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Influence of Anomalous Upwelling on the Water Mass of South Java during Two Positive Indian Ocean Dipole in 2015 and 2019

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Abstract: Upwelling is a phenomenon that often occurs in the ocean. Upwelling can be interpreted as the process of rising sea water masses from below the surface to the surface due to the vacancy of sea water masses at the surface. The upwelling phenomenon will cause many anomalies that have a direct impact on ocean dynamics, one of which is the dynamics that occur in the waters south of Java. The formation of the coastal upwelling phenomenon in the waters south of Java in 2015 and 2019 was the cause of the active Positive IOD in both years. By carrying out time series analysis and spatial data visualization processes as well as correlation methods to determine the relationship between parameters, this research aims to discuss and find out about the influence of coastal upwelling dynamics on the waters of southern Java in 2015 and 2019. The results obtained from this research show that the coastal upwelling phenomenon formed in 2015 and 2019 along the waters of southern Java resulted anomalies in dynamic patterns in the form of decreasing sea surface temperatures and increasing chlorophyll-a concentrations.

Keywords: Chlorophyll-a; Coastal Upwelling; Ekman Transport; Positive IOD; Sea Surface Temperature (SST); Upwelling; Waters of Southern Java; Wind Stress.

Introduction

Indonesia's geographical location between the Indian Ocean and the Pacific Ocean means that the climate and weather in Indonesia always change every year and even every season. It should be noted that climate change not only presents challenges for environmental sustainability, but also has broad social and economic impacts. Many factors influence climate change in Indonesia, even causing extreme climate change. One of the factors causing extreme climate change is the active phenomenon of the Indian Ocean Dipole (IOD) anomaly, the impact of which can be directly felt in western to central Indonesia (Iskandar, 2013, Yuan et al., 2017). It should be noted that basically IOD events continue to occur every year, but the anomalies of IOD (Positive IOD and Negative IOD) themselves do not always occur every year but rather there is a certain period of time, namely once every two to four years (Utari et al., 2019).

Referring to one of the IOD anomalies, namely the Positive IOD, western Indonesia (Sumatra to Java) will experience severe drought and previous research shows that when the Positive IOD is active, it will not rain until the IOD anomaly ends (Wang et al., 2020; Irfan et al, 2021). The active Positive IOD is of course triggered by the interaction between the sea and the atmosphere that occurs in the Indian Ocean. For example, the active Positive IOD phenomenon, especially in 2015 and 2019, shows how important it is to understand the role that ocean and atmospheric processes play in influencing regional climate. Previous research shows that the upwelling phenomenon that occurs in the waters of southwest Sumatra to the south of Java is a very

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important factor for the blooming process of Positive IOD which is characterized by various changes in sea parameters ranging from changes in sea surface temperature to chlorophyll-a concentrations on the surface (Iskandar, 2009; Horii et al., 2022).

The upwelling phenomenon itself is a phenomenon in which masses of deep sea water, which are rich in nutrients, rise to the surface. It usually occurs when winds blowing along the coast push warm, light sea surface water offshore. As a result, cooler and nutrient-rich water rises to the surface to replace the vacancy in the water mass at the surface (Rao et al., 2008; Ogata et al., 2017). Note that the upwelling phenomenon will have a significant impact on changes in ocean and atmosphare. As in 2015 and 2019, the upwelling phenomenon is the trigger for the appearance Positive IOD whose impacts could be felt in Indonesia (both years experienced prolonged extreme drought). On the other hand, the upwelling phenomenon provides fertility for the waters along the west coast of Sumatra to the south of Java, where it is certain that when the upwelling phenomenon forms, there will be lots of fish along these waters. The waters south of Java, which is the intersection of water masses from the Pacific Ocean, Indian Ocean and Indonesian Sea, are often a place for active upwelling phenomena. The upwelling phenomenon that occurs in the waters south of Java cannot be separated from the dynamic pattern of upwelling itself. The dynamics in question are the relationship between ocean and atmospheric parameter which will later become a supporting factor in determining the emergence of the upwelling phenomenon. Then the relationship between each of these parameters will produce climatological dynamics which will ultimately produce anomalous dynamics that need to be taken into account (Netty et al., 2021). When an upwelling phenomenon occurs, it will result in anomalies appearing. The emergence of this anomaly will cause the ocean dynamics pattern in the southern waters of Java to experience significant changes, especially changes in sea surface temperature.

With the delving further the role of upwelling dynamics and its influence on sea surface temperatures, this research is expected to provide a more comprehensive understanding of the complex interactions between the ocean and the atmosphere play an important role in causing extreme climate change in the Indonesian region. Therefore, this research will focus on studying the dynamics of upwelling and its influence on sea surface temperature (SST) of waters of southern Java when the Positive IOD phenomenon occurred in 2015 and 2019. The reasons for choosing the Positive IOD phenomenon in 2015 and 2019 as research study is: It should be noted that in 2015 there was not only a Positive IOD phenomenon, but also an El-Niño phenomenon which had a direct impact on eastern to central Indonesia, including a direct impact to southern Indonesia. Meanwhile, 2019 was a year where the Positive IOD was formed very strongly compared to previous years in the last decade. The focus of the analysis in this study is on the spatial and temporal variability of anomalies and coastal upwelling intensity variations associated with the Positive IOD events of 2015 and 2019. This analysis will rely on SST and surface wind data (wind pressure & Ekman transport) originating from satellite observations.

Method

The area in this study is located along the waters of southern Java which is known as the intersection of water masses from the Pacific Ocean, Indian Ocean and Indonesian Sea (Sprintall et al., 1999). with a spatial astronomical location between 0°S - 15°S, 90°E - 125°E (Figure 1) and focusing on the region 9°S - 5°S, 102°E - 107°E (region A) and 12 °S - 8°S, 111°E - 115°E (region B). The research data that has been collected will be averaged based on regions A and B and the two will be compared based on the focus of the research year.

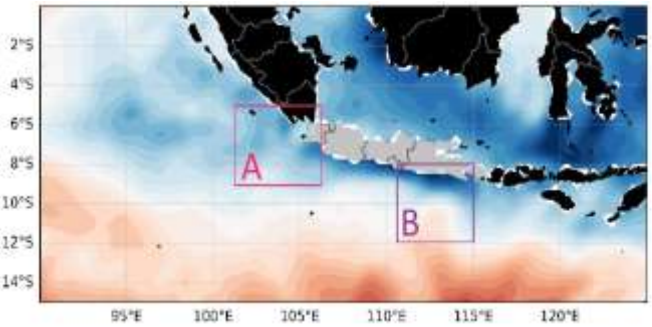

Figure 1. Map of the research area in waters south of Java (0°S - 15°S and 90°E - 125°E). The color shows the SST anomaly in October 2015, with regions A (pink box) and B (purple box) are the research focus areas.

The research will be carried out in four stages: 1) Literature Study, data collection; 2) Calculation of the Dipole Mode Index (DMI) and analysis of climate change anomalies that occurred in 2015 and 2019 in general through the results of DMI calculations; 3) Interpret and calculate each data parameter that has been collected into climatology & anomalies, as well as calculate the relationship between parameters using the Pearson correlation method; 4) Analyze and draw conclusions from the results of climatology interpretation, anomalies and correlation.

Data and Procedures

To determine the bloom of coastal upwelling in the waters south of Java, the data used in this research consists of SST, surface wind and surface chlorophyll-a data during the period January 2003 – December 2020. SST data was obtained from ECMWF ERA 5 which is available on the Climate website Copernicus with a resolution of 0.5° to determine changes in sea surface temperature due to the influence of upwelling. Then, surface wind data was obtained from ECMWF ERA 5 which is available on the Climate Copernicus website with a resolution of 0.5° which was used to calculate wind pressure anomalies and Ekman transport at positive IOD in 2015 and 2019. Then the last one, chlorophyll-a data was obtained from The Medium Resolution Imaging Spectroradiometer (MODIS) is provided by the National Aeronautics and Space Administration (NASA) with a uniform longitudinal and latitudinal resolution of 0.04° to determine the variability of chlorophyll-a on the surface along the waters of southern Java during upwelling active. According to Grill (1983), Ekman transport is defined by equation (1 & 2).

$$M_x = \int_0^z \rho \frac{1}{f\rho} \frac{\partial(\rho_a C_D |\bar{U}_{10}| \bar{U}_{10})}{\partial z} dz \qquad (1)$$

$$M_y = -\int_0^z \rho \frac{1}{f\rho} \frac{\partial(\rho_a C_D |\bar{V}_{10}| \bar{V}_{10})}{\partial z} dz \qquad (2)$$

Where M_x and M_y denote the zonal and meridional Ekman transport, respectively, and ρ is the density of seawater. f represents the Coriolis force, τ represents wind pressure, ρ_a represents air density (1,25 $kg\ m^{-3}$), C_D is the drag coefficient (2,6×10^{-3}), and $\bar{U}_{10}$ and $\bar{V}_{10}$ are zonal and meridional winds at a height of 10 m above sea level.

Climatology and Anomaly calculations

To get spatial visualization results as a model to see the dynamics of upwelling in 2015 and 2019, the data for each parameter will be processed and calculated first of the climatology value using equation (3).

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \qquad (3)$$

Where $\bar{X}$ is the average of a series of data, X_i is the i-th data value, dan N is the total amount of data. Furthermore, from the results of existing climatological data calculations, the data can be directly processed and the anomaly value calculated.

$$A_i = X_i - \bar{X} \qquad (4)$$

Where A_i is a i-th data anomaly, $\bar{X}$ is the average of a series of data, and X_i is a i-th data value.

Regression calculations and Pearson Correlation Analysis

Then, to explain the upwelling dynamics that form in the waters south of Java, especially in regions A and B, this research uses a linear regression method to obtain the relationship and interaction between each parameter.

$$Y = a + bX \qquad (5)$$

Where Y is the dependent variable, a is a constant, b is the regression coefficient, the b value is R in Pearson correlation, and X is the independent variable.

Then, to measure the strength and direction of the linear relationship between one parameter and another parameter in regions A and B, Pearson correlation analysis will be used. So apart from processing the data to get a good visual and regression model, the value of the relationship and interaction of each parameter will also be calculated using equation (6) Pearson correlation.

$$R = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n(\sum X^2) - (\sum X)^2] - [n(\sum Y^2) - (\sum Y)^2]}} \qquad (6)$$

With R is correlation value, Y is dependent variable, X is the independent variable, and n is the number of rows and columns of data. If the Pearson correlation value between the parameters is close to 1 (positive) or -1 (negative), it will indicate that there is a strong linear relationship between each parameter. On the other hand, if the result is close to 0, it will indicate a weak linear relationship between each parameter. To understand more easily and clearly the results of the relationship between parameters, we categorize the correlation values as follows:

Table 1. Correlation value interval to categorize the relationship between parameters.

Correlation Value [R]	Relationship Category
0 – 0.2	Very Weak
0.21 – 0.4	Weak
0.41 – 0.6	Medium
0.61 – 0.8	Strong
0.81 – 1	Very Strong

Result and Discussion

To see an IOD phenomenon in certain years, it is very important to calculate the Dipole Mode Index (DMI). Previous research explains that the Dipole Mode Index (DMI) is obtained from the difference between the average sea surface temperature of the west pole of the Indian Ocean and the average sea surface temperature of the east pole of the Indian Ocean (Iskandar, 2012; Cai et al., 2018; Doi et al., 2020; Utari, 2021; Ling et al., 2022). If the results show positive numbers for a period of more than 3 months in a particular year, then it can be seen that in that year the Positive IOD phenomenon occurred. Then, if the results show negative numbers for a period of more than 3 months in a particular year, then it can be seen that in that year the Negative IOD phenomenon occurred.

The DMI graph explains the temporal evolution of positive IOD that occurred in 2015 and 2019 (Figure 2). It is clear that both contain different information, where in the positive IOD phase in 2015 it could be said that it was just an ordinary positive IOD whose appearance period was not too long. The increase in DMI was observed since early August and showed a stable pattern until mid-November (Figure 2a—black curve). Please note, the DMI value in 2015 reached a maximum of +1.4°C. Meanwhile, the positive IOD in 2019 can be said to be the strongest positive phase (massive positive IOD) during the last decade (2011–2020) and its formation period was longer than in 2015. This is due to the increase in DMI observed since mid-July, even though the anomaly has occurred since the start of the decline in June. Then DMI experienced a fairly sharp decline in mid-August, then increased again in early September until ending in mid-December (Figure 2b—black curve). The peak DMI in 2019 reached a maximum of +2.4°C which occurred in October.

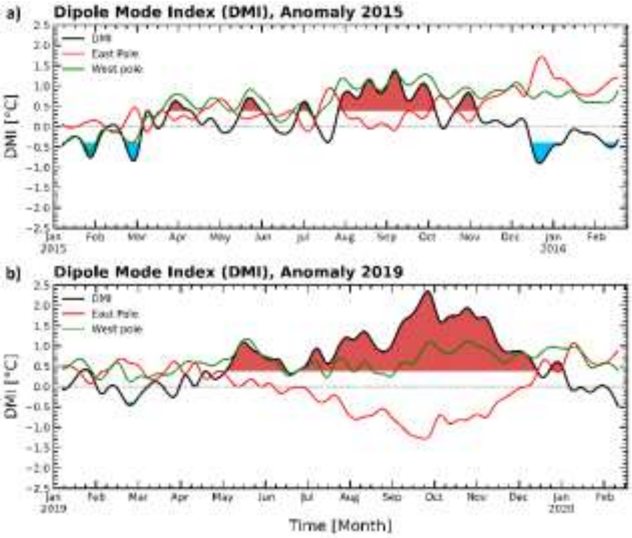

Figure 2. Time series of (**a**) Dipole Mode Index in 2015 (black) and (**b**) Dipole Mode Index in 2019. Note that the red shaded area indicates DMI values above one standard deviation, with a standard deviation value of 0.4°C and -0.4°C.

Previous study shown that the rise and fall of DMI is controlled by the variability of sea surface temperature (SST) at the western and eastern poles of the Indian Ocean (Morioka et al., 2014; Iskandar et al., 2021; Bahiyah et al., 2023). We argue that this sea surface temperature variability is caused by the formation of upwelling (east pole) and downwelling (west pole) dynamics. In 2015, it was seen that the tropical region of the eastern Indian Ocean remained in normal conditions since May, then increased in mid-July and decreased in early August until increasing again in mid-November (Figure 2a—red curve). Meanwhile, the western Indian Ocean was also in normal conditions from May to the end of July, which finally increased in early August, but this condition continued and was stable until December (Figure 2a—green curve). The process of increasing temperature in the east pole of the Indian Ocean in mid-November stopped positive IOD activity in 2015, thus proving that the DMI evolution in 2015 was dominated by east pole variability.

Meanwhile, in 2019, the eastern part of the tropical Indian Ocean actually started to cool in early May until it reached its peak in October (Figure 2b—red curve). However, the tropical western Indian Ocean began to experience warming at the end of July, then cooled in August before finally experiencing stable warming again in early September and reaching a peak at the end of October (Figure 2b—green curve). The process of increasing temperature in the eastern Indian Ocean at the end of October until it returned to normal in mid-December resulted in positive IOD activity stopping. So, this explains that the evolution of DMI in 2019 was also dominated by east polar variability which was the main factor in the emergence of positive IOD.

Seasonal Variations

To explain the dynamic pattern of coastal upwelling that occurred along the southern waters of Java in 2015 and 2019, especially in the two areas that were the focus of the research, namely regions A and B (figure 1), we first look at seasonal variations. Figure 3 shows the seasonal variations of sea surface temperature (SST), wind stress, and Ekman transport during the DJF, MAM, JJA, and SON seasons. In the DJF season, SST shows warming along the waters of southwest Sumatra to southern Java. This warming of SST is caused by westerly winds blowing quite strongly in the Indian Ocean which tends to bring warmer sea water masses. Surface wind pressure during the DJF season is seen forming Kelvin waves that move at the equator towards the waters southwest of Sumatra to the waters south of Java (Figure 3a-3b). Meanwhile, westerly winds moving towards the waters southwest of Sumatra and southern Java produce strong land Ekman transport along these waters.

Even though in the first transition season, offshore Ekman transport was clearly visible, which was caused by easterly winds, it was observed along the waters of southwest Sumatra to the south of Java (Figure 3a-3b—MAM). However, this season still shows a warm SST pattern along the waters of southwest Sumatra to southern Java. We found that solar radiation (heat flux) influences and plays an important role in the SST warming process in this first transition season. Climatologically, during 2003 – 2020 SST in region A reached the highest temperature in May (29.46°C) while the highest temperature SST in region B occurred in March and April (29.27°C), see figure 3c.

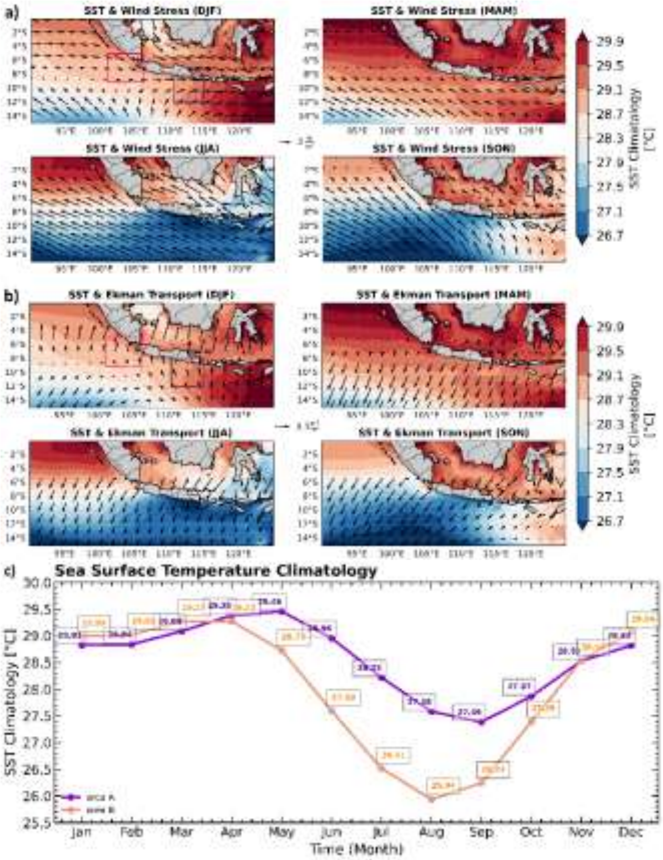

Figure 3. (**a**) Seasonal SST (°C—colored) overlaid with wind stress (N/m^2—vector), (**b**) Seasonal SST (°C—colored) overlaid with Ekman transport (m^2/s—vector); and (**c**) Monthly SST climatology time series averaged over regions A (pink box) and B (purple box). The unit vector for wind pressure is 0.3N/m^2 and for Ekman transport 0.3m^2/s.

The JJA and SON seasons clearly show that relatively lower SST are observed along the waters of southern Java compared to the previous two seasons (Figure 3a-3b). The lowest point of SST in region A occurred in September (27.39°C) while region B occurred in August with a much lower value (25.94°C) than region A (Figure 3c). This is of course caused by strong offshore Ekman transport which is influenced by strong easterly winds along the waters south of Java. So, this relatively lower SST can indicate the formation of coastal upwelling dynamics in the JJA and SON seasons.

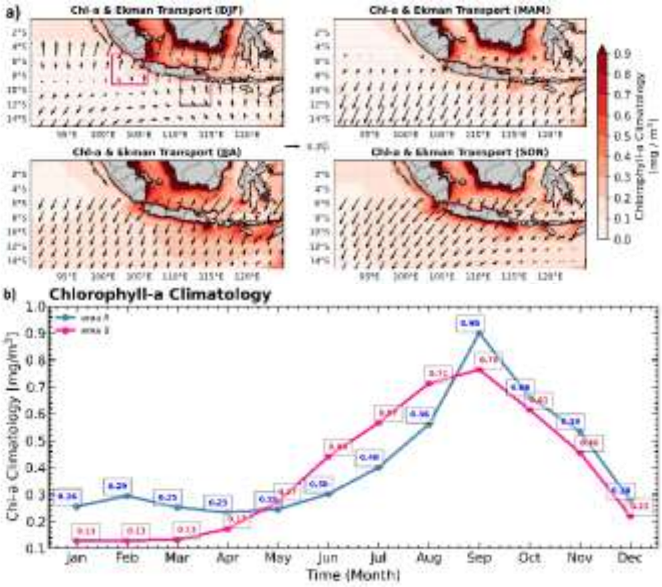

Figure 4. (a) Seasonal chlorophyll-a (mg/m^3—colored) overlaid with Ekman transport (m^2/s—vector); and (b) monthly climatological time series of chlorophyll-a averaged over regions A (pink boxes) and B (purple boxes).

Previous research shows that upwelling will cause a decrease in SST in the waters of southern Java (Marioka et al., 2015; Iskandar et al., 2022; Horii et al., 2023). So, this will make the variability in surface chlorophyll-a concentrations observed along the waters of southern Java become abundant, especially in regions A and B during the JJA and SON seasons (Figure 4a). The climatology graph shows that the highest chlorophyll-a concentration occurred in September, where the concentration in region A reached 0.90mg/m^3 while the concentration in region B reached 0.76mg/m^3 (Figure 4b).

Anomalous Variations

Then, to clearly see the dynamics of upwelling that occurred along the waters south of Java in 2015 and 2019, it can be clearly seen through variations in SST anomalies and wind stress. Therefore, Figure 5 shows the time series of SST anomalies in the waters south of Java during the Positive IOD period of 2015 and 2019. It is clear that the SST in this region has decreased far below normal temperatures. We found that the decrease in SST was caused by the influence of the upwelling phenomenon which triggered a positive IOD surge in 2015 and 2019. The Hovmöller diagram (figure 5a), shows that the SST in 2015 was observed to start decreasing in August to mid-November. Meanwhile, the SPL in 2019 was observed to experience an earlier decline, namely from June to the end of November. The peak anomalous temperature decline in 2015 occurred in September (region A) with a value of -1.89°C and occurred in August (region B) with a value of -2.17°C (Figure 5b—SST anomaly 2015).

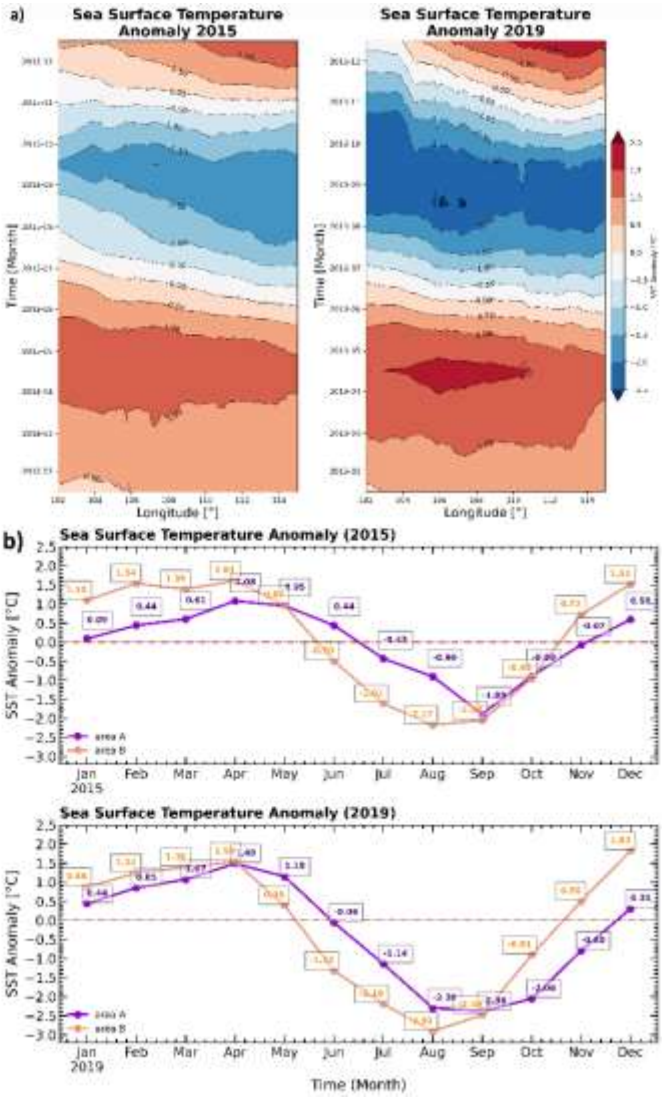

Figure 5. (**a**) SST anomalies (°C—Hovmöller from a longitude viewpoint over time during 2015 and 2019) and (**b**) and (**c**) time series of monthly anomalies in 2015 and 2019 averaged over regions A and B, (colored boxes in figure 1).

Meanwhile, the peak anomalous temperature decline in 2019 occurred in the same month as 2015 but with a much lower value than in 2015, namely in region A it reached -2.38°C and region B reached -2.91°C, see (Figure 5b—SST anomaly 2019). It should be noted that the SST anomaly that formed along the waters of southwest Sumatra to the south of Java in 2019 had a lower temperature with a longer event duration compared to the SST anomaly in 2015 (Figure 5). Of course, this is caused by the influence of the easterly wind in 2019 which blew much stronger than the easterly wind that blew in 2015.

In the other hand, we found that the variability of chlorophyll-a concentrations increases at the same time as the SST anomaly decreases. The Hovmöller diagram (Figure 6a) shows that chlorophyll-a concentrations in 2015 were observed starting to bloom in August and ending in November along the waters of southern Java, with peak concentrations reaching 0.644mg/m^3 (region A) and 0.513mg/m^3 (region B) in September (Figure 6b—Chlorophyll-a anomaly 2015). Meanwhile, in 2019, chlorophyll-a concentrations were observed starting to bloom from June until November, with peak concentrations reaching 1.87mg/m^3 (region A) and 0.63mg/m^3 (region B) in September (Figure 6b—Chlorophyll-a anomaly 2019).

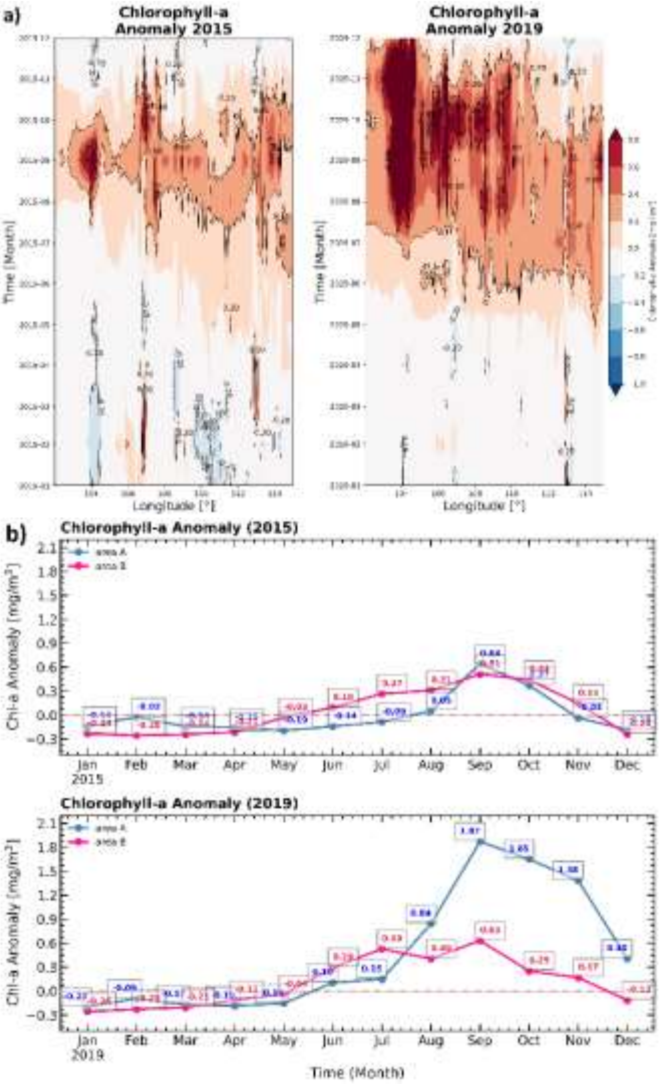

Figure 6. (**a**) Chlorophyll-a anomalies (mg/m^3— Hovmöller from a longitude versus time perspective for 2015 and 2019); and (**b**) monthly time series of anomalies for 2015 and 2019 averaged over regions A and B, (boxes colored in figure 1).

If we focus on the SST in 2015, it will be clear that there was a quite drastic drop in temperature in September and October along the waters southwest of Sumatra to the south of Java. Meanwhile, the SST anomaly in 2019 shows a drastic decrease in temperature in August-November in the same location as in 2015. This certainly shows that in the peak months when the temperature drops drastically, the coastal upwelling that is formed is much stronger. It should be noted that the offshore Ekman transport observed during the 2015 and 2019 SST anomaly periods was almost the same along the waters south of Java (Figure 8). So, we found that in the peak months when SST drops drastically in region B it is purely caused by upwelling.

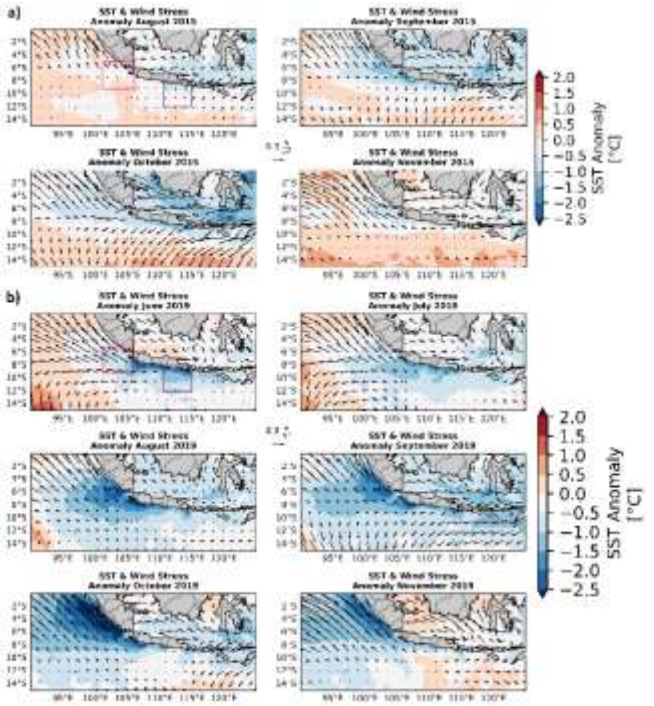

Figure 7. Monthly SST anomalies (°C—colored) overlaid with wind stress anomalies (N/m^2—vector) in regions A (pink box) and B (purple box) during the months (**a**) August – November 2015 and (**b**) June – November 2019. The unit vector for wind pressure is 0.3N/m^2.

Previous research shows that changes in sea surface height can result in mass displacement of sea water. This mass transfer of sea water will also result in a transfer of sea surface temperature through currents produced by differences in sea level gradients (Zhuang et al., 2010; Utari et al., 2019). Therefore, in region A it was found that upwelling not only influences and causes a decrease in temperature in the peak months of 2015 and 2019. However, there is also another influence in the form of currents that carry sea water masses from the Java Sea (which also has cold SST) out through The Sunda Strait goes to region A then spreads to the waters southwest of Sumatra to the south of Java. It should be noted that currents that exit through the Sunda Strait will form a sea level gradient in the area which also has a strong influence in helping the process of sea water mass transfer.

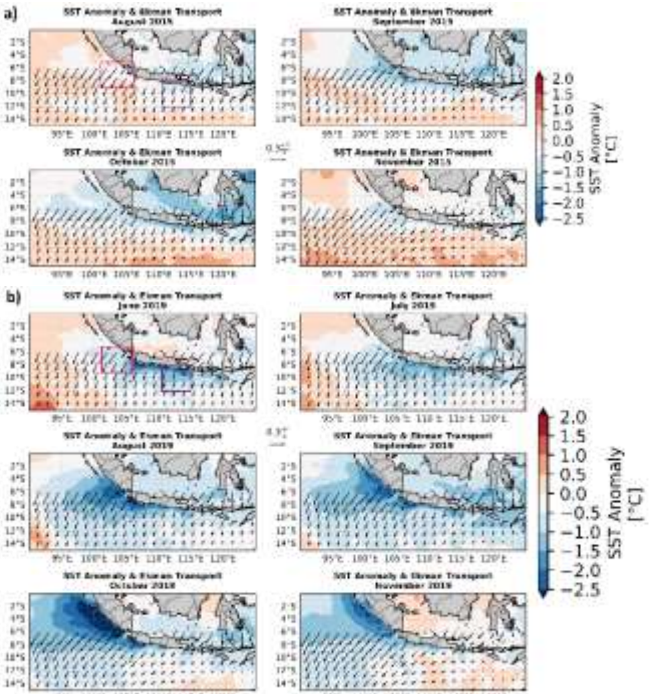

Figure 8. Monthly SST anomalies (°C—colored) overlaid with Ekman transport (m^2/s—vector) in regions A (pink box) and B (purple box) during the months (**a**) August – November 2015 and (**b**) June – November 2019. The unit vector for Ekman transport is 0.3m^2/s.

For comparison, Figure 9 shows the correlation between SST and wind pressure. It is clear that the correlation results in region A (Figure 9a) are greater than the correlation results in region B (Figure 9b). So, it is clear that surface winds moving from the Java Sea to the Indian Ocean (via the Sunda Strait) trigger the formation of ocean currents which influence the decrease in SST in region A. However, according to the categorization in table 1, the correlation results in region A in 2015 show a linear relationship which is categorized as 'moderate' (Figure 9a-2015), while the correlation results in region A in 2019 show a linear relationship which is categorized as 'strong' (Figure 9a-2019). Then the correlation results in region B in 2015 and 2019 show a linear relationship which is categorized as 'medium' (Figure 9b).

So, we found that when anomalous changes in SST occurred in 2015 and 2019, wind pressure did not completely influence the decrease in SST in regions A and B. In this case the upwelling phenomenon is another factor that plays an important role of decreasing SST. This is proven by the variability of chlorophyll-a concentrations at the surface along the waters of southern Java. Previous studies show that the upwelling process will increase the concentration of chlorophyll-a at the surface (Iskandar et al., 2010; Jiang et al., 2022; Sari et al., 2022; Iskandar et al., 2023). Figure 10 shows that variability in chlorophyll-a concentrations is very abundant along the waters south of Java, especially in regions A and B.

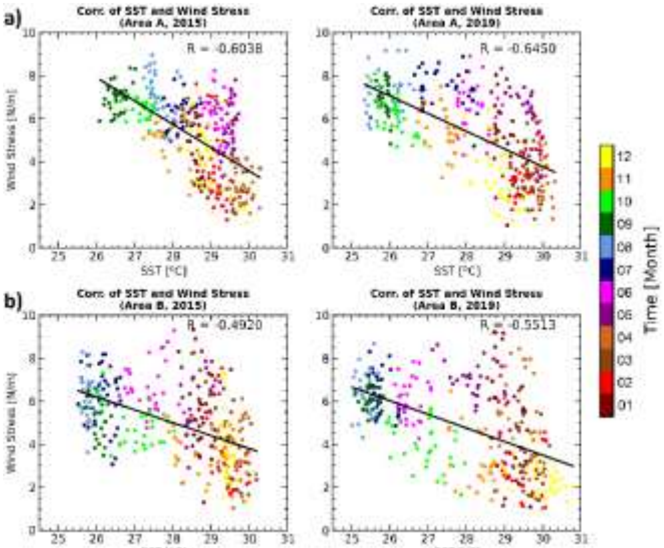

Figure 9. Correlation between SST and wind pressure in regions (**a**) A and (**b**) B during 2015 and 2019.

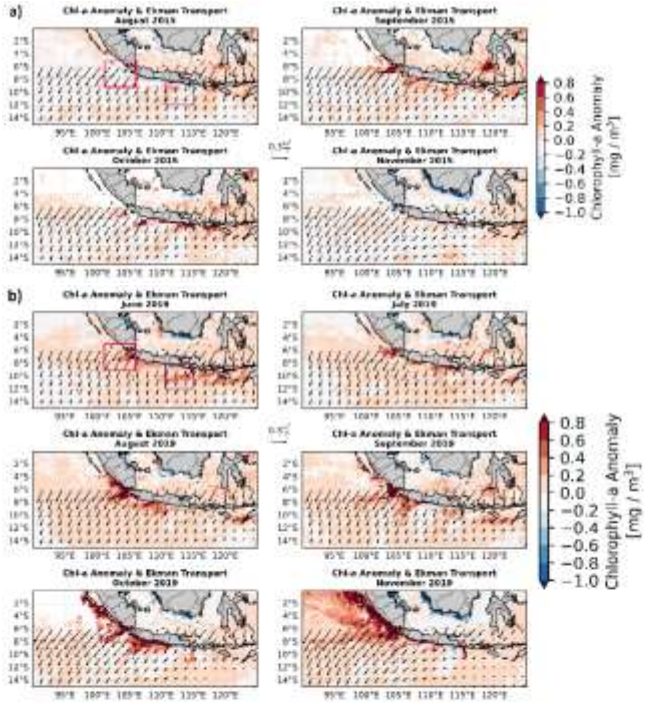

Figure 10. Chlorophyll-a concentration anomaly (mg/m^3—colored) overlaid with Ekman transport (m^2/s—vector) in regions A (pink box) and B (purple box) during the months (a) August – November 2015 and (a) June – November 2019.

Previous research shows that ocean currents can carry and push sea water masses and sea surface temperatures to move in the direction of the ocean currents themselves, and then ocean currents can cause an expansion in the variability of chlorophyll-a concentrations on the surface (Iskandar et al., 2017; Sari et al., 2018). Therefore, if we focus on region A in 2015 and 2019, it is clear that the concentration of chlorophyll-a is much more abundant than the concentration of chlorophyll-a in region B. As in the previous explanation, apart from the influence of upwelling, the concentration of chlorophyll-a in region A is also influenced by currents that exit through the Sunda Strait which then push nutrients from Javanese waters into the Indian Ocean which then spread to the waters of southwest Sumatra and southern Java. Meanwhile in region B, the concentration of chlorophyll-a is purely caused by upwelling. But in general, it should be noted that the chlorophyll-a concentration in 2019 was much higher than the chlorophyll-a concentration in 2015. Thus, this proves that the upwelling formed in 2019 was much stronger than in 2015.

As proof to see that the upwelling phenomenon that occurred in 2019 was much stronger than that which occurred in 2015, it can be seen in Figure 11 (showing the relationship between chlorophyll-a and SST). Based on the categorization in table 1, it is clear that the correlation results of chlorophyll-a and SST in 2015 and 2019 show a linear relationship which can both be categorized as 'very strong'. But in general, it was found that in 2019 the correlation of chlorophyll-a and SST was much stronger (region A reached -0.90 and region B reached -0.90) compared to 2015 (region A was -0.84 and region B was -0.89).

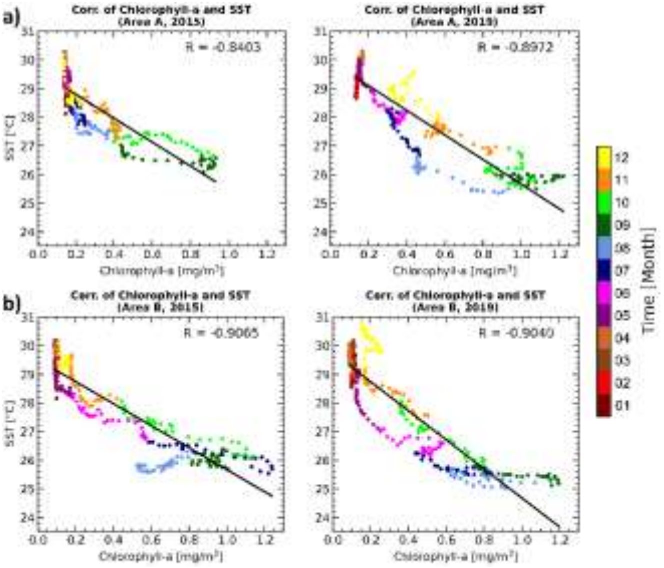

Figure 11. Correlation between Chlorophyll-a and SST in regions (**a**) A and (**b**) B during 2015 and 2019, as the impact of the upwelling phenomenon.

Conclusion

The Dipole Mode Index (DMI) shows that when the 2015 and 2019 Positive IODs were formed, the sea surface temperature in the waters of the western Indian

Ocean was anomalously higher than the sea surface temperature in the waters of the eastern Indian Ocean. The formation of an upwelling phenomenon in the waters of the eastern Indian Ocean was the main trigger for the rise of Positive IOD in 2015 and 2019 which caused many anomalies in Indo-Australian waters, especially in waters south of Java in regions A and B. It should be noted that the influence of ocean and atmospheric dynamics is a factor in the formation upwelling in waters south of Java. The easterly winds that form the offshore Ekman transport push sea surface currents (which tend to be warmer in temperature) away from the waters south of Java towards the Indian Ocean, so this results in a vacuum of water masses on the surface waters south of Java. This emptiness of sea water masses on the surface will cause sea surface temperatures to decrease and result in the formation of coastal upwelling. The upwelling phenomenon that forms along the waters of southern Java, especially areas A and B, causes nutrients from the deep layers to rise to the surface, causing the concentration of chlorophyll-a at the surface to increase. This is reinforced by the correlation between sea surface temperature and chlorophyll-a which shows a linear relationship that can be categorized as 'very strong' in regions A and B in 2015 and 2019. Thus, an increase in chlorophyll-a concentration at the surface can be seen through a decrease in sea surface temperature. It should be noted that the abundant concentration of chlorophyll-a due to coastal upwelling makes the waters of southern Java abundant in fish and marine animals.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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