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Effects of sea level rise on frequency analysis of 1% annual maximum water levels in the coast of Florida

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ABSTRACT

Traditionally, annual maximum water levels (AMWLs) data mixed with sea level rise (SLR) effects have been used in probability analysis of extreme values. However, considering that SLR can be described by a regression equation, the deterministic variables of SLR should be separated from the extreme value probability analysis. To account for the SLR impact on the extreme high water level in the Florida coastal waters, frequency analysis of AMWL in Pensacola and Fernandina Stations in Florida coast are investigated in this study. With the data for the past 89 and 100 years, regression equations have been derived to predict the SLR trends in Pensacola and Fernandina stations, respectively. Consider sea level rise is not a random variable, historic AMWLs are modified by removing SLR to provide SLR-removed AMWLs for frequency analysis. By comparison to SLR-removed AMWLs, the GEV (general extreme value) and Xu–Huang distributions are shown to provide reasonable predictions of AMWLs. After frequency analysis of SLR-removed AMWLs, SLR impacts are included by adding the SLR from the SLR regression equation in the future. AMWLs with SLR impacts for any return period up to year 2100, with tables for 100-year AMWLs, are provided to support coastal hazard mitigation planning.

1. Introduction

Coastal regions, particularly some low-lying river deltas, have very high population densities. Billions of dollars are invested in coastal infrastructure immediately adjacent to the coast. Today, low-elevation coastal zones below 10 m elevation contain ~10% of the world population (Nicholls and Cazenave, 2010). Many of the world's mega cities (populations of many millions) are on the coast. Sea level rise (SLR) is widely considered as a significant consequence of climate change (Carbognin et al., 2010). Coastal environments and communities have been highly impacted by sea level rise. SLR contributes to coastal erosion and inundation of low-lying coastal regions, particularly during extreme sea level events. It also leads to saltwater intrusion into aquifers, deltas, and estuaries. For instance, increased damage from flooding has even more important economic consequences for Florida, which has a relatively low lying coastal zone (Walton 2007). Various climatic modeling studies have been conducted in the past 20 years (Church et al., 1991; Tsimplis et al., 2010; Miller and Douglas, 2004; Becker et al., 2009). A linear trend in SLR is conducted in the previous study (Douglas, 1991; Kang et al., 2009). The linear fit analysis on SLR is also provided by the NOAA stations (National Oceanic and Atmospheric Administration (NOAA), 2010). Walton (2007) compared the 1st order, 2nd order and exponential fit on SLR in five long historical stations in Florida. The second order method is recommended for projecting SLR in Florida due to the economic concern. The second order method also shows the acceleration of SLR that has been widely acknowledged (Hinkel et al., 2010; Hunter, 2010). The effect of SLR has been studied in many relative fields (Smith et al., 2010; Nicholls and Cazenave, 2010; Walton, 2007; Chini et al. 2010; Purvis et al., 2008). For instance, the potential influence by SLR on the hurricane storm surge hazards in Sarasota County of Florida are studied by Frazier et al. (2010). The analysis shows that SLR significantly affects storm surge impacts of future land-falling hurricanes in Sarasota County. The study also demonstrates that even if hurricanes neither become more frequent nor more intense, SLR will still increase the impacts of storm surge. If hurricanes do become more frequent or more intense, there will be more potential risks associated with storm surge damage. The coupled sea level rise impact plus increased storminess show the effects of climate change. To analyze the contribution from SLR to coastal erosion and inundation during extreme sea level events, the acceleration of SLR needs to be considered on the estimation of extreme high water levels.

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The Federal Emergency Management Agency (FEMA) of the United States maintains and updates the National Flood Insurance Program maps (Federal Emergency Management Agency (FEMA) of the United States, 2005). Flood mapping is based on the annual maximum water levels (AMWLs) throughout the study area that have a 1% chance of being exceeded in any given year, which is called the 100 years extreme water level. Therefore, adequate estimation on 100-year AMWLs is very important for coastal planning and flood hazard mitigation in Florida coastal waters. The observed annual maximum water levels are resulted from many driving forces, including tides, winds, sea level rise, etc. When long-term observations of AMWLs are available, frequency analysis for estimating extreme water levels such as 100-year AMWLs is recommend by Federal Emergency Management Agency (FEMA) of the United States (2005). Some studies on the 100-year AMWLs in the worldwide coastal areas have been conducted (Sobey, 2005; Xu and Huang, 2008; Xu and Huang, 2011). Previous frequency analysis study on Florida coastal stations by Xu and Huang (2008) are based on observed AMWLs. However, in almost all previous frequency analyses of extreme water levels, SLR effects have not been separately studied. Therefore, further investigations are needed. Walton (2007)'s study indicates that the sea level rise trends in Florida coast can be described by regression equations. This means that sea level rise is not a random variable, which should be separated from the random variables of the observed annual maximum water levels for frequency analysis. However, most traditional frequency analyses for coastal extreme water level analysis are based on observed AMWLs without separating SLR signals (eg., Federal Emergency Management Agency (FEMA) of the United States, 2005; Walton, 2007; Sobey, 2005; Huang et al., 2008; Xu and Huang, 2011). From the previous review of the relative studies, the SLR effect need to be valued and may have significant impacts on the estimation of 100-year AMWLs.

In this study, two NOAA stations (Pensacola and Fernandina) with long history observed annual water levels in Florida are chosen for the frequency analysis. Observed annual maximum water levels are separated into SLR-removed AMWLs (random variables) and the SLR trends (deterministic variables). Because probability theories are only applied for analysis of random variables, frequency analysis in this study is conducted only for the random variables of SLR-removed AMWLs. This provides more reliable theoretical estimations of the AMWLs at different frequency. SLR trends are described by regression equations, which can be used to project the additional increase of sea levels in a given year in the future.

2. Datasets

For the analysis of SLR in the studied sites, the monthly mean water level datasets of Pensacola and Fernandina stations are selected for this study. The datasets used in the fitted sea level rise are obtained from the National Oceanic and Atmospheric Administration (NOAA) tide gage station network in Florida. These two stations are chosen for this study because most of the other stations only have short periods of data and are not suitable for the study of SLR and frequency analysis. Fernandina and Pensacola stations have the longest historical water level datasets in the coast of Florida.

The necessary length of dataset to analyze was discussed by Walton (2007). Short record of dataset may not be able to reflect the trend of SLR. Thus previous studies on SLR were based on long historical datasets. For instance, the longest continuous record (140 years) in the US was chosen for the study by Douglas (1991). By analysis of sea level records at Bermuda and Charleston, DC, USA, Roemmich (1992) suggested that at least 50-year records of sea levels are necessary to understand the fluctuations at a given coastal location. Five NOAA stations with long historical datasets in Florida were chose to study the SLR trend. The projected SLR to the year of 2080 in the studied stations is proposed (Walton, 2007). In Walton's study, the minimal length of the dataset is more than 50 years.

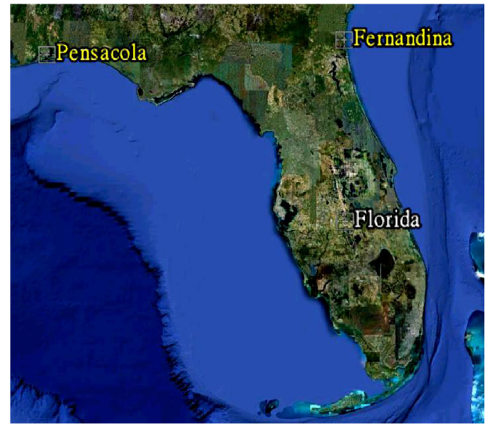

Fig. 1. Locations of studied sites (Pensacola and Fernandina).

Locations of the two study stations are shown in Fig. 1. The monthly mean sea level series of the two stations based on MSL (mean sea level) datum were chosen for the analysis to find the SLR trend in the studied locations. In this study, an 88-year dataset during 1923–2010 is available for Pensacola station. The historical water level dataset for Fernandina station is from 1898 to 2010. There is a data gap for the period of 1960–1969, which results in a dataset of 100 years of AMWLs in Fernandina station.

Long historical dataset is also required for frequency analysis on 1% AMWLs (Federal Emergency Management Agency (FEMA) of the United States, 2005; Sobey, 2005). The effect of different length datasets in estimating 100 and 200 years AMWLs in Wusong station of China are compared (Xu and Huang, 2011). The comparison shows that shorter periods of dataset may cause significant errors for estimating of 100 and 200 years of AMWLs. Therefore, the reliable frequency analysis of extreme water levels should be based on long period data sets. In this study, an 88 years period of AMWLs based on MSL datum is available for the Pensacola station (shown in Fig. 2). The Fernandina station has an even longer period of data with 100 years data. Despite the missing time period (shown in Fig. 3), 100 years of AMWL data based on MSL datum are available for Fernandina station for frequency analysis

3. Regression equations for sea level rise trend in Pensacola and Fernandina

In this study, historical sea level rise trends are fitted by regression methods. There are two different popular fitting methods. In NOAA website (〈http://tidesandcurrents.noaa.gov/〉), linear equation has been recommended to project SLR trend. An alternative 2nd order equation has been proposed by Walton (2007) to account for possible acceleration in SLR due to the climatic influence of greenhouse gases. In this study, performance of those two fitting equations as shown below for SLR has been evaluated by comparing to historical SLR data.

$$y = at^2 + bt + c \quad (1)$$

$$y = at + b \quad (2)$$

After applying the least square fit method, the parameters a, b and c in Eqs. (1) and (2) are estimated.