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Sea level anomalies in straits of Malacca and Singapore

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ABSTRACT

This paper studies sea level anomaly (SLA) behaviour in Malacca and Singapore straits which serve part of a major maritime trade route between Indian and Pacific Ocean using both observed data and numerical model. Spatio-temporal behaviour of SLA in the region is analyzed based on 15 years of in-situ and remote sensing data. Results show that SLA signatures can be distinctly different in the two straits, with vastly opposite behaviours during certain months. By further analyzing spatial dependency of observed SLA in the region, SLA in Malacca and Singapore straits are found to be under the influence of Indian Ocean and South China Sea, respectively. Based on this insight, a numerical model is built with the appropriate non-tidal forcing derived from meteorological model and satellite dataset to properly represent SLA in Malacca and Singapore straits with Root Mean Square Error of less than 10 cm. With this well calibrated model, the effect of different types of forcing on volume flux through the straits is investigated. Combined tidal and non-tidal forcing in the model gives 4 to 7×10^{11} m^3 of annual net westward volume flux through the straits which is four to seven times higher than that of tidal forcing alone. Furthermore with this combined forcing, a distinct seasonal trend with westward net flow during northeast monsoon (November to March) and eastward net flow during southwest monsoon (May to September) can be observed through the straits in the model which is not observed with tidal forcing. The findings of this paper highlight the importance of these non-tidal forcing in the model to obtain accurate SLA and flow representation in the straits that is vital to environmental fate and transport modelling during operational forecast.

1. Introduction

Malacca and Singapore straits serve part of an important maritime trade route between Indian Ocean and Pacific Ocean that links major Asian economies such as India, China, Japan and the Southeast Asian countries. Located between two large water bodies: South China Sea (via Singapore Strait) and Indian Ocean, Malacca Strait is highly complex hydrodynamic system. Indian Ocean is dominated by semi-diurnal tides while South China Sea is dominated by both diurnal and semi-diurnal tides [1]. Tidal waves, especially semi-diurnal M_2 tidal component generated at the Indian Ocean [2] and mixed diurnal and semi-diurnal waves from South China Sea meet and interact approximately at southern end of Malacca Strait where it links to Singapore Strait. This also results in a higher tidal range at the west compared to the east within Singapore Strait [1]. For example, tidal ranges are between 2.7 m in the west and 1.4 m in the east during spring tide, with 40% of spring tidal range across the strait during neap tide. This creates complicated tidal dynamics along the two narrow straits [3,4]. Fig. 1 illustrates the geography and topography of the region.

Although this region is mainly tide-dominated, non-tidal flows in the form of sea level variations are observed in Malacca and Singapore straits [5]. These variations of sea level from deterministic tide are defined as Sea Level Anomalies (SLA) in this paper, and are induced by non-tidal flows related to surface wind, density-driven flow, large scale oceanographic processes, geographical landscape, or abrupt variation of topography. Resultant flow pattern could significantly deviate from the deterministic tidal flow or even cause a flow reversal of tidal flows [6]. SLA observed in Singapore Strait has shown to have characteristics of non-stationary non-periodic ocean behaviour of varying temporal and spatial scales [5]. Tkalich et al. [7] suggest that the local SLA is caused by several large scale oceanographic and meteorological parameters such as winds, atmospheric pressure gradient, sea

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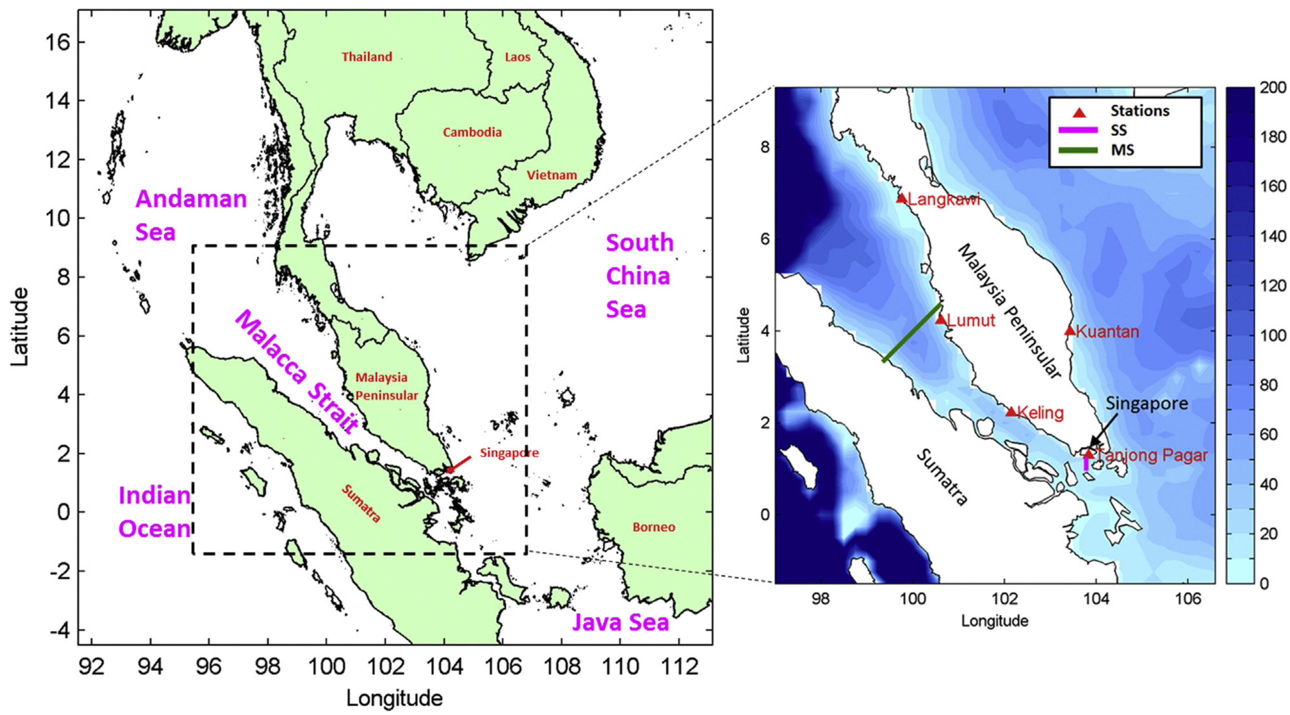

Fig. 1. Map showing geography and topography of Malacca and Singapore straits with location of stations and cross sections MS (Malacca Strait) and SS (Singapore Strait).

surface temperature and fresh water run-off. Rao et al. [5] find that SLA in this region is strongly correlated with the monsoon winds of the seasonal monsoon seasons; northeast monsoon from November to February and southwest monsoon from May to August. Especially during northeast monsoon period, strong winds from Asia continent prevails over South China Sea and triggers positive SLA events in Singapore waters [5]. Tkalich et al. [7] conclude that SLA is positive in Singapore Strait and negative at the other end of South China Sea near Taiwan during northeast monsoon, and vice-versa during southwest monsoon. In contrast, there are fewer literatures focusing on SLA in Malacca Strait. A recent SLA study in Malacca Strait by Luu et al. [8] discusses the sea level variability at seasonal, inter-annual and long-term (more than 25 years) time scales along coastline of Malaysia Peninsular based on long term time series observation. Studies by Luu et al. [8] and Soumya et al. [9] have shown that sea level variabilities in Malacca and Singapore straits are affected by coupled ocean-atmosphere oscillations, such as El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). SLA in Malacca Strait is modulated by ENSO and IOD up to 7 and 5 cm, respectively. Effect of IOD decreases from Andaman Sea towards Singapore Strait [8], while SLA due to ENSO may be up to the order of 5–8 cm during strong El Niño/La Niña episodes [10].

Complimenting earlier SLA studies based on analysis of observed data have brought many insights to the behaviour of SLA in Malacca and Singapore straits, process-based numerical models that describe spatial and temporal hydrodynamics can further enhance understanding of SLA, current velocity and volume transport in the region. As this region is tide-dominated, early numerical studies were mostly tidal [11–13] and focusing on Singapore Strait. The so-called Singapore Regional Model built by Kernkamp and Zijl [14] and further improved by Kurniawan et al. [4] is one of the first published numerical models to encompass both Malacca and Singapore straits in its modelling domain. The model is applied in other hydrodynamic studies such as van Maren and Gerritsen [15] and Hasan et al. [16], and model forecast is improved using data-driven techniques [17–23]. Adopting the same open boundary in Malacca Strait, Tay et al. [24] built a numerical model covering Malacca and Singapore straits and the entire South China Sea and Java Sea with good tidal representation. As for the SLA in this region, most numerical studies [25,26], have been carried out in the barotropic mode as the local non-tidal flows are known to be monsoon-driven rather than baroclinically induced [5,7]. One recent study of non-tidal modelling in this region is Kurniawan et al. [6] who applied basin scale wind over entire South China Sea to represent SLA i.e. wind-induced water level (i.e. surge) in Singapore regional waters covering the vicinity of east coast of Malaysia Peninsular, Singapore Strait and Malacca Strait. Though SLA is well represented in Singapore Strait and east Malaysia Peninsular in their model, SLA in Malacca Strait is poorly represented with tide and wind forcing. SLA along east coast of Malaysia Peninsular has been shown to be caused by basin scale wind blowing over South China Sea [6]. However on the other side of the peninsular, source of SLA in Malacca Strait remains poorly described as local SLA could not be represented using the same wind-driven modelling approach. Results of Kurniawan et al. [6] suggest that SLA in Malacca Strait may originate in large regions located far away—as far as Andaman Sea or Indian Ocean. This motivates need for further understanding of origin of SLA in Malacca Strait and supports need to correctly represent associated mechanisms. Other non-tidal hydrodynamic modelling studies solely focusing on Malacca Strait such as Rizal et al. [2] and Chen et al. [27] have focused on the current fields caused by wind during different seasons (monsoons and inter-monsoons). However, other than the monthly surface current vector plots reported by Wyrtki [28], there are no current data available for this area. Therefore no proper quantitative validation of model results was carried out by Rizal et al. [2] and Chen et al. [27]. To the authors' best knowledge, no numerical modelling study has explicitly shown proper representation of SLA in Malacca Strait. As such, the first objective of this paper is to determine the origin and behaviour of the SLA in Malacca and Singapore straits based on observation data. Based on this knowledge, the second objective of this paper will attempt to properly represent the SLA in numerical model and gain insights to the non-tidal flow in the strait.