Intercomparison between Retracked Sea Levels from SARAL/AltiKa Satellite Altimetry and Ocean Data Model over the Maginal Seas at the South East Asia

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Abstract
In this paper, comparison between retracked sea levels from SARAL/AltiKa satellite altimetry with the data model from the Coriolis Data Centre is performed. The study focuses on the Marginal Seas at the South East Asia, which includes the Straits of Malacca, the South China Sea and the Sulu Sea. The SARAL/AltiKa sea level is based on the standard ocean (i.e. Maximum Likelihood, MLE4) retracker. The analysis is performed by computing the correlation coefficient and root mean square (RMS) error during the north-east and south-west monsoon seasons in 2014-2015. In comparison with the data model, both datasets have high (≥0.8) correlation coefficient and low (≤61 cm) RMS error over the South China Sea during both monsoon seasons. In contrast, the Sulu Sea has low (<0.5) correlation and high (≥56 cm) RMS error during both seasons. It can be concluded that the accuracy of the datasets really depends on the coastal topography of the ocean region itself. More complex regions have greater influence on the altimetry observations, thus reducing the accuracy of the estimations.

1. Introduction

Over decades, satellite radar altimetry has been beneficial for monitoring global oceans. SARAL/AltiKa is a new generation of satellite altimetry that equipped with wide Ka-band altimeter (35.75 GHz). In contrast to the conventional satellite altimetry (e.g. Jason-2) that uses C and Ku bands, SARAL/AltiKa can produce finer (40 Hz) spatial resolution with along-track sampling of ~174 m. This is two times better than those of Jason-2 that produces 20 Hz with along-track sampling ~300 m. At the equator, the cross-track distance of SARAL/AltiKa is much smaller (~75 km) than those of Jason-2 (315 km). These enable high density coastal and open ocean observations, thus beneficial to the various ocean applications (Quartly and Parasso, 2014). Several studies (e.g., Abdalla, 2014, Troupin et al., 2015, Idris et al., 2014a, Palanisamy et al., 2015, Quartly and Parasso, 2014 and Valladeau et al., 2015) have been carried out to assess the quality of SARAL/AltiKa over coastal oceans. Troupin et al., (2015) has 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 the accuracy of sea level anomaly (SLA) as about 2 cm. Results from Idris et al., (2014a) has 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 over the eastern coast of Australia. Excellent data coverage by SARAL/AltiKa is due to the advantageous of small footprint size of SARAL/AltiKa, thus minimizing the impact of land towards the altimetric signals. Recent study from Palanisamy et al., (2015) has addressed the difference in the SLA estimates of SARAL/AltiKa with respect to Jason-2 over the Maritime Continent. The observed difference was about 3 cm. 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. In this paper, we study the quality of satellite altimetry datasets over the Marginal Seas at the South East Asia. This is to support the initiative of the 'Year of the Maritime Continent', an international framework for collaboration on field observations and modelling to better understanding

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the role of the region. As the Maritime Continent is located in a region that contains many islands, peninsulas and shallow seas, satellite altimetry produces various waveform patterns due to interference with land (Cipollini et al., 2013). The aim of this research is to derive SLAs from 40 Hz SARAL/AltiKa data over the Marginal Seas at the South East Asia during north-east monsoon and south-west monsoon in 2014. The retracked SLAs derived from SARAL/AltiKa satellite altimetry are compared to the retracked SLAs from the Coriolis Data Centre. The retracked data are obtained through a waveform retracking method, which is known as data post-processing where surface height is defined precisely by measuring the leading edge of return waveform from satellite altimetry (cf. Gommenginger et al., 2011). The SLAs from the Coriolis Data Centre are the data products that were derived from the combination of Jason-2 satellite altimetry data and coastal tide gauges. The quality and consistency between both datasets are relatively compared in this study. The paper is organized as follows: the study area and data resources are described in Section 2; the derivation of retracked sea levels from SARAL/AltiKa satellite altimetry data are provided in Section 3; the results and analysis are shown in Section 4; and the conclusions and recommendations are presented in Section 5.

2. Study Area and Data Resources

This study focuses on the region of the Marginal Seas at the South East Asia, which includes the South China Sea, Straits of Malacca and Sulu Sea (see Figure 1). The South China Sea is the largest marginal sea in the world. It lies above a continental shelf with the average water depth of 200 m, and contains about 250 small islands (Morimoto et al., 2000 and Yanagi et al., 2001). It is connected with the Sulu Sea through several narrow and shallow straits. The Sulu Sea consists of many small islands, reefs, and narrow straits. The bottom topography varies rapidly, with ocean depth ranges from ~4000 m to <30 m (Cai et al., 2009) The Malacca Strait is a narrow and shallow sea with the average water depth of 60 m at the northern part, and 40 m at the southern part. It is a long strait that stretches about 805 km between the Peninsular Malaysia and Sumatera. During the seasonal monsoon, the South China Sea, the Sulu Sea and the Strait of Malacca receive strong winds and rains associated with the monsoon forces (Aziz et al., 2012 and Gan et al., 2006). The complex coastal and bottom topography, and the seasonal climate changes affect the satellite altimeter measurements (Aziz et al., 2012, Md Din et al., 2012 and Idris and Deng, 2012). It has a complex coastal topography which includes islands, peninsulas and shallow seas. This produces various altimetric waveform shapes, thus reducing the accuracy of SLA estimations. The main data utilized is the 40 Hz along-track data from SARAL/AltiKa Sensor Geophysical Data Product (SGDR) that uses Ka-band with high frequency (35.75 GHz). Since it has a small size of footprint, it creates less noise on the parameter estimates, particularly the range that is related to SLAs (AVISO, 2010). The data from June to July 2014, which corresponds to south-west monsoon, and December 2014 to January 2015, which corresponds to north-east monsoon were downloaded from Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO) server (ftp://avisoftp.cnes.fr/AVISO-/pub/saral/sgdr_t/). Figure 1 shows the SARAL/AltiKa ground tracks over the experimental region, which comprises of 100 passes. When deriving SLAs from SARAL/AltiKa, the geophysical corrections are applied to the datasets (see equation 1). They 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 SLAs from the Coriolis Data Centre are the data model from the Operational Mercator Global Ocean Analysis and Forecast System. It can be obtained from http://www.coriolis.eu.org/. The SLAs are the data product, which were derived from hourly tide gauges data and ~9 days Jason-2 satellite altimetry data. The product has gridded data at 1/12° spatial resolution, providing global ocean forecasts that is updated daily and weekly for ocean analysis. It has been reported that the accuracy of the SLAs is about 4 cm (Collecte Localisation Satellites, 2011).

3. Derivation of Retracked Sea Levels from SARAL/AltiKa Satellite Altimetry Data

SLA (h_{sla}) from satellite altimetry can be derived from (AVISO, 2013).

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

Equation 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_{mm} 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. These corrections are provided in the SGDR product. Concerning the retracked range parameter, this study applied the retracked range from the MLE4 algorithm (Thibaut et al., 2010). It is noted that SARAL/AltiKa SGDR product provides four retracking algorithms, which are the MLE4, Ice-1, Ice-2 and Sea Ice. The MLE4 retracker is applied in this study because it is the standard retracking solutions over the ocean, whilst the other three retrackers are meant for inland water and sea ice. The MLE4 retracker is based on the second order Bassel function of the Brown (1977) model to retrieve parameters of range, significant wave height, amplitude and off-nadir angle (AVISO, 2010) from the altimetric waveforms. The retracker is capable of providing precise SLA estimates even though return echoes do not fully confirm to the Brown (1977) model (Thibaut et al., 2010) such as waveforms near coastal region.

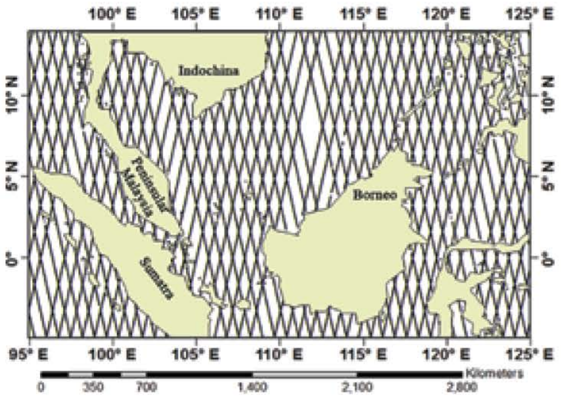

Figure 1: The SARAL/AltiKa ground tracks over the Marginal Seas at the South East Asia

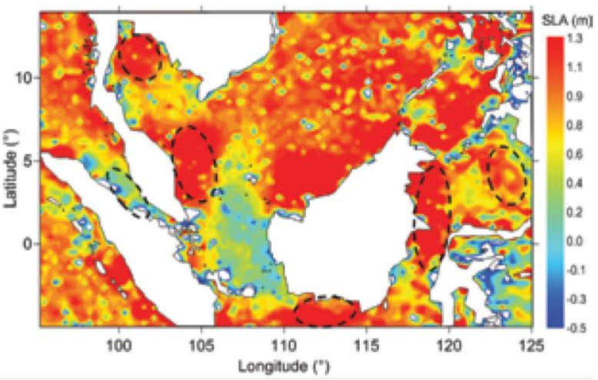

Figure 2: Map of SLA from SARAL/AltiKa during south-west monsoon (Circles indicate difference of SLA with Coriolis Data Centre)

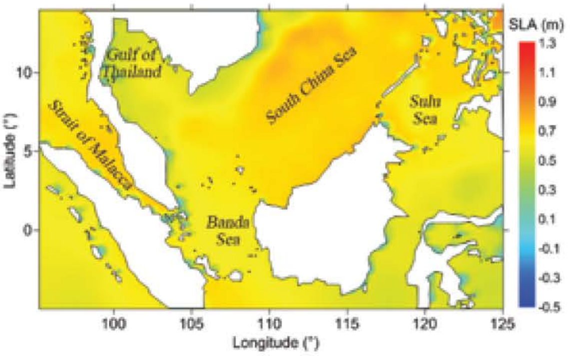

Figure 3: Map of SLA from Coriolis Data Centre during south-west monsoon

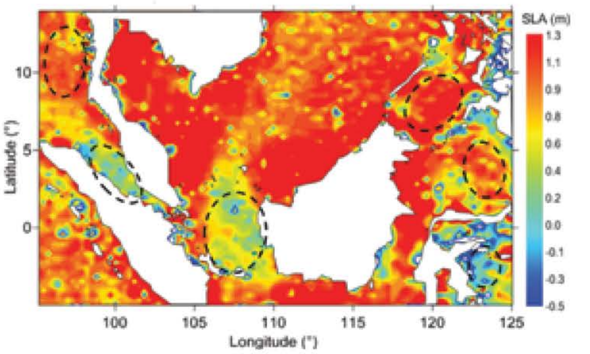

Figure 4: Map of SLA from SARAL/AltiKa during north-east monsoon (Circles indicate difference of SLA with Coriolis Data Centre)

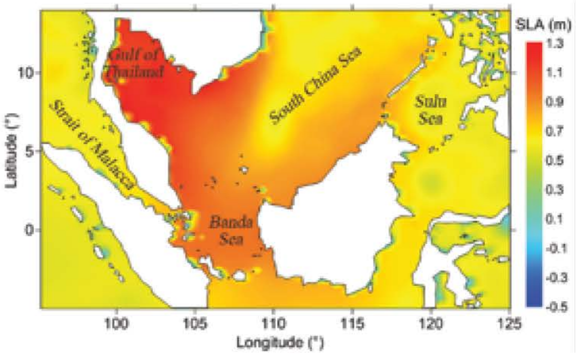

Figure 5: Map of SLA from Coriolis Data Centre during north-east monsoon

4. Results and Discussions

In this section, the assessments are performed based on the qualitative and quantitative analyses. The qualitative analysis is based on visual comparison among both datasets during south-east and north-east monsoons. The quantitative analysis is performed by computing the correlation coefficient and root mean square error (RMSE) between both datasets. In the computation, about 100 data samples have been randomly selected and well distributed over the region. The analysis 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.

4.1 Qualitative Analysis

Figures 2 and 3 represents the SLAs during south-west monsoon from SARAL/AltiKa and Coriolis Data Centre, respectively, and Figures 4 and 5 during north-east monsoon. During south-west monsoon (Figure 2 and 3), different amplitude of sea levels can be observed from both datasets. It is seen that the SARAL/AltiKa produces higher SLA variation than those of the data model. The former SLA ranges from -0.5 m to 1.3 m and the latter from 0.1 m to 0.7 m. The SLAs from the data model is much smoother when compared to the SARAL/AltiKa. From Figures 2 and 3, SARAL/AltiKa records high (≥1 m) SLAs at the east coast of Peninsular Malaysia, of Borneo and Gulf of Thailand, while the model records low (≤0.7 m) SLAs. The differences are shown in the dash line rings in Figure 2. During north-east monsoon (Figures 4 and 5), generally, both datasets are well-agreed particularly over the Gulf of Thailand and the South China Sea, where the values of SLAs are ~0.9 m to 1.3 m. However, discrepancies are observed over Banda Sea, where SARAL/AltiKa records low (≤0.5 m) SLAs while data model shows vice versa (≥0.8 m). The differences are shown in the dash line rings in Figure 4. The discrepancies between datasets are partly due to the discrepancies in the data processing, in which the SLAs from data model have been filtered, both in space and time, while the along-track SARAL/AltiKa SLAs only have been filtered in space. It is noted that the daily data model are derived from the assimilation of Jason-2 and tide gauge data. Since tide gauge data are available hourly at several stations along the coastline, and Jason-2 data are available every ~9 days along the satellite tracks, temporal and spatial interpolations were performed to derive the daily data product with 1/12° grid size. The data model has been derived from Kalman filter with a 3-dimensional multivariate model that spatially interpolates the datasets to smooth out forecast error. Smoothing algorithm also have been applied for temporal interpolation in order to moderate the past and future information about the SLA (Lellouche and Regnier, 2015). These create a smooth data model. Concerning the SLA from SARAL/AltiKa, the instantaneous SLAs were spatially smoothened using moving average filter with 8 km cut-off wavelength to match the grid size of the data model. Kriging method for spatial interpolation was applied to fill in the data gaps between the satellite tracks. In addition, inaccurate tidal correction which was based on the global GOT4.8 model has been applied on SARAL/AltiKa data. The importance of applying accurate tide model for coastal regions has been discussed in several studies (e.g. Andersen and Scharroo, 2011 and Idris et al., 2014b and Obligis et al., 2011). Results reported by Idris et al., (2014b) indicated that the global tide models (i.e. GOT 4.8, DTU10, FES 2012) can introduce errors as large as 70 cm over coastal regions. Therefore, more accurate tidal corrections are necessary. Due to differences in the data processing that create significant discrepancies between both datasets, further study is crucial to identify the methodology for enabling comparison between both datasets. Theoretically, south-west monsoon drives the ocean currents from the southern South China Sea to the northern parts. The ocean circulation leads to the increase in 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 experienced at the Gulf of Thailand and Banda Sea (cf. Liu et al., 2008). Based on the results in Figures 2 and 3, these theoretical patterns are hard to be visualized on both figures. In contrast, the results in Figures 4 and 5 match quite well to the theoretical ocean circulation pattern 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 (cf. Liu et al., 2008). This water movement leads to water increase at the east coast peninsular Malaysia, Gulf of Thailand, and the southern part of South China Sea.

4.2 Quantitative Analysis

In this section, correlation coefficient and RMS error are computed between the SLAs of SARAL/AltiKa and data model. Again, the values are computed for the three regional areas. Table 1 summaries the correlation coefficient and the RMS error over those regions. It is noted that one should not compare the value of correlation coefficient and

RMS error between different regions because the total number of samples used in the computation were different among regions. The result in Table 1 indicates that both datasets have a good agreement over the South China Sea suggesting that they are reliable over the region.

Table 1: RMSE and correlation based on regions

Region	Period (monsoon)	RMSE (cm)	Correlation
South China Sea	South-west	61	0.8
	North-east	40	0.9
Strait of Malacca	South-west	35	0.6
	North-east	26	0.6
Sulu Sea	South-west	66	0.4
	North-east	56	0.5

The correlation coefficients are high ($\geq$0.8) and the RMS errors are reasonably low ($\leq$61 cm). In contrast, the Sulu Sea records low correlation with $\leq$0.5 and high RMS error with $\geq$56 cm. This indicates that on average, the SARAL/AltiKa explains $\leq$50% of data model's total variance suggesting that both datasets are inconsistent to each other over the Sulu Sea. Over the Strait of Malacca, moderate agreement between both datasets was recorded with correlation coefficient of 0.6 and RMS error $\leq$35 cm. The reasons that maybe responsible to the discrepancy have been discussed in Section 4.1.

5. Conclusions and Recommendations

The results indicate that the SLAs from the new generation of SARAL/AltiKa satellite altimetry and the data model of the Coriolis Data Centre well-agreed, particularly over the South China Sea, where they have a high correlation and low RMS error. Contrary, different results are observed over the Sulu Sea and the Straits of Malacca, in which both datasets have shown inconsistency to each other. It can be concluded that the accuracy of both datasets varies depending on the coastal topography and characteristics of the ocean region itself. Less complicated region i.e. the South China Sea has better agreement with the data model, while complex regions i.e. the Sulu Sea and Strait of Malacca shows discrepancy among both datasets. Further research is currently undertaken to validate the retracked SLAs from SARAL/AltiKa with other in-situ data such as tide gauge to identify their consistency. Regional ocean tides model also should be considered when deriving SLAs over the regions to better resolve the tidal signals from the measurements.

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