Wind-Wave Relationship Model and Analysis of Typhoon Wave Fields in the South China Sea From HY-2A Satellite Observations

Zengzhou Hao, Qianguang Tu, Siqi Zhang, Jianyu Chen, and Delu Pan

***Abstract*—Significant wave height is an important parameter for characterizing ocean surface waves. With the development of remote sensing technology, satellite radar altimetry has become an essential tool for obtaining significant wave height estimations. However, its measurement only covers the satellite track on the ground and cannot be applied to large regions or areas. In this study, we obtained significant wave height from the Hai Yang-2A (HY-2A) radar altimeter and sea surface wind speed at a 10-m height from the HY-2A microwave scatterometer for October 2013, and then proposed a wind-wave relationship model for the South China Sea using linear/nonlinear regression analysis at high/low wind speeds (0–40 m s^{-1}). By comparison with two other wind-wave models and validation with HY-2A observations in November 2013, our results show that the proposed wind-wave relationship model is credible, and at low wind speed exhibited good consistency with the wind-wave model from *in situ* observations. According to the proposed model, significant wave height from the HY-2A microwave scatterometer-retrieved wind speed and ocean wind wave analysis during the "1329" Typhoon Krosa were successfully obtained and determined. Data coverage of the computed significant wave height was far wider than that of the satellite radar altimeter observations and demonstrated development of typhoon wave fields over a large region. Overall, this study and proposed model provide useful information for the analysis and forecast of typhoon waves and potential storm surge disasters.**

***Index Terms*—Hai Yang-2A (HY-2A) satellite, significant wave height, South China Sea, typhoon, wind field, wind-wave model.**

I. Introduction

OCEAN wind waves, which are small-scale surface gravity waves generated by wind, affect the exchange of material, energy, and momentum at the air–sea interface and within the internal upper ocean [1], [2]. In general, sea state consists of local generated wind sea and swells [3], [4]. Local generated wind sea, or wind waves, are waves that occur on the ocean surface due to the local wind field, whereas swells are a series of waves that propagate from other places [5], [6]. These waves are common and natural phenomena in the ocean; however, very large ocean wind waves can threaten marine activities, such as navigation, fisheries, marine engineering, and military activities, and can also breach and damage sea embankments, harbors, and coastal constructions [7]. Therefore, it is important for marine scientific research and wave disaster analysis to observe and potentially forecast ocean wind waves effectively.

Significant wave height is an important parameter to characterize ocean surface waves. While traditional *in situ* observations obtained from buoys or ships are spatially limited, measurements from remote sensing technology, such as altimeters, spectrometers, and synthetic aperture radars, can cover wide or large regions [8]. Since July 1991, more than ten satellite altimeters have provided almost continuous significant wave height measurements [9]. However, due to the limitations of radar principles, significant wave height observations based on altimeters are still recorded along the subsatellite track at nadir and only cover the global ocean once every 10–35 d. In comparison, sea surface temperatures and wind fields observed from space cover 90% of the global ocean each day. Thus, satellite-based radar altimeter technology does not yet meet the demands of wave forecasting and actual application.

Researchers have studied the wave spectrum since the mid-twentieth century and have attempted to build a simple correlation between wave height and wind speed for ocean wind wave forecasting [10], [11]. Many wind-wave models have been proposed based on empirical relationships between the present state of the sea, expected wind conditions, and direction of wave propagation [12]–[17], for example, the pioneering work of the Joint North Sea Wave Project (JONSWAP) derives a wave spectrum model [13], which have been tested to predict wave height from local wind fields [18]. And some evolutions of the wave spectrum are described as the sum of the local wind input, wave dissipation, nonlinear wave-wave interaction and the propagation of waves from nonlocal sources based on the physical-based wave modeling, such as the WAVEWATCH model [19], WAM model [20], and SWAN model [21]. Other studies have also focused on the relationship between wind

Manuscript received April 23, 2020; revised June 23, 2020; accepted July 1, 2020. Date of publication July 7, 2020; date of current version July 22, 2020. This research was supported in part by the National Key Research and Development Program of China under Grant 2016YFC1401903 and in part by the "Global Change and Air-Sea Interaction" project of China under Grant JC-PAC-YGST and Grant JC-SCS-YGST. *(Corresponding author: Zengzhou Hao.)*

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Digital Object Identifier 10.1109/JSTARS.2020.3007495

stress and wave slope, thus describing the transfer of energy and momentum directly from wind to surface waves [22]–[28]. To summarize, for wind-generated waves, the subject of the present paper, previous studies have estimated various nonlinear relationships between significant wave height and wind speed based on *in situ* observations or measurements over the Arabian Sea, Bay of Bengal [29], Nordic seas [30], the Gulf of Mexico [31], UK coastal waters [32], [33], and other regions [34], [35].

Additionally, several studies have been presented and revealed the wind-wave relationship based on satellite observations. Some authors only use satellite radar altimeter measurements, such as SEASAT [36], GEOSAT [37] and Jason-1 [38], and others use the coincident measurements of wind speed from scatterometer and significant wave height from altimeter, for example, using coincident measurements of wind speed from NSCAT or QSCAT and significant wave height from TOPEX or ERS-2 [39], [40]. The Hai Yang-2A (HY-2A), which is the first Chinese marine dynamics environmental satellite, simultaneously observes wind and waves from space, and therefore it may be possible to obtain a wind and wave relationship model.

We used the HY-2A satellite data to construct a wind-wave relationship model over the South China Sea and then analyzed ocean wind waves during a typhoon event from satellite-retrieved wind speed using the proposed model. Details on the HY-2A satellite observations and methods for data quality control and swell elimination are described, in Sections II and III, respectively. The wind-wave relationship model was established, validated, and applied to analyze ocean wind waves during a typhoon, as discussed in Section IV. Discussion and conclusions are presented in Sections V and VI.

II. Data and Methods

A. HY-2A Satellite Observations and Retrievals

The HY-2A satellite, launched on 16 August 2011, is the first Chinese marine dynamics environmental satellite. Its initial sun synchronous orbit occurred at a 971-km altitude and 99.34°, with a 14-d cycle during its first two years. Since then, it has taken a geodetic orbit at a 973-km altitude, with a 168-d cycle and 5-d subcycle. The objective of HY-2A is to monitor ocean dynamics with four microwave sensors, including a radar altimeter, microwave scatterometer, microwave radiometer, and atmosphere correction radiometer. The radar altimeter measures sea surface height, significant wave height, and wind speed, whereas the microwave scatterometer measures the sea surface wind fields at a 10-m height [41]. Further details are as follows.

1) The HY-2A microwave scatterometer uses pencil beam conical scanning mode and has a wide area of observation, with a swath of $\sim$1750 km and ground resolution of 25 km. Therefore, it can cover more than 90% of the global ocean within one day. Based on the relationship between the wind field at 10 m and the backscattering coefficient, the geophysical model function can be established and the sea surface wind field at a 10-m height can then be retrieved indirectly from the backward scattering coefficient, which can be measured using the HY-2A microwave scatterometer [42]. By validation with the *in situ* observations, other remote sensed and model data, its wind speed measurement precision is less than 2.1 m s^{-1} and wind direction accuracy is less than 26° [43]–[47].
2) The HY-2A radar altimeter is an active microwave sensor that uses a dual-frequency observation system: i.e., Ku band (13.58 GHz) and C band (5.25 GHz). By analyzing the echo characteristics to launching pulse signal vertically, the sea surface height and significant wave height can be obtained [48]. Significant wave height measurement ranges from 0.5 to 20 m and measurement accuracy is less than 10% or 0.5 m [49]–[52].

The satellite observations used in this article, which covered the South China Sea basin (100°–125°E, 0°–26°N) from October to November 2013, were provided by the Chinese National Satellite Ocean Application Service. The data were divided into two parts, one of which was used to establish the wind-wave relationship model in October and the other for validation and application in November. The data tracks on 1–15 and 16–30 October are shown in Fig. 1, which indicate that the observations were repeated within 14 d but did not cover the whole region.

B. Quality Control for Satellite Observations

For sea surface wind speed at a 10-m height (U_{10}), the wind speed was required to be in the range of 0–40 m s^{-1}. Based on the assumption that the wind vector exhibits continuous temporal and spatial changes, each observation point for the sea surface wind vector was taken as the center, and the surrounding inversion data observation points within the 5 $\times$ 5 window were taken as sample points; two conditions were met: 1) the difference between the wind speed observed at the observation point and the average value of wind speeds observed around the points within the 5 $\times$ 5 window was less than 2 m s^{-1}; and 2) the standard deviation of wind speeds within the 5 $\times$ 5 window was less than 1 m s^{-1}. Thus, the data observed at the sea surface wind vector observation points were taken as valid sea surface wind vector data.

For significant wave height ($H_{1/3}$), according to standard criteria provided by the user manual of the HY-2A satellite radar altimeter [53], invalid data caused by abnormal observations, missing data, error calibration, and inversion of echo waveform, were eliminated from further analysis. In addition, the ocean wind waves were assumed to be continuous, that is, the changes in significant wave height were spatially continuous. Two conditions were met: 1) the absolute difference between the observation value at nadir and the significant wave height at an adjacent point was less than 1 m; and 2) the standard deviation of the significant wave height observed within the 5 $\times$ 5 window around nadir was less than 1 m. Such observation values were taken as valid significant wave heights.

C. Elimination of Swell-Affected $H_{1/3}$

Radar altimeter-measured $H_{1/3}$ reflects the combination of wind waves and swells. To estimate the relationship between $H_{1/3}$ and U_{10} under wind-wave conditions, it is necessary to remove the swell-affected $H_{1/3}$ and retain the observations under pure wind-wave conditions as far as possible. Many different

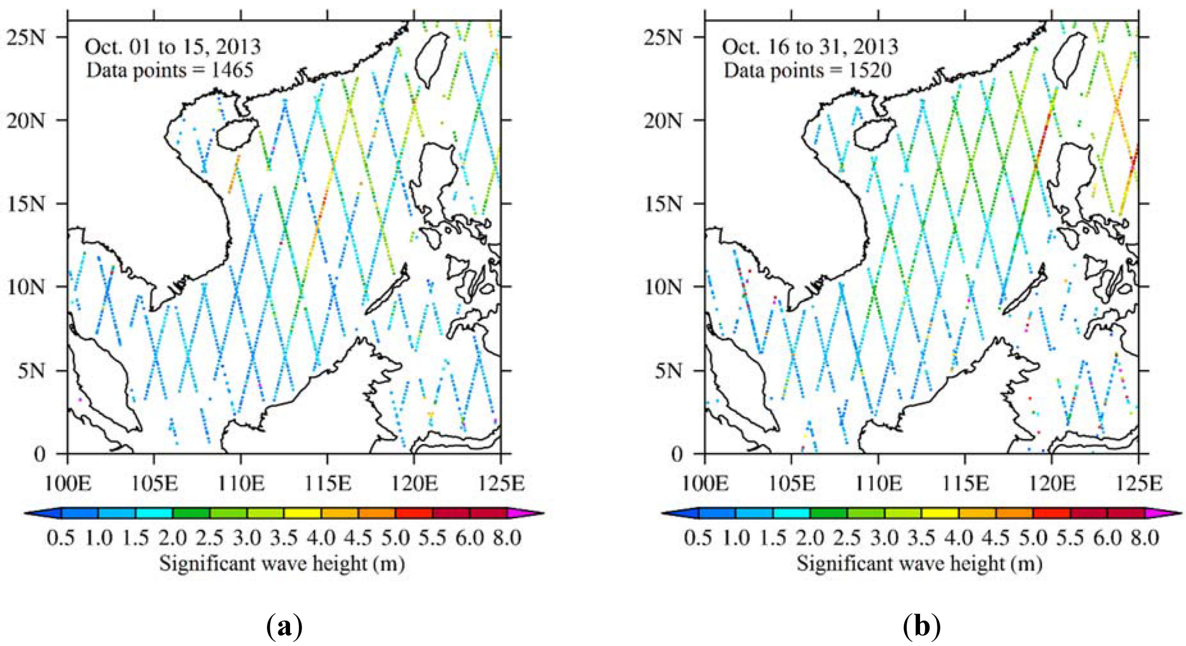

Fig. 1. Data tracks of HY-2A radar altimeter-retrieved significant wave height from the South China Sea. (a) 1–15 October 2013. (b) 16–31 October 2013.

methods have been proposed to distinguish wind-waves and swells [54]–[57]. In our study, the criterion applicable to satellite altimetry proposed by Pandey (1986) was used to distinguish wind-wave and swell from wave energy [29].

First, according to the Longuet–Higgins relationship [58], the wave energy contained in the wave characterized by altimetric measurements (E_{alt}) was calculated from the satellite-retrieved $H_{1/3}$, and expressed as follows:

$$E_{\mathrm{alt}} = 0.0625\left(H_{1/3}\right)^2. \tag{1}$$

Second, with the same concepts as E_{alt} and based on the Pierson and Moskowitz wave spectrum [12] and empirical relationship proposed by Mognard [59], the wave energy for the fully developed sea (E_{fd}) was calculated from U_{10}, which was measured concurrently with microwave scatterometer measurements from HY-2A, and expressed as follows:

$$E_{\mathrm{fd}} = 0.0625\left(H_{1/3}\right)_{\mathrm{fd}}^2 \tag{2}$$

where $(H_{1/3})_{\mathrm{fd}} = 0.025{U_{10}}^2$.

Finally, the difference between the total wave energy (E_{alt}) and the fully grown wave energy (E_{fd}) were regarded as the swell energy. Therefore, when E_{alt} is less than or equal to E_{fd}, the effect of swell is minimal, and the extracted data can be used as pure wind-wave conditions. That is, when $E_{\mathrm{alt}} > E_{\mathrm{fd}}$, the swell-affected $H_{1/3}$ can be removed.

After quality control for satellite observations and removing swell-affected $H_{1/3}$, a total of 931 matched-up points (see Fig. 2), which accounted for 2985 data points for concurrent $H_{1/3}$ and U_{10} measurements for October 2013 (see Fig. 1), were retained as pure wind-wave conditions. As seen from Fig. 2, their distribution was almost uniform over the South China Sea region. The results obtained from the matched-up data can represent the wind-wave characteristics in the South China Sea.

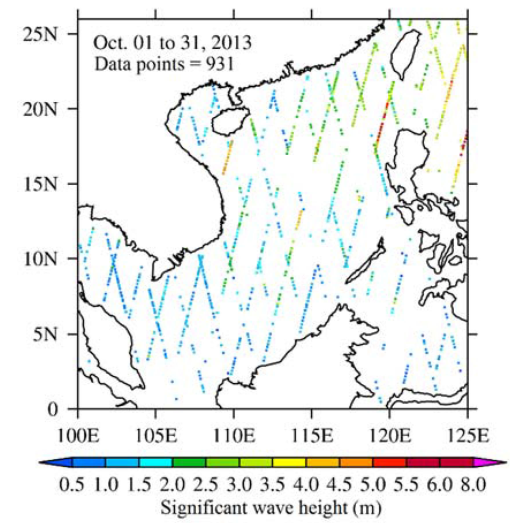

Fig. 2. Data track of significant wave height for wind-waves in the South China Sea, in October 2013.

III. Results

A. Wind-Wave Relationship Model

To construct the wind-wave relationship model at low and high wind speed, respectively, the above matched-up data points were divided into two subsets using a threshold wind speed value of 16 m s^{-1}. The U_{10} versus $H_{1/3}$ plots are shown in Fig. 3, which demonstrate nonlinear behavior at low wind speeds but a linear relationship at high wind speeds, consistent with previous

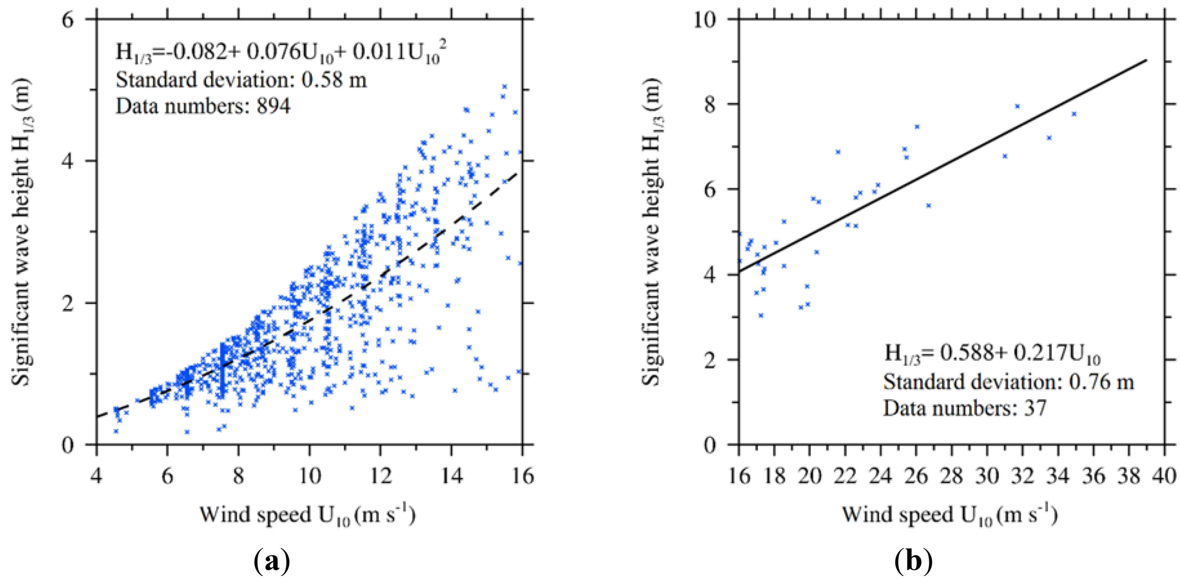

Fig. 3. Relationship between significant wave height and wind speed. (a) Low wind speed. (b) High wind speed.

literature [29]–[40]. Under low wind speed, the fitted significant wave height $H_{1/3}$ was less than 3.95 m, with a standard deviation of 0.58 m, whereas under high wind speeds, the fitted $H_{1/3}$ was more than 4.06 m, with a standard deviation of 0.76 m.

The two fitted $H_{1/3}$ values at the division wind speed of 16 m s^{-1} did not accord well, showing a difference of about 0.11 m. To eliminate this difference and maintain uniform continuity with wind speed, the intersection of the two curves was selected, where U_{10} was 16.808 m s^{-1}. Thus, the wind-wave model in the South China Sea was established as follows:

$$H_{1/3} = \begin{cases} -0.082 + 0.076 \times U_{10} + 0.011 \times U_{10}^2 & 0 < U_{10} \leq 16.808 \\ 0.588 + 0.217 \times U_{10} & 16.808 < U_{10} < 40 \end{cases}. \tag{3}$$

The correlation coefficients between the $H_{1/3}$ fittings from formula (3) and HY-2A satellite observed $H_{1/3}$ was 0.83.

B. Validation of Wind-Wave Relationship Model

To assess and verify our proposed wind-wave relationship model, the Pierson–Moskowitz wave model (PM model) [12], based on the assumption of a completely unbiased relationship development theory, and the Thiruvengadathan model (T model) [see 29], established based on buoy measurements, are selected with the following relations in (4) and (5). For low wind speed, the models have similar nonlinear variation characteristics, with the proposed wind-wave relationship model highly consistent with the T model. While our proposed linear model at higher wind speeds can moderate their divergence caused by the quadratic function of the other two.

$$H_{1/3} = 0.025 \times U_{10}^2 \tag{4}$$

$$H_{1/3} = 0.17 + 0.0087 \times U_{10} + 0.014167 \times U_{10}^2. \tag{5}$$

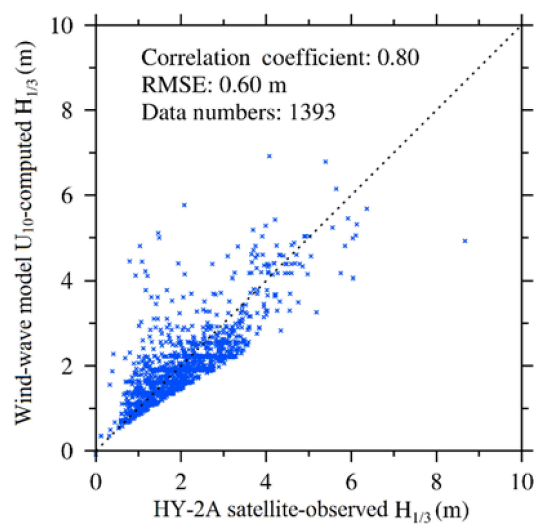

Fig. 4. Validation of the wind-wave model from this study.

To validate the accuracy of our model, concurrent $H_{1/3}$ and U_{10} observations from HY-2A in November 2013 were selected by the process of quality control and swell elimination. A total of 1393 data points between the U_{10}-computed $H_{1/3}$ and HY-2A satellite-observed $H_{1/3}$ were compared, as shown in Fig. 4. Their correlation coefficient was 0.8 and the root mean square error was 0.6 m, indicating that the established wind-wave relationship model was reliable.

C. Analysis of Storm Waves From "1329" Typhoon Krosa

The "1329" Typhoon Krosa formed in the northwest Pacific Ocean on 30 October 2013, moved westward stably and entered the northeast region of the South China Sea northeast of Luzon island at about 03:00 A.M. on 1 November. It intensified into a strong typhoon at 11:00 P.M. on 1 November, then weakens

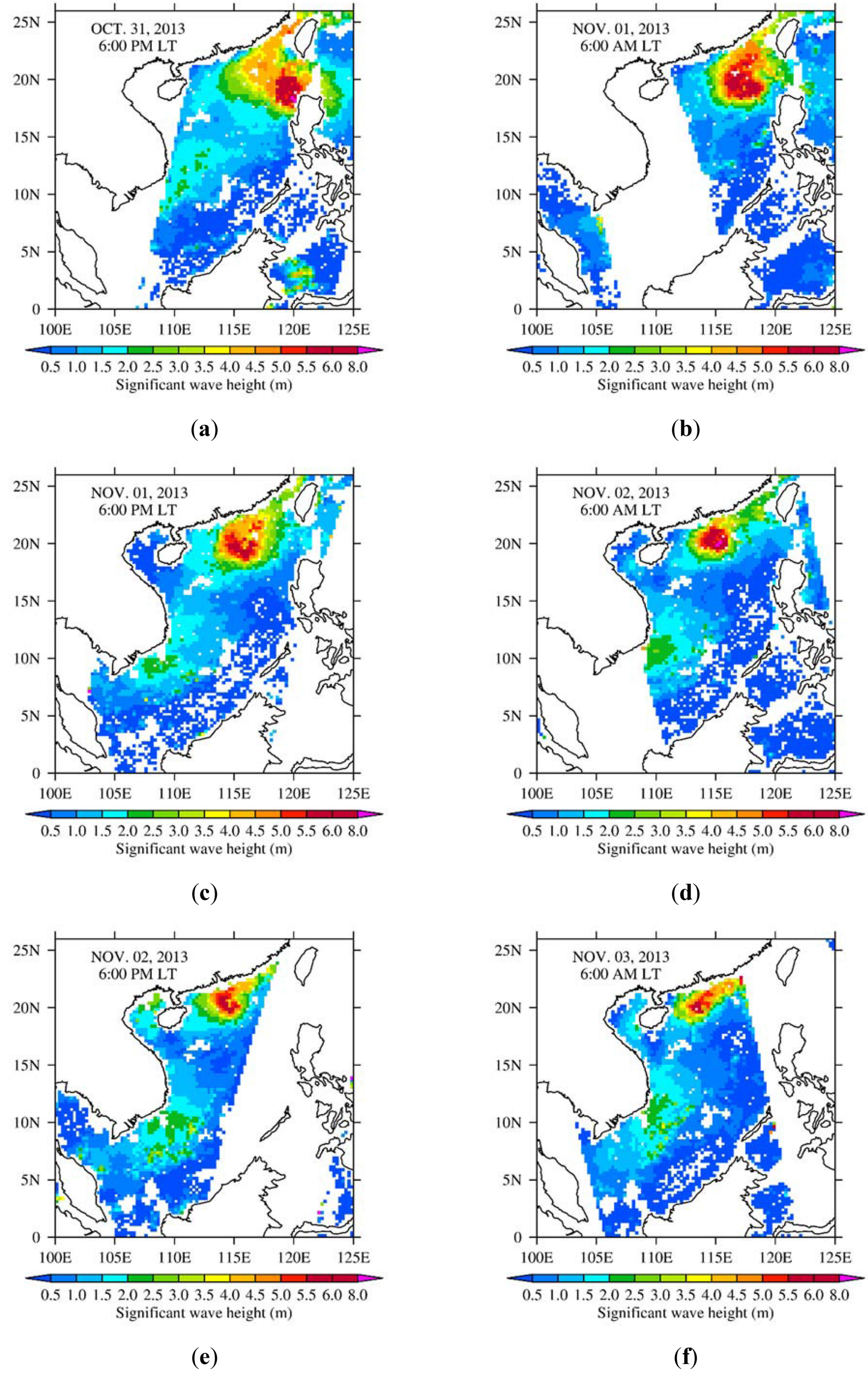

Fig. 5. Computed significant wave height at six consecutive time points during Typhoon Krosa: (a) 6:00 P.M. local time, 31 October 2013; (b) 6:00 A.M. local time, 1 November 2013; (c) 6:00 P.M. local time, 1 November 2013; (d) 6:00 A.M. local time, 2 November 2013; (e) 6:00 P.M. local time, 2 November 2013; (f) 6:00 A.M. local time, 2 November 2013.

from 3 November and became a tropical storm at 12:00 P.M. on 3 November. During this process, it caused surges in the South China Sea. Using the proposed wind-wave relationship model, the significant wave heights during this typhoon event were calculated from the satellite-retrieved wind speeds. Fig. 5 shows the computed significant wave height at six consecutive time points. Our results clearly revealed the distribution and variation of ocean wind waves as the typhoon entered the South China Sea to its weakening into a tropical storm. The highest significant wave height during this typhoon event was about 8 m and the higher significant wave heights were concentrated in the area surrounding the typhoon center. With the development of the typhoon, the significant wave height also decreased gradually and became a strip parallel to the coast at about 06:00 A.M. on 3 November. These results not only demonstrated the distribution and variation in significant wave height during Typhoon Krosa, but could also be used to analyze, forecast, and prevent typhoon waves and storm surge disasters in the future.

IV. Discussion

A wind-wave relationship model from the HY-2A satellite observations for wind and wave fields is built and applied successfully to analysis of storm waves in the South China Sea. Although the proposed model is only based on the one-month observations, the match-up points are filled and have uniform distribution over the South China Sea region. Our proposed wind-wave relationship model is similar with the theoretical PM model and has a good consistency with the observation-based T model at the lower wind speed. However, the higher is wind speeds, the more divergent is significant wave height obtained from those two models. For high wind speeds, the proposed linear model is reasonable and can moderate their divergences. Additionally, the model computed $H_{1/3}$ from HY-2A Scattermeter-retrieved U_{10} is close to the HY-2A Altimeter-observed $H_{1/3}$ for the other observations, their correlation coefficient is about 0.8 and the root mean square error is 0.6 m. Therefore, it is reasonable to believe that our model could show the wind-wave characteristics in the South China Sea.

To construct the wind-wave relationship model, poor and swell-affected observations were removed as soon as possible by the data quality control procedure and the ocean wind wave energy relationship criteria. However, it is noticed that this model is an empirical one based on HY-2A observations. When significant wave height on a large area is forecast from other satellite-retrieved wind speeds using this model, the systematic bias between HY-2A-retrieved wind speed and others needs to be considered and adjusted in advance.

In addition, this study focused on the significant wave height of wind-waves over a large region; however, to express ocean surface waves accurately, swell-produced significant wave height still needs to be considered and added to the comprehensive analysis of sea state in the future.

V. Conclusion

Based on HY-2A satellite observations, we established a wind-wave relationship model at high and low wind speeds in the South China Sea and determined significant wave height over a large region during the occurrence of a typhoon. By comparison with two other models, the proposed wind-wave model at low wind speed exhibited good consistency with the model based on *in situ* measurements and at high wind speed improved their divergences. At the same time, comparing the significant wave heights obtained from the satellite-observed wind fields with those obtained using the wind-wave model showed the model to be feasible and valid. Furthermore, the computed significant wave height from the HY-2A-observed wind speed using the model provided considerable ocean wind wave distribution data over a large region, thereby greatly expanding the observation area to over 90% of the ocean and providing superior information compared with radar altimeter observations at nadir. As an example, the continuous distribution and development of significant wave height for typhoon waves were clearly displayed. Thus, the wave fields obtained from the satellite-retrieved wind speeds using the proposed model can provide more valuable information for ocean wind wave analysis and could be used to potentially forecast ocean wind waves and reduce storm disasters in the future.

To construct the wind-wave relationship model, poor and swell-affected observations were removed by quality control and wave energy relationship criteria. However, this model is an empirical one based on HY-2A observations. When significant wave height is forecast from other satellite-retrieved wind speeds using this model, the systematic bias between HY-2A-retrieved wind speed and others needs to be considered and adjusted in advance. In addition, this study focused on the significant wave height of wind-waves over a large region, however, to express ocean surface waves accurately, swell-produced significant wave height still needs to be considered and added to the comprehensive analysis of sea state in the future.

Acknowledgments

The authors would like to thank the Chinese National Satellite Ocean Application Service for providing the HY-2A satellite observations and retrievals.

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