Seasonal and Interannual of Sea Level Variability in the Indonesian Seas using Satellite Altimetry

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Abstract. Sea-level rise is an extreme issue for the world that has been scientifically proven. That is why sea-level variability presents a significant role in ocean and air interactions. This study was directed to get seasonal and interannual variability in the Indonesian Seas. The research area is in the Indonesian Seas with coordinates boundaries: of 20°N - 20°S latitudes and 90°E - 150°E longitudes. The data were obtained from the Radar Altimeter Database System (RADS) for Jason Series altimetry (2008 to 2018). The analysis has been performed by taking the correlation between detrended Sea Level Anomaly (SLA) and El Nino Southern Oscillation (ENSO). The outcome showed that the seasonal and interannual sea level anomaly in Indonesian seas fluctuates. Seasonal varieties of Sea Level Anomaly in the Timor Sea, Northern Java Sea, and the Halmahera Sea were low. The high seasonal changes occurred in the Flores Sea, the Natuna Sea, and the Karimata Strait. Besides, the interannual variation of SLA fluctuated from 2009 to 2018. The impact of ENSO on the variance of SLA was strong, with a coefficient correlation of -0.66. In the most recent ten years, the SLA in the Indonesian Seas demonstrated a lowering trend.

1. Introduction
Indonesian Seas territory is located between the Indian Ocean and the Pacific Ocean. There is Indonesian Throughflow (ITF), where the water from the Pacific Ocean meets the Indian Ocean. It is one of the key elements in worldwide circulation, warmth, and freshwater. ITF is thought to assume the main role in the seasonal variations of the general mid-latitude circulation in the Pacific and Indian Ocean [1].

Sea level rise (SLR) becomes an extreme issue for the world that has been scientifically proven [2]. The main variables contributing to an increment in sea level rise are warm expansion. In the period 1993 - 2010, the variable rate of warm expansion added to expanding sea air mass by 30% with an amount of 1 ± 0.3 mm per year [3]. Another contribution to the expansion in the mass of seawater is the melting of ice sheets or non-polar glacialis, but it cannot be ascertained the amount of increase because not all glacial regions on earth can be produced. These factors were the sea-level rise of 6 cm in the nineteenth century and 19 cm in the twentieth century. At the point when the velocity and acceleration of seawater mass keep on happening, it is assessed that the level of global air movement will increase by 34 cm in the 21st century [4].

With the issue of increasing seal level, research about seasonal and interannual sea-level variability in Indonesia is needed. The study of sea-level variability should be possible by various methods; one of the methods is satellite altimetry observation. The observation of the SLR in Indonesia using altimetry satellites shows a range of 1.7 - 8 mm per year in the period 1993-2011 [5]. The variety of sea level is affected by the phenomenon of the sea in the western Pacific Ocean, the South China Sea, the eastern Indian Ocean, and ENSO.
2 Data and Methods

2.1 Study Area

The location of this research was restricted in Indonesian Seas with coordinates of 20° N - 20° S and 90° E - 150° E. The research location can be found in Figure 1.

Figure 1. The Indonesian Seas

2.2 Data and Methods

In this study, we extracted the RADS of Jason 2 and Jason 3 in the period 2008 to 2018. The data must be rectified for all range, and geophysical adjustments include ionospheric, dry, and wet tropospheric delays, sea state bias, tides, and inverted barometer adjustment. Referring to [6], a simple formulation to calculate the Sea Surface Height (SSH) and SLA are as follows:

\[
SSH = H - R - \sum_j \Delta R_j \tag{1}
\]

\[
\sum_j \Delta R_j = \Delta h_{dry} + \Delta h_{wet} + \Delta h_{iono} + \Delta h_{SSB} \tag{2}
\]

\[
SLA = SSH - MSS \tag{3}
\]

Where satellite height above ellipsoid (altitude) is H, R is observation range, \( \Delta h_{dry} \) is a dry tropospheric correction, \( \Delta h_{wet} \) is a wet tropospheric correction, \( \Delta h_{iono} \) is an ionospheric correction, \( \Delta h_{SSB} \) is sea state bias, and MSS is mean sea surface.

We calculate the mean of SLA per cycle to intercalibrate tandem mission satellite data. This calibration aims to eliminate bias between satellites that overlap at the same time or tandem mission. Then we decompose the SLA data to get three components, such as seasonal, trend, and error.

After the data are decomposed, then grouped the SLA according to the seasonal pattern. The seasonal pattern is Northwest Season (December - February), First Transitional Season (March-May), Southeast Season (June - August), and Second Transitional Season (September - November). Furthermore, we calculate SLA per year to get the interannual variability. The size of gridded data is 3°x 3°, appropriate satellite’s ground track spacing in the equatorial distance.

To know the relation between SLA and ENSO events, we utilized the Multivariate ENSO Index. The Multivariate ENSO Index (MEI) is the most common indicator to define El Nino and La Nina occasions where the MEI v.2 typically uses bi-monthly mean, and El Nino or La Nina are defined as when the MEI v.2 SLA exceeds +/-0.5. When it is more significant than 0.5, then it is
expressed as the El Niño period; when lower than -0.5, then it is expressed as the La Niña period, respectively. In this study, we used the bi-monthly data of MEI v.2 from NOAA to determine the Elnino and La Nina episodes, where the SLA was taken toward the bi-monthly of MEI v.2 during the period 2009-2018.

Besides, correlation analysis was also performed on the SLA variations on a whole Indonesian Seas. The correlation equation is the Pearson correlation, which is formulated as follows:

\[ \rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \cdot \sigma_y} \]

\[ \sigma_{xy} = \frac{\sum (X - \mu_x)(Y - \mu_y)}{n} \]  

Where \( \rho_{xy} \) is the Pearson correlation, \( \sigma_{xy} \) is the covariance of XY, \( \sigma_x \) is the standard deviation of X, \( \sigma_y \) is the standard deviation of Y, \( \mu_x \) is mean of x, \( \mu_y \) is mean of y, n is the amount of sample, X is an independent variable, Y is a dependent variable. The degree of connection between the variables in the correlation analysis depends on the values in Table 1 below.

| Interval       | Level of relationship |
|----------------|-----------------------|
| 0.80 ≤ \( \rho_{xy} \) ≤ 1.00 | Very Strong          |
| 0.60 ≤ \( \rho_{xy} \) < 0.80 | Strong               |
| 0.40 ≤ \( \rho_{xy} \) < 0.60 | Moderate             |
| 0.20 ≤ \( \rho_{xy} \) < 0.40 | Low                  |
| \( \rho_{xy} \) < 0.20       | Very low             |

### 3. Results and Discussion

#### 3.1 Seasonal Pattern and Variation of SLA

The SLA seasonal pattern in the Indonesian Seas in 2018 varied, as appeared in Figure 2. In the Northwest Season, SLA at the Southern Java Sea, Arafura Sea, and the Banda Sea was extremely high, which reach >0.2 mm, while the most lower SLA occurred in the Flores Sea with 0.05 mm. SLA pattern in the First Transitional Season started to change, but it did not significant, where the higher SLA move toward the north, particularly the central part of the Indonesian Seas. SLA in the Halmahera Sea was higher than the Northwest Season.

SLA decrease in the Southeast Season; the lower SLA occurred at Karimata Strait with -0.013 mm and Natuna Sea with -0.004 mm. The higher SLA occurred at the Halmahera Sea with 0.199 mm. Generally, SLA in the Second Transitional Season demonstrated a different pattern to the Southeast Season in Makassar Strait; the Banda Sea and Northern Java Sea has the higher value instead of the Southeast Season.
Figure 2. SLA Seasonal Pattern in Indonesian Seas 2018

Figure 3. SLA Seasonal Variation in Indonesian Seas 2018

Figure 3. indicated the SLA seasonal variation in the Timor Sea, Northern Java Sea, and the Sulawesi Sea was low, and the range of SLA value is 0.05 to 0.15 mm. The different patterns showed in the Karimata Strait, Natuna Sea, and the Banda Sea, in the period of the Southeast Season has low SLA, which reached -0.012 mm. However, in the Northwest Season, it has a higher SLA, which reached 0.276 mm.
Seasonal variation in the Halmahera Sea and the Maluku Sea had a similar pattern, with the greatest SLA, which occurred in the Northwest Season and least SLA was in the Second Transitional Season. Meanwhile, SLA in the Flores Sea had the maximum SLA in the First Transitional Season and the minimum in the Second Transitional Season.

3.2 Interannual Variation and Trend SLA
The interannual distribution of SLA in the Indonesian Seas from 2009 to 2018 is demonstrated in Figure 4. Generally, the SLA in 2009-2018 had a propensity to indicate a positive dominant. A high positive anomaly, for the most part, happened in 2010 and 2013, in the Flores sea and Northern Java Sea, which reaches 0.01 mm in 2010 and 0.06 mm in 2013. The high negative anomaly occurred in 2015 and 2016, which reached -0.04 mm and -0.01 mm.

The SLA interannual variation in the Indonesian Seas was very unstable, as appeared in Figure 5. The fluctuation value of SLA obtained by the Northern Java Sea, Flores Sea, and the Banda Sea was the lowest, which a standard deviation of 0.047 mm. The Halmahera Sea, the Natuna Sea, and the Sulawesi Sea have the highest fluctuation with a standard deviation of 0.057 mm.

Figure 4. Annual SLA in Indonesian Seas 2009-2018

The SLA interannual variation in the Indonesian Seas was very unstable, as appeared in Figure 5. The fluctuation value of SLA obtained by the Northern Java Sea, Flores Sea, and the Banda Sea was the lowest, which a standard deviation of 0.047 mm. The Halmahera Sea, the Natuna Sea, and the Sulawesi Sea have the highest fluctuation with a standard deviation of 0.057 mm.
In the last ten years, SLA interannual variation in the Indonesian Seas showed a lowering trend. The linear equation is $y = -0.08883x + 133.67$

3.3 Correlation between SLA and MEI

3.3.1 Correlation between SLA and MEI

The correlation between SLA and MEI is -0.66, so the relationship between the two variables is strong but inversely proportional. El Nino occurs when the MEI value is positive, and La Nina occurs when the MEI value is negative. Based on Figure 7, a strong El Nino event occurred in 2015, and a strong La Nina occurred in 2010. There was an increase in SLA generally, but there was a decrease when El Niño happened. When La Nina (2010) occurred, the SLA condition in the
Indian Ocean was higher than in the Pacific Ocean region, according to reference [8]. In 2010 the SLA had a high positive anomaly shown in Figure 4. In 2015 the SLA had a high negative anomaly and related to the El Nino event at that time.

3.4 Temporal analysis between Sea Level Anomaly

The results of the annual SLA periodogram show that some patterns are consistent. A strong annual pattern in November-January and semi-annual pattern in July-October. It shows that annual and semi-annual climate characteristics dominate Indonesian waters. Based on Figure 8, Indonesian seas have a dominant rainy season with maximum frequency (intensity) in November-January, decreasing in December and increasing again in January. In contrast, the dry season is indicated when the low frequency occurs in March-June.

4 Conclusion

The seasonal and interannual variation around the Indonesian Seas has been performed using Jason-2 and Jason-2 Altimeter satellites. The result shows that the SLA seasonal and interannual in Indonesian Seas were varied. The monsoon system influenced the seasonal variation. Generally, the interannual variation of SLA 2009-2018 tends to dominate positive anomaly. The most significant anomaly happened in 2010 and 2013, while the least anomaly happened in 2015 and 2016. ENSO has a strong correlation with SLA. The coefficient correlation is -0.66. It means when the SLA value is high, and then the MEI is low. Furthermore, within ten years, the Indonesian seas had a decreasing trend of SLA.
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