

Sea Level Anomaly Variability Due to Global Climate in the Western Waters of Sumatra

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Paper History

Received: 02-May-2025

Received in revised form: 12-July-2025

Accepted: 30-July-2025

ABSTRACT

The western waters of Sumatra are part of the Indonesian waters that directly interact with the Indian Ocean, which is a climatologically complex area due to influenced by various atmospheric and marine phenomena that are seasonal and inter annual. Therefore, the purpose of this study is to analyze the influence of the El Niño Southern Oscillation (ENSO) phenomenon on changes in sea level in Western Sumatra waters during the period of 1997-2023. The data used include sea level anomaly (SLA), Oceanic Niño Index (ONI), and Dipole Mode Index (DMI). The results show that strong El Niño, such as in 1997/1998, cause sea level to drop to - 0.3 meters due to intense upwelling. In contrast, El Niño 2015/2016 increased sea level by + 0.2 meters due to the dominance of down welling. During the La Niña period, sea level rose significantly, reaching 0.3 meters in 2022/23. The long-term trend shows an average sea level rise of 0.056-0.064 meters over the last 26 years, with different variations between regions.

KEYWORDS: *The western waters of Sumatra, ONI, El Niño, La Niña, Sea level anomaly.*

1.0 INTRODUCTION

Western Sumatra waters are waters that directly interact with the Indian Ocean. These waters are included in the eastern waters of the Indian Ocean and have an inter-annual phenomenon of [1]. These phenomena are influenced by climate change. A phenomenon that usually occurs in the Pacific Ocean region is a change in sea surface temperature from normal conditions, often called El Niño and La Niña. El-Niño is a natural phenomenon scientifically defined as an

increase in sea surface temperature (SST) in the Central and Eastern Pacific region along the equator that exceeds its average value [2].

La Nina is the opposite of El Niño. This phenomenon occurs when El Niño begins to weaken, causing warm ocean water in the Peru-Ecuador waters to move westward again. As a result, seawater temperatures in the eastern Pacific Ocean region return to their original cooler conditions, and the upwelling process returns. Based on the ONI index, ENSO intensity itself is divided into three classifications consisting of:

1. + 1.5°C (strong El Niño)
2. +1.0°C to +1.5°C (moderate El Niño)
3. +0.5°C to +1.0°C (moderate El Niño [3].

The most vulnerable areas affected by the phenomenon of sea level rise are coastal areas. Coastal areas are highly vulnerable to environmental pressures, both from land-based sources and marine sources. Research conducted has shown that from 1950 to 2003, a sea level elevation of 39 cm per year is estimated in the Semarang area, attributed to the phenomenon of global warming. From the data, it can be concluded that the trend or rate of sea level rise in Semarang reached 7.36 mm per year.[4].

A frequently studied oceanographic parameter related to physical changes in water areas is sea level anomalies. These anomalies refer to deviations that occur from average sea level conditions. Sea level variability is also caused by the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena. The IOD is a pattern of variability in the Indian Ocean characterized by changes in sea surface temperature (SST) that are lower than normal [5]. IOD climate variability usually uses Dipole Mode Index (DMI) data, which is an index that describes differences in sea surface temperature anomalies in the form of monthly indices. DMI itself is divided into several classifications:

1. $DMI > 0.48^{\circ}\text{C}$ (positive DMI)
2. $-0.48^{\circ}\text{C} \leq DMI \leq 0.48^{\circ}\text{C}$ (neutral DMI)
3. $DMI < -0.48^{\circ}\text{C}$ (negative DMI) [6].

Sea level rise is a phenomenon that occurs due to the negative impacts of climate change. Climate change that causes global warming plays an important role in this process, where there is a mass exchange of water and ice between land and ocean. These impacts ultimately result in changes to the global mean sea level (GMSL) [7].

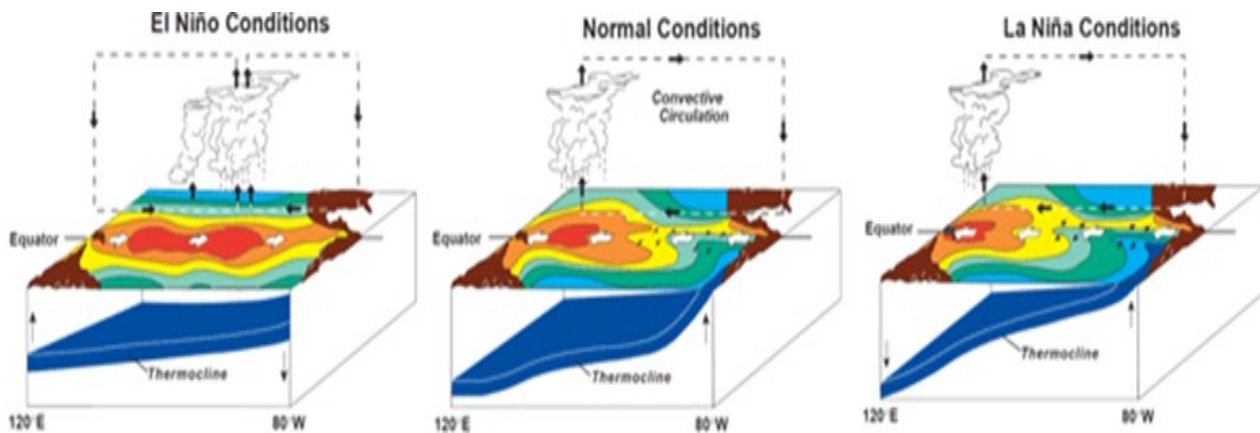


Figure 1. Modeled surface temperatures, winds, rising air area, and thermocline (blue surface) in the tropical Pacific during El Niño, normal, and La Niña conditions.
(Source: NOAA/PMEL/TAO Project Office, Dr. Michael J. McPhaden, Director)

Satellite altimeter measurements of sea level rise have been made and suggest that sea levels are currently rising by about 1 mm per year and are expected to continue growing. According to predictions, by 2080, the rate of sea level rise will reach about 4.2 mm per year [8]. Sea level rise results in a reduction in land area, including changes in coastlines. A very significant impact of this increase will be felt by Indonesian communities in coastal areas, especially in the Sumatra region. The trend of sea level rise has been identified and recorded that the waters of West Sumatra experienced an increase in sea level of 1.35 mm per year based on altimetry monitoring from various satellites during the period 1993 to 2015. These results indicate that there is a trend of continuous sea level rise in this region, so further studies are needed to understand the factors that cause it, including the influence of climate variability such as ENSO and IOD [9]. Therefore, a study was conducted to specifically investigate how annual and inter-annual climate phenomena such as El Niño-Southern Oscillation (ENSO) and Indian

Ocean Dipole (IOD) affect sea level anomalies (SLA) in the Western Sumatra Waters, with a focus on the years 1997 to 2023.

2.0 METHODS

2.1 Research Location

The research was conducted in the Western Waters of Sumatra. The research location was at coordinates 95°-110°BT and 11°LS - 6°LU. Represented by five areas, namely Aceh (4°N; 95°N), North Sumatra (2°N; 96°N), West Sumatra (1°N; 99°N), Bengkulu (3°N; 101°N), and Lampung (6°N; 103°N). The data used are monthly average sea level anomaly data for 26 years, starting from 1997 to 2023, Ocean Niño Index (ONI), and Dipole Mode Index (DMI) data.

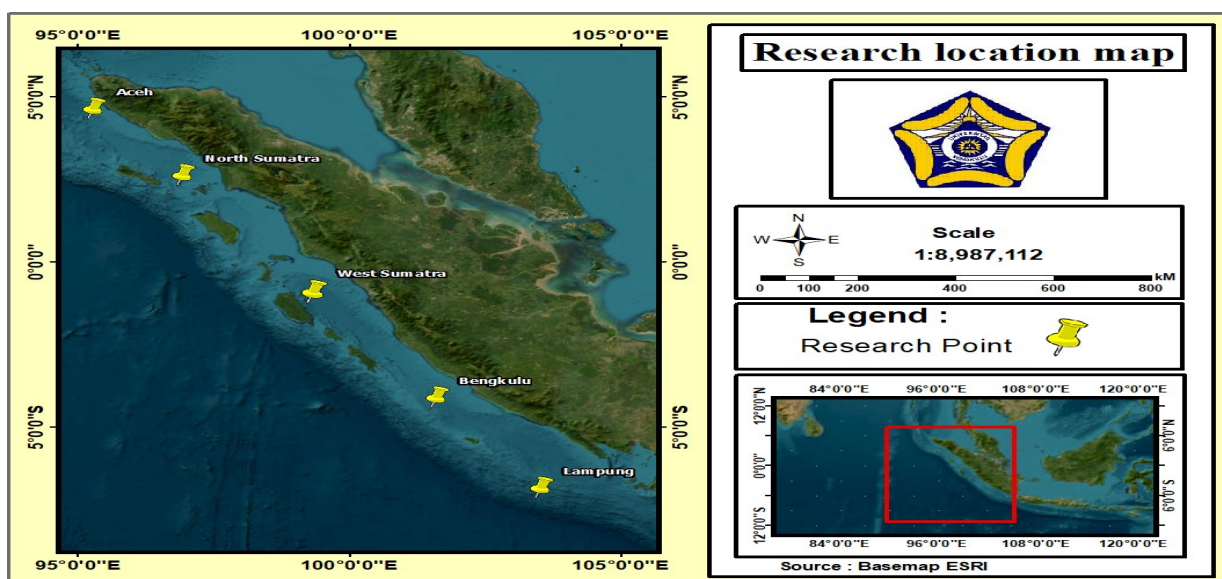


Figure 2: Research Location

2.2 Research Methods

The data used SLA (sea level anomaly) taken from the Copernicus Marine MyOcean Viewer site from 1997 - 2023, ONI, and DMI data taken from Climate Variability: Oceanic Niño Index | NOAA Climate.gov from 1997 - 2023. ONI data was an index that shows the division of regions and measures the value of SST (Sea Surface Temperature) in these regions in the Pacific Ocean [10]. So, the ONI and DMI indices themselves are indices related to sea surface temperature [11].

The methods used descriptive and quantitative methods. The descriptive methods were used to analyze SLA distribution maps, as well as graphs of ONI and DMI data. Quantitative was used to analyze the numbers of each parameter, namely SLA, ONI, and DMI. Data processing was carried out using Microsoft Excel and Panoply software. Panoply software was used to draw a distribution map of SLA, while Microsoft Excel was used to create time series graphs of SLA, ONI, and DMI.

3.0 RESULTS AND DISCUSSION

3.1 The Effect of El Niño on SLA in Western Sumatra Waters

El Niño has occurred several times in Indonesia with varying impacts, ranging from severe drought to extreme weather disturbances. The strongest El Niño has occurred twice. The current El Niño of 2015-2016 could be "one of the strongest ever" [12]. And the 1997/1998 El Niño had the highest index value since the previous 64 years [13].

The El Niño phenomenon has occurred 6 times [14]. This study focuses on three cases of El Niño and La Niña from 1997 to 2023 (Red box) and La Niña (Green box) in Western Sumatra Waters (Figure 3), which are used for comparison. Based on the trend graph of SLA, ONI, and DMI at several points in Western Sumatra waters, sea level has increased by 0.1 m every year for 26 years from 1997-2023. El Niño usually begins to develop in the middle of the year (June-August) and reaches its peak at the end of the year (November-January). This is due to the interaction between the atmosphere and the ocean in the Pacific Ocean, where sea surface warming in the central and eastern Pacific is maximized during this period. Based on the trend graph (Figure 3), the strongest El Niño occurred from November 1997 to January 1998 and November 2015 to January 2016. El Niño in that year experienced a very significant height. In 1997/1998, the height of ONI almost reached 2.5°C and was followed by a positive IOD of more than 1.5°C. And in 2015/2016 the ONI height reached 2.5°C with a positive IOD of 0.5°C.

During El Niño in 1997/1998, the sea level experienced a very low decrease of -0.3 m. The combination of high ONI (strong El Niño) and high DMI (positive IOD) caused a significant decrease in sea level in the Western Sumatra

Waters. This effect occurs due to changes in sea surface temperature, wind patterns, and ocean currents that reduce the volume of warm water in the coastal waters of Sumatra.

Unlike the 1997/1998 El Niño case, the 2015/2016 El Niño did not cause a significant drop in sea level. This can be seen in Figure 3, where sea level only decreased by 0.1m. This is because the positive IOD in 2015/2016 was not too high (IOD > 0.5). When the positive IOD is higher, the temperature difference between the western and eastern parts of the Indian Ocean is greater. As a result, sea level in the eastern Indian Ocean (including the Western Sumatra Waters) tends to fall.

In 2002/2003, the Western Sumatra Waters experienced a moderate El Niño with ONI reaching 1.2°C followed by a positive IOD of almost 0.5 degrees. The sea level drop this year was very insignificant (by 0.1 m) because El Niño 2002/03 was classified as an El Niño of moderate intensity and relatively short duration, so its impact on ocean and atmospheric dynamics was not as strong as an extreme El Niño.

During the La Niña period, sea levels in Western Sumatra increased (Figure 3). This is shown in the green boxed graph. During La Niña 2007/08 and 2010/2011, the sea level rose by 0.2 m and was accompanied by a strong La Niña of -1.5°C, and in 2022/2023, the increase was 0.3 m with a La Niña of -1°C. The sea level rise should have been followed by a very strong La Niña. However, in 2022/2023 there was a very significant increase. It was followed by a very strong positive IOD of 0.6°C. The combination of these phenomena led to an unusual anomaly in 2022/2023, with a larger than usual sea level rise during the strong positive IOD.

3.2 Variability of Sea Level Anomaly

Sea level anomalies at 5 points in the West Sumatra waters have different SLA heights. This can be seen clearly in the graph of sea level change trends in Figure 3(e) (Lampung), experiencing a very significant trend of increase and decrease in sea level when compared to Figure 3(a) (Aceh). In Lampung waters, the average SLA for 26 years was 0.062 m, with the highest increase of 0.4 m (2016) and the lowest of -0.3 m (2010) in contrast to Aceh, which has an average SLA of 0.056 m with the highest of 0.3 m (2016) and the lowest of -0.3 m (2010).

In the averaged sea level anomalies map of Western Sumatra, the blue color on the map represents a negative anomaly, which is a decrease in sea level, indicating upwelling. Meanwhile, yellow to red colors represent positive anomalies or an increase in sea level, indicating downwelling. The three periods studied show striking differences in the distribution of sea level anomalies due to variations in El Niño intensity.

In November 1997, Figure 4(a) shows that the west coast of Sumatra experienced a significant negative anomaly, with the sea level dropping to -0.3 meters. Zones A, B, C, D, and E all experienced negative anomalies, indicating strong upwelling.

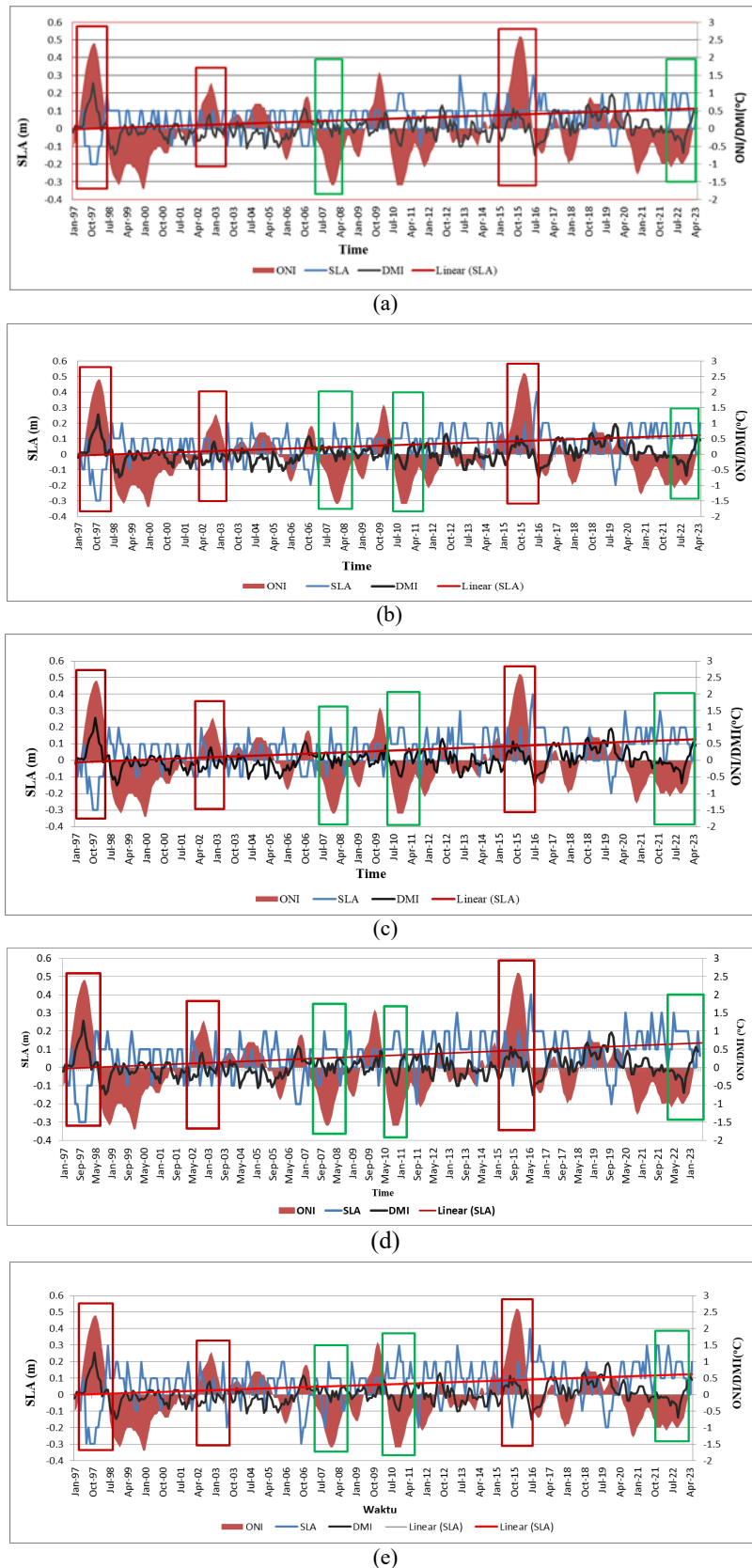


Figure 3. Trend graphs of SLA, ONI, and DMI at five locations along the western waters of Sumatra from 1997 to 2023, (a) Aceh, (b) North Sumatra , (c) West Sumatra, (d) Bengkulu, and (e) Lampung.

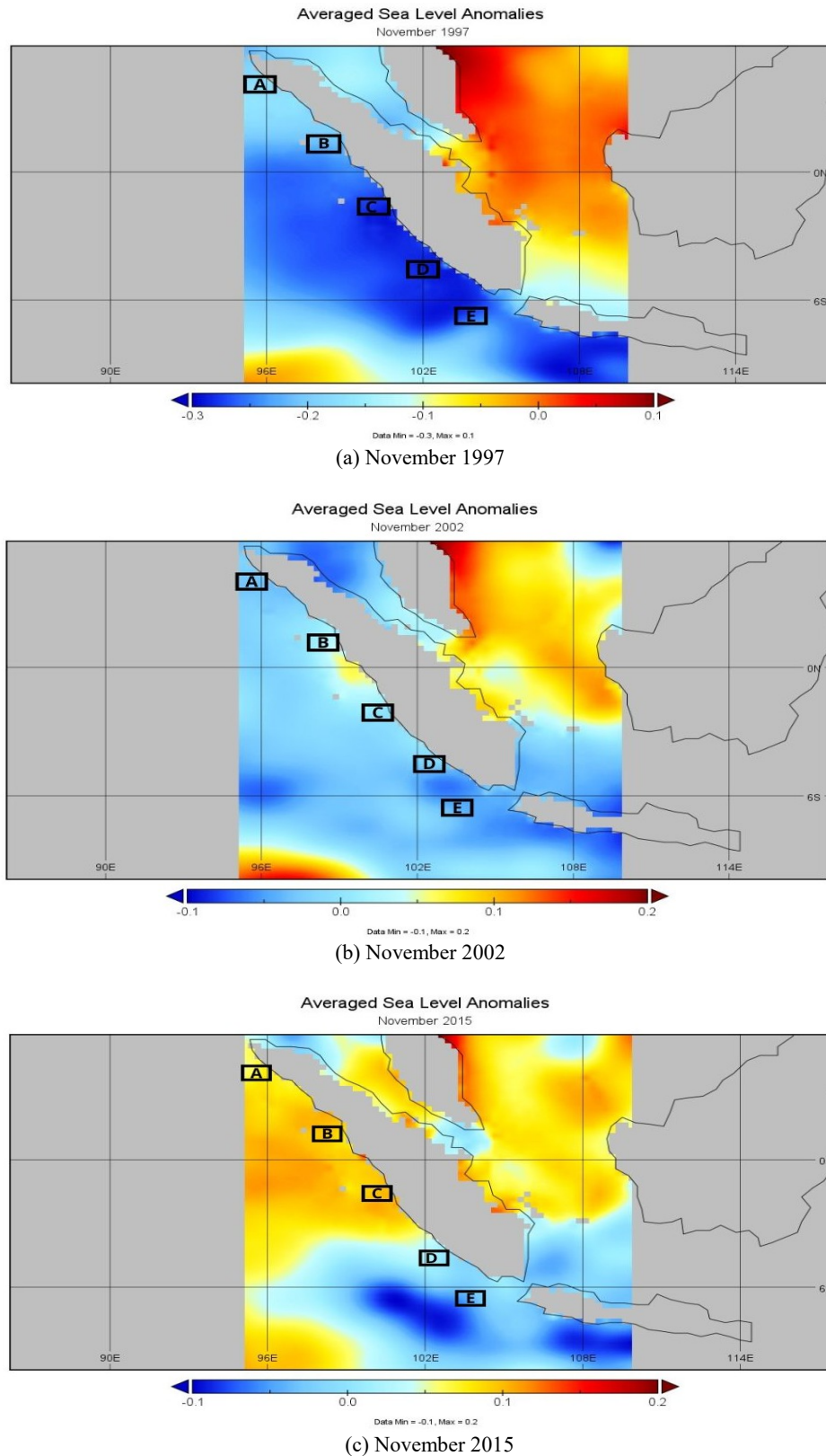


Figure 4. Map of averaged sea level anomalies during Peak El Niño Periods in November 1997 (a), November 2002 (b), and November 2015 (c) in Western Sumatra waters

In November 2002 El Niño phenomenon was classified as neutral, with weaker impacts than the 1997 El Niño. In 2002 Figure 4(b), the analysis shows that the Western Sumatra waters are still predominantly blue but lighter than in 1997, showing weaker negative anomalies, around -0.1 to -0.2 meters.

In November 2015, El Niño Figure 4(c) shows the West

Coast of Sumatra experienced a positive anomaly, with an increase in sea level of up to +0.2 meters. Zones A, B, and C showed an increase in sea level, indicating down-welling. Meanwhile, zone D still experiences a negative anomaly, but the intensity was much weaker. On the other hand, zone E experienced a slight negative anomaly with a decrease in sea level of around -0.1 meters.

Table 1: Average SLA over 26 years in Western Sumatra waters

Region	Aceh	Sumatra Utara	Sumatra Barat	Bengkulu	Lampung
Average SLA (m)	0.0546	0.060	0.058	0.064	0.062

Table 2: Comparison of El Niño and IOD Impacts on SLA in Western Sumatra Waters

Year	Intensity El Niño (ONI)	Intensity Dipole Mode Indexes (DMI)	SLA	Domain Pattern
Nov 1997	Strong (2.4°C)	Strong positive (1.279 °C)	-0.28 m	Upwelling
Nov 2002	Medium (1.3°C)	Neutral (0.096 °C)	0 m	Neutral
Nov 2015	Strong (2.6 °C)	Neutral (0.0347 °C)	+0.08 m	Down-welling

Although all three years experienced the El Niño phenomenon, its impact on sea level in Western Sumatra waters showed different variations. El Niño 1997 caused the most significant decrease in sea level, thus strengthening upwelling in Western Sumatra, while El Niño 2015 experienced an increase in sea level, which weakened upwelling and potentially down-welling. This was triggered by the fact that November also saw the transmission of Kelvin waves [15].

SLA fluctuations influenced by the ENSO and IOD phenomena not only impact oceanographic parameters but also have direct consequences for coastal communities. Sea level rise is a threat to coastal areas, which can cause flooding, land subsidence, and coastal erosion [16]. Therefore, this research can be used in designing mitigation and adaptation strategies, especially for vulnerable areas on the west coast of Sumatra.

4.0 CONCLUSION

Research shows that the intensity and pattern of El Niño have a significant impact on sea level dynamics. A strong El Niño in 1997/1998 caused a decrease in sea level of -0.3 meters due to upwelling. In contrast, El Niño 2015/2016, also classified as strong, increased sea level by +0.2 meters due to the dominance of down-welling. This difference in impact is due to variations in the interaction between ONI and IOD. During the La Niña period, there was a more significant sea level rise, reaching 0.3 meters in 2022/23. Overall, SLA has averaged 0.056-0.064 meters over the past 26 years, with fluctuations varying between regions. The sea level will rise by 0.1 m annually, which can lead to flooding and land reduction on the coast, which greatly affects coastal communities, especially in western Sumatra. These findings confirm that annual and inter annual climate variability has direct implications for ocean dynamics that have the potential to affect ecosystems in coastal areas. Therefore, this study provides a strong scientific basis to support coastal adaptation

planning and the development of climate-based early warning systems.

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