Sea Level Variability around the Java Sea (study Area: northern of Gresik and Surabaya) using Cryosat-2 Altimeter

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Abstract. Sea level rise is one of the issues that are on the highlight today. Seawater that is in direct contact with the coastal area makes the region vulnerable to the environment. The Java Sea in Indonesia with a wide enough coverage will have many impacts on the coastal areas if there is an increase in sea level. For these observations, a sea-level anomaly (SLA) is calculated to understand sea level and its changes over time. SLA calculations use data from Cryosat-2 Satellite. Cryosat-2 is an altimetry satellite that was designed for the ice sheet observation mission and oceanography observation missions. This altimetry satellite has an excellent level of accuracy even though it does not have a microwave radiometer. This research is expected to know sea level variability of the Java Sea surface from 2011 to 2019. Obtained based on linear regression of the Cryosat-2 SLA trend, the Java Sea has decreased by 27.9746 mm at a rate of -3.55 mm/year. It is caused by the phenomenon of El-Niño Southern Oscillation (correlation coefficient of the SLA and MEI detrended indicating indicates a strong but not unidirectional correlation. The higher the MEI index, the lower the SLA value will be in the Java Sea, a vice versa, and MEI detrended, indicating a strong but not unidirectional correlation. The higher the MEI index, the lower the SLA value will be in the Java Sea, and vice versa.

Keywords - sea level rise, SLA, Cryosat-2, ENSO, MEI.

1. Introduction

Coastal areas are areas that very vulnerable to the environment, both originating from land and the sea. One of the highlight issues about the coastal area is the rise of the sea-level rise [1]. Sea level rise problems impact natural problems, and the population's affects the eco-social around the coast [2]. ENSO or El-Niño Southern Oscillation can represent an important part of global climate change because it affects weather and climate on a global scale. The phenomenon is shown by the presence of warmer surface water along the Pacific Ocean equator on intervals of 2 to 7 years [3]. ENSO has more influence on the east and southwest parts, where the Pacific Ocean's southwestern region Indonesia [4]. Between 1997 and 1998, the El-Niño phenomenon occurred where Indonesia experienced a prolonged increase in the dry season. Whereas in 1999, the La-Niña phenomenon occurred, Indonesia experienced an increase in high rainfall and increased sea level, causing flooding in most parts of Indonesia, especially coastal areas [5].
The Java Sea is a sea directly adjacent to the north side of Java and has a surface area of around 467,000 km². This vast area does not allow conventional observations, so it utilizes altimetry satellite technology. It is an appropriate alternative because the high-quality altimetry satellite missions provide direct and global observations of the ocean and its temporal and spatial variability.

Cryosat-2 is a type of satellite altimetry used in this research and launched in 2010 with an average altitude of 710 km, an inclination of 92°, and an orbit period of 369 days 30-day sub-cycle. The primary payload is SIRAL (SAR Interferometer Radar Altimeter), which has the additional ability to meet the requirements of ice sheet elevation measurements [6]. SIRAL is designed with three measurement modes based on geographical cross-zone zones, namely LRM, SAR, and SARin, which can be used for sea and ice sheet observations [7]. Cryosat-2 has an outstanding accuracy level above the ocean even though it does not have a microwave radiometer, so correction values are obtained from the models. The data generated consists of two types, namely Level 1b and Level 2, where Level 2 is data with complete correction.

As an archipelago state with a vast sea and one of them is the Java Sea, many sea-level rises in the coastal region. Because of that, it is necessary to know the value of sea-level rise and its factors. So in this research, a sea-level anomaly (SLA) was calculated to obtain sea level rise values and correlation calculations to determine ENSO factors' relationship in the Java Sea region. This research uses Cryosat-2 satellite SAR Level 2 data from 2011 to 2019.

2. Data and Methods
The location used in this research is the Java Sea, which has coordinates 2° 55' to 7° 46' south latitudes and 105° 46 ' to 119° 28' east longitude.

![Figure 1. The Study Area, the Java sea. The green lines represent the along-track of the Cryosat-2 satellite.](image)

2.1. Data
The data used are 20Hz Level 2 Cryosat-2 altimeter satellite Mode SAR from 2011 to 2019. Parameters used in data calculation are altitude, range (window delay and track correction
obtained), observation time, dry and wet tropospheric corrections, sea state bias (SSB), tides corrections, Dynamic Atmospheric Correction (DAC), ionospheric correction, and mean sea surface (MSS).

The other data used is the Multivariate ENSO Index (MEI) as a value representing the Pacific Ocean's ENSO phenomenon. The data is to correlate the results of satellite data calculations.

2.2. Methods

Cryosat-2 Satellite data used has the extension *.dbl. The model for each parameter used is also determined based on Table 1 [8].

| Parameter           | Model          |
|---------------------|----------------|
| Altitude            | CNES GDR-E     |
| Range               | Ku-band        |
| Dry Tropospheric    | ECMWF          |
| Wet Tropospheric    | ECMWF          |
| Ionospheric         | GIM            |
| Sea State Bias      | Hybrid         |
| Dynamic Atmospheric Correction | MOG2D |
| Solid tide          | FES2004        |
| Pole tide           | FES2004        |
| Ocean tide          | FES2004        |
| Load tide           | FES2004        |
| Mean Sea Surface    | UCL04          |

The predetermined data model will limit each parameter's limit to make the parameters do not contain outliers data [9]. The limit of each parameter is based on Table 2.

| Parameter         | Limit (m) |
|-------------------|-----------|
| Dry Tropospheric  | -2.40 to -2.10 |
| Wet Tropospheric  | -0.60 to 0.00  |
| Ionospheric       | -0.40 to 0.04  |
| Sea State Bias    | -1.00 to 1.00  |
| Dynamic Atmospheric Correction | -1.00 to 1.00 |
| Solid tide        | -1.00 to 1.00  |
| Pole tide         | -0.10 to 0.10  |
| Ocean tide        | -5.00 to 5.00  |
| Load tide         | -0.50 to 0.50  |
| Mean Sea Surface  | -200 to 200   |
| Sea Level Anomaly | -2.00 to 2.00 |

Data that has NaN value is replaced with a value that exceeds the limit so that it is selected in the process of correction and data quality control. The parameters that have been given a limit can be used to calculate Sea Level Anomaly. This calculation uses the MATLAB software. SLA is obtained through the following equation [10]:

\[
SLA = H - \delta h - \Delta \delta \theta_y - \Delta \delta \omega - \Delta \delta \delta - \Delta \delta \delta - \Delta \delta \delta - \Delta \delta \delta - \Delta \delta \delta - \Delta \delta \delta - \delta h (1)
\]
to calculate $R_{obt}$ based on equation [9]:

$$R_{obt} = R_{as} + R_{atrack}$$  \(2\)

wherein $H$ = altitude (height of the satellite orbit regarding an ellipsoid), $R_{as}$ = range, $\Delta R_{dry}$ = dry tropospheric correction, $\Delta R_{wet}$ = wet tropospheric correction, $\Delta R_{iono}$ = ionospheric correction, $\Delta R_{sst}$ = sea state bias, $\Delta R_{dynamics}$ = dynamic atmospheric correction, $\Delta R_{tides}$ = tides (solid earth, ocean, load and pole) correction, $MSS$ = mean sea surface [11], $R_{wd}$ = window delay and $R_{atrack}$ = track correction obtained. All variables in meters unit, but for analysis, SLA units can be converted to millimeters.

Every SLA data will be leveled by latitude weighting. Calculation of the average SLA is done by-cycle and by-month (sub-cycle). Weights are applied to each observation value considered based on the cosine of its latitude position [12]. Match the MEI data with Bi-monthly SLA (leveled SLA from the middle of the month and next). Average SLA results will be stored in the *.txt extension.

Furthermore, SLA data leveled by-month (sub-cycle) is processed in RStudio software for Time Series Decomposition. This process is to extract SLA data into four graphs. There are raw data, trend, seasonal, and remainder graph. The method used for decomposition is Seasonal-Trend Decomposition Procedure Based on Regression, which uses iterative loess smoothing to obtain trend patterns [13]. The results of SLA trends are trends that have been removed from seasonal patterns.

Calculate linear trends to determine the phenomenon of rising or decreasing sea level against Cryosat-2 sub-cycle trend data. The calculation uses a linear regression approach with the following equation [14]:

$$y = ax + b$$  \(3\)

Wherein $y$ is the independent variable, $x$ is the independent variable representing time, $a$ is the slope of the function of the line, and $b$ is the intersection of the straight line (the value of $y$ when crossing the Y-axis). The value of $y$ is the trend of sea-level rise.

Next is calculating the value of the correlation coefficient between the bimonthly SLA Cryosat-2 detergent data and the Multivariate ENSO Index (MEI). One technique for determining the correlation coefficient is Pearson’s correlation coefficient, with the following formula[15]:

$$Q_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$$  \(4\)

wherein $Q_{xy}$ is the correlation coefficient, $\sigma_{xy}$ is the covariance of $xy$, $\sigma_x$ is the standard deviation of $x$, and $\sigma_y$ is the standard deviation of $y$. The values range of coefficient correlation is -1 to 1, which means that a positive value indicates a direct relationship, and a negative value indicates a non-direct relationship. The interpretation of the coefficient values’ strength is needed to make it easier to analyze [16].
Table 3. Interpretation of Correlation Strength

| Correlation | Interpretation         |
|-------------|------------------------|
| 0 to 0.3    | Correlation is very weak|
| (0 to -0.3) |                        |
| 0.3 to 0.5  | Correlation is weak    |
| (-0.3 to -0.5) |                    |
| 0.5 to 0.7  | Correlation is enough  |
| (-0.5 to -0.7) |                   |
| 0.7 to 0.9  | Correlation is strong  |
| (-0.7 to -0.9) |                  |
| 0.9 to 1    | Correlation is very strong|
| (-0.9 to -1) |                        |

The coefficient +1 indicates the existence of a perfect positive correlation, and the coefficient of -1 indicates the existence of a perfect negative correlation [17]. Correlation coefficient 0 indicates that there is no correlation between the two variables.

3. Results and Discussion

3.1. Calculation of SLA and Average SLA

SLA calculations are performed by each cycle data, which are calculated on average SLAs. The highest average SLA value was 249.9 mm in cycle 4 in 2012. The lowest average SLA value was 64.9 mm in cycle 9 in 2015. In the sub-cycle data, the highest average SLA value is 329.8 mm in June 2013, while the lowest average value was 20.1 mm in September 2015. In the SLA bi-monthly data, the highest average SLA value was 323.7 mm in 2013, and the lowest average SLA value was 27.8 mm in 2015.

![Figure 2. SLA Average of Cryosat-2 in the Java Sea area](image)

Figure 2 shows the pattern of low and high SLA by-subcycle average, which was mentioned the lowest in September 2015 and the highest in June 2013.

3.2. Decomposition Time Series and Trend Processing

Processing time series decomposition in Rstudio software produces four graphics: raw data, seasonal, trend, and remainder.
Figure 3 shows a seasonal graph that looks at repetitive patterns every year, but there is one decreasing pattern that occurs twice during the observation period. The trend graph above has a trend with a descending pattern.

The decomposition results also showed a drastic downward trend in 2014-2015 of 59.7019 mm. From 2017 to 2019, a downward trend of 76.4 mm occurred.

3.3. Calculation of Linear Trends

Linear regression calculations from the average SLA trend data get a chart pattern like in Figure 4 with the equation \( y = -3.5529x + 7.324,1893 \). Variable \( a \) in the equation has a negative value, which indicates a linear downward trend.

Based on the SLA linear regression, the Java Sea surface from 2011 to 2019 decreased by 27.9 mm at a rate of -3.55 mm/year.
3.4. Calculation of Correlation Coefficient

The depiction of the relationship between the SLA bi-monthly with MEI data is represented in Figure 5. The data of the SLA bi-monthly is drawn with a purple line. Red graph slices represent positive values on the MEI data based on the phenomenon of El-Niño (warm phase), and blue slices represent negative values based on the phenomenon of La-Niña (cold phase). Overall, the figure above shows the unidirectional relationship between the SLA bi-monthly data and the MEI data from 2011 to April 2019.

Figure 5. Graph of Bi-Monthly SLA Cryosat-2 with Multivariate ENSO Index (MEI)

Figure 6. Correlation between Detrended SLA and MEI
Figure 6 shows the red line is a trend linear of SLA bi-monthly detrended data with MEI having the equation $y = -0.0199673x + 3.1891576$. Detrended SLA is the reduction in the value of the Cryosat-2 SLA linear trend to the value of the SLA itself. The negative value of variable $a$ indicates a decrease in the linear trend in line with the value of the correlation coefficient between detrended SLA and MEI of $-0.6451$. A negative correlation value indicates a non-directional relationship meaning that the higher the MEI value, the lower the SLA value.

The interpretation of correlations based on Table 3 states that correlation coefficients have enough relationship. This relationship can be seen from Figure 5; when the El-Nino phenomenon began to occur, variations in the surface of the Java Sea began to decrease, and when the El-Nino phenomenon occurred, the surface of the Java Sea experienced a decreased. When the La-Nina phenomenon began to occur, variations in the surface of the Java Sea began to rise, and when the La-Nina phenomenon occurred, the surface of the Java Sea increased.

Refer to [18] explained that in the mid-March 2015 to the end of June 2015, the El-Niño phenomenon began with a weak intensity and continued to increase with a vigorous intensity in November 2015. This phenomenon causes a decrease in the surface of the Java Sea.

4. Conclusion

Based on the research, it can be concluded that during the period 2011 to 2019, the Java Sea experienced a decrease in sea level. The decrease in sea level was based on trends during the research period of 27.9746 mm at a rate of -3.55 mm/year in the Java Sea. This phenomenon is influenced by ENSO, especially in 2014-2015, during El-Nino with vigorous intensity. The correlation coefficient of the Multivariate ENSO Index (MEI) data with SLA Cryosat-2 is $-0.6451$, which indicates a strong but not unidirectional correlation. The higher the MEI value, the lower the SLA value will be in the Java Sea.

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