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Studying Sea Level Variability in Indonesia Sea Based on Satellite Altimetry

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Abstract. Sea level variability is one of the fundamental parameters for scientific development such as modeling the Earth's climate. In addition, this parameter also playing crucial rules to mitigate socio-economic hazards due to sea-level changes, especially in coastal areas. Mitigating the sea-level hazards in an archipelagic country like Indonesia becomes more essential since the country is geographically constructed by various bathymetric depths with different types of seas. One of the attempts to study sea-level variability is to take benefit from satellite altimetry data. The satellite altimetry missions have observed the sea level more than 25 years, and hence the rate of sea-level variability can thoroughly be studied by comparing Mean Dynamic Topography with Sea Level Rise in the research area. The result shows positive and negative correlation in several areas that can be examined as regional-scale variations in sea level over the Indonesian sea.

Key words: MDT, SLA, SLR, Altimetry, Indonesia

1. Introduction

Sea surface variability is one of the fundamental parameters for scientific development such as modeling of Earth's climate. In addition, this parameter also playing crucial rules to mitigate socio-economic hazards due to sea-level changes, especially in coastal areas. Reducing sea-level hazards in an archipelago like Indonesia is significant because this country is geographically built by various bathymetry depths with various types of sea. Sea surface variability can be studied by studying the sea level phenomenon, in geodesy perspective, sea surface variability can be measured geometrically using geodetic measurement technology. The geodetic method uses vertical distance measurement between altimetry satellites position and the instantaneous sea surface which subsequently results in a measurement of the height of the sea level for a particular reference area, the ellipsoid. The altimetry satellite mission, since its launch, has observed sea level for more than 25 years (including Jason 1-2, Topex Poseidon, Envisat, and GFO-1) thus the study the level of sea-level variability in Indonesia can be recognized from the full period of long-wavelength.

The vertical distance of the instantaneous sea surface with respect to the ellipsoid reference is Sea Surface Height (SSH), known as the result of reducing the vertical distance between satellite's position relative to ellipsoid reference with the vertical distance measurement between satellite and sea level. Since the ellipsoid reference field is a mathematical geometric field, to obtain a physical picture of potential phenomena in accordance with ocean phenomena, the SSH is converted to Sea Surface Topography (SST) by using geoid as the reference field and geoid undulation as the transformation parameter. [1] states that SST represents all phenomena of sea water motion in spatial and temporal coverage, namely tides and sea waves. By studying SST, it is expected to know the effect of global phenomena such as El Nino and La Nina in Indonesia. SST is a superposition of Dynamic Ocean Topography (DOT) as a time-dependent component and Dynamic Topography as a time-dependent component [1] [2]. Tidal, wave, wind, and current phenomena are factors that cause DOT. To obtain a comprehensive picture of global ocean circulation, the Mean Dynamic Topography (MDT) value information is used as a superposition of the average SSH value to the geoid undulation value [3]. In general, MDT can be determined using 3 methods, namely, the altimetric geodetic method (using the mean sea surface data with geoid undulation) which conducted in this study, oceanography method (oceanographic data in situ: temperature, salinity, current) and a combination of geodetic-oceanographic methods [4]. The MDT results are compared with the Sea Level Rise (SLR) value of each observation position, where the SLR value is derived from the Sea Level Anomaly (SLA) value. SLA itself is a variability of the instantaneous sea surface SSH with its mean value (Mean Sea Surface Height/MSSH) with ellipsoid as a reference. The SLA used in this study is the SLA from [5] [6] described in its linear trend. Thus, it is expected that the correlation value between MDT and SLR can provide geodetic constructions for marine studies in Indonesian territory.

2. Method and Data

The satellite altimetry description and the method of sea level geometric height determination relative to the ellipsoid (SSH) and relative to geoid (SST) has been described by [7] [8]. While the altimetry database used in this study is from RADS Data Center [9] with the same strategy used by [6] using data interpolation within a 5 km radius for data smoothing as the phenomenon occurs in large area resolution. The data used is shown in Figure (1) and table (1), which uses Jason 1-2, Topex Poseidon, Envisat, and GFO-1 satellite data. The selection was made with consideration for the coverage of Indonesia, and the long duration overlapping of observations from these four satellites can represent the long wavelength pattern of the ocean surface cycle.

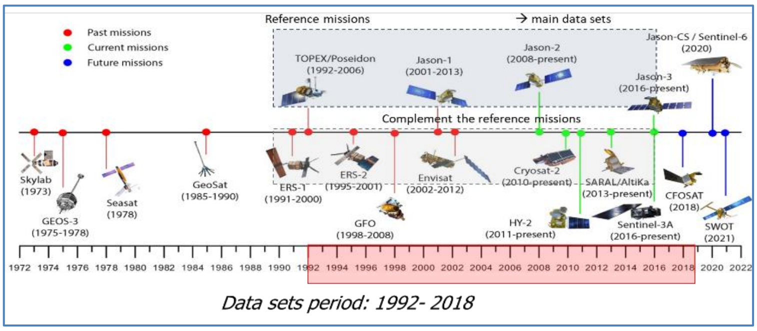

Figure 1. Satellite Altimetry and data sets period for 1992-2018

Table 1. Altimetry Satellite Specification

SATELIT	PHASE	RESOLUSI TEMPORAL (HARI)	JUMLAH HARI	INKLINASI (DERAJAT)	WAKTU PENGAMATAN	EKUATOR ALTITUTDE	SEMI MAJOR AXIS
TOPEX	A	9.9156	364	66.04	25 Sep 1992 - 11 Aug 2002	1336 Km	7714427.8 m
POSEIDON	A	9.9156	361	66.04	01 Oct 1992 - 12 Jul 2002	1336 Km	7714427.8 m
JASON-1	A	9.9156	260	66.04	15 Jan 2002 - 26 Jan 2009	1336 Km	7714427.8 m
JASON-2	A	9.9156	303	66.04	04 Jul 2008 - 02 Oct 2016	1336 Km	7714427.8 m
JASON-3	A	9.9156	88	66.04	12 Feb 2016 - 06 Jul 2018	1336 Km	7714427.8 m
ERS-1	C	3	18	98.516	14 Apr 1992 - 20 Dec 1993	785 Km	7153138 m
ERS-2	A	35	169	98.5421	29 Apr 1995 - 04 Jul 2011	785 Km	7159495.65 m
GEOSAT	B	17	67	108	08 Nov 1986 - 30 Dec 1989	840 Km	7166400 m
GFO-1	A	17	186	108.04	07 Jan 2000 - 17 Sep 2008	840 Km	7166400 m
SARAL	A	35	35	98.55	14 Mar 2013 - 04 Jul 2016	800 Km	7159496 m
CRYOSAT2	A	369 (30 hari sub cycle)	103	92	14 Jul 2010 - 06 Jul 2018	717 Km	7095.34856 m
SENTINEL-3A	A	27	33	98.645589	01 Mar 2016 - 06 Jul 2018	814.5 Km	--
ENVISAT1	B	35	88	98.5429	14 May 2002 - 22 Oct 2010	712.4 - 799.8 Km	7159495.65 m

By satellite altimetry measurements (figure 2), obtained indirectly, the height of the Instantaneous Sea Surface Height (ISSH) or better known as SSH is obtain through the reduction of the height of the orbit with the distance from the satellite to the sea level relative to the reference ellipsoid. The SSH were transformed using the geoid undulation value N (i.e. the vertical distance between the geoid and the ellipsoid) into the SST value to get a physical picture of the sea phenomenon using the next equation.

$$SST_{(\varphi,\lambda,t)} = SSH_{(\varphi,\lambda,t)} - N = DT_{(\varphi,\lambda)} + DOT_{(\varphi,\lambda,t)} \quad (1)$$

where SST is the height of the instantaneous sea level with respect to geoid surface, DT is the variable part of SST that is not affected by time, DOT is the variable part of SST that is affected by time, SSH is the height of the instantaneous sea level with respect to the ellipsoid surface, N is the height difference between geoid and ellipsoid, λ is Longitude (degree), φ is Latitude (degree) and t is the time of observation.

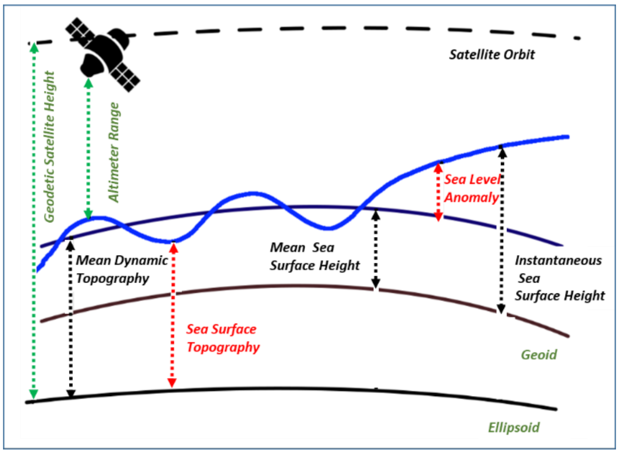

Figure 2. Basic Principle of Satellite Altimetry

The standard of Altimetry data processing described by [2] have eliminated the effect of surface variations on the DOT component using geophysical correction, namely the effect due to ocean tides [1] [10] and the effect of atmospheric pressure loading [11]. The mean value of SSH, Mean Sea Surface Height (MSSH), then becomes the superposition of the mean value of SST, MDT, which describes the pattern of ocean currents and global ocean circulation [12]. The MDT value is obtained from the equation

$$MDT_{(\lambda,\varphi)} = MSSH_{(\lambda,\varphi)} - N_{(\lambda,\varphi)} \tag{2}$$

and the deviation from SSH relative to MSSH is Sea Level Anomaly (SLA), that can be obtained using the equation

$$SLA_{(\lambda,\varphi)} = SSH_{(\lambda,\varphi)} - MSSH_{(\lambda,\varphi)} \tag{3}$$

A linear trend from SLA is determined and the Sea Level Rise (SLR) value is also determined using the increased value at each observation point.

3. Result and Discussion

The research area for Indonesia is -15^{0}S / 90^{0}E to 15^{0}N / 15^{0}E, while the altimetry satellite data used are Jason 1-2, Topex Poseidon, Envisat, and GFO-1 taken with consideration of the long duration of observation and the coverage of the data recording area that can be overlapped each other. The time range of altimetry satellite data taken in this study was from 1992 to 2018, while the value of the geoid undulation (N) was taken from the global gravity model EGM-2008 with consideration of the Indonesia's regional geoid model absence and currently, the EGM-2008 model is the model that can represent Indonesia's geoid. The spherical harmonic degree taken from this global gravity model is 360^0 with consideration of the low frequency effect of the sea surface. Thus, the high frequency effect of the diversity of coastal morphology can be considered as an anomaly that is expected to be deciphered in the future, taken into the account, the research area is an archipelagic country that is in the need of validation of the local effects of each coastal area and is currently both in temporal and spatial coverage is not fully available.

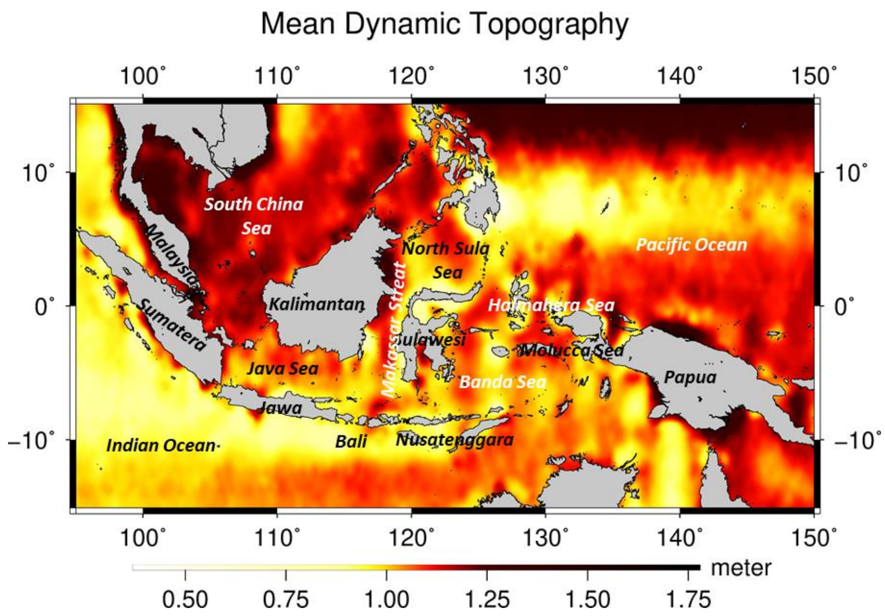

Figure 3. Mean Dynamic Topography (MDT) 1992-2018

MDT values for the study area with a range of 1992-2017 data have been analyzed by [13], and one year of data was added in this study, throughout 2018. The results obtained remained at the theoretical value, i.e. did not experience any deviation from the range ± 2 m. Figure 3 shows the MDT values in the interval 1992-2018, the same pattern is still visible, namely the value for the entire territory of Indonesia ranging from 0.5 meters to 1.75 meters, with a general pattern of low-value MDT which ranges from 0.5 meters to 1.1 meters stretching from low latitude in the south towards the equator, and tends to be higher until it exceeds 1.75 meters the further away from the equator to the north. MDT spatial based analysis can be classified into 2 parts, namely the western and eastern parts of Indonesia with the Makassar strait located between the islands of Kalimantan and the island of Sulawesi as the center. For the western part of Indonesia, in the Indian Ocean region, MDT values vary between 0.5 meters to 1.1 meters which are worth the range of 0.7 meters at latitudes below -10^0S which then tends to decrease towards the equator until the northernmost tip of the island of Sumatra reaches the lowest value of 0.5 meters. Whereas at the interval of -7.5^0S to -12.5^0S there was a tendency of an increase in MDT values in the Indian Ocean heading east between Indonesia and Australia from a value of 0.75 meters to 1.1 meters. For the Java Sea region there are variations in values between 0.75 meters to 1.2 meters with a low-value pattern located in the northern part of the Java Island and increasing towards the southern part of Borneo Island.

In general, MDT values subsequently increase gradually up to 1.5 meters to the north, clearly visible in the South China Sea and in the Makassar Strait. The high MDT value in the Riau Islands located in the eastern part of Sumatra Island is estimated due to the noise effect of rapid changes between land and sea zones that affect altimetry data. For the eastern part of Indonesia, at latitudes of -7.5^0S to -12.5^0S there was a tendency to pattern continuous of ascension from the Indian Ocean to 1.2 meters, and a decrease in the Timor Sea part reached 0.75 meters. Heading north, the Banda Sea looks back downward towards 0.7 meters and higher westward towards Sulawesi Island and north through the Molucca Sea. For the northern part of Papua Island, which is in the Pacific Ocean, there was a fairly extreme change in pattern from interval 1 to 1.1 meters between latitude 0^0N to 0.4^0N, then dropped until it approached the number 0.5 in its northern part. This pattern continues to rise rapidly to 1.75 above latitude 10^0N. This pattern as it is known illustrates the El Nino and La Nina phenomena originating from the eastern Pacific Ocean.

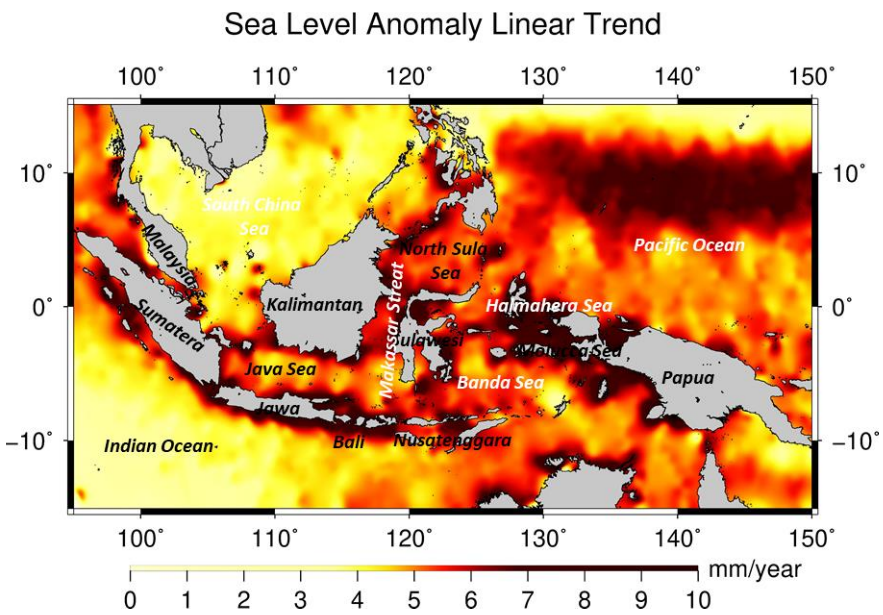

Figure 4. Sea Level Anomaly Linear Trend 1992-2018

The SLA rate in the Indonesian region mentioned by Sarsito [6] varies between 3.4 mm/year to 5.3 mm/year in spatiotemporal variations, where this rate is higher than the global value of SLA which is around 3.2. mm / year. Figure 4 shows the Sea Level Anomaly Linear Trend pattern in the Indonesian region for 1992-2018 data with values ranging from 1 mm/year to 9 mm/yr if taken diagonally from the Indian Ocean which is located in the most south-western part towards the Pacific Ocean in the section most east-north. The reverse pattern occurs when drawn diagonally from the southern tip of Papua towards the Andaman Sea, which is the most west-north which experiences the lowest decline in the South China Sea up to between 1-2 mm/year. The spatial linear SLA analysis based on the spatial is again divided into 2 parts as described above, namely the western and eastern parts of Indonesia with the Makassar strait as the center. For the western part of Indonesia, the Indian Ocean has the lowest SLA linear trend, which is around 1 mm/year and tends to increase northward up to the West Coast of Sumatra and the south coast of Java with a range of 6 mm/year. This pattern is also increasing towards the east, namely the Timor Sea. For the West Coast region of northern Sumatra and the Andaman Sea, high linear patterns can be seen that vary between 5 mm/year to 6.5 mm/year.

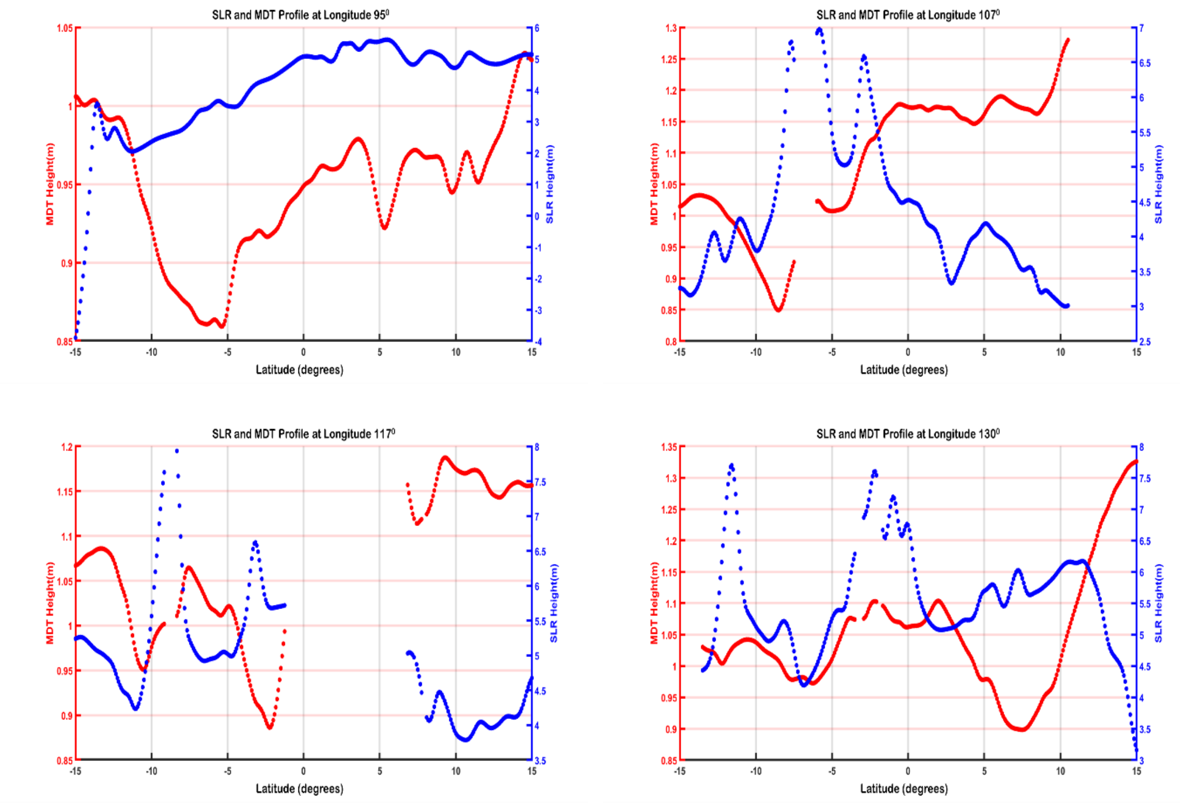

Figure 5. SLR and MDT Profile at Longitude 95^{0}E, 107^{0}E, 117^{0}E and 130^{0}E

The high majority of values are seen in the Mentawai islands in western Sumatra and between the east coast of Sumatra and Malaysia due to noise levels due to rapid changes between land zones and sea zones that affect altimetry data. For the Java Sea, the same pattern is seen along the north coast of the island of Java, the Bangka Belitung Islands, located between Southern Sumatra and Kalimantan and the southern coast of Kalimantan. This linear trend pattern then goes down again in the South China Sea which lies north of Kalimantan at intervals of between 1-4 mm/year. For the eastern part of Indonesia, the majority have a high linear trend from 4.5 mm/year to 9 mm/year. Alignment with the El Nino and La Nina patterns can be seen in the same location as MDT, namely in the Pacific Ocean with the highest linear trend reaching 9 mm / year. This pattern decreases southward towards Papua's North Coast. Whereas for the Molluca Sea and Halmahera Sea areas the pattern is seen to be rising again, but this is expected due to the noise effect from altimetry satellite data as in other islands in Indonesia, and this pattern reappears more smooth linear trend decline in the open Banda Sea with trends up to 4.5 mm / yr To get a better picture of the correlation between MDT as a long-term effect with SLA values, the SLA values are then divided into Sea Level Rise values based on trends at each point of observation as shown in Figures 5 and 6.

Figure 5 shows a cross-section along a latitude that runs from south to north latitude. Profile at latitude 95^0E passes through the majority of the open ocean zone in the Indian Ocean. MDT values range from 0.86 - 1.03 meters and SLR values range from 2.5 - 5.5 meters stretching from south to north with a gradual increase from latitude -15^0S and reach a peak at latitude 5^0N of 5.5 meters and subsequently fluctuate around 0.25 meters up to latitude 15^0N. The highest value is located near the northernmost tip of the island of Sumatra. Overall at this latitude, there is a negative correlation since longitude -15^0S and changes to a positive correlation with the MDT value through which starts at latitude -5^0S with the greatest bias which is also located at the same position with a value ranging from 2.5 meters with a cause not yet known with certainty and a large enough bias occurs again at latitude 5^0N which is where the highest SLR is around the northernmost tip of the island of Sumatra. The next profile was chosen in latitude 107^0E, where some cut off the Indian Ocean in the southern part of Java Island and continued north through the waters of the Bangka Belitung Islands to the South China Sea. In this profile there is a combination of positive correlation and positive correlation between MDT and SLR, where MDT values range from 0.85 - 1.3 meters, and SLR values range from 3-7 meters. At longitude -15^0S there is a negative correlation, namely the decrease in MDT values from 1.025 meters to 0.85 meters at latitude -8, while the SLR values fluctuate from 3.25 meters to the highest peak of 7 meters at latitude -5.5. Positive correlations emerged from latitude -8^0S to passing through Java and the Bangka Belitung islands, namely the increase in MDT values from 0.85 meters to 1.125 meters and SLRs from 4.25 meters to 7 meters. Correlation returned to negative at latitude around -3.5^0S where MDT continues to increase towards the South China Sea to the highest value of 1.3 meters, while SLR has decreased from 6.5 meters to 3 meters.

The next profile is at latitude 117^0E, where in the southern part it cuts the Indian Ocean through a row of Java - Bali - West Nusa Tenggara and then across the Makassar Strait, which lies between Kalimantan Island and Sulawesi Island. In this profile there is a combination again of positive correlation and negative correlation between MDT and SLR, where MDT values range from 0.87 - 1.2 meters and SLR values range between 3.75 - 7.8 meters. At this longitude, there is a difference with the two previous profiles located in the western part of this profile, which is precisely there is a positive correlation at latitude -15^0S to -5^0S, although there is a surge in SLR increase from latitude -12^0S to -8^0S with a value of 4.2 meters up to 8 meters, which is much higher than the value of the MDT increase of only 0.05 meters. Negative correlations were seen again at latitude -5^0S and stopped when crossing Kalimantan Island to the South China Sea where MDT increased by 0.075 meters and SLR decreased by 2.5 meters. The final profile is at latitude 130^0E which crosses the Banda Sea and Mollusca-Halmahera Sea to the Pacific Ocean. Similar to the previous profiles, in this profile there is a combination again of positive correlation and negative correlation between MDT and SLR, where MDT values have increased from 0.9 meters to 1.3 meters, and SLR values have increased in the range of 3 - 7.75 meters. In this profile, negative correlation patterns reappear at latitudes of -15^0S to -10^0S with high SLR hikes from -4.5 meters to 7.75 meters which are likely to be predominantly biased due to proximity to land. After latitude -10, the correlation turns positive with the SLR increasing from 4.2 meters to a peak of 7.5 meters at latitude -3^0S and MDT also increasing from values of 0.98 meters to 1.1 meters at the same location at latitude -3^0S. Furthermore, at latitude 2^0N again there is a continuous negative correlation to the north to coincide in the Pacific Ocean at latitude 15^0N where an extreme increase in MDT from 0.9 meters to 1.33 meters and SLR experienced an extreme decrease starting from latitude 12^0N that is from 6 meters to 3 meters.

To get a clearer picture of the correlation between SLR and MDT, a cross-section along longitude is used that runs from west to east (Figure 6). Profile at longitude 7.5^0N through the South China Sea and Pacific Ocean with MDT values ranging from 0.5 - 1.25 meters, and SLR values ranging from 3.25 - 8 meters. In the South China Sea area there is a change from a positive correlation, namely the increase in MDT (0.2 meters) and SLR (2.25 meters) in the Andaman Sea, to a negative correlation after passing through the Malaysian mainland to the east. Negative correlations namely decreasing MDT (0.4 meters) and increasing SLR (2.25 meters) occur along the South China Sea crossing. Correlation returned to positive after passing Kalimantan Island along the Pacific Ocean, namely the increase in the value of MDT (0.5 meters) and SLR (3.25 meters) with a peak at around latitude 139^0E. Overall MDT in this profile experienced a change from a decrease in the west to an increase in the eastern part, while the SLR is increasing in value from west to east and there is a slight bias towards the major correlation pattern that occurs when in the transition zone between sea and land. The next profile is at longitude 00N through several large islands (Sumatra, Kalimantan, Sulawesi, and Papua) and interspersed with sea or strait, where MDT values range from 0.8 - 1.2 meters and SLR values range from 3.75 - 8 meters. For the western region of Sumatra, there is a negative correlation when through the Indian Ocean (MDT decrease by 0.05 meters and an increase in SLR 2.25 meters) where this correlation subsequently changes after going through the Sumatra Island to be positive along the South China Sea stretch and continues after passing through Kalimantan Island in the North Sulawesi Sea, namely the increase in MDT by 0.375 meters and SLR by 5.25 meters. This correlation turns negative again at longitude around 131^0E where the MDT value continues to increase by 0.15 meters while the SLR value decreases by 1.25 meters. Along this path, a slight bias can be seen again in the major correlation pattern, the transition zone between sea and land.

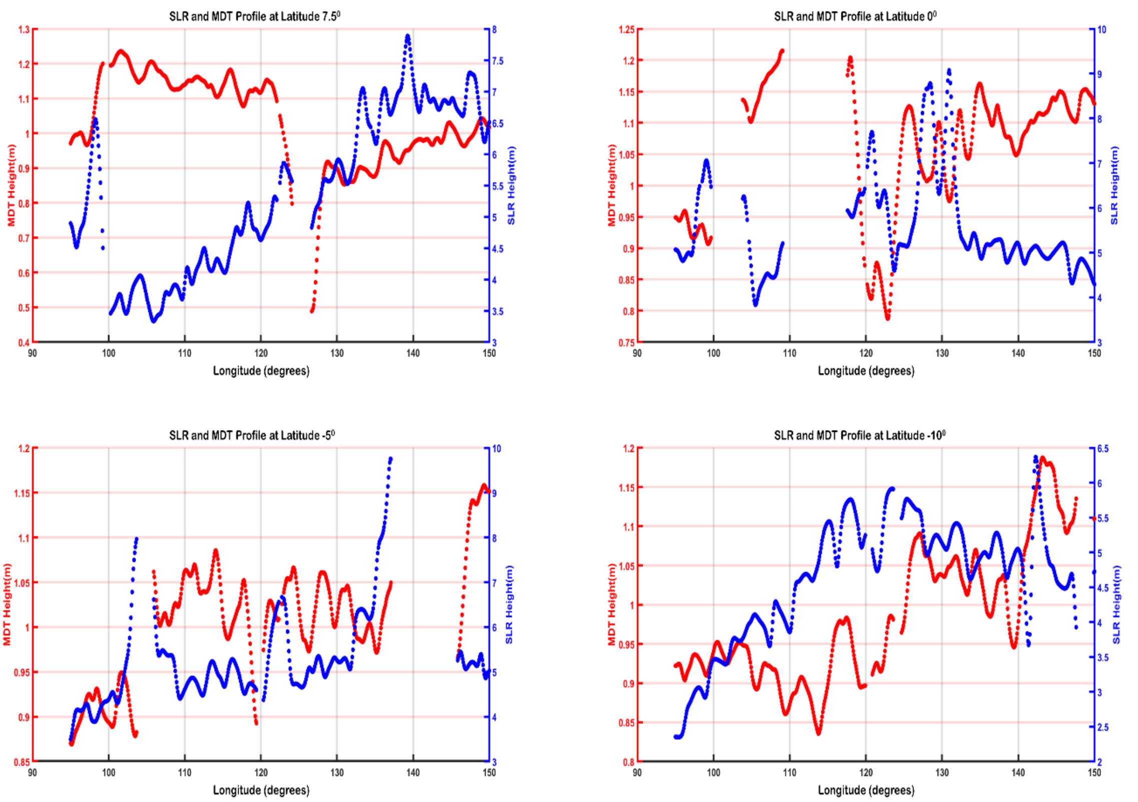

Figure 6. SLR and MDT Profile at Latitude 7.5^0N, 0^0N, -5^0S and -10^0S

The next profile is at longitude -50S through the Indian Ocean, Sumatra, Java Sea, Sulawesi, Banda Sea, and Papua open areas with MDT values ranging from 0.875 - 1.15 meters and SLR values ranging from 3.5 - 8.5 meters. For the Indian Ocean region, a positive correlation emerged, namely an increase in the value of MDT (0.125 meters) and SLR (2 meters). This correlation then turned negative throughout the Java Sea after going through the island of Sumatra, namely a small increase in MDT (0.05 meters) but the SLR decreased by 1 meter. Bias again occurs when approaching Sumatra Island and Sulawesi Island due to the transition of land and sea areas. Correlation returned to positive when passing the Banda Sea with an increase in MDT values of 0.05 meters and a high SLR of 4 meters. For regions after passing through Papua Island, the correlation value is rather difficult to analyze because of its short coverage even though it shows a negative correlation pattern that is a small increase in MDT values (0.025 meters) and a small decrease in SLR values (0.4 meters). The last profile chosen was through longitude -100S, which is mostly through the Indian Ocean open ocean, with MDT values ranging from 0.84-1175 meters and SLR values ranging from 2.3 to 6.25 meters. For the Indian Ocean region, a positive correlation was seen again that the increase in the value of MDT (0.05 meters) and SLR (1.4 meters) was relatively smaller than the previous profile at the same location. Negative correlations appear in the zone around latitude 103, although still in the Indian Ocean zone, which decreases the MDT value of 0.125 meters, and SLR increases by 1.05 meters. Correlation returned to positive again starting around latitude 113 with an increase in MDT value of 0.375 meters and SLR of 1.75 meters.

Based on the depiction of the MDT and SLR correlation in the Indonesian region, it can be seen that for the Indian Ocean region can be divided into three parts, namely for the open seas in the west and south of the island of Sumatra have a positive correlation that is the increasing value of MDT and SLR, where this pattern is then changing when moving eastward (in the southern part of Java) becomes a negative correlation (increasing value in SLR but the MDT value has decreased). After reaching the southern part of Bali until the south of Papua, the correlation turned back to positive, namely an increase in MDT and SLR. Changes in this phenomenon are expected due to the influence of currents in the south of the equator, but still requires further analysis with seabed morphology. For the South China Sea region, in general, have negative correlation where the MDT value has increase but SLR has decreased (this area is the deep sea but rather closed), and the Java Sea (a shallow closed sea) in the south has a negative correlation as well but with a slightly higher value and accompanied by changes to be positively correlated to the west approaching the island of Sumatra and to the east (around the Makassar Strait to the Banda Sea). In the Banda Sea region, continuing north of Halmahera and the Molucca Sea to North Sulawesi Sea, the correlation seen is positive where there is an increase in MDT and SLR. For the Pacific Ocean region, there are two types of correlations, namely negative in the northern part of Papua where there is an increase in the value of MDT and a decrease in SLR value, and increasingly towards higher latitudes in the north, the correlation turns into positive i.e. there is an increase in MDT and SLR. The phenomenon of correlation in the Pacific Ocean shows the influence of the effects of El Nino and La Nina that occur in the area. Deviations or biases towards the closest major correlation, occur almost in every place that is a transition zone of the land zone with the sea zone as well as in small islands such as on the west coast and east coast of Sumatra.

4. Conclusion

As described above, one method to figure out the sea phenomena is by sea-level variability studying. The variability component that can be learned using altimetry satellite data is the sea level change by MDT estimation as a long-term effect, that during interval 1992-2018 has values ranging from 0.5 meters to 1.75 meters with a distribution pattern that is highly dependent on geographical conditions. Another component of variability, namely SLA, has a linear trend pattern during the interval 1992-2018 in the Indonesia territory, with a rate of 1 mm/year to 9 mm/year. By converting the SLA rate to SLR rate for each position relative to its MDT value, the two types of correlations are obtained for the Indonesian region, namely a positive correlation where there is an increase or decrease in MDT and

SLR rates in parts of the Indian Ocean, the Banda Sea and the Pacific Ocean, and negative correlations where MDT or SLR does not have the same pattern of increasing or decreasing in the southern part of Java Island, the South China Sea and the southern part of Pacific Ocean close to Papua.

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