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Improvement to flooding risk assessment of storm surges by residual interpolation in the coastal areas of Guangdong Province, China

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ABSTRACT

Estimation of the extreme Total Water Levels (TWL_t) is critical for inundation modeling and risk analysis. TWL_t consists of the extreme Storm Surge (SS_t) and Astronomic Tide (AT_t), which are strongly affected by local topography and have large spatial heterogeneity. One common method is to compute the TWL_t using the long-term TWL recorded at the limited standard tide gauges and then interpolate them into areas without gauges (here called total interpolation), often generating large uncertainties. This study develops a residual interpolation method to estimate the extreme TWL_t for those areas without standard tide gauges. The core of this method is first to compute the extreme AT_t for the 2-year return period using the tidal datum at the dense secondary stations, and then the residuals of AT_t between return periods of T (T = 10, 20, 50, 100, 200 and 500 years) and 2 years at the standard stations are interpolated into the secondary tide stations; meanwhile, the extreme SS_t computed at the standard stations are interpolated into the secondary tide stations as well. The sum of $AT_{t=2}$, AT_t residuals and SS_t forms the maximum water level and is converted into the extreme TWL_t, which are further interpolated into elevation grids for inundation modeling and risk analysis. Results show that cities in the Pearl River Delta face extremely high storm surge risk, and other regions, such as ChaoZhou and ShanTou in the north and ZhanJiang in the south also have large areas within the extremely high risk zones. The residual interpolations can better capture the spatial variability of the storm tide than the traditionally total interpolation. Accordingly, the flooding risk uncertainty is greatly reduced by the residual interpolation, thus offering better supports for coastal development planning and flooding hazards risk management.

1. Introduction

Typhoon and storm surges have abrupt and severe impacts on the coastal areas, resulting in sea water intrusion, coastal erosion, civil infrastructure damage and even large death tolls (Menendez and Woodworth, 2010; Plater et al., 1999). For instance, the super typhoon Rammasun formed in the western North Pacific swept Philippines, Hainan, Guangdong and Guangxi Provinces of China from July 16 to 18, 2014 and added the death toll of 98 people in Philippines and 18 in China (HKO, 2014). The storm surge induced by Rammasun caused 13.12 billion Yuan (RMB) direct economic loss and affected 2.56 million people in Guangdong Province, China (Deng et al., 2014).

The impacts of Storm Surges (SS) are exacerbated by the high Astronomical Tides (AT). AT is the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon, the Sun and the Earth and the Earth's rotation, while SS is the abnormal rise of sea water associated with low pressure weather systems, such as tropical cyclones (typhoons) and strong extratropical cyclones (Peek and Young, 2013). SS is a random phenomenon caused by the weather/atmospheric pressure system and is unpredictable at long-term scales, e.g., months and years. In contrast, the height of AT along the open coast can be predicted with high confidence and in months or years ahead by tidal

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harmonic analysis according to the location, date and time. The combination of SS and AT forms the Total Water Level (TWL) height, which is also called as storm tide. In practice, SS is obtained by subtracting the predicted AT from the observed TWL. When a large SS encounters with a high AT, it will generate an extremely high sea level, leading to a huge disaster to the low-lying coastal areas.

The coastal areas bear a large proportion of population and economy and are exposed to typhoon and storm surges. Risk assessment and managements are significant non-engineering measures for disaster mitigation and prevention (Field et al., 2014). Several studies have used numerical models (Brown et al., 2007; Wang et al., 2012; An et al., 2015) or static inundation models (Webster et al., 2006; Yin et al., 2011) to analyze the flooding risk of storm surges. One of the critical steps for flooding risk assessment on storm surges is to compute the extreme TWL_t along the coastal areas in different return periods.

The extreme TWL_t are expressed in terms of a given occurrence probability and return periods and calculated by frequency analysis such as Gumbel, Pearson III and Exponential distribution from the long-term records of annual peak TWLs (Zhang et al., 2013). However, TWLs have large spatial heterogeneity and the in situ records of TWLs are quite sparse in most coastal areas. It is rather challenging to derive the TWLs for those coastal areas without tidal records. One solution is to transfer the TWLs from the gauged sites to the nearby un-gauged sites by Regional Frequency Analysis (RFA) in tidal homogeneous regions (Arns et al., 2013). Another solution is to directly interpolate the return levels of TWL_t from sparse gauged sites to the nearby un-gauged sites by spatial interpolation methods such as Kriging and Inverse Distance Weight (IDW) (Archfield et al., 2013; Ball et al., 2014). Both RFA and the direct spatial interpolation generate large uncertainties especially in those areas, where TWLs have large spatial heterogeneity. An alternative approach is to utilize a numerical multi-decadal model to hindcast the extreme water levels, whose bias correction function is obtained at the gauged sites and then interpolated to the nearby un-gauged model grid sites (Arns et al., 2013, 2015). One of the primary uncertainty sources of the above methods is that they can not represent the spatial variations of the local astronomical tides, which are the primary base height of the extreme storm tides, especially in the estuary and shallow bay areas.

Instead of using the tidal model simulations, this study proposes a residual interpolation method to estimate the return levels of TWL_t based on the tidal datum of the dense secondary tide stations and the long-term records of TWLs at the standard tide stations in the coastal areas of Guangdong Province, China. There are only 10 standard tide stations along the 3300 km coastline of Guangdong Province, while having over 90 secondary tide stations. The tidal datum is the reference (often lowest) plane of tidal height observations and can represent the amplitudes of the local maximum astronomical tide to some extent (Hess, 2003). The tidal datum at the dense secondary stations is utilized to estimate the 2-year astronomic tide heights, thus can better capture the local variations of the astronomic tides. The residuals of the T-year ATs and 2-year AT obtained at the standard tide stations have small spatial variations and are interpolated to the nearby secondary stations.

Therefore, the primary objective of this study is to develop a residual interpolation method to estimate the extreme TWL_t in different return periods at un-gauged coastal regions. Then, an inundation model is established to simulate the coastal flooding caused by storm surge. Finally, economy loss and affected population are used to assess the flooding risk in the coastal areas of Guangdong Province, China.

2. Study areas and data

The study area is located in the Guangdong Province of South China at 20°13′–25°31 N′ and 109°39′–117°19′ E (Fig. 1). It is in subtropic and tropic climate settings and stroked by 2.8 typhoons per year recently (Tang et al., 2003). The coastline length is 3360 km, and many coastal areas are low-lying terrains, especially in the Pearl River Delta. There are about 10 standard tide stations with long-term records of TWLs, while having 91 secondary tide stations along the coastline. The 10 standard tide stations used in this study are Shantou, Haimen, Shanwei, Chiwan, Huangpu, Denglongshan,

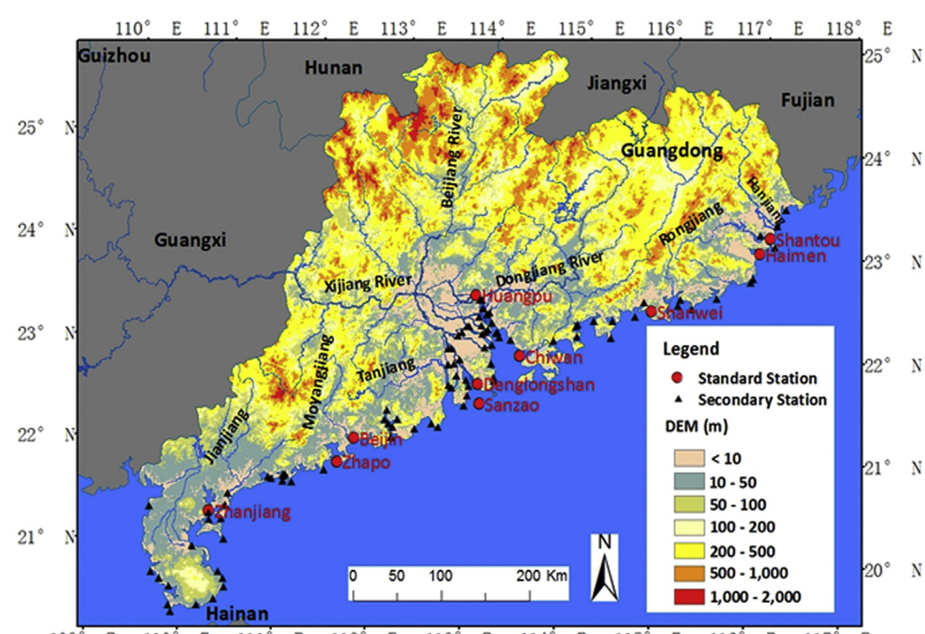

Fig. 1. Study area (Guangdong Province, China) and tide stations. There are 10 national standard tidal stations that have long-term tide level records, and 91 secondary stations that only have tidal datum and total water levels and storm surge observations occasionally.

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