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RESEARCH ARTICLE

# Seasonal Variability of Sea Surface Chlorophyll-a at West Borneo Island

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**Abstract**. The optimization of marine fisheries activities can be achieved through an understanding of the timing of fishing, access to good information, and knowledge of oceanographic conditions. These conditions often lead to significant nutrient enrichment in the surface layer of the ocean, which in turn increases the sea surface chlorophyll-a (SSC). In the context of the west Borneo Island region, seasonal variability in SSC plays a crucial role in determining potential fishing grounds. The objectives of this study are examining the seasonal variability of SSC, identifying upwelling and downwelling processes through analysis of sea surface wind (SSW), and determining the climatological distribution of Sea Surface Temperature (SST) and sea surface height (SSH) within the water off Labuan Island, Malaysian Borneo, and the Karimata Strait, West Kalimantan, Indonesia. Remote sensing data spanning from 2007 to 2021 were analyzed, encompassing SSC, SST, SSH anomalies, SSW, wind stress curl, and Ekman pumping. Additionally, rainfall and river discharge were examined as supplementary indicators of these oceanographic processes. The findings indicate that SSW plays a pivotal role in driving upwelling and downwelling processes, which in turn influence SSC variability. In Labuan waters, upwelling occurs primarily from November to February, while downwelling predominates from June to September. In contrast, in the Karimata Strait, upwelling is identified from July to September, with downwelling prevalent between March and May. Upwelling events in both regions are characterized by increasing SSC, accompanied by decreasing SST and SSH, while the opposite trends are observed during downwelling events. The peak of rainfall and river discharge in December is noted to potentially enhance SSC variability in the Karimata Strait compared to Labuan Island waters.



## 1. Introduction

The most crucial components of a water body's food chain include bacteria, phytoplankton, zooplankton, and sea surface chlorophyll-a (SSC). Their abundance typically correlates with the fertility of the water body (Ochocka and Pasztaleniec, 2016). Over time, SSC has been utilized as a proxy for assessing phytoplankton biomass and photosynthetic potential. SSC, being closely associated with fishing data (Ningsih et al., 2013; Feng et al., 2018), serves as a valuable metric for evaluating the potential productivity of fishing grounds.

Enhancing the effectiveness and optimization of marine fisheries, particularly in determining fishing timing, necessitates understanding surface SSC characteristics (Ningsih et al., 2013; Napitupulu et al., 2022). Seasonal and annual variations in phytoplankton production and biomass significantly influence the overall variability of marine biological and biogeochemical processes (Wang et al., 2019). For instance, squid catches in the Karimata Strait are influenced by sea surface temperature variables, with SSC catches predominantly occurring during the transition from the second transitional season to the western season (Muskananfola and Wirasatriya, 2021). Seasonal SSW influences the movement of seawater masses from the Indian Ocean into the Karimata Strait and the Java Sea (Susanto et al., 2006; Heriati et al., 2015).

Coastal and estuarine ecosystems typically exhibit high temporal and spatial variability in SSC concentrations due to various factors, including climatic, biological, and physical factors (e.g., runoff, seasonality, ocean circulation, upwelling, temperature, stratification, mixing, and fronts) as well as chemical conditions (Wijaya et al., 2020). Conversely, low SSC concentrations in offshore waters result from the lack of direct nutrient supply from land. However, certain areas of offshore waters may exhibit high SSC concentrations due to physical processes, such as upwelling, where nutrients are lifted from deep layers to the surface (Sarsito et al., 2019). This upwelling process leads to an increase in SSC concentrations in surface waters (Atmadipoera et al., 2020), subsequently affecting sea surface temperature (SST) and sea surface height (SSH) in the surrounding area.

The waters off Labuan Island in Malaysian Borneo and the Karimata Strait in Indonesia offer significant potential for studying fisheries resources (Wang et al., 2019). Labuan Island serves as a prominent fishing center in Sabah, housing a fishing data center under the Malaysian Department of Fishing. Similarly, the Karimata Strait is a notable fishing hub in West Kalimantan, with a fishing data center located at the Pemangkat Nusantara Fishing Port in Indonesia.

Remote sensing enables the estimation of SSC values, as chlorophyll-containing phytoplankton contributes to SSC, which absorbs blue and red colors and reflects green colors, detectable by sensors like MODIS on satellites (Muskananfola and Wirasatriya , 2021). In recent years, MODIS imagery has gained widespread usage due to its high spectral resolution, extensive temporal and spatial coverage, availability of free data, and rapid data acquisition (Wu et al., 2009; Maslukah et al., 2022). The objectives of this study are to compare the spatial and temporal variations of SSC in the waters of Labuan Island and the Karimata Strait, utilizing seasonal fluctuations of SST, SSH, precipitation, river discharge, sea surface wind (SSW), and Stokes drift to assess seasonal SSC variability.

## 2. Material and Methods

### Study Area

The study area encompasses the region of West Borneo Island, with particular emphasis on the waters off Labuan Island, Malaysian Borneo, and the Karimata Strait, West Kalimantan Indonesia (Figure 1). The designated area spans between 100° to 121° E longitude and 6° S to 12° N latitude. Labuan Island is renowned as a premier destination for sport fishing, situated approximately 8 kilometers off the coast of the Malaysian state of Sabah (Ibrahim, et al, 2015). On the other hand, the Karimata Strait is a broad passage linking the Natuna Sea with the Java Sea. Positioned between the Indonesian islands of Sumatra and Kalimantan, it ranks among the largest straits in Indonesia.

### Data Collection

Monthly imagery from the Moderate-Resolution Imaging Spectroradiometer (MODIS) Level 3, acquired from Aqua and Terra satellites, enables the acquisition of synoptic spatial and temporal data that cannot be solely obtained through in situ sampling. Ocean color remote sensing is utilized to enhance the monitoring of SSC near the water surface more effectively and practically. A series of remote sensing images were analyzed for SSC, SST, and SSH from ten sampling points in both study areas (Figure 1). The SSC Level 3 Standard Mapped Image (SMI) data with 4 km spatial resolution was obtained from NASA's Aqua satellite, which incorporates the MODIS sensor used for SSC (ocean color). The SSC dataset consists of monthly composites available from January 2003 to the present, downloadable at https://coastwatch.pfeg.noaa.gov/erddap/griddap (accessed on January 11, 2023). However, for this study, the monthly SSC data were retrieved from January 2007 to December 2021, spanning a period of 15 years. The standard MODIS algorithm demonstrates effectiveness in Indonesian marine waters for both in-water algorithms and atmospheric correction models (Muskananfola and Wirasatriya , 2021). The accuracy of SSC estimation ranges from 60-85% using MNB (%) in the Indonesian Seas (Winarso and Marini, 2014), indicating that satellite-derived SSC products can exhibit spatial and temporal variations.

SSH and SST were estimated as global ocean conditions through the OCEAN5 operational system. The OCEAN5 system is an ocean ice ensemble reanalysis system that enables global vortex eddies (5 members) (Zuo et al., 2019). For this study, monthly SSH and SST datasets spanning January 2007 to December 2020, with a spatial resolution of $0.25^0$ x $0.25^0$, were downloaded from https://www.ecmwf.int (accessed

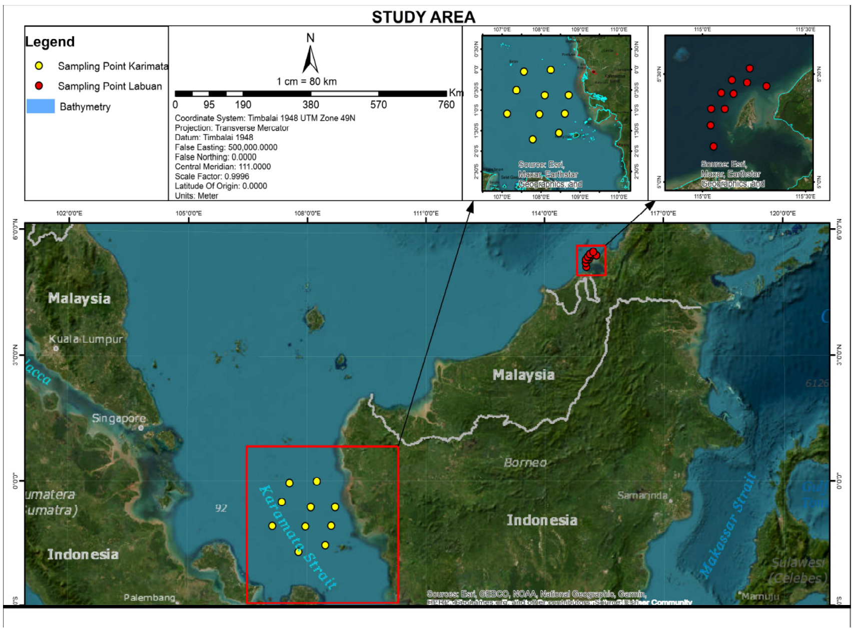


Figure 1. Location of Karimata Strait, Indonesia, and Labuan Island, Malaysian Borneo. The dot point is the location of ten sampling points in the Karimata Strait, Indonesia, and Labuan Coastal Waters, Malaysia.

on February 8, 2023). Monthly data were sourced from sea surface wind (SSW) data at the 10 m level and Stokes drift field from the ECMWF Reanalysis v5 (ERA5) with a horizontal resolution of $0.25^0$ x $0.25^0$ since 1940 (Hersbach et al., 2018). Hourly datasets from January 2007 to December 2021 (15 years), were downloaded from https://cds.climate.copernicus.eu/ (accessed on March 8, 2023) for this study. Additionally, meteorological data (daily precipitation) from https://chc.ucsb.edu/data/chirps (accessed on March 28, 2023) were collected to understand the influence of the monsoon system on marine productivity in this region. CHIRPS combines $0.05^0$ x $0.05^0$ resolution satellite imagery within situ station data to create compiled precipitation time series for trend analysis and seasonal drought monitoring (Funk et al., 2015). The operational global river discharge reanalysis product of GloFAS-ERA5 is utilized to determine river discharge from https://cds.climate.copernicus.eu/cdsapp (accessed on April 8, 2023). Both precipitation and river discharge data are from the global gridded datasets with a horizontal resolution of $0.1^0$ x $0.1^0$ and a daily step (Harrigan et al., 2020), extracted from January 2007 to December 2021 (15 years).

### Data Analysis

The SSC values were estimated using an algorithm developed by Hu et al., (2019), which combines an empirical band difference approach for low SSC concentrations with a band ratio approach for higher SSC concentrations (O'Reilly and Werdell, 2019). Mapped distributions of SSC, SST, and SSH were color-scaled from the highest to the lowest range based on the spatial distribution of SSC, SST, and SSH obtained. Mean values of SSC, SST, and SSH at ten sampling points were calculated monthly to assess temporal distribution. These mean values of SSC, SST, SSH, and precipitation were then analyzed across four seasons: the West Season (December-February), Transitional I Season (March-May), East Season (June-August), and Transitional II Season (September-October). However, the southwesterly winds predominantly influence the South China Sea (SCS) known as the southwest monsoon (from June until August) (Satar, et al, 2020). When the wind reversed its direction to northeasterly, the SCS dominated by the northeast monsoons (from December until February) (Wang et al., 2013; Wyrtki, 1961). SST, SSH, precipitation, and river discharge data were utilized to explore the seasonal variability of SSC. The seasonal changes influence Ekman transport. Ekman transport occurs when ocean surface waters are influenced by the wind friction force. The calculation of Ekman pumping velocity (EPV) at each grid point is expressed as shown in Equation 1

$$w_E = -\nabla \times \left(\frac{\tau}{\rho f}\right) \quad (1)$$

where $\tau$ is the wind stress calculated from the 10-m wind, $\rho$ is the mean sea water density, with a value of $1025\times10^3$ kg/m$^3$, and $f$ is the Coriolis parameter.

## 3. Result and Discussion

### Seasonal Variability of SSC

The average spatial distribution of monthly SSC climatology between 2007 and 2021 is depicted for the region of West Borneo Island (Figure 2).. The highest range of SSC content in Labuan Island waters and the Karimata Strait occurs in January and September, respectively. The seasonal variability of SSC content reaches its maximum range in Labuan Island waters (1.00 - 1.80 mg/m$^3$), compared to the Karimata Strait (0.80 - 1.00 mg/m$^3$).

Seasonal phytoplankton blooms in Labuan waters are significantly influenced by upwelling events and the effects of surface water transport to the South China Sea (Shang et al., 2021). During the Transitional I Season, SSC concentrations decrease from 1.01 to 0.89 mg/m$^3$, with the lowest SSC content occurring in April. Subsequently, during the East Season, SSC concentrations increase from 0.89 to 0.95 mg/m$^3$, followed by a further increase from 0.95 to 1.20 mg/m$^3$ during the Transitional II Season. The coastal region of Labuan maintains consistently high SSC concentrations towards the end of the year. However, phytoplankton blooms predominantly emerge from the southern region of Labuan Island and extend to its offshore waters in October (Chuan et al., 2021).

The highest average SSC content in the Karimata Strait was observed in September (Transitional II Season), with values ranging from 0.80 to 1.20 mg/m$^3$. However, the range of SSC values decreased (0.36 to 0.52 mg/m$^3$) during the Transitional I Season, with the lowest SSC content occurring in April at 0.36 mg/m$^3$. During the western season, SSC values ranged from 0.46 to 0.63 mg/m$^3$, but the SSC value increased from 0.62 to 0.76 mg/m$^3$ during the East Season. There was an increasing trend in SSC values from 0.49 to 1.00 mg/m$^3$.

Tropical sea waters generally exhibit low SSC due to limited nutrients and strong water column stratification. The stratification of the water column is primarily caused by the continuous heating of the water surface throughout the year (Woodgate and Peralta, 2021). However, SSC content can increase with a high supply of nutrients from nearby human settlements. Human activities in the islands of Bangka Belitung and Kalimantan have contributed to the input of nutrients and SSC into the Karimata Strait (Hamzah et al., 2020). Sediments carried by these rivers transport nutrients originating from human activities inland. Notably, there is a decreasing trend in SSC concentration values from coastal areas, particularly river estuaries, towards the open sea (Bao et al., 2021).

Temperature measurements at the study site indicate that the shallow Karimata Strait is still primarily influenced by SSW (drag force) (Putri et al., 2016). SSW patterns, including wind convergence and shearling, can trigger the uplift of air masses, potentially leading to the formation of rain clouds in the region (Bao et al., 2021). Convergence areas, where SSW encounters each other, are commonly observed in the South China Sea (SCS) region, the northern part of Kalimantan, and the Karimata waters. The presence of convergence areas often results in the growth of convective clouds and the occurrence of moderate to heavy rainfall in the region (Saragih et al., 2018).

### Seasonal Variability SST, SSW, SSH, and Precipitation

SST and SSC are commonly used indicators for studying upwelling events. Upwelling events are characterized by the movement of colder, nutrient-rich waters from deeper layers to the surface, resulting in changes in SST and SSC values. Satar et al (2020) have reported the occurrence of upwelling in the northwest Sabah during the northeast monsoon. In Labuan, clear changes in SST and SSC were observed during the northeast monsoon (November to February). It was identified that lower SST and higher SSC values coincided with each other for each month, indicating the occurrence of an upwelling event (Figures 2-3).

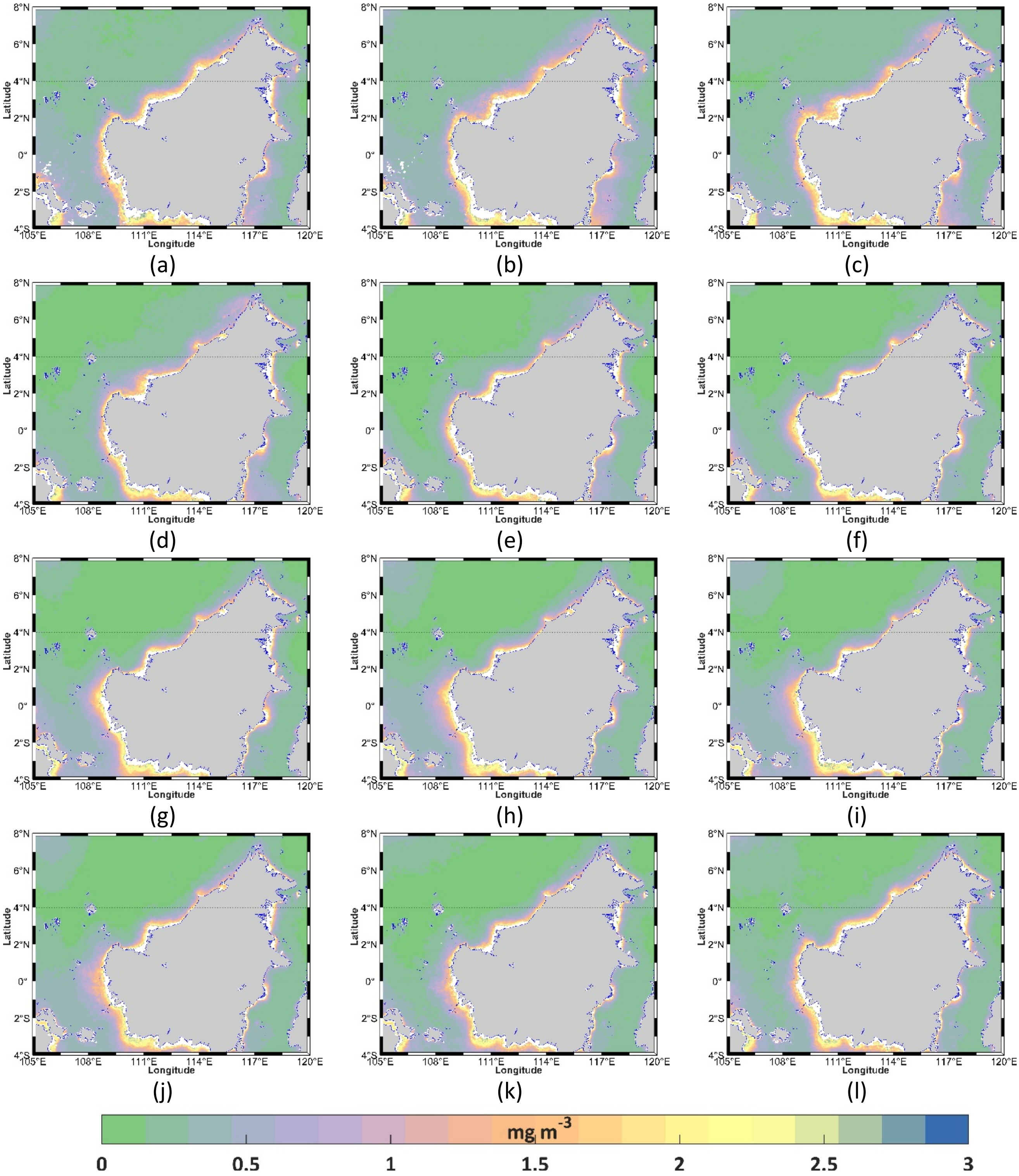


Figure 2. Climatology distribution of SSC in (a) December, (b) January, (c) February, (d) March, (e) April, (f) May, (g) June, (h) July, (i) August, (j) September, (k) October, and (l) November during the period of 2007-2021.

Strong northeasterly SSW (Figure 4) are expected in the western and northern waters of Labuan from November to February (during the West and Transitional I Seasons). During the western season, cold northeasterly SSW blowing along the coast cause cooling and condensation of surface waters, resulting in strong vertical mixing. The depth of the mixed layer descends to the seabed in most parts of the region, enriching the surface layer with nutrients and promoting photosynthetic activity (Loisel et al., 2017). While heat flux can also impact SST, the monthly climatological average net heat flux from 2007 to 2020 indicates a high positive heat flux (absorbed heat) present in the study area, particularly during January, and continuing to increase until March. However, despite the high heat flux recorded, it does not seem to contribute to the low SST observed. This discrepancy may be attributed to the Vietnam Coastal Current diverging from the Vietnam Coast and splitting into two directions. One direction moves eastward towards Natuna and Kalimantan Island (Pa'suya et al., 2014). Hence, an additional parameter, SSH as shown in Figure 5, is utilized to identify upwelling events.

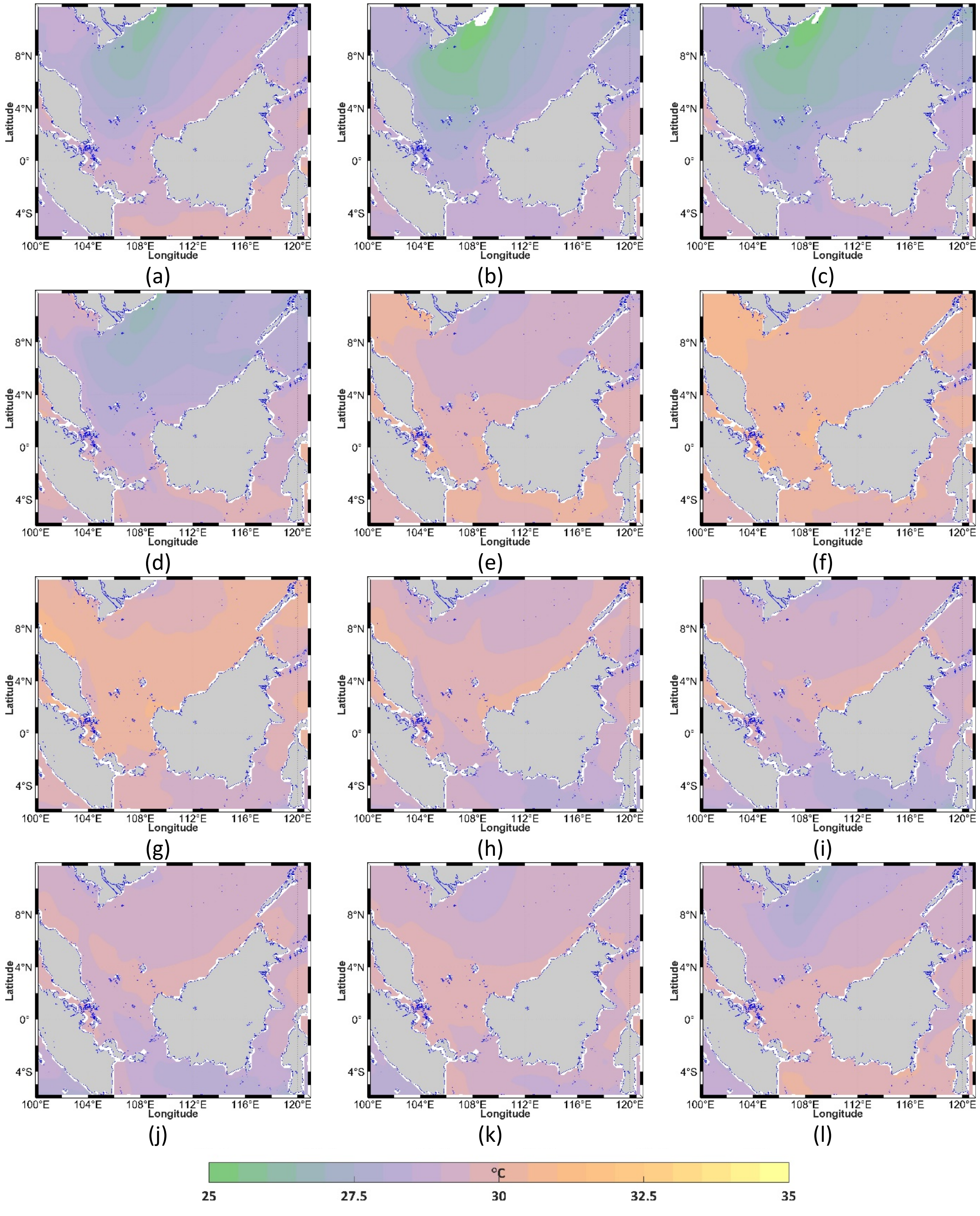


Figure 3. Climatology distribution of SST in (a) December, (b) January, (c) February, (d) March, (e) Aril, (f) Mei, (g) June, (h) July, (i) August, (j) September, (k) October, and (l) November during the period of 2007-2020.

In Labuan waters, downwelling occurred during the period from June to September, with average SSC values below 1.20 mg/m$^3$ (Figure 6a). Strong SSW are the primary factor contributing to the increase in downwelling (Figure 4). Typically, as per theoretical expectations, SST values should decrease during downwelling events; however, in practice, there is an opposite trend observed where SST values actually increase (Figure 6b). Therefore, the SSH indicator becomes significant in identifying downwelling events (Figures 5, 6c). During this period, strong southwest SSW blow towards the east and north coasts of Kalimantan (Triana et al., 2021). When these SSW pass the equator and move northward, they are referred to as the Southwest monsoon.

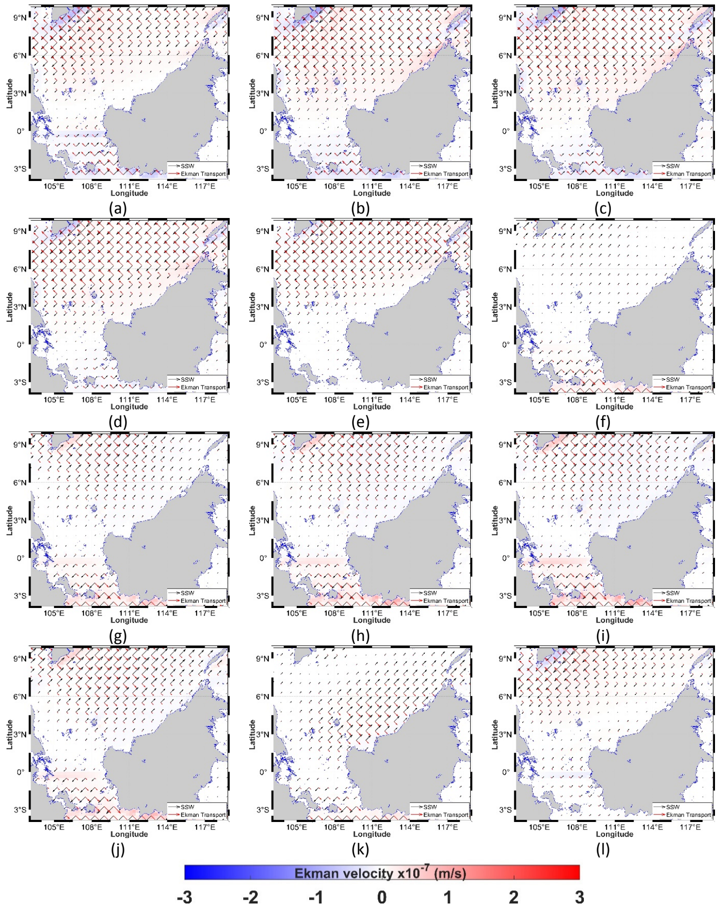

Figure 4. Climatology distribution of SSW and Ekman Pumping in (a) December, (b) January, (c) February, (d) March, (e) Aril, (f) Mei, (g) June, (h) July, (i) August, (j) September, (k) October, and (l) November during the period of 2007-2020

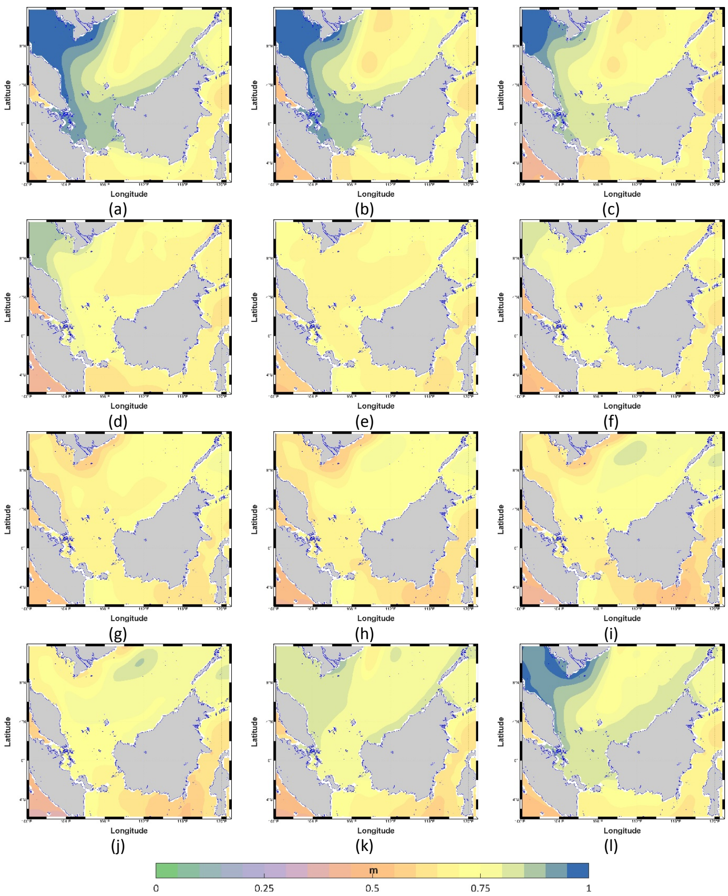

Figure 5. Climatology distribution of SSH in (a) December, (b) January, (c) February, (d) March, (e) Aril, (f) Mei, (g) June, (h) July, (i) August, (j) September, (k) October, and (l) November during the period of 2007-2020.

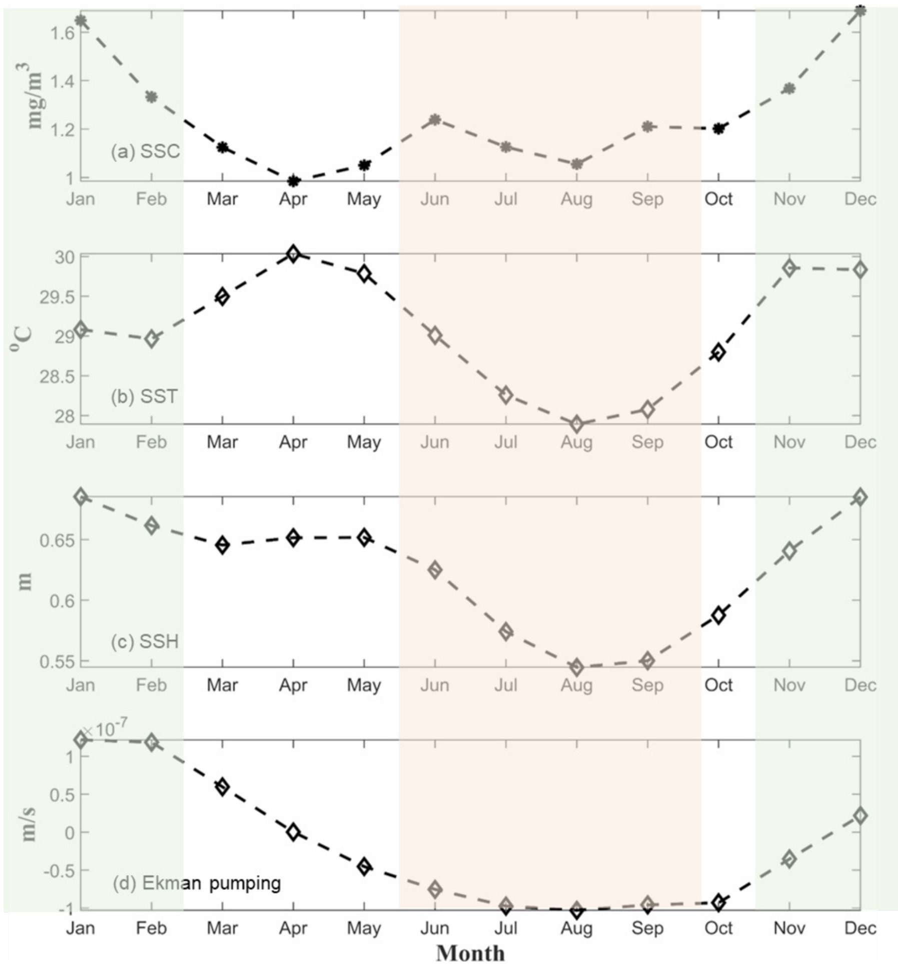


Figure 6. Climatology monthly mean variables averaged from ten sampling points in Labuan sides: (a) SSC, (b) SST, (c) SSH, and (d) Ekman pumping. The orange-shaded area indicates the downwelling season and the green-shaded area indicates the upwelling season.

During the West Monsoon, significant cyclonic eddies form in the south-central region of the SCS, indicating the potential occurrence of upwelling phenomena and an increase in SSH (Figures 5, 6c). In the East Monsoon period, the circulation pattern with cyclonic eddies in the south-central SCS diminishes and is replaced by anticyclonic eddies formed near the east coast of the Malaysian Peninsula. During the transition period between the first and second monsoon seasons, geostrophic currents tend to be weaker compared to the West and East Monsoon periods (Mustajap et al., 2015; Tan et al., 2023).

From December to February, the upwelling pattern follows the West Monsoon pattern, influenced by the West Monsoon SSW, quantified by Ekman pumping values (Figure 6d). However, in early April, there is a decrease in SSH (Figures 5, 6c) and SSC (Figures 2, 6a) due to northward flow and the formation of anticyclonic eddies around $8^0$N, $110^0$E and $9^0$N, $103^0$E (Tan et al., 2023).

In the waters of Labuan, upwelling events are identified by an increase in SSC and a decrease in SSH and SST. Several significant upwelling events have been recorded in 2007, 2009, 2011, 2016, and 2017, with an average SSC exceeding 1.00 mg/$m^3$. Strong northeasterly SSW are expected to occur along the west and north coasts of Sabah from November to February. During the West Monsoon (Figure 4), the cold northeasterly SSW blowing along the coast cause surface water cooling and densification, resulting in intense vertical mixing. The mixed layer extends to the bottom in most areas, contributing to nutrient enrichment in the surface layer, which supports photosynthetic activity (Loisel et al., 2017).

## Upwelling and Downwelling Process in Labuan Island Waters

The upwelling process is primarily influenced by coastal topography and SSW patterns. The influence of seafloor topography on upwelling processes should also be considered in Labuan waters (Figure 7b). The presence of steep continental slopes can focus or amplify the upward flow of water, potentially enhancing upwelling in specific regions. In the case of Labuan, upwelling is primarily observed north of the island, as indicated by the changes in SST, SSH, and SSC (Figures 7d-f). Coastal upwelling is observed when SSW blow parallel to the southwest coast of Borneo Island (Figure 7a). According to Satar (2020), upwelling favorable conditions during the northeast monsoon due to the Ekman transport and Ekman pumping. The SSW are deflected to the right due to the Coriolis effect, as Labuan Island is located in the northern hemisphere. The SSW induce Ekman transport, pushing surface water away from the coast (Figure 7b). Consequently, this displacement allows deeper, colder, and nutrient-rich water from the submarine layer to rise to the surface, a phenomenon known as upwelling. During the peak upwelling period (January), the Ekman pumping speed is estimated to be around $1.2\times10^{-7}$ m/s (Figures 7c, 4). The peak of downwelling induced by alongshore SSW and Coriolis force occurs in August with the estimated Ekman pumping speed of $-1.0\times10^{-7}$ m/s.

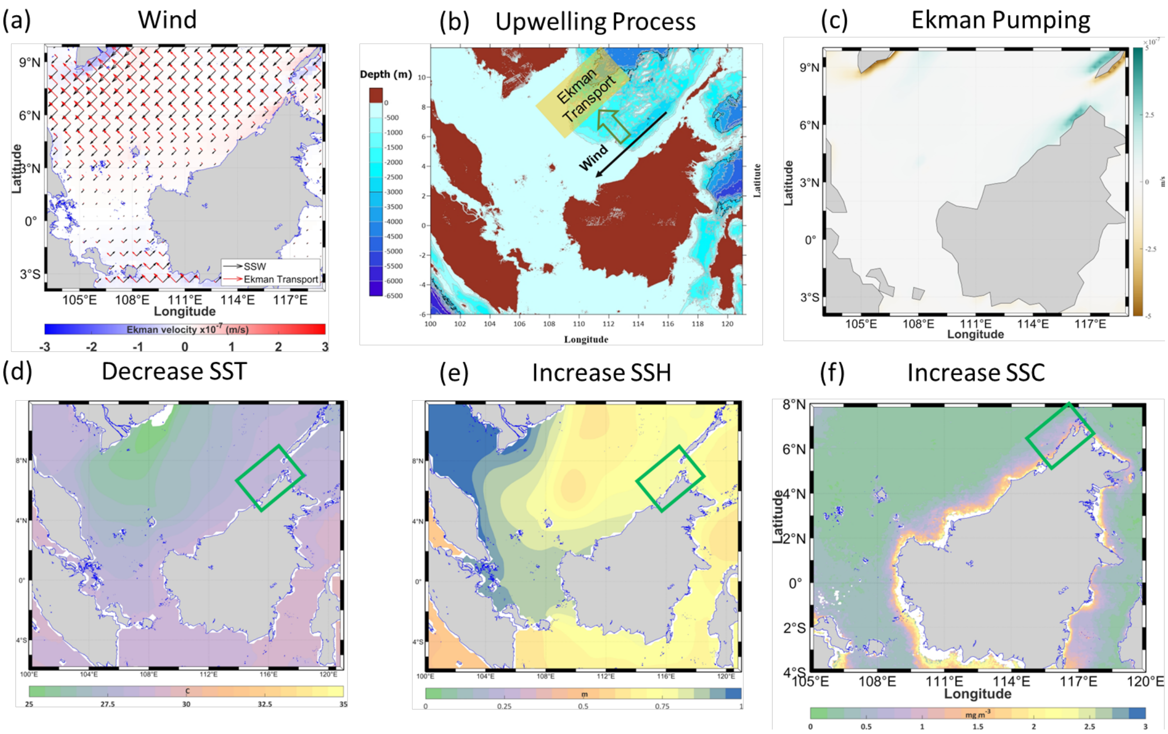


Figure 7. The process of upwelling in Labuan in the west season which reaches its peak in January starts from (a) wind (vector), (b) Ekman transport, (c) Ekman pumping. Upwelling can be identified by (d) decrease SST, (e) increase SSH, and (f) increase SSC. Green-colored boxes are areas that experience upwelling.

The upwelling processes are responsible for reducing the SST and SSH values from 29.9 °C in December to 29.3 °C in January (Figures 7d-e). This indicates that colder water from the subsurface is replacing the warm surface water. Both parameters also rise from December to February. A peak of 0.08 in SSH was observed in January (Figure 7e), suggesting that changes in SSW patterns and ocean circulation are associated with upwelling. As water rises through upwelling, temperature and pressure differences between the rising water and the surrounding water can contribute to an increase in SSH. Upwelling transports nutrient-rich waters, including nitrogen and phosphorus, from the deep ocean layers to the surface. The availability of these nutrients supports optimal conditions for phytoplankton growth, resulting in increased SSC from November to February (Figure 7f). This peak in SSC in January is consistent with enhanced phytoplankton growth stimulated by upwelling.

In Labuan Island waters, downwelling is a process characterized by the descent of surface water to deeper water. Various factors, including SSW, SST, SSH, and SSC, can help identify downwelling events. Coastal downwelling occurs when SSW consistently flow parallel to the northeast coast along the coastline (Figure 8a). The Coriolis force causes the SSW direction to deflect toward the coast. Strong and sustained SSW lead to the accumulation of water masses at the surface, influencing seawater movement. As the SSW pushes the water mass toward the surface, water accumulates around the coast (Figure 8b), creating a flow toward deeper waters at a speed of approximately $-1\times10^{-7}$ m/s (Figures 8c, 5d).

In Labuan waters, the higher SST (30 °C) was revealed in August compared to its surrounding SST areas (29 °C) (Figure 8d), indicating a temperature difference suggestive of the downward movement of warmer water masses and the occurrence of downwelling. The decrease in SSH from July to September, with the lowest point occurring in August at 0.05 m (Figure 8e), aligns with the characteristics of downwelling, which in turn influences current patterns and ocean wave dynamics, leading to significant reductions in wave height. The decrease in SSC concentration from July to September, with the lowest peak in August (Figure 8f), indicates changes in phytoplankton biomass. The downwelling process transports relatively warmer water masses from the sea surface, potentially affecting the distribution and concentration of SSC, contributing to the decrease in primary productivity and the availability of nutrients for photosynthetic organisms in the area during downwelling events.

## Seasonal Variability SST, SSH, and Precipitation in Karimata Straits:

The climatology monthly mean variables of SST, SSH, and Precipitation exhibit peak values in the Karimata Strait between December and November (Figure 9a). The increase in SSC and SST (Figure 9b) within these months can be attributed to environmental changes such as high precipitation. The increase in precipitation in December (Figure 9c) leads to an increase in river discharge (Figure 9d), which transports nutrients from the mainland to the waters of the Karimata Strait. Nutrients such as nitrogen and phosphorus play a crucial role in supporting phytoplankton growth in the marine ecosystem. The coastal waters of West Kalimantan receive a significant amount of nutrient flow from the mainland, particularly through the Kapuas River (Gordon et al., 2019). The concave shape of the West Kalimantan coast contributes to the accumulation of organic matter carried by incoming water masses, as well as the presence of abundant vegetation, such as mangroves and seagrasses (Putri et al., 2016). High nutrient input triggers phytoplankton growth, as proven by the observed rise in SSC.

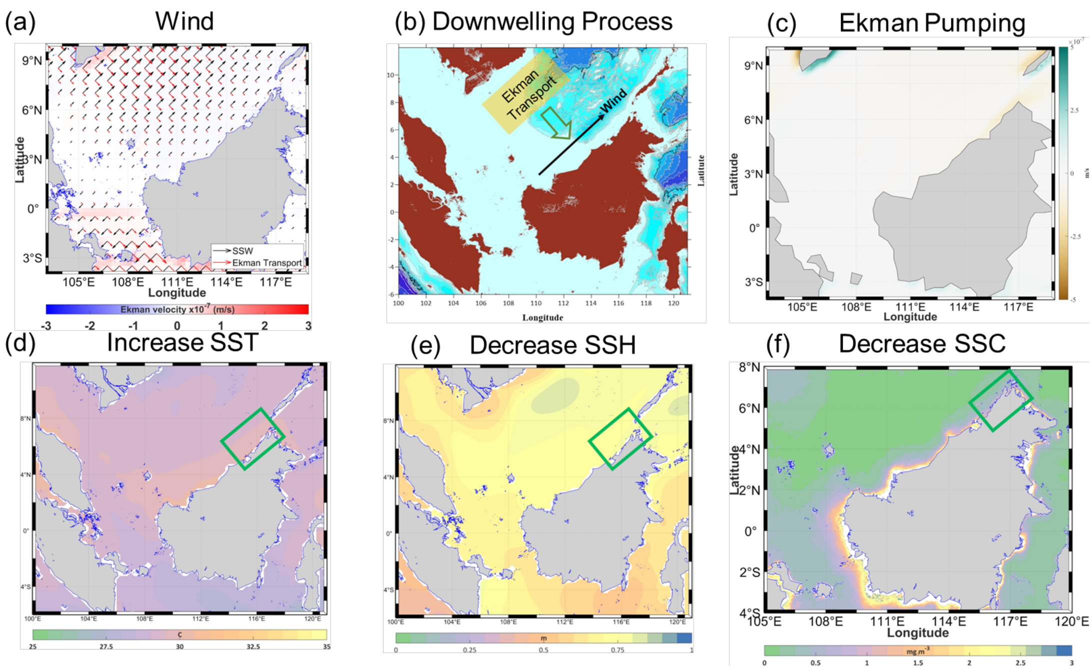


**Figure** 8. The process of downwelling in Labuan in the east season which reaches its peak in August starts from (a) SSW (vector), (b) Ekman transport, (c) Ekman pumping. Downwelling can be identified by (d) increase SST, (e) decrease SSH, and (f) decrease SSC. Green-colored boxes are areas that experience downwelling.

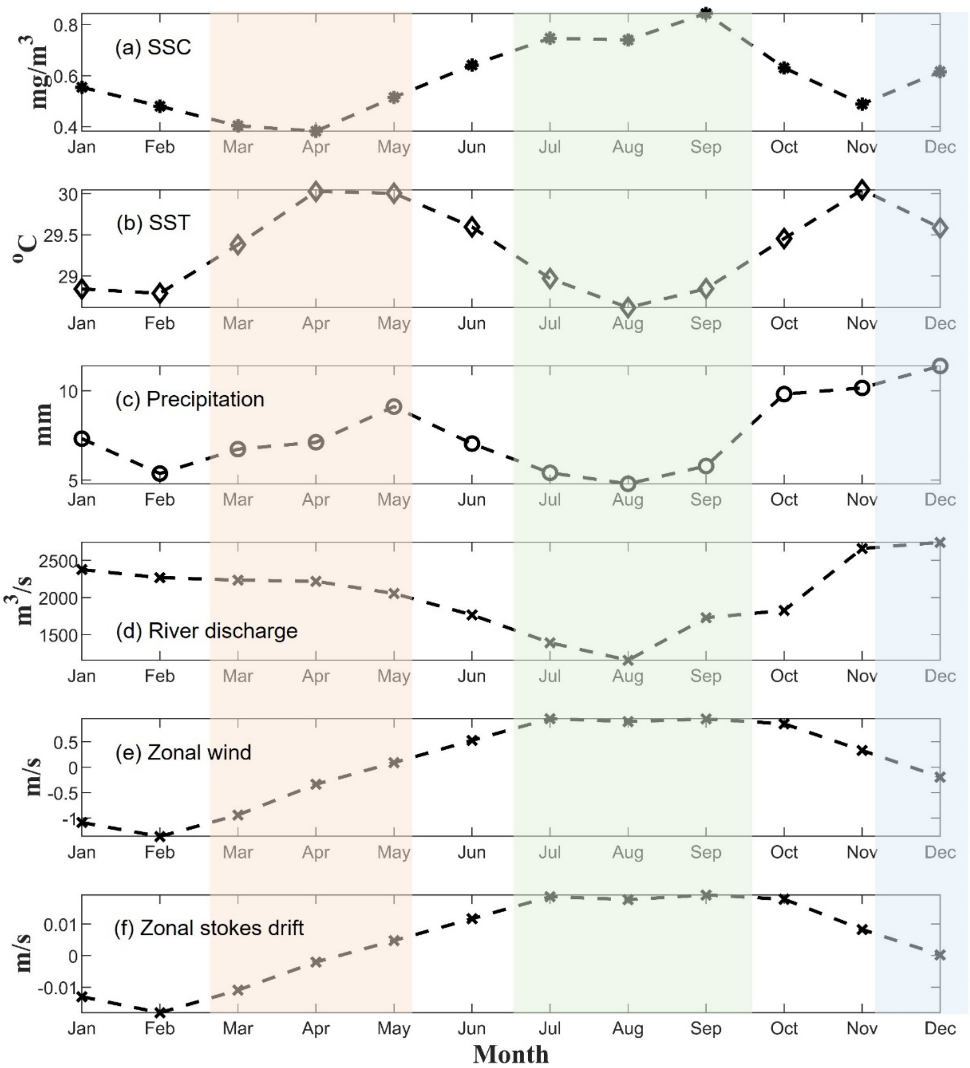


**Figure** 9. Climatology monthly mean variables averaged from ten sampling points in Karimata strait sides: (a) SSC, (b) SST, (c) SSH, (d) river discharge, (e) sea surface zonal wind, and (f) sea surface zonal Stokes drift. The orange-shaded area indicates the downwelling season, the green-shaded area indicates the upwelling season and the blue-shaded area indicates the increasing SSC due to precipitation.

The largest river flowing into the Karimata Strait is the Kapuas River, which covered approximately 49% of forest designated as a forest area in 2006. Presently, the forest covers about 19,298.9 $km^2$ and consists mainly of primary dryland (Herawati et al., 2015), which may trigger the sea's Suspended Sediment Concentration. The precipitation pattern in this area is evenly distributed throughout the year (Figure 9c). High precipitation is directly related to peak discharge in the river (Figure 9d). The rainy season generally starts in November and ends in January. Based on data taken from Supadio Station between 1968 and 2014 (Herawati et al., 2015), the dry season occurs from June to August. During this period, a reverse trend occurs where SSC values increase while SST, precipitation, and river discharge tend to decrease (Figures 9a-d).

The SSW pattern influences surface water mass movement in the ocean (Figure 4). High and continuous SSW blowing from east to west (Figure 9e) lead to the formation of Stokes drift (Figure 9f), causing movement of surface water masses due to wind friction. Stokes drift affects nutrient advection from the subsurface to the surface via the upwelling process and supports intensive phytoplankton growth. The maximum zonal wind speed and Stokes drift occur from July to September, resulting in increased SSC in the Karimata Strait.

During the Transitional I Season (March to May), SSC values decrease (Figure 9a) to their lowest point in April following a period of minimal precipitation in February (Figure 9c). The decrease is due to low precipitation, resulting in reduced water inflow carrying nutrients into the Karimata Strait (Figure 9d). The scarcity of nutrients at the sea surface can impede phytoplankton growth and chlorophyll production. Although maximum wind speed and Stokes drift approach the coast of the Karimata Strait during Transitional Season I (Figures 9e-f), strong and persistent SSW blowing toward the coast can induce a downwelling process (Figure 4). These SSW cause the accumulation of water masses at the sea surface near the coast, preventing nutrient and chlorophyll-rich water from efficiently reaching the surface layer. This phenomenon leads to minimal SSC values during this season. The average SST decreases from 29.35 °C to 0.50 °C during upwelling and increases to 0.68 °C during downwelling.

During the Transitional I Season, the maximum SST value plays a role in determining the minimum SSC values. The SST value increases from March and peaks in May (30 °C). During this season, the sun's movement across the equator allows sunlight to fully illuminate the sea surface (Wei et al., 2019). Warmer water tends to exhibit stronger thermal stratification, creating a stable thermal structure in the water column. This stable thermal stratification inhibits vertical mixing between surface and subsurface layers, further hindering the delivery of nutrients and chlorophyll to the sea surface.

The combination of downwelling induced by onshore SSW and stable thermal stratification results in minimal SSC values during the Transitional I Season. These conditions contribute to low chlorophyll production and nutrient concentrations at the sea surface. Power spectrum density analysis of SSC values in the Karimata Strait reveals that water exchange is largely influenced by the monsoon.

## 4. Conclusion

Based on the Seasonal Variability of SSC climatology, Labuan Island waters have higher SSC concentrations compared to the Karimata Strait. SSC concentrations peak during the East Season and transition towards the Transitional II Season. In the Karimata Strait, the highest average SSC content is observed in September (Transitional II Season). The presence of rivers flowing into the Karimata Strait serves as sources of nutrients, contributing to the high SSC in the area.

Sea surface wind (SSW) plays a significant role in driving upwelling and downwelling processes, which are the main drivers of SSC variability in Labuan waters and the Karimata Strait. In Labuan, upwelling occurs from November to February, followed by downwelling from March to May. During the upwelling season, the average Sea Surface Temperature (SST) decreases from 29.09 °C to 1.20 °C, while the average SSC increases from 1.25 $mg/m^3$ to 0.44 $mg/m^3$. Conversely, during downwelling, the average SSC decreases to 0.27 $mg/m^3$, and SST increases to 0.95 °C.

In the Karimata Strait, upwelling occurs from July to September, followed by downwelling from March to May. The formation of upwelling and downwelling processes is influenced by Stokes drift perpendicular to the coast, generated by cross-shore SSW and the neglected Coriolis force (near the equator). During the upwelling season, the average SSC increases from 0.59 $mg/m^3$ to 0.26 $mg/m^3$ in September, while the average SST decreases from 29.35 to 0.50 °C. In December, peak precipitation and river discharge contribute to an increase in SSC to 0.03 $mg/m^3$ in this area. SSW and Stokes drift play significant roles in transporting nutrients and chlorophyll at the sea surface. Satellite observations provide valuable insights into the seasonal variability of SSC, but the importance of in-situ measurements to enhance quantification accuracy is emphasized. This study contributes to the knowledge base for fisheries management in Labuan and the Karimata Strait.


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## Data Availability

The data presented in this study are openly and freely available. SSC data are available at https://coastwatch.pfeg.noaa.gov/erddap/griddap (accessed on January 11, 2023), SSH and SST data are available at https://www.ecmwf.int (accessed on February 8, 2023), SSW data are available at https://cds.climate.copernicus.eu/ (accessed on March 8, 2023), precipitation data are available at https://chc.ucsb.edu/data/chirps (accessed on 28 March 2023), and river discharge data are available at https://cds.climate.copernicus.eu/cdsapp (accessed on 8 April 2023).

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