Merged enisat and jason satellite altimeters using crossovers adjustment to determine sea level variability

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Abstract. It is considered that climate change has been increasing the global air temperature and rising sea level. Thus, the monitoring of sea level is necessary to mitigate the hazard risk. For estimating sea level change from various altimetric missions, attention must be taken to determine the bias of measurements between altimetric different missions. The aim of this study is to merge both of Jason series and Envisat satellite altimeters for estimating sea level variability around the Indonesian Seas. To create sea level time series, two adjustment methods are employed: tandem mission data and sea level anomaly differences at crossovers. The adjustment using tandem mission between Jason-1 and Jason-2 obtained a relative difference of 32.8 ± 5.4 mm. The adjustment method at crossovers is applied for combining Envisat and Jason series which is already intercalibrated. The mean crossovers differences between Envisat and reference missions are less than 2.5 cm. By using merged datasets from all missions, it is discovered that the trend in the Indonesian seas for a period of 10 years is 11.9 mm years⁻¹. The map of sea level trends from all satellites data for that period is performed in 1° x 1° regular grids.

1. Introduction

Sea level is an important indicator of global climate change due to global warming. The increasing rate of global temperatures can change the climate, which is affecting the life on land and water, as oceans respond to global warming, seawaters warm and expand, and thus sea level rises [1]. Sea level rise can be a serious problem for the future life, particularly in coastal areas. Low-lying coastal plains are vulnerable to inundation, suffering serious consequences of salt intrusion into aquifers and threatening coastal ecosystems [2][3]. According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), the projections of global mean sea level rise (GMSLR) were estimated to be up to 98 cm in 2100 [4]. Concerning this issue, it is urgent to make a plan for adapting the inevitable consequences of the sea level rise.

Satellite altimetry brought a revolution in the sea level study and it became the important tool to monitor sea level and ocean circulation. In the early 1990s, the precise satellite altimetry was begun by the launch of the TOPEX and Poseidon (T/P), the joint mission of NASA (National Aeronautics and Space Administration, USA) and CNES (Centre National d’Études Spatiales, France) in 1992. The main objective was to improve the knowledge of the global ocean circulation for the understanding of ocean’s rule in global climate changes. This mission was followed by Jason-1 in 2001, Jason-2 in 2008, and Jason-3 in 2016. These satellites provide precise and continuous datasets for sea level
studies with nearly global coverage and moderate spatiotemporal resolution. Meanwhile, the European Space Agency (ESA) built the satellite to observe the Earth, in particular, its ocean and atmosphere systems. ESA launched the European Remote-Sensing Satellite (ERS)-1 in 1991 and ERS-2 in 1995 [5]. The follower mission of them was Envisat (Environmental satellite) that was launched in 2002 [6].

There are two main differences of both satellites: (1) a cross-track separation in the equator, (2) a repeat cycle period that obtain the impact of spatial and temporal coverages. Jason satellites have a cross-track separation of 316 km and Envisat has 80 km a cross-track average in the equator. In a repeat orbit period, 10-day and 35-day are to Jason satellites and Envisat, respectively. The use of Jason satellites give moderate dense data measurements and can be gridded on 4° x 4° regular grids in equatorial areas, although these satellites provide a short period of ~10 days. Envisat provides high dense data measurements that can be gridded on 1° x 1° regular grids. However, the temporal resolution is longer than Jason satellites, it is 35 days.

Regarding those differences as mentioned above, its effect on the Indonesian seas is significant. The Indonesian seas are crossed the equatorial line on the middle of Indonesian region (Figure 1). The Indonesian seas are also located between the western Pacific Ocean (WPO) that has high sea level variability [7] and the eastern Indian Ocean (EIO). Due to the uniqueness of the Indonesian seas characteristics, the understanding of sea level is urgent. Therefore, the monitoring and determination of sea level variability using high precision and dense data measurements of satellite altimetry become urgent.

In order to obtain the sea level variability with precise in a spatial and temporal resolution, the objectives of this study are: (i) to merge both data of Jason satellites and Envisat using crossovers adjustment; (ii) to determine the sea level variability using a merged data altimeter.

Figure 1. Along track of Jason-1 and Jason-2 (in blue lines) and Envisat (in red lines)
2. Data and methods

2.1. Satellite altimetry dataset

The altimeter data in this study were extracted from the Radar Altimeter Database System (RADS) [8]. The data cover a period of 10 years (2002–2012) due to the overlapping between Envisat’s periods (2002–2012) and Jason series (2001–2009 for Jason-1 and 2008–present for Jason-2). In this study, the coverage area is around the Indonesian seas within coordinates: the latitude range 20°N – 20°S and longitude range 90°E – 150°E.

In the satellite altimetry, the sort pulse of microwave radiation is transmitted from the onboard radar altimeter toward the sea surface point at nadir and is partly returned back to the satellite, and then the round-trip travel time is being measured by the ultra-stable oscillator [9]. Range and geophysical corrections have to be applied to observe data before being used to estimate the sea surface height. For sea level studies, sea level anomaly (SLA) is often used to refer the sea surface height to the mean sea surface height rather than geoid due to the removal of the temporal mean of dynamic sea surface [10]. The SLA is determined as the following equation:

\[ h_{SLA} = H - R_{OBS} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{SSB} - h_{DAC} - h_{tides} - h_{mss} \] (1)

Wherein, \( H \) is a satellite height above a reference ellipsoid determined by the precise satellite orbit determination, \( R_{OBS} \) is an observation range corrected by instrument errors, \( \Delta h_{dry} \) & \( \Delta h_{wet} \) are dry and wet tropospheric corrections, respectively, \( \Delta h_{iono} \) is ionospheric correction, \( \Delta h_{SSB} \) is sea state bias (SSB) correction and \( h_{DAC} \) refers to dynamic atmospheric correction (DAC), \( h_{tides} \) are tide corrections including ocean tide, load tide, solid earth tide and pole tide, and \( h_{mss} \) refers to the mean sea surface model.

The parameters used to compute SLA are ERA-Interim for dry and wet tropospheric corrections, ionospheric correction applied smoothed dual frequency for Jason-1, Jason-2, and Envisat (only for cycles 6 – 65), and JPL GIM for Envisat’s cycles 66 – 112. For SSB, Jason-1 and Jason-2 used a Tran2012 model and Envisat used a hybrid model. MOG2D and GOT 4.10 were used in all satellites for DAC and tides model, respectively. The CNES-CLS 2011 was used for mean sea surface model [11]. SLA around the Indonesian seas was estimated.

In order to obtain the stability and continuity of the sea level time series data, the inter-satellite SLAs are calibrated during the tandem phases when the pair of satellites sampled the same ground track within one minute of each other. The relative difference between Jason-1 and Jason-2 (\( J2, J1 \)) was determined by the average of the differences from all tandem phase of both, as shown as follows:

\[ SLA_{Corrected}(J2) = SLA(J2) - bias(J2, J1) \] (2)

2.2. Crossovers adjustment with respect to reference-missions

To obtain SLA time series from merged multi-satellite missions, the satellite has to be intercalibrated. Jason-1 and Jason-2 missions are used as a reference for the Envisat mission. The intercalibrated SLA time series for the former missions was obtained through using the dual-satellite crossovers adjustment approach (for details, please see [12][13][14]), between Envisat with respect to the reference missions (Jason-1 and Jason-2). The mean values of these crossover adjustments were used to calibrate the non-reference altimetric missions. Due to the difference of the repeat cycle of Jason series (10 days) and Envisat (35 days), the combination of both should be close to the repeat cycle of the reference missions, i.e. around 10 days. Envisat has been “re-arranged” into the new 10-day cycles based on the Jason series cycles using pseudo-cycles. By this way, a merged multi-mission time series was built, for each 10-day period, by considering the weighted mean of all observations for that period, from all satellites. SLA computation used a weighted SLA as a function of the cosine of latitude. SLA time
series have been decomposed into seasonal, interannual trend, and residual by Seasonal Trend decomposition based on LOESS (STL) [15]. The trend of SLA was computed by the Original Least Square (OLS) fitting. With regard to the calculation of SLA time series for the missions, a mean SLA grid of 1° x 1° (latitude and longitude) regular grid was performed.

3. Results and discussions
This section shows the results of the SLA time series using the data of all missions from 2002 to 2012. Figure 2 shows SLA estimated from Jason-1 and Jason-2. There is a relative difference between both satellites due to several corrections. It is important to correct the altimeter data for relative measurement differences. For combining the time series from Jason-1 and Jason-2, these missions are linked together during the tandem phase. In this case, tandem cycles for Jason-1 and Jason-2 are cycles 240 - 259 and 001 – 020, respectively. By computing the average difference for the 20 cycles of both, a relative difference of 32.8 ± 5.4 mm was obtained. The result is shown in Figure 3. Despite the fact that the relative difference is slightly big, the pattern of difference seems homogeneous. It is due to the identicality of both instruments [16]. Figure 4 presents the intercalibrated SLA time series from Jason-1 and Jason-2. It shows the continuity of the SLA time series.

![Figure 2](image2.png)

**Figure 2.** Uncalibrated SLA time series of Jason-1 and Jason-2

![Figure 3](image3.png)

**Figure 3.** Mean SLA (in mm) for the Jason-1 and Jason-2 tandem mission periods
Figure 4. Intercalibrated SLA time series of Jason-1 and Jason-2

As shown in Figure 5, there are two of SLA time series from Envisat which is derived by the 35-day repeat cycle and Jason-1 and Jason-2 which are derived using the 10-day repeat cycle. To combine those missions, Jason-1 and Jason-2 (already calibrated) are used as a reference for Envisat. Then, the crossovers adjustment is applied. Figure 6 shows the mean values of crossovers differences between the reference and Envisat missions. The maximum value of the differences is less than 2.5 cm. After the corrections (from the mean crossover differences) were applied to Envisat, the merged SLA time series from all missions was obtained, as shown in Figure 7.

Figure 8 illustrates intercalibrated SLA time series around the Indonesian seas from a combination of all missions between 2002 and 2012. The original signal has been filtered by eliminating the 59-day signal and decomposed into interannual trend using STL. The significant trend of 11.9 mm year\(^{-1}\) is computed by the OLS fitting of the interannual signal. It is higher than the GMSLR that is raised up to 3.4 mm year\(^{-1}\) [17]. Figure 9 shows the geographical pattern of SLA trend for a period of 2002 – 2012. The map was computed on the 1° x 1° regular grid from the mean cycle values of SLA time series. From the map, the trend is not rising uniformly due to spatial variation of the ocean warming. It was shown by light blue colour (it means a low negative trend) to dark red (it means a high positive trend). In this period, the light blue was located around the EIO, and the dark red was in WPO. The high positive trend mostly occurs in the north-east of the Indonesian seas or the WPO. It can be understood that the area is strongly influenced by El Niño Southern Oscillation (ENSO) phenomena [7]. According to Hasson A et al. (2014) [18], a phase of ENSO, it is called La Nina, was appeared in mid-2010 to mid-2012. During the event, La Nina increases the sea level on the Indonesian seas. However, La Nina also drops the sea level at a global level [19]. The impact of La Nina has been seen in the map (Figure 9); the maximum trend value is about 20 mm year\(^{-1}\).
Figure 5. SLA time series for Envisat (green) which has 35-day repeat cycle and Intercalibrated of Jason-1 (red) and Jason-2 (blue) which has a 10-day repeat period

Figure 6. Mean crossovers differences (in cm) for Envisat relative to reference mission (Jason-1 and Jason-2)

Figure 7. Merged SLA time series: Jason-1, Jason-2, and Envisat
Figure 8. SLA (in mm) time series for a period 10 years derived using all missions

Figure 9. Map of SLA time series of mean cycle values $1^\circ \times 1^\circ$ grid derived using all satellites (2002 – 2012)

4. Conclusions
In this study, the merged SLA between Envisat and Jason series has been performed for the Indonesian seas in a period of 10 years. The linear trend of sea level in these areas is 11.9 mm year$^{-1}$ for the period between 2002 and 2012. The result shows that ENSO is an important component of global climate change characterized by the appearance of the warmer surface along the tropical Pacific. It can change the precipitation, temperature, and water vapor. Furthermore, it is known that the trend in this region is higher than in the other regions of the globe due to the influence of ENSO,
particularly the La Nina effect in this period. From the interannual variability, the strongest La Nina was in 2011. The map of sea level rise has been derived using a finer 1° x 1° regular grid. The highest rate is located in the north-east of the Indonesian seas or WPO.

The sea level trend has been deduced using only three satellite altimetry data measurements. For the future work, in order to estimate the long period’s sea level trend in the Indonesian seas, it is necessary to combine the multi missions, e.g. TOPEX/Poseidon, ERS-1 an ERS-2, Jason-3, and SARAL.

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