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Evaluation of sea level rise in Bohai Bay and associated responses

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Abstract

Tide gauge data from 1950 to 2015 are used to analyze sea level change, tidal change, return levels, and design tide levels under rising sea level scenarios in Bohai Bay. Results show the following: 1) Since 1950 sea levels in Bohai Bay show a significant rising trend of 3.3 mm per year. The speed has been particularly rapid in 1980–2015 at a rate of 4.7 mm per year. 2) Astronomical tides showed a clear long-term trend in 1950–2015. The amplitude and phase lag of the M2 tide constituent decreased at a rate of 0.21 cm per year and 0.11° per year, respectively and the phase lag of K1 decreased at a rate of 0.09° per year, whereas there was little change in its amplitude. The mean high and low tides increased at a rate of 0.08 and 0.52 cm per year, respectively, whereas the mean tidal range decreased at a rate of 0.44 cm per year. Results from numerical experiments show that local sea level rise plays an important role in the tidal dynamics change in Bohai Bay. 3) It is considered that the sea level return periods will decrease owing to the influence of sea level rise and land subsidence, therefore design tide level will change in relation to sea level rise. Therefore, the ability of seawalls to withstand water will diminish, and storm surge disasters will become more serious in the future.

Keywords: Bohai Bay; Sea level rise; Astronomical tide; Design tide level; Land subsidence

1. Introduction

Ocean thermal expansion and glacier mass loss are considered to be the dominant contributors to global mean sea level (MSL) rise during the 20th century (IPCC, 2013). Projections of sea level rise through the 21st century and beyond suggest that coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion. The population and assets exposed to coastal risk, and human pressures on coastal ecosystems will significantly increase in the coming decades owing to population growth, economic development, and urbanization (IPCC, 2014). Regional distributions of sea level rise are important because, together with local land motion, they have the most direct impact on society and the environment (UNESCO/IOC, 2010). A rise in sea level increases the water depth leading to intensification in wave propagation and modification of reflected and incident waves. Sea level rise and its impact on tides in the Bohai Sea have already been studied (Li et al., 2016; Pelling et al., 2013; Wang et al., 2013; Yu et al., 2003, 2007; Zhang et al., 2013), and it is suggested that there are certain distribution patterns in the differences between amplitude and phase with differing increments of sea level. It is also known that sea level rise in Bohai Bay causes a decrease in the amplitude of M2 tide constituent. The long-term effect of sea level rise not only influences the tidal dynamic system but also increases the risk of extreme tide levels. Although some studies have been conducted on the effect of sea level change by calculating the design and extreme tide

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levels for multiyear return periods (Yu et al., 2013; Yu and Yu, 2003; Zuo et al., 2001), a limited number of quantitative studies have been conducted on the influence of sea level rise on coastal systems in China, particularly in the Bohai Bay area (Fu, 2011).

As a city with one of the lowest elevations in China, Tianjin suffers from land subsidence. Some areas in the Binhai New Area of Tianjin already lie below MSL and are at severe risk of sea level rise and land subsidence. With rapid economic development, the demand for land resources is increasing and to solve the problem of land shortage, sea reclamation has been undertaken for years in this area. A large number of sea reclamation zones have been planned and built, with the focus on housing and emerging industries. However, such zones are at high risk of marine disaster and their locations, particularly where they directly face the sea, increases the risk of disasters caused by sea level rise, storm surge, disastrous waves, and floods.

Focusing on Bohai Bay, in this paper we study sea level change and its influence on major tide constituents, tide ranges, extreme tide levels, and coastal systems. Tide gauge data are used to analyze changes in sea level, astronomical tides, and extreme tide levels. Furthermore, the impact of sea level rise on return levels and future storm surge disasters are assessed, and strategies and suggestions are made for mitigating sea level rise.

2. Data and methods

2.1. Data

Bohai Sea is a shallow semi-closed sea covering a total area of 77,000 km^2 with an average water depth of 18 m (Bian et al., 2016). It is divided into five general regions, Liaodong Bay, Bohai Bay, Laizhou Bay, the Central Bohai Sea, and the Bohai Strait. Bohai Bay is one of the three bays in the Bohai Sea, it extends from the Daqing River estuary in the north to the new Yellow River estuary in the south and covers a total area of 14,700 km^2 with a coastline of 1076.5 km. The bay is ringed by four major ports, Tianjin, Jingtanggang, Caofeidian, and Huanghua. Five cities (Tangshan, Cangzhou, Binzhou, Dongying, and the Binhai New Area of Tianjin) are located along its coast and cover a total land area of 47,324 km^2. The western Bohai Sea coastline twists and turns, and the tide gauges are not uniformly located (Fig. 1). The sea level data used in this study are obtained from five tide gauges along the coast in the west and southwest Bohai Sea (Jingtanggang, Caofeidian, Tanggu, Huanghua, and Longkou). Tanggu is a tide gauge station that belongs to the Global Sea Level Observing System (GLOSS) network. It was constructed in March 1949 and continuous data is available from 1950. However, the homogeneity of this data is not very good as the tide gauge has been moved several times and is now located in an area that has suffered from land subsidence in past years. Jingtanggang was constructed in October 1998 and continuous data is available from September 2008 (there were many gaps in the observed tidal records prior to 2008 when it was moved to its current position). Caofeidian was constructed in April 2006 and continuous data is available from May 2008. Huanghua continuous data is available from May 2008. Longkou was constructed from 1961, but this station absence of measuring the sea level data from January 1990 to June 1991.

To identify whether anthropogenic or natural factors are responsible for changes in sea level at the tide gauges mentioned above, two neighboring tide gauges, Qinhuangdao and Longkou, were selected as reference stations in this study. Tanggu, Qinhuangdao, and Longkou experience the same daily, monthly, and annual sea level change characteristics. A homogeneity correction was made in relation to these tide gauges using the method described by Wang et al. (2013) and the regional sea levels in Bohai Bay were estimated using these tide gauge data. It should be noted that data obtained from these tide gauges stand for relative sea levels, which means that the sea level changes from these data includes changes in land subsidence. It has been estimated by Liu et al. (2015) that the rates of land subsidence at Tanggu and Longkou are 1.82 and 1.65 mm per year, respectively.

2.2. Methods

A stochastic dynamical method was used to obtain the linear trend at the selected stations. The critical period in the time series is obtained using the maximum entropy spectrum method and an *F*-test is used to check the significance of the output period. More detail on this method can be found in Tian et al. (1993).

Wavelet transform is a way of analyzing a signal in both the time and frequency domains. It was originally formulated by Goupillaud et al. (1984). A detailed description of this technique can be found in Torrence and Compo (1998).

The Estuarine Coastal Ocean Model (ECOM) of Blumberg and Mellor (1983) was used to analyze the impact of sea level rise on astronomical tides. The ECOM is a three-dimensional, free-surface, finite difference, nonlinear, hydrodynamic model formulated in a vertical terrain-following sigma coordinate and has been widely used for coastal numerical simulation. The main astronomical tide constituents, M1 and M2, were simulated using ECOM. According to the method described by Fang et al. (1986), the amplitude and phase lag of M1 are equal to the average of K1 and O1, respectively, and thus, both M1 and M2 can be analyzed using calculated sea level data from one lunar day cycle (because the M1 frequency is just half that of M2).

The P-III method, as recommended by the Code of Hydrology for Ports and Waterways (MTPRC, 2015), is widely used to calculate return levels. In this study, the P-III method was used to analyze the extreme tidal values in 1950–2015 (Fig. 8).

3. Sea level change

3.1. Long-term trend

Sea level change in Bohai Bay from 1950 to 2015 has been studied using the Tanggu tide gauge data. Results (Fig. 2)