Physical forces driving chlorophyll-a variability in the South Java Sea Shelf: a spatio-temporal analysis

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Abstract. The wind and current are two physical forces that strongly influence the biogeochemistry in coastal waters. Both of these forces could enhance the Chlorophyll-a (Chl-a) concentration through the upwelling process. Here we examine the contribution of the wind and current to the Chl-a variability in the South Java upwelling system in terms of wind stress and bottom stress respectively using satellite-derived and reanalysis data from 2002 to 2017. Ten longitudinally cells were used for further analysis. A long-term Chl-a shows a strong longitudinal gradient of Chl-a with the highest value on the shelf. Seasonal and Inter-annual Chl-a analysis shows the evidence of the monsoon winds and other forcing effects relevant to the previous studies. Wind stress ($\tau_{wx}$) has a strong seasonal variation which is upwelling-favorable during southeast monsoon coincide with higher Chl-a suggesting wind as the main forces during that time, while bottom stress ($\tau_{bx}$) has more complicated variations, but it’s seen that $\tau_{bx}$ mostly downwelling-favorable or eastward circulations. There were about 39.92-52.94\% of positive Chl anomalous events generated by the combination of upwelling-favourable $\tau_{wx}$ and downwelling-favorable $\tau_{bx}$, higher than other combinations. In terms of Oceanographic drivers, the wind has a higher effect on enhancing Chl-a through a negative correlation. $\tau_{wx}$ leads the Chl-a anomalies by about 15 – 24 days with a correlation coefficient of more than 0.6.

1. Introduction

Southern Java coast is well known as the upwelling system in the South East Tropical Indian Ocean (SETIO). Previous studies show an upwelling signal along Southwest Sumatra and South Java due to the Southeast wind during the Southeast monsoon (SE monsoon) \cite{1}, \cite{2}, \cite{3}. The resultant of Ekman transport offshore causes a divergence of water masses in the surface near the coast and drives cold and nutrient-rich water from below to rises to the surface \cite{4}, \cite{5}. According to \cite{4} and confirmed by the study of \cite{3}, the upwelling center migrates westward and toward the equator during the southeast monsoon. The upwelling off Java and Sumatra becomes more intense during the positive Indian Ocean Dipole (IOD) event, enriching nutrients, and leading to Chl-a blooms \cite{5}, \cite{6}. In connection with El Niño–Southern Oscillation (ENSO), \cite{4} shows that interannual variability of the Java-Sumatera upwelling is linked to ENSO through the ITF where the upwelling strength was enhanced (reduced) during El Nino (La Nina) as the ITF carries colder (warmer) water shallowing (deepening) thermocline depth.

Chl-a variability in Southern Java is closely related to the occurrence of upwelling. During the upwelling event, southern Java waters rich in nutrients and Chl-a. Satellite-derived sea surface temperature (SST) and surface Chl-a data show that the decrease in the SST off Java during the
southeast monsoon is associated with the upwelling of nutrient-rich subsurface water supporting high primary productivity [7], [8]. Using SeaWiFS data for Chl-a concentration, [9] show that stronger upwelling-favorable winds during the southeast monsoon of 2006, associated with an IOD event, triggered a Chl-a bloom along the southern coasts of Java and Sumatra. According to the previous studies, the upwelling which increases the Chl-a concentration in South Java is primarily caused by the wind [1], [4].

Studies have shown that upwelling can be intensified or even be generated through both wind-driven and current-driven processes. In the case of current-driven processes, upwelling can be generated through 1) the interaction of boundary currents over variable topography [10], [11], [12], 2) encroachment of the boundary current flow to the coast [13], and 3) cyclonic eddies [14], [15]. [9] stated that the relative control of winds and oceanic processes on Chl-a distribution off Java and Sumatra are spatially dependent and their quantification will be a major challenge for future studies.

We hypothesize that the currents circulating among the South Java sea shelf have a part in shaping the chlorophyll variability beside wind. The circulations that occur in southern Java is the Indonesian Throughflow (ITF) [16], [17], the South Java Current (SJC) [18], [19], the South Equatorial Current (SEC) [16], Kelvin waves [20], [21], [22], Rossby waves [22], [23], and the occurrence of eddies [14], [15]. Since upwelling is closely related to Chl-a variations in southern Java, this study is focused on two physical forces that might drive upwelling as described above, those are wind and currents. Here, we examined the contribution of the circulations in terms of bottom stress to the Chl-a variability on shelf area in addition to winds through the Spatio-temporal analysis. The bottom stress is expected to be directed mainly alongshore since alongshore flows generally predominate in the coastal ocean [24]. It has been found that the bottom stress can be caused by the interaction between near-bottom currents by the boundary current, current encroachment, eddy activity, and rugged bathymetry [25]. As a result, bottom stress used here is generated from the net of circulations that occur in the shelf area.

Although South Java upwelling has been the focus of many researchers, they still focus on the wind as the physical forces which drive upwelling and influences Chl-a variability [1], [2], [3], [26]. Studies of South Java upwelling in connection with the bottom stress which might influence the Chl-a variability have not yet been conducted, particularly in the shelf area. Here, the contribution of alongshelf bottom stress as the other physical forces was investigated for the first time. In this study, We aimed to: (1) describe the spatial and temporal variability of Chl-a (2) quantify the contribution made by wind (in terms of alongshore wind stress) and current (in terms of alongshelf bottom stress) in influencing the Chl-a variability in the South Java.

2. Data and method

2.1. Study site
The study site spanned longitudinally from 108˚E to 113˚E (Figure 1) including the recently investigated upwelling region [3], [26]–[28] with the focus on the shelf area (isobaths 40–200 m). The shelf was separated into ten cells, each has a width of 0.5˚ longitudinally (Figure 1).
Figure 1. Study domain with ten 0.5 longitudinal cells at the shelf from 108 – 113 ° E. The longitudinal cells are marked by numbers used to compute the mean shown in Figure 2 and Table 1. Isobath 40 m, 200 m, 1000 m, and 2000 m drawn by contour lines. Inset is our study domain among Indonesian islands.

Enhanced Chl-a in this region is well known as a response to wind-driven upwelling but the possibilities for other forces or processes that leading this phenomenon have never been studied and known well. In this study, we present the quantification of the relative contributions of the SJC to the enhanced Chl-a on the southern coast of Java. We aimed to: (1) describe the spatial and temporal distribution of Chl-a with a focus on the shelf region within the area of 108-113E and 7-10S; (2) quantify the contribution made by upwelling-favorable wind stress (hereinafter written as: $\tau_{sx}$) and bottom stress (hereinafter written as: $\tau_{sb}$) to positive Chl-a anomalies.

2.2 Data
Satellite remotely-sensed Chl-a (mg m$^{-3}$) data obtained from daily globally L4 ocean color reprocessed from https://resources.marine.copernicus.eu/. The Chl-a data have a spatial resolution of about 4km covering the period of 2000–2018. These Chl-a products (Daily, Monthly, and Climatology) are based on the merging of the sensors SeaWiFS, MODIS, MERIS, VIIRS-SNPP&JPSS1, OLCI-S3A&S3B. The application of remotely sensed Chl-a data is limited in shallow coastal shelf water due to a range of factors including bottom albedo, suspended sediment, and coastal turbidity [29], [30], [31] exclude the effect of land or riverine inputs to Chl-a in the coastal zone by removing or masking the 4 km near coast concentration, [32] and [33] restricting the interpretation and analysis to water deeper than 40 m. Here, the limitation of remotely sensed Chl-a concentrations was considered by using the Chl-a concentration of area with a depth of more than 40 m isobaths.

A 10-m daily winds data used an ERA5 [34], the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate for the period 2002–2017. Products have 12.5 km spatial resolution and can be downloaded from https://cds.climate.copernicus.eu/. Currents obtained from GLOBAL_REANALYSIS_PHY_001_030 [35], distributed through the Copernicus Marine Environment Monitoring Service (CMEMS), a global
ocean eddy-resolving (1/12° horizontal resolution, approximatively 8 km, and 50 vertical levels) reanalysis covering the altimetry era 1993-2018. It is based largely on the current real-time global forecasting CMEMS system. This product can be downloaded from https://resources.marine.copernicus.eu/.

2.3 Method
Spatial patterns of Chl-a were examined by separating our domain into ten 0.5° longitudinal cells, applying existing methods of [31], from 108° to 113°E across the continental shelf (40 to 200 m, hereinafter referred to as 'shelf'), and spatially averaged using a geometric mean because the Chl-a concentration in shelf waters is generally lognormally distributed [31], [32]. The 0.5 longitudinal cells are referenced in the text by their central longitude (108.25 refers to 108–108.5). The mean climatology was used for the temporal analysis,

Alongshore wind stress ($\tau_{wx}$) calculated by the following formulation

$$\tau_{wx} = \rho_a C_w u_w \sqrt{u_w^2 + v_w^2}$$

$u_w$ (m s$^{-1}$) and $v_w$ (m s$^{-1}$) are west-east and south-north components of wind velocity. $C_w$ is a velocity-dependent drag coefficient (0.0015) [36] and $\rho_a$ is the density of air with 1.3 kg m$^{-3}$.

Alongshelf bottom stress ($\tau_{bx}$) calculated using the current at the bottom level for the period of 2002 – 2017. The formula to calculate $\tau_{bx}$ following the theory described by [37] and applied e.g. by [31], [38], and [32]:

$$\tau_{bx} = \rho_w C_D u_b \sqrt{u_b^2 + v_b^2}$$

$u_w$ (m.s$^{-1}$) and $v_w$ (m.s$^{-1}$) are west-east and south-north components of wind velocity. $C_w$ is a velocity-dependent drag (0.0025) coefficient (see [36]) and $\rho_w$ is the density of seawater with 1025 kg m$^{-3}$. The velocity component was not rotated to the alongshore direction (e.g. [31]) which potentially underestimated the alongshelf bottom stress [32]. $\tau_{xw}$ and $\tau_{xb} < 0$ N.m$^{-2}$ was considered as upwelling favorable while $\tau_{xw}$ and $\tau_{xb} > 0$ N.m$^{-2}$ was considered as downwelling favorable. The bottom stress was calculated at the shelf edge (isobath 175 - 225 m). The most favorable conditions leading to positive Chl-a anomalies revealed by examining the simultaneous occurrence of different upwelling or downwelling processes as described by [31].

Correlation analysis was performed on the daily climatology of Chl-a, wind stress, and bottom stress. Pearson analysis was used to obtain the strength of a partial correlation between those two variables to Chl-a. The analysis was continued with cross-correlation between those three variables to see the time distances.

3. Results
3.1. Spatial pattern of chl-a
The mean of Chl-a for the period 2002 to 2017 on the shelf, slope, and rise show a strong longitudinal gradient in Chl-a along the length of the study domain (Figure 2). The highest mean Chl-a for each longitudinal cell across all years (>1 mg.m$^{-3}$) occurred at the most easterly longitude (110.5 – 111.5°E; Figure 2 (top); Table 1). Chl-a was highest on the shelf, with a difference of about 0.5 to 1.17 mg.m$^{-3}$ from the continental slope and about 0.65 – 1.74 mg m$^{-3}$ from continental rise Chl-a concentration (Figure 2).
Figure 2. The mean Chl-a for the period (2002–2017) within the 0.5° longitudinal cells. Data is partitioned based upon bathymetry, for the (a) shelf (40–200 m), (b) continental slope (200–1000 m), and (c) continental rise (1000–2000 m).

The eastern cells on the shelf have a higher Chl-a long-term mean. Compared to continental slope and rise, the shelf has a higher Standard Deviation (SD) (Table 1) which indicates that the variation of Chl-a concentration in this region is higher. For this reason, further analysis will be carried out in the shelf area to determine the forces affecting the Chl-a dynamics.

Table 1. Geometric mean of Chl-a concentration (mg.m⁻³) and it standard deviation (SD) for each longitudinal cell

| Cell | Longitude | Mean Chl-a at shelf/slope/rise | Standard Deviation (SD) |
|------|-----------|--------------------------------|-------------------------|
| 1    | 108.25    | 1.0 / 0.66 / 0.46              | 2.73 / 1.79 / 1.2       |
| 2    | 108.75    | 0.9 / 0.45 / 0.31              | 2.2 / 1.09 / 0.65       |
| 3    | 109.25    | 0.95 / 0.44 / 0.25             | 2.09 / 1.0 / 0.4        |
| 4    | 109.75    | 0.96 / 0.54 / 0.28             | 2.4 / 1.45 / 0.6        |
| 5    | 110.25    | 1.53 / 0.66 / 0.28             | 3.7 / 1.84 / 0.51       |
| 6    | 110.75    | 1.37 / 0.62 / 0.28             | 3.56 / 1.83 / 0.64      |
| 7    | 111.25    | 2.13 / 0.78 / 0.35             | 5.76 / 2.45 / 1.02      |
| 8    | 111.75    | 2.05 / 0.71 / 0.32             | 5.82 / 1.88 / 0.62      |
| 9    | 112.25    | 1.72 / 0.67 / 0.34             | 4.94 / 1.46 / 0.5       |
| 10   | 112.75    | 2.2 / 1.03 / 0.44              | 5.72 / 3.04 / 1.2       |

The mean monthly climatology of the Chl-a anomaly shows that the analyzed Chl-a anomaly was negative from January to May and start to positive in June and reach its peak in September while a higher anomaly (>0.2 mg.m⁻³) cross the continental rise (Figure 3). Even though it was negative from January to May, the Chl-a was still above the background value of 0.25 mg m⁻³ and sometimes was significantly larger with maxima of about 1 mg m⁻³ (Figure 2A). It also shows that a positive Chl-a anomaly was propagated westward. There was a striking feature in July where there were negative anomalous spots at 110°E - 112°E and the presence of long filaments offshore at 108°E - 110°E.
A positive anomaly seen trapped between isobaths 200 and 2000 m at latitude 110˚E - 112˚E in December is another noticeable feature.

Figure 3. Mean monthly climatology Chl-a anomaly (mg m$^{-3}$) for the period 2002 - 2017. Data source: https://resources.marine.copernicus.eu/. 40 m, 200 m, 1000 m, and 2000 m isobath shown by contour lines.
3.2. Temporal pattern of chl-a
The yearly profile of Chl-a in all cells shows a strong interannual variability of mean Chl-a with cycles of about 3 years (Figure 4A). Yearly, seasonally, and a monthly mean of Chl-a shows higher concentration at easternmost cells (cell 7 – 10, marked by a colored dash line in Figure 4). Chl-a starts rising from May to November (SE monsoon) indicate the strong influences of monsoonal wind (Figure 4B and 4C).

![Figure 4](image)

**Figure 4.** Yearly (A), seasonally (B), and monthly (C) mean of Chl-a anomalies for ten longitudinal cells.

3.3. Oceanographic drivers of chl-a dynamics
In addition to the seasonal variability, oceanographic processes had a large role in determining the patterns in surface Chl-a. From the long-term mean of Chl-a, upwelling-favorable wind stress resulted in the highest Chl-a at most of our cells, reversely, downwelling- favorable wind stress resulted in low Chl-a but still above the Chl-a background value (Figure 5). In contrast, the bottom stress has different
characteristics. Instead of resulting in low Chl-a, bottom stress downwelling-favorable resulted in a high Chl-a, higher than resulted while upwelling-favorable. Also, the bottom downwelling-favorable profile is the same as the wind upwelling-favorable profile with a slight difference, indicating a strong connection between the two conditions.

Figure 5. Long-term mean Chl-a for each longitudinal band resulted when upwelling and downwelling-favourable wind stress ($\tau_{wx}$) and bottom stress ($\tau_{bx}$) occur. Upwelling-favorable condition refers to the value $< 0$ N.m$^{-2}$.

Since cells 5, 7, and 10 show higher Chl-a than the other, we examine the wind and bottom stress contributions to increased Chl-a at those 3 cells. There was a strong seasonal variation in the Chl-a anomaly and wind stress from 2002 to 2017 (Figure 6A) with a higher level during SE monsoon. Chl-a during SE monsoon in 2010 and 2016. The wind has a seasonal pattern, it downwelling-favourable ($\tau_{wx} > 0$) during northwest monsoon (NW monsoon) and upwelling-favorable ($\tau_{wx} < 0$) during SE monsoon (Figure 6B). Bottom stress has a more complicated pattern but it is clear that the bottom stress was downwelling-favourable ($\tau_{bx} > 0$) near year-round with upwelling-favorable bottom stress ($\tau_{bx} < 0$) occurs mostly during the beginning of the year or NW monsoon (Figure 6C).

Figure 6. Chl-a anomalies (A), wind stress (B), and bottom stress (C) from 2002 to 2017 at cell 5 (blue), 7 (green), and 10 (red).
The combination of upwelling-favorable wind stress and downwelling-favorable bottom stress resulted in the highest positive Chl-a anomaly by 52.64% (cell 5), 43.44% (cell 7), and 39.92% (cell 10) followed by the combination of upwelling-favorable wind stress and bottom stress (Table 2).

**Table 2.** The percentage of occasions that positive Chl-a anomalies result from a combination of upwelling/downwelling favorable wind stress and bottom stress at Cell 5, Cell 7, and Cell 10. These longitudinal bands correspond to the region with a large response to upwelling events in Figure 5.

|          | τ_{wx}upwelling | τ_{bx}downwelling |
|----------|-----------------|-------------------|
| Cell 5   | 16.92%          | 8.95%             |
| Cell 7   | 16.81%          | 10.14%            |
| Cell 10  | 14.04%          | 6.78%             |
| Cell 5   | 52.64%          | 8.68%             |
| Cell 7   | 43.44%          | 10.86%            |
| Cell 10  | 39.92%          | 14.04%            |

Daily mean climatology shows that Chl-a started to increase in May and peaked in August to September in all 3 cells with higher concentrations at cell 7 (Figure 7A, green solid line). Upwelling-favorable wind-stress occurs during SE monsoon, starting from May to November, and reaches its peak from August to September (Figure 7A), coincide with thicker Chl-a anomaly bands and covered almost our domain at that time in Figure 3. This indicates that wind is the main driver for high Chl-a during those times in our domain. Downwelling-favorable bottom stress (τ_{bx} > 0) occurs mostly throughout the year, from April to November (Figure 7C) with only 3 months (December - March) of upwelling-favorable condition. This indicates that the circulation at the bottom mostly eastward with weakening even reversing flow during NW monsoon which can be seen by the low bottom stress. The bottom stress relatively high (downwelling-favourable) during the monsoon transitions (April-May and October-November).

**Figure 7.** Daily mean climatology of Chl-a anomalies (A), the wind stress τ_{wx} (B), and the bottom stress τ_{bx} (C) for the period 2002 - 2017.

3.4. **Correlation analysis**

Pearson correlation analysis between wind stress, bottom stress, and Chl-a anomalies yield a correlation coefficient value of -0.55 (0.54) at cell 5, -0.62 (0.55) at cell 7, and -0.64 (0.34) at cell 10 which significant at the 0.01 level (2-tailed) (Table 2). This indicates that wind has a stronger connection with Chl-a especially at cell 10 through a negative correlation. The more negative wind stress (upwelling condition), the higher the Chl-a.
The bottom stress and Chl-a anomalies have a positive correlation, the more positive the bottom stress (downwelling condition), the higher the Chl-a as shown in Figure 6 and Table 2. The cross-correlation analysis at those 3 cells yields that wind stress leads the Chl-a anomalies by about 18 – 24 days (Table 3) in the direction of negative correlation and accordance with the Pearson results. Wind stress leads to bottom stress at cell 5 and 7 for about 6 days, but wind stress slightly lags at cell 10 about 1 day from bottom stress with a negative correlation. Bottom stress leads Chl-a anomalies at cell 5 and 7 about 2 days but lags about 7 days at cell 10. At cell 10, the correlation of \( \tau_{bx} \) with the other two variables relatively weaker than the other 2 cells. This resulted can be found also in Pearson analysis in Table 2, suggesting that wind is the main force for the increased Chl-a at this cell.

### Table 3. Pearson correlation analysis (significant at the 0.001 level (2-tailed) result from 3 variables used in this study

| Variables               | Cell5  | Cell7  | Cell10 |
|-------------------------|--------|--------|--------|
| \( \tau_{wx} \) vs Chl_a anomalies | -0.55** | -0.62** | -0.64** |
| \( \tau_{bx} \) vs Chl_a anomalies  | 0.55** | 0.55** | 0.34** |
| \( \tau_{wx} \) vs \( \tau_{bx} \)   | -0.64** | -0.75** | -0.40** |

### Table 4. Cross-correlation for \( \tau_{wx} \), \( \tau_{bx} \), and Chl-a anomalies. Lags are the value outside the bracket (days) and the value inside the bracket is the correlation coefficient at that lag.

|                     | Cell 5 | Cell 7 | Cell 10 |
|---------------------|--------|--------|---------|
| \( \tau_{wx} \) vs Chl-a anomalies | -24 (-0.64) | -23 (-0.68) | -18 (-0.68) |
| \( \tau_{wx} \) vs \( \tau_{bx} \)   | -6 (-0.66) | -6 (-0.75) | +1 (-0.4) |
| \( \tau_{bx} \) vs Chl-a anomalies  | -2 (0.56) | -2 (0.56) | +7 (0.36) |

Sign for lags: ‘-’ = leads, ‘+’ = lags

### 4. Discussion

The Chl-a variability along the South Java sea shelf from 108 E to 113 E and the possibility of the alongshelf bottom stress contribution was investigated through Spatio-temporal statistical analysis. Our investigation focus on both wind and current as an upwelling driver. Wind and current upwelling assessed through the wind stress and the bottom stress on the shelf respectively.

The bottom stress considered in this study resulted from the net ocean's circulation. The contribution of individual processes to the net flow is not considered here and is subject to future investigations. This includes the role of the circulations that occur in southern Java in the Indonesian Throughflow (ITF) [16], [17], the South Java Current (SJC) [18], [19], the South Equatorial Current (SEC) [16], Kelvin waves [20], [21], [22], Rossby waves [22], [23], and the occurrence of eddies [14], [15]. [20] Iskandar et al. (2005) suggested that both remote and local wind forcings are necessary to explain the intraseasonal variability along the southern coast of Java. Some of the features that were not studied appeared in the form of anomalies in the analysis results. Even though these anomalies will be explained briefly here, further studies are needed for a good explanation of these anomalies.

The upwelling signal represented by positive Chl-a anomaly as seen in Figure 3 was moves westward, relevant to the studies earlier by [4] and [3]. A very different feature seen in July in Figure 3 where the negative anomalies of Chl-a observed in shelf compared to other surrounding areas is strongly suspected to be due to the presence of eddies that transport Chl-a offshore [14], [15]. This assumption is quite reasonable because the meander features are visible to the high seas in that month in Figure 3. However, further studies are needed to investigate this. [9] stated that although the upwelling-favorable winds along the coast initiated the offshore extension of Chl-a, its intensification offshore was further enhanced by a series of westward-propagating cyclonic eddies. Using composite analysis, [14] found that cyclonic eddies in this area induce both vertically and horizontally Chl-a
anomalies that elevate nutrient-rich water from the coast to the offshore. [40] suggested that the upwelling produced by cyclonic currents provides a continuous source of nutrients to the upper ocean and can be sustained throughout the entire year. Meanwhile, another feature that is clearly seen is the appearance of positive anomalies spots at 111°E to 111.5°E on the continental slope (depth: 500 – 1000 m) in December in Figure 3, this feature can also be seen from the daily mean climatology (Figure 7A) and needed for further analysis since our analysis limited to the shelf area (40-200 m).

Generally, the year-to-year Chl-a shows a seasonal pattern with several noted features in certain years. Blooming phytoplankton showed by very high Chl-a concentration coincided with positive IOD in 2006 as reported by [9] resulted in the highest positive anomalies as shown in Figure 6A and a significantly increased concentration in all cells as shown in Figure 4A. Meanwhile, one possible explanation for the relatively lowest positive anomalies in 2010 and 2016 (Figure 6A) is the La Niña that coincided with negative IOD during that time (Figure 9C in [3]). During La Nina, ITF carries warmer water deepening thermocline depth and reducing upwelling strength [4]. The wind has strong seasonal patterns from year to year as a consequence of the seasonal reversal of the monsoons [14], [41], [42].

Chl-a was higher during SE monsoon from May to November coincided with the upwelling-favorable wind stress (negative wind stress) as shown in Figure 7A, B relevant with previous studies [1], [2], [3], [43], [44], [45] that wind is the most dominant force that generates South Java upwelling. Although the bottom stress has a more complex pattern, it was downwelling-favourable throughout the year and was more negative or upwelling-favourable during the beginning of the year from December to March (NW monsoon) (Figure 6C and 7C). Based on this temporal pattern, we assumed that the dominant circulation in the focus area is the SJC. It has been previously studied that an eastward flow of the SJC occurred mostly throughout the year while the weakening even reversing flow occurred during the NW monsoon [18], [41]. In addition, this assumption is confirmed by the results of the power spectrum analysis which reveals the 180-day, 90-day, and 60-day variation of bottom stress (Figure 8), relevant with the SJC spectrum resulted in the earlier studies (Figure 7 in [46]).

**Figure 8.** Power spectrum of $\tau_{bc}$ at 3 cells. Small text lied above the most significant period which fulfills the 95% confidence interval at those 3 cells.

Pearson analysis (Table 2) shows a strong correlation between wind and Chl-a indicating wind as the dominant force affecting the Chl-a variability through wind-driven upwelling. This conclusion is confirmed by the high difference of Chl-a between upwelling and downwelling-favourable winds as shown in Figure 5. The relatively high positive correlation value between bottom stress and Chl-a indicates that the wind-driven upwelling occurs simultaneously with the eastward circulation in the focus area. This is not surprising as the temporal analysis yielded circulation to the East for most of the year including during the upwelling period.
This study uses remotely-sensed and reanalysis data, no in-situ data is used. Future studies are encouraged, combining in situ experiments with satellite-based measurements and reanalysis data for better analysis and results. The Chl-a variability only involves 2 upwelling drivers, those are wind (in terms of the wind stress) and current (in terms of the bottom stress). Other influencing factors to phytoplankton growth and its Chl-a biomass such as light availability and nutrients [47], [48] are not involved and need to be taken into account in interpreting the results. In addition, Chl-a which represents phytoplankton communities and biomass are governed by many limiting and controlling factors, such as nutrient availability, light climate, temperature, salinity, competition, parasites and grazing.

5. Conclusions
Seasonal variations are evident in Chl and wind analysis where higher Chl-a occur coincided with upwelling-favorable wind stress ($\tau_{wx}$) during SE monsoon. These results confirm wind as the main force that generating upwelling in South Java. Circulations among the study domain which is manifested by the bottom stress ($\tau_{wb}$) have more complicated variations, but it can be seen that bottom stress mostly downwelling-favorable or eastward circulation throughout the year except during NW monsoon. Every cell in our analysis shows a different response of Chl-a to wind and bottom stress forcing. Wind and bottom current have a different results in giving effect to the Chl-a variation. However, the wind is the main force that causes an increased Chl-a at the south Java shelf through wind-upwelling. This conclusion can be obtained from the analysis results which show that positive anomalies of Chl-a occur mostly during wind upwelling-favourable conditions. Another reason that strengthens this conclusion is the relatively higher correlation between wind stress and Chl-a. However, statistical analysis reveals a separate role of the bottom stress on Chl-a variation. Further investigation is needed to determine this certain role or contribution for the detailed result.

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References
[1] Wyrtki K 1962 The Upwelling In The Region between Java and Australia during the SOutheast Monsoon Australian Journal of Marine and Freshwater Research 13(3) 217 - 225 https://doi.org/10.1071/MF9620217
[2] Bray N A, Hautala S, Chong J, & Pariwono J 1996 Large-scale sea level, thermocline, and wind variations in the Indonesian throughflow region. Journal of Geophysical Research: Oceans 101(C5) 12239-12254
[3] Wirasatriya A et al 2020 Ekman dynamics variability along the southern coast of Java revealed by satellite data Int. J. Remote Sens. 41(21) 8475–8496 doi: 10.1080/01431161.2020.1797215
[4] Susanto R D, Gordon A I, Zheng Q 2001 Upwelling along the coasts of Java and Sumatra and its relation to ENSO Geophys. Res. Lett. 28(8) 1599–1602 doi: 10.1029/2000GL011844
[5] Susanto R D and Marra J 2005 Along the Southern Coasts of Java and Sumatra Oceanography 18(4)1996–1999 https://doi.org/10.1029/2000GO11844
[6] Murtugudde R G, Signorini S R, Christian J R, Busalacchi A J, McClain C R, & Picaut, J 1999 Ocean color variability of the tropical Indo-Pacific basin observed by SeaWiFS during 1997 1998 Journal of Geophysical Research: Oceans 104(C8) 18351-18366 https://doi.org/10.1029/1999JC900135
[7] Asanuma I, Matsumoto K, Okano H, Kawano T, Henriarti N, & Sachoemar S I 2003 Spatial
distribution of phytoplankton along the Sunda Islands: The monsoon anomaly in 1998 *Journal of Geophysical Research: Oceans* 108(C6) doi: 10.1029/1999jc000139

[8] Susanto R D, Moore T S, and Marra J 2006 Ocean color variability in the Indonesian Seas during the SeaWiFS era *Geochemistry Geophys. Geosystems* 7(5)1–16 doi: 10.1029/2005GC001009

[9] Iskandar I, Rao S A, and Tozuka T 2009 Chlorophyll-a bloom along the southern coasts of Java and Sumatra during 2006 *Int. J. Remote Sens.* 30(3)663–671 doi: 10.1080/01431160802372309

[10] Dai S, Zhao Y, Li X, Wang Z., Zhu, M., Liang, J., ... & Sun, X. (2020). The seamount effect on phytoplankton in the tropical western Pacific. *Marine Environmental Research*, 162, 105094. doi:https://doi.org/10.1016/j.marenvres.2020.105094

[11] Jung G and Prange M 2020 The effect of mountain uplift on eastern boundary currents and upwelling systems *Clim. Past* 16(1)161–181 doi: 10.5194/cp-16-161-2020

[12] Silva M et al. 2021 Ocean Dynamics and Topographic Upwelling Around the Aracati Seamount - North Brazilian Chain From in situ Observations and Modeling Results *Front. Mar. Sci.* 8 415 doi: 10.3389/fmars.2021.609113

[13] Xie S, Huang Z, and Wang X H 2021 Remotely Sensed Seasonal Shoreward Intrusion of the East Australian Current: Implications for Coastal Ocean Dynamics *Remote Sensing* 13(5)854 doi: 10.3390/rs13050854

[14] Yang G, Zhao X, Li Y, Liu L, Wang F, and Yu W 2019 Chlorophyll variability induced by mesoscale eddies in the southeastern tropical Indian Ocean *J. Mar. Syst* 199-103209 doi: 10.1016/j.jmarsys.2019.103209

[15] Ismail M F A, Ribbe J, Arifin T, Taofiqurohman A, and Anggoro D 2021 A census of eddies in the tropical eastern boundary of the Indian Ocean *J. Geophys. Res. Ocean.* 126(10)2021JC017204 doi: https://doi.org/10.1029/2021JC017204

[16] Ningsih N S, Sakina S L, Susanto R D, and Hanifah F 2020 Zonal Current Characteristics in the Southeastern Tropical Indian Ocean (SETIO) *Ocean Sci. Discuss.* 1–37 doi: 10.5194/os-2020-91

[17] Pang X, Bassinot F, and Sepulcre S 2021 Indonesian Throughflow variability over the last two glacial-interglacial cycles: Evidence from the eastern Indian Ocean *Quat. Sci. Rev.*256-106839 doi: https://doi.org/10.1016/j.quascirev.2021.106839

[18] Sprintall J 1999 Dynamics of the South Java Current in *Geophys. Res. Lett.* 26(16)2493–2496

[19] Utari P A, Setiabudidaya D, Khakim M Y N, and Iskandar I 2019 Dynamics of the South Java Coastal Current revealed by RAMA observing network *Terr. Atmos. Ocean. Sci.* 30(2)235–254 doi: 10.3319/TAO.2018.12.14.01

[20] Iskandar I, Mardiansyah W, Masumoto Y, & Yamagata T 2005 Intraseasonal Kelvin waves along the southern coast of Sumatra and Java *Journal of Geophysical Research: Oceans, 110*(C4) 1–12 doi: 10.1029/2004JC002508

[21] Syamsudin F and Kaneko A 2013 Ocean variability along the southern coast of Java and Lesser Sunda Islands *J. Oceanogr.*69(5)557–570 doi: 10.1007/s10872-013-0192-6

[22] Pujiana K and McPhaden M J 2020 Intraseasonal Kelvin Waves in the Equatorial Indian Ocean and Their Propagation into the Indonesian Seas *J. Geophys. Res. Ocean.* 125(5)1–25 doi: 10.1029/2019JC015839

[23] Gualdi S, Guilyardi E, Navarra A, Masina S, and Delecluse P 2003 The interannual variability in the tropical Indian Ocean as simulated by a CGCM *Clim. Dyn.*20(6)567–582 doi: 10.1007/s00382-002-0295-z

[24] Brink K H 2018 Rectified flow in a stratified coastal ocean *J. Mar. Res.*76(1)1–22 doi: 10.1357/002224018824082016

[25] Ribbe J, Toaspern L, Wolff J O, and Ismail M FA 2018 Frontal eddies along a western boundary current *Cont. Shelf Res.*165: 51–59 doi: https://doi.org/10.1016/j.csr.2018.06.007

[26] Rachman H A, Lumban-Gaol J, and Syamsudin F 2020 Remote Sensing of Coastal Upwelling
Dynamics in the Eastern Indian Ocean off Java, Role of ENSO and IOD in 2020 IEEE Asia Pacific Conference on Geoscience, Electronics and Remote Sensing Technology (AGERS) 1 6 doi: 10.1109/AGERS51788.2020.9452779
[27] Horii T, Ueki I, & Ando K. 2018 Coastal upwelling events along the southern coast of Java during the 2008 positive Indian Ocean Dipole Journal of Oceanography 74(5)499-508 doi: 10.1007/s10872-018-0475-z
[28] Lumban-Gaul J, Siswanto E, Mahapatra K, Nath N M N, Nurjaya I W, Hartanto M T, ... & Permana A 2021 Impact of the Strong Downwelling (Upwelling) on Small Pelagic Fish Production during the 2016 (2019) Negative (Positive) Indian Ocean Dipole Events in the Eastern Indian Ocean off Java. Climate 9(2)1–11 doi: 10.3390/cli9020029
[29] Moses W J, Gitelson A A, Perk R L, Gurlin D, Rundquist D C, Leavitt B C, ... & Brakhage P 2012 Estimation of chlorophyll-a concentration in turbid productive waters using airborne hyperspectral data Water research 46(4)993-1004 doi: 10.1016/j.watres.2011.11.068
[30] Brewin R J, Ciavatta S, Sathyendranath S, Jackson T, Tilstone G, Curran K, ... & Raitos D E 2017 Uncertainty in ocean-color estimates of chlorophyll for phytoplankton groups Front. Mar. Sci. 4-104 doi: 10.3389/fmars.2017.00104
[31] Everett J D, Baird M E, Roughan M, Suthers I M, and Doblin M A 2014 Progress in Oceanography Relative impact of seasonal and oceanographic drivers on surface chlorophyll -a along a Western Boundary Current Prog. Oceanogr. 120:340–351 doi: 10.1016/j.pocean.2013.10.016
[32] Brieva D, Ribbe J, and Lemckert C 2015 Estuarine, Coastal and Shelf Science Is the East Australian Current causing a marine ecological hot-spot and an important fisheries near Fraser Island , Australia? Estuar. Coast. Shelf Sci. 153:121–134 doi: 10.1016/j.ecss.2014.12.012
[33] Azis Ismail MF, Ribbe J, Karstensen J, & Rossi V 2019 Remote sensing of upwelling off Australia's north-east coast Ocean Science Discussions 1-31
[34] Hersbach H. et al. 2020 The ERA5 global reanalysis Q. J. R. Meteorol. Soc. 146(730)1999–2049 doi: 10.1002/qj.3803
[35] Drévillon 2021 QUALITY INFORMATION DOCUMENT For Global Ocean Reanalysis Products GLOBAL REANALYSIS PHY_001_030 1–25
[36] Quadfasel D and Cresswell G R 1992 A note on the seasonal variability of the South Java Current J. Geophys. Res.97(C3)3685 doi: 10.1029/91jc03056
[37] Qu T & Meyers G 2005 Seasonal characteristics of circulation in the southeastern tropical Indian Ocean. Journal of Physical Oceanography 35(2)255-267.
[38] Murtugudde R, McCreary Jr J P, & Busalacchi A J 2000 Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998 Journal of Geophysical Research: Oceans 105(C2)3295-3306
[39] Wirasatriya A, Maslukah L, Satriadi A, & Armanto R D 2018 Different responses of
chlorophyll a concentration and Sea Surface Temperature (SST) on southeasterly wind blowing in the Sunda Strait. In *IOP Conference Series: Earth and Environmental Science* 139(1)012028 doi: 10.1088/1755-1315/139/1/012028

[45] Hadi S, Ningsih N S, Baskoro M S, Wirasatriya A, & Kuswardan, A R 2020) The classification of upwelling indicators base on sea surface temperature, chlorophyll-a and upwelling index, the case study in Southern Java to Timor Waters. In *IOP Conference Series: Earth and Environmental Science* 530(1)012020 doi: 10.1088/1755-1315/530/1/012020

[46] Iskandar I, Tozuka T, Sasaki H, Masumoto Y, & Yamagata T 2006 Intraseasonal variations of surface and subsurface currents off Java as simulated in a high-resolution ocean general circulation model *Journal of Geophysical Research: Oceans, 111*(C12) doi: 10.1029/2006JC003486

[47] Pei S *et al.* 2019 Nutrient dynamics and their interaction with phytoplankton growth during autumn in Liaodong Bay, China *Cont. Shelf Res.* 186(3)34–47 doi: 10.1016/j.csr.2019.07.012

[48] Corredor-acosta A, Pizarro-koch M, Medell J, and Sald G S 2020 Spatio-Temporal Variability of Chlorophyll-A and Environmental Variables in the Panama Bight *Remote Sens.* 12-2150 doi:10.3390/rs12132150.