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Interannual sea level variability in the Pearl River Estuary and its response to El Niño–Southern Oscillation

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ABSTRACT

The South China coast, especially the Pearl River Estuary (PRE) region, is prosperous and densely populated, but vulnerable to sea level changes. Sea level anomalies (SLA) during 1954–2012 from tide gauge station data and regional SLAs during 1993–2012 from satellite altimetry are analyzed and compare to the El Niño–Southern Oscillation (ENSO). Results show that sea level declines during El Niño events and rises during La Niña. Sea level in the PRE responds to ENSO with ~3–month lag. The ENSO can cause sea level in the PRE to fluctuate from −8.70 to 8.11 cm. Sea level cycles of 3 and 5 years are related to ENSO. The ENSO mechanism affecting sea level in the PRE was analyzed by identifying dominant regional and local forces. Weak/strong SLAs in most El Niño/La Niña events may be attributed to less/more seawater transport driven by anomalously weak/strong north winds and local anomalously high/low sea level pressure. Wind-driven coastal current is the predominant factor. It generated coastal seawater volume transport along a ~160 km wide cross section to decrease by 21.07% in a typical El Niño period (January 2010) and increase by 44.03% in a typical La Niña period (January 2011) as compared to an ENSO neutral situation (January 2013). Results of sea level rise and its potential mechanism provide insight for disaster protection during extreme El Niño/La Niña events.

1. Introduction

Coastal regions are often of economic importance, but are vulnerable to global sea level rise. The global sea level has risen at ~3.1 mm annually on average since the 1990s and continues to rise (Nerem et al., 2010; Church and White, 2011). However, global sea level changes are not at the same rate everywhere. Extensive studies have shown that greater rise rates of sea level occurred in the western tropical Pacific, southern oceans and eastern Indian Ocean in recent decades (Li et al., 2002; Cazenave and Nerem, 2004; Chowdhury et al., 2010; Tseng et al., 2010). At regional scale, the sea level rise rate in the South China Sea (SCS) is substantially higher than the global mean rate (Cheng and Qi, 2007; Fang et al., 2006). Locally, coastal areas of South China are also experiencing a faster rise rate than the global mean (Peng et al., 2013; Wang et al., 2016).

As the global temperature changes, so does the sea level. Sea level is often considered an effective indicator of climate change. Thermal expansion from global warming, water input from glaciers and ice sheets have changed sea level on various time scales (Cheng et al., 2008; Rahmstorf, 2007). Recent studies found that El Niño and La Niña events have strong impacts on sea level interannual variation (Llovel et al., 2011; Cazenave et al., 2012; Fasullo et al., 2013). Sea levels at low latitudes, i.e., tropical and subtropical, are more responsive to ENSO than at mid–high latitudes (Soumya et al., 2015; Yuan et al., 2009). Although ENSO has major impacts on the sea level in low-latitude regions, i.e., causing it to fluctuate, it has not altered the rising trend (Cheng et al., 2016). After removing interannual variability caused by ENSO, the global mean sea level in recent decades showed a continuous rapid rise rate of 3.3 ± 0.4 mm per year (Cazenave et al., 2014). Furthermore, spatial variations in extreme positive sea level anomalies over the past 20 years were closely associated with regional modes such as ENSO (Woodworth and Menendez, 2015).

In the western Pacific Ocean, interannual sea surface height (SSH) oscillations have been associated with ENSO (Chang et al., 2013; Zhuang et al., 2013). The SCS is a semi-closed sea exchanging water with the adjacent East China Sea, Indian Ocean and western Pacific Ocean (Fig. 1). In the SCS, ENSO affects sea surface temperature (SST), the monsoon, precipitation, and tropical cyclones (Nan et al., 2014; Wang et al., 2012; Chang et al., 2008; Q. Zhang et al., 2015; R. Zhang et al., 2015). ENSO also influences interannual sea level variation in the SCS at different spatial and temporal scales through various processes such as water transport, anomalous Ekman pumping, and anomalous

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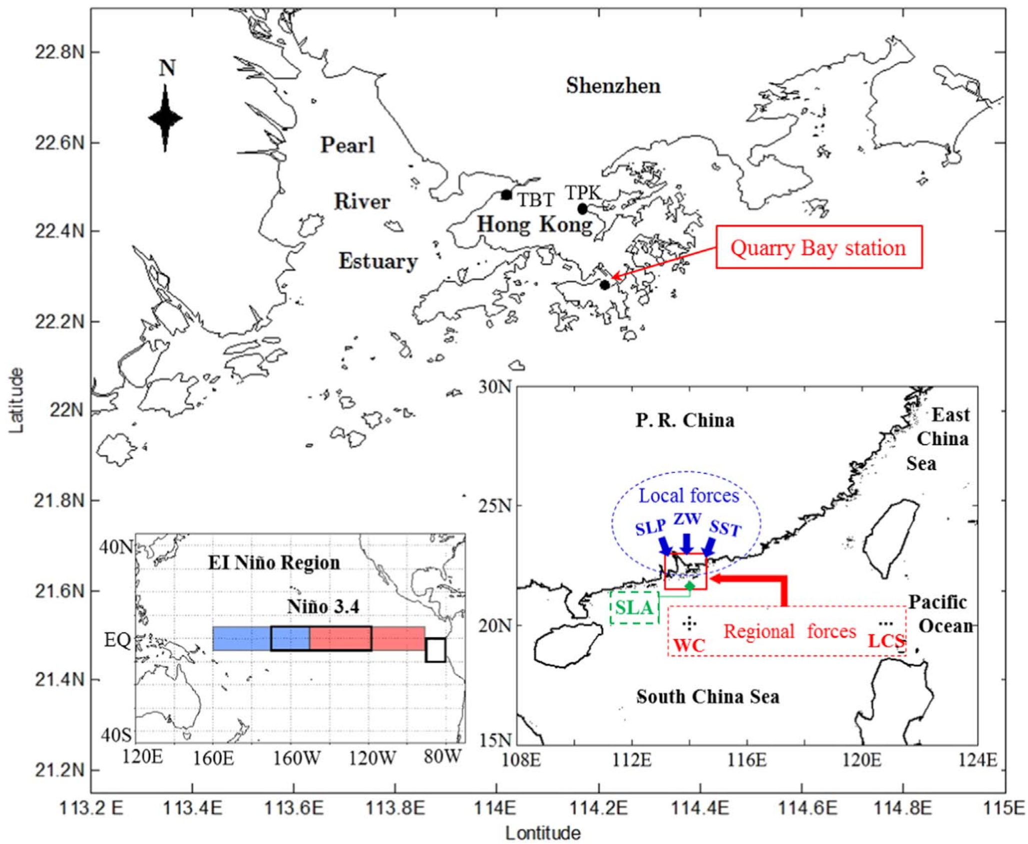

Fig. 1. Study area and locations of tide gauge stations in the PRE, representative regional SLA (green color), El Niño 3.4 region, and regional factors of Luzon Strait Current (LSC) and westward current (WC). Also shown are local forces of sea level pressure (SLP), zonal wind (ZW) and sea surface temperature (SST). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

SST (Chen et al., 2014; Han and Huang, 2009; Liu et al., 2011; Liu et al., 2015; Peng et al., 2013; Rong et al., 2007). Furthermore, ENSO may affect sea level maxima by modulating the number of tropical cyclones reaching China's coasts (Feng and Tsimplis, 2014).

The Pearl River Delta meets the northern SCS, with ~60 million people in the nine largest cities of the PRE region. This area is strongly affected by sea level rise (Shi et al., 2008; R. Huang et al., 2004; Z. Huang et al., 2004). The latest report from the China Oceanic Information Network estimates that the sea level at South China coasts will rise 75–165 mm in the next 30 years (http://www.coi.gov.cn). This will increase the risk of seawater intrusion (Yuan et al., 2015), with more sediment accumulation (Zhang and Mao, 2015; Wu et al., 2014) and coastal inundation (R. Huang et al., 2004; Z. Huang et al., 2004). This will in turn threaten freshwater supplies and human lives. In this region, sea level interannual variation is also affected by ENSO. For example, Ding et al. (2001a, b) found that sea level interannual variability in Hong Kong waters within the PRE was related to ENSO. However, the potential mechanism by which ENSO affects PRE sea level variation remains unclear and the impacts have not been quantified. The strong El Niño in 1997–1998 may have caused 32 million USD losses to Hong Kong fisheries because of anomalously warm seawater (Yin et al., 1999). Because the South China coast, especially the PRE, is economically important and densely populated, ENSO impacts should be quantified and related mechanisms investigated to provide insights for disaster prevention.

The overall objectives of the present study were to 1) quantify interannual variation of the PRE sea level, 2) examine how ENSO affects PRE sea level variability, specifically amplitude and periodicity, and 3) investigate potential drivers at multi-decadal scales and various spatial scales (including large, regional, and local). For prediction purposes, we also developed empirical models to quantify the relationship between sea level interannual variation in the PRE and ENSO.

2. Data and methods

2.1. Study area and data collection

Water level data from three tide gauge stations in Hong Kong waters of PRE were used to analyze sea level variation (Fig. 1). The Quarry Bay station is registered in the core network of the Global Sea Level Observing System, and its observed sea level data are often used to study long-term sea level changes (Ding et al., 2001a, b; Zhang and Ge, 2013). Two other stations, Tai Po Kau and Tsim Bei Tsui, are also within Hong Kong waters. However, only the Quarry Bay station has the longest and the most complete record of sea level and temperature data. Furthermore, that station is located off the mouth of the river and the effect of surface runoff is relatively weak. In a previous study, we found that water level data from the three stations were correlated, with correlations of 0.61–0.96. Moreover, the mean local SLA estimated from the three stations is correlated with offshore SLA, with a correlation coefficient of 0.73 (Wang et al., 2016). Therefore, the Quarry Bay station was selected for time series analysis. Regional SLAs from satellite altimetry for a broader region (19.5°–23.5°N and 111°–117.5°E) were downloaded from AVISO (http://www.aviso.altimetry.fr/) to analyze the relationship between regional SLA and ENSO.

The tide gauge data was provided by Hong Kong Observatory (HKO) and corrected for subsidence based on prior studies (Ding et al., 2001a, b). For hourly water level data, a 40-h lowess filter was applied to remove the tide-related component. Then, inverted barometer correction was done using sea level pressure (SLP) from the National Centers for Environmental Prediction (NCEP) (http://www.ncep.noaa.gov/) (Bi et al., 2011). The monthly water level was calculated after removing its linear trend. Finally, a 7-month moving average SLA was obtained to analyze sea level variations. The Butterworth filter with a band pass of 2 and 7 years was used to obtain the component of sea level variation related to ENSO.

The Southern Oscillation Index (SOI) and the Oceanic Niño Index