Along-track High Resolution Sea Levels from SARAL/AltiKa Satellite Altimetry Data over the Maritime Continent

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***Abstract* — A new generation of satellite altimetry with a high spatial resolution is a very useful tool for providing information about ocean characteristics including the study of sea levels. This paper is concerned on the comparison of sea levels from the newly launched SARAL/AltiKa satellite altimetry data with the data model from the Coriolis Data Centre. The paper focuses over the regions of the Maritime Continent, which includes the Straits of Malacca, the South China Sea, and the Sulu Sea. The statistical analysis is performed over these three seas because they have different coastal characteristics and ocean variabilities, therefore, the quality of the derived sea levels may be varies. The results show that the sea levels from SARAL/Altika generally well-agree to those of Coriolis Data Centre. However, significant differences are observed at certain regions especially at the Strait of Malacca and Banda Sea. The highest correlation is found over the South China Sea while the lowest value is found over the Sulu Sea. The lowest RMSE is observed at Strait of Malacca while the highest value is over the Sulu Sea.**

Index Terms – SARAL/AltiKa, sea level anomaly, ocean climate and Maritime Continent.

I. INTRODUCTION

Over decades, satellite radar altimetry was used for revising global oceans and climate changes using radar band. SARAL/Altika is a new generation of satellite altimetry that equipped with wide Ka-band altimeter (35.75 GHz). SARAL/Altika satellite altimetry can produce finer spatial resolution of 40 Hz data which corresponds to ~174 m along-track sampling. It also has smaller cross-track distance at the equator which is 75 km compared to Jason-2 with 315 km. This produces high density ocean measurements [1] and applicable for various ocean applications [2].

Previous studies have shown that SARAL/Altika satellite altimetry data are consistent with hydrographic data such as glider and coastal ocean dynamics applications radar (CODAR) over coastal regions with accuracy of sea level anomaly (SLA) is about 2 cm [3]. Results from [4] identified that SARAL/Altika can provide data up to 2 - 3 km from the coastline, while Jason-2 satellite altimetry can provide only up to 5 km from the coastline over the east Australia coastal region. This is may be due to the advantageous of small footprint size of SARAL/Altika that minimize the impact of land towards the waveforms.

Recent study from [5] has addressed significant differences in the sea surface height estimates of SARAL/Altika with respect to Jason-2 over the Maritime Continent. The reasons that may be responsible to the discrepancy is due to the difference in orbit and geophysical corrections, particularly sea state bias, as the sea state bias in SARAL/Altika is yet to be adjusted. Therefore verification towards the SARAL/Altika geophysical data corrections is crucial. The two issues arose of satellite altimetry measurements over coastal area are the contamination of satellite waveforms due to lands and coastal sea states, and inaccurate geophysical corrections [6]. To overcome this problem, various retracking methods, e.g., [7-9] and geophysical corrections, e.g., [10-12] have been developed to obtain meaningful estimates.

In this paper, we focus on the derivation of SLA from SARAL/Altika over the Maritime Continent during different monsoon seasons. The results are compared with data model from Coriolis Data Centre to identify their consistency.

II. STUDY AREA AND DATA

This study focuses on the region of Maritime Continent (see Fig. 1) because it has a complex coastal topography including islands, peninsulas and shallow seas that produce various waveform shapes. Therefore, the performance of SARAL/Altika in the region needs to be identified.

The main data utilized is the new generation of 40 Hz satellite altimetry SARAL/Altika that uses Ka-band. The satellite data can be obtaining though Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO) webpage (http://www.aviso.oceanobs.com/). In this study, the data utilized are from June to July 2014 and December 2014 to January 2015 which correspond to south-west monsoon and north-east monsoon, respectively.

The corrections used in this study are the dry and wet tropospheric corrections from European Center for Medium range Weather Forecasting (ECMWF) model, ionospheric correction from Jet Propulsion Laboratory Global ionosphere maps (JPL GIM) model, high frequency fluctuation, ocean tide solution 1 and load tide solution 1 from Global Ocean Tide (GOT4.8) model, solid earth tide and pole tide.

The data used for comparison with SARAL/Altika satellite altimetry result are the daily SLA data model from the Operational Mercator Global Ocean Analysis and

Forecast System from the Coriolis Data Centre. It can be obtained from http://www.coriolis.eu.org/. Data from the Coriolis Data Centre are derived from tide gauge and Jason-2 satellite altimetry with SLA accuracy provided is about 4 cm (Collecte Localisation Satellites, 2011).

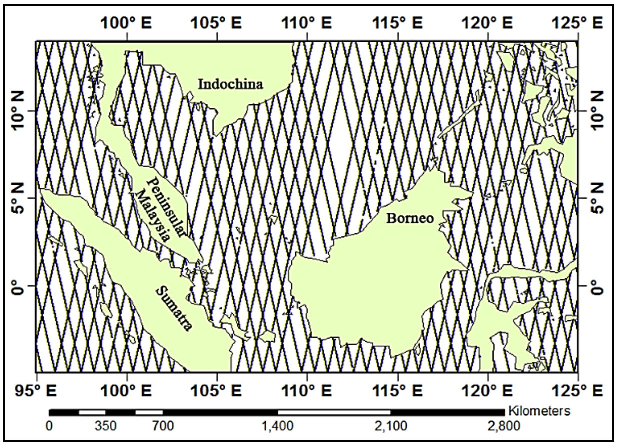

Fig. 1 Study area and SARAL/Altika tracks.

III. Derivation of Sea Levels

Sea surface height can be calculated by determining the time travelled of signal pulse, t and corresponding to speed of light, c (2.998x10^{8}ms-1). However, corrections to the estimates must be applied due to several errors such as atmospheric corrections (i.e. ionosphere, troposphere and sea state bias) and geophysical corrections (i.e. tides and inverse barometer). SLA (h_{sla}) can then be derived by subtracting with mean sea surface:

$$h_{sla} = H - (R_{observed}+h_{wet}+h_{dry}+h_{iono}+h_{ssb}) - h_{mms} - h_{ot} - h_{solid} - h_{pole} - h_{load} - h_{inv} - h_{hf} \quad (1)$$

Where, H is satellite altitude, $R_{observed}$ is MLE4 retracked range, h_{wet} is troposphere correction, h_{dry} is dry troposphere correction, h_{iono} is ionosphere correction, h_{ssb} is sea state bias correction, h_{mms} is mean sea surface height, h_{ot} is ocean tides, h_{solid} is solid earth tides, h_{pole} is pole tides, h_{load} is tidal loading, h_{inv} is inverse barometer height correction, and h_{hf} is high frequency fluctuations.

In this study, the retracked range from the MLE4 algorithm is applied. Retracking is known as data post-processing where surface elevation is defined precisely by measuring the leading edge of return waveform from satellite altimetry. This study focuses on MLE4 retracking algorithm because it is capable of providing precise SLA estimates even though return echoes do not fully confirm to the Brown (1977) model [9]. The MLE4 algorithm is based on the second order Bessel function of the Brown (1977) model to retrieves parameters of range, significant wave height, amplitude and off-nadir angle [13].

In this study, the sea state bias and inverse barometer corrections are not applied due to erroneous estimation over coast.

IV. Result and Analysis

The result of SLA derived from SARAL/Altika is access based on qualitative and quantitative analysis. Qualitative analysis is based on visual comparison with data model from the Coriolis Data Centre during south-east and north-east monsoons. Quantitative analysis is performed by computing the correlation and root mean square error (RMSE) between both datasets. It is carried over three regional areas: 1) the South China Sea, 2) the Sulu Sea, and 3) the Malacca Strait, where they have different ocean characteristics and variability. The samples points have been selected randomly over the regions.

Correlation coefficient is also computed to define the relationship between both data from SARAL/Altika and Coriolis Data Centre.

A. *Qualitative Analysis*

Fig. 2 and Fig. 3 represent the SLAs from SARAL/Altika satellite altimetry data and Coriolis Data Centre, respectively during south-west monsoon, and Fig. 4 and Fig. 5 during north-east monsoon.

In generally, both dataset shows nearly similar features of the sea levels. During south-west monsoon (see Fig. 2 and Fig. 3), high water levels can be seen at the eastern part of Indochina coast, north coast of the Borneo and the northern part of South China Sea, while low water level can be seen at Banda Sea. During north-east monsoon (see Fig. 4 and Fig. 5), high water levels can be seen at the Gulf of Thailand, east coast of the Peninsular Malaysia, and over the coast of Borneo except the west coast.

However, there are certain areas where both datasets shows discrepancy. For examples, during south-west monsoon, SARAL/Altika records high ($\geq$1 m) SLAs at the east coast of Peninsular Malaysia and of Borneo while the Coriolis Data Centre records low ($\leq$0.7 m) SLA. During north-east monsoon, SARAL/Altika records low ($\leq$0.5 m) SLAs at Banda Sea while Coriolis Data Centre shows vice versa ($\geq$0.8 m). The differences are shown in the dash line rings in Fig. 2 and Fig. 4.

It is seen that results from SARAL/Altika are much noisier than the Coriolis Data Centre. The range of SARAL/Altika SLAs is also higher (-2 m to 3 m) when compared to the Coriolis Data Centre (-0.5 m to 1.3 m). There are four reasons that may be responsible to the differences: 1) the SARAL/Altika SLAs are computed from high resolution of 40 Hz data, which leads to high variability of SLAs, meanwhile the Coriolis Data Centre SLAs are derived from 20 Hz Jason-2 satellite altimetry and tide gauges, which produce less dense SLAs when compared to SARAL/Altika, 2) the Coriolis Data Centre SLAs have been filtered using smoothing filter [14], while no filtering has been applied on SARAL/Altika SLAs, 3) inaccurate tidal corrections have been applied on SARAL/Altika which is based on the global GOT4.8 model, and 4) the differences in temporal resolution of both datasets in which SARAL/Altika is measured instantaneously at real time while the Coriolis Data Centre is measured daily.

Theoretically, south-west monsoon drives the ocean currents from the southern South China Sea to the northern parts. The ocean circulation leads to the increasing of water levels near the Indochina coast to the northern part of South China Sea. The Strait of Malacca also experiences high water level. Meanwhile, low water levels are experiences at the Gulf of Thailand and Banda Sea (cf. [15]). During the north-east monsoon, the ocean circulation in the South China Sea is inversely moved from the direction during south-west monsoon, in which the water flows from the upper South China Sea to the southern areas [15]. This water movement leads water increasing at the east coast peninsular Malaysia, Gulf of Thailand, thus the southern part of South China Sea.

B. *Quantitative Analysis*

In this section, correlation coefficient and RMSE are computed and analysed over three regional areas which are the South China Sea, Sulu Sea and Malacca Strait. Table 1 summaries the correlation coefficient and the RMSE over regions, respectively.

The results in Table 2 indicate that the South China Sea during south-west monsoon has the highest correlation (0.78) when compared to the other regions. The lowest correlation is recorded by the Sulu Sea during south-west monsoon with coefficient of 0.42. The average correlations for the South China Sea, Malacca Straits and Sulu Sea during the periods are 0.83, 0.57 and 0.49, respectively. This shows that in general, the Sulu Sea has the lowest correlation while South China Sea has the highest value.

The highest RMSE is recorded at the Sulu Sea with 66 cm during south-west monsoon while the lowest value is at the Strait of Malacca with 26 cm. The averages RMSE for the South China Sea, Malacca Straits and Sulu Sea during the periods are 50 cm, 31 cm and 61 cm, respectively.

The results derived from the SARAL/Altika may be inaccurate due to 1) differences in temporal measurements, 2) the inverse barometer and sea-state bias corrections were not applied when deriving the SLAs, and 3) the global ocean tide model fails to fully resolve the tidal signal from the altimetry measurements.

Table 1 RMSE and correlation based on regions.

Region	**Period (monsoon)**	**RMSE (cm)**	**Correlation**
South China Sea	South-west	61	0.78
	North-east	40	0.87
Strait of Malacca	South-west	35	0.58
	North-east	26	0.56
Sulu Sea	South-west	66	0.42
	North-east	56	0.55

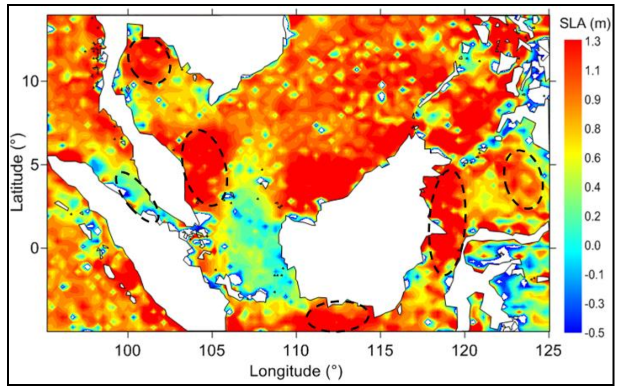

Fig. 2 Map of SLA from SARAL/Altika during south-west monsoon

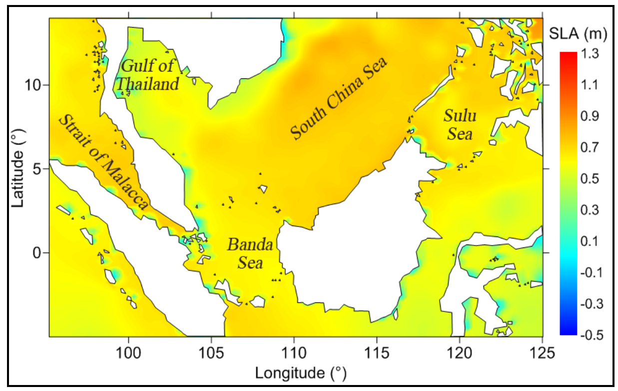

Fig. 3 Map of SLA from Coriolis Data Centre during south-west monsoon.

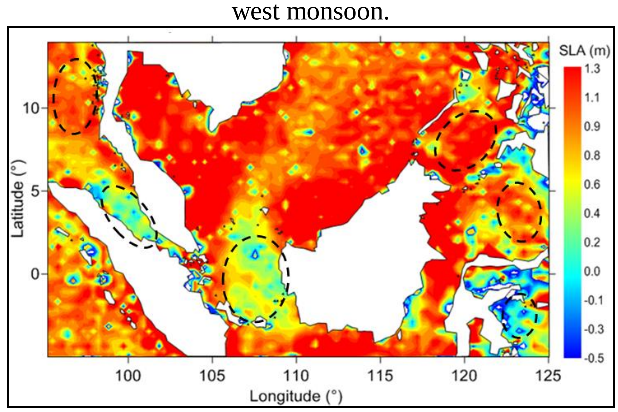

Fig. 4 Map of SLA from SARAL/Altika during north-east monsoon.

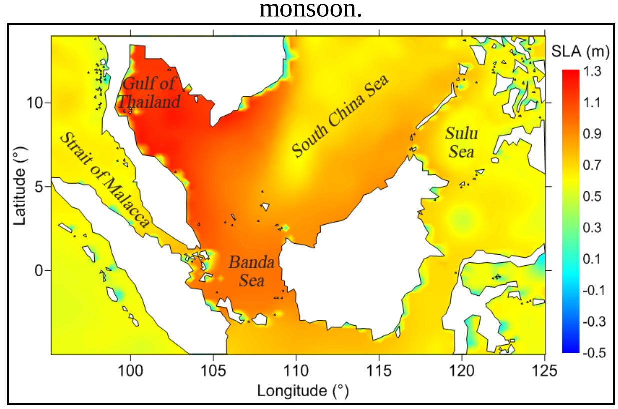

Fig. 5 Map of SLA from Coriolis Data Centre during north-east monsoon.

V. Conclusions and Recommendations

The results show that the SLAs from SARAL/Altika generally well-agree to the Coriolis Data Centre. However, significant differences are observed at certain regions especially at the Strait of Malacca and Banda Sea. The highest correlation is found over the South China Sea while the lowest value is found over the Sulu Sea. The lowest RMSE is observed at Strait of Malacca while the highest value is over the Sulu Sea.

Future research should consider the regional tides model when deriving SLAs over the regions to better resolve the tidal signals from the measurements. The validation of the results with other independent in-situ data such as tide gauges is also crucial to identify the accuracy of the results.

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