



SEASONAL SEA LEVEL VARIABILITY AND ANOMALIES IN THE SINGAPORE STRAIT

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Abstract: We have analyzed measured sea level data and extracted sea level anomalies (SLAs) for the Singapore Strait for the last 24 years. We have also analysed NCEP winds over the South China Sea for the same period in order to understand the underlying phenomena behind the development of extreme SLAs. It is found that a sea level gradient is built up by the monsoon wind-driven forces along the longest axis of the South China Sea, accounting for SLAs above 30 cm in the Singapore Strait and a maximum exceeding 80cm. The extreme sea level anomalies are associated with strong persistent winds over the South China Sea. An empirical relationship is attempted between wind speeds and SLAs which could be used to predict quickly extreme sea level anomalies.

Keywords: South China Sea; Singapore Strait; Sea Level Anomaly; Storm surges; Monsoon winds.

INTRODUCTION

Sea level variations are caused by several oceanographic and meteorological parameters such as winds, atmospheric pressure, sea surface temperature and fresh water run-off, and accordingly, sea level oscillate with periodicities ranging from hours to years. When the variations reach extremes, they can cause floods and associated damages. Research on sea level variability and extremes has been taken up by almost all countries because of its impact on the coastal region in the long run. In Singapore, an analysis of long term tide gauge data collected at Tanjong Pagar gauge reveal that wind is the primary causative factor for the sea level extremes, especially during northeast (NE) and southwest (SW) monsoons.

In the last 25 years, several studies on sea level variation in the South China Sea (SCS) have been carried out using tide gauge and altimetry data. When analysing impact of sea level variations in the Singapore Strait (SS) and along the coast, it would be more suitable to use the gauge data, rather than altimetry data, because of its high temporal resolution. However, we have used sea level anomalies (SLAs) obtained from altimeter data also to get a broad picture for the entire SCS.

Several authors have estimated long term sea level trends (e.g. Douglas, 1991; Cabanes et al.,

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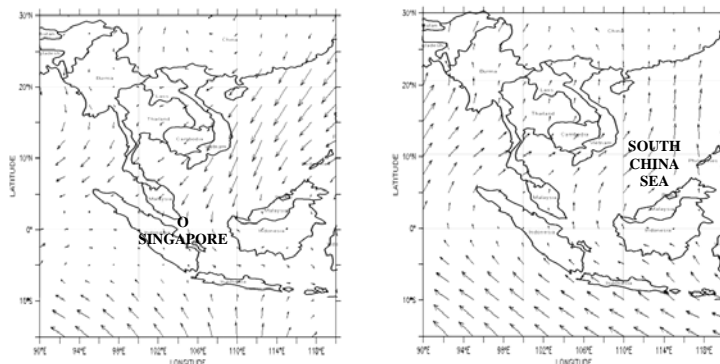
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2001; Church et al., 2001; White et al., 2005). Larger sea level variations are observed in the western tropical Pacific, eastern Indian and Southern Ocean (Carton et al., 2005; Cheng and Qi, 2007).

We have used Tanjong Pagar tide data NCEP winds in the SCS and TOPEX / POSEIDON altimetry data. In this study, we bring out an analysis of SLA climatology, typical events of extreme sea levels (above 3.3m) and extreme SLAs (above 30cm) present in the de-tided residual heights, and associate the extremes to winds in the SCS.

MONSOON SYSTEM AND SEA LEVEL ANOMALY

Monsoon system over the South China Sea is a part of the Asian monsoon system; however, it has some regional characteristics different from that over the Indian Ocean and Indian subcontinent. The NE monsoon prevails from November to February, whereas SW monsoon occurs from June to August (Figure. 1).



(a) NE Monsoon (Nov, Dec, Jan and Feb) (b) SW Monsoon (Jun, Jul and Aug)
Fig. 1. Climatological NCEP winds averaged over the years 1980 - 2006.

Even though, currents in the Singapore Strait are predominantly tidal driven, they follow the regional trend of having NE monsoon drift when mean flow heads southwest, and SW monsoon drift pushing mean flow to northeast. A sea level gradient is built up by the monsoon-driven wind forces along the longest axis of the South China Sea accounting for about 20-30 cm seasonal mean sea level deviation at both sides of the axis. SLAs could be highly non-uniform both in time and space, subject to interplay of regional atmospheric and geostrophic forces. For some extreme events, the highest recorded SLA exceeds 80 cm (Figure. 2).

In order to obtain non-tidal signals that are modulated by otherwise well-defined tidal constituents, the tidal records maintained by PSMSL/GLOSS worldwide and by MPA (2008) in the Singapore Strait need to be de-tided. Residuals represent the water level fluctuations due to non-periodic sources such as wind bursts, storm surges, any other ocean-atmospheric fluctuations, or simply being “noise” of unidentified origin. To ensure correct de-tide procedure, the obtained residuals are verified with TOPEX/POSEIDON altimetry data (<http://apdrc.soest.hawaii.edu>, Figure. 3).

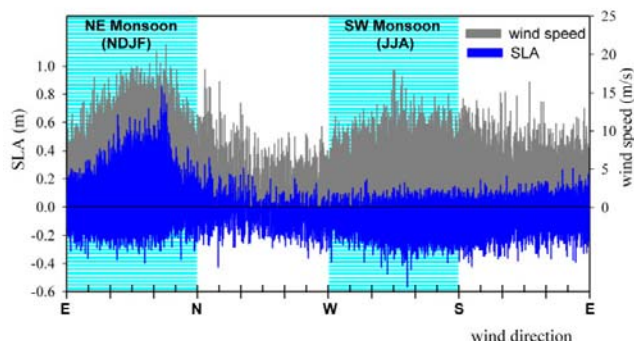


Fig. 2. SLAs at the Singapore Strait versus winds off Vietnam for the period 1980 - 2006.

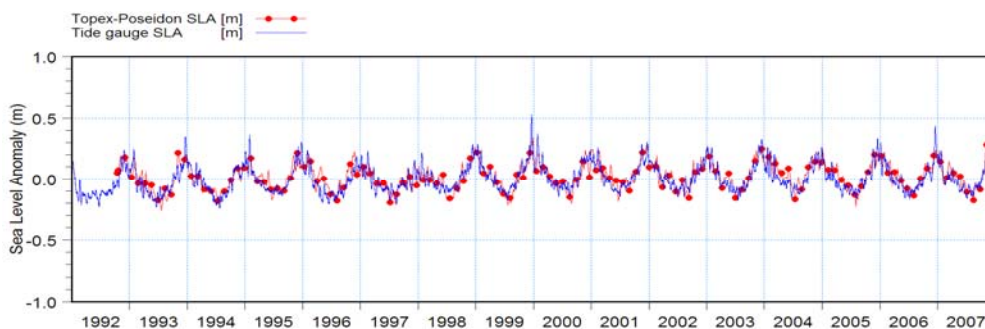


Fig. 3. Comparison of SLAs at Tanjong Pagar tide station with T/P SSH anomalies.

Time-series of hourly tide gauge SLAs were also weekly averaged, and compared with altimeter SSHs for the period 1992-2007. As expected, high resolution tide gauge data might show higher peaks as compared to lower resolution satellite altimetry, but both data sets are still inter-comparable and show simultaneously residual peaks at several instances (such as extreme sea level anomaly on 23 Dec 1999). Analysing such cases versus different met-ocean variables one can understand conditions leading to such extreme events and try to predict SLA magnitude.

EXTREME SEA LEVEL ANOMALIES

There were reports of extreme sea levels in the Singapore Strait during the NE monsoon. The events are not periodic, and are believed to be associated with surges due to strong persistent northeast winds in the SCS overlapped with the winter spring tide. In order to understand underlying physical phenomena, we analysed a few most prominent cases, and results of the same are discussed below.

SLA on 9 February 1974

One well-known case occurred on 9 February 1974 with a record extreme sea level of 3.86m at Sembawang tide gauge (Wong, 1992). The extreme sea level occurred on a spring tide day

accompanied by a strong northeast wind (Fig. 4). When the two phenomena coincided, the maximum sea level has occurred.

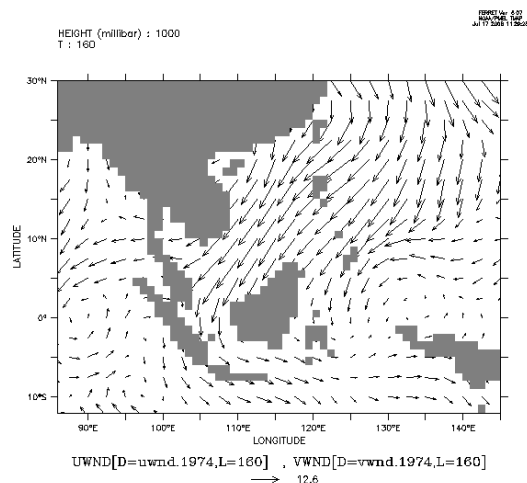
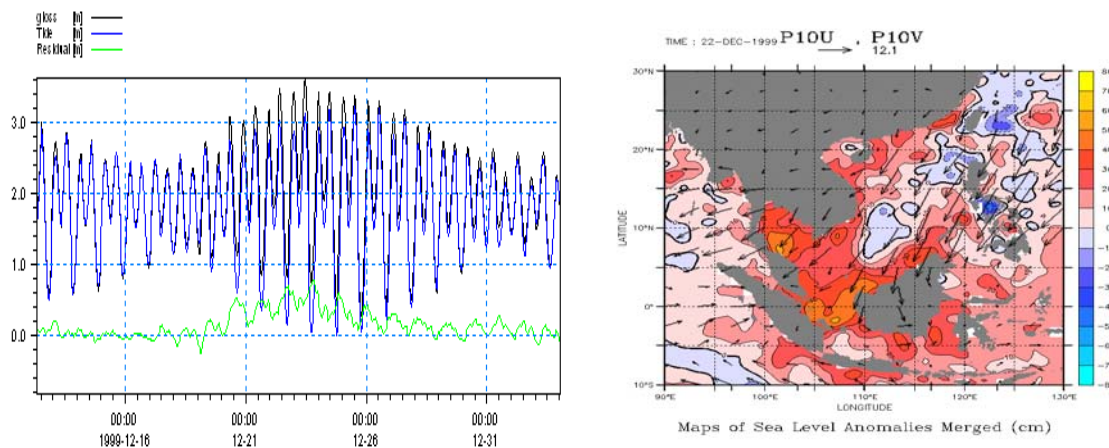


Fig. 4. Wind vectors on 9 February 1974.

SLA during 22-24 December 1999

Another example of extreme event was observed on 22-24 December 1999 as recorded by a tide gauge in Singapore Strait (Fig. 5a) and other stations in the South China Sea. During these days the sea level readings during high spring tide were exceptionally high, with a maximum value of 3.63m, presenting a sea level anomaly of 43 cm.



(a) Sea level (black) and SLA (green) at Tanjong Pagar (Singapore)

(b) Wind vectors and SLA (in cm and coloured) on 22 Dec 1999

Fig. 5. Sea level at Singapore Strait, SLA and wind over the SCS during 22-24 December 1999.

This extreme anomaly occurred due to strong northeasterlies blowing persistently over the South China Sea for several consecutive days, leading to the storm surge at the Singapore region (Fig. 5b). The spring tide occurred on the 23rd has added up to this anomaly causing

the observed extreme.

Hurricane Vamei during 26-28 December 2001

Vamei was a tropical cyclone that formed 90 nm north of the equator. This was the first recorded occurrence of a tropical cyclone near the equator (Chang, 2003). Vamei developed on December 26 at 1.4 N in the South China Sea, and made landfall approximately 60km northeast of Singapore in the southeastern portion of the Malaysian state of Johor (Fig. 6a). Naval ships reported maximum sustained surface wind of 39 m s^{-1} and gust wind of up to 54 m s^{-1} . It is interesting to trace sea level anomalies associated with this rare event. Indeed, the sea level residuals show over 50 cm anomaly in the region (Fig. 6b), which is not only due to this particular hurricane, but more likely due to prevailing northeast winds in the South-China Sea similar to the previous extreme cases. It appears that though the hurricane was strong, the short-duration wind blowing across narrow waterway such as Singapore Strait is not conducive to affect enough volume of water for SLA to show up.

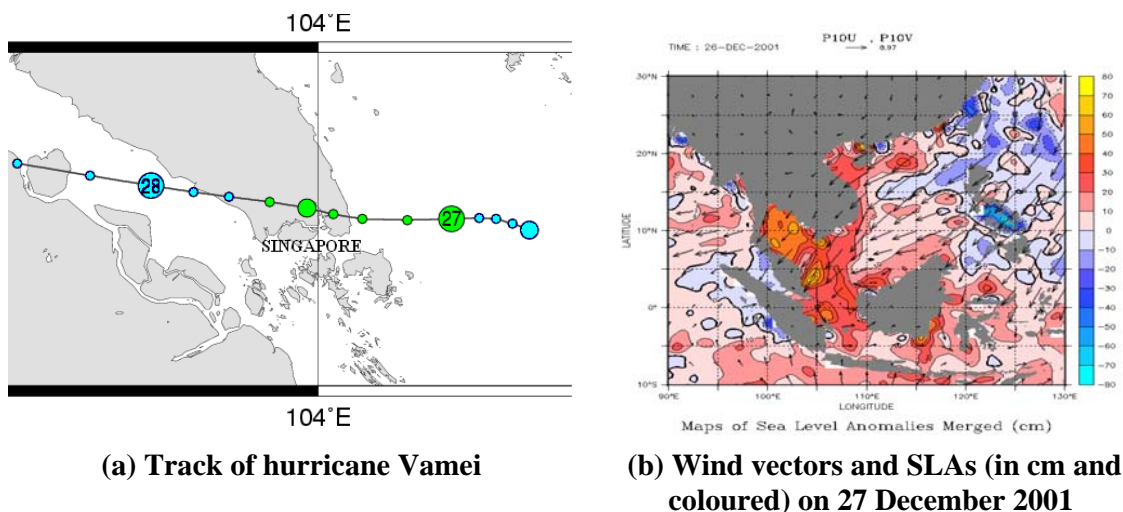
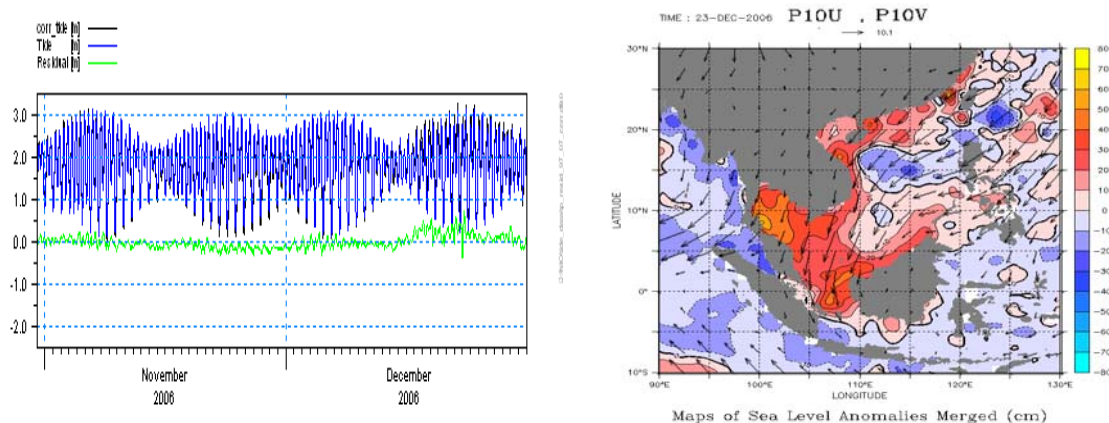


Fig. 6. Track of hurricane Vamei, wind vectors and SLAs during 26-28 December 2001.

SLA on 23 December 2006

On this day, the resultant sea level shown by the tide gauge is just marginally elevated over the spring tide, but the analysis brings out high residuals over 60cm (Fig. 7a). The corresponding winds and SLAs over the SCS are shown in Fig. 7b.



(a) Sea level (black) and SLA (green) at Tanjong Pagar (Singapore)

(b) Wind vectors and SLAs (in cm and coloured) on 23 December 2006

Fig. 7. Sea level at Singapore Strait, SLA and wind over the SCS on 23 December 2006.

WIND- SLA EMPIRICAL RELATIONSHIP

Analysis of other cases shows that high SLAs are observed in the Singapore Strait during NE monsoon when winds are strong in the SCS (off the coast of Vietnam) for a few days prior to SLA peaks. The time lag between the wind and SLA peaks is about 36 to 42 hours. During the NE monsoon, the Singapore Strait SLA has positive correlation with the wind, while SW wind causes negative SLAs relatively the mean sea level. Such recurring scenarios allow fitting of an empirical relationship to predict SLAs based on wind speed (Fig. 8 for NE wind).

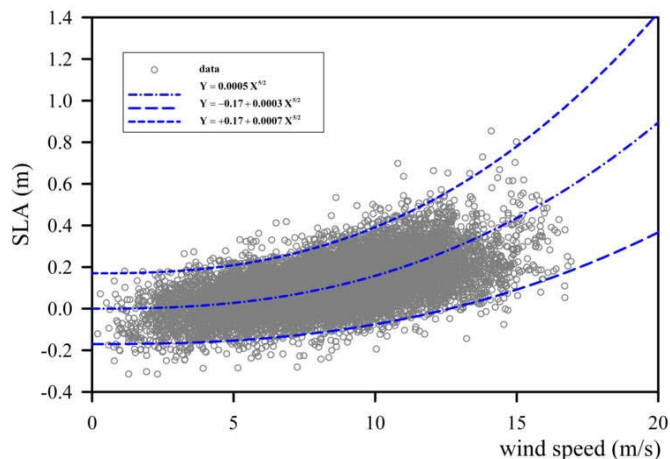


Fig. 8. Relationship between SLAs in the SS and winds off Vietnam during NE monsoon.

CONCLUSIONS

The extreme SLAs analysed in the paper clearly indicate that the primary causative factor is the wind over the South China Sea; therefore, the anomalies could be classified as storm surges. Storm surges of the order of 80 cm could be observed irrespective of tide phases. An empirical relationship is suggested to quickly predict SLAs in the Singapore Strait from winds over the South China Sea.

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