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Study of storm surge trends in typhoon-prone coastal areas based on observations and surge-wave coupled simulations

Xingru Feng[a,b], Mingjie Li[d], Baoshu Yin[a,b,c,*], Dezhou Yang[a,b], Hongwei Yang[e]

[a] Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[b] Function Laboratory for Ocean Dynamics and Climate, Qingdao National Laboratory for Marine Science Technology, Qingdao 266237, China
[c] University of Chinese Academy of Sciences, Beijing 100029, China
[d] National Marine Environmental Forecasting Center, Beijing 100081, China
[e] Shandong University of Science and Technology, Qingdao 266590, China

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ABSTRACT

This is a study of the storm surge trends in some of the typhoon-prone coastal areas of China. An unstructured-grid, storm surge-wave-tide coupled model was established for the coastal areas of Zhejiang, Fujian and Guangdong provinces. The coupled model has a high resolution in coastal areas, and the simulated results compared well with the in situ observations and satellite altimeter data. The typhoon-induced storm surges along the coast of the study areas were simulated based on the established coupled model for the past 20 years (1997–2016). The simulated results were used to analyze the trends of the storm surges in the study area. The extreme storm surge trends along the central coast of Fujian Province reached up to 0.06 m/y, significant at the 90% confidence level. The duration of the storm surges greater than 1.0 and 0.7 m had an increasing trend along the coastal area of northern Fujian Province, significant at confidence levels of 70%–91%. The simulated trends of the extreme storm surges were also validated by observations from two tide gauge stations. Further studies show that the correlation coefficient (R_{TE}) between the duration of the storm surge greater than 1 m and the annual ENSO index can reach as high as 0.62, significant at the 99% confidence level. This occurred in a location where the storm surge trend was not significant. For the areas with significant increasing storm surge trends, R_{TE} was small and not significant. This study identified the storm surge trends for the full complex coastline of the study area. These results are useful both for coastal management by the government and for coastal engineering design.

1. Introduction

Among the variety of marine disasters in China, storm surges cause the most significant economic losses and casualties (Feng et al., 2015; Dong et al., 2016). Many studies have been conducted on prediction skill and disaster assessment (Yin et al., 2009; Zhang et al., 2010; Feng et al., 2012; Gan et al., 2012; Feng et al., 2016) to help reduce the losses caused by storm surges in China. The study of trends in storm surges is also very important for long-term forecasting and coastal management. Paprotny (2014) studied the trends in the probability of storm surge occurrence along the coast of the Polish Baltic Sea by analyzing long-term water level records at three tide gauge stations. Androulidakis et al. (2015) investigated the trends of the extreme storm surges in the Mediterranean Sea, and found a general decreasing trend. Sang et al. (2016) found an increasing trend in extreme storm surges in Busan harbor based on observations. For the coastal areas of Brazil, Chou et al. (2016) showed that the storm surge frequency and intensity are increasing. Studies on the storm surge trends along the coastal areas of China have also been conducted based on observations and simulations (Feng and Tsimplis, 2004; Feng et al., 2015; Oey and Chou, 2016).

Studies of storm surge trends based on observations are limited for the coastal areas of China because most of the water level observations are still kept confidential (Feng et al., 2015). Furthermore, the distribution of the tide gauge stations is sparse, and a comprehensive trend study of the full coastal area of China is not possible. Previous storm surge trend studies based on observations have used data mainly from the University of Hawaii Sea Level Center (Feng and Tsimplis, 2004; Feng et al., 2015). Besides the sparse distribution of the stations, another limitation of this dataset is that the data records for most of the stations are only available before 1997. Therefore, it is not possible to analyze the trends over the past 20 years.

Numerical simulations can be used to make up for the lack of

* Corresponding author at: Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China.
E-mail address: bsyin@ms.qdio.ac.cn (B. Yin).

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observations. Recent studies show that the interaction between tides and a storm surge can cause a difference of up to 20 cm in a storm surge (Zhang et al., 2010). Feng and Tsimplis (2004) showed that the tide-surge interaction is significant at many tide gauge stations. Therefore, the storm surge-tide interaction should be included in the storm surge simulations. Another physical mechanism that can influence the storm surge is the wave-current interaction (Xie et al., 2008; Moon et al., 2009; Kim et al., 2010; Huang et al., 2010; Feng et al., 2016). Xie et al. (2008) found that the contribution of waves to the storm surge reached up to 0.76 m during hurricane Hugo in Charleston Harbor. Kim et al. (2010) also found that the contribution of the wave-induced radiation stress to the peak sea level rise reached as high as 40% during typhoon Anita (1970) on the coast of Tosa Bay, Japan. Feng et al. (2016) showed that the storm surge-wave-tide coupled model can simulate the wave height and storm surge better than the model components alone. Therefore, this type of coupled model is applied in this study.

Many storm surge disasters in China are caused by strong typhoons. Emanuel (2013) predicted an increasing trend in typhoon intensity and frequency in the western North Pacific. According to the statistics of Feng and Tsimplis (2004), the annual number of typhoon-influenced events in China between 20°N and 30°N is greater than 10, making this region the most typhoon-affected area. We therefore focused on the coastal areas of Fujian, Zhejiang, and parts of Guangdong provinces. Considering the complex coastline of this area, the numerical model was based on an unstructured grid, which includes the effect of the complex geometry better than models based on a structured grid.

The objective of this study was to study storm surge trends for the typhoon-prone coastal areas of China. A state-of-the-art unstructured-grid storm surge-wave-tide coupled model was applied to simulate typhoon-induced storm surges for the past 20 years (1997–2016). The model has high resolution in the coastal area, and the simulated results can be used to analyze the storm surge trends for the full coastline of the study area. The coupled model, the wind field forcing, and the model validation are described in Section 2. Section 3 presents the analysis of the trends of the storm surge based on the simulation results. Discussion on the results is provided in Section 4. The conclusions are presented in Section 5.

2. Methods

The storm surge-wave-tide coupled model was used to simulate the typhoon induced storm surges in the study area from 1997 to 2016. The model results were validated by tide-gauge observations and remote sensing data. The dataset of storm surges over the 20 years was then used for trend analysis.

2.1. Storm surge-wave-tide coupled model

To simulate a storm surge, the unstructured-grid storm surge-wave-tide coupled model SWAN + ADCIRC (Dietrich et al., 2011; Dietrich et al., 2012) was adopted in this study. The SWAN (Simulating WAves Nearshore) model is a spectral wave model that is designed for shallow water areas (Booij et al., 1999). SWAN solves the action balance equation, allowing the input of ocean currents and water level (Holthuijsen, 2008). The ADCIRC (ADvanced CIRCulation) model is an ocean current model based on the finite-element difference method and an unstructured computational grid (Westerink et al., 1991), in which water currents and water levels are computed by solving the vertically integrated momentum equations and vertically integrated continuity equation. In the coupled model, the wave-induced radiation stress (Longuet-Higgins and Stewart, 1964) was calculated to force the storm surge. The wave effect on wind stress was included using the wind stress drag coefficient formula presented by Donelan et al. (1993), which takes the wave age into account. Based on Donelan et al. (2004), the wind stress drag coefficient was limited to 0.0025 when the wind speed is greater than 33 m/s. The coupling of the physical mechanism

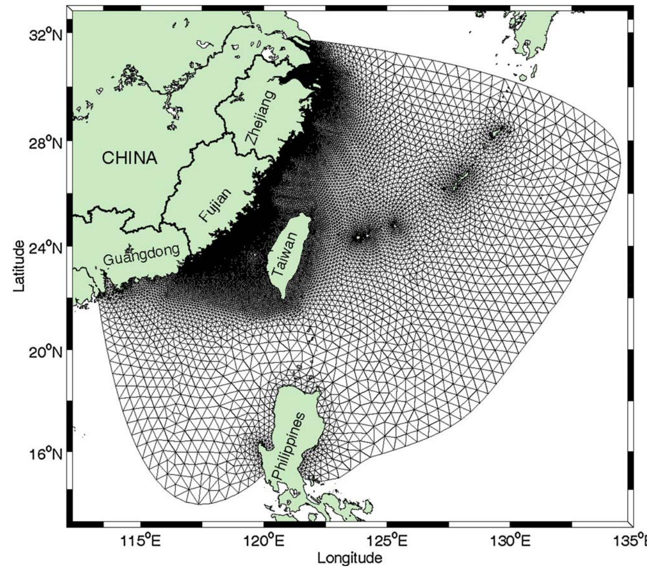

Fig. 1. Model domain and the computational grid.

was described in detail in Feng et al. (2016), and the computational algorithms can be found in the model user manual of Luettich and Westerink (2004).

The model domain and computational grid (Fig. 1) cover the coast of Fujian, Zhejiang, and parts of Guangdong provinces, which are the typhoon-prone areas of China. The resolution of this grid ranges from 50 km at the open boundary to 100 m in the coastal area. The ADCIRC and SWAN models were run with the same grid. Eight tidal constituents (M2, S2, N2, K2, K1, O1, P1, and Q1) from the NAO99 database (Matsumoto et al., 2000) were used to calculate elevations as open boundary forcing for the ADCIRC model. The lateral boundary conditions for the SWAN model are the radiation boundary conditions. The frequency of the resolved wave spectrum ranges from 0.04 Hz to 1.8 Hz. Both models were run from stationary initial conditions.

2.2. Wind field of the typhoons

A combined wind field of the analysis products and typhoon model was adopted to drive the coupled model. The analysis products were extracted from the ERA Interim dataset of ECMWF (European Centre for Medium-Range Weather Forecasts, http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/) with one wind field every 6 h. The typhoon model applied was the circular typhoon model by Jelesnianski (Jelesnianski, 1965). The process of creating the combined wind field is described in Eq. (1). The wind field was completely calculated by the circular typhoon model inside the radial region of $r \le 8R_{max}$, in which R_{max} is the radius of the maximum wind speed. The radial distance between $8R_{max}$ and $10R_{max}$ is the transition zone, where the wind and air pressure fields were calculated using linear weight averaging of ECMWF and the circular typhoon model fields. Outside of $10R_{max}$, only the ECMWF fields were used.

$$V, Pa = \begin{cases} Circular\ \ typhoon\ \ model(r \le 8R_{max}) \\ Transition\ \ zone(8R_{max} < r \le 10R_{max}), \\ ECMWF\ \ wind\ \ field(r > 10R_{max}) \end{cases} \tag{1}$$

where V is wind speed and Pa represents air pressure.

To analyze the trend of the typhoon-induced storm surge, the typhoons that may have caused a storm surge in the study area from 1997 to 2016 were selected and the corresponding wind fields were calculated using the above method. The paths of these typhoons are shown in Fig. 2. There were 158 typhoons. The path and strength data for the typhoon records were obtained from the CMA-STI (Shanghai Typhoon