stations.

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ous that NSD decreases with increasing intensity of hurricanes at location A (Fig. 8a) and at location B (Fig. 8b). The results imply that the relative effect of the hurricane translation speed on waves decreases with increasing intensity of the hurricane. The percentage of increase at the front-right location of hurricanes is reduced and meanwhile the percentage of decreasing at rear-left of hurricanes increased. In other words, its impact on the asymmetry of the wave field decreases with increasing intensity of the hurricane.

The mechanism used in Section 4.1 can also be applied here to explain this phenomenon. The influence of hurricane translation speed on waves is mainly due to the possibility of interaction (resonance) between local wind-generated waves and swells induced by past wind. Stronger winds (intense hurricane) will result in higher peak wave periods, and higher group velocities. So for a given sub-critical hurricane translation speed, more intense hurricanes are further from the resonance condition. The relative effect of swells would be less important under an intense hurricane than under the situation of a weak hurricane.

4.4. The effect of hurricane wind distribution on waves

Actual hurricanes in nature are usually not symmetric in either wind speed or shape. In all previous experiments (A, B, C), symmetric hurricanes are used. In this subsection, the effect of an asymmetric hurricane wind field on hurricane-induced wave field will be examined. It is important to quantify the effect of wind asymmetry on surface wind waves in order to provide either a justification for the current practice of using symmetric hurricane wind model for wave forecasting, or recommend the use of asymmetric wind models. To evaluate the effects of wind asymmetry on waves, two hurricane wind models are employed to simulate Hurricane Bonnie's (1998) wind field. One is assumed to be symmetric, as simulated by the H1980, and the other to be asym-

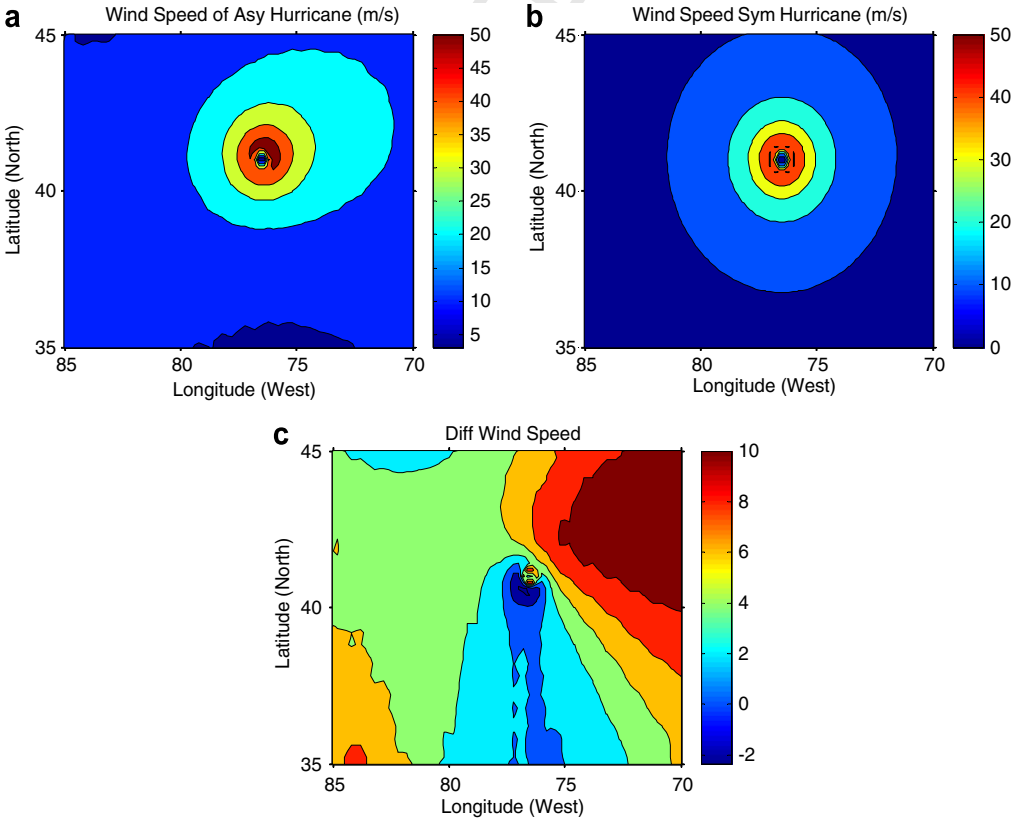

Fig. 10. (a) The distribution of symmetric hurricane wind fields (Bonnie) at 18:00 of Aug 25, 1998; (b) same as (a) but for asymmetric hurricane wind and (c) the difference between these two wind fields.

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metric as simulated by HN2006. These simulations are referred to as Exp. D. The hurricane central pressure, translation speed and RMW are obtained from the NOAA "best track" database.

As Exp. D assumes an actual hurricane forcing, the domain is different from that used for the idealized cases in Exps. A, B, and C. Fig. 9 shows the model domain, extending latitudinally from 25° to 35° north and longitudinally from 85° to 70° west. Bottom topography is derived from the ETOP5 bathymetry database. The tracks of Bonnie and Floyd, which were used in the experiment, are also shown in Fig. 9 (time interval is 3 h). The track data is obtained from the NOAA "best track" database. Fig. 9 also shows the distribution of buoy stations, whose data was used to compare with the model results.

Fig. 10 displays the distribution of two hurricane wind fields and the difference between them at 18:00 of August 25, 1998 in the model domain. It is obvious that wind speeds to the front right of the hurricane track in the asymmetric hurricane are higher than those in the symmetric hurricane. Meanwhile, wind speeds to the rear left of the hurricane track in the asymmetric hurricane are weaker than those in the symmetric hurricane. Intuitively, this asymmetric wind speed distribution would cause the waves to be stronger in the front right areas and weaker in rear left areas than those generated by the symmetric hurricane. The distribution of SWH generated by these two hurricane wind fields and the difference between them are shown in Fig. 11a–c, respectively. It is apparent that the differences among them mainly appear in the front right and rear left quadrants. The SWH generated by the asymmetric hurricane are higher than that induced by the symmetric hurricane in front right areas, as expected. In contrast, the SWH are lower in the rear left areas, also as expected. These differences evidently reflect the asymmetry of the wind speeds. In other words, more wind speed asymmetry causes more asymmetric distribution of waves.

The above analysis clearly indicates the influence of asymmetric hurricane wind structure on waves. Presumably, the asymmetric hurricane wind model (HN2006) should produce more accurate wave forecasts.

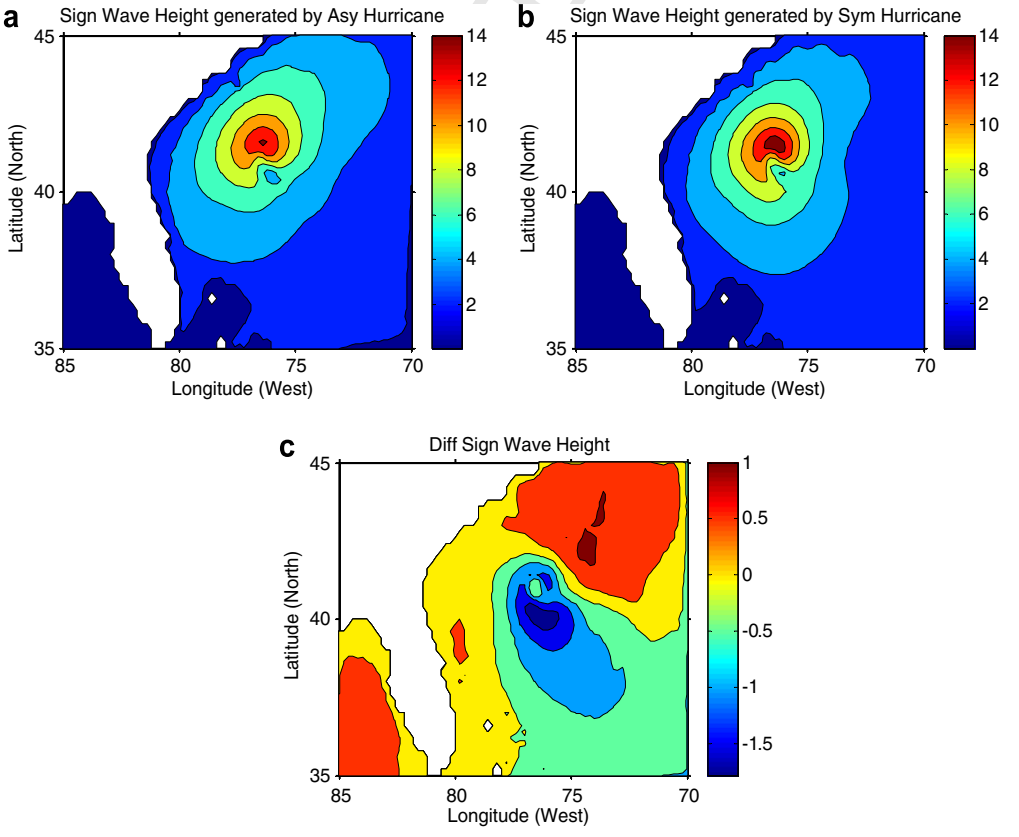

Fig. 11. (a) The distribution of SWH generated by symmetric hurricane wind (Bonnie) at 18:00 of Aug 25, 1998; (b) same as (a) but driven by asymmetric hurricane wind and (c) the difference between these two SWH fields.

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To assess the performance of the wave model driven by the asymmetric, as opposed to the symmetric, hurricane winds, the SWH generated by the two hurricane wind fields and the SWH obtained from the observational data at different buoy stations are compared (Fig. 12). The comparison shows that the SWH generated by the asymmetric hurricane (HN2006) resembles more closely to the buoy data than do that generated by the symmetric hurricane (H1980) in most stations, especially at the Fpsn7 station (shown in Fig. 9), which is located on the right side of Bonnie's track. The root mean square error (RMSE) of SWH generated by HN2006 at three stations (41002, 41004 and Fpsn7) are 0.3182, 1.002 and 0.162 meters, respectively. As a comparison, the RMSE are 0.385, 1.146, and 0.6547 meters, respectively, in the H1980 case. The wind speed at station Fpsn7 is stronger than that at a point the same distance to the left of Bonnie's track. The SWH simulated by the asymmetric wind field agrees very well with the observational data. Compared to the results from the asymmetric wind model, the SWH produced by the symmetric wind field shows a much larger difference from the observations taken at station Fpsn7, clearly indicating an under-prediction. However, compared to the improvement of SWH simulation at station Fpsn7, the improvements at stations 41002 and 41004 are only marginal. This may be due to the fact that stations 41002 and 41004 are located further away from the storm than Fpsn7 (Fig. 9).

4.5. The effect of background wind field on waves

In this subsection, the effect of background wind field on waves will be investigated by using hurricane Floyd ~~(~~1999~~)~~ as an example. Two hurricane wind models are employed to simulate Hurricane Floyd's ~~(1999)~~ winds. One is asymmetric as simulated by the HN2006 without incorporating the background wind

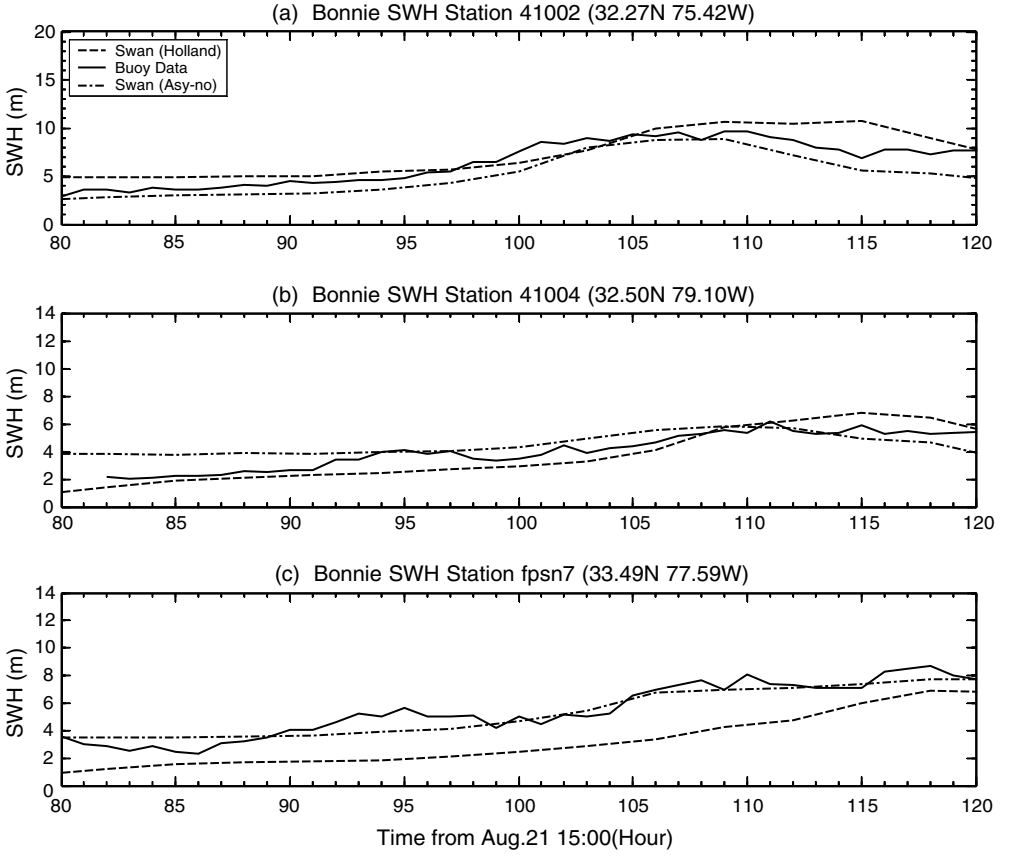

Fig. 12. SWH values during hurricane Bonnie at buoy station (a) 41,002; (b) 41,004 and (c) Fpsn7. Solid line is buoy data, dashed line is model results driven by symmetric hurricane and dot-dash line is model results driven by asymmetric hurricane wind.

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field, and the other is asymmetric as simulated by HN2006, but also incorporates the background wind field. The domain and settings of the parameters used in SWAN wave model are the same as in Section 4.4.

In general, parametric hurricane wind models such as H1980 or HN2006 do not include environmental wind field. Thus, the simulated wind field will be zero before the front edge of a hurricane reaches the model domain. The actual wind field, however, would not be zero even if the storm does not reach the domain because of the presence of an environmental wind field. This phenomenon can be obviously seen from Fig. 13. It shows the wind speed simulated by two hurricane wind models as compared to the observed wind speeds at different buoy stations. The wind speed simulated by HN2006 without the background wind field is almost zero at the beginning (Fig. 13), but the actual wind speed measured by the buoy is clearly not zero. The waves driven by winds simulated by HN2006 without the background wind field is close to zero which is clearly unrealistic before the storm winds enter the domain (Fig. 14). On the other hand, the wind speed modeled by HN2006 with a merged background wind field is much closer to the observations during the early hours (Fig. 13). The RMSE of wind speed simulated by HN2006 with a merged background wind field at three stations (41004, 41008 and Fpsn7) are 1.044, 0.927 and 0.836 (m/s), respectively, during the first 24 h. As a comparison, the RMSE are 1.205, 1.285, and 1.047 (m/s), respectively, in HN2006 without the background wind field. Fig. 14 also shows the SWH generated by the two hurricane wind fields and the SWH obtained from the observational data at different buoy stations. These figures show that the SWH produced by the merged hurricane and background wind field (RMSE are 0.182, 0.226 and 0.199 m at stations 41004, 41008 and Fpsn7, respectively) is better than those generated by HN2006 alone (RMSE are 0.621, 0.304 and

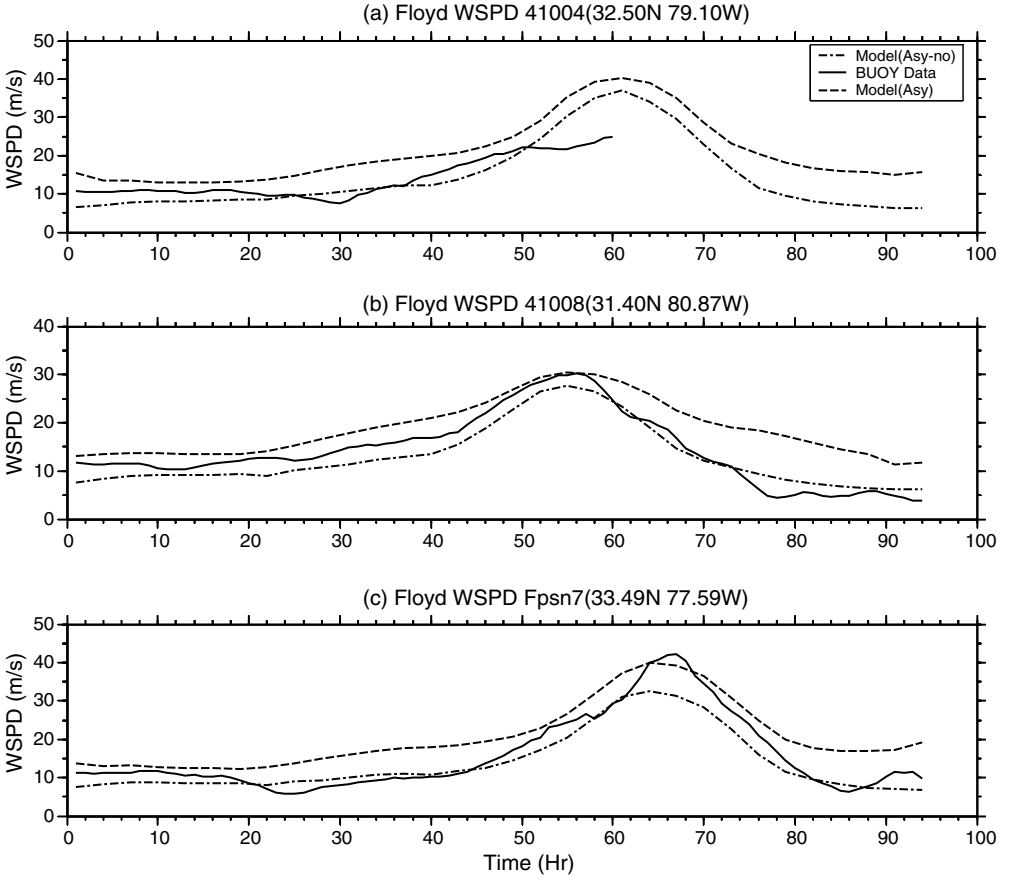

Fig. 13. Wind speed during hurricane Floyd at buoy station (a) 41,004; (b) 41,008 and (c) Fpsn7. Solid line is buoy data, dashed line is the result of asymmetric hurricane model including background wind field and dot-dashed line is the result of asymmetric hurricane model without background wind field.

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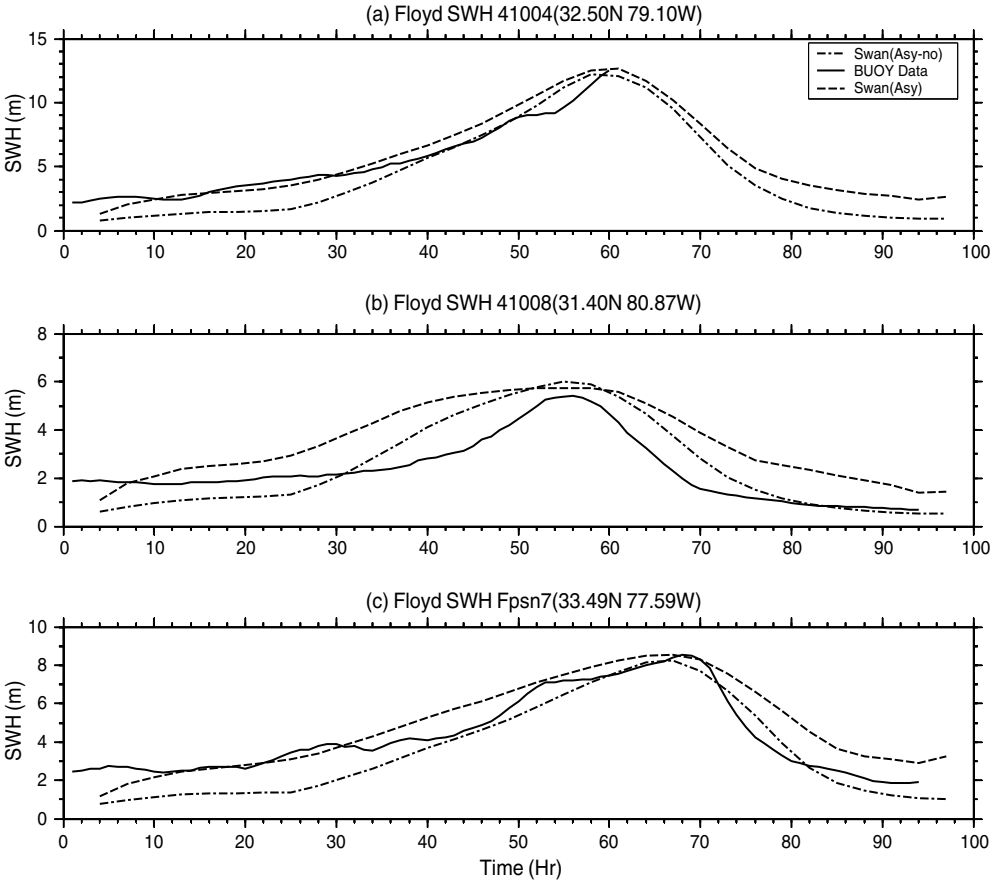

Fig. 14. Same as Fig. 13 but for SWH field.

0.575 m) during the first 24 h. It should be noted that, as seen from Fig. 13, including the background winds improves the overall wind speed in the early hours, but not necessarily better than the stand-along HN2006 after the storm's winds reaches the buoy, suggesting that whether or not including background winds is not critical for the prediction of the peak waves produced by a storm.

5. Discussion and conclusions

In this study, the effect of hurricane wind distribution, translation speed, intensity, and background wind field on sea surface wind waves was examined by using the SWAN wave model.

The results suggest that the hurricane translation speed makes a significant contribution to the asymmetric structure of the waves. Furthermore, the translation speed can enhance of the SWH in the front-right quadrant of the hurricane track because of the resonance effect. This effect is significant when the hurricane translation speed increases to a value comparable to the group speed of the dominant waves; but small when the hurricane translation speed is much larger or less than the group speed of the dominant waves. On the other hand, the translation speed can reduce the value of the SWH in the rear-left quadrant of the hurricane track because of a lessening of the wind forcing time and effective fetch. However, the waves may gain some energy when the hurricane translation speed increases to the level that is comparable to the group speed of the dominant waves.

The effect of hurricane intensity on waves is found to be such that SWH increases with increasing wind speed. On the other hand, the hurricane translation speed causes less asymmetry for more intense hurricanes than for weaker storms. Another factor affecting the structure of the wind waves is the asymmetric distribution

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of hurricane winds. Considering the actual asymmetric structure of a hurricane can considerably alter the SWH distribution produced by the hurricane and improve the skill of wind wave prediction. The effect of background wind field on waves can be significant before the effect of hurricanes reaches the forecast domain. Thus, the prediction of the wave SWH in the initial hours can be improved by merging the environmental wind field into the hurricane wind field.

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References

Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions, 1. Model description and validation. J. Geophys. Res. 104 (C4), 7649–7666.

Bowyer, P.J., MacAfee, A.W., 2000. The theory of trapped-fetch waves with tropical cyclones – an operational perspective. Weather Forecast. 20, 229–244.

Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E., Kruseman, P., Meerburg, A., Müller, P., Olbers, D.J., Richter, K., Sell, W., Walden, H., 1973. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Dtsch. Hydrogr. Z. Suppl. 12, A8.

Holland, G.J., 1980. An analytic model of the wind and pressure profiles in Hurricanes. Mon. Wea. Rev. 108, 121–1218.

King, D.B., Shemdin, O.H., 1978. Radar observations of hurricane wave directions, paper presented at 16th International Conference on Coastal Engineering, Hamburg, Germany.

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M., 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press, New York, 532 pp..

Kurihara, Y., Bender, M.A., Ross, R.J., 1993. An initialization scheme of hurricane models by vortex specification. Mon. Wea. Rev. 121, 2030–2045.

Miles, J.W., 1957. On the generation of surface waves by shear flows. J. Fluid Mech. 3, 185–204.

Moon, I.J., Ginis, I., Hara, T., Tolman, H.L., Wright, C.W., Walsh, E.J., 2003. Numerical simulation of sea surface directional wave spectra under hurricane wind forcing. J. Phys. Ocean. 33, 1680–1760.

Moon, I.J., Ginis, I., Hara, T., 2004. Effect of surface waves on air-sea momentum exchange. Part II: behavior of drag coefficient under tropical cyclones. J. Atm. Sci. 61, 2334–2348.

Ou, Shan-Hwei, Liau, Jian-Ming, Hsu, Tai-Wen, Tzang, Shiaw-Yih, 2002. Simulating typhoon waves by SWAN wave model in coastal waters of Taiwan. Ocean Eng. 29, 947–971.

Phillips, O.M., 1957. On the generation of waves by turbulent wind. J. Fluid Mech. 27, 4815–4827.

Ris, R.C., Holthuijsen, L.H., Booij, N., 1999. A third-generation wave model for coastal regions, 2. Verification. J. Geophys. Res. 104 (C4), 7667–7681.

Tolman, H.L., 1991. A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. J. Phys. Oceanogr. 21, 782–797.

Walsh, E.J., Wright, C.W., Vandemark, D., Krabil, W.B., Garcia, A.W., Houston, S.H., Murillo, S.T., Powell, M.D., Black, P.G., Marks, F.D., 2002. Hurricane directional wave spectrum spatial variation at landfall. J. Phys. Oceanogr. 32, 1667–1684.

WAMDI Group, 1988. A third-generation model for wind waves on slowing varying, unsteady and inhomogeneous depths and currents. J. Phys. Oceanogr. 21, 782–797.

Wang, D.W., Mitchell, D.A., Teague, W.J., Jarosz, E., Hulbert, M.S., 2005. Extreme waves under hurricane Ivan. Science 309, 896.

Wright, C.W., Walsh, E.J., Vandemark, D., Krabil, W.B., Garcia, A.W., Houston, S.H., Powell, M.D., Black, P.G., Marks, F.D., 2001. Hurricane directional wave spectrum spatial variation in the open ocean. J. Phys. Oceanogr. 31, 2472–2488.

Xie, L., Wu, K., Pietrafesa, L.J., Zhang, C., 2001. A numerical study of wave–current interaction through surface and bottom stresses: wind-driven circulation in the South Atlantic Bight under uniform winds. J. Geophys. Res. 106 (C8), 16841–16855.

Xie, L., Bao, S., Pietrafesa, L.J., Foley, K., Fuentes, M., 2006. A real-time hurricane surface wind forecasting model: formulation and verification. Mon. Wea. Rev. 134, 1355–1370.

Young, I.R., 1988. Parametric hurricane wave prediction model. J. Waterway Port Coastal Ocean Eng. 114, 637–652.

Young, I.R., 2006. Directional spectra of hurricane wind waves. J. Geophys. Res. 111 (C8), C08020. doi:10.1029/2006JC003540.

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