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THE EFFECT OF THE INDIAN OCEAN DIPOLE (IOD) PHENOMENON ON OCEANOGRAPHIC PARAMETERS IN THE MALACCA STRAIT

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ABSTRACT

The Indian Ocean Dipole (IOD) phenomenon is a phenomenon that occurs in the Indian Ocean due to differences in sea surface temperature anomalies between the Western Indian Ocean and Eastern Indian Ocean regions. This interaction produces high pressure in the Eastern Indian Ocean (South of Java and West of Sumatra) which causes the flow of air masses to blow westward. The IOD phenomenon affects oceanographic parameters such as sea surface temperature, salinity, currents, and sea level rise in Indonesian waters. The Malacca Strait is a very important waterway because it connects the Indian Ocean and the South China Sea (Pacific Ocean) so it is strongly influenced by the IOD phenomenon. This research was conducted from November 2022 - February 2023. Global data collection in this study was located in the waters of the Strait of Melaka and data collection for validation was carried out in the waters of North Rupat. This study uses data analysis using secondary data and primary data to validate the secondary data used so that it can prove that the global data in this study are accurate. The results of this study found that in the period 2013 - 2022, the range of sea surface temperature of the Malacca Strait is 27 - 32°C. The salinity of the Malacca Strait waters ranges from 32.54 - 33.49 ppt. The current speed in the Malacca Strait is classified as weak to strong with the direction of movement of the Malacca Strait ocean currents back and forth. The Malacca Strait waters have a mixed tidal type of double daily inclination with an F value of 0.6 cm. The sea level rise in the Malacca Strait ranges from 0.50 - 0.76 cm. The IOD phenomenon affects sea surface temperature, salinity, sea level rise, and current velocity depending on the IOD phase.

Keywords: Indian Ocean Dipole (IOD), Sea Surface Temperature, Currents, Sea Level Rise

1. INTRODUCTION

The Indian Ocean Dipole (IOD) phenomenon is a phenomenon that occurs in the Indian Ocean due to differences in sea surface temperature anomalies between the Western Indian Ocean region and the Eastern Indian Ocean region. This interaction produces high pressure in the Eastern Indian Ocean (South of Java and West of Sumatra) which causes the flow of air masses to blow to the West. This wind gust will push the water mass in front of it and lift the water mass from below to the surface[1]. The IOD shows the ocean-atmosphere conditions in the Indian Ocean. These conditions are measured using an index called the Dipole Mode Index (DMI), which is the difference between sea surface temperature anomalies in the Western Indian Ocean. The IOD phenomenon is divided into three phases: neutral phase, positive phase, and negative phase. The IOD phenomenon affects oceanographic parameters such as sea surface temperature, salinity, currents, and sea level rise in Indonesian waters.

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Sea level rise is a phenomenon of rising sea levels caused by many factors one of which is global warming and IOD so it will have an impact on drought or increased rainfall intensity which affects temperature and salinity values[2]. If the average salinity increases, the IOD will increase, as well as when the average salinity decreases the IOD will decrease. Based on quality standards for marine biota, the range of natural salinity values is 33 ppt to 34 ppt[3]. In addition, IOD is also influenced by sea surface temperature.

Sea surface temperature in Indonesia varies because the temperature value in the waters is influenced by external factors[4]. Generally, the optimum seawater temperature for plankton growth in tropical seas is between 25-32°C, and sea surface temperatures in Indonesian waters generally range from 28-31°C[5]. The main cause of temperature variations in Indonesian waters is the Indian Ocean Dipole (IOD). In the positive IOD phase, the warm pool will shift to the African coast and the sea surface temperature in western Indonesia will be cooler, resulting in a decrease in condensation and rainfall levels, resulting in a dry season. Warm or cold sea surface temperature anomalies in the western Indian Ocean are followed by cold or warm sea surface temperature phenomena in the eastern Indian Ocean so that the polar region (pole) has a cold temperature which results in the IOD phenomenon.

In Indonesian waters, research on the influence of the IOD phenomenon on several oceanographic parameters has been widely studied. However, studies on the effect of IOD on oceanographic parameters such as temperature, salinity, currents, and sea level rise, especially in the Malacca Strait waters, have never been conducted. The Malacca Strait is a very important waterway because it connects the Indian Ocean and the South China Sea (Pacific Ocean), so it is strongly influenced by the Indian Ocean Dipole (IOD) phenomenon. The northern part of the Malacca Strait is classified as deep and wide waters and is strongly influenced by the dynamics of the Andaman Sea, while the southern part of the strait is classified as shallow waters with narrow topography and is influenced by the dynamics of the South China Sea[6]. Therefore, the author is interested in researching the influence of the Indian Ocean Dipole (IOD) phenomenon on these oceanographic parameters.

2. RESEARCH METHOD

Time and Place

This research was conducted from November 2022 - February 2023. Global data collection in this study was located in the waters of the Strait of Malacca and data collection for validation was carried out in the waters of North Rupat (Figure 1).

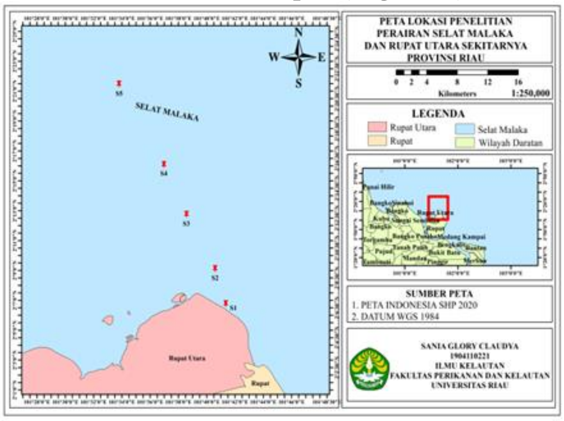

Figure 1. Map of research locations

Methods

The method used in this research is the survey method, which is to observe the characteristics and conditions of the waters and take data directly in the field. Data processing and analysis using descriptive methods that serve to describe the influence of the IOD phenomenon on oceanographic parameters through the results of data analysis that has been processed.

Procedure

Current Velocity

Current speed data will be processed using Microsoft Excel by entering the results of the current speed formula. The results will be made in the form of graphs which will then be compared with data obtained through global data to be used as verification data.

Sea Surface Temperature

Sea surface temperature data will be processed using Microsoft Excel so that a graph is obtained, then the results will be compared with data obtained through global data to be used as verification data.

Sea Level Rise

Sea level rise data is obtained by downloading Altimetry satellite image data through the site https://marine.copernicus.eu/. The data format obtained is in the form of a file format, namely NETCDF. Data processing with grads begins with entering data that has been downloaded using a script then the data is processed by entering the time range to be studied and will produce a map. Then processed again to find the range of sea level rise values that occur. After the value of sea level rise is obtained, it will be processed using Microsoft Excel to get a time series graph.

Salinity

Salinity data is obtained by downloading Altimetry satellite image data through the site https://marine.copernicus.eu/. The data format obtained is in the form of a file format, namely NETCDF. Data processing with grads begins with entering data that has been downloaded using a script then the data is processed by entering the time range you want to study and will produce a map. Then processed again to find the range of salinity values that occur. After the salinity value is obtained, it will be processed using Microsoft Excel to get a time series graph.

Current

Current data is obtained by downloading Altimetry satellite image data through the site https://marine.copernicus.eu/. The data format obtained is in the form of a file format, namely NETCDF. Data processing with grads begins with entering data that has been downloaded using a script then the data is processed by entering the time range you want to study and will produce a map. Then processed again to find the range of current values that occur. After the salinity value is obtained, it will be processed using Microsoft Excel to get a time series graph.

Sea Surface Temperature

Sea surface temperature data is obtained by downloading Altimetry satellite image data through the site https://oceancolor.gsfc.nasa.gov/. Data processing with grads begins by entering Aqua MODIS data that has been downloaded using a script then the data is processed by entering the time range you want to study and will produce a map. Then processed again to find the range of salinity values that occur. After the salinity value is obtained, it will be processed using Microsoft Excel to get a time series graph.

Tides

Tidal data is obtained through the Naotide program which will be processed again in Microsoft Excel using the admilatry method to determine the type of tides that occur. In the Admiralty method, the tidal harmonic constants M2, S2, K1, and O1 are obtained through calculation stages starting from Scheme 1 to Scheme 8. Determining the tidal type by calculating the Formzahl value. Formzahl is a number to determine tidal type using a formula. The following equation is used in this study, as used by Wijaya et al[7] as follows:

$$F = \frac{O_1 + K_1}{M_2 + S_2}$$

After obtaining the results of the formula will classify the type of tides in the research[8] as follows:

$F < 0.25$ = semidiurnal
$0.25 < F < 1.50$ = mixed, mainly semidiurnal
$1.50 < F < 3.00$ = mixed, mainly diurnal
$F > 3.00$ = diurnal

Indian Ocean Dipole (IOD)

IOD data in the form of DMI (Dipole Mode Index) data obtained through the Noaa website will be processed in Microsoft Excel by finding the average of each month and year to get the results in the form of graphs. After obtaining the results, the years of positive, negative, and neutral DMI events will be identified, which are carried out by the statement Ramadhanty et al.[2] as follows, DMI > 0.48℃ = positive DMI; -0.48℃ ≤ DMI ≤ 0.48℃ = neutral DMI; DMI < 0.48℃ = negative DMI

Data Analysis

The test parameters in this study were the data analysis used in this research is descriptive. Includes spatial and temporal analysis. Spatial analysis was carried out by processing secondary data using grads with the final result in the form of maps of sea level rise, salinity, currents, and temperature. And temporal analysis is analyzed with the results of processed data processed using Microsoft Excel to get the final result in the form of a time series graph to be able to determine the increase and decrease in the value of the parameters observed. The data obtained were analyzed descriptively by comparing literature and research results and then presented in the form of maps, tables, and graphs.

3. RESULT AND DISCUSSION

The Strait of Malacca is located between two large land masses, the island of Sumatra and Peninsular Malaysia. Currently, three sovereign countries border the Strait of Malacca, namely Indonesia, Malaysia, and Singapore. The length of the Malacca Strait is about 805 km or 500 miles with a width of 65 km or 40 miles on the south side and a widening to the north by about 250 km or 155 miles.

The boundaries of the Malacca Strait are in the West bordered or parallel to the northernmost part of the island of Sumatra (5°40′LU 95°26′BT) and Lem Voalan in the southernmost part of Goh Phuket (Phuket Island) in Thailand (7°45′LU 98°18′BT). On the East, it is parallel between Tanjong Piai (Bulus), and the southernmost part of Peninsular Malaysia (1°16′E 103°31′BT) and then towards Karimun (1°10′E 103°23.5′BT). On the North side it is bounded by the Southwest coast of Peninsular Malaysia and from the South it is bounded by the Northeast coast of Sumatra Island to the East of Tanjung Kedabu (1°06′N 102°58′BT) then to the island of Karimun.

Oceanographic Parameter Conditions
Sea Surface Temperature

SST conditions in the Malacca Strait can be known by using secondary data and primary data obtained in the field. Primary data collection in this study is useful for comparison with secondary data (global data) to obtain accurate data. Data obtained directly from the field can be seen in Table 1.

Table 1. Validation of Malacca Strait Sea Surface Temperature

Research Station	SST ℃
St 1	30
St 2	30
St 3	29
St 4	29
St 5	28

Table 1 shows the temperature value of the Malacca Strait waters by taking data directly from the field. Based on the field data obtained, the Malacca Strait SST value ranges from 28-30 ℃, the lowest SST is found at station 5 and the highest at stations 1 and 2. This is because station 5 is in mid-ocean waters, while stations 1 and 2 are still waters close to the coast.

The SST value at the time of the study is different from the SST value obtained using satellite imagery. This happens because the temperature at the time of the study was taken in February 2023 while the temperature in the global data was taken in 2013 - 2022. The SPL value can be seen in the time series graph, there is a change in SST every month from 2013-2022 (Figure 2).

Overall, Figure 2 shows that the monthly average SPL in the period January 2013 - October 2022 ranged from 28.72 - 31.45 °C. In general, the SST value looks relatively stable within 10 years and has almost the same distribution pattern every year. However, there was a significant fluctuation in 2014, where the SST experienced a considerable increase and decrease in the same period. The highest increase occurred in August 2014 while the lowest occurred in January 2014.

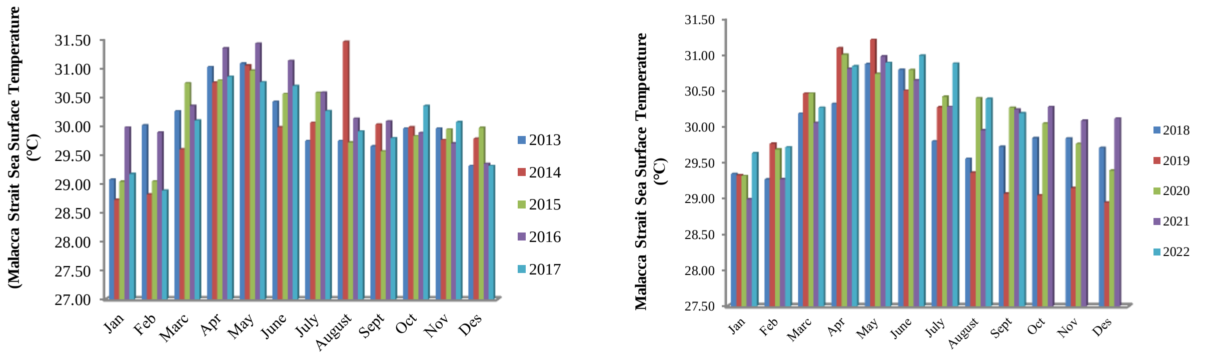

Figure 2. Malacca Strait SST values 2013-2022 (Monthly)

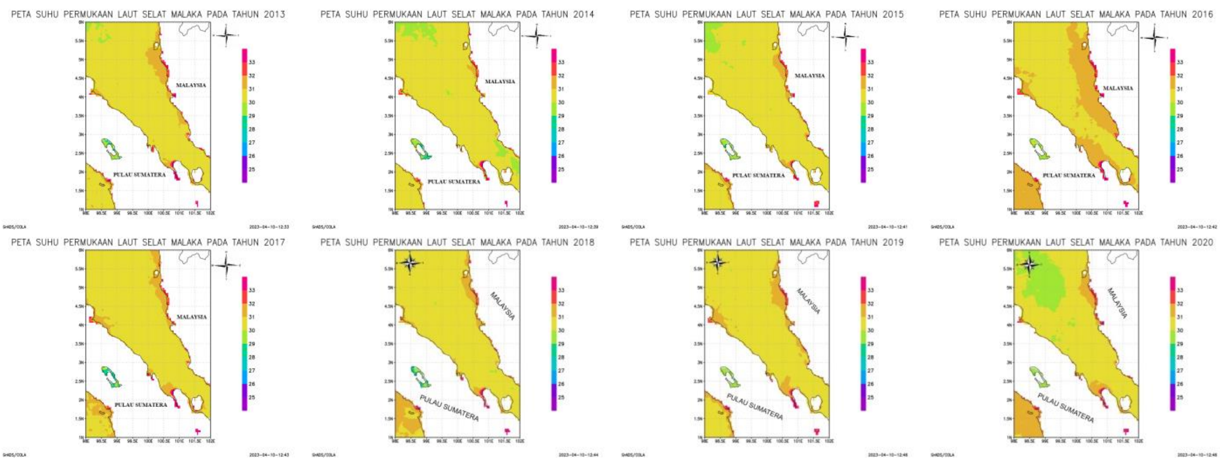

Figure 3. Sea Surface temperature map of the Malacca Strait 2013-2020

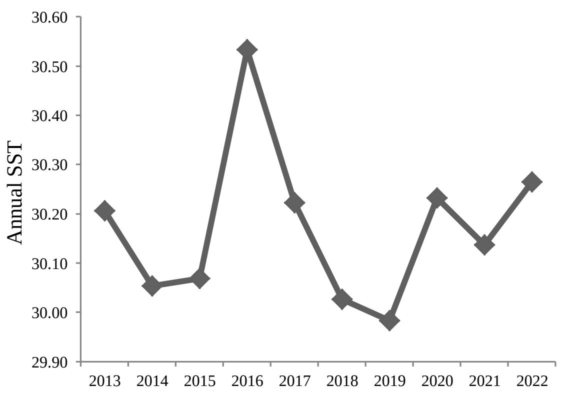

Figure 4. Average annual SST

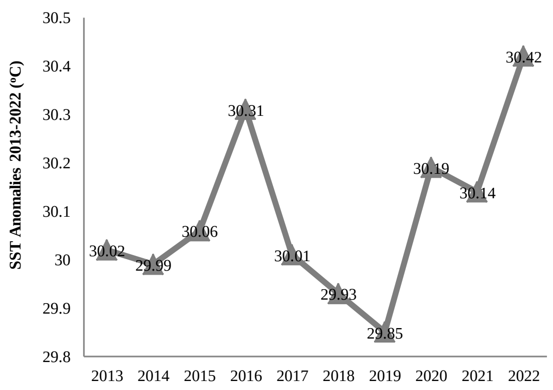

Figure 5. SST anomalies 2013-2022

In Figure 3 there is a map of SPL processed using remote sensing, namely AQUA Modis satellite data with grads software. The annual SPL data obtained on the AQUA Modis satellite only reaches 2020, there is no recent data from 2021 - 2022.

Figure 4 shows that the highest average annual SST value occurred in 2016 with an SST value of 30.53℃ while the lowest average SST value occurred in 2019 with an SST value of 29.98℃.

Based on the graph of monthly and yearly SPL values, there is a temperature change that is not too significant when experiencing a decrease or increase in SPL. Figure 5 show that the SPL anomaly in the Malacca Strait for the period 2013-2022 shows varying SPL values. The highest SPL occurred in 2022 at 30.42℃, while the lowest SPL occurred in 2019 at 29.85℃. This shows an increase and decrease in SPL in the Malacca Strait during this period.

The occurrence of SPL fluctuations is due to the influence of weather, water depth, waves, measurement time, convection movement, location of altitude from the surface, and the amount of light intensity received by the waters. In addition, ocean currents play an important role in the distribution of SPL and change in its trends in the Indonesian region. According to Swandiko et al.[9], SST variability in the Malacca Strait is dominantly influenced by wind and surface currents. Ocean surface currents generated by the wind influence the distribution of water masses which will affect SST.

The Malacca Strait is an inter-oceanic water mass exchange route where areas traversed by currents from the Indian and Pacific Oceans appear to experience more pronounced trends in SST changes[10]. So far, the observed temperature range is still within the limits of the optimal range of seawater temperatures, namely 27 - 32 ℃, this is by the statement of Patty & Akbar[11]. that the temperature range commonly found in Indonesian marine waters ranges from 27-32 ℃.

Salinity

Salinity conditions in the Malacca Strait can be determined using global data, namely altimetry data. The data is used to estimate salinity conditions in the Malacca Strait and processed using GrADS software to get results in the form of maps and graphs.

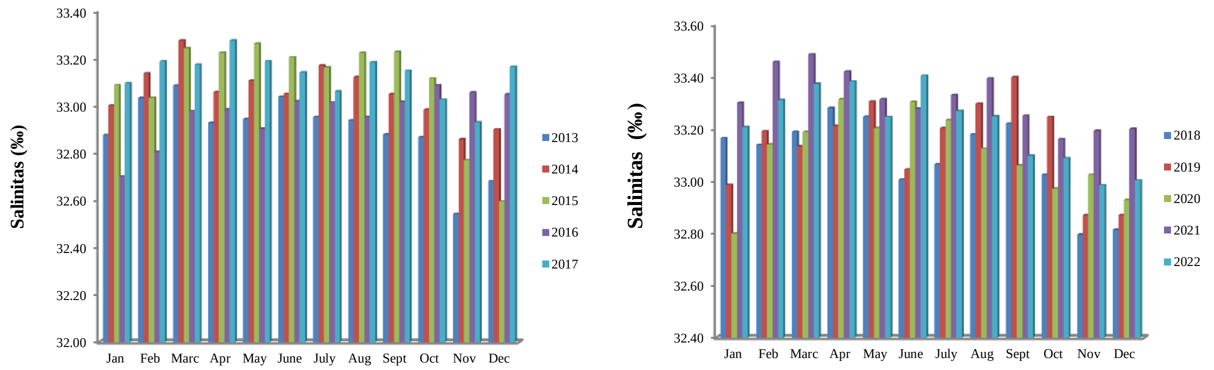

Figure 6. Salinity value of the Malacca

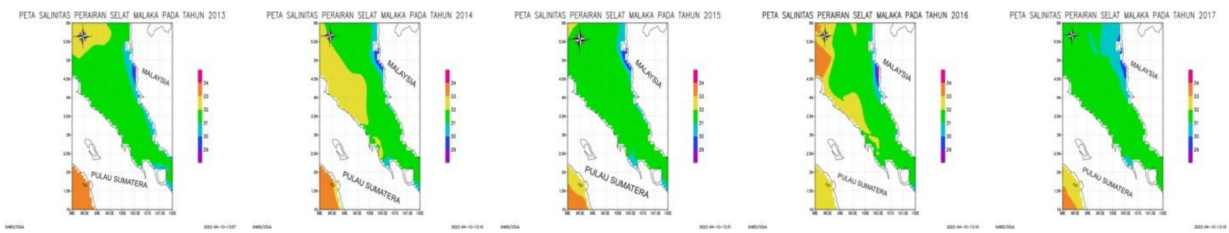

Figure 7. Salinity map of the Malacca Strait and surrounding waters 2013 – 2022

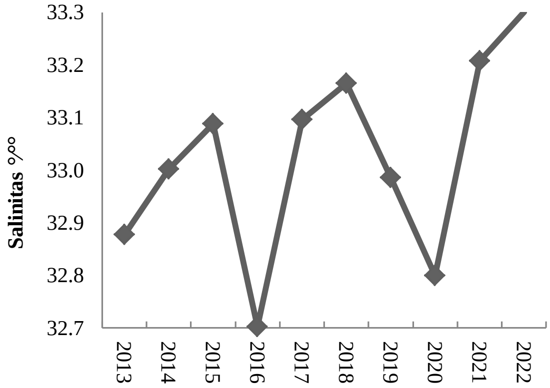

Figure 8. Average annual salinity

In Figure 7 there is a salinity map processed using remote sensing, namely altimetry satellite data with grads software. Based on the results of the Malacca Strait salinity map above, it appears that the salinity value ranges from 29 - 33‰. The salinity value can be seen in the time series graph where there is a change in salinity every month from 2013-2022.

Figure 8 shows that the highest annual salinity value occurred in 2022 with a salinity value of 33.30‰, while the lowest salinity value occurred in 2016 with a salinity value of 32.70‰. Based on the graph of salinity values per month and year, there is a change in salinity every month which is not too significant when experiencing a decrease or increase in salinity only reaches a range of 0-10‰. In general, for monthly salinity values, the high salinity phase occurs in March or April while at the end of the year such as in November and December salinity begins to decrease.

The Malacca Strait is located in the tropics, where hot weather conditions and low rainfall tend to make seawater saltier. However, although the salinity value is quite high, the change in salinity each month is not too significant. Changes in seawater salinity can be influenced by several factors. The factor of high rainfall in coastal areas can affect the value of seawater salinity. This is because high rainfall will bring fresh water to the sea so that it can reduce the salinity value. In addition, the level of evaporation of seawater can also affect the salinity value of seawater. High evaporation can increase the salinity value because it makes the salt concentration in seawater higher.

According to research by Syech & Malik[12] said that the salinity of the central and northwestern waters of the Malacca Strait along the coast of Riau Province is the influence of mixing with other solutes. In addition, the high and low value of salinity is influenced by high solar irradiation resulting in low salinity concentrations, but too low solar irradiation will also result in reduced salinity values. The salinity value of the Indonesian sea area generally ranges from 28-33, therefore the salinity value of the Malacca Strait waters is still considered optimal.

Current

The current data obtained in this study are current speed and direction. The speed and direction of the current in the

Malacca Strait can be known by using secondary data and primary data obtained in the field. Primary data collection in this study is useful for comparison with secondary data (global data) to obtain accurate data. Data obtained directly from the field can be seen in Table 2.

Table 2. Validation of Malacca Strait Waters Current Velocity

Research station	Current speed (m/s)	Current direction
St1	0,10	Northwest
St2	0,11	West
St3	0,09	West
St4	0,05	North
St5	0,09	Northeast

Table 2 shows the current speed of the Malacca Strait by taking data directly to the field. Based on the field data obtained, the current speed of the Malacca Strait ranges from 0.05 - 0.10 m⁄s with different current directions. The maximum current velocity occurs at station 2, which are 0.11 m/s with the current direction to the west. While the minimum current velocity occurs at station 4, which is 0.05 m/s with the current direction to the north. This can be caused by the shallower water depth at that location, thus reducing the current velocity.

In Figure 9 there is a current map processed using remote sensing, namely altimetry data with grads software. Based on the results of the Malacca Strait current map above, it appears that the direction of the Malacca Strait current varies every year. The narrow and elongated shape of the Malacca Strait causes convergence and divergence of currents in these waters so that a rotating current pattern (gyre) is obtained near the Andaman Sea. The current pattern in the Malacca Strait near the Andaman Sea is more influenced by tidal currents.

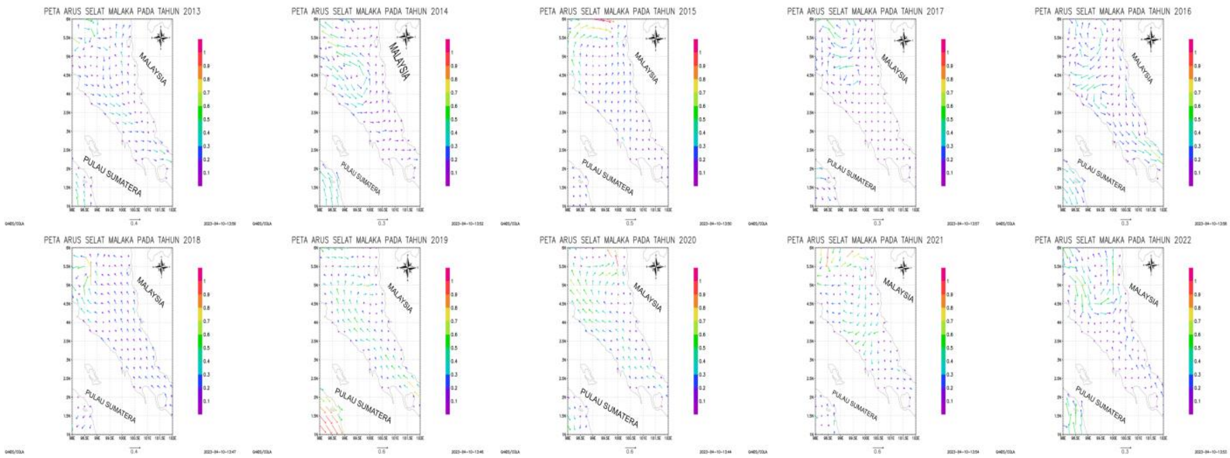

Figure 9. Current map of the Malacca Strait and surrounding waters 2013 – 2022

At high tide, the current flows from the Andaman Sea into the Malacca Strait and produces a northeastward current in the western part of the Malacca Strait. At peak tide, the current reaches its maximum speed and strong currents can form eddies around the western part of the Malacca Strait near the Andaman Sea. Meanwhile, at low tide, the current flows from the Strait of Malacca to the Andaman Sea, and strong currents can produce eddies to the southwest in the western part of the Strait of Malacca. According to Syech and Malik[12]. The current pattern in the Malacca Strait depends on the difference in sea level in the Northwest (Andaman Sea) and the Northeast (South China Sea). Therefore, there is a current that flows throughout the year to the northwest. The results of current processing using global data for 10 years can be seen in Figure 10.

The scatter plot above is used to present the distribution of ocean current speed and direction through the U and V components. From the scatter plot, it can be observed that the direction of ocean current movement is alternating, which is indicated by the presence of dots on each side. The current speed also varies as indicated by the different sizes and distribution of the dots on the scatter plot.

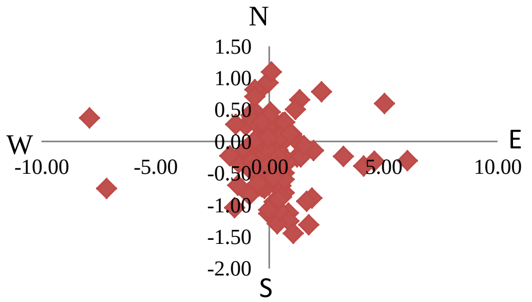

Figure 10. Scatter plot of Malacca Strait current

In the U component, the maximum current velocity value is around 6.05 (m/s) and the minimum current velocity value is around -7.90 (m/s). While in the V component, the maximum current velocity value ranges from 1.09 (m/s) and the minimum current velocity value ranges from -1.45 (m/s).

Based on the results obtained from field data and global data, the current speed and current direction in the Malacca Strait are different. The current pattern in the Malacca Strait is also complex and changes spatially and temporally. In general, the current in the Malacca Strait flows from northeast to southwest or from the South China Sea to the Indian Ocean. However, this current pattern can change depending on the factors that influence it. From these results, it can be concluded that the current speed in the Malacca Strait is classified as weak to strong. This is to the research of Sukuryadi[13] which states that the current speed is categorized as weak if the speed is <0.4 m/s, moderate if the speed is 0.4 - 1 m/s, and strong if the speed is >1 m/s.

Sea Level Rise

The admiralty method is one of several methods in tidal analysis that can describe the characteristics of the water level including information on tidal harmonic constants, water level elevation, and tidal type. The amplitude and phase values of the main tidal components M2, S2, K1, O1, MS4, M4, K2, and P1 from the measurement results for ½ month (15 days) can be seen in Table 3.

Table 3. Final tidal harmonic constant results

	So	M2	S2	N2	K2	K1	O1	P1	M4	MS4
A cm	121.9	17.3	14.1	11.8	3.2	1.5	17.1	0.5	0.5	0.5
g		28.5	309.5	267.7	309.5	119.6	280.4	119.6	66.9	322.4

Based on Table 3, the tides at the research site are dominated by the influence of semi-diurnal tides by the lunar drag with a value of M2, which is 17.3 cm. The amplitude value (S0) is the value of the mean sea level (MSL), which is 121.9 cm. The frequency of daily high and low tides determines the tidal type and quantitatively the tidal type can be determined by the ratio between the amplitude (half wave height) of the main double tidal elements (M2 and S2) and the main single tidal elements (K1 and O1). The above tidal fluctuations can be seen in Figure 11.

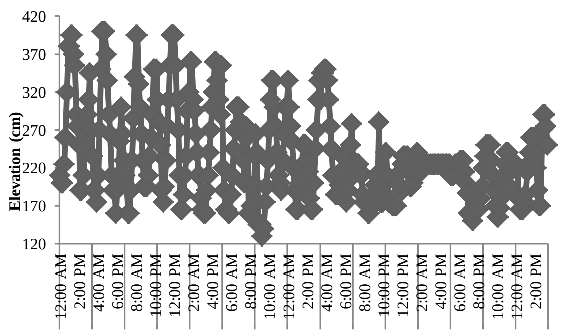

Figure 11. 15-Day Tidal Elevation Curve

The result of the calculation of the F value (Formzahl number) at the research location is 0.6 cm. This is included in the condition of 0.25 < F < 1.5 so that the type of tide at the research site is a mixed tide prevailing semidiurnal type. This means that in one day there are two tides and two low tides but have different heights and periods. This is to the statement of Ichsari *et al* (2020), namely the type of tides in the waters around the Malacca Strait and Indian Sea according to the double daily type. In addition, sea level rise can also be seen using satellite imagery processed using grads software.

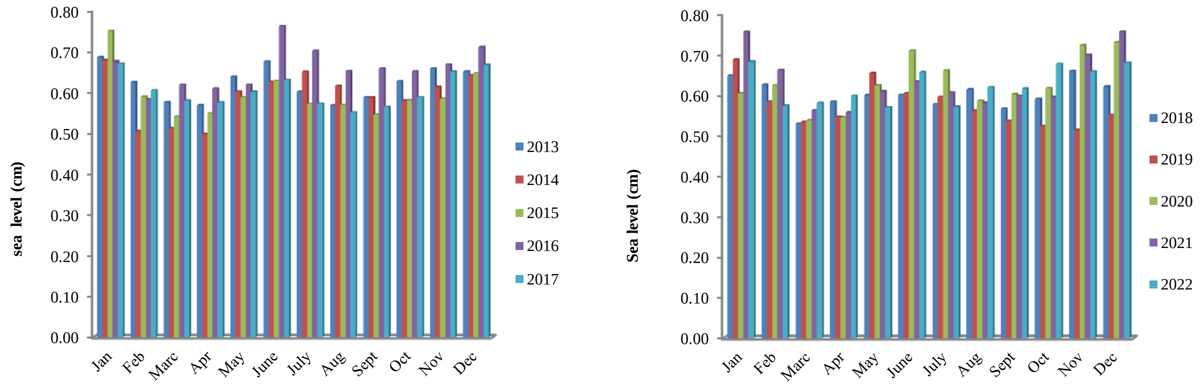

Figure 12. Malacca Strait sea level value 2013 - 2022 (Monthly)

Overall, Figure 12 shows that the monthly average sea level for the period January 2013 - December 2022 ranges from 0.50 - 0.76 cm. In general, the sea level values appear relatively stable over the 10 years. However, there are some months where the sea level reaches quite high or low numbers, such as in December 2021 where the highest increase occurred, while in April 2014 the lowest decrease occurred.

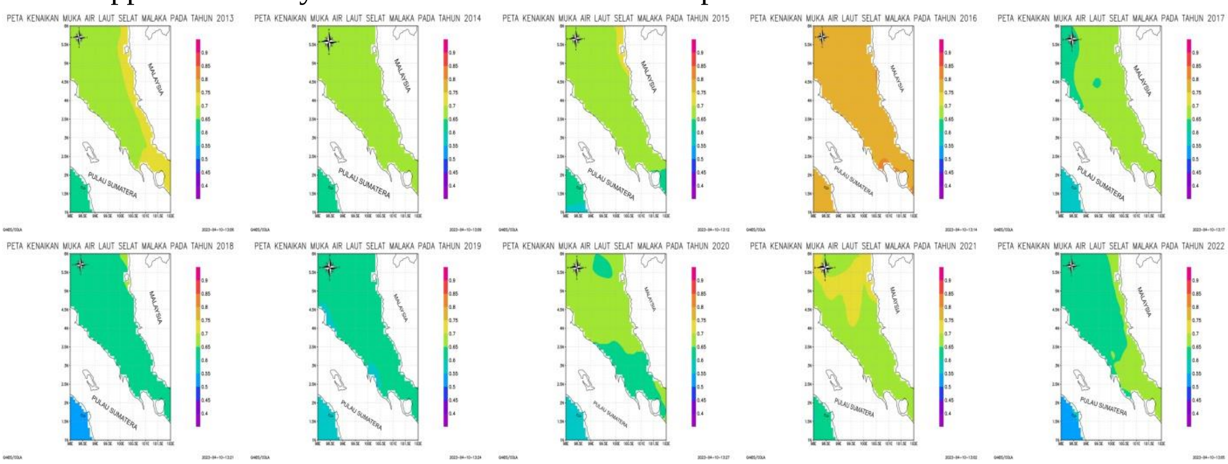

Figure 13. Sea level rise map of the Malacca Strait and surrounding waters

In Figure 13 there is a map of sea level rise processed using remote sensing, namely altimetry data with grads software. Based on the results of the Malacca Strait sea level rise map above, it appears that the sea level rise in the waters of the Malacca Strait is in the range of 0.55 - 0.8 cm. The highest sea level rise occurred in 2016 reaching 0.8 cm, this occurred due to several factors, such as global warming and the melting of polar ice caps which caused seawater to become higher, as well as ocean currents and tidal influences.

The highest annual sea level value occurs in 2021 with a sea level value of 0.76 cm while the lowest sea level value occurs in 2020 with a sea level value of 0.60 cm (Figure 14). Based on the graph of the value of sea level per month and year, there is a change in sea level every month which is not too significant when experiencing a decrease or increase in sea level only reaches a range of 0 - 0.25 cm. This indicates an increase in sea level in the Malacca Strait in the last 10 years. This increase in sea level can be caused by several factors such as global warming, melting polar ice caps, and tidal influences.

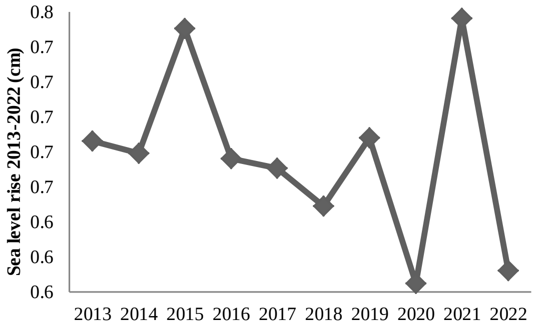

Figure 14. Annual Malacca Strait sea level value

The average annual sea level change varies between 3.4 - 5.3 mm, higher than the average global sea level change of 3.2 mm/year. This indicates that the Malacca Strait has a higher sea level rise than the global sea level rise in general. The continuous increase in sea level rise will have an impact on various aspects such as ecosystem damage, coastal erosion, and others.

Effect of Indian Ocean Dipole (IOD) on Oceanographic Parameters

The Malacca Strait is a strait that connects the Indian Ocean and the South China Sea. The strait is located between western Sumatra Island and Peninsular Malaysia and southern Thailand. In the Indian Ocean around the equator, climate aberrations are produced by ocean-atmosphere interactions called the Indian Ocean Dipole (IOD).

The interaction generates high pressure in the eastern Indian Ocean (south of Java and west of Sumatra) which causes the flow of air masses to blow to the west. This wind gust will push the water mass in front of it and lift the water mass from below to the surface. IOD conditions are measured using an index called the Dipole Mode Index (DMI), which is the difference between sea surface temperature anomalies in the Western Indian Ocean.

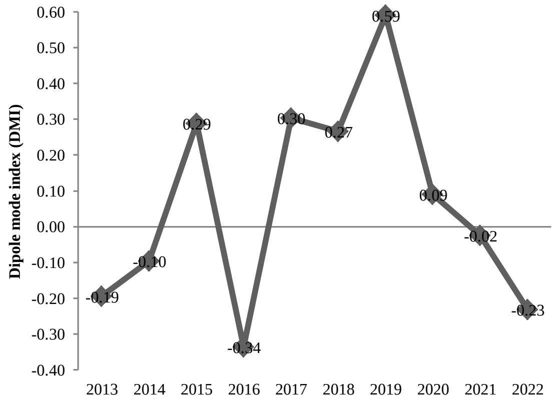

Figure 15. Average IOD in 2013 – 2022

In Figure 15, it can be seen that the average DMI for the period 2013 - 2022 ranges between - 0.34 - 0.59, so positive IOD is obtained in 2019 and others include neutral IOD types. The monthly DMI values can be seen in Appendix 7. Both phases will affect oceanographic parameters in the Malacca Strait waters.

IOD Effect on SPL and Salinity

The Dipole Mode graph shows the results of data processing of Dipole Mode index values and SPL values in the Malacca Strait waters. In Figure 15 there are positive, neutral, and negative DMI values to show the condition of temperature anomalies on the water surface in Indian Ocean waters, which are precisely in the Malacca Strait.

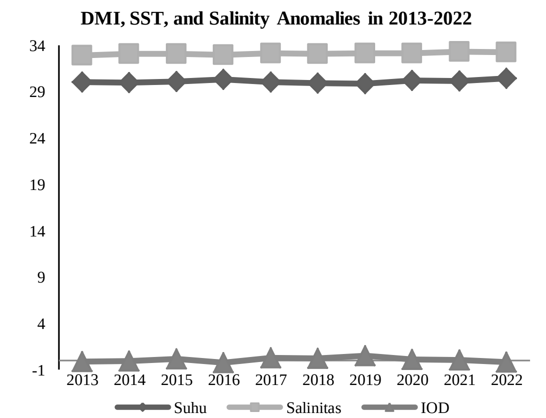

Figure 16. Graph of DMI, SPL, and salinity anomalies in the Malacca Strait waters 2013 - 2022

Figure 16 shows that the Malacca Strait waters from 2013 to 2022 were affected by the neutral and positive IOD phenomena. During the neutral IOD phenomenon, the average DMI value is 0.01 while the SPL value is 30.12 ℃ and salinity is 33.10. The positive IOD phenomenon phase occurred in 2019 with a DMI value of 0.53 while the SPL value was 29.85℃ and salinity was 33.15.

During the positive IOD phase, there was an increase in salinity and a decrease in temperature in the Malacca Strait region. This is probably because there is a significant temperature difference between the western and eastern regions of the Indian Ocean, resulting in the flow of colder seawater from the eastern region to the western region. The increase in salinity in the Malacca Strait is only 0.05 and the decrease in SPL in the Malacca Strait is 0.27℃.

From the SPL and salinity data, it can be concluded that the IOD phenomenon can affect sea conditions in the Malacca Strait waters with varying effects depending on the IOD phase that occurs. This is supported by the research of Nababan et al.[14] which states that during the positive IOD phenomenon, the sea surface temperature is relatively lower than during the negative or neutral IOD phenomenon, and according to Wardani et al.[15] which states that, if the average salinity increases, the IOD will increase, as well as when the average salinity decreases the IOD will decrease.

The Effect of IOD on Current

During the positive IOD phase, the temperature difference between the western and eastern regions of the Indian Ocean increases, resulting in the flow of warmer seawater from the eastern region to the western region. This can cause an increase in current speed in eastern African waters and a decrease in current speed in western Indonesian waters. Conversely, in the negative IOD phase, there is a flow of colder seawater from the western region to the eastern region, which can lead to an increase in current speed in western Indonesian waters and a decrease in current speed in eastern African waters.

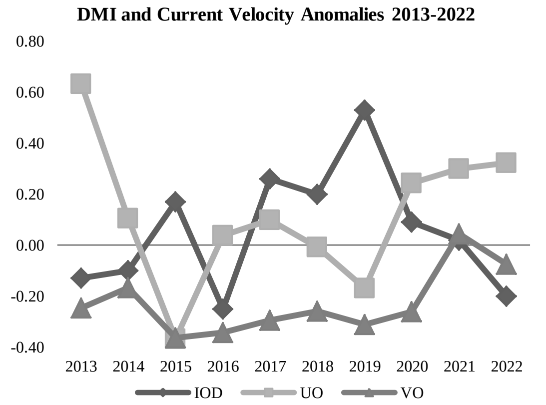

Figure 17. Graph of DMI Anomalies and Malacca Strait Current Speed 2013 – 2022

Figure 17 shows that the waters of the Malacca Strait in 2013-2022 are exposed to neutral and positive IOD phenomena, in addition, there is a value of separation of the U (East-West) and V (North-South) components. During the neutral IOD phenomenon with an average DMI value of 0.01 while the value of the U component, which is 0.15 (m/s), and the value of the V component, which is - 0.22 (m/s). In this phase, the currents in the Malacca Strait include weak currents.

The phase of the lowest positive IOD phenomenon occurred in 2019 with a DMI value of 0.53 while the value of the U component, namely 0.63 (m/s), and the value of the V component, namely 0.04 (m/s). In this phase, the currents in the Malacca Strait include moderate currents compared to the neutral IOD phase.

From the results obtained, the IOD phenomenon can affect the current speed in the Malacca Strait. When the IOD phenomenon is positive, the current speed in the Malacca Strait tends to be stronger than in the neutral IOD phase. However, it is inversely proportional to the research of Hafizhurrahman et al.[16] that when DMI is positive, the current speed is slow, otherwise when DMI is negative, the current speed is faster. This can occur due to differences in the study area and year studied.

The IOD's Effect on Sea Level Rise

The graph below shows the DMI anomaly and sea level rise for 10 years to see the effect of IOD on sea level rise.

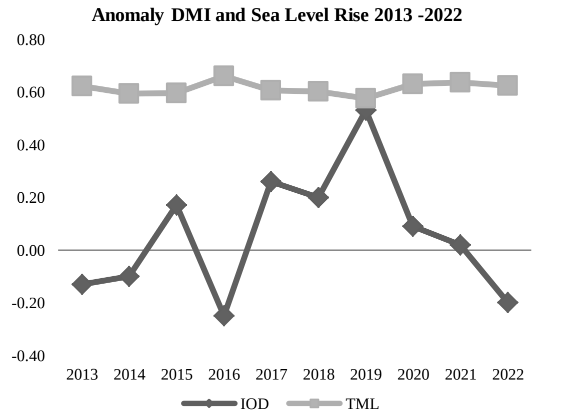

Figure 18. Graph of DMI anomaly and sea level rise in the Malacca Strait 2013 – 2022

Figure 18 shows that the waters of the Malacca Strait in 2013-2022 were exposed to neutral and positive IOD phenomena; in addition, there is a value of sea level rise in the waters of the Malacca Strait. During the neutral IOD phenomenon, the average DMI value is 0.01, while the value of the sea level is 0.62 cm. The positive IOD phenomenon phase occurred in 2019 with a DMI value of 0.59 while the sea level value was 0.66 cm.

From the above results, it can be concluded that the increase in sea level in the Malacca Strait waters experienced a not-too-high increase, which was only 0.4 cm. This shows that the IOD phenomenon influences sea level rise in the Malacca Strait. In the positive IOD phase, there is a higher increase in sea level rise than during the neutral IOD phenomenon.

4. CONCLUSION

The conclusions obtained are based on the results that have been analyzed, namely: 1) the observed SPL range of the Malacca Strait in the period January 2013 - December 2022 is still within the limits of the optimal range of seawater temperatures, namely 27 - 32 °C. 2) The salinity value of the Malacca Strait waters is still classified as optimal, namely, the salinity of the Malacca Strait in the period January 2013 - December 2022 ranges from 29 - 33‰. 3) The current speed in the Malacca Strait is classified as weak to strong and the current pattern in the Malacca Strait is also complex and changes spatially and temporally. 4) The Malacca Strait has a mixed tide prevailing semidiurnal type with an F value of 0.6 cm. The Malacca Strait sea level rise is higher than the global sea level rise in general, the range of sea level in the period January 2013 - December 2022 ranges from 0.55 - 0.8 cm. and 5) The IOD phenomenon can affect SPL, salinity, current speed, and sea level rise depending on the phase of the IOD.

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