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Contemporary sea level rise rates around Malaysia: Altimeter data optimization for assessing coastal impact

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ABSTRACT

The increase of anthropogenic activities has triggered global sea level rise to threaten many low-lying and unprotected coastal areas. Without measures, global sea levels will continue to rise at an accelerating rate in the 21st century. This paper quantifies sea level trends around the Malaysian seas using measurements from multiple altimeter missions over 1993–2015. Sea level anomalies (SLAs) are determined using data from the Radar Altimeter Database System (RADS) covering 8 altimeter missions. We use an enhanced processing strategy to optimize sea surface heights from RADS for the derivation of SLAs, including filtering, data gridding and moving average. Tidal height measurements at eight tide gauge stations around Peninsular Malaysia and East Malaysia are used to assess SLAs from altimetry. Our assessment results in similar patterns of SLAs, high correlation coefficients (> 0.9) and small (few cm) root mean square differences (RMSE) between SLAs from altimetry and tide gauges over the same period. Sea level trends are determined by the robust fit regression analysis for the SLA time series. Our result shows that sea level rise trends around Malaysia range from $3.27 \pm 0.12\,\mathrm{mm\,yr^{-1}}$ off eastern Malaysia to $4.95 \pm 0.15\,\mathrm{mm\,yr^{-1}}$ west of Malaysia. Over 1993–2015, the mean rising rate around Malaysia is $4.22 \pm 0.12\,\mathrm{mm\,yr^{-1}}$, and the cumulative sea level rise is 0.05 m. This paper predicts the impact of such rising sea levels on environment, urban planning and climatology in the coastal areas of Malaysia.

1. Introduction

Society has been disturbed by the alarming climate change henceforth a consequence of this occurrence should be warned. Climate change initiated by the anthropogenic effects has led to various outcomes, primarily including the global sea level rise. Global sea levels have been rising through the past century and are projected to rise at an accelerated rate throughout the 21st century (IPCC, 2014). It has motivated an enthusiasm for earth scientists to search for already occurring accelerations and rising rates, which would be, if present, critical for appropriate coastal protection planning. AVISO's Sea Level Research Team conducts a study to investigate the Global Mean Sea Level (GMSL), demonstrates that from January 1993 to December 2015, the sea level has been rising at the rate of $3.37\,\mathrm{mm\,year^{-1}}$ (AVISO, 2016). The two major contributions of global mean sea level change are water mass exchange with continents and steric effects, modulated by regional to global circumstances, such as variations in ocean circulation, El-Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (Lombard et al., 2005; Church et al., 2008; Luu et al., 2015). Sea level rises due to climate change vary globally, thus demanding regional estimates. Such estimates could assist in a proper coastal planning and management, since most heavily populated coastal cities are especially vulnerable to inundation. As such, it is important to obtain local sea level estimates that are as accurate as possible. This study is driven by this need of highly accurate sea rising rates around Malaysia.

Measuring sea level change and understanding its causes have improved considerably in the recent years, significantly due to accessible in-situ and remote sensing data sets. Satellite altimeter measures the absolute sea level from space, compliments the deficiency of in-situ measurement, i.e. tide gauge instrument for monitoring sea level change, particularly for the deep ocean. Satellite altimetry can overcome the uneven geographical distributions of tide gauge installed in

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coastal areas (Mohamed, 2003; Din et al., 2015a,b; PSMSL, 2016). The Southeast Asian region, especially Malaysia, is exemplified by its unique geographical settings that are bounded by two major oceans: Pacific and Indian Oceans. Malaysia is surrounded by a large population inhabit low lands in coastal areas (Din et al., 2015a,b), efficient sea level measurement are necessary. The AVISO team has calculated the mean sea level rate using data from the TOPEX/POSEIDON series of satellites, including TOPEX/POSEIDON, Jason-1 and Jason-2. Saral, ENVISAT, ERS-1 and ERS-2 are also used by the team, 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). By implementing the same method like the one used by the AVISO team, for data from Radar Altimeter Database System (RADS), the absolute sea level from the satellite altimeter is acquired for sea level quantification around Malaysia. Though the principle of satellite altimeter is simple, the approach for estimating precise sea level measurements is actually can be very complex demanding an optimization in altimetry data processing. This paper is focused on optimizing our processing procedures for data from RADS to determine finest sea level trend and magnitude appropriate for Malaysian seas. Implications of such sea level trends will be presented.

2. Data and methods

2.1. Multi-mission altimetry data processing in RADS

Eight (8) satellite altimeter missions employ in this study; TOPEX, Jason-1, Jason-2, ERS-1, ERS-2, ENVISAT, CryoSat-2 and SARAL. The time span of altimetry data employed in this study is from January 1993 to December 2015. Details regarding the altimetry data used in this study are described in Table 1.

RADS performs as processing software for altimetry data to extract the sea level anomaly for this study which is a part of crucial procedure in order to achieve the finest sea level anomaly data. Hence, RADS provides user to able to define the most suitable corrections to be applied to the data (Naeije et al., 2000, 2008; Din et al., 2015a,b). Fig. 1 shows the outline of optimization of altimetry data processing in RADS employed in this study.

The altimeter corrections and bias removal step in RADS data processing are carried out by applying specific models on each satellite altimeter mission in RADS. The final corrections/models applied for multi-mission altimeter processing in RADS are shown in Table 2.

The afterwards step is to perform crossover adjustments. Crossover adjustment is a useful approach to reckon errors and refine multi-mission satellite altimeter observations. The sea surface heights (SSH) from different satellite missions are adjusted to a “standard” surface to reduce orbital errors and the discrepancy of the satellite’s orbit frame. The minimization of crossover differences was achieved by holding fixed the orbit of the NASA-class satellites, while adjusting those of the ESA-Class satellites. This then allows NASA-class satellites to control the accuracy of the orbits and measurements of the ESA-class satellites (Trisirisatayawong et al., 2011; Din et al., 2015a,b).

Then, the daily altimetry data from NASA-class and ESA-class are then filtered and gridded to sea level anomaly bins of certain size, using Gaussian weighting function in order to 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.

Table 1
Altimetry data selected for deriving altimetry data.

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

The altimetry data extracted in this study ranges between $0^\circ N \leq \text{Latitude} \geq 14^\circ N$ and $95^\circ E \leq \text{Longitude} \geq 126^\circ E$ over the Malaysian seas.

We further refine the set of data by applying a distance-weighted gridding in order to retain as much information as possible, while suppressing interfering grid points located between tracks. The purpose of the weighting function is to assign larger weights to data at the points close to the centre, while down-weighting data at the points far from the centre. The weighting function is based on the Gaussian distribution (Singh et al., 2004; Din et al., 2015a,b):

$$F_w(r) = e^{-\frac{r^2}{\sigma^2}} \tag{1}$$

where σ (sigma) is a parameter governing the smoothness of the filter result, and r (in the same unit as σ) is the distance between the data point and the grid point. Then the daily data from multi-mission satellite altimeter are filtered and gridded to sea level anomalies at bins using the Gaussian weighting function. By applying a distinct set of sigmas i.e. sigma 1.5, 1.0, 2.0, and 2.5, we enhance the altimetry data processing to improve the data accuracy and precision of SLA data, particularly for the sea level trend analysis.

Altimetry data are originally given along satellite ground tracks. For ease of use and compatibility with other datasets, such along-track data are interpolated onto a regular grid. Gridding involves both temporal and spatial weightings. In this paper, we gridded the daily NASA-class and ESA-class altimetry data are to form sea level anomalies over bins using the Gaussian weighting function. A bin is a square mesh with a block size. In this paper, we have experimented with block sizes of 0.125°, 0.25°, 0.5° and 1 to optimize our altimetry data processing for the best SLA estimates. Although gridding is not a correction process, it is crucial to all subsequent processing, enhancement, display, and interpretation.

For gridding, the inverse Distance Weighting (IDW) method is used. IDW uses along-track SLA values surrounding a prediction location to compute the SLA as

$$h(x) = \frac{\sum_{i=1}^{n} w_i(x, x_i) h_i}{\sum_{i=1}^{n} w_i(x, x_i)} \tag{2}$$

where the weight function is the inverted distance given by

$$w_i(x) = \frac{1}{d(x,)} \tag{3}$$

and h_i, x_i are along-track SLA and its location associated with the interpolated point (Shepard, 1968; Din et al., 2014). Eq. (3) shows that the weight of h_i increases with decreasing distance to the location of x, at the bin (centre). Those measured values closest to the prediction location will have more influence, which diminishes with distance.

We used the so-called dual-crossover minimization method to adjust the ESA-class sea surface heights (SSHs) from RADS using the NASA-class SSHs, based on differences of SSHs at orbital intersections (Schrama, 1989 & Trisirisatayawong et al., 2011). This step is performed after applying altimeter corrections and removing bias in RADS processing. Sufficient crossover information is necessary to estimate the smoothness (one cycle per orbital revolution) of orbit error function fitting thus, the area for the crossover minimization is often extended than the study area. As example, Jason-2 follows a repeat cycle of ten days designed to monitor ocean variations, they pass over the same points fairly frequently, but their ground tracks are some 315 km apart. Instead, ENVISAT only returns the same point on the globe for every 35 days (repeat cycle), but the utmost distance between two tracks at