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Discussions

Technical Note: Mean sea level variation in the Singapore Strait from long-term tide data

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Abstract

Winds over the South China Sea (SCS) are primarily responsible for the observed variability in sea level anomalies (SLAs) in the Singapore Strait (SS). The present study focuses on remote forcing contributing to local mean sea level changes in the SS in seasonal and inter-annual scales, and relating the long term mean sea level variation to El Niño/ENSO. As Tanjong Pagar (TP) tide station in the SS has nearly 23.5 yr (1984–2007) of time series data with less data gaps, this data was subject to harmonic and sea level analyses. The mean sea level changes suggest that the fluctuations are quasi-periodic. Rising and falling of sea level is noticed atleast 7 times in a period of 15 yr, with 3 distinct sharp falls (1984–1987, 1989–1992 and 1995–1996) and 4 sharp rises (1987–1988, 1992–1993, 1994–1995 and 1997–1999). These sea level falls are related to El Niño events. When we segregated the results into 2 time spans, we find that from 1984 to 1999 the sea level was on the rising trend in spite of sharp falls, and from 1999 to 2007 on gradual falling trend. More or less similar trend was observed by other researchers for the SCS with altimetry data. During the El Niño periods of 1987 and 1992, the inter-annual MSL variability is the highest, of the order of 7 cm. In one of the events, sea level recovered from a fall of 60 mm (in 1987) to a rise of 40 mm (in 1988). During 1992 to 1999, sea level was continuously on rising trend (from −50 mm to +60 mm), except in one year (1995–1996). The analysis shows a MSL rise rate of 15.7 mm yr^{-1}, which is very closer to MSL in the SCS. The average rate of sea level rise around Singapore as shown by the Tanjong Pagar tidal station is 1.6 mm yr^{-1}, and this matches with the global sea level rise.

1 Introduction

Sea level variations are caused by oceanographic and meteorological parameters such as winds, atmospheric pressure, sea surface temperature and fresh water run-off. Accordingly, sea level oscillates with periodicities ranging from hours to years. In the last

30 yr, several studies have been carried out on sea level variation in the South China Sea (SCS) using tide gauge and altimetry data. Church et al. (2006) pointed out that as there is a large inter-annual variability in sea level, especially during El Niño. Therefore, in order to accurately determine the long-term sea-level trend, it is necessary to have high-quality sea level records of longer duration. As Tanjong Pagar (TP) tide station in the Singapore Strait (SS) has nearly 23.5 yr of time series data, we have taken up the Tanjong Pagar tide data for the present study.

Michael and Andrew (2008) suggest that local sea level rise is a combination of global sea level variability due to changes in water mass and variations in its density as well as local and regional effects, and thus, a good understanding of the dominant local forcing parameters is required in order to assess future sea level changes on the basis of any expected changes in these forcing parameters. It has been studied by several researchers (for example, Qu et al., 2005; Yu et al., 2007) that in the SCS surface, the inflow of cold and salty Pacific water is through the Luzon strait in winter and outflow of warm and fresh water is through the Mindoro and Karimata straits in summer in accordance with monsoon winds – termed as the South China Sea throughflow (SCSTF). These water transports are likely to cause sea level variations during El Niño and La Niña years.

Several studies have been carried out globally by different researchers to estimate long term sea level trends (for example, Douglas, 1991; Cabanes et al., 2001; Church et al., 2001; White et al., 2005; Bindoff et al., 2007). Larger sea level variations are observed in the Western tropical Pacific, Eastern Indian and Southern Ocean (Carton et al., 2005; Cheng and Qi, 2007). According to Trenberth and Hurrell (1994), Chambers et al. (2002) and Church et al. (2004, 2006), the tropical Pacific and Indian Ocean regions have considerable inter-annual and decadal sea level variability associated with the El Niño-Southern Oscillation (ENSO), the Asian-Australian monsoon and phenomena like the North Pacific Decadal Oscillation. These studies further indicate that large inter-annual variability of the tropical Pacific and Indian Ocean region is a clear evidence of rising trend in global average sea level.

Our earlier studies (Pavel et al., 2011) showed that wind over the SCS is arguably the most important factor which determines the observed variability in sea level anomalies (SLAs) in the Singapore Strait. Climatological SLAs in the Singapore Strait were found to be positive, and of the order of 30 cm during northeast monsoon, but negative, and of the order of 20 cm during southwest monsoon. The present study is an extension of our earlier work, and it focuses on the remote forcing of basin-wide phenomena contributing to local mean sea level changes in seasonal and inter-annual scales, and relating long term mean sea level variation in the SS to ENSO in the SCS.

2 Area of study

Singapore is enclosed by South China Sea (SCS) and Malacca Strait (Fig. 1a, b). The Singapore Strait is connected to the South China Sea and Pacific Ocean to the east and the Indian Ocean via the Malacca Strait to the west. Water transport is of the order of 0.1 to 0.2 Sv from east to west – a minor component of the Indonesian throughflow (Wannasingha et al., 2003). As located very close to the equator, tropical climate prevails over Singapore and the adjacent seas throughout the year. Air temperature varies between 26 and 34 °C, and humidity is above 90 %. The sea bed topography of SS is complicated and the maximum depth is 120 m. The neap and spring residual flow pattern is same, but the residual flow is stronger in the western region, and progressively weakens towards east (Zhang and Gin, 2000). The South China Sea (SCS) is the largest semi-enclosed marginal sea in the Northwest Pacific Ocean. SCS is bounded by 99–122° E and 0–25° N. It consists of a deep basin with two continental shelves along the north and southwest coasts. SCS is connected to the East China Sea through the Taiwan Strait, the Pacific Ocean through the Luzon Strait and the Java Sea through the Karimata Strait (Fig. 1a). Tidal waves propagate in the SCS through Luzon Strait, and there are several amphidromic points in the continental shelves of SCS.

3 Data and methodology

There are 12 tide gauge stations in the Singapore and Johor Straits; 8 stations along the coast of Singapore and 4 in the offshore. As Tanjong Pagar (TP/TG) tide station has nearly 23.5 yr of time series data and has less data gaps compared to other stations, we have used Tanjong Pagar electronically recorded data for the present analysis. It may be noted that though TP/TG has data from 1974, the data before 1984 are sporadic and available only in charts. The data gaps were filled with reconstructed time series, generated using tidal harmonics for Tanjong Pagar. These tidal harmonics are further used for the prediction of missing values. The Tanjong Pagar (TP/TG) tidal station, NCEP wind cells chosen in the SCS and TOPEX/POSEIDON data grids considered for this study are shown in Fig. 1a, and the data details are given in Table 1. The entire 23.5 yr data was subject to harmonic analysis, and thereby computed the amplitude and phase of 69 constituents (Table 2).

We do not expect any contamination in the tide gauge data due to vertical movements, presence of Singapore harbor or land reclamation as TP station is relatively away from these effects. To prove this, we have extracted one year tide data from the neighbouring tidal stations (Raffles Lighthouse, Sultan Shoal, Ubin as well as Tanjong Pagar), where simultaneous measurements are available, and sea levels from these stations are presented in Fig. 2. Time series data of all these stations show that there is no abnormal value, and the sea level heights are within the expected range. Tide-gauge data have been smoothed/ averaged for 6 hourly, weekly, monthly or seasonally depending on the phenomenon to be studied.

We could observe that sea level anomalies in the SS have direct relationship with seasonal winds (Pavel et al., 2011). Hence, we have detided the tide data, retaining the annual (S_a) and semi-annual (S_{sa}) harmonics along with the residual heights (SLAs). Sea level changes are estimated from the monthly averages of sea levels (Fig. 3).

4 Results and discussions

4.1 Winds and sea level anomalies

For the analysis we have selected 18 five-degree areas (cells) covering the entire SCS and part of Bay of Bengal as shown in Fig. 1a. Our previous study reveals that the seasonal and extreme winds and their persistence and direction play the primary role in generating SLAs of different magnitudes in the Singapore Strait. The tide gauge data also confirm the seasonal variability of sea level anomalies in Singapore Strait: positive during NE monsoon and negative during SW monsoon. One could observe negative anomalies in SS upto 0.5 m during SW monsoon, but, of course, smaller compared to positive anomalies. One reason is that the NE monsoon surges are larger than the SW monsoon surges. In an another study, Cheng and Qi (2007) found that the climatological sea level is lower over the entire deep basin of SCS during NE monsoon compared to SW monsoon. Therefore, we assume that for the SLA in SS to increase or decrease beyond the climatological values, strong winds must persist for a longer period in a specific direction (Pavel et al., 2012).

As Singapore Strait is under the influence of southwest monsoon winds during May–September and northeast monsoon winds during November–February, and forced by the Indian Ocean through the Malacca Strait and the Pacific Ocean through the South China Sea, we have studied the seasonal changes in MSL by taking monthly means of 23.5 yr of sea level data. The results are shown in Fig. 4. This figure clearly depicts the variation in the MSL due to short-term weather changes. The sea level variation is of the order of 10 to 17 cm for the winter monsoon and 5 to 11 cm for the summer monsoon. These small scale sea level variations are associated with monsoon winds and other oceanographic features.

4.2 Mean sea level changes and El Niño and ENSO events

The mean sea level changes suggest that the fluctuations are quasi-periodic. Figure 3, in general, provides the time evolution of mean sea level variability for the Singapore region; it clearly brings out inter-annual variability in MSL during the period 1984–2007. Rising and falling of sea level is noticed atleast 7 times in a period of 15 yr, with 3 distinct sharp falls (1984–1987, 1989–1992 and 1995–1996) and 4 sharp rises (1987–1988, 1992–1993, 1994–1995 and 1997–1999). The largest falls are during 1986–1987, 1990–1991 and 1995–1996 (Fig. 3). Moreover, we find that there have been only 2 minor falls since 1999, but above mean sea level (2001–2002 and 2003–2005) and 2 minor rises above mean sea level (2002–2003 and 2005–2006). These sea level falls are related to El Niño events. When we segregate the results into 2 time spans, we find that from 1984 to 1999, the sea level is on the rising trend, in spite of sharp falls, and subsequently, the sea level is on gradual falling trend till 2007. More or less similar trend was observed by Cheng and Qi (2007) for the SCS with altimetry data, especially after 2000, but with higher falling rates.

During the El Niño periods of 1987 and 1992, the inter-annual MSL variability is the highest, of the order of 7 cm (Fig. 3). This agrees with the observation of Church et al. (2006), who observed that sea level is anomalously high in the Eastern tropical Pacific and low in the Western tropical Pacific.

The average rate of sea level rise around Singapore as shown by the Tanjong Pagar tidal station is 1.6 mm yr^{-1}, and this matches with the global sea level rise. The trend line has smoothed the ENSO events occurred between 1984 and 2007. In one of the events (Fig. 3), sea level recovered from a fall of 60 mm (in 1987) to a rise of 40 mm (in 1988). During 1992 to1999, sea level was continuously on rising trend (from −50 mm to +60 mm), except for one year during 1995–1996 (that is, a rise of approximately 15.7 mm yr^{-1}). When Fig. 2a of Church et al. (2006) is referred to (used T/P altimeter for the period 1993–2001), we find that Malacca Strait and Sunda Shelf show a rise of 10–15 mm yr^{-1} and 5–10 mm yr^{-1}, respectively. As Singapore Strait is connected to

Eastern Indian Ocean through Malacca Strait and Western Pacific/SCS through Sunda Shelf, we find the influence of sea level change of global oceans in the Singapore Strait also.

During 1993–2001, there was a sea-level rise over the Western Pacific and Eastern Indian Oceans (rates approaching $\approx 30\,\mathrm{mm\,yr^{-1}}$) and sea-level fall in the Eastern Pacific and Western Indian Oceans (rates approaching $\approx -10\,\mathrm{mm\,yr^{-1}}$), and this reflects weak El Niño like conditions in the early years of the TOPEX/POSEIDON mission and more La Niña like conditions in 2001 (Church et al., 2006). More or less the same trend prevailed in the SS during the period 1991 to 2005 (it may be noted that 1991, 1992, 1993, 1994, 1996 and 1997 are El Niño years and 1995 and 1999–2004 are La Niña years). Li et al. (2002) analysed T/P altimeter data for the SCS and showed that MSL has risen at a rate of approximately $10.0\,\mathrm{mm\,yr^{-1}}$ for the period 1993 to 1999, but the rise was not uniform in the entire SCS.

To examine the trends of sea level variations near the coast and islands, Cheng and Qi (2007) selected 4 tide gauge stations in the SCS. They found that during 1993–2000, the sea level rise rate in these 4 tide stations varied between 10.7 and $17.3\,\mathrm{mm\,yr^{-1}}$, and indicated that the sea level trends in the shallow water areas are similar to that of deep basin. The analysis of tide data of Tanjong Pagar (a coastal station) also shows a MSL rise rate of $15.7\,\mathrm{mm\,yr^{-1}}$ during this period, closely following the SCS MSL. However, as there is large inter-annual variation in the SLA, we have to take caution while predicting trends in the MSL variation using the present data (1984–2007: data is not long enough).

5 Conclusions

The position of the Singapore Strait is such that it is highly influenced by the seasonal surges of NE monsoon winds, leading to higher SLAs. The analysis of long-term tide data provides the time-evolution of MSL variability of the SS. As Singapore Strait is connected to Eastern Indian Ocean through Malacca Strait and Western Pacific/SCS through Sunda Shelf, we find the influence of sea level change of global oceans in the Singapore Strait also. It is planned to analyse long-term sea level data of other regions in the SCS and the Indian Ocean to further understand the sea level anomalies and mean sea level changes in the Singapore Strait.

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Table 1. Details of data used.

Data source	Latitude (° N); Longitude (° E)	Duration	Remarks
Tide gauge data			
Tanjong Pagar	1° 15.686′; 103° 51.124′	Jan 1984–May 2007	Hourly sea level records
Sultan Shoal	1° 14.402′; 103° 38.886′	Jan–Dec 1988	
Raffles Lighthouse	1° 09.604′; 103° 44.492′	Jan–Dec 1988	
Ubin	1° 25.166′; 103° 55.666′	Jan–Dec 1988	
NCEP wind			
W1	00–05; 105–110	Jan 1984–Dec 2007	NCEP 2.5° × 2.5° grid
W2	00–05; 110–115		NCEP *u* and *v* wind components averaged over 5° × 5° grid
W3	05–10; 100–105		
W4	05–10; 105–110		
W5	05–10; 110–115		
W6	10–15; 110–115		
W7	10–15; 115–120		
W8	15–20; 105–110		
W9	15–20; 110–115		
W10	15–20; 115–120		
W11	15–20; 120–125		
W12	20–25; 115–120		
W13	20–25; 120–125		
W14	05 S–0 N; 090–095		
W15	05 S–0 N; 095–100		
W16	10 S–05 S; 090–95		
W17	10 S–05 S; 095–100		
W18	05 S–0 N; 105–110		
Wind (measured)	Changi Airport	Dec 2001	No data between 23:00 and 03:00 h
T/P Altimeter	0–5 N; 100–107.5 E	Oct 1992–2007	SSH Anomaly

Table 2. Harmonic constituents of Tanjong Pagar tide data.

S. No	Constituents	Amplitude (m)	Phase (°)
1	ZO	1.6921	0
2	2Q1	0.0097	322.993
3	SIG1	0.0056	252.048
4	Q1	0.0578	17.8
5	RO1	0.012	16.772
6	O1	0.3014	56.582
7	MP1	0.0155	273.746
8	M1	0.0026	46.445
9	CHI1	0.0016	318.534
10	PI1	0.0071	110.187
11	P1	0.0984	102.292
12	S1	0.0168	219.367
13	K1	0.3126	109.37
14	PSI1	0.0079	15.954
15	PHI1	0.0048	348.778
16	TH1	0.0013	152.453
17	J1	0.0161	122.382
18	SO1	0.0049	342.148
19	OO1	0.0101	196.012
20	OQ2	0.0039	261.465
21	MNS2	0.0051	96.278
22	2N2	0.0288	269.577
23	MU2	0.0045	141.416
24	N2	0.1573	299.69
25	NU2	0.032	299.925
26	OP2	0.0049	276.351
27	M2	0.7926	322.569
28	MKS2	0.0092	24.648
29	LAM2	0.0181	336.691

Table 2. Continued.

S. No	Constituents	Amplitude (m)	Phase (°)
30	L2	0.0297	336.647
31	T2	0.0115	21.877
32	S2	0.3212	16.758
33	R2	0.0045	246.015
34	K2	0.0977	16.346
35	MSN2	0.0151	230.147
36	KJ2	0.0053	252.406
37	2SM2	0.018	252.396
38	MO3	0.0141	52.343
39	M3	0.0027	250.14
40	SO3	0.014	111.463
41	MK3	0.0233	92.13
42	SK3	0.0069	161.091
43	MN4	0.0047	288.091
44	M4	0.0146	308.018
45	SN4	0.0015	304.308
46	MS4	0.0196	345.266
47	MK4	0.0081	319.861
48	S4	0.004	8.369
49	SK4	0.0015	315.301
50	2MN6	0.0046	102.358
51	M6	0.0089	110.596
52	MSN6	0.004	168.396
53	2MS6	0.0152	170.795
54	2MK6	0.0061	171.345
55	2SM6	0.0066	244.371
56	MSK6	0.005	228.885
57	MA2	0.0234	196.799
58	MB2	0.0086	25.963

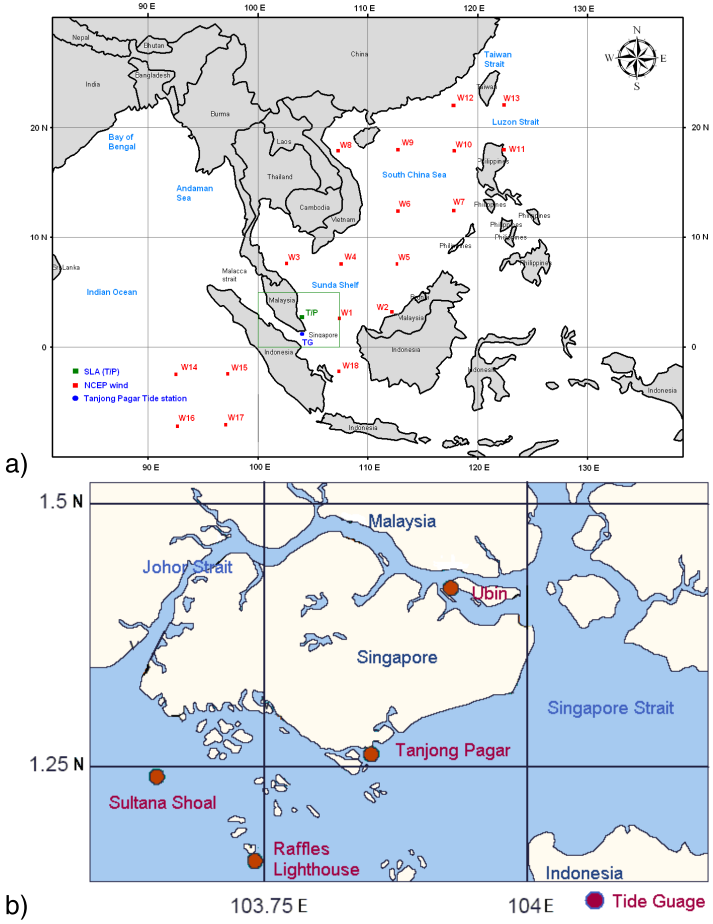

Fig. 1. (a) Study area: larger domain with South China Sea including selected NCEP wind cells and T/P altimeter SLA data grid. **(b)** Study area: smaller domain with Singapore Strait, Johor Strait and tide stations.

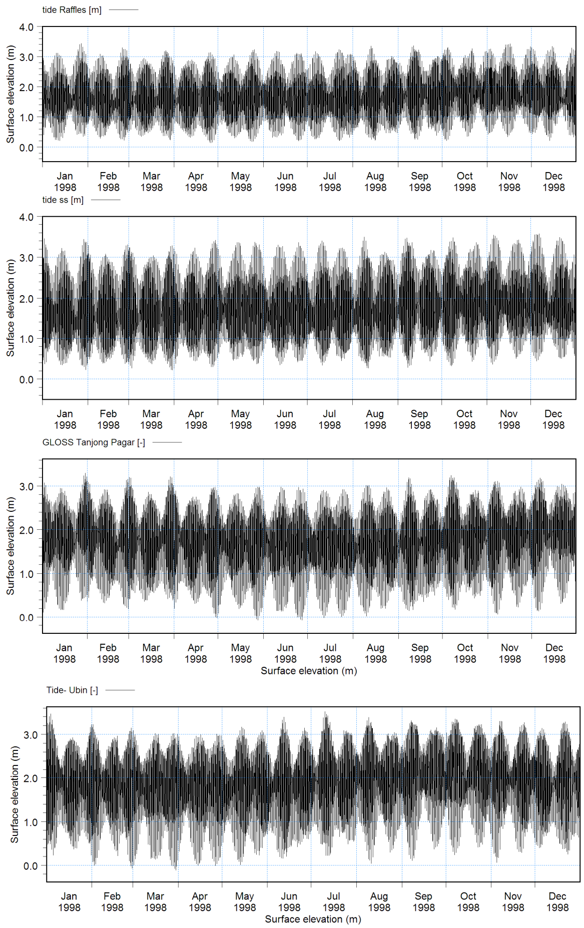

Fig. 2. Typical one year simultaneous tide gauge data from Raffles Lighthouse, Sultan Shoal, Ubin and Tanjong Pagar tide stations (for assessing contamination if any in the T/P data).

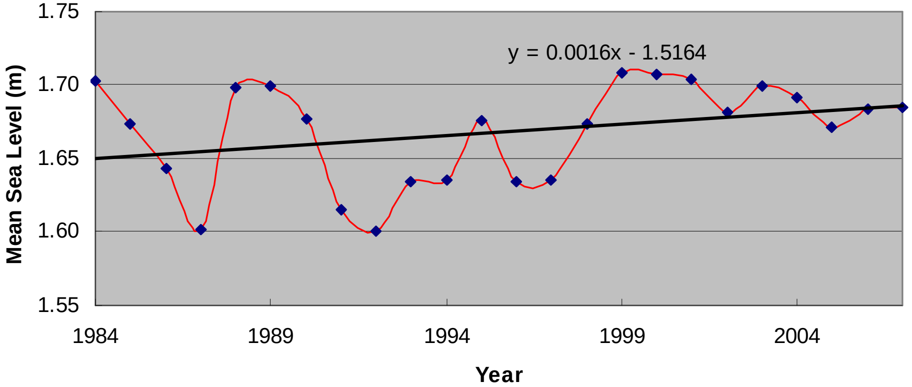

Fig. 3. Annual mean sea level computed from tide gauge data for the period 1984–2007. Black line is the MSL trend line.

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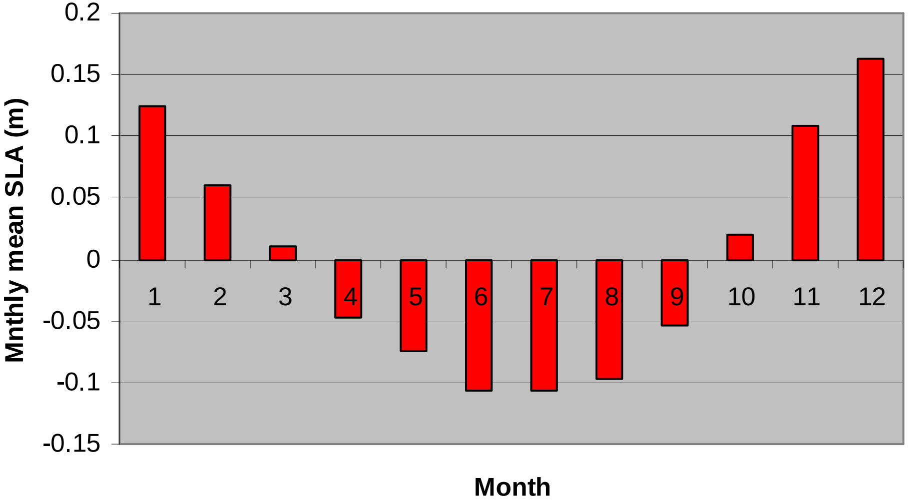

Fig. 4. Monsoonal and seasonal influence on sea level variation (monthly means of sea level).