Int J Appl Earth Obs Geoinformation 73 (2018) 52–62

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Long-term hazard analysis of destructive storm surges using the ADCIRC-SWAN model: A case study of Bohai Sea, China

Yanping Wang[a], Xinyan Mao[a,*], Wensheng Jiang[a,b]

[a] Physical Oceanography Laboratory, Ocean University of China, Qingdao 266100, PR China
[b] Laboratory of Marine Environment and Ecology, Ocean University of China, Qingdao 266100, PR China

ARTICLE INFO

Keywords:
Storm surge
Long-term
Coupled models
Bohai Sea

ABSTRACT

Destructive storm surges bring large waves and unusually high surges of water to coastal areas, resulting in many human casualties and significant economic loss. In this study, an unstructured grid wave-current coupled model was developed for the Bohai Sea, China, using the ADCIRC (ADvanced CIRCulation) and SWAN (Simulating WAves Nearshore) models to simulate 32 disastrous storm surge events from 1985 to 2014. The return storm surge elevation in the Bohai Sea using the Gumbel method is obtained and compared with previous results. It is found that extratropical cyclones and cold air play important roles in storm surges in the Laizhou Bay and have more influence than tropical cyclones. Moreover, the joint probabilities of surge and wave are obtained by using the Gumbel logistical model. The results show that the effect of waves in surge-wave joint probabilities on the central basin of the Bohai Sea is more significant than that on the Bohai Sea coast. By establishing a system to assess the relative risks of storm surges in the Bohai Sea, it is found that Laizhou Bay is in the greatest danger.

1. Introduction

Storm surges are anomalous rises and falls in water level caused by strong atmospheric disturbances (Feng, 1982). Their energy is palpably destructive in coastal regions, resulting in destructive of infrastructure and great economic loss (Storch et al., 2008; Kang et al., 2016). As a coastal country, China has been endangered by storm surges for many years. (Feng et al., 2015). The Bohai Sea (Fig. 1), which is China's northernmost sea, covers an area of about 77 thousand km^2, is surrounded by land on three sides, and connects to the Yellow Sea through the Bohai Strait. Historically the Bohai Sea has not only been affected by tropical cyclones but also by extratropical cyclones and cold air, hence, the storm surges that have occurred have frequently caused severe damage (Zhao and Jiang, 2011; Feng et al., 2012a; Ding and Wei, 2016). For example, when the typhoon Mamie (8509) went through the Bohai Sea in 1985, the high-tide period of the astronomical tide occurred at the same time, leading to a serious storm surge (Song et al., 2002; Feng et al., 2014). Likewise, due to cold air flowing strongly southward and a pressure trough moving north, the Bohai Sea experienced a powerful storm surge in 2009, with direct economic losses of about RMB 620 million in Hebei province, Tianjin and Shandong province (China's marine disasters communique, 2009). There are therefore significant social and economic reasons to conduct a study of storm surges in the Bohai Sea.

Although wind-driven waves and currents are separated in the spatiotemporal spectrum, the interactions between waves and currents are quite complicated in the actual coastal environment (Feng et al., 2012b). The interactions mainly concern two areas. On the one hand, wave propagation has an influence on hydrodynamics, such as water level fluctuation and wave-induced nearshore currents caused by wave deformation, while on the other hand, changes from hydrodynamics can affect waves. Water levels can affect wave propagation and dissipation due to depth-limited breaking, and currents can affect wave energy due to the Doppler effect (Dietrich et al., 2011; Dietrich et al., 2012). In recent years, the ADCIRC-SWAN wave-current coupled model has been applied to various sea areas. Xie et al. (2016) discussed wave distribution and circulation in the Gulf of Maine using of the coupled model. Sebastian et al. (2014) used the ADCIRC-SWAN hurricane model to analyze storm surge behavior in Galveston Bay. Feng et al. (2016) applied the MCT-coupled model in Fujian province (developed by the ADCIRC-SWAN coupled model), and his results have shown that the coupled model is more accurate in simulating storm surges and waves. It is therefore necessary to use wave-current coupled models to simulate currents, surges, and water levels of storm surges.

As important elements of a dynamic marine environment, surges and waves have significant value in determining hydrological design parameters for marine engineering, and in carrying out marine disaster prevention and reduction (Xie et al., 2014). Although the relationship

* Corresponding author.
E-mail address: maoxinyan@ouc.edu.cn (X. Mao).

https://doi.org/10.1016/j.jag.2018.03.013
Received 30 September 2017; Received in revised form 26 March 2018; Accepted 30 March 2018
0303-2434/

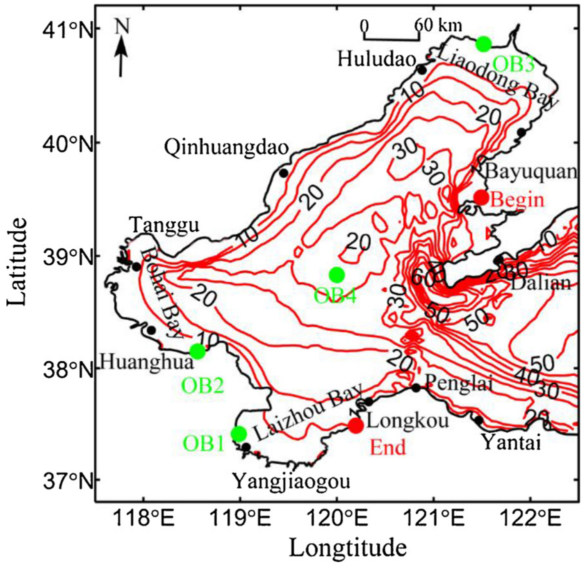

Fig. 1. The topography of the Bohai Sea, and 10 tide gauges: Yantai, Penglai, Longkou, Yangjiaogou, Huanghua, Tanggu, Qinhuangdao, Huludao, Bayuquan, and Dalian. Red dots denote the starting and ending gauge station along the coast in Fig. 10. Green dots are typical points used in Section 4.3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between extreme surges and waves has complex and random features, joint probability analysis can still clearly show the relationship between them. By clarifying the relevance, it can provide a reference for a more reasonable determination of marine and coastal engineering design standards.

There have been numerous studies on storm surges in the Bohai Sea from the 1980s on. Xia et al. (2013) used a coupled model to study strong storm surges in the Bohai Sea, and found the model to have a high accuracy in simulating wave and water levels. Wu et al. (2015) studied the return period of storm surges around the Shandong peninsula with the ADCIRC, but only considered typhoon storm surges. Zhao and Jiang (2011) studied the effects of different cold-air currents in the Bohai Sea. Similarly, Li et al. (2015) simulated the Bohai Sea's storm surge combined with a method of data assimilation, while the return period around the Bohai Sea and Yellow Sea was obtained using the Pearson distribution.

In this paper, 22 extratropical storm surges and 10 typhoon (Fig. 2) storm surges affecting the Bohai Sea from 1985 to 2014 are simulated by the ADCIRC-SWAN coupled model. It is important to note that these 22 extratropical storm surges were selected according to China's marine disasters communique and the 10 typhoon storm surges were selected on the basis of whether the typhoon paths were able to reach the north Yellow Sea. Based on the results, the differences in water levels between the ADCIRC model and the ADCIRC-SWAN coupled model are discussed. We use the Gumbel model to calculate the surge return period of the whole Bohai Sea, and utilize the Gumbel logistical model to obtain the joint probabilities of extreme surges and corresponding waves in Bohai Bay, Laizhou Bay, Liaodong Bay and the center basin respectively. Additionally, the surge risk of the Bohai Sea is ranked according to statistical methods.

The details of the rest of the paper are as follows: the introduction to the ADCIRC and the SWAN models, model configuration and probability statistical analysis are given in Section 2. Model validation is presented in Section 3. The analysis of return periods, tidal effect, joint probability distribution and risk grades are presented in Section 4, and conclusions are presented in Section 5.

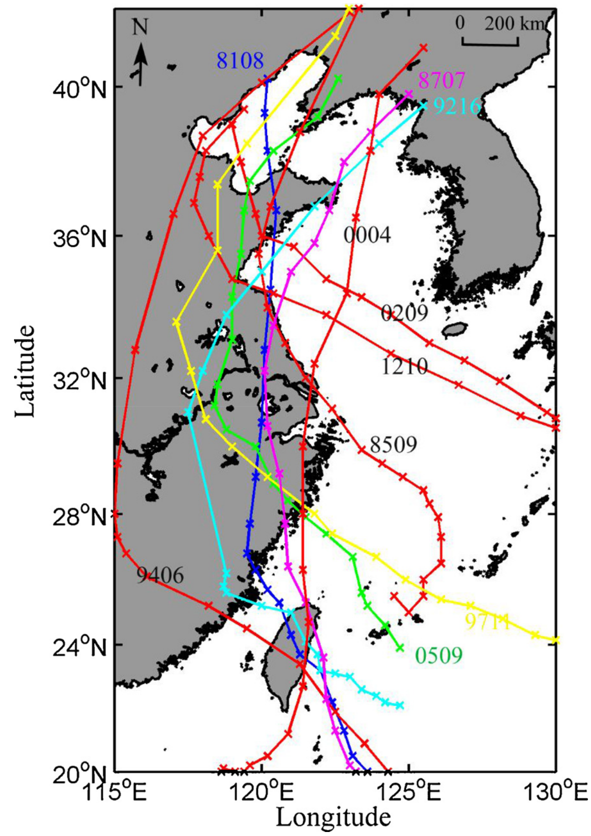

Fig. 2. Paths of 10 typhoons which mainly affected the Bohai Sea from 1985 to 2014. The number is the name of typhoon in China.

2. Method

2.1. Model description

The ADCIRC model is a finite-element ocean model developed by the University of North Carolina in the United States, combined with the unstructured triangular grids, which can simulate the complex shoreline well (Westerink et al., 1992). Because storm surges are essentially barotropic and the Bohai sea is also quite shallow, the 2D depth integrated hydrodynamic model is used in this study. The ADCIRC basic equations are described in Luettich and Westerink (2004).

At the bottom, a nonlinear mixed bottom friction formula is used,

$$\tau^* = \frac{C_f (U^2 + V^2)^{1/2}}{H} \tag{1}$$

For the bottom friction coefficient,

$$C_f = C_{fmin}\left[1 + \left(\frac{H_{break}}{H}\right)^{\theta}\right]^{\frac{\lambda}{\theta}} \tag{2}$$

where H_{break} is critical depth; θ determines how rapidly the hybrid bottom friction relationship approaches; λ determines the speed of the bottom friction growth from deep water to shallow water. According to the formula, C_f will be close to C_{fmin} in deep water (H $>$ H_{break}), and to $C_{fmin}(H_{break}/H)^{\lambda}$ in shallow water (H $<$ H_{break}). In this paper, C_{fmin} is set as 0.0013.

The SWAN model is a spectral wave model designed for shallow water areas and was developed by the Delft University of Technology (Booij et al., 1999). As a third-generation wave model, it computes random, short-crested wind-generated waves in coastal regions and inland waters (Booij et al., 1999; Ris et al., 1999). Its basic equation in the Cartesian coordinate is described in Booij et al. (1999).

The ADCIRC and the SWAN models use the same unstructured