Influence of 2019 strong positive IOD on the upwelling variability along the southern coast of Java

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Abstract. The seas along the Southern Coast of Java, which are parts of the Indian Ocean, are exposed to climate variability conditions that influence the dynamic of oceanographic parameters in these areas. In terms of interannual climate variability, previous studies showed that Indian Ocean Dipole (IOD) variability is more influential than El Niño Southern Oscillation on the upwelling variability along the Southern Coast of Java. This study aimed to determine the effect of strong positive IOD in 2019 on the upwelling along the Southern coast of Java and investigate the possible mechanisms. This study used sea surface temperature data from OISST, wind speed data from the ASCAT satellite, chlorophyll-a data from the Aqua-MODIS, and sea level anomaly data obtained from altimetry satellites. All data were processed using the composite method. The results show enhanced southeast monsoon upwelling during the 2019 strong positive IOD along the Southern Coast of Java as denoted by higher positive (negative) anomaly of chlorophyll-a (SST) from the climatology. Interestingly, the easterly wind speed is lower than the climatology. Since the IOD influences upwelling along the Southern Coast of Java through the propagation of Kelvin wave, our results indicate the enhancing (weakening) upwelling (downwelling) Kelvin wave during the strong positive IOD in 2019 with the propagation speed of about 1.16 m/s. This Kelvin Wave propagation may amplify the coastal upwelling along the Southern Coast of Java.

1. Introduction
The condition of the southern coast of Java is related to the dynamics of oceanography and meteorology in the eastern Indian Ocean. The dynamics in this area include factors such as the monsoon system, Indian Ocean Dipole (IOD), El Niño Southern Oscillation (ENSO), Kelvin waves, South Equatorial Current (AKS), the west coast current of Sumatra Island, and the South Java Current [1]. The season has no effect on IOD climate variability in the Java Sea; during positive IOD conditions in the northwest and southeast monsoons, SST becomes cooler; during negative IOD conditions, SST becomes warmer [2]. The positive IOD phase causes westerly winds to weaken along the equator and cause warm water to shift eastward. Changes in the wind cause cold water to rise in the east from the ocean to the surface. This mechanism causes temperature differences throughout the tropical Indian Ocean. The east Indian Ocean has cooler water than normal water, and the west has warmer water [3]. Upwelling can increase fisheries productivity. The water mass increase has a cold temperature, high salinity, and nutrient-rich water. Therefore, the upwelling process will increase the fertility of the aquatic environment. During the southeast monsoon, the southeasterly wind blowing along the southern java
coast creates Ekman transport, which pushes water mass away from the coast. Then there is a change of water mass from deep water to surface [4]. The southeasterly wind blowing along the southern coast of Java generates upwelling, and the sea surface temperature becomes colder because the water mass is lifted [5]. According to [6], sea level height along the southern coast of Java during the La Niña phenomenon was negative, and when the positive IOD phenomenon in 1994 and 1997 was negative. At the time of the positive IOD phenomenon, coastal areas have low sea levels, the currents along the coast lead to the west, and eddy currents formed. According to [7], in 1997, the negative anomaly of sea level indicated upwelling. The statement by [4] supports the explanation from [6] and [7] denote that upwelling in the Indian Ocean is more influenced by IOD than ENSO, which is characterized by decreased sea surface temperatures and increased chlorophyll-a. Based on these researchers, a very strong IOD phenomenon in 2019, which reached 1,123°C will be related to upwelling in the Indian Ocean, especially the Southern Coast of Java.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The positive IOD in 2019 reached the highest value compared to the previous year that is 1,123°C.

2. Materials and Methods

2.1. Data

Sea surface temperature data is obtained from OISST (Optimum Interpolation Sea Surface Temperature) daily level 4 from 2007 to 2019. Sea surface temperature data is downloaded through the open-source website http://www.remss.com/ with 8 km resolution in Network Common Data Form (NetCDF) format. The OISST analysis developed by Richard Reynolds from the National Climatic Data Center (NCDC) is an analysis of the results of satellite observations and direct observations (in situ). In situ data was obtained from observation by boat and buoys. Satellite data on OISST has an Advanced Very High-Resolution Radiometer (AVHRR) instrument and combined AVHRR data with an Advanced Microwave Scanning Radiometer (AMSR) [8].

Chlorophyll-a data was obtained from the Aqua-MODIS daily level 3 data with 4km resolution from 2007-2019. Chlorophyll-a data was downloaded via the open-source website https://www.oceancolour.org/ in Network Common Data Form (NetCDF) format. The aqua-MODIS satellite (moderate resolution imaging spectrometer) is located 705 km above the earth's surface and has a recording area of 2330 km. This satellite used an ascending pass orbit system to move from south to north of the earth, and it was completed at 1:30 p.m. [9].

ASCAT satellite data in Net Common Data File (NetCDF) format is used to generate the wind data. As data components, u and v components are used. The data can be obtained from the open-source website https://marine.copernicus.eu/. The data used here is daily level 3 data with a resolution of 12.5 km. The data was downloaded from 2007 to 2019, and it was used to cover the research area, which was the waters of Java's southern island and the Indian Ocean. The ASCAT satellite's data is the result of a microwave scatterometer, which can determine the speed and direction of the wind 10 m above sea level [4].

The open-source site https://resources.marine.copernicus.eu collects sea level anomaly data from altimetry satellites. The data used is Net Common Data File (NetCDF) format level 4 observation data with a 25km resolution from 2007 to 2019. The data was used to cover the study area, which included
the southern coast of Java and the Indian Ocean. Sea Level Anomalies (SLA) is the product of Altimetry satellites processing data from all altimeter missions: Jason-3, Sentinel-3A, HY-2A, Saral/AltiKa, Cryosat-2, Jason-2, Jason-1, TOPEX/Poseidon, ENVISAT, GFO, ERS1/2. Ka-band altimetry from Saral/AltiKa and SAR mode altimetry Cryosat-2 and sentinel 3 have better and lower spatial resolution than TOPEX/Poseidon, ENVISAT, Jason, allowing observational data to be obtained at greater distances. Get closer and more precise. The ka-band and SAR modes were validated by comparing altimetry satellite estimates with tide gauge records [10].

In this study, the DMI data, which is the IOD index data, shows statistical data on differences in sea surface temperature anomalies in the western and eastern Indian Oceans. From 2007 to 2019, data is downloaded in the Net Common Data File (NetCDF) format. The open-source site https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php was used to obtain IOD data.

2.2. Methods

2.2.1. Data processing method of sea surface temperature, chlorophyll-A, wind. Software programming languages are used to process data in NetCDF format. Cutting the image according to the research area is the initial stage of data processing. Because it can affect the spatial value of the data distribution, image cropping must use the same coordinates for each variable. The data display is extracted and displayed daily in the next stage, which is daily data extraction. The data is then compiled on a monthly measure to establish the monthly average. By averaging the daily data pixel values, a monthly compilation is produced. The monthly compiled data is then climatologically compiled; at this point, the monthly average data is compiled into the annual average data [11]. Climatology data was compiled over a 13-year period to determine the average month from January to December. The following is a formula for putting together a compilation [12],

\[ X(x, y) = \frac{1}{n} \sum_{i=1}^{n} x_i(x, y, t) \]  

Description:
\( X(x, y) \) = Monthly & climatological average  
\( n \) =number of hours, days or months in day, month or year  
\( i = 1 \) =Day or month i  
\( x_i(x, y, t) \) =Daily or monthly data to i  
If \( x_i \) is an empty pixel, the count does not include it.

Anomaly calculations were performed after obtaining monthly composite data and climatology to aid in the research. Monthly anomaly values for all variables were obtained by subtracting the monthly climatological mean value from each corresponding month for anomaly calculation. As a result, a positive/negative value of Chl-a anomaly, for example, indicates that the Chl-a concentration is above/below the mean climatology [13]. This is to see the changes from January 2007 to December 2019. Climate maps, anomaly maps, and Hovmoller diagrams in *png and *tiff formats are used in the implementation.

2.2.2. SLA data processing method. The daily SLA data and the image cropping in NetCDF format are processed using programming language software (IDL). The data is extracted and composited into daily data using formula (1). Then, the composited daily data is composited again into monthly data to produce a monthly average from January 2007 to December 2019. The monthly composite was linked with the climatological composite to calculate the average from January to December over 13 years using a formula (1). Create anomaly and Hovmoller maps from monthly composite data to aid in the analysis. Maps and Hovmoller anomalies can show changes in sea level anomalies.

2.2.3. IOD data processing method. Climate variability in Southern Java is identified based on the IOD phenomenon because it is located in the Indian Ocean, according to [14]. The parameter applied is an anomaly index of sea surface temperature in the west Indian Ocean (10°LS-10°LU and 50°BT-
70°BT) and the east Indian Ocean (10°LS-10°LU and 50°BT-70°BT) (10°LS-0°LU and 90°BT-110°BT). The following step is to compute the IOD value:

- Dipole Mode Index > +0.35°C (Positive IOD)
- -0.35°C < Dipole Mode Index < +0.35°C (Normal IOD)
- Dipole Mode Index < -0.35°C (Negative IOD)

2.2.4. Correlation analysis. Analysis was required to determine the relationship between the two variables. Spearman correlation is a statistical test tool that can be used to test the relationship between variables if the data is on an ordinal scale, according to [15]. The Spearman correlation coefficient ranges from -1 to 1. If the result is 0, the variables x and y have no relationship. If the obtained r is positive, the variables x and y are directly related; as the value of x increases, so does the value of y. If r is negative, the values of x and y are inversely related, which means that when the value of x decreases, the value of the y variable will increase. The Spearman correlation analysis is performed using the following formula:

$$r_s = 1 - \frac{6 \sum_{i=1}^{n} d_i^2}{n(n^2-1)}$$  \hspace{1cm} (2)

The following is an interpretation table of the criteria for the strength of the relationship between two variables based on the value of the correlation coefficient:

| Arti R           | Interval R               |
|------------------|--------------------------|
| Pure Negative    | -1                       |
| Strong Negative  | -1 < r < -0.9            |
| Moderate Negative| -0.9 < r < -0.5           |
| Weak Negative    | -0.5 < r < 0             |
| Uncorrelated     | 0                        |
| Weak Positive    | 0 < r < 0.5              |
| Moderate Positive| 0.5 < r < 0.9            |
| Strong Positive  | 0.9 < r < 1              |
| Pure Positive    | 1                        |

3. Results and Discussion
According to a seasonal analysis of sea surface temperature in the southern coast of Java, the southeast monsoon is cooler than the northwest monsoon. The southeast monsoon (June, July, and August) has temperatures ranging from 26.2°C to 27.6°C, with the highest temperature in the southern coast of Java. Table 2 shows the northwest season (December, January, and February), sea surface temperatures range from 27.7°C to 28.5°C. (Table 2) shows the analysis of sea surface temperature and monthly climatological average chlorophyll reveals several phenomena. Sea surface temperatures are lower from July to October than from November to June. In November-June, the concentration of chlorophyll-a on the southern coast of Java is higher than in the open seas. This is caused by the wind blowing from Sumbawa to the southern coast of Java and then being deflected to the southwest. This causes the mass of water on the southern coast of Java to be pushed towards the open sea, generating an emptiness of water mass that causes colder water to resurface, leading through cooler sea surface temperatures from July to October. The coldest month is September when the temperature drops to 26.1°C. Upwelling occurs on the southern coast of Java during the southeast monsoon (June, July, and August), and chlorophyll-a levels are highest in August. The research results of the seasonal variability analysis in the Southern coast of Java region are in line with the observations of [5], who noticed that the sea surface temperature in the Southern coast of Java fluctuates seasonally, ranging from 28°C to 31.2°C during the warmer temperatures northwest season compared to the southeast monsoon, which ranges from 28°C to 31.2°C.
Seasonally, the concentration of chlorophyll-a in the southern coast of Java fluctuates. Table 2 shows that chlorophyll-a levels in the Southern coast of Java were higher during the southeast monsoon than during the northwest monsoon. Because during the northwest monsoon have the ekman transport and wind stress [16]. In the southeast monsoon, chlorophyll-a concentrations ranged from 0.28 mg/m$^3$ to 0.38 mg/m$^3$, while in the west monsoon, it was 0.21 mg/m$^3$. According to [17], a circular current or eddy current is formed in the Southern coast of Java during the east monsoon. The Java Coastal Current (APJ) and the South Equatorial Current confluence cause the circular current (AKS). Circular currents can reach depths of 500-1000 m, transferring nutrients from the deep layers to the sea surface.

**Table 2.** Climatology Data of wind, chlorophyll-a and sea surface temperature for the Past 13 Years (2007-2019) in the southern coast of Java.

| ASCAT (m/s) | Month | Chlorophyll-a (mg/m$^3$) | Month | SST (°C) | Month |
|------------|-------|--------------------------|-------|----------|-------|
| 2.68405    | 1     | 0.07992                  | 1     | 28.2107  | 1     |
| 2.06617    | 2     | 0.07686                  | 2     | 28.5749  | 2     |
| 3.12831    | 3     | 0.10669                  | 3     | 28.8598  | 3     |
| 6.00956    | 4     | 0.10286                  | 4     | 28.8675  | 4     |
| 7.73509    | 5     | 0.12606                  | 5     | 28.3329  | 5     |
| 7.15949    | 6     | 0.1274                   | 6     | 27.6879  | 6     |
| 8.02551    | 7     | 0.16776                  | 7     | 26.8855  | 7     |
| 8.07287    | 8     | 0.22574                  | 8     | 26.285   | 8     |
| 8.08115    | 9     | 0.19814                  | 9     | 26.1621  | 9     |
| 7.41332    | 10    | 0.14275                  | 10    | 26.4148  | 10    |
| 6.79362    | 11    | 0.10526                  | 11    | 27.1944  | 11    |
| 4.81254    | 12    | 0.08501                  | 12    | 27.7778  | 12    |

Description: min max
Figure 2. Monthly Climatology of August for 13 Years (2007-2019).

The climatological picture for August (Figure 2) shows that the distribution of surface winds is shifting to the west, the speed is increasing, but the sea surface temperature is increasing while moving to further west, proving that a decrease does not follow an increase in wind speed in sea surface temperature in the west. According to [4], this disparity is due to the effects of climate change on the distribution of sea surface temperatures along the southern coast of Java during the southeast monsoon. The offshore EMT on South Java's west coast is stronger during the southeast monsoon than the offshore EMT on the east coast. The EMT dynamic shows changes in the negative EPV (upward movement) in the east and positive EPV (downward movement) in the west. Because of Ekman's dynamics, the upwelling in the eastern part of the southern coast Java was stronger than in the western part. The sea surface temperature in the eastern part of South Java is lower than in the western part, indicating upwelling. During the southeast monsoon, IOD has a greater impact on offshore EMT and EPV than ENSO. Positive IOD consistently increases the intensity of offshore EMT and EPV.

The Spearman correlation test was used to determine the relationship between variables such as sea surface temperature, chlorophyll-a, and wind. When the result is a positive sign (+), it can be concluded that the relationship between the two variables is comparable, and conversely, if the relationship between variables is negative (-), it is inversely proportional [18].

Table 3. Correlation of wind, temperature, and chlorophyll-a.

| Correlation      | Wind  | Temperature | Chlorophyll-a |
|------------------|-------|-------------|---------------|
| Wind             | 1     | -0.71485    | 0.67845       |
| Temperature      | -0.71485 | 1          | -0.9079       |
| Chlorophyll -a   | 0.67845 | -0.9079    | 1             |
Relationships in Table 3 based on the results of the Spearman correlation test, we can deduce that there is a link between temperature and wind that is moderate negative category with a value of -0.71485, which means it is inversely proportional when the temperature is high and the wind speed is low, and conversely. With a value of 0.67845, the relationship between chlorophyll-a and wind falls into the moderate positive category, indicating that when chlorophyll-a is high, the wind is also strong, and conversely. With a value of -0.9079, the relationship between chlorophyll-a and sea surface temperature falls into the strong negative category, indicating that the relationship between chlorophyll-a and sea surface temperature is inversely proportional, meaning that when the sea surface temperature is high, the chlorophyll-a concentration is low. These facts have been proven in this case in South Java. The case of Southern Java in 2019 demonstrates a mismatch between easterly wind and sea surface temperatures. In August, when the easterly wind speed has a strong negative anomaly, the sea surface temperature also has a negative anomaly. This is in contrast to the moderately negative correlation between easterly wind speed and climatological sea surface temperature.

![Figure 3](image_url)

**Figure 3.** Anomalies of a) sea surface temperature, b) Chlorophyll-a, c) zonal wind speed (component U), d) sea level anomaly in August 2019 in the southern coast of Java. Positive (negative) anomaly means that the sea surface temperature, chlorophyll-a, zonal wind speed, and sea level anomaly are higher (lower) than the climatological average.

The anomaly in August shows that August is the peak of upwelling in South Java (Figure 3). In August 2019, when the IOD was positive, the sea surface temperature in South Java had a negative anomaly,
chlorophyll-a had a positive anomaly, the easterly wind speed had a negative anomaly, and the sea level anomaly had a negative anomaly. A positive anomaly has a higher value than the climatological average, while a negative anomaly has a lower value. 2019 had a very strong IOD+, with a strong positive IOD from May to November. Upwelling in the Indian Ocean, specifically in South Java, can be caused by various phenomena, including Kelvin waves, IOD, and monsoon. The formation of upwelling is also influenced by global climate variability.

**Figure 4.** The study of the Hovmoller manufacturing area from the Indian Ocean's equator to the southern coast of Java. The black box represents 144 sample areas with 0.50 x 0.50 bin sizes.

**Figure 5.** (a) Hovmoller sea level anomaly (b) Hovmoller monthly sea surface temperature, (c) Hovmoller wind monthly component u (d) IOD index in the Indian Ocean for 13 Years (2007-2019).

The Kelvin wave is defined by the movement of water masses from west to east from the Indian Ocean's equator. Based on Figure 5, the Hovmoller diagram of the sea level anomaly explains how Kelvin wave propagation from the Indian Ocean's equator to the southern coast of Java alternates between positive and negative anomalies. During the east monsoon, the sea level has a positive anomaly.
Figure 6. Hovmoller easterly wind anomaly, sea surface temperature anomaly, and sea level anomaly during the positive IOD phenomenon in 2019.

The Hovmoller diagram of the easterly wind anomaly (Figure 6) explains that in the 2019 positive IOD phenomenon, an easterly wind blows with anomaly negative in South Java from May to November. The lower the air pressure in the western Indian Ocean and the higher the air pressure in the eastern Indian Ocean, the higher the IOD index. The wind blows from high to low-pressure areas [17]. In 2019 the easterly wind had a negative anomaly, meaning it is lower than the climatological average. Even though the easterly wind is weaker than the climatological average, it can still cause upwelling in the waters of Southern Java, characterized by increased chlorophyll-a and decreased sea surface temperature. The Kelvin Wave influences the effect of IOD on upwelling. Kelvin waves lift the thermocline layer in the east, causing the sea surface temperature to fall in the east [19]. Upwelling in the southern coast of Java was suspected because the sea level anomaly had a weak downwelling Kelvin wave (positive anomaly) and a strong upwelling kelvin wave (negative anomaly) at the time of the positive IOD 2019. The speed of the Kelvin wave that propagates at the equator until it hits the island of Sumatra is 1.16 m/s.

Figure 7. Hovmoller easterly wind anomaly, sea surface temperature anomaly, and sea level anomaly during the negative IOD phenomenon in 2016.

In contrast to the negative IOD in 2016 (Figure 7), it produced a strong downwelling Kelvin wave (positive anomaly) as well as an upwelling Kelvin wave (anomaly) preventing upwelling in southern
Java because an increase in the sea level anomaly tends to result in a decrease in seawater mass or downwelling. Variability of the Kelvin wave is related to the IOD phenomenon [4]. There will be a positive anomaly of chlorophyll-a and a negative anomaly of strong sea surface temperature during upwelling and a positive IOD index, even if local EMT and EPV are not significantly different from the seasonal average. During the southeast monsoons of 2007, 2008, 2011, 2012, 2015, 2017, and 2018, high chlorophyll and low sea surface temperatures could not be separated from the influence of upwelling and Kelvin wave effects.

4. Conclusion
Upwelling along the southern coast of Java occurred during the east monsoon and the positive IOD phase, with the peak of upwelling occurs in August. The sea surface temperature dropped to 25.70 °C and chlorophyll-a levels peaked at 0.45 mg/m3 in August, indicating upwelling in the southern coast of Java. In 2019, when the easterly wind speed had a strong negative anomaly, meaning it was lower than the climatological average, it could still cause upwelling on Java's southern coast, which was indicated by a strong negative anomaly of sea surface temperature.

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