

ENSO-induced inter-annual sea level variability in the Singapore Strait

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Sea level data from four tide gauge stations in the SS (Tanjong Pagar, Sultan Shoal, Sembawang and Raffles Lighthouse) for the period 1970 – 2012 were extracted to study the ENSO-induced interannual sea level variability. Sea level during this period is dominated by inter-annual fluctuations. Monthly sea level anomalies were filtered using a Butterworth low pass filter to obtain inter-annual signals. It is found that at interannual scale, sea level and ENSO index vary coherently in the SS: drops are associated with El Niño phase and rises are related to La Niña episodes. Wind stress variations and reduced SCS volume transport play significant roles in ENSO-induced sea level variability.

[Keywords: Singapore Strait, ENSO, Sea level variability, Wind stress.]

Introduction

The Singapore Strait (SS) is situated in the south-western part of the South China Sea (SCS). The SCS is a semi-enclosed marginal sea in the western Pacific. SS is a shallow and narrow water body centrally located at the Sunda Shelf. This Strait experiences the effects of non-linear dynamical interaction between three larger water bodies—SCS to the east, the Malacca Strait and the Indian Ocean to the west, and Java Sea to the south. De-tided sea level data show high variability of water level residuals in the SS. Recent studies^{1,2} showed that winds over the SCS are primarily responsible for the observed sea level variability in the SS.

The SCS dynamics is dominated by the seasonally reversing monsoon system with northeasterly (NE) winds during boreal winter (November-February) and southwesterly (SW) winds during summer (June-August). Monsoon wind induces seasonal variations of physical characteristics in the upper ocean of SCS³. NE monsoon winds are stronger in the SCS, with strongest winds recorded during December⁴. During this period, up surge of sea level is observed along western boundary of the SCS including SS, being amplified by shallow depth of Sunda Shelf⁵.

SCS is connected to the Pacific Ocean and the Indian Ocean through several straits. Water can exchange with the East China Sea, the western Pacific and the Indian Ocean through the Taiwan Strait, the

Luzon strait and the Malacca Strait, respectively, that play an important role on SCS sea level variability. There are a few studies in which the interannual variations of SCS sea level anomalies are correlated with ENSO⁶⁻⁸. Indian Ocean Dipole (IOD) has important implications in climate variability for the regions surrounding the Indian Ocean⁹. At interannual scale, sea level drops are associated with El Niño event, and rises are with La Niña events, both in the range of ± 5 cm in the SS². Rong et al.⁸ investigated different mechanisms that lead to the interannual variability of SCS. The present study examines ENSO-induced sea level variability in the SS region.

Materials and Methods

The Four tide gauge records of monthly sea level anomalies are obtained from Permanent Service for Mean Sea Level (PSMSL). The details of the study area, locations of tide gauges and sea level data of four tide gauges are presented in Fig. 1 and Table 1. A monthly climatology of sea level is constructed and subtracted from the respective monthly sea level data to obtain sea level anomalies (SLA) for that month (Fig. 2). It can be seen that SLAs are mainly dominated by interannual and interdecadal fluctuations. Since, we focus at the inter-annual variability of sea level; a Butterworth low-pass filter of order 5 with cut-off frequency of 2 year was applied. The ENSO index (SOI) is downloaded from <http://www.cpc.ncep.noaa.gov/data/indices/>. Volu

me transport is estimated using SODA (Simple Ocean Data Assimilation) global reanalysis dataset, having 0.5°x0.5° horizontal resolution with 40 levels from 5 m to 5347 m depth for the period 1958 to 2008. However, for the estimation of net meridional volume transport and examination of the ENSO-induced changes in volume transport, only the upper 300 m has been considered. Wind stress is calculated from ERA-Interim reanalysis surface wind products with 1.5° resolution, obtained from <http://data-portal.ecmwf.int/data/>.

Table 1—Sea level data used for the study

Stations	Latitude (°N)	Longitude(°E)	Duration
Sembawang	1.45	103.83	1973-2011
Sultan Shoal	1.23	103.63	1970-2011
Tanjong Pagar	1.25	103.85	1989-2011
Raffles Lighthouse	1.15	103.73	1980-2011

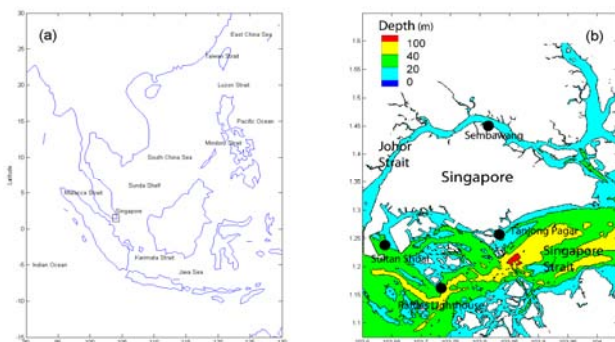


Fig. 1—(a) Study area; (b) Tide gauges in the Singapore Strait (courtesy: Tkalic et al., 2013)

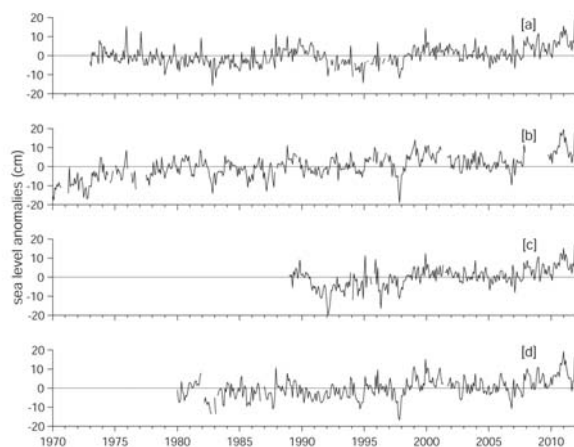


Fig. 2—Sea level anomalies in Singapore Strait [a] Sembawang, [b] Sultan shoal, [c] Tanjong Pagar and [d] Raffles Lighthouse.

ENSO-related sea level variations in scs

SLAs show interannual and decadal variations (Fig. 2). Decadal sea level variation is related to Pacific Decadal Oscillations (PDO) in the Pacific Ocean. PDO having significant climate impacts in the SCS¹⁰. IOD also has significant impact on SCS sea level. Sea level drops are observed in SCS during positive IOD events¹¹.

Recently studies on the sea level changes in SS using tide gauge data showed varying trends in the sea level over the period 1975-2009². Sea level in the SS is rising at the rate of 1.2-1.7 mm/y for the period 1975-2009. Low frequency components of SLAs and SOI are shown in Fig. 3. It can be seen that interannual variability modulates the low frequency changes. The relation between interannual sea level variability in the SS and ENSO is studied using southern oscillation index (SOI) - a proxy for ENSO. SLAs in this four stations and SOI vary coherently with drops observed during El Niño peaks in the years 1977, 1983, 1987, 1992, 1997, 2003, 2007 and 2009. Sea level rises during 1973, 1975, 1984, 1988, 1999-2000, 2008 and 2011 are related to La Niña. Interannual SLAs show positive correlation of 0.45 at Sembawang, 0.55 at Sultan Shoal, 0.54 at Tanjong Pagar and 0.60 at Raffles Lighthouse. SLAs and SOI show high coherence at ENSO band (Fig. 4).

Because of geographical position of SCS between eastern Indian Ocean and the western Pacific Ocean, it experiences a considerable seasonal and longer-term variability associated with Pacific circulation and East Asian monsoon. In this study, we focus at mechanisms of sea level response to ENSO by

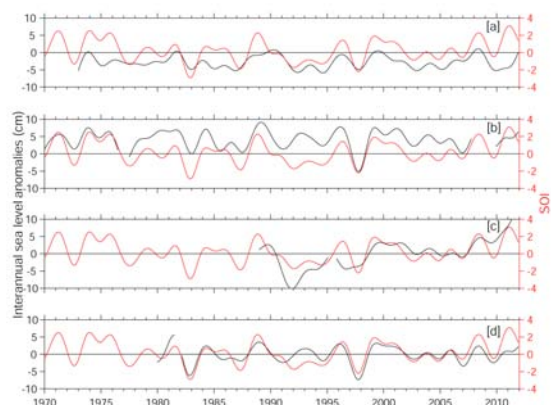


Fig. 3—Comparison of low frequency SLAs and SOI in SS. [a] Sembawang, [b] Sultan Shoal, [c] Tanjong Pagar and [d] Raffles Lighthouse

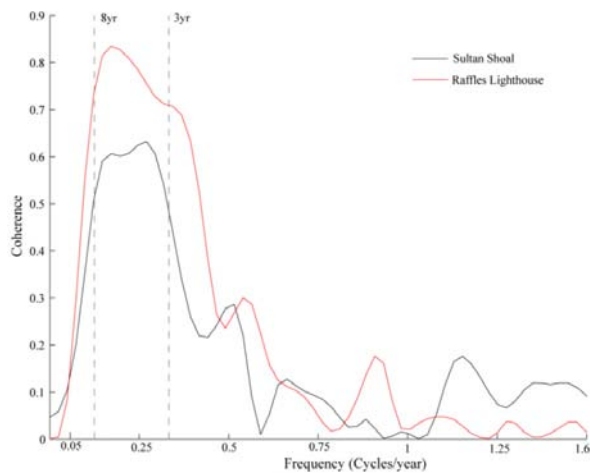


Fig. 4—Coherence of SLAs to SOI. Dashed line denotes ENSO band frequencies.

analyzing wind stress and South China Sea through Flow (SCTF).

Possible mechanisms of Ss Sea level response to ENSO Effect of wind

The upper layer circulation in the SCS is mainly controlled by winds. The basin-scale upper layer circulation in the SCS exhibits seasonal variability corresponding to winter and summer monsoons. The annual mean upper layer circulation in the SCS is cyclonic³. Interannual variability of circulation in SCS is caused mainly by wind stress¹². Interannual zonal wind stress over SS is compared with SLAs at the four tide gauges in the SS. Low frequency components of SLA maintained positive correlation with zonal wind stress. Correlation is about 0.58 in Raffles Lighthouse and 0.4 at the rest stations. During typical El Niño periods of 1982, 1991, 1997, 2002 and 2009, zonal wind stress reached minimum (Fig. 5), indicating that westward wind is weak at the beginning stage of El Niño in the SS region. It can be seen in Fig. 5 that in 1982-1983, 1991-1992, 1997-1998 and 2009-2010 winds turned to easterlies. But due to the combined effect of wind stress and bathymetry at the western boundary of the SCS, the alongshore current turn northeast¹². This may lead to low sea level along the western SCS.

SCTF on interannual sea level variations

South China Sea Through Flow (SCTF) involves water in the western Pacific which enters the SCS through Luzon strait, flows out to Sulu Sea through the Mindoro and Balabac Strait and to Java Sea

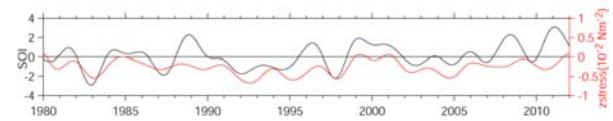


Fig. 5—Low frequency components of SOI and zonal wind stress

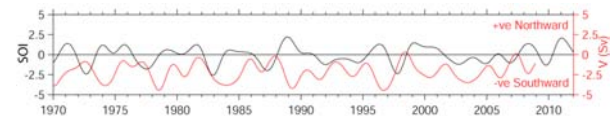


Fig. 6—Low frequency components of SOI and SCTF volume transport

through Karimata Strait, and may return to Pacific through Makassar Strait¹³. During El Niño period, Luzon Strait transport increases and more water with higher temperature flows out through Mindoro and Balabac Strait, which leads to cooling in SCS⁸. As the result, net southward volume transport in the SCS reduces during El Niño years. Net meridional volume transport calculated over a region in the southern SCS shows strong interannual variability. During strong El Niño events of 1972, 1986, 1991 and 1997, net southward volume transport reduces, and situation reverses during strong La Niña events such as 1988, 1996 and 1999 (Fig. 6). When southward volume transport is smaller, SLA reduces and vice versa.

Conclusions

Analysis shows that interannual sea level variability in the SS is strongly correlated with ENSO. Sea level drops in response to El Niño are remarkably evident during the years of 1982, 1991-1992, 1997-1998 and 2006. Sea level variations are caused by combined effect of wind stress changes and amplified by shallow bathymetry in the SS region. Analysis shows that net southward volume transport in the southern SCS reduces during El Niño years, which may lead to reduction of sea level in the SS region.

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