

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

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[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Abstract

Peninsular Malaysia is bounded from the west by Malacca Strait and the Andaman Sea both connected to the Indian Ocean, and from the east by South China Sea being largest marginal sea in the Pacific Basin. Resulting sea level along Peninsular Malaysia coast is assumed to be governed by various regional phenomena associated with the adjacent parts of the Indian and Pacific Oceans. At annual scale, sea level anomalies (SLAs) are generated by the Asian monsoon; interannual sea level variability is determined by the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD); while long-term sea level trend is related to global climate change. To quantify the relative impacts of these multi-scale phenomena on sea level trend and variability around the Peninsular Malaysia, long-term tide gauge record and satellite altimetry are used. During 1984–2011, relative sea level rise (SLR) rates in waters of Malacca Strait and eastern Peninsular Malaysia are found to be  $2.4 \pm 1.6 \text{ mm yr}^{-1}$  and  $2.7 \pm 1.0 \text{ mm yr}^{-1}$ , respectively. Allowing for corresponding vertical land movements (VLM;  $0.8 \pm 2.6 \text{ mm yr}^{-1}$  and  $0.9 \pm 2.2 \text{ mm yr}^{-1}$ ), their absolute SLR rates are  $3.2 \pm 4.2 \text{ mm yr}^{-1}$  and  $3.6 \pm 3.2 \text{ mm yr}^{-1}$ , respectively. For the common period 1993–2009, absolute SLR rates obtained from both tide gauge and satellite altimetry in Peninsular Malaysia are similar; and they are slightly higher than the global tendency. It further underlines that VLM should be taken into account to get better estimates of SLR observations. At interannual scale, ENSO affects sea level over the Malaysian coast in the range of  $\pm 5 \text{ cm}$  with a very high correlation. Meanwhile, IOD modulates sea level anomalies mainly in the Malacca Strait in the range of  $\pm 2 \text{ cm}$  with a high correlation coefficient. Interannual regional sea level drops are associated with El Niño events and positive phases of the IOD index; while the rises are correlated with La Niña episodes and the negative periods of the IOD index. Seasonally, SLAs are mainly monsoon-driven, in the order of 10–25 cm. Geographically, sea level responds differently to the monsoon: two cycles per year are observed in the Malacca Strait, presumably due to South Asian-Indian Monsoon; whereas single annual cycle is noted along east coast

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of Peninsular Malaysia, mostly due to East Asian-Western Pacific Monsoon. These results imply that a narrow topographic constriction in Singapore Strait may separate different modes of annual and interannual sea level variability along coastline of Peninsular Malaysia.

## 1 Introduction

The Peninsular Malaysia is located on the middle of Sunda Shelf, encompassed from the east by the South China Sea (SCS) being the largest marginal sea in the Pacific Basin, and from the west by the Andaman Sea of the Indian Ocean. Sea level around the Peninsular Malaysia is governed by a variety of phenomena, ranging from global to regional scales, resulting in complicated sea level trend and variability along the coast.

It is well established that global mean sea level (GMSL) has been rising at the rate of  $1.7 \pm 0.2 \text{ mm yr}^{-1}$  since the beginning of last century (Nerem et al., 2006; Church and White, 2011; Stammer et al., 2013). A significant acceleration of sea level rise (SLR) in the order of  $0.01 \text{ mm yr}^{-2}$  has also been observed since early 20th century, leading to the rate of  $1.9 \pm 0.4 \text{ mm yr}^{-1}$  during the 1961–2009 era (Jevrejeva, 2008; Church and White, 2011). For the recent period (1993–2009), GMSL has been rising much faster: in situ data displayed the rate  $2.8 \pm 0.8 \text{ mm yr}^{-1}$  (Church and White, 2011), while satellite altimetry suggested a consistent increment of  $3.3 \pm 0.4 \text{ mm yr}^{-1}$  (Nicholls and Cazenave, 2010). However, sea level change is highly non-uniform spatially and temporally, mostly due to local adjustment to the global warming as well as variability of regional climate drivers. For example, in the tropical western Pacific and eastern Indian Oceans, rise rate seemingly approached  $30 \text{ mm yr}^{-1}$  for the period 1993–2001 (Church et al., 2006; Becker et al., 2012); however, this pattern was largely attributed to the variability of El Niño–Southern Oscillation (ENSO) and North Pacific Decadal Oscillation (Trenberth and Hurrell, 1994; Church et al., 2004; Becket et al., 2012; Tkalic et al., 2013). It is likely that the subtropical gyres in the North Pacific and South Pacific have expanded and strengthened since 1993 leading to the elevated SLR trend in

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the adjacent region. Thus, quantification of regional sea level trend requires sufficiently long datasets to filter out the climate variability.

In areas adjacent to the Peninsular Malaysia, a few studies have analyzed sea level trends, including the Gulf of Thailand (Trisirisatayawong et al., 2011), the Singapore Strait (Tkalich et al., 2013) and the SCS (Peng et al., 2013). Trisirisatayawong et al. (2011) used tide gauge data corrected by the Vertical Land Motion (VLM) to obtain a SLR rate  $3.0 \pm 1.5 \text{ mm yr}^{-1}$  for the Gulf of Thailand during the period 1940–2004, thus qualifying the rate to be significantly faster than the global tendency. In the Singapore Strait, Tkalich et al. (2013) obtained a SLR rate of  $1.2\text{--}1.7 \text{ mm yr}^{-1}$  during the period 1975–2009 and  $1.8\text{--}2.4 \text{ mm yr}^{-1}$  during the years 1984–2009. Taking into account an estimate of land subsidence rate,  $1\text{--}1.5 \text{ mm yr}^{-1}$  in Singapore, the trend of absolute SLR in the strait follows the regional tendency. Recently, Peng et al. (2013) examined the sea level trend and variability in the SCS since 1950 by analyzing two-dimensional past sea level reconstruction (produced by Meyssignac et al., 2012) and observed satellite altimetry. For the period 1993–2009, it was found that the reconstructed sea levels exhibit an average rise speed of  $3.6 \pm 0.4 \text{ mm yr}^{-1}$ , which is similar to the satellite altimetry rate of  $3.9 \pm 0.9 \text{ mm yr}^{-1}$ . On average, the SLR rate over 1950–2009 period was estimated at  $1.7 \pm 0.1 \text{ mm yr}^{-1}$ , which is slightly lower than the global tendency ( $1.8 \pm 0.1 \text{ mm yr}^{-1}$ ). When comparing their reconstruction for the period 1950–2009 with altimetry era 1993–2009, the acceleration of SLR in the Sunda Shelf and southern SCS is slightly higher than these in other regions.

Noticeable rates of VLM have been detected in the Peninsular Malaysia (Simons et al., 2007), spanning from a subsidence rate of  $-0.60 \pm 2.89 \text{ mm yr}^{-1}$  to an uplift value of  $1.70 \pm 1.90 \text{ mm yr}^{-1}$ . Although being of the same order as regional SLR rates, VLM was unlikely accounted for by Peng et al. (2013). For instance, the SLR rate in the Gulf of Thailand for the period 1993–2009 estimated by Peng et al. (2013) was  $2\text{--}3 \text{ mm yr}^{-1}$ , which is significantly different from the absolute rate  $3.5\text{--}4.5 \text{ mm yr}^{-1}$  obtained by Trisirisatayawong et al. (2011). Hence, the inclusion of more tide gauge data

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



with VLM correction is clearly required to derive robust sea level trend around the Peninsular Malaysia.

Meanwhile, at interannual scale, the ENSO is a renowned climatic driver governing sea level variability over the tropical Pacific. In the SCS, interannual sea level variability has a strong signature of the ENSO (Wang et al., 2006; Cheng and Qi, 2007; Rong et al., 2007; Chen et al., 2012; Tkalich et al., 2013; Peng et al., 2013). In the Singapore Strait, sea level anomaly (SLA) is highly correlated ( $-0.7$ ) with the Multivariate ENSO Index (MEI) during the observation period (1984–2011). Drops and rises of mean sea level (MSL) in the strait in the order of  $\pm 5$  cm are associated with El Niño and La Niña episodes, respectively (Tkalich et al., 2013). The influence of ENSO becomes stronger toward southern region of the SCS (Rong et al., 2007; Peng et al., 2013). Qu et al. (2004) suggested that the intrusion of Kuroshio Current through the Luzon Strait coupled with atmospheric teleconnection is likely to cause such interannual variability. In the Bay of Bengal and the Andaman Sea, the ENSO alters the MSL within the range of  $\pm 15$  cm (Aparna et al., 2012; Sreenivas et al., 2012).

Similar to the ENSO, the Indian Ocean Dipole (IOD) affects sea level as well as climate of countries surrounding the Indian Ocean basin, extending from eastern Africa to southern Australia (Saji et al., 1999; Iizuka et al., 2000). The west IOD pole exists in the Arabian Sea, while its east pole occurs in the southern sea of Indonesia. The signature of IOD has been detected in the sea level in the Gulf of Bengal, which varies in the range  $\pm 20$  cm (Aparna et al., 2012; Sreenivas et al., 2012). It is not known to what extent sea level around the Peninsular Malaysia is affected by the IOD, as it is shielded behind the Kalimantan and Sumatra Islands.

At seasonal scale, sea level variability across the SCS is predominantly driven by the Asian monsoonal wind (Wyrтки, 1961; Lau et al., 1998; Ding and Johnny, 2005; Tan et al., 2006; Wang et al., 2009; Liang and Evans, 2011). At a closer look, the Asian monsoon is branching to two major parts: the East Asian – Western Pacific (EAWP) Monsoon (Li and Zeng, 2002; Wang et al., 2008) and the South Asian – Indian (SAI) Monsoon (Goswami et al., 1999; Wang and Fan, 1999), each modulates its effective

**Sea level trend and variability around the Peninsular Malaysia**

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



region quite independently (Liang and Evans, 2011). Located in the interferential domain, sea level around the Peninsular Malaysia thus may experience monsoon in different ways. Along east coast of Peninsular Malaysia, observed positive SLAs are induced by the wind shear during northeast monsoon (boreal winter), while negative anomalies are caused by the southwest monsoon (Tkalich et al., 2012; Chen et al., 2012). For example, monsoonal wind may increase or decrease the sea level in the Singapore Strait up to 20 cm (Tkalich et al., 2013).

Our aim in this paper is to quantify the sea level trend and variability around the Peninsular Malaysia at various temporal scales, from seasonal to decadal, using research-quality tide gauge data combined with local VLM information and satellite altimetry. Section 2 presents the data, and discusses how sea level variability is connected to climate indices. In Sect. 3, sea level variability is quantified at various time-scales, from seasonal pattern to interannual variability and long-term tendency. Main findings are then summarized and discussed in the last section.

## 2 Data and methodology

The annual and monthly sea level data for all considered stations in the domain are obtained from the Permanent Service for Mean Sea Level (PSMSL, 2013; Holgate et al., 2013). We use data from 12 research-quality tide gauges out of 25 available at PSMSL, which have more than 20 years of records and minimum gaps. The tide gauges are equally distributed in the domain (Fig. 2): six stations in the Malacca Strait including Langkawi, Pinang, Lumut, Kelang, Keling and Kukup; six stations are located in the eastern Peninsular Malaysia region including Geting, Cendering, Gelang, Tioman, Sedili and Johor Bahru. Representative annual MSL along each side of the Peninsular is averaged using annual MSLs of available stations. Four stations in the Singapore waters (namely Sultan Shoal, Raffles Lighthouse, Tanjong Pagar and Sembawang) are further used for the discussion.

### Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In order to get the absolute SLR rate, tide gauge records have to be corrected for VLM. This highly localized phenomenon may occur due to glacial isostatic adjustment (GIA), the dislocation of tectonic plates of the Earth, or solidity of underground soil and sediments. In Malaysia, Simons et al. (2007) reported regional VLM rates during the 1994–2004 period using data from 14 nationwide Global Positioning System (GPS) stations. These values were interpolated by the Kriging method to obtain local VLM rates at tide gauge locations (Fig. 2). Linear trends (Table 1) were obtained by the least square fitting to straight lines, and uncertainties ( $\pm$ ) were calculated at 95 % confidence level.

In correlating interannual sea level variability to ENSO and IOD events, the Multi-variate ENSO Index (MEI, 2013) and the Dipole Mode Index (DMI, 2013), respectively, are used as proxies. The MEI index comprises of six main physical variables (sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky), which have been measured over the North Pacific for many years (Wolter and Timlin, 1993, 1998). The DMI index is represented by the anomalous sea surface temperature gradient between two areas: a western pole in the Arabian Sea and an eastern pole in the eastern Indian Ocean south of Indonesia (Saji et al., 1999).

Gappy data may lead to incorrect estimates of MSL trend (Douglas, 2001; Wahl et al., 2010; Becker et al., 2012). Around the Peninsular Malaysia, gappy data are seen at all 12 considered stations, where (for instance) Lumut tide gauge records miss as much as 25 % data since 1993. Due to a strong seasonal variability of sea level, even one month gap necessitates removal of the respective year out of trend analysis. At the same time, the gappy years cannot be simply neglected because annual increment due to SLR could be one order smaller than annual and interannual sea level variability. To overcome the problem, Tkalich et al. (2013) and Luu and Tkalich (2014) suggested to fill the gaps utilizing empirical relationship between sea level annual variability and the ENSO index and the reanalyzed wind stress, being applied to the analysis of sea level trend in Singapore Strait. Similarly, as interannual sea level variability around the

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Peninsular Malaysia is highly correlated with ENSO, and at some regions (i.e., Malacca Strait) partly linked to IOD, the technique could be applied to the extended domain. Here, it is assumed that total annual sea level anomaly is the arithmetic sum of sea level constituents associated with ENSO and IOD, where each constituent is represented as a linear function of corresponding proxy index (MEI and DMI, respectively). Least-square minimal algorithm is applied in order to fit linear parameters. The derived function is then used to fill the missing data in the respective years.

To assess the reconstruction algorithm, satellite altimetry observation (AVISO, 2013) during the common period (1993–2011) is used as a baseline. Improvement of reconstructed data over original PSMSL records is small at most individual gauges; however, the total accumulative difference is clearly seen at averaged trend for each side of the Peninsular. For example, original data for the period 1993–2009 show sea level trend ( $-0.2$ )  $\text{mm yr}^{-1}$  (Malacca Strait) and  $2.5$   $\text{mm yr}^{-1}$  (eastern Peninsular Malaysia); whereas, respective reconstructed values ( $3.2$   $\text{mm yr}^{-1}$  and  $3.6$   $\text{mm yr}^{-1}$ ) are significantly closer to altimetry trend  $3.6$   $\text{mm yr}^{-1}$  during the same period (see also Table 1 and Sect. 3.3).

### 3 Results and discussions

#### 3.1 Seasonal sea level variability

Figure 3 presents the seasonal pattern of sea level at different regions around the Peninsular Malaysia. Sea level varies at the eastern coast of Peninsular Malaysia in the range of  $\pm 25$  cm throughout a year, yielding single peak during Northeast (NE) monsoon and trough during Southwest (SW) monsoon (Fig. 3c). The phenomenon at southwestern edge of the SCS has been described by Tkalic et al. (2012) as being part of the domain response to reversing monsoon. During (boreal) winter months of the EAWP monsoon, the NE wind causes sea level elevation in the Gulf of Thailand



and along east coast of Peninsular Malaysia. During summer months, SW wind pulls water mass off the Sunda Shelf, leading to the drop of sea level.

In the Malacca Strait, quasi-periodic annual cycle is observed twice a year within the range of  $\pm 15$  cm (Fig. 3a). Positive peaks are observed during May and November, while negatives are seen during February–March and September. The complexity of the pattern is arguably due to competing of the seasonal wind from the SCS with the wind curl from the Andaman Sea blowing toward the Malacca Strait. Liang and Evans (2011) pointed out that this region is influenced by the SAI monsoon, which regulates local dynamics independently from the EAWP monsoon.

Singapore Strait sea level records (Fig. 3b, after Tkalich et al., 2013) show transient features of both sides of Peninsular Malaysia. The node is located between Raffles Lighthouse and Tanjong Pagar stations, most likely at the narrowest part of Singapore Strait.

### 3.2 Interannual sea level variability

Figure 4 presents the interannual variability of sea level around the Peninsular Malaysia during the observation period. Averaged annual sea level at different parts of the domain as well as annual records from individual tide gauges are highly correlated with MEI, as in Figs. 5 and 6, respectively. Sea levels in the Malacca Strait have slightly larger correlations with MEI with an average of  $(-0.69)$  and the largest of  $(-0.73)$  at Kelang and Pinang tide gauges; while arithmetic mean of correlations in the eastern Peninsular Malaysia is  $(-0.64)$ . Prominent annual sea level troughs are clearly observed during extreme El Niño episodes in the years 1987, 1991–1992, 1997, 2002, 2006 and 2009; while sea level peaks are tangible amongst La Niña phases in the years 1988–1989, 1996, 1999 and 2008. The magnitude of annual sea level variability is proportional to the intensity of ENSO events. During extreme periods of El Niño or La Niña, annual sea level may rise or drop by an average 4 cm in the Malacca Strait, and 3 cm along the east coast of Peninsular Malaysia (Fig. 5). Until now, interactive mechanism of ENSO variability and sea level change is yet to be fully understood –

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



most likely due to a combination of signals from atmospheric teleconnection feedback and oceanic lateral fluxes.

Whilst ENSO signatures are evident at most of tide gauge records along the Malaysian coasts, the IOD signals are detected merely in the Malacca Strait. The correlation between sea level change and DMI is significant ( $-0.5$ ) along the Malacca Strait (Fig. 6). As a secondary force, extreme IOD events may raise or lower sea level by 2 cm. Explanation for how IOD drives the sea level change is also not well revealed – probably through the easterly zonal wind-induced equatorial Kelvin waves generated in the Indian Ocean during IOD events and propagating to Malacca Strait through the Andaman Sea (Vinayachandran et al., 1999; Mutrugudde et al., 2000).

The correlation coefficient between DMI and annual sea level in the Malacca Strait gradually decreases eastward from Andaman Sea toward Singapore Strait, being ( $-0.60$ ) at Langkawi tide gauge, ( $-0.43$ ) at Kukup, and ( $-0.02$ ) at Johor (Fig. 6a). Zooming into the Singapore waters, a sharp reduction of correlation is observed between Raffles Lighthouse ( $-0.47$ ) and Tanjong Pagar ( $-0.15$ ) as shown in Fig. 6b. It is coincident with the separation found in the seasonal variations of sea level (Sect. 3.1), which may be explained by the fact that IOD evolution is locked to seasonal changes (Toshio et al., 2003).

The concurrence of ENSO and IOD impacts may strengthen the sea level anomaly. For instance, in 1997 when both MEI and DMI gained their highest positive values, sea level in the Malacca Strait dropped more than 7 cm on average (Fig. 5). Sea level drop up to 10 cm is observed at Langkawi, Pinang and Kelang stations (Fig. 4), which are more exposed to the IOD impact due to the geographic location (Fig. 6).

### 3.3 Long-term sea level trend

During the period 1984–2011, relative SLR rates in the Malacca Strait and eastern Peninsular Malaysia have been  $2.4 \pm 1.6 \text{ mm yr}^{-1}$  and  $2.7 \pm 1.0 \text{ mm yr}^{-1}$ , respectively (Table 1); which is lower than to the speed  $3.2 \pm 1.2 \text{ mm yr}^{-1}$  observed in the Singapore Strait (Tkalich et al., 2013). During the period 1993–2009, SCS relative SLR rate

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



was estimated from reconstruction dataset as  $3.9 \pm 0.6 \text{ mm yr}^{-1}$  (Peng et al., 2013); while Singapore Strait records exhibited an increment of  $3.4 \pm 2.4 \text{ mm yr}^{-1}$  (Tkalic et al., 2013). These regional relative rates are significantly higher than measurements in the Malaysia Peninsular for the same years (Malacca Strait:  $2.7 \pm 3.6 \text{ mm yr}^{-1}$ ; eastern Peninsular Malaysia:  $2.2 \pm 1.9 \text{ mm yr}^{-1}$ ).

Taking into account the VLM, absolute SLR rates obtained from Peninsular Malaysia tide gauges for the 1984–2011 era are  $3.2 \pm 4.2 \text{ mm yr}^{-1}$  (Malacca Strait) and  $3.6 \pm 3.2 \text{ mm yr}^{-1}$  (eastern Peninsular Malaysia), as shown in Table 1. For the common period 1993–2009, both satellite altimetry and corrected tidal record show similar absolute SLR rates. In the Malacca Strait, estimates are  $3.4 \pm 6.2 \text{ mm yr}^{-1}$  (tide gauges) and  $3.6 \pm 2.7 \text{ mm yr}^{-1}$  (satellite data); while at the eastern coast of Peninsular Malaysia, they are  $3.1 \pm 4.1 \text{ mm yr}^{-1}$  and  $3.6 \pm 1.6 \text{ mm yr}^{-1}$ , respectively. These rates are slightly higher than the global tendencies observed from tide gauges ( $2.8 \pm 0.8 \text{ mm yr}^{-1}$ , Church and White, 2011) and satellite altimetry ( $3.3 \pm 0.4 \text{ mm yr}^{-1}$ , Nicholls and Cazenave, 2010) for the same years.

Present in situ estimate of global SLR rates mostly rely on the GIA, which is solely applicable to correct VLM in polar region (Church and White, 2006, 2011). As no correction is applied to tide gauges beyond this region such as around equatorial areas, the global estimate of SLR rate could be improved with local VLM information. As shown in the above example, corrected SLR rate around the Peninsular Malaysia is about 30% higher than the relative speed measured directly at tide gauges. Meanwhile, present network of GPS stations is sparse and recent (for instance, only 10 year VLM data are available for the Malaysia region). Accordingly, our study underlines the fact that more efforts should be put forward in the future to measure the VLM in addition to the tide gauge records, in order to get better in situ estimates of SLR phenomena.

## 4 Conclusions

Tide gauge records, satellite altimetry data, VLM as well as climate proxies are used to quantify sea level trend and variability along Peninsular Malaysia coast. It is found that during 1984–2011 years, relative sea level rise (SLR) rates at Malacca Strait and eastern coast of Peninsular Malaysia are found to be  $2.4 \pm 1.6 \text{ mm yr}^{-1}$  and  $2.7 \pm 1.0 \text{ mm yr}^{-1}$ , respectively. Allowing for corresponding VLMs ( $0.8 \pm 2.6 \text{ mm yr}^{-1}$  and  $0.9 \pm 2.2 \text{ mm yr}^{-1}$ ), their absolute SLR rates are  $3.2 \pm 4.2 \text{ mm yr}^{-1}$  and  $3.6 \pm 3.2 \text{ mm yr}^{-1}$ , respectively. For the common period 1993–2009, absolute SLR rates obtained from tide gauges and satellite altimetry along Peninsular Malaysia coast are similar; and they are slightly higher than the global tendency. This result underlines the fact VLM must be taken into account to get better estimates of in situ SLR observations.

At interannual scale, ENSO modulates sea level variability around the peninsular, while IOD affects the west coast (Malacca Strait) mainly. Interannual regional sea level drops are associated with El Niño events, while the rises are correlated with La Niña episodes; both variations are in the range of  $\pm 5 \text{ cm}$  having correlation coefficient of  $(-0.7)$  with respect to MEI. The IOD modulates interannual sea level variability in the Malacca Strait in the range of  $\pm 2 \text{ cm}$  with a correlation coefficient  $(-0.5)$  relative to DMI. At annual scale, SLAs are mainly monsoon-driven, in the order of  $10\text{--}25 \text{ cm}$ . They respond differently to the Asian monsoon; having two quasi-periodic cycles annually in the Malacca Strait, presumably due to South Asian-Indian Monsoon; but a single one annually in the remaining region, mostly due to East Asian-Western Pacific Monsoon. We suggest that a topographical and hydrodynamic constriction located between Raffles Lighthouse and Tanjong Pagar tide gauges in the Singapore Strait may separate sea level variabilities observed at both sides of the Peninsular Malaysia.

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## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## References

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## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

**Table 1.** Linear trends (mm yr<sup>-1</sup>) of SLR and VLM rates over selected periods.

Source of record (Location)	Period	SLR rate from tide gauge record				SLR rate from satellite <sup>i</sup>		VLM rate <sup>a,h</sup>
		Entire period		1993–2009		1993–2011	1993–2009	
		Relative	Absolute <sup>i</sup>	Relative	Absolute <sup>i</sup>			
Langkawi (99°46' E, 6°26' N)	1986–2011	3.0 ± 2.0	4.4 ± 4.7	1.9 ± 4.2	3.3 ± 6.9	3.4 ± 2.6	2.8 ± 3.2	1.4 ± 2.7
Pinang (100°21' E, 5°27' N)	1986–2011	3.7 ± 2.1	4.5 ± 5.8	4.4 ± 4.4	5.2 ± 8.1	3.3 ± 2.3	2.7 ± 2.8	0.8 ± 3.7
Lumut (100°37' E, 4°14' N)	1985–2010	2.1 ± 1.7	2.0 ± 4.4	2.2 ± 3.5	2.1 ± 6.2	4.3 ± 2.6	3.8 ± 3.2	-0.1 ± 2.7
Kelang (101°21' E, 3°03' N)	1984–2011	1.8 ± 1.8	2.3 ± 4.1	1.4 ± 3.8	2.0 ± 6.1	4.1 ± 2.7	3.3 ± 3.2	0.5 ± 2.3
Keling (102°09' E, 2°13' N)	1985–2011	2.4 ± 1.7	2.9 ± 4.0	2.9 ± 3.6	3.4 ± 5.9	4.7 ± 2.1	4.5 ± 2.7	0.5 ± 2.3
Kukup (103°27' E, 1°20' N)	1986–2011	3.0 ± 1.6	4.4 ± 3.6	3.3 ± 3.3	4.7 ± 5.3	5.2 ± 2.2	4.5 ± 2.7	1.4 ± 2.0
Malacca Strait	1984–2011	2.4 ± 1.6	3.2 ± 4.2	2.7 ± 3.6	3.4 ± 6.2	4.1 ± 2.2	3.6 ± 2.7	0.8 ± 2.6
Johor (103°48' E, 1°28' N)	1984–2011	2.3 ± 1.1	3.5 ± 3.1	1.9 ± 2.3	3.1 ± 4.3	5.0 ± 2.1	4.2 ± 2.6	1.2 ± 2.0
Sedili (104°07' E, 1°56' N)	1987–2011	2.5 ± 1.2	2.8 ± 3.3	1.8 ± 2.1	2.1 ± 4.2	4.0 ± 1.5	3.5 ± 1.7	0.3 ± 2.1
Tioman (104°08' E, 2°48' N)	1986–2011	3.0 ± 1.2	3.3 ± 3.5	2.6 ± 2.0	2.9 ± 4.3	4.0 ± 1.4	3.4 ± 1.6	0.3 ± 2.3
Gelang (103°26' E, 3°59' N)	1984–2011	3.2 ± 1.0	3.8 ± 3.4	3.5 ± 1.8	4.1 ± 4.2	3.9 ± 1.5	3.4 ± 1.8	0.6 ± 2.4
Cendering (103°11' E, 5°16' N)	1985–2011	3.3 ± 1.1	4.7 ± 2.6	2.3 ± 2.0	3.7 ± 3.5	3.9 ± 1.4	3.2 ± 1.6	1.4 ± 1.5
Geting (102°06' E, 6°14' N)	1987–2011	3.1 ± 1.5	4.7 ± 4.2	1.1 ± 2.4	2.7 ± 5.1	4.4 ± 1.4	3.9 ± 1.7	1.6 ± 2.7
Eastern Peninsular Malaysia	1984–2011	2.7 ± 1.0	3.6 ± 3.2	2.2 ± 1.9	3.1 ± 4.1	4.2 ± 1.4	3.6 ± 1.6	0.9 ± 2.2
Singapore Strait <sup>b</sup>	1984–2011	3.2 ± 1.2		3.4 ± 2.4				
Gulf of Thailand <sup>c</sup>	1940–2004		3.0 ± 1.5				3.6 ± 0.7	
South China Sea <sup>d</sup>	1950–2009	1.7 ± 0.1		3.9 ± 0.6				
Global tidal gauge <sup>e</sup>	1900–2009		1.7 ± 0.2		2.8 ± 0.8			
Global altimetry	1993–2013		3.2 ± 0.4 <sup>f</sup>		3.3 ± 0.4 <sup>g</sup>			

<sup>a</sup> VLM rates and uncertainties are interpolated from Simons et al. (2007);

<sup>b</sup> Tkalich et al. (2013);

<sup>c</sup> Trisirisatayawong et al. (2011) at Ko Lak tide gauge;

<sup>d</sup> Peng et al. (2013);

<sup>e</sup> Church and White (2011);

<sup>f</sup> Nerem et al. (2010);

<sup>g</sup> Nicholls and Cazenave (2010);

<sup>h</sup> Assume that VLM speed is constant beyond its observational period.

<sup>i</sup> SLR rate obtained from AVISO satellite altimetry data. Calculated uncertainties are at the 95% confidence level.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

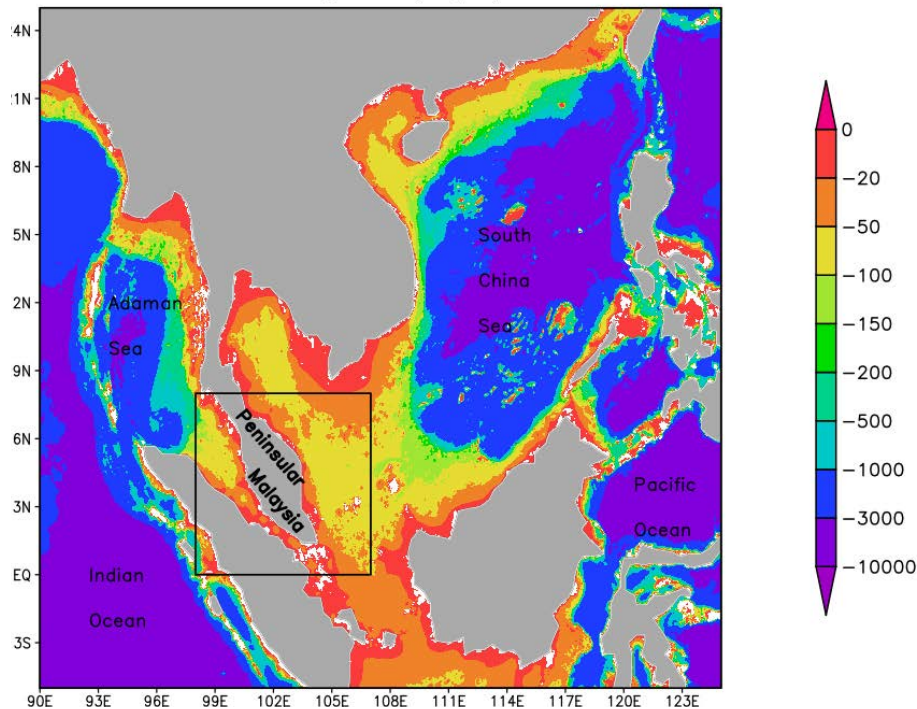


## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

### Bathymetry (m)



**Figure 1.** Study area. Contours show bathymetry; black box indicates the region covering Peninsular Malaysia.

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



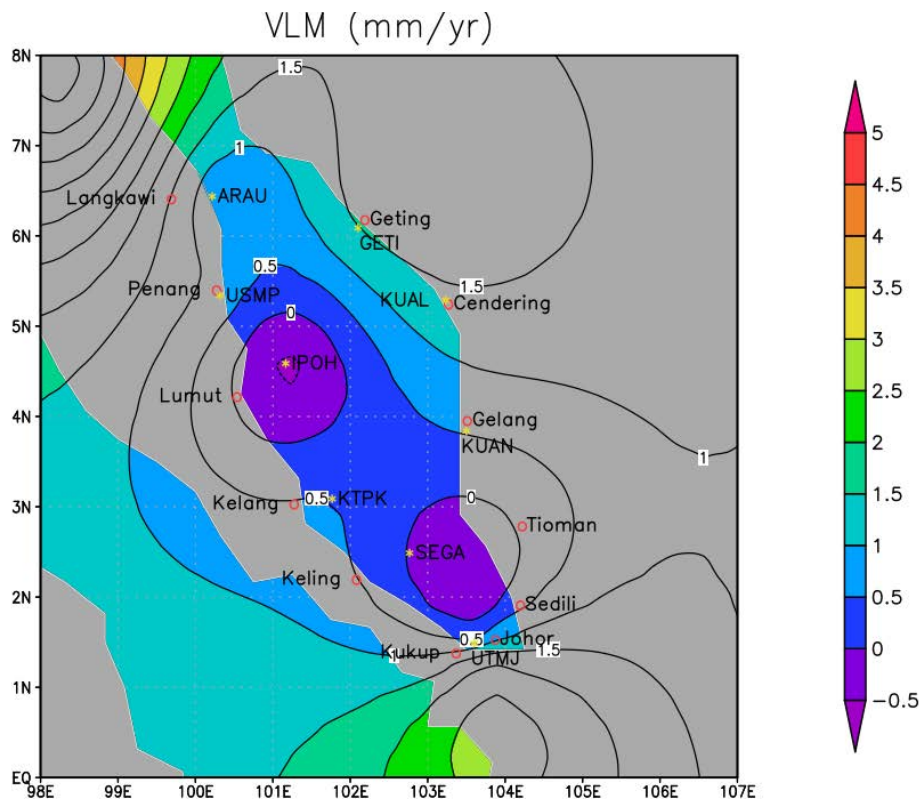
Back

Close

Full Screen / Esc

Printer-friendly Version

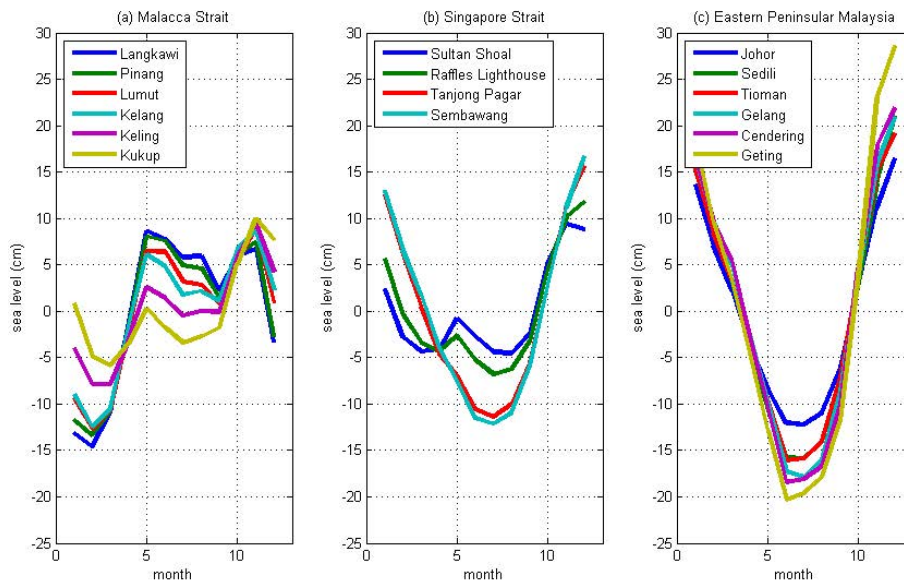
Interactive Discussion



**Figure 2.** Locations of and GPS stations (yellow symbols) extracted from Simons et al. (2007) and tidal gauge stations (red circles) archived from PSMSL (2013) along the coasts of Peninsular Malaysia. Contours represent VLM rates ( $\text{mm yr}^{-1}$ ).

## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.



**Figure 3.** Monthly climatology of SLA in the: **(a)** Malacca Strait; **(b)** Singapore Strait (after Tkalich et al., 2013); **(c)** eastern Malaysia Peninsular. The climatology is derived by taking monthly average at each station over its entire period.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

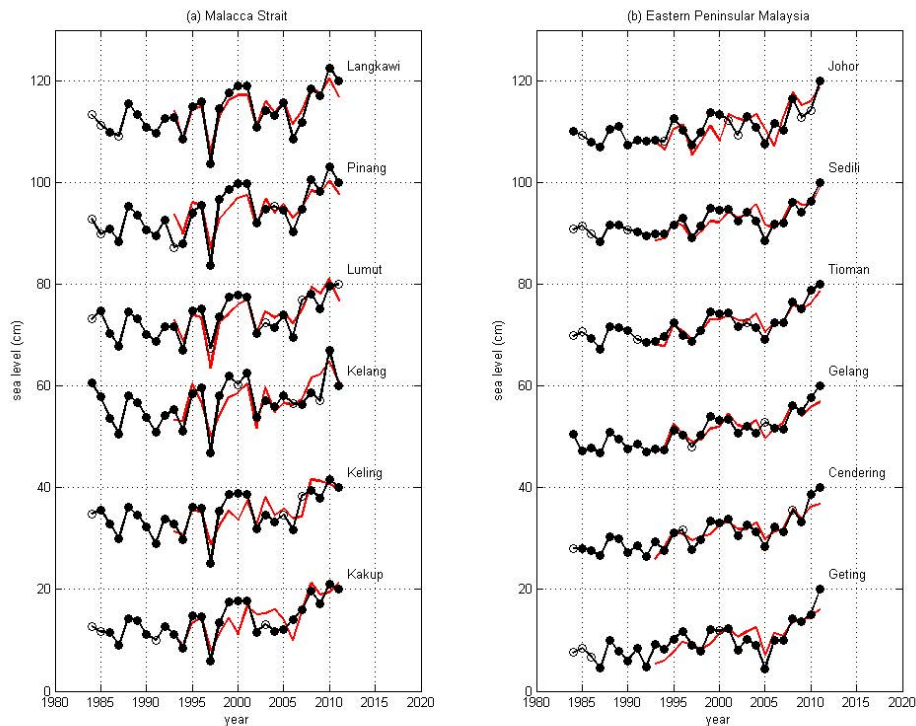
Printer-friendly Version

Interactive Discussion



## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.



**Figure 4.** Annual sea level at tidal gauges around the Peninsular Malaysian: **(a)** Malacca Strait, **(b)** eastern Peninsular Malaysia. Filled circles show data from PSMsL; while open circles indicate restored missing data. Red lines represent annual satellite altimetry data.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

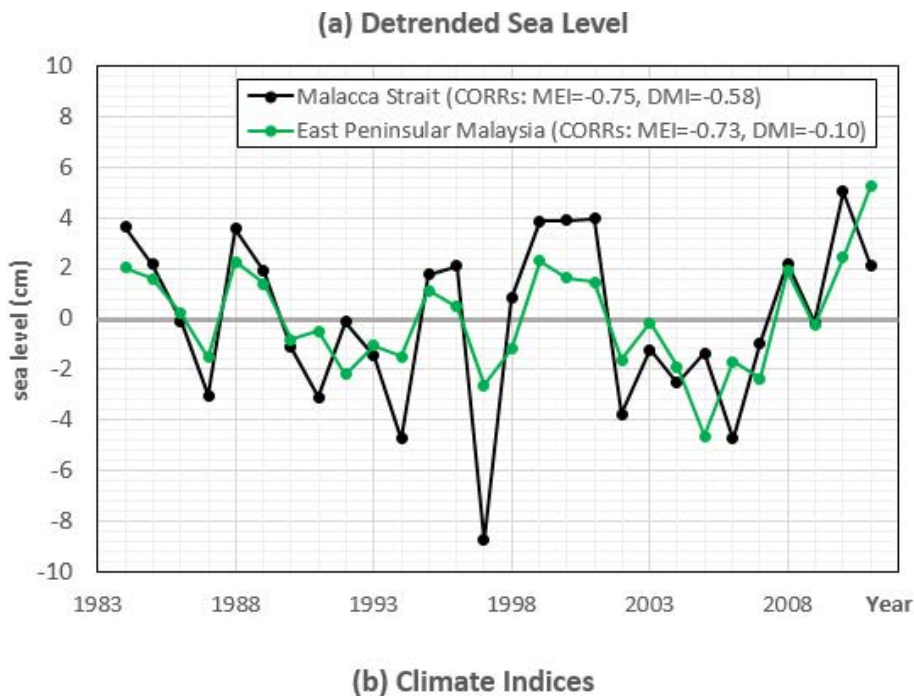
Printer-friendly Version

Interactive Discussion



**Sea level trend and variability around the Peninsular Malaysia**

Q. H. Luu et al.



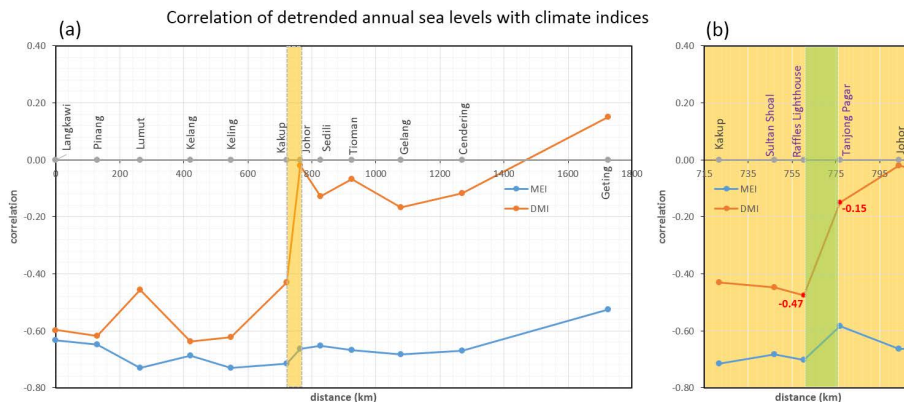
**Figure 5.** (a) Detrended annual sea levels around the Peninsular Malaysia; and (b) annual MEI and DMI indices.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



## Sea level trend and variability around the Peninsular Malaysia

Q. H. Luu et al.



**Figure 6.** Correlations of interannual sea level with MEI (blue lines) and DMI (red lines) at tide gauges **(a)** along the Peninsular Malaysia, and **(b)** in the Singapore Strait. The correlation coefficients are computed using de-trended annual sea level from PSMSL (before reconstruction).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

