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Inter-annual sea level variability in the southern South China Sea

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ABSTRACT

The South China Sea (SCS) is the largest marginal sea in the western Pacific Basin. Sea level anomalies (SLAs) in the southern South China Sea (SSCS) are assumed to be governed by various phenomena associated with the adjacent parts of the Indian Ocean and the Pacific Ocean. We have used monthly sea level anomalies obtained from 12 tide gauge stations of PSMSL and UHSLC and merged and gridded AVISO products of SLAs (sea level anomalies) derived from satellite altimeter. We find that IOD-influenced inter-annual variations are found only in the southwestern and southeastern coastal regions of SSCS. Our analysis reveals that inter-annual regional sea level drops are associated with positive phase of the IOD, and the rises with negative phase of the IOD. SLA variations at decadal scale in the southeastern and northern Gulf of Thailand correlate with Pacific Decadal Oscillations (PDO). Multiple linear regression analysis of inter-annual SLAs and climate indices shows that IOD induced inter-annual variations dominate in the southwestern SCS and it contributes to about ~40% of inter-annual sea level variation. Meanwhile, ENSO contributes to around ~30% variation in sea level in the southwestern and ~40% variation in the southeastern SSCS. The present study also suggests that inter-annual SLA variations in the SSCS can occur by ENSO and IOD induced changes in wind stress curl and volume transport variations.

1. Introduction

The South China Sea (SCS) is one of the western marginal seas of the Pacific Ocean, surrounded by South China, Indo China Peninsula, Malaysian Peninsula, Philippines and Borneo Island. The SCS is a semi-enclosed basin connected to the western Pacific Ocean through Taiwan Strait and Luzon Strait, Sulu Sea through Mindoro Strait and Balebec Channel, Java Sea through Gasper and Karimata Straits, and to the Indian Ocean through the Strait of Malacca. All the Straits are shallow, except the Luzon Strait, which features a sill deeper than 2000 m. The maximum depth of SCS is about 4700 m in the middle of the basin, but it is much shallower towards the southern part, especially in the Sunda Shelf region and in the Gulf of Thailand where depth is less than 100 m. Southwestern SCS includes Gulf of Thailand, Malaysia Peninsula and Singapore Strait. Southernmost regions in the SCS encompass narrow straits and numerous small islands. Singapore Strait at the central part of the shallow Sunda shelf connects the SCS and Java Sea and part of the deep basin of the Andaman Sea.

As an Asian marginal sea, the SCS dynamics is dominated by East Asian monsoon system with north easterly winds during winter (November–February) and southwesterly winds during summer (June–August). These seasonally varying northeast (NE) and southwest (SW) monsoons induce seasonal variations in the physical characteristics in the upper ocean of SCS (Wyrtki, 1961). NE monsoon winds are stronger in the SCS, with strongest winds recorded during December (Camerlengo and Demmler, 1997). Due to these winds, an up surge of sea level is observed along the western SCS. Due to the persistence of NE monsoon winds, water tends to pile up on the western SCS (Shaw and Chao, 1994). This positive set up in sea level during winter at the southern SCS is amplified by the shallow depth of Sunda Shelf (Chen et al., 2012). Circulation in the southern SCS is relatively weak (Qu et al., 1999). In winter, a strong cyclonic gyre exists along the western part of the south SCS and a weaker anticyclonic circulation along the eastern part of the SCS. Circulation in the SCS is characterized by a cyclonic gyre in winter (Chu et al., 1999; Qu et al., 2000; Wyrtki, 1961). The southward jet in winter follows throughout the western boundary, but the northward jet in summer moves away from the coast of Vietnam at about 12°N (Shaw and Chao, 1994) and there is an anticyclonic gyre in the Southern SCS and a cyclonic gyre in the northern SCS in summer (Wyrtki, 1961; Fang et al., 2002; Wang et al., 2003). Overall SCS sea level is higher during summer and lower during winter (Shaw et al., 1999; Ho et al., 2000).

As the SCS is embedded between the western Pacific and the Indian Oceans, it is considerably influenced by inter-annual and decadal sea level variability associated with El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) in the Pacific Ocean and Indian Ocean Dipole (IOD) in the Indian Ocean. Though ENSO is centered in the Pacific Ocean, it can influence global climate through oceanic and atmospheric teleconnections. ENSO peaks during the boreal winter while its influences on other ocean basins normally peak 1–2 seasons later

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(Alexander et al., 2002). The warm phase of ENSO (El Niño) begins by a weakening of trade winds and convective activity in the equatorial western Pacific, shifts eastward leading to an altered Walker circulation with anomalous ascent over equatorial central and eastern Pacific, and descent over the SCS region. This leads to reduced convection, decrease in cloud cover and reduction in precipitation; this situation reverses during La Niña events. Hadley circulation strengthens over the eastern Pacific but weakens over the Indo-Western Pacific (Klein et al., 1999). During the cold phase (La Niña), intensified trade winds shift the warm pool farther west. This plays a significant role of SLA variation during ENSO. The strength of ENSO is measured by Southern Oscillation Index (SOI). The SOI is the surface air pressure difference between Tahiti, south Pacific islands and Darwin (Australia). El Niño episodes are associated with negative values of SOI.

SCS climate is part of the East Asian monsoon system and appears to be connected with ENSO in the Pacific (Zhang et al., 1997). There have been numerous studies describing inter-annual sea level variations in the SCS with most of the variations linked to ENSO (Hwang, 2001; Fang et al., 2006; Rong et al., 2007; Zhou et al., 2012 and Peng et al., 2013) and PDO (Deng et al., 2013; Wu, 2013), and are confined to northern and eastern SCS. Rong et al. (2007) investigated different mechanisms that lead to the ENSO driven inter-annual sea level variability of SCS. Responses of SCS sea level anomalies (SLAs) and sea surface temperature (SST) anomalies to ENSO are completely out of phase. ENSO induced SST variation in the SCS is believed to be through the atmospheric circulation changes. SST anomalies show double peak with relaxation between two peaks during El Niño events. A change in atmospheric circulation influences surface heat fluxes and oceanic circulation in the SCS that in turn influence the SST variation over the SCS (Wang et al., 2006a,b). Sea level and SST have inverse responses to ENSO in SCS. But, the thermosteric sea level anomalies, corresponding to the temperature in the intermediate layers, correlate with SOI (Rong et al., 2007).

The inter-annual relationship between the ENSO and the global climate is not stationary and can be modulated by the PDO (Mantua et al., 1997; Wu and Wang, 2002). Inter-annual variability in the low latitude western Pacific has been more closely related to PDO than ENSO in recent years (Wu, 2013). The PDO is the predominant source of inter-decadal climate variability in the Pacific Northwest, defined using the monthly anomalies of sea surface temperature (SST) in the Pacific, poleward 20°N (Mantua et al., 1997). During the positive (negative) phase of the PDO, the northwestern Pacific is characterized by negative (positive) SLAs. Geochemical studies of coral obtained from the northeastern SCS reveal the PDO activity in the SCS (Deng et al., 2013). Prominent decadal variability of SCTF is in phase with wind stress anomalies associated with PDO. The upper layer of SCTF strengthens during the positive phase of PDO (Yu and Qu, 2013).

Being a semi-enclosed ocean basin, SCS water can be exchanged with the surrounding ocean through the Straits. This plays an important role in sea level variations in the SCS. Intrusion of the northwest Pacific water through the Luzon Strait in the SCS is referred to as Luzon Strait transport (LST). As a direct response to the Pacific wind, Pacific origin water enters the SCS and part of the water continues southwards into the Java Sea and returns to the Pacific through the Makassar Strait (Qu et al., 2004), known as South China Sea Through Flow (SCTF). SCTF involves the inflow of cold and salty water through Luzon Strait and the outflow of warm and freshwater through the Mindoro and Karimata Straits. SCTF during ENSO increases southward flow into the Makassar Strait, inhibits tropical Pacific water injection into Makassar Strait, thereby reduces Indonesian through Flow (ITF) into the Indian Ocean (Gordon et al., 2012). Most of the water entering the SCS circulates along the western boundary of SCS and exits through Karimata Strait. Water exchange between SCS and Pacific Ocean is mostly concentrated in the upper 300 m (Shaw and Chao, 1994). The LST carries the ENSO signals into the SCS. Water enters the SCS with a low temperature through LST and leaves with a higher temperature through Karimata and Mindoro Straits. Increased LST during El Niño produces a stronger than normal cooling advection, which eventually cools SCS and leads to negative SLAs (Qu et al., 2004). SCTF plays an important role in the climate variability of Indo-Pacific Ocean by changing the upper ocean thermal structure. Decadal variability was identified as the dominant mode of upper ocean heat content (Song et al., 2014). Wind stress variations in the western Pacific play a major role in the inter-annual and decadal variabilities of SCTF (Wang et al., 2006a,b and Liu et al., 2010a,b).

SCS summer monsoon is influenced by IOD through its impacts on atmospheric circulations (Yuan et al., 2008). The IOD is the coupled ocean and atmosphere phenomena in the equatorial Indian Ocean that evolves a positive mode (PIOD) and negative mode (NIOD) in which western Indian Ocean becomes alternatively warmer and colder than eastern Indian Ocean (Saji et al., 1999). The positive IOD events generally occur during El Niño and negative IOD with La Niña events, but they can occur independently (Yamagata et al., 2004). IOD shows a quasi-biennial variation due to the sequential existence of NIOD followed by a PIOD (Saji et al., 1999; Rao et al., 2002; Behera and Yamagata, 2003; Feng and Meyers, 2003). Dipole Mode Index (DMI), proxy for IOD is the difference between sea surface temperature (SST) in the western (50°E–70°E, 10°S–10°N) and eastern (90°E–110°E, 10°S–0°S) equatorial Indian Ocean (Saji et al., 1999).

In the present study, satellite altimetry SLA data for the last two decades, as well as tide gauge records at 12 locations are employed to examine the inter-annual sea level variations in the Southern SCS.

2. Data

Monthly sea level anomalies were obtained from Permanent Service for Mean Sea Level (PSMSL) and University of Hawaii Sea Level Centre (UHSLC). Fig. 1 shows locations of tide gauge stations. Details of sea level stations and data duration are given in Table 1. Merged and gridded products of MSLA (Maps of Sea Level Anomaly), derived from satellite altimeter, are obtained from https://www.aviso.oceanobs.com. This MSLA is produced by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data), based on TOPEX/Poseidon, Jason 1, ERS-1 and 2 altimeter observations. In this study, we have averaged the sea level anomaly data available at weekly intervals to obtain monthly mean sea level anomalies for 1993–2011.

In this study, we characterize the main climate modes that drive the inter-annual sea level variation over the SCS, by analyzing the correlation between SOI (Southern Oscillation Index), DMI (Dipole Mode Index) and PDO (Pacific Decadal Oscillation) index. The ENSO index (SOI) is downloaded from http://www.cpc.ncep.noaa.gov/data/indices/ and DMI defined by Saji et al. (1999) is downloaded from http://www.jamstec.go.jp/frcgc/research/d1/iod/e/iod/dipolemode_index.html. PDO, based on north Pacific SST variations, are obtained from http://jisao.washington.edu/pdo/PDO.latest. Classification of IOD events into positive and negative and warm and cold phases of ENSO into El Nino and La Nina years (Table 2) is done based on available literature information.

Volume transport between SCS and adjacent oceans is estimated based on SODA (Simple Ocean Data Assimilation) global reanalysis datasets. These datasets are provided on 0.5° × 0.5° horizontal resolution with 40 levels from 5 m to 5347 m depth range for the period 1958 to 2008. Zonal and meridian velocities are used to calculate the volume transport in the upper 300 m. ERA-Interim reanalysis surface wind products with 1.5° resolution are downloaded from http://data-portal.ecmwf.int/data/.

3. Methodology

In order to study the relationship between the sea level variation in SCS and climatic modes at inter-annual time scale, the observed monthly sea level data series were subtracted from mean to obtain sea