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Numerical estimation of extreme waves and surges over the northwest Pacific Ocean

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A B S T R A C T

A coupled modelling framework, consisting of the FVCOM circulation model and FVCOM-SWAVE wave model, was used to numerically estimate extreme waves and surges over the northwest Pacific Ocean. The ECMWF ERA-Interim atmospheric reanalysis data with modification by a parametric typhoon model were used as surface forcing to simulate waves and surges for a 35-year period. The extreme waves and surges with a 100-year return period were then estimated with the Gumbel distribution. The results showed that the extreme wave heights generally decreased northward and shoreward, varying from 23 m in deepwater areas to less than 7 m in near-shore areas. The extreme wave heights in the east and southeast directions were found to be larger than those in other directions; and the extreme waves in summer and autumn were found to be larger than those in other seasons. The extreme surge levels were relatively large in the radial sandy ridge area of the Jiangsu coast, Hangzhou Bay and north of the Qiongzhou Strait. This study demonstrated an effective approach to improve the representation of typhoon in the numerical estimation of extreme events. The results provide insights into the temporal and spatial distributions of extreme waves and surges over the northwest Pacific Ocean.

1. Introduction

The northwest Pacific Ocean region (Fig. 1) is the path of a large number of typhoons every year. The typhoons often come with strong winds and low sea surface pressures that generate extraordinarily large waves and surges and cause great damage to the affected areas. On the other hand, the rapid economic development and population growth have put this region under increasing pressure for a better protection from and reduced vulnerability to the extreme waves and high sea levels during typhoon events (Yin et al., 2011; Zhang and Sheng, 2015). To minimize and mitigate the damages caused by the extreme typhoons and to ensure a safe and effective design for ocean and coastal engineering projects, it is desirable and essential to gain a better understanding of the temporal and spatial distributions of the extreme waves and surges in both offshore and nearshore areas.

In recent years, there have been a number of studies focused on the spatial and temporal distribution features of mean and extreme waves in this region based on the analysis of field observational data or remote sensing data (Yao et al., 1992; Qi et al., 1997; Wang and Yi, 1997; Liu and Sun, 2000; Chen et al., 2006a,b). There have also been studies on the spatial and temporal distribution of extreme sea levels based on the analysis of tide gauge observation data (Xu and Huang, 2011; Li and Li, 2013; Feng and Tsimplis, 2014; Feng and Jiang, 2015). However, because of the limited observation data, the results from those studies are only applicable to local areas, which may not be adequate for large domains such as the northwest Pacific Ocean region.

With significant advancement in computing techniques and power, numerical modelling has become an effective way to study the long-term wave climate over the northwest Pacific Ocean region. Third-generation spectral wave models such as WAM (WAMDIG, 1988), WAVEWATCH III (Tolman, 1991) or SWAN (Booij et al., 1999) are commonly used for wave modelling. A series of wind data, which usually comes from a global or regional reanalysis dataset, is used to drive the wave model for long-term wave hindcasting and analysis of the wave characteristics in an entire study region. For example, Lv et al. (2014) used the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis wind data to drive the SWAN model to perform a 20-year wave hindcasting in the Bohai Sea; then, the annual and seasonal distributions of mean wave

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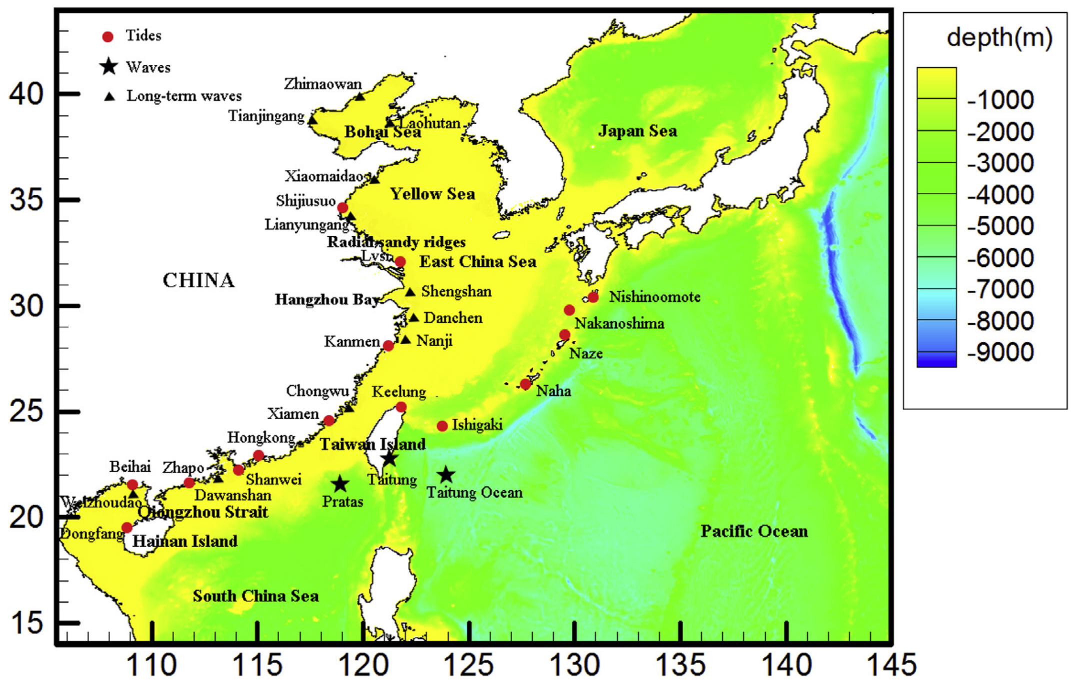

Fig. 1. The northwest Pacific Ocean region and locations of tide and wave observation stations.

characteristics in the Bohai Sea were analysed. Liang et al. (2014) used the wind data obtained from the Weather Research and Forecasting (WRF) Model to drive the SWAN model for a 22-year wave hindcasting in the Bohai Sea, Yellow Sea and East China Sea (BYECS); the spatial distributions of mean and largest significant wave heights in four seasons in BYECS were then specified. Zheng and Li (2015) used the CCMP (Cross-Calibrated Multi-Platform) surface wind data to drive the WAVEWATCH III model for a 24-year wave hindcasting, and the annual distributions of mean wave height and wave power density in the China Sea were discussed in detail.

In addition to the analysis of mean wave characteristics, numerical modelling has also been applied to estimate the extreme waves over a large domain. Lee and Jun (2006) used the ECMWF reanalysis wind data to drive the WAM model for a 25-year wave hindcasting, and simulated the typhoon waves for 106 major typhoons that affected the waters around the Korean Peninsula individually. The design wave heights for the return periods of 10, 20, 30, 50 and 100 years for 16 directions were estimated by means of the extreme wave analysis method. Chen et al. (2013) used the NCEP/NCAR (National Centers for Environmental Prediction/National Centre for Atmospheric Research) reanalysis wind data to drive the WAM wave model for hind-casting waves over 60 years in the East China Seas, and the results were used to estimate the extreme waves with 50-year and 100-year return periods. Li et al. (2016a) used both NCEP and ECMWF wind data to drive the WAM wave model and calculated the extreme waves in the same region. Waves with a 100-year return period generated by both wind datasets were compared with those measured at several observation stations along the China coasts. Although the ECMWF wind data were regarded relatively better in terms of resolution than other wind datasets (e.g. NCEP/NCAR), the extreme waves were found in general underestimated in comparison with the measurements, indicating the necessity for improvement of the original ECMWF wind data, particularly during the period of typhoon events. Li et al. (2016b) applied the method proposed by Pan et al. (2016) of modifying the ECMWF reanalysis data and found that the modified wind field considerably improved the accuracy of simulated extreme waves in the China Seas. Although a number of relevant studies have shown the feasibility of using wave models to reveal the temporal and spatial distributions of extreme waves over the entire region of the northwest Pacific Ocean, further detailed research is still much needed to obtain a more accurate estimation.

Apart from the extreme waves, the determination of extreme surges is also important for the design of coastal and offshore structures. Considering its destructive power, the relevant literature on modelling of storm surge has usually focussed on the temporal and spatial distribution of storm surge during a single storm event (Guo et al., 2009; Zhang et al., 2007; Beardsley et al., 2013; Yoon et al., 2014). Recently, Zhang and Sheng (2015) used the NCEP/CFSR (Climate Forecast System Reanalysis) wind data to drive the POM (Princeton Ocean Model) for a period of 32 years and analysed the extreme sea levels from surges and tides in the northwest Pacific Ocean. However, studies using coupled wave-current models for detailed analyses of spatial and temporal variations of extreme surges, especially from long-term simulations, are still lacking. Given the strong nonlinear interaction between waves and currents during typhoon periods, especially in the coastal area (Yoon and Jun, 2015), it is essential to consider the effects of wave-current interaction in long-term simulations to study the extreme waves and surges.

In this study, a coupled modelling framework, which consisted of the FVCOM circulation model and FVCOM-SWAVE, was set up over the northwest Pacific Ocean region for hindcasting waves and surges for a period of 35 years from 1979 to 2013. The modelling system was driven by the surface forcing based on the newly released ECMWF ERA-interim reanalysis data, and the tide forcing at the open boundaries from TPXO 7.2 data (Egbert and Erofeeva, 2002). To take account for the effects on typhoons events occurred in the region, the ECMWF data were also modified by a parametric typhoon model as proposed by Pan et al. (2016). The hindcasting results were then used to estimate the temporal and spatial distributions of extreme waves and surges over the entire northwest Pacific Ocean region.

The paper is organized as follows. The description of the wave and surge model used for the hindcasting and the method used for extreme analysis of annual maxima is presented in Section 2. The details of model setup and model validation are presented in Sections 3 and 4, respectively. The results of mean and extreme waves with a 100-year return period are presented and discussed in Section 5. The results of extreme surges with a 100-year return period are presented in Section 6, followed by a few conclusions in Section 7.