Ocean Engineering 136 (2017) 80–93

Contents lists available at ScienceDirect

Ocean Engineering

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

Effects of sea level rise and typhoon intensity on storm surge and waves in Pearl River Estuary

Kai Yin[a], Sudong Xu[a,*], Wenrui Huang[b,c], Yang Xie[a]

[a] Department of Port, Waterway and Coastal Engineering, School of Transportation, Southeast University, Nanjing 210096, China

[b] Key Lab of Yangtze River Water Environment of Ministry of Education, Department of Hydraulic Engineering, Tongji University, Shanghai 200092, China

[c] Department of Civil and Environmental Engineering, Florida State University, Tallahassee, FL 32310, USA

ARTICLE INFO

Keywords:
Storm surge
Sea level rise
Typhoon intensification
ADCIRC
SWAN
Pearl River Estuary

ABSTRACT

Climate changes, including sea level rise (SLR) and typhoon intensification (TI), have had widespread impacts on natural systems. Through the use of coupled ADCIRC+SWAN models, this study investigates the effects of potential SLR as well as TI on storm surges and waves in Pearl River Estuary, China. Meanwhile, examination of how SLR and TI impact seawalls has been conducted. Results demonstrated that TI has a greater impact on storm surge, whereas SLR has a greater impact on wave heights in the estuary. There is no substantial difference of peak surge height (referring to the mean sea level of the corresponding SLR scenarios) in response to the increase of sea level in the study area. However, by combining the sea level rises of 0.5–1.0 m, the surface elevations of peak storm surge increased under SLR conditions. Besides, enhanced typhoon intensity was found to cause the increase of peak surge height as well as wave height in some shallow areas. Furthermore, the combination of those two factors also increased peak surge height and greatly increased wave height. By running the coupled ADCIRC and SWAN models, the simulated results can be employed in flood mitigation and design of seawalls in Pearl River Estuary.

1. Introduction

Settlements in coastal lowlands are vulnerable to storm surge resulting from tropical cyclones as experienced by recent tropical cyclones including Katrina (2005), Ike (2008), Nargis (2008) and Haiyan (2013). The storm surge induced by Typhoon Haiyan alone, which was the deadliest typhoon to hit the Philippines in recent history, resulted in 6300 dead, 1061 missing and 28,689 injured (Lagmay et al., 2015). Along the coast, storm surge from typhoons is often the greatest threat to life and property. According to the China Marine Hazards Communique, storm surge in China accounted for 99.7% of the direct economic loss of the total marine hazards in 2014 (State Oceanic Administration, 2014). Meanwhile, low elevation coastal zones below 10 m in elevation cover 2% of the world's land and contain 10% of the world's population; among them, China is ranked first in the world in terms of population (143,880,000) living in low elevation coastal zones (McGranahan et al., 2007). With increasing sea level rise (SLR) and typhoon intensification (TI), the vulnerability to storm surge will likely increase in low elevation coastal zones. This will bring about damage to coastal defenses and cause the water to pile up, seawall submerging and inland flooding. Storm surges may also cause changes in coastal sediment transport, which may result in changes to coastal morphology (Biria et al., 2015). Being one of the most economically developed and urbanized regions in China, the Pearl River Estuary (PRE) is characterized by low-lying terrain and is sensitive to storm surge (Chen et al., 2014). From 2005 to 2014, the direct economic loss for Guangdong Province had reached 50.29 billion Chinese Yuan as a consequence of storm surge, and more than 1610 km of coastal engineering was demolished. Since PRE is frequently and seriously suffering from storm surge every summer, the hazard of storm surge from typhoons in PRE needs to be quantified in response to SLR and TI, thus providing useful information to coastal planners and decision makers for minimizing the destruction and losses caused by storm surge.

SLR has traditionally taken the brunt of the blame for causing more serious inundation of low elevation coastal zones, destruction of coastal infrastructure such as seawalls and the intensification of storm surge, coastal erosion, seawater intrusion and soil salinization. There is a general consensus that climate change is a major cause of SLR. More specifically, ocean thermal expansion and glacier mass loss together contribute to about 75% of the observed global mean SLR (IPCC, 2014). The Intergovernmental Panel on Climate Change (IPCC)

* Corresponding author.
E-mail address: sudongxu@seu.edu.cn (S. Xu).

http://dx.doi.org/10.1016/j.oceaneng.2017.03.016
Received 20 May 2016; Received in revised form 2 February 2017; Accepted 12 March 2017
0029-8018/

estimated the average rate of global mean SLR of 1.7 mm/yr [1.5–1.9] between 1901 and 2010, and recently (1993–2010) the global mean SLR was reported of 3.2 mm/yr [2.8–3.6]. The IPCC confirmed the continuous increase of global mean sea level during the 21st century. Relative to 1986–2005, global mean SLR change at the end of the 21st century (2081–2100) was projected to likely exceed 0.63 m for modeling of very high greenhouse gas emissions. However, regional SLR could in fact differ substantially due to fluctuations in ocean circulation, which can be several times larger or smaller than the global mean SLR for periods of several decades (IPCC, 2014). For example, in the Bulletin of the Chinese Sea Level in 2015, which was released by the State Oceanic Administration, it was explicitly stated that the sea level changes of Chinese coastal areas appeared to increase at an average rate of 3.0 mm/yr between 1980 and 2015, which was higher than the reported global average (State Oceanic Administration, 2016). For the region of PRE, previous studies of SLR have produced many substantial and insightful results. Huang et al. (2004) assumed that a 30 cm SLR at the mouth of the PRE is possible by 2030. Following similar lines, Shi et al. (2008) predicted the SLR in some regions of Guangdong coast up to 30 and 50 cm in 2030 and 2050, respectively, by taking ground subsidence and sea level fluctuations into consideration. He et al. (2014) utilized both satellite altimetry datasets and tide gauge records to develop estimates of the SLR trends. The calculated rate of SLR was 4.08 mm/yr over the period 1959–2011 and the results indicated an acceleration over recent decades. The State Oceanic Administration estimated the future SLR of 75–155 mm for the coastal region of Guangdong Province in the next 30 years.

Aside from SLR, another crucial climate-related influencing factor on storm surge is TI. It is certain that tropical cyclones have become more powerful in the North Atlantic since 1970 (Elsner and Jagger, 2009; IPCC, 2014). The IPCC concluded that the upper 75 m of ocean warmed by 0.11 °C per decade during the period from 1971 to 2010 globally, and it was claimed that more energy would be stored in the climate system under ocean warming conditions. A number of scientists have joined the consensus and stated that increasing sea surface temperature may lead to increasing intensity of tropical cyclones (Elsner and Jagger, 2009; Knutson et al., 2010; Knutson and Tuleya, 2004; Lloyd and Vecchi, 2011; Montgomery et al., 2014; Webster et al., 2005; Yasuda et al., 2014). Emanuel (1987) pointed out that the maximum pressure drop and peak wind speed of tropical cyclones will likely increase by 30–40% and 15–20% respectively for 3 °C increase in sea surface temperature. Aiming at hurricane proportions, Holland and Bruyère (2013) indicated that the proportion of Category 4 and 5 hurricanes have increased at a rate of 25–30% per °C of global warming. The future projections based on potential intensity theory and high-resolution dynamical models given by Knutson et al. (2010) consistently indicated that the globally averaged intensity of tropical cyclones will increase by 2–11% by 2100.

Impacts of future SLR on storm surge and waves have been a focus of recent research (Lee et al., 2013; Mariotti et al., 2010; Parker, 2014; Wamsley et al., 2009; Warner and Tissot, 2012). Zhao et al. (2014) applied a coupled ADCIRC (ADvanced CIRCulation) + SWAN (Simulating WAves Nearshore) model to investigate the potential impacts of SLR on the storm surge at the Changjiang Estuary and Hangzhou Bay. The simulated results indicated that the extreme surge elevation is not very sensitive to SLR. However, this study did not take the change of bottom roughness caused by SLR into account. Another view is given by Smith et al. (2010) who used the numerical storm surge model ADCIRC and the nearshore spectral wave model STWAVE to investigate the potential impacts of 0.5 and 1.0 m of relative SLR on hurricane surge and waves in southeast Louisiana. This study demonstrated that surge propagation over broad, shallow, wetland areas is highly sensitive to relative SLR, wave heights also generally increase for all relative SLR cases. Through statistical analysis, Tebaldi et al. (2012) pointed out that some locations may suffer from extreme water levels annually that were treated as 100-year Annual Maximum Water Level nowadays owing to SLR by mid-century. Yang et al. (2015) suggested that the average water depth in the inundated areas increases linearly with SLR in the Snohomish River estuary, Washington, USA. Different from these two studies, Ding et al. (2013) and Bilskie et al. (2014) both indicated that the response of storm surge to SLR is nonlinear. Atkinson et al. (2013) joined the consensus and demonstrated that the relationship between storm surge and relative SLR varies between geographic region and storm scenario. Gao et al. (2008) pointed out that storm surge response to mean sea level rise is non-uniform spatially and changes as typhoon process differs, their simulation results showed the extreme high surge elevation decreases for typhoon Prapiroon. Not only does SLR have an influence on storm surge and waves, Mousavi et al. (2011) emphasized that both SLR and TI should be considered when evaluating potential future hurricane flood conditions. To estimate and rank the exposure of major coastal cities to coastal flooding due to high wind and storm surge, Nicholls et al. (2008) combined the effect of a global SLR of 0.5 m and TI. However, the TI is captured by a storm enhancement factor of 10% that reflects the potential increase in extreme water levels due to more intense storms. Condon and Sheng (2012) evaluated the coastal inundation hazard in southwest Florida for incorporating changes in hurricane intensity and frequency as well as SLR, results showed that greater flood hazard would happen due to SLR.

Although these studies all involve how SLR or TI impact storm surges, and have made outstanding achievements, owing to the complexities of depending on typhoon intensity, track and local topography, there is no one-size-fits-all response to SLR and TI descriptive of all locations. Therefore, to some extent, the impacts must be further investigated. Furthermore, few studies have been carried out to estimate the impacts in PRE where with serious storm surge disaster and substantial SLR. The purpose of this paper is to estimate the potential impacts of SLR and TI on storm surge as well as waves in PRE, especially for seawalls. This is accomplished through numerical simulation of storm surge and wave for the SLR of 0.5 m and 1.0 m as well as the TI of 5% and 10%, which would likely occur in the next fifty to one hundred years based on previous research.

2. Numerical model description

The ADCIRC model developed by Dr. Rick Luettich and Dr. Joannes Westerink (Luettich and Westerink, 1991), which has been widely used in the world, can carry out simulations of storm surge, flooding, tides, wind driven circulation, larval transportation, near shore marine operations, dredging feasibility and material disposal. ADCIRC can be run either as a two-dimensional depth integrated model or as a three-dimensional model. The two-dimensional version of ADCIRC is selected to solve the two-dimensional, depth-integrated, shallow water equations. The governing equations in Cartesian Coordinates consist of continuity equations and momentum equations, which are discretized using the finite element method in space and using the finite difference method in time (Luettich and Westerink, 2004).

The SWAN model developed by Delft University of Technology (The Netherlands) can be used to simulate the evolution of random, short-crested wind-generated waves in estuaries, tidal inlets, and lakes (Deltares, 2013). The SWAN model is selected as the wave model because of its advantage of coupling capacity with ADCIRC (Dietrich et al., 2011). This model is based on the discrete spectral action balance equation and is fully spectral (Hasselmann et al., 1973).

3. Model setup and verification

3.1. Tidal current model

3.1.1. Model domain and mesh

The hydrodynamic process in PRE is extraordinarily complex due