Interpreting the sea level variability over Malaysian seas using multi-mission satellite altimeter

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Key words: Sea Level Rise, Sea Level Variability, Multi-mission Satellite Altimeter, Positioning and Measurement

SUMMARY

This is a summary paper based on interpreting the sea level variability over Malaysian Seas using Multi-mission Satellite Altimeter. As one of the contributions of climate change is rising sea levels, we should all be concerned since it is proven that global sea levels have been rising through the past century and are expected to rise at an accelerated rate throughout the 21st century. Eventually, rising sea levels will endanger many low-lying and unprotected coastal areas in many ways. This study is proposing a significant effort to interpret the sea level trend and its variability over Malaysian seas; Malacca Straits, South China Sea, Sulu Sea and Celebes Sea. It will present an approach to quantify the sea level trend based on a combination of multi-mission satellite altimeter from 1993 to 2015 (~ 23 years). There are 8 altimeter missions involved in this study, namely, Topex, Jason-1, Jason-2, ERS-1, ERS-2, ENVISAT, Cryosat-2, and Saral. Multi-mission satellite altimetry data will be derived and processed by using Radar Altimeter Database System (RADS).The daily solutions for sea level anomaly data are then combined for monthly average solutions for sea level quantification and sea level variability study. Afterwards, the time series of the sea level trend is quantified using robust fit regression analysis. The findings clearly show that the absolute sea level trend with respect to the Malaysian seas is rising with the rate of sea level varying and gradually increasing from east to west of Malaysia. Highly confident and correlation level of the 23-year measurement data with an astonishing root mean square difference permits the absolute sea level trend of the Malaysian seas to have risen at the significant acceleration of 4.22± 0.12 mm yr^{-1} and a rise of about 0.05m from 1993 to 2015. In conclusion, the information on sea level change and variability in this region are expected to be valuable for a wide variety of climate applications, coastal mitigation and to study environmental issues such as global warming in Malaysia.

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1. INTRODUCTION

The global sea level rise has been a primary outcome as a result of climate change. It has been rising through the past century and throughout the 21st century, and it is expected to rise at an accelerated rate (IPCC, 2014). Numerous earth scientists have conducted studies to search for current performance of sea level trends and magnitudes, which is important for efficient coastal protection planning. According to AVISO's Sea Level Research Team, from January 1993 to August 2017, global sea level has thus been estimated to rise at the rate of 3.29 mm yr^{-1} (AVISO, 2017). The major influence of global sea level rise in reality is the mass exchange of water with continents and steric effects, while regional circumstances mainly due to ocean circulation, El-Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (Lombard et al., 2005; Church e. al., 2008; Stammer et al., 2013; Luu et. al., 2015). Given that sea level is varying globally, regional estimates have become a necessity.

With the advancement of new technology, Satellite Altimeter is capable of measuring the absolute sea level from space, complimenting the lack of in-situ measurement, i.e. tide gauge instrument for monitoring sea level change, especially deep-ocean. Southeast Asia, particularly Malaysia, is epitomized by its unique geographical location that is bounded by two major oceans, Pacific and Indian Oceans, surrounded by a large population residing in the low-lying coastal areas. Therefore, accurate sea level information is mandatory for a proper coastal planning. This paper is aimed to interpret the sea level variability over Malaysian Seas using multi-mission satellite altimeter with the help of multi-mission satellite altimeters (Topex/Poseidon, Jason-1 and Jason-2). Saral, Envisat, ERS-1 and ERS-2 are also used, after being adjusted to a certain reference missions, in order to improve spatial resolution by combining all these missions together (Ablain et al., 2006; AVISO, 2016).

2. DATA AND METHODS

2.1 Principle of Satellite Altimeter

Since the 90s, satellite altimetry has operated with an excellent basic measurement accuracy range of 2 cm to 3 cm (Fu and Cazenave, 2001; CEOS, 2008). The main parameter is to measure range R from the satellite to the sea surface. A short pulse of microwave radiation with known power toward the sea surface is transmitted from the altimeter. This state-of-the art machine works in a way where the pulse interacts with the rough sea surface and part of the incident radiation reflects back to the altimeter.

To be practical for oceanographers, the range estimate must be transformed to a fixed coordinate system. Independent tracking systems are used to compute the satellite's three-dimensional position relative to an earth-fixed coordinate system. Consequently, profiles of sea surface height, or sea level, with respect to a reference ellipsoid is obtained by combining these two measurements (Fu and Cazenave, 2001; Din, 2014). Sea level derived or sea level anomaly (SLA) derived is used to compute the sea level trend. However, these progressive technological developments have limitations that must be taken into consideration to ensure the data acquired are precise. The sea level data are corrected for orbital altitude and altimeter range, which is altered in terms of instrument bias, sea state bias, ionospheric delay, dry and wet tropospheric corrections, solid earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias and inverse barometer correction (Naeiji et al., 2008).

By adopting a similar concept from Fu and Cazenave (2001) the corrected range $R_{observed}$ is converted to the sea surface height, h relative to the reference ellipsoid as:

$$h = H - R_{corrected} = H - (R_{obs} - \Delta R_{dry} - \Delta R_{wet} - \Delta R_{iono} - \Delta R_{ssb}) \quad (1)$$

Where
H : The height of the mass centre of the spacecraft above the reference ellipsoid
ΔR_{dry} : Dry tropospheric correction
ΔR_{wet} : Wet tropospheric correction
ΔR_{iono} : Ionospheric correction
ΔR_{ssb} : Sea-state bias correction

R_{obs} = c t/2 is the computed range from the travel time, t, observed by the on-board ultra-stable oscillator (USO), and c is the speed of the radar pulse neglecting refraction (approximate 3 x 108 m/s).

The actual obtained sea surface height, h, is not sufficient for oceanographic applications because it is a superposition of geophysical signals. Corrections for geophysical effects are implement as Rcorrected. All corrections are assumed as sea surface height corrections then. For instance, ΔRwet = – Δhwet, etc. Normally, for sea surface height variation studies, it is more appropriate to refer to the sea surface height to the mean sea surface (MSS) rather than to the geoid surface, thus forming the sea level anomaly, hsla, written as:

$$h_{sla} = H - R_{obs} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{ssb} - h_{MSS} - h_{tides} - h_{atm} \quad (2)$$

where,

H_{sla} : Sea level anomaly
h_{geoid} : Geoid correction
h_{tides} : Tides correction
h_{atm} : Dynamic atmospheric correction

Subtracting the MSS conveniently eliminates the dynamic sea surface height temporal mean variations and forms sea level anomaly that, in principle, have zero mean. When eliminating the temporal mean, the temporal mean of the corrections is eliminated and only the time variable component of the corrections is then a concern (Andersen and Scharroo, 2011).

2.2 Multi-mission Altimetry Data Processing

Eight (8) satellite altimeter missions are employed in this study: TOPEX, Jason-1, Jason-2, ERS-1, ERS-2, ENVISAT, CryoSat-2 and SARAL are utilized for the extraction of sea level anomaly data. The time period covered of altimetry data in this study is from January 1993 to December 2015. Details regarding the altimetry data of this study are described in Table 1.

Table 1. Altimetry data selected for deriving sea level anomaly

Satellite	Phase	Sponsor	Period	Cycle
TOPEX	A, B	NASA/Cnes	Jan 1993 - Jul 2002	11 - 363
Jason-1	A, B	NASA/Cnes	Jan 2002 - Jun 2013	1 - 425
Jason-2	A	NASA/Cnes	Jul 2008 - Dec 2015	0 - 276
ERS-1	C, D, E, F, G	ESA	Jan 1993 - Jun 1996	91 - 156
ERS-2	A	ESA	Apr 1995 - Jul 2011	0 - 169
ENVISAT	B, C	ESA	May 2002 -Apr 2012	6 - 113
CryoSat-2	A	ESA	Jul 2010 - Dec 2015	4 - 77
SARAL	A	ESA	Mac 2013 - Dec 2015	1 - 31

RADS performs as processing software for altimetry data and enables the user to define the most suitable corrections to be applied to the data (Din, 2014). The altimeter corrections and bias removal step in RADS data processing are carried out by applying specific models for each satellite altimeter mission. The sea level data are corrected for instrument, sea state bias, ionospheric delay, dry and wet tropospheric corrections, solid earth and ocean tides, ocean tide loading, pole tide electromagnetic bias and inverse barometer corrections before retrieving sea level anomaly data. Fig 1 shows the overview of regarding altimetry data processing in RADS.

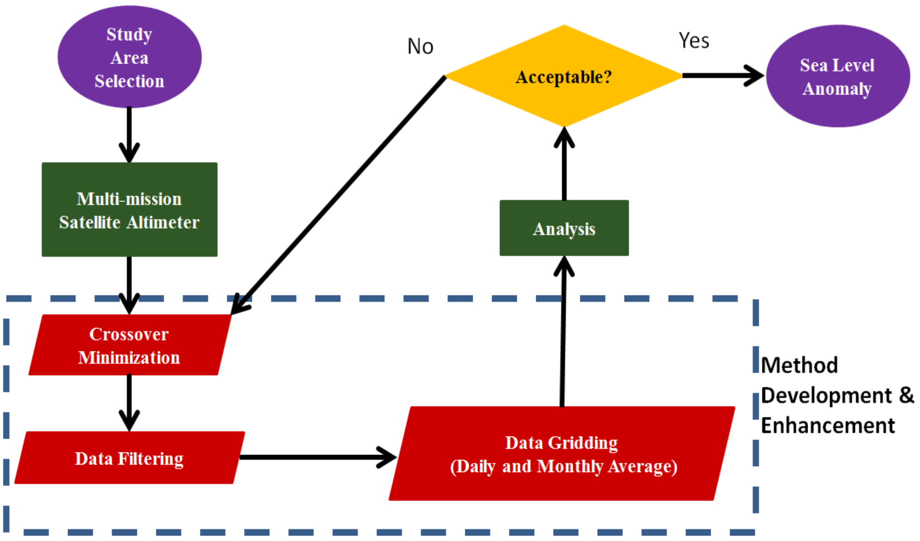

Fig 1. Overview of altimetry data processing in RADS (Din, 2014)

The subsequent step is then to perform crossover adjustments which is a useful approach to correct errors and refine multi-mission satellite altimeter observations. Orbital errors and the discrepancy of the satellite's orbit frame limits the accuracy of the data, therefore the sea surface heights (SSH) from different satellite missions need to be adjusted to a "standard" surface. The minimization was achieved with the orbit of the NASA-class satellites held fixed and those of the ESA-Class satellites adjusted given that NASA-class satellites surpass the accuracy of the orbits and measurements of the ESA-class satellites (Trisirisatayawong et al., 2011; Din, 2014).

Then, the daily altimetry data from NASA-class and ESA-class are filtered and gridded to sea level anomaly bins of certain size using Gaussian weighting function which recognize the points close to the centre considered to be the true value and points far from the centre to be relatively irrelevant. Essentially, the application of distance-weighting function is to obtain meaningful value for grid points located between tracks.

The daily solutions for sea level anomalies are then combined with the monthly average solutions. This is to standardize the final monthly altimeter solution with the monthly tide gauge solution while improving the correlation between monthly solutions of altimetry and tidal data.

2.3 Robust Fit Regression for Sea Level Analysis

The time series of the sea level trend in this study is quantified by using robust fit regression analysis in order to deal with solution determination and outlier detection. Iteratively Re-weighted Least Squares (IRLS) technique is a linear trend that is fitted to the annual sea level time series on each station (Holland and Welsch, 1977). Weights of measurements are adjusted accordingly depending on the deviations from the trend line. The trend line is then re-fitted and it is repeated until the solution converges. The weights of the observations (w_i) are readjusted by the adopted bi-square weight function, whose relationship with normalised residuals, (u_i) can be written as (Holland and Welsch, 1977):

$$w_i = \begin{cases} \left(1 - (u_i)^2\right)^2 & |u_i| < 1 \\ 0 & |u_i| \geq 1 \end{cases} \tag{3}$$

where,

$$u_i = \frac{r_i}{K.S.\sqrt{1 - h_i}}$$

r_i : Residuals,
h_i : Leverage,
S : Mean absolute deviation divided by a factor 0.6745 to make it an unbiased estimator of standard deviation
K : A tuning constant whose default value of 4.685 provides for 95% asymptotic efficiency as the ordinary least squares assuming Gaussian distribution

Observations that are assigned zero weights in any iteration are declared as outliers and eliminated from further computation (Holland and Welsch, 1977; Din, 2014).

3. RESULTS

3.1 Altimetry Data Verification

Data verification between monthly altimetry tidal solution of SLAs is emphasized on the time series pattern and the correlation analysis. Daily altimetry solutions from RADS are averaged into monthly solution as well as tidal solution to monthly tide gauge solution. The pattern and correlation of both measurements are evaluated over the same period for every location in order to produce comparable results as displayed in Fig. 2 (Peninsular Malaysia) and 3 (Sabah and Sarawak), starting from 1st January 1993 and continuing to 31st December 2015. Eight tide gauges fronting the South China Sea are benchmarked with the nearby altimeter track to the tide gauge location.

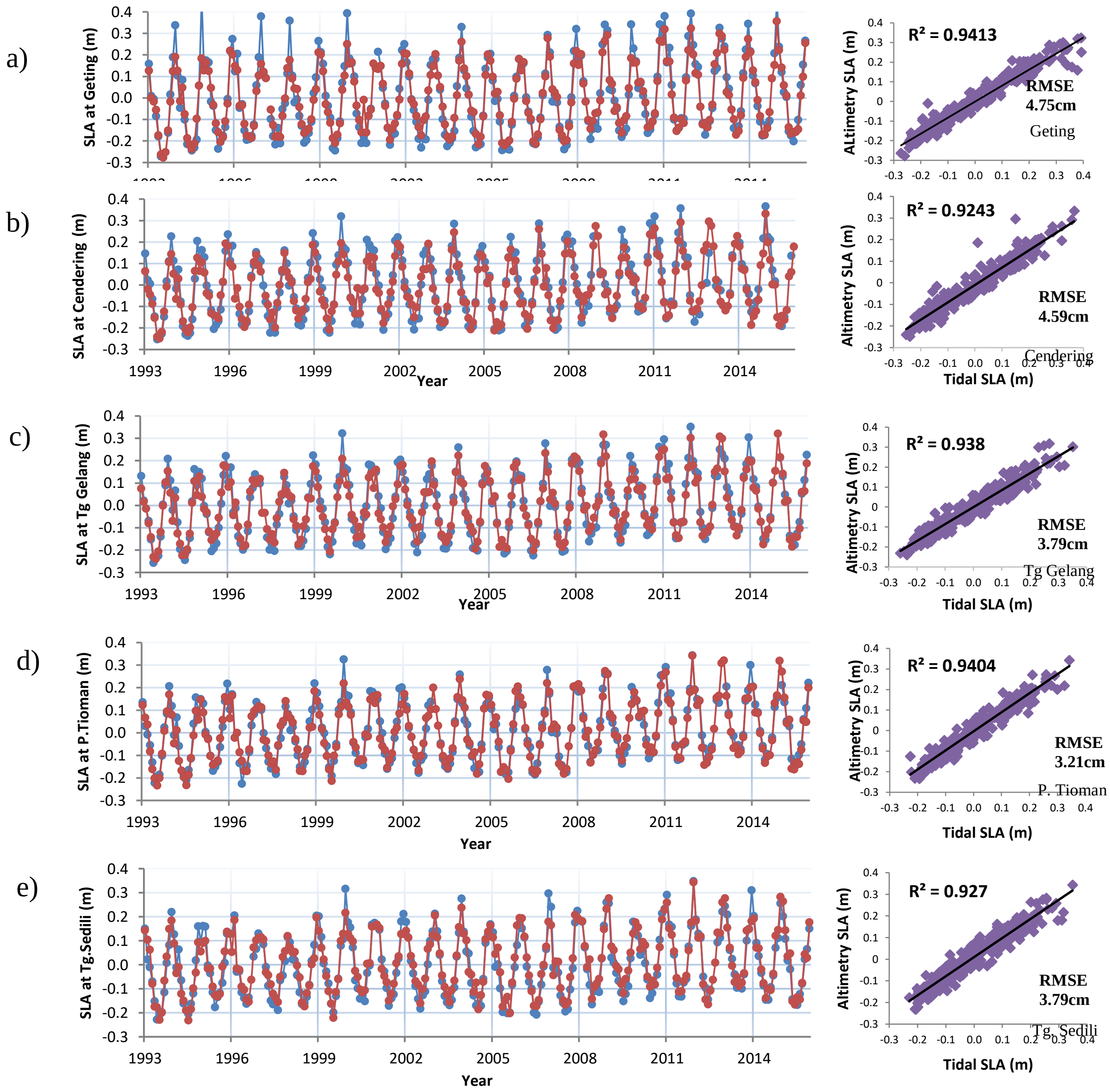

Fig 2. Time series pattern of tide gauge monthly-average (blue) and from altimetry (red) between altimetry and tidal data at Geting (a), Cendering (b), Tg. Gelang (c), P. Tioman (d), Tg Sedili (e)

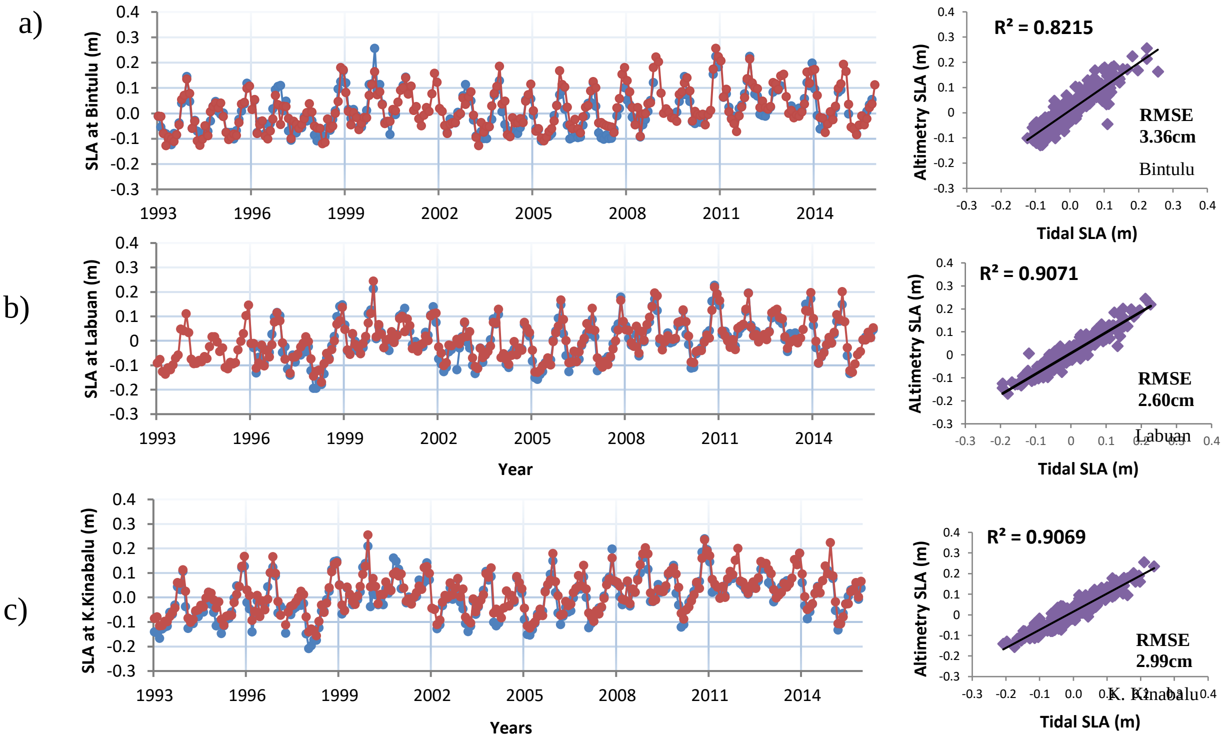

Fig 3. Comparison of time series pattern of tide gauge monthly-average (blue) and those from altimetry (red) between altimetry and tidal data at Bintulu (a), Labuan (b), K. Kinabalu (c) of Sabah and Sarawak

Based on Figs. 2 and 3, similar pattern of all graphs indicate a good agreement between satellite altimeter data and tide gauge data. A fall in sea level from late 2015 to 2016 is obvious in every time series pattern, signifying the strong impact of El Niño that occurred in 2015. The effect of La Niña can also be seen in the time series during the period from 1999 to 2000. All tidal data achieves a significant root mean square (RMS) difference when compared to altimetry data that ranges from 2.60cm to 4.75cm. The highest RMS difference obtained is from Geting tide gauge station, which is 4.75cm, whereas Labuan tide gauge station got the lowest RMS difference (2.60cm). R^2 value of all tide gauge stations show a confidence result of the correlation analysis that is ranged from 0.9243 to 0.9413. The summary of R^2 and RMS difference at each station is displayed in Table 2.

Table 2. R^2 and RMS difference value

Stations	R^2	RMS difference (cm)
Geting	0.9413	4.75
Cendering	0.9243	4.59
Tg. Gelang	0.9380	3.79
P. Tioman	0.9404	3.21
Tg. Sedili	0.9270	3.79
Bintulu	0.8215	3.36
Labuan	0.9071	2.60
K. Kinabalu	0.9069	2.99

3.2 Analysis and Interpretation of Sea Level Rate using Robust Fit Regression

The absolute sea level trend is clearly rising and varying from place to place over the Malaysian seas as displayed in Fig 4. The rate of sea level varies and gradually increases from east to west of Peninsular Malaysia. Meanwhile, for Sabah and Sarawak, the Sulu and Celebes Seas have a mixed tide prevailing semidiurnal characteristic and have a higher absolute sea level rise than other locations. This may be because the Sulu Sea is an enclosed sea as it is isolated from the surrounding waters by a chain of islands (Din, 2014; Hamid *et al*., 2016).

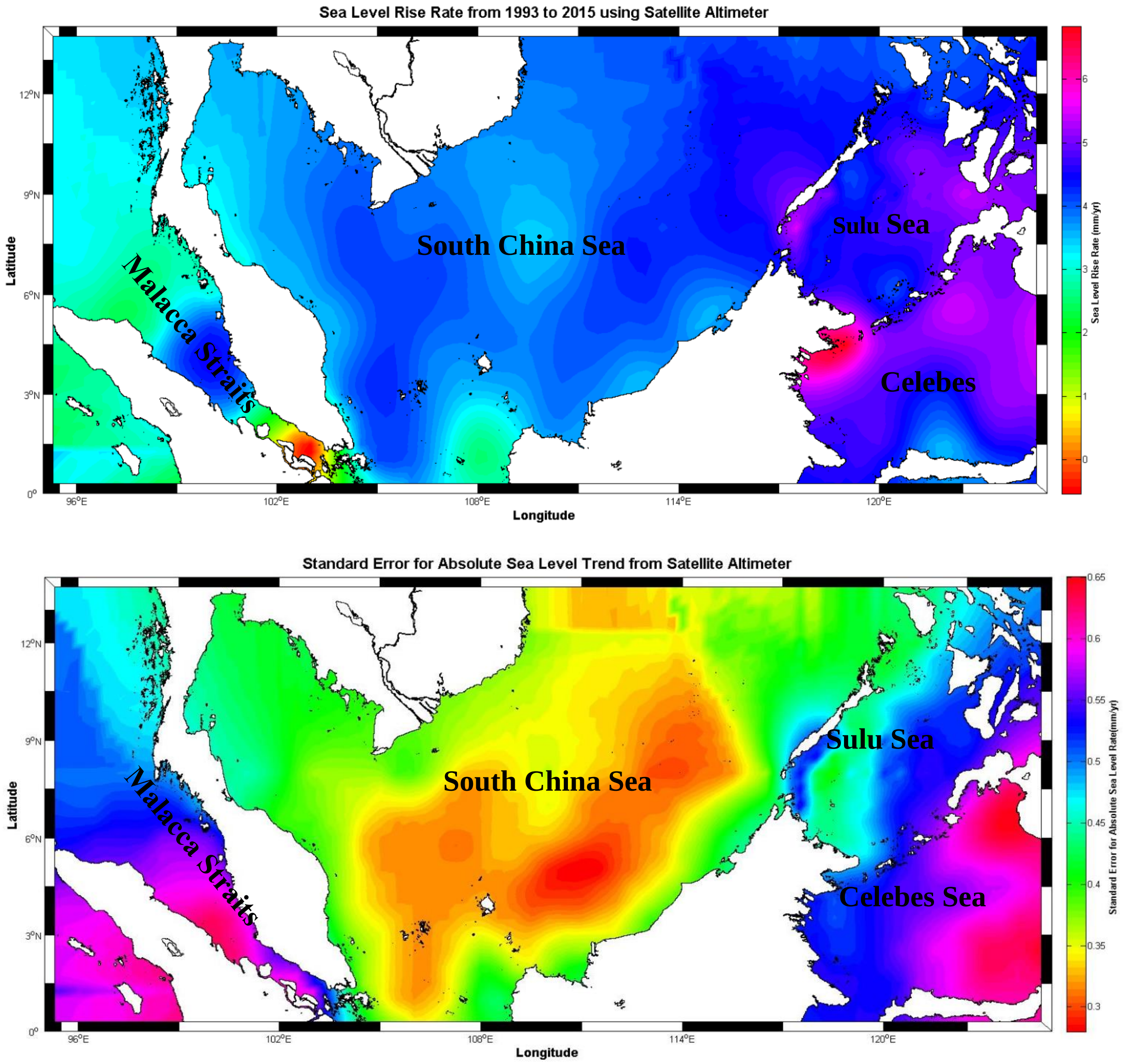

Fig. 4. Map of absolute sea level trend (upper) and its standard error (lower) over the Malaysian Seas

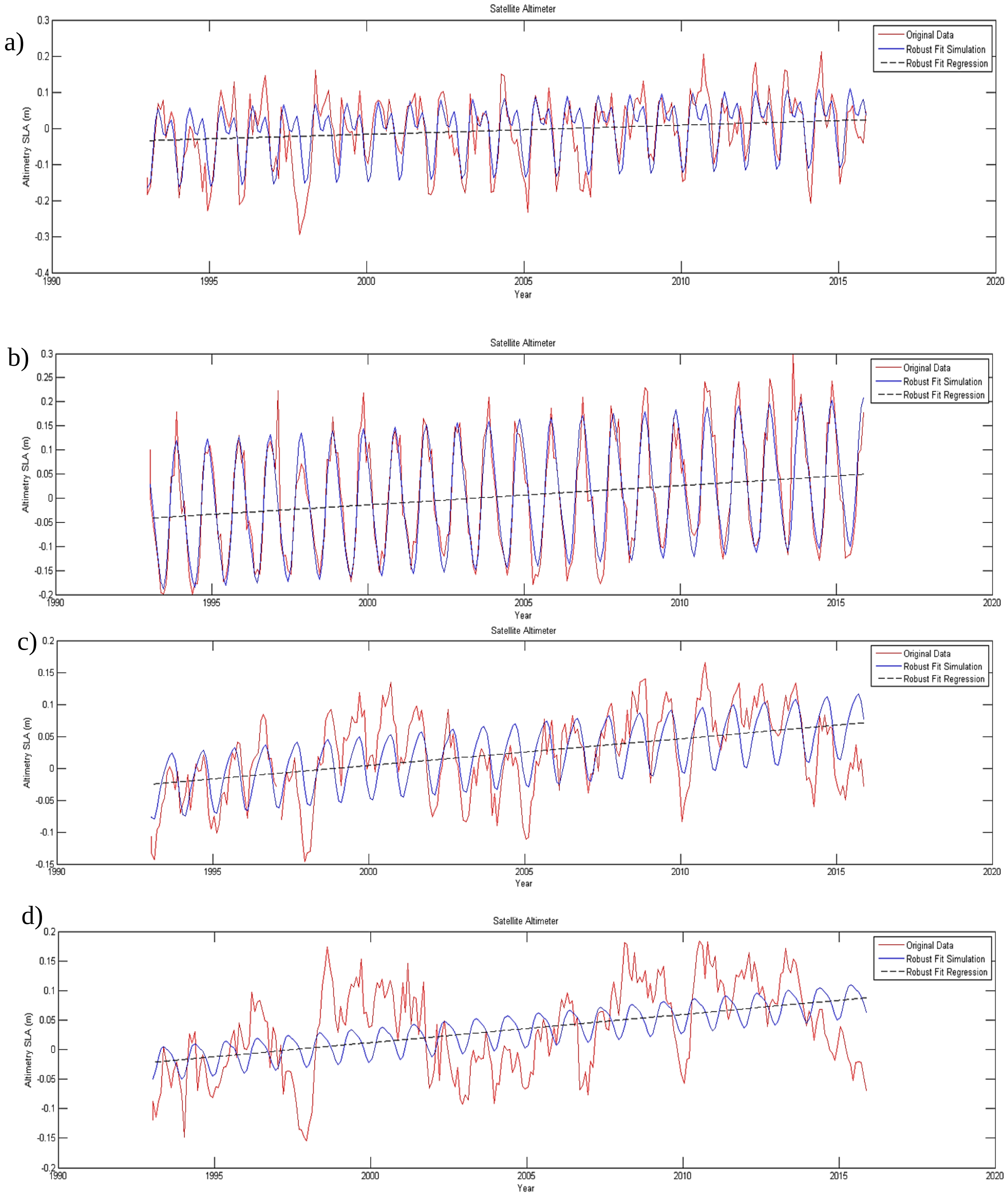

Fig. 5 Absolute sea level trend time series analysis of Malacca Straits (a), South China Sea (b), Sulu Sea (c) and Celebes Sea (d)

Fig. 5 represents the robust fit data graph of Malacca Strait, South China Sea, Sulu Sea and Celebes Sea. Irregular patterns are noticeable in Fig. 5(a) as tides or water flows mainly enter from side of the strait that is driven by the geometrical changes from the north-west to south-east and the tiny islands at the south-east end (Akdag, 1996). Malacca Straits is shallow and has rather narrows waters, with the result that the long term tidal pattern seems irregular. El-Niño and La-Niña affected the 1997 to 1998 sea level as sea level drops below normal values in late 1997 (El-Niño) and overshoots at the end of 1998 (La-Niña) (Din, 2014). Whilst the South China Sea is a typical marginal sea characterized with a deep basin, shelf break, and shallow shelf (Choi *et al*., 2013), the South China Sea is not affected by these events. This may be because the Sulu and Celebes are semi-closed seas. Late in 2015, El-Niño once again hit the Malaysia region. It is visible in Fig. 5 when a sudden drop in late 2015 occurred at most Malaysian seas. This circumstance would affect the sea level of this region where the sea level is decreased compared to the previous sea level.

From Fig. 6, it is apparent that Tawau has a higher sea level rate as represented by the colour red in this area. However, it is discovered that in this area of concern, there is a less satellite track as compared to other locations as illustrated in Figure 22.

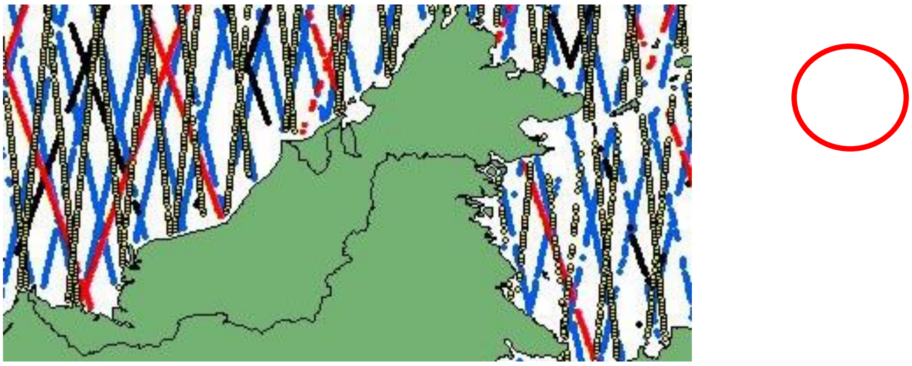

Fig. 6. Satellite track of Cryosat-2 (yellow), Jason-1 (red), Jason-2 (black), and Saral (blue) while area concerned (Tawau) is in the red circle.

Tawau tide gauge has been utilized to further investigate the behaviour of this area as shown in Fig. 7. It should be noted that there is a large number of data gaps and outliers in the Tawau tidal data. Tawau tide gauge and by satellite altimeter time series analysis graph revealed by Fig. 8 indicates an above average sea level rate, which is 5.36 ± 0.59mm yr^{-1} and 6.99 ± 0.52mm yr^{-1}, respectively**.** This might be because the Celebes Sea is accentuated by very steeply sloping margins, with water depths increasing rapidly from very narrow shelves. Thus, the depth of Celebes can exceed 5700m for the deepest basin while most of the floor of the Celebes Sea lies at water depths between 4500m to 5500m (Lewis, 1991). When the Celebes Sea water is accumulated in an enclosed area in addition to deep water basin, the rise in sea level around this vicinity may differ from other areas. Monsoon season can also be one of the reasons for the rise of sea level here since the highest increase in rainfall was up to 200mm recorded in south-east Sabah (MMD, 2009).

Fig. 7. Tawau tide gauge station (as indicated by green arrow) in eastern Malaysia (Google Map, 2017)

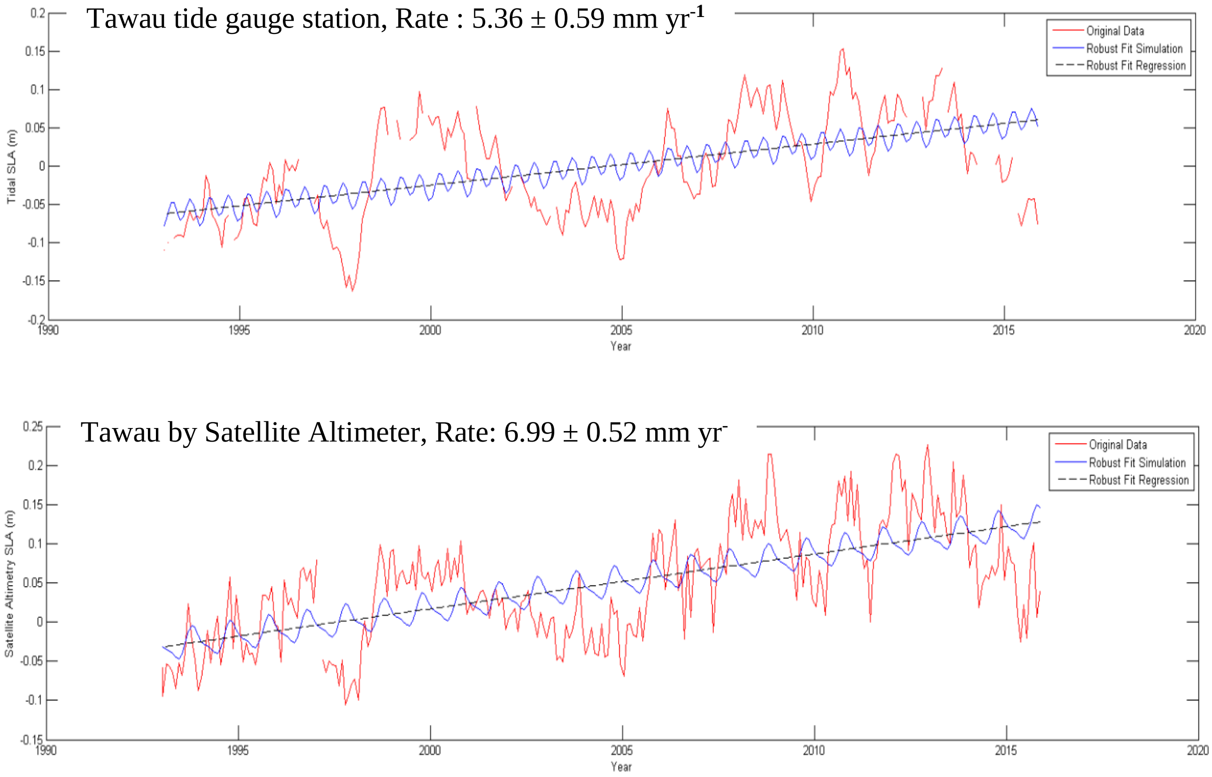

Fig. 8. Absolute sea level trend time series analysis of Tawau tide gauge station (upper) and by satellite altimeter (lower)

The sea level at Malacca Straits has the lowest rate of absolute sea level trend that ranges from 1.42 ± 0.57mm yr^{-1} to 4.45 ± 0.59mm yr^{-1} and with an average of 3.27 ± 0.12mm yr^{-1}. Besides the fact that the depth and shape of the Malacca Straits is shallow and narrow, the short term circulation dynamics seem to not average out over this area for the reason that the mean sea level has a somewhat disturbed annual cycle with a lot of higher harmonics (Din *et al.*, 2012). The South China Sea absolute sea level trend settles at a rate of 2.52 ± 0.32mm yr^{-1} to 4.38 ± 0.32mm yr^{-1} while the average rate is 3.88 ± 0.05 mm yr^{-1}. The presence of many straits and channels further forms a complex topography of South China Sea (Choi *et al*, 2013) which has mixed tide prevailing diurnal characteristic.

Sulu and Celebes Seas, however, have a higher absolute sea level trend compared to Malacca Straits and South China Sea, with the mean absolute rate of 4.77 ± 0.14mm yr^{-1} and 4.95 ± 0.15mm yr^{-1}, respectively. The Sulu Sea is an enclosed sea, isolated from the surrounding by a chain of islands (Wang *et al.*, 2006; Din, 2014, Hamid *et al.*, 2016). This may explain the significantly high sea level rates of Sulu and Celebes seas compared to other locations. The effect of El-Niño on the absolute sea level was noticeable when the sea level began to fall abnormally in late 1997 and reverted back to normal after 1998 for both areas.

Table 3 Summary of the absolute sea level rate over the Malaysian seas

Group	Sea Level Rate (mm yr^{-1})
Malacca Straits	3.27 ± 0.12
South China Sea	3.88 ± 0.05
Sulu Sea	4.77 ± 0.14
Celebes Sea	4.95 ± 0.15
Mean	**4.22 ± 0.12**

Table 3 summarizes the output from the robust fit graph as illustrated from Fig. 8. A change in uncertain climate in Malaysia creates the need for ongoing studies, especially its impact on Malaysian sea level rise level. It can be presumed that there is a correlation from both outputs of time series analysis and rate of sea. It can be concluded that the sea level rise for the Malaysian seas from 1993 to 2015 has been accelerated at the rate of 4.22 ± 0.12mm yr^{-1}.

3.3 Analysis and Interpretation of Sea Level Magnitude from 1993 to 2015

The magnitude of sea level over Malaysian seas has exceeded about 5cm from 1993 to 2015, ranging from -17.7cm to 16.3cm. From Fig. 9, all Malaysian seas encounter similar rise, which if not taken seriously, would severely affect the Malaysian coastal areas.

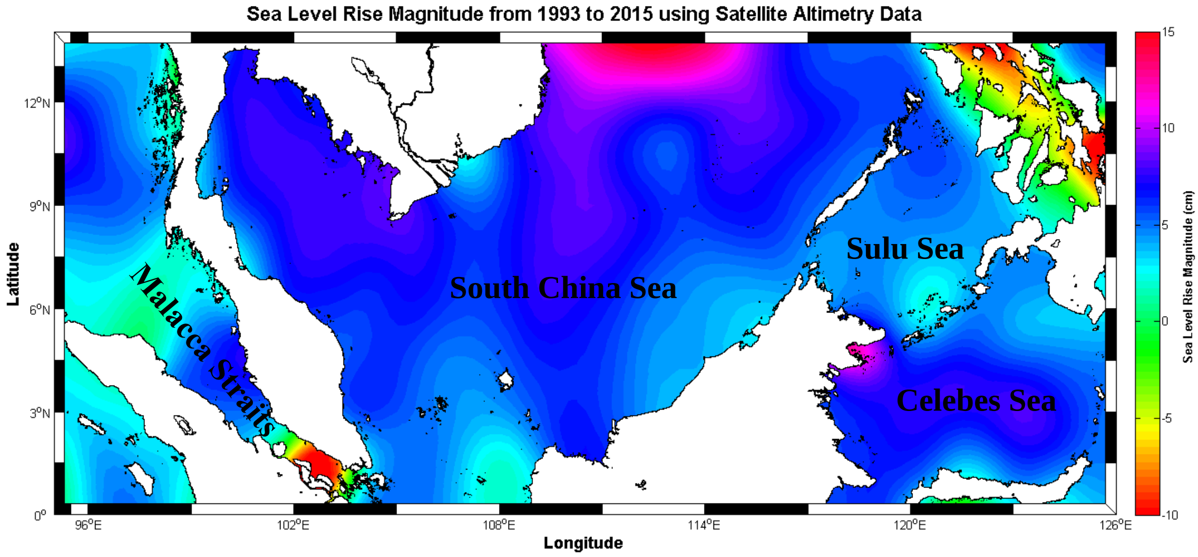

Fig. 9. Map of sea level rise over the Malaysian Seas

The magnitude reading is higher near the Tawau area as implied by the colour map in Fig. 9. As discussed in Section 3.2, we also comprehensively investigate the area with tide gauge that is available there and it indicates a very high sea level rate. The sea level rise is about 0.04m in this area; however, when calculated using altimetry data, the sea level rise can be up to 0.09m. Nevertheless, there is a quite abundant data gap and outliers in the Tawau tidal data. It seems to be higher compared to other places, which may be because the Celebes Sea consists of very narrow shelves that cause the water depths to increase rapidly, monsoon seasonal change besides El-Niño and La-Niña events.

On the other hand, orange colour shown in Fig. 9, which is at the Malacca Straits, is caused by the lack of satellite track that passes this area. Fig. 10 shows the satellite area that travel across this area. The affected area can be seen in the red circle. There are only a few satellite altimeters that actually travel in this area i.e. Saral and Cryosat-2. No NASA-class satellite altimeters are orbiting in this area and it is crucial for the so-called dual-crossover minimization analysis (Schrama, 1989; Trisirisatayawong, 2011) since the quality of the radial accuracy of the orbits of the NASA-class satellites surpasses the accuracy of the orbits of the ESA-class satellites. Meanwhile the ESA-class satellite altimeters only have ~35 days repeat cycle.

The Philippine archipelago in upper Sabah seems not affected by the Sulu Sea level rise by the range of sea level magnitude around -10cm to 0cm, which may due to the inconsistency of satellite altimeter near the coastal area (Din, 2014). There is also less altimetry data due to the limited NASA-class satellite altimeters around the Philippine archipelago and less data due to ESA-class satellite altimeters limited repeat cycle. Table 4 sums up the outcome of the sea level rise magnitude over Malaysian seas. Malaysian seas somewhat have the same increment in sea level from year 1993 to 2015 though each Malaysian seas have a different sea level rate.

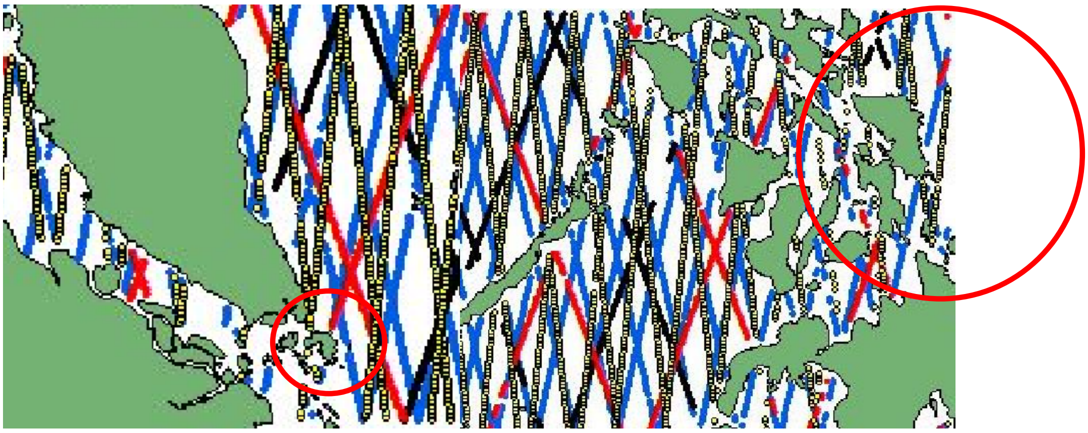

Fig. 10. Satellite track of Cryosat-2 (yellow), Jason-1 (red), Jason-2 (black), and Saral (blue) while the area of concern is in the red circle, which is around Malacca Straits (left) and Philippine archipelago (right).

Table 4 Summary of the sea level rise over the Malaysian seas

Group	Sea Level Rise (cm)
Malacca Straits	5.4
South China Sea	5.3
Sulu Sea	4.7
Celebes Sea	5.6
Mean	**5.3**

4. CONCLUSION

Malaysian seas have been accelerated at the rate of 3.27 ± 0.12 mm yr^{-1} to 4.95 ± 0.15 mm yr^{-1} for the chosen sub-areas with an overall mean of 4.22± 0.12mm yr^{-1} (solely based on satellite altimeter). This overall significant acceleration for the Malaysian seas appears to drop slightly compared to the sea level rate from Din (2014), which is from 1993 to 2011, where the rate of sea level rise is 4.56 ± 0.65 mm yr^{-1}. The sea level rate is also higher than the published values by AVISO's Sea Level Research Team (2016), where from 1993 to 2015, the global sea level rise is estimated at a rate of 3.39 mm yr^{-1} by using only a combination of Topex/Poseidon, Jason-1 and Jason-2 altimetry data. It can be clarified that strong El-Niño event that occurred in 2015 caused the rate of sea level over Malaysian seas to drop abruptly. Meanwhile, the Malaysian sea level rose approximately 5cm from 1993 to 2015.

While the information about sea level trends in this region is indeed valuable for the coastal management, town development, and flood mitigation, it is also important to be used in projecting the sea level rise for future regional climate. A coastal area with sea level rise projection can use this information for coastal adaptation. Mangrove creation etc. should be taken to limit the negative impact of sea level rise in Malaysia Therefore, this paper is recommended to those who want to learn more about satellite altimeters and sea level rise.

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