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Modelling of Extreme Wave Climate in China Seas

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ABSTRACT

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Accurately estimating the extreme wave climate is important to the ocean and coastal engineering design. In this study, the long-term wave climate from 1979 to 2013 over the northwest Pacific Ocean, centred at the China Seas (including the East China Seas and the South China Sea), is hindcasted by using the spectral wave model WAMC4. The model is driven by the wind forcing obtained from the recently released 6 hourly ECMWF (European Centre for Medium-range Weather Forecasts) reanalysis data, with the spatial resolution of 0.125°×0.125°. For the typhoon events, the parametric typhoon wind fields are generated and blended in the typhoon affected area. The statistical analysis of the extreme waves with 100-year return period at several observation stations are carried out. The results show a good agreement with the observation data, indicating that using the blended wind field for the modelling of extreme wave climate in China Seas can considerably improve the accuracy of the predicted wave heights.

ADDITIONAL INDEX WORDS: *Parametric typhoon model, ECMWF reanalysis data, WAMC4 wave model.*

INTRODUCTION

The region of China's Seas, which includes the East China Seas (Bohai Sea, Yellow Sea and East China Sea) and part of the South China Sea (Figure 1), are often threatened by extreme events like typhoons and storm waves (Xiao *et al*., 2011). Better understanding of the extreme wave climate in this region is essential to safe and economic design for coastal engineering.

Usually extreme wave statistics are calculated based on the long-term field measurement data (Qi *et al*., 1998; Wang and Yi., 1997; Liu and Sun., 2000; Chen *et al*., 2006). However, due to the low spatial resolution of the data, it is difficult to obtain the extreme wave climate in the whole area. Alternatively, wave mapping from modelling results could be used to study the temporal and spatial distributions of extreme waves in a larger area (Valchev *et al*., 2010; Yamaguchi, 2002; Yamaguchi and Hatada, 2003 and Lee and Jun, 2006), provided that wave models used are well calibrated and validated. The accuracy of the model predictions depends heavily on the accuracy of the wind field generated by weather models as the surface forcing. It is well known that wave height is proportional to the square of wind speed, where 10% error in wind speed may result in an error of at least 20% in hind-casted wave heights (Tolman, 1998). Therefore, accuracy of input wind forcing is important to the wave model. In the past, one challenge in long-term wave simulations was the availability of reliable wind data required for wave models. Nowadays, high quality long-term reanalysis wind data have been made available from agencies such as ECMWF and NCEP.

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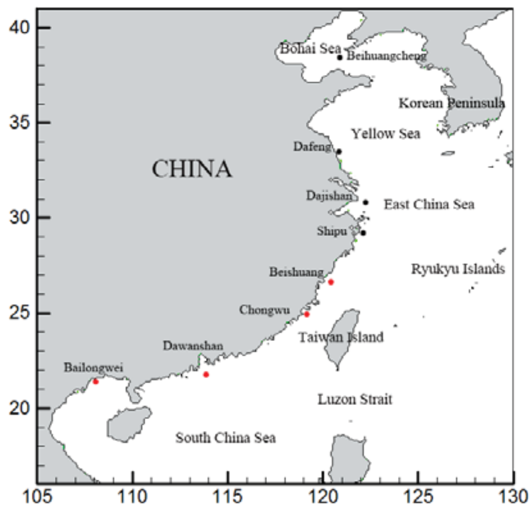

Figure 1. The region of China Seas and the locations of eight observation stations, of which four stations in the region of East China Seas, marked as black point, and the other four stations in the South China Sea, marked as red point.

In the region of China Seas, a number of relevant studies have been carried out. For example, Lv *et al.* (2014) used the 0.25°×0.25° ECMWF reanalysis wind data to drive the SWAN model for 20-year wave hind-casting in the Bohai Sea and then analysed the annual and seasonal distributions of significant wave height, wave period and wave direction in that area. Zheng and Li (2015) used the CCMP wind data to drive the WAVEWATCH III (WW3) model for wave hind-casting in the whole China Seas over 24 years. Chen *et al.* (2013) used the NCEP/NCAR reanalysis wind data, which has the spatial resolution of 2.5°×2.5°, to drive the WAM model for 60 years' wave hind-casting in the East China Seas (Bohai Sea, Yellow Sea and the East China Sea) and the results were further used to estimate the extreme waves with 50-year and 100-year return periods in the East China Seas. Zheng *et al.* (2014) used the Quick SCAT/NCEP wind data to drive the WW3 wave model and calculate the extreme wave height with return periods of 20 years and 30 years in the East China Sea.

Although the reanalysis wind data performs well in describing the normal average weather climate, the resolution is often insufficiently high enough to describe the atmospheric forcing during a typhoon event (Appendini et al., 2013). As the large waves generated by the strong winds during a typhoon are what we are concerned most, here we propose to superpose the parametric typhoon wind field on the reanalysis data during the typhoon event, in order to improve the description of performance of the wind field data in the typhoon affected area. This study uses the ECMWF reanalysis wind as the background wind field, and blends the wind field generated from a parametric typhoon wind model in the typhoon affected area onto it. The resulting wind field and the unblended ECMWF reanalysis wind field are then used to drive the wave model to hind-cast the wave climate in the region of China Seas over 35 years. The extreme waves with 100-year return period are calculated by using the Gumbel distributions from the annual maximum wave heights of the hind-casted waves. The extreme wave heights at several observation stations are compared with the observation data, so that the relative accuracy of the estimated extreme wave heights can be assessed from both wind fields.

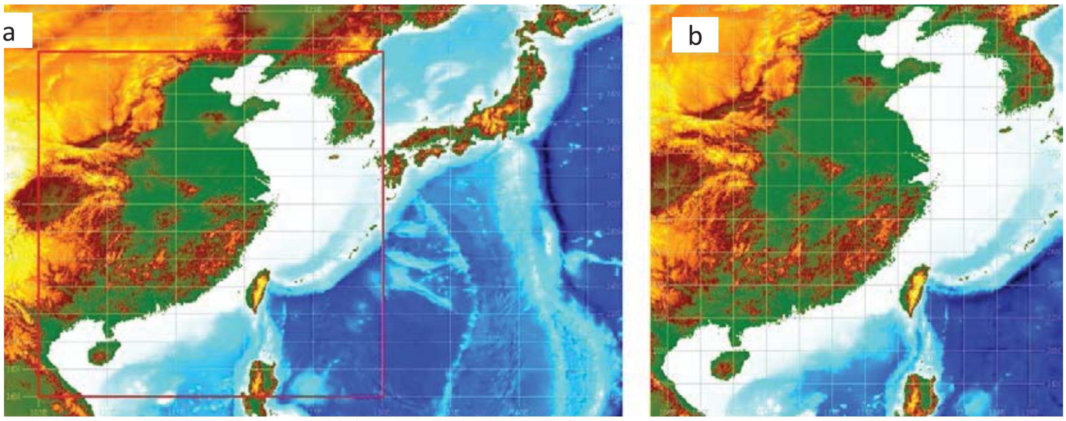

Figure 2. The two-level nested domains: (a) coarse grid domain and (b) fine grid domain

METHODS

The wave model used in this study is the latest version WAM model, namely WAMC4. The model solves the wave energy transport equation explicitly without any pre-described shape of wave spectrum. The WAM model simulates the 2D wave spectral evolution with the consideration of the energy input by wind, the energy dissipation by whitecapping and bottom friction, and the non-linear wave–wave interactions (Jennifer *et al.*, 2010). It is suitable for any given regional grid with a prescribed topography. The grid resolution of model is arbitrary in space and time (Cherneva *et al.*, 2008).

The original atmospheric forcing, which is used to drive the wave model, is 6-hourly ECMWF ERA-Interim reanalysis wind data, provided by ECMWF (http://www.ecmwf.int) with the spatial resolution of 0.125°×0.125°. Although the ECMWF reanalysis wind data is finer than many other reanalysis datasets, it is still not fine enough to describe the atmospheric forcing for a typhoon event (Zhang and Sheng, 2015; Appendini *et al.*, 2013). In order to get more accurate wind field in the area surrounding the typhoon centre, the parametric typhoon wind field proposed by Jelesnianski (1965) is used to generate local typhoon wind field, which is subsequently superposed onto the ECMWF wind field. As the typhoon centre in the reanalysis data usually does not coincide with the measured one, a shifting of the reanalysis wind field is required first, and then an optimal radius R_{opt} is determined as the distance at which the typhoon model and the reanalysis data has the same magnitude of accuracy. The wind speed calculated by the parametric typhoon model is used inside the optimal radius while that obtained from the reanalysis data is used outside the optimal radius. For the surrounding area around the R_{opt}, a smoothing technique is introduced to integrate the different types of wind fields

$$v = (1-e)v_{ECMWF} + ev_{TY} \quad (1)$$

where v is the blended wind speed; v_{ECMWF} is the original or ECMWF reanalysis wind speed; v_{TY} is the parametric wind speed; and e is the weight coefficient (0.3 is used in this study).

In total, 862 typhoon events which occurred over the northwest Pacific Ocean during 1979-2013 are blended onto the ECMWF reanalysis data.

RESULTS

To examine the accuracy of the wind data for the long-term wave modelling, the ECMWF wind data is compared with the blended wind data at eight observation stations, *i.e.*, Beihuangcheng, Dafeng, Dajishan, Shipu, Beishuang, Chongwu, Dawanshan, Bailongwei along the China coast (see Figure 1), with the observation data from these stations. For brevity, only the results at four stations, *i.e.* Beishuang, Chongwu, Dawanshan and Bailongwei, in the South China Sea are shown here.

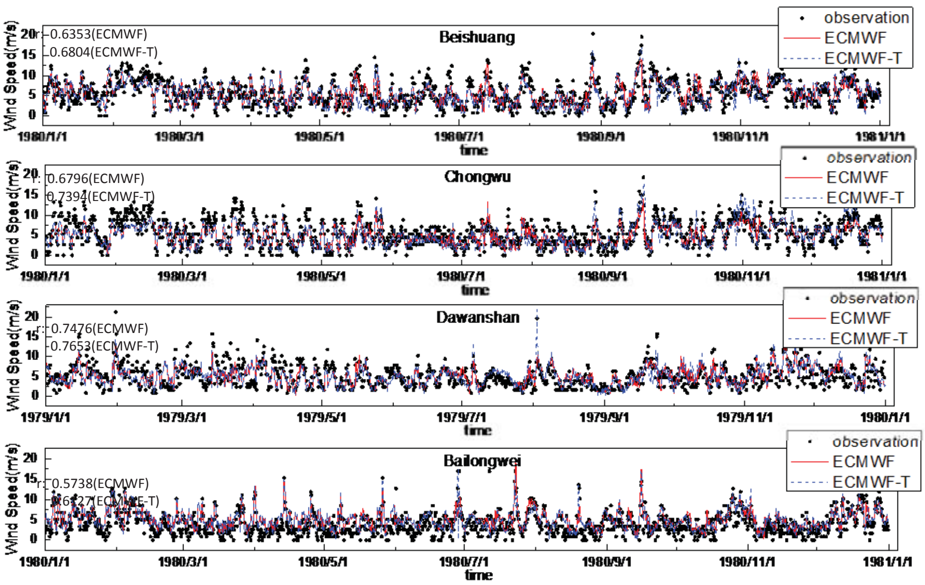

Figure 3. Comparison of wind speeds between ECMWF data (denoted by “ECMWF”), blended wind data (denoted by “ECMWF-T”) and observation data in stations in the South China Sea

Figure 3 shows the comparison between the original (un-blended – denoted as “ECMWF”) and blended wind data (denoted as “ECMWF-T”), and both agree well with the observations during the normal conditions. However, in the summer and autumn seasons when typhoons frequently pass these stations, the original (un-blended) wind data underestimates the large winds to some extent, while the blended wind data show more accurate estimations of large winds for typhoon events. The correlation coefficients (r) calculated between un-blended ECMWF, blended winds and the observations shown in Figure 3 verify that ECMWF-T data is more accurate than the un-blended one. Figure 4 shows the Quantile-Quantile scatter plots of the wind speeds with a certain accumulative percentage between the blended (ECMWF-T) and un-blended (ECMWF) winds against the measurements. The results also show that the waves generated by the blended wind data can provide more accurate surface forcing for the wave model in the following study.

For the purpose of model validation, the wave model WAMC4 is run with both unblended and blended ECMWF winds to generate the long-term wave climate over 35 years, *i.e.*, from 1979 to 2013. The annual maximum wave heights taken from the waves computed by WAMC4, are used to fit the Gumbel distributions to calculate the extreme wave heights with 100-year return period at 10 wave observation stations. The location details of the observation stations and duration of measurement data availability are given in Table 1.

Table 1. *Location of the observation stations and duration and data availability.*

Station	Longitude(°)	Latitude(°)	Depth(M)	Data length
Laohutan	121.68	38.87	28.0	1962-2009
Zhimaowan	119.92	40.00	6.0	1963-2007
Tianjingang	117.82	38.57	7.0	1960-1979
Xiaomaidao	120.42	36.05	23.8	1961-1995
Shengshan	122.82	30.70	40.0	1960-2009
Dachen	121.90	28.45	15.3	1960-2009
Nanji	121.10	27.42	20.0	1960-2009
Chongwu	118.93	24.83	11.0	1962-2009
Dawanshan	113.72	21.93	28.9	1995-2009
Weizhoudao	109.12	21.02	13.0	1962-2002

Figure 5 shows the results of extremes wave heights with 100-year return period in North (N) and South-East (SE) directions generated from the ECMWF, blended ECMWF winds in comparison with those calculated from the observation data. It can be seen that the distribution trend of extreme waves along the China coasts: the extreme wave heights increase first and then decrease from north to south. This is because those stations located in the south of the East China Sea (east coast of Jiangsu and Zhejiang Province) are closer to the open seas which are more often affected by the typhoons. It can be seen that the simulated wave driven by the blended wind data is more precise than the ones driven by the original ECMWF data.

DISCUSSION

The extreme wave fields of the whole China Seas are calculated. Figure 6 shows the modelled extreme waves with 100-year return period in the entire China Seas. It can be seen that the largest extreme wave height obtained from the blended winds is more than 16 m, located at the southeast of Taiwan. However, the largest extreme wave height driven by the unblended winds is no more than 15 m, located in the waters near Ryukyu Islands. These differences largely exists in the southeast part of China Seas in which is often affected by the typhoon events. The measured typhoon tracks over 35 years from 1979 to 2013 (not shown here) have confirmed that the southeast of China, particularly the area near the Taiwan Island, has the largest frequency to be affected by typhoon events. Since the parametric typhoon model is better than the ECMWF winds for the simulation of typhoon winds, it is understandable the extreme waves driven by the blended winds are better than the waves driven by the ECMWF winds in the typhoon affected areas.

CONCLUSION

The method to generate the improved typhoon wind fields for long-term and extreme wave simulation is introduced in this paper. 6-hourly ECMWF reanalysis wind field is blended by the parametric typhoon wind field. Both original and blended wind data are used to drive the WAMC4 model for long-term modelling of wave conditions with applications to the typhoon-affected area in China Seas. The comparisons of the model results and the observation data indicate a higher accuracy in the blended wind data. This study provides a useful approach to modify the wind data when simulating long-term and extreme wave climate during typhoon events in the China Seas.

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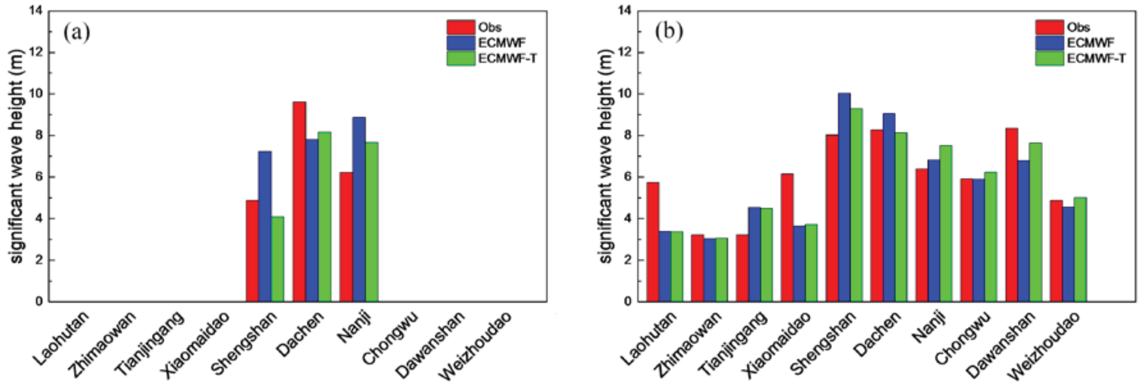

Figure 5. Comparison of 100-year extreme wave heights from ECMWF winds, blended winds (ECMWF-T) and the field measurements (Obs) in (a) N, and (b) SE directions

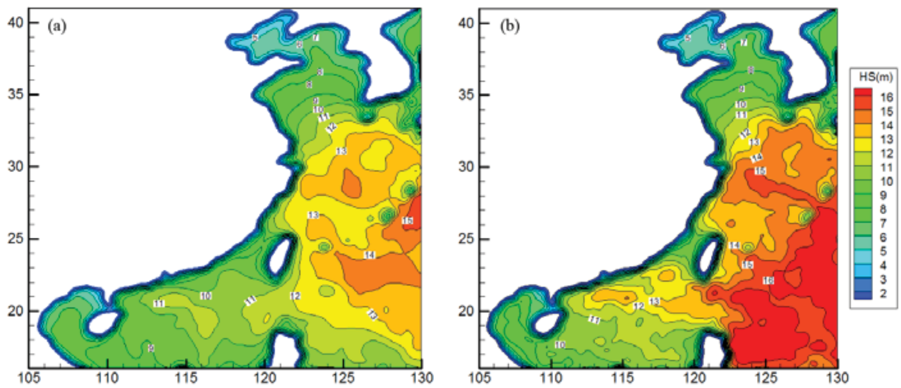

Figure 6. Modelled extreme waves with 100 year return period generated by (a) ECMWF winds, and (b) blended winds