

Seasonal Variability of Surface Ocean Currents in the Southern Java Offshore based on Global Reanalysis Data

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Abstract Surface ocean currents are a key component of marine circulation systems and play an important role in controlling physical and ecological processes in Indonesian sea. The Southern Java sea, which are directly connected to the eastern Indian Ocean, are characterized by dynamic surface circulation influenced by large-scale oceanic processes and seasonal monsoonal forcing. This study investigates the patterns and characteristics of surface ocean currents in the Southern Java sea using global ocean reanalysis data visualized through the Earth Nullschool platform. Seasonal variability was examined using representative monthly maps corresponding to the major phases of the Asian and Australian monsoon system, including January (West Monsoon), April (first transition season), July (East Monsoon), and October (second transition season). A descriptive analytical approach was applied to identify spatial and temporal variations in surface current direction and relative intensity across both coastal and offshore areas. The analysis reveals distinct seasonal differences in surface current behavior. During the East Monsoon period, surface currents exhibit stronger intensity and a more consistent alongshore orientation, reflecting enhanced wind-driven circulation and offshore transport. In contrast, the West Monsoon and transitional seasons are marked by weaker currents and greater directional variability, particularly in nearshore sea. These findings indicate that monsoonal wind forcing, combined with large-scale Indian Ocean circulation, is the primary driver of surface current variability in the study area. This study highlights the usefulness of reanalysis-based visualization for regional-scale oceanographic assessments in areas with limited in-situ observations. The results provide baseline information that supports regional oceanographic research and offers practical insights for marine resource management, fisheries, navigation, and coastal planning in the Southern Java sea.

Keywords: Surface ocean currents, Southern Java sea, Monsoon system, Global reanalysis.

1. Introduction

Indonesian sea are widely recognized as one of the most dynamically complex marine regions in the world and play a crucial role in the global ocean circulation system. This complexity arises from Indonesia's unique geographical position between the Pacific Ocean and the Indian Ocean, which facilitates interactions between major ocean basins, atmospheric circulation, and regional-scale ocean processes. As a result, Indonesian seas function as a key pathway for the redistribution of heat, salt, and momentum, influencing both regional ocean conditions and large-scale climate variability (Alfaris et al., 2020). A defining characteristic of Indonesian sea is the exchange of water masses between the Pacific and Indian Oceans through a network of straits and marginal seas, commonly referred to as the Indonesian Throughflow (ITF). This throughflow regulates the thermal and salinity structure of the Indian Ocean and plays an important role in modulating global climate systems, including the Asian monsoon and interannual climate variability such as the El Niño–Southern Oscillation. Variations in ocean current patterns within Indonesian sea therefore have implications that extend beyond the regional scale (Sprintall et al., 2014).

Within the Indonesian marine system, the Southern Java sea represent a region with particularly strong and distinctive oceanographic characteristics. This area directly borders the eastern Indian Ocean and is exposed to open-ocean conditions, allowing large-scale circulation and atmospheric forcing to directly influence coastal and offshore sea (Wirasatriya et al., 2020). The relatively unobstructed coastline along southern Java enhances the interaction between oceanic currents, wind stress, and coastal processes, resulting in complex surface circulation patterns (Utari et al., 2019). The oceanographic dynamics are strongly governed by the Asian–

Australian monsoon system, which induces pronounced seasonal variability in surface ocean currents, and other physical parameters (Firdaus et al., 2023).

Surface ocean currents in the Southern Java sea play a vital role in shaping marine environmental conditions and supporting a wide range of human activities. The direction and velocity of these currents directly influence navigation safety, particularly for shipping routes and small-scale fisheries operating along the southern coast of Java. In addition, surface currents control sediment transport processes that affect coastal morphology, shoreline stability, and nearshore habitat distribution (Romli, 2022). They also govern the dispersal of marine organisms such as plankton, fish larvae, and other early life stages, thereby influencing recruitment patterns and ecosystem connectivity in the region. Beyond their direct impact on human activities, surface ocean currents are closely associated with key physical oceanographic processes that regulate the marine environment (Krisnafi, 2020). Processes such as water mass mixing, horizontal advection, and nutrient redistribution are largely driven by surface current dynamics. In the Southern Java sea, these processes are often linked to seasonal upwelling events that enhance nutrient availability in surface layers, supporting increased primary productivity and contributing to the high fisheries potential observed in certain periods. Consequently, variations in surface current patterns can have cascading effects on marine productivity and biological resources along the southern coast of Java (Purba et al, 2025).

Despite their critical importance, detailed and continuous observations of surface ocean currents in the Southern Java sea remain limited, particularly in offshore areas. In-situ measurements are often constrained by logistical challenges, including difficult sea conditions, limited research infrastructure, and the high operational costs associated with long-term oceanographic monitoring (Siagian et al., 2023). Furthermore, the spatial and temporal coverage of existing observations is often insufficient to fully capture the variability of surface currents, especially those associated with seasonal and interannual forcing mechanisms (Sprintall et al, 2019). These limitations hinder the ability to comprehensively characterize spatial heterogeneity and seasonal changes in surface current dynamics across the Southern Java sea. As a result, important features such as transient current structures, variability in current strength, and the response of surface circulation to atmospheric forcing may be underrepresented in observational datasets (Sadhotomo, 2017). This situation highlights the need for alternative and complementary data sources that can provide broader spatial coverage and longer temporal records of ocean current conditions (Alfaris et al., 2024).

In recent years, global ocean reanalysis datasets have increasingly been adopted to address data gaps in oceanographic research. Reanalysis products combine numerical ocean circulation models with satellite observations and available in-situ measurements to generate spatially and temporally consistent representations of ocean conditions. These datasets enable the examination of surface current variability across large spatial domains and extended time periods, offering valuable insights into regional and seasonal circulation patterns that are difficult to capture through direct observations alone (Hersbach et al., 2020). Web-based visualization platforms such as Earth Nullschool further enhance the accessibility and usability of reanalysis data. By providing intuitive visual representations of surface ocean currents, these platforms allow researchers to efficiently explore current direction, relative velocity, and spatial variability at multiple temporal scales. Earth Nullschool, in particular, facilitates rapid interpretation of reanalysis outputs and supports exploratory analysis of surface current dynamics in data-scarce regions such as the Southern Java sea.

This study aims to analyze the patterns and characteristics of surface ocean currents in the Southern Java sea using global reanalysis data visualized through the Earth Nullschool platform. The analysis focuses on identifying dominant current directions, relative current strength, and their spatial distribution across coastal and offshore areas. In addition, temporal variations in surface current behavior are examined to capture changes associated with seasonal forcing and broader atmospheric–oceanic interactions. By emphasizing both spatial and temporal variability, this research provides a more comprehensive overview of surface current dynamics in the Southern Java sea compared to studies based solely on limited observations. The use of reanalysis data allows for the examination of surface current patterns over broader spatial scales and extended time periods, offering valuable insights into regional circulation features that may not be fully resolved through in-situ measurements alone. This approach also facilitates the identification of consistent circulation tendencies and areas of pronounced variability within the study region. The outcomes of this research can also serve as a reference for future studies that integrate reanalysis data with observational measurements or apply quantitative modeling approaches to further investigate ocean dynamics in the Southern Java sea.

2. METHODS

2.1. Study Area

This study was conducted in the Southern Java sea, geographically located between approximately 7°–11° S latitude and 105°–115° E longitude. The study area extends from the coastal zone along the southern coastline of Java Island to offshore sea that directly border the eastern Indian Ocean. This region was selected due to its exposure to open-ocean conditions and its strong sensitivity to large-scale atmospheric and oceanic forcing. The Southern Java sea are characterized by a relatively straight coastline with limited island obstruction, allowing direct interaction between wind-driven circulation and Indian Ocean currents. Such geographical conditions facilitate the development of alongshore currents and enhance the influence of monsoonal winds on surface circulation. The inclusion of both coastal and offshore domains enables comparative analysis of surface current characteristics across different marine environments within the same regional setting.

2.2 Data Source and Reanalysis Product

The data used in this study consist of surface ocean current information derived from global ocean reanalysis products and visualized through the Earth Nullschool platform (<https://earth.nullschool.net>). Earth Nullschool is a web-based visualization tool that provides access to gridded global atmospheric and oceanographic datasets generated from numerical models that assimilate satellite observations and available in-situ measurements. The surface ocean current fields displayed on Earth Nullschool originate from established global ocean circulation models that are part of reanalysis systems. These systems combine physical ocean modeling with observational data assimilation to produce spatially and temporally continuous representations of ocean conditions. Although Earth Nullschool itself functions as a visualization interface, the underlying reanalysis data are widely used in scientific studies for regional and large-scale oceanographic assessments.

2.3 Temporal Scope and Data Selection

The temporal scope of the analysis was designed to represent seasonal variability associated with the Asian–Australian monsoon system. Surface current data were examined at selected time periods corresponding to different phases of the monsoon cycle, particularly conditions representative of contrasting wind regimes. The selection of multiple observation times allows for the identification of temporal changes in surface current direction and relative velocity. This approach facilitates the assessment of seasonal circulation patterns and their variability, which are key characteristics of surface current dynamics in the Southern Java sea. Temporal comparisons were conducted qualitatively by observing changes in current structure across different dates and times.

2.4 Data Extraction and Visualization Procedure

Data extraction in this study was performed through visual inspection and interpretation of surface current outputs provided by the Earth Nullschool platform. The visualization displays surface ocean currents as vector fields, where arrow direction represents the direction of current flow and arrow density or length indicates relative current strength. The visualization parameters were adjusted to focus specifically on the Southern Java sea, ensuring that both coastal and offshore regions were clearly represented. For each selected observation time, screenshots of surface current patterns were captured and used as the primary materials for analysis. These visual outputs served as the basis for identifying dominant flow directions, areas of intensified currents, and zones of complex circulation.

2.5 Surface Currents Surface Current Velocity Representation and Basic Formulation

Spatial analysis focused on examining the distribution and orientation of surface current vectors across the study area. Particular attention was given to identifying dominant alongshore or offshore flow patterns and differences in circulation characteristics between coastal and offshore sea. The analysis also considered spatial heterogeneity in current behavior, such as areas exhibiting stronger currents or more variable flow directions. By comparing current patterns across different parts of the study area, this research provides insights into how geographical setting and proximity to the coastline influence surface circulation in the Southern Java sea.

Temporal analysis was conducted by comparing surface current patterns across different observation times. This analysis aimed to identify changes in current direction, relative velocity, and circulation structure associated with seasonal atmospheric forcing. By examining variations in surface current behavior over time, the study highlights the dynamic nature of surface circulation in the Southern Java sea. The temporal perspective enables the identification of consistent circulation tendencies as well as periods characterized by increased variability, which are often linked to changes in monsoonal wind patterns.

Surface ocean currents are commonly represented as two-dimensional horizontal vector fields consisting of zonal and meridional components. In this study, surface current data visualized through the Earth Nullschool platform are based on reanalysis outputs that provide current velocity components in the east–west (zonal) and north–south (meridional) directions. The zonal component of the surface current is denoted as u (m s^{-1}), representing eastward or westward flow, while the meridional component is denoted as v (m s^{-1}), representing northward or southward flow. The magnitude of the surface current velocity (V) can be expressed as:

$$V = \sqrt{u^2 + v^2} \quad \dots\dots (1)$$

This formulation describes the resultant speed of the surface current vector derived from its horizontal components. Although numerical velocity values were not extracted directly in this study, the visualization provided by Earth Nullschool reflects relative differences in current magnitude based on this standard vector formulation.

2.6 Directional Analysis of Surface Currents

A descriptive and exploratory analytical approach was applied in this study. The analysis emphasizes qualitative characterization of surface current patterns rather than quantitative statistical modeling or numerical simulation. This approach is appropriate given the objective of providing an initial overview of surface current dynamics in a region with limited direct observations. The interpretation of current patterns was based on visual comparison and logical reasoning supported by established oceanographic principles. While numerical values of current velocity were not explicitly analyzed, relative differences in current strength were inferred from the visualization outputs. This methodological approach enables a clear and intuitive understanding of surface current behavior at a regional scale.

This study relies on global reanalysis data visualized through a web-based platform and does not incorporate direct validation using in-situ measurements. As a result, the analysis is qualitative in nature and may not capture small-scale or short-term variability in surface currents. The spatial resolution of reanalysis data may also limit the representation of fine-scale coastal processes. However, despite these limitations, the methodological framework provides valuable baseline information on surface current characteristics in the Southern Java sea. The approach adopted in this study is suitable for regional-scale assessments and can serve as a foundation for future research that integrates reanalysis data with in-situ observations, satellite-derived products, or quantitative modeling techniques. The direction of surface ocean currents (θ) is defined as the angle of the resultant velocity vector relative to the eastward axis and can be calculated using the arctangent function:

$$\theta = \tan^{-1} \left(\frac{v}{u} \right) \quad \dots\dots (2)$$

This directional formulation underpins the vector arrows displayed in the Earth Nullschool visualization. In this study, current direction was interpreted qualitatively by examining the orientation of vector arrows across the study area. Dominant flow directions, such as alongshore or offshore currents, were identified based on consistent vector alignment patterns. To support descriptive comparison of surface current strength across different spatial and temporal conditions, current intensity was classified qualitatively into relative categories based on vector density and arrow length observed in the visualization. Although exact numerical thresholds were not applied, relative current intensity was interpreted using the following conceptual framework: Weak currents: sparse vectors with short arrow lengths; Moderate currents: moderately dense vectors with intermediate arrow lengths; Strong currents: dense vectors with

elongated arrow lengths. This qualitative classification approach allows comparative analysis of current intensity patterns while remaining consistent with the exploratory nature of the study.

3. RESULTS AND DISCUSSION

3.1 Overview of Seasonal Surface Current Patterns in the Southern Java Sea

The surface ocean currents in the Southern Java sea exhibit pronounced seasonal variability, reflecting the combined influence of the Asian–Australian monsoon system and large-scale circulation in the eastern Indian Ocean. Analysis based on seasonal representative maps demonstrates clear differences in current direction, spatial organization, and relative intensity between monsoonal and transitional periods. The selected representative months January, April, July, and October, successfully capture the main phases of the regional monsoon cycle and provide a robust framework for examining seasonal changes in surface circulation characteristics. During the peak monsoon seasons, surface current patterns appear more coherent and spatially organized, particularly in offshore areas directly exposed to the Indian Ocean. Current vectors during these periods tend to align predominantly along the southern coastline of Java, indicating strong wind-driven forcing and the influence of regional-scale ocean circulation. In contrast, transitional periods are characterized by increased spatial variability, with surface currents exhibiting less consistent direction and reduced relative intensity across both coastal and offshore zones.

Spatial contrasts between coastal and offshore sea are evident throughout the seasonal cycle. Offshore regions generally display more uniform current directions and stronger relative intensity, reflecting the dominance of large-scale oceanic processes. Meanwhile, nearshore areas show greater heterogeneity in current patterns, likely influenced by coastal morphology, bathymetric variations, and land–sea interactions. These differences highlight the role of local factors in modifying surface circulation superimposed on broader regional flow patterns.

The observed seasonal contrast underscores the dominant role of atmospheric forcing in controlling near-surface circulation along the southern coast of Java. Variations in wind direction and strength associated with monsoonal transitions strongly influence the orientation and intensity of surface currents. As a result, periods of intensified monsoonal winds promote more organized alongshore flow, whereas weakening winds during transition seasons allow for increased influence of localized processes and enhanced variability in surface circulation. Overall, the seasonal overview reveals that surface ocean currents in the Southern Java sea are governed by a dynamic interplay between large-scale monsoon-driven forcing and local coastal processes. Understanding this seasonal framework is essential for interpreting more detailed spatial and temporal variations discussed in subsequent sections and provides an important contextual basis for assessing the implications of surface current variability for physical oceanographic processes and marine activities in the region.

3.2 Surface Current Characteristics during the West Monsoon (January)

January, representing the peak phase of the West Monsoon, is characterized by relatively moderate but well-organized surface current patterns in the Southern Java sea. During this period, the prevailing monsoonal winds over the eastern Indian Ocean play a dominant role in shaping near-surface circulation. The analyzed surface current vectors show a predominantly westward orientation, with a clear tendency for alongshore flow parallel to the southern coastline of Java, particularly in offshore sea. Offshore regions exhibit a coherent and spatially consistent current structure, indicating the strong influence of large-scale Indian Ocean circulation combined with persistent monsoon-driven wind forcing. The alignment of surface currents along the coast suggests a wind-driven response typical of the Northwest Monsoon, where westerly winds generate surface stress that promotes westward transport along the southern Java margin. This organized flow pattern highlights the dominance of regional-scale forcing over local variability in offshore areas during this season.

In contrast, coastal and nearshore sea display greater variability in current direction and relative intensity. Surface current vectors in these areas are less uniform and show localized deviations from the dominant westward flow. This variability is likely associated with the interaction between incoming oceanic currents and local coastal processes, including complex coastline geometry, shallow bathymetry, and increased bottom friction. Such factors tend to weaken and distort the surface flow near the coast, resulting in reduced current intensity compared to offshore regions. Overall, surface current intensity during the West

Monsoon is generally moderate, with stronger currents observed offshore and weaker flow near the coast. This spatial gradient reflects the combined effects of wind stress, oceanic inertia, and coastal boundary constraints. While the West Monsoon is not typically associated with strong upwelling along the southern Java coast, the persistence of alongshore currents remains a critical mechanism for horizontal transport and redistribution of surface water masses, nutrients, and biological material.

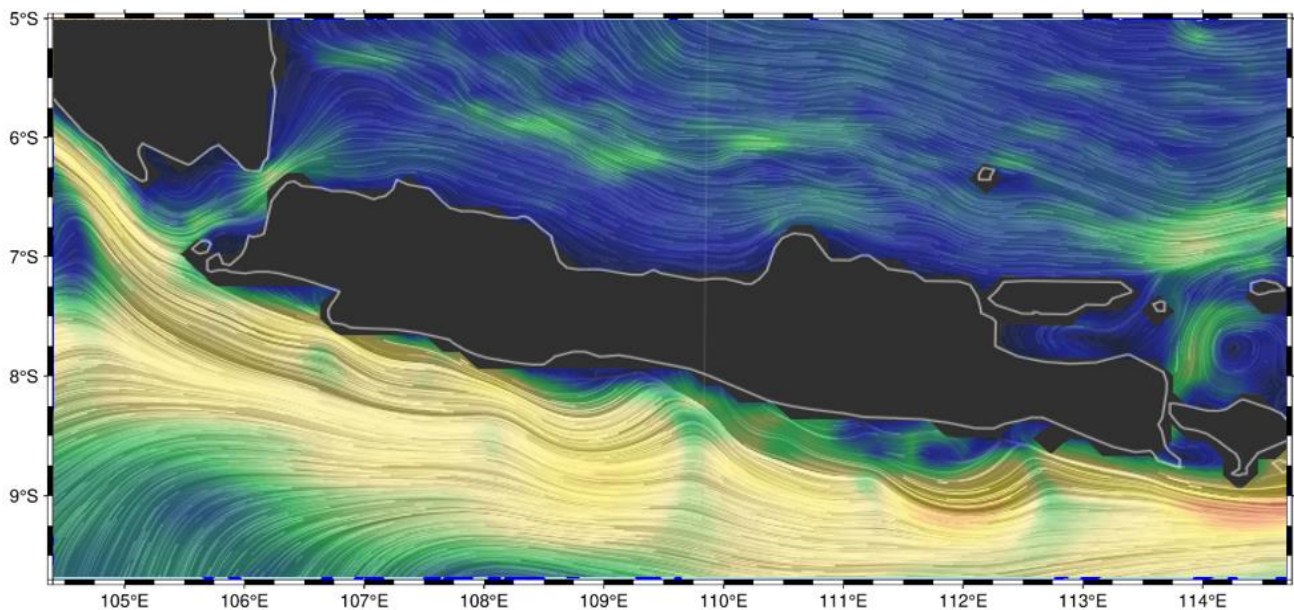


Figure 1. January (West Monsoon)

The circulation pattern observed in January is consistent with classical and contemporary studies describing westward and alongshore surface flow along the southern coast of Java during the Northwest Monsoon. These studies emphasize that, despite the relatively weaker wind-induced upwelling during this season, monsoon-driven circulation continues to play an essential role in regional ocean dynamics. The present findings reinforce this understanding by illustrating the spatial organization and seasonal characteristics of surface currents during the West Monsoon, thereby providing a baseline for comparison with circulation patterns observed during transitional and East Monsoon periods.

3.3 Surface Current Variability during the First Transition Season (April)

April marks the First Transition Season between the West Monsoon and the East Monsoon, a period characterized by significant changes in atmospheric forcing over the Southern Java sea. During this transitional phase, the dominant monsoonal wind system weakens and becomes more variable in direction, leading to a noticeable reduction in wind-driven surface circulation. As a result, surface current patterns during April exhibit increased spatial and directional variability compared to the more organized flow observed during the peak monsoon seasons. Analysis of surface current vectors indicates that no single dominant current direction prevails across the study area during April. In coastal regions, surface currents display a combination of alongshore and cross-shore orientations, reflecting the growing influence of local oceanographic processes. These include coastline configuration, shallow bathymetry, and interactions with mesoscale features such as eddies and coastal recirculation zones. The reduced wind stress during this period allows such local factors to exert a stronger control on near-surface circulation, particularly in the nearshore environment.

In offshore sea, surface currents remain relatively coherent compared to coastal zones; however, their intensity is generally weaker than that observed during the West Monsoon. The attenuation of current speed suggests a transitional adjustment of the ocean surface layer as it responds to shifting atmospheric conditions. This adjustment phase represents a balance between residual monsoonal circulation and the emerging influence of the upcoming East Monsoon wind regime. Consequently, offshore currents during April appear less organized and show greater variability in orientation than during fully developed monsoon periods. The spatial contrast between offshore and nearshore circulation patterns highlights the sensitivity of surface currents to both large-scale and local forcing mechanisms during the transition season. While

offshore circulation is still partially governed by basin-scale dynamics of the eastern Indian Ocean, coastal sea respond more rapidly to changes in wind forcing and boundary interactions.

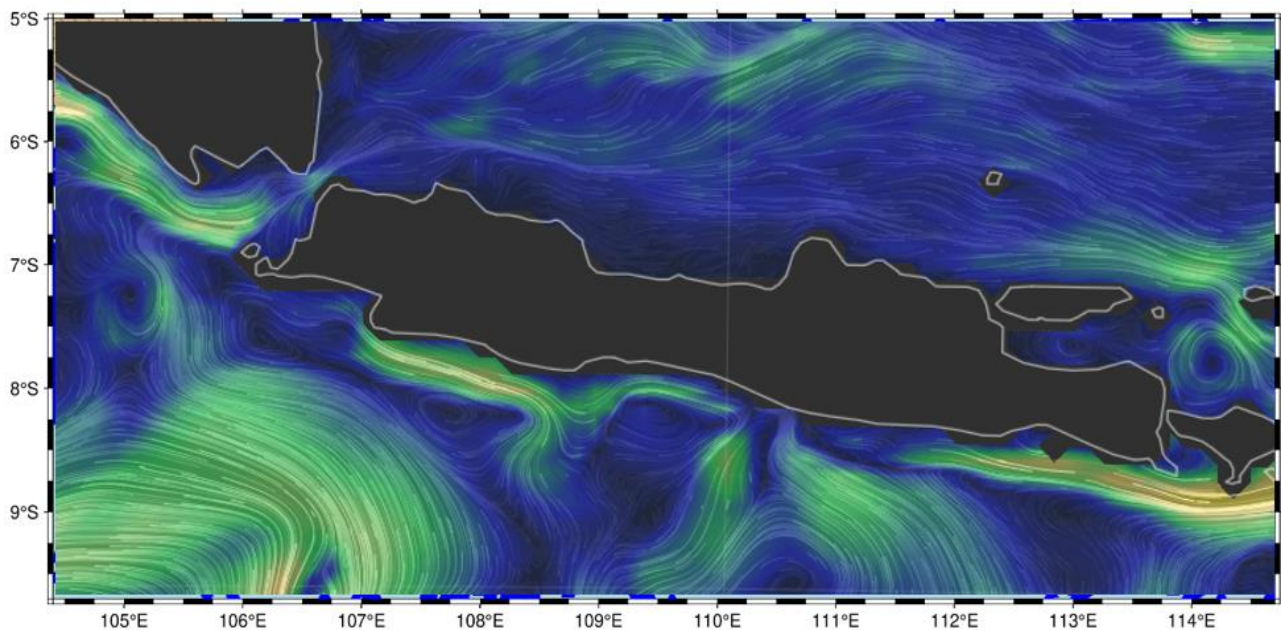


Figure 2. April (First Transition Season)

The increased variability observed during April underscores the dynamic and transitional nature of surface circulation in the Southern Java waters. During this First Transition Season, the weakening of dominant monsoonal winds reduces the control of large-scale atmospheric forcing, allowing surface currents to respond more sensitively to local and short-term influences. As a result, circulation patterns become less predictable, with frequent changes in direction and intensity that reflect the ongoing adjustment of the ocean surface layer to evolving atmospheric conditions. Such variable circulation conditions have important implications for the dispersion of marine organisms, suspended sediments, and other oceanic tracers. The presence of multiple and shifting current pathways can enhance horizontal mixing while simultaneously altering dominant transport routes. This may lead to increased retention of materials in certain areas or, conversely, facilitate their redistribution across broader spatial scales. From a physical standpoint, these processes contribute to the development of spatially heterogeneous surface properties, including temperature and salinity gradients.

From an ecological perspective, the transitional circulation regime during April may strongly influence biological connectivity between coastal and offshore ecosystems. Variability in surface currents can affect the transport and survival of planktonic organisms, particularly the early life stages of fish and invertebrates that rely on surface circulation for dispersal. Changes in connectivity patterns may, in turn, impact recruitment processes and the spatial structure of marine populations along the southern coast of Java. Overall, the surface current characteristics observed during the First Transition Season highlight the critical role of seasonal shifts in atmospheric forcing in shaping short-term and spatially heterogeneous circulation patterns. Understanding these transitional dynamics is essential for interpreting seasonal variability in physical and biological processes in the Southern Java waters and for assessing their implications for ecosystem functioning and marine resource sustainability.

3.4 Intensified Alongshore Flow during the East Monsoon (July)

July represents the peak of the East Monsoon period, during which surface ocean circulation in the Southern Java sea exhibits the most intensified, organized, and spatially coherent patterns observed throughout the annual cycle. Analysis of surface current vectors reveals a dominant eastward and strongly alongshore flow, particularly evident in offshore sea adjacent to the southern coast of Java. This circulation pattern reflects the strong influence of persistent southeasterly monsoon winds that prevail during this season and exert substantial wind stress on the ocean surface. Compared to other seasons, relative current intensity during July is markedly higher, indicating a strengthened wind-driven surface circulation. The

enhanced current speeds suggest efficient momentum transfer from the atmosphere to the ocean surface, resulting in a well-developed alongshore jet. This intensified flow is more pronounced in offshore areas, where the influence of bottom friction is reduced, allowing currents to maintain higher velocities and greater directional consistency. In contrast, nearshore sea still exhibit some variability due to coastal boundary effects, although the general alongshore orientation remains dominant.

The strong alongshore surface currents observed during the East Monsoon play a critical role in promoting offshore transport of surface waters through Ekman dynamics. Under persistent southeasterly wind forcing, surface waters are driven away from the coast, resulting in a net offshore displacement that is characteristic of wind-driven coastal circulation in the Southern Java waters. This offshore transport effectively induces coastal upwelling along the southern coast of Java, a process widely recognized as a key physical mechanism controlling seasonal ocean productivity in the region. During the upwelling phase, cooler and denser subsurface waters are brought into the surface layer, replacing the displaced surface waters. These upwelled waters are typically enriched with nutrients such as nitrate and phosphate, which enhance nutrient availability within the euphotic zone. The increased nutrient supply stimulates phytoplankton growth, leading to elevated primary productivity during the East Monsoon period. This seasonal enrichment of surface waters represents a fundamental link between physical oceanographic processes and biological responses in the Southern Java waters.

Enhanced primary productivity during upwelling conditions has important ecological and socio-economic implications, particularly for fisheries. Increased phytoplankton biomass provides a critical food source for zooplankton and higher trophic levels, supporting the abundance and distribution of commercially important fish species. Consequently, the East Monsoon upwelling system plays a vital role in sustaining fisheries productivity along the southern coast of Java, reinforcing the significance of monsoon-driven circulation in shaping both marine ecosystem dynamics and coastal livelihoods in the region.

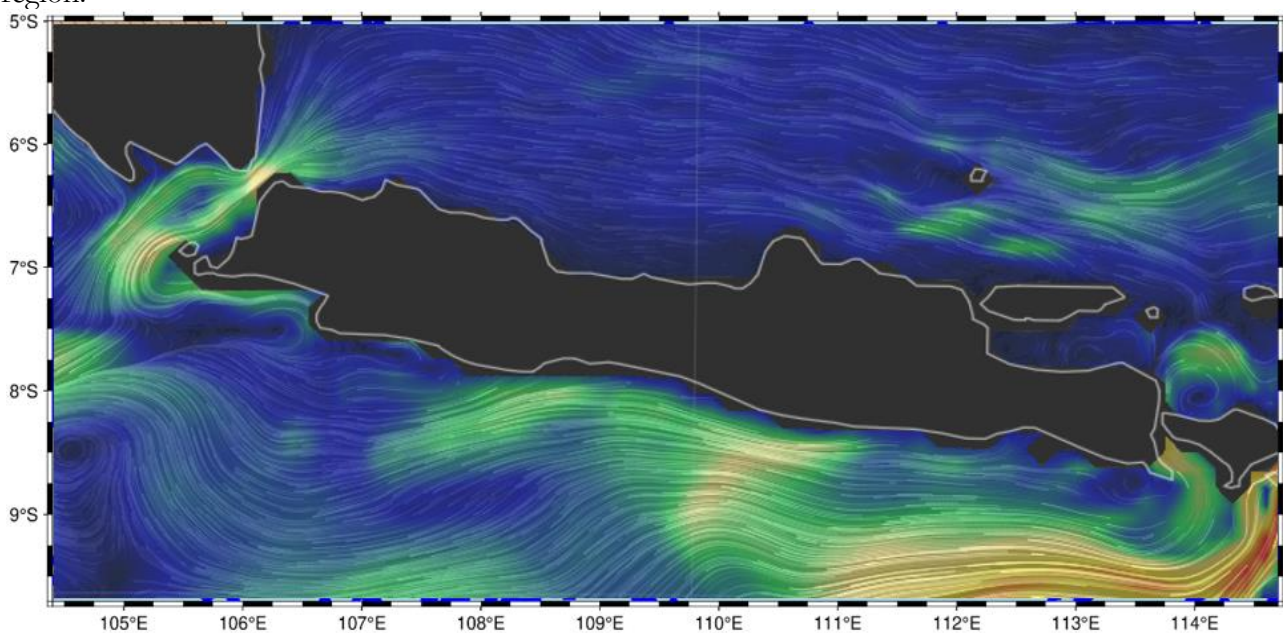


Figure 3. July (East Monsoon)

The circulation features identified in July are consistent with established oceanographic understanding of the Southern Java sea and the eastern Indian Ocean, where the East Monsoon is the primary driver of seasonal upwelling and biological productivity. The strong and coherent alongshore flow observed in this study highlights the dominant role of monsoonal wind forcing in regulating surface circulation, water mass redistribution, and ecosystem dynamics in the region. Furthermore, the clear contrast between the East Monsoon and other seasonal phases underscores the importance of seasonal wind variability in shaping both physical and ecological processes in the Southern Java sea.

3.5 Surface Current Adjustment during the Second Transition Season (October)

October represents the Second Transition Season, marking the gradual shift from the East Monsoon toward the West Monsoon in the Southern Java waters. During this period, atmospheric forcing undergoes

substantial reorganization as the previously dominant southeasterly monsoon winds progressively weaken and begin to change direction. This weakening of wind stress reduces the efficiency of wind-driven surface circulation, leading to a noticeable decline in current intensity and a marked increase in spatial and directional variability across the study area. Surface current vectors observed during October reveal less organized and more heterogeneous flow patterns compared to those characteristic of the East Monsoon. The previously dominant eastward alongshore currents weaken considerably, particularly in offshore regions, while coastal waters exhibit more complex circulation structures. In nearshore areas, surface currents display a wide range of orientations, including alongshore, offshore, and locally rotating patterns. This variability suggests an increasing influence of local forcing mechanisms such as coastline geometry, bathymetric complexity, and short-term fluctuations in local wind conditions.

The spatial heterogeneity of surface currents during October highlights the transitional nature of the circulation regime, in which large-scale monsoonal forcing no longer exerts dominant control over surface dynamics. Instead, circulation patterns emerge from the combined effects of residual monsoon-driven flow, background ocean circulation, and localized coastal processes. Offshore waters generally maintain relatively coherent currents, although with reduced magnitude, while nearshore zones respond more rapidly to changing atmospheric conditions and boundary interactions. These circulation characteristics indicate that the Second Transition Season represents a key adjustment phase in the annual circulation cycle of the Southern Java waters. During this period, the ocean surface layer transitions from a strongly wind-driven regime toward conditions increasingly influenced by the emerging West Monsoon. Understanding this transitional circulation behavior is essential for interpreting seasonal changes in oceanographic conditions, as well as for assessing its implications for marine transport processes, coastal dynamics, and ecosystem variability along the southern coast of Java.

In offshore areas, surface currents remain relatively coherent compared to those in coastal zones; however, their overall magnitude is noticeably reduced during this period. The decline in current intensity reflects the weakening wind stress associated with the gradual breakdown of the East Monsoon system. As the southeasterly monsoon winds lose strength, the direct transfer of momentum from the atmosphere to the ocean surface becomes less effective, resulting in slower and less energetic surface currents in offshore. During this transitional phase, the ocean surface layer undergoes a gradual adjustment as it shifts from a strongly wind-driven circulation regime toward conditions increasingly influenced by residual background circulation and the early development of West Monsoon wind forcing. This adjustment is not instantaneous and often involves complex interactions between remaining monsoonal flow, basin-scale circulation in the eastern Indian Ocean, and local oceanographic processes. As a consequence, surface circulation patterns may exhibit temporal and spatial irregularities even in offshore regions where flow is generally more organized.

Such transitional dynamics can give rise to localized convergence and divergence zones within the surface current field, particularly in offshore areas where residual circulation interacts with weakening monsoonal forcing. These zones represent areas where surface waters either accumulate or disperse, leading to enhanced horizontal mixing and increased variability in surface properties. Through these processes, the redistribution of heat, salt, and other oceanic tracers within the upper ocean becomes more efficient, contributing to spatial heterogeneity in temperature and salinity patterns during the transition season. Although the circulation during this period is less energetic than that observed under peak monsoon conditions, the offshore circulation adjustments play a crucial role in reorganizing the surface ocean structure. The gradual weakening of wind-driven currents allows the upper ocean to recover from strong upwelling conditions, facilitating the re-establishment of stratification and modifying the vertical distribution of physical properties. These adjustments help stabilize the surface layer and prepare the ocean system for the subsequent influence of the West Monsoon.

By redistributing water masses and modifying surface ocean characteristics, transitional circulation processes contribute to the continuity of the annual circulation cycle in the Southern Java waters. This resetting mechanism ensures that oceanographic conditions evolve smoothly from one monsoonal phase to the next, rather than shifting abruptly. Consequently, understanding the role of convergence and divergence features during transition seasons is essential for interpreting seasonal variability in surface circulation, heat content, and tracer transport, as well as for assessing their broader implications for marine ecosystem dynamics along the southern coast of Java.

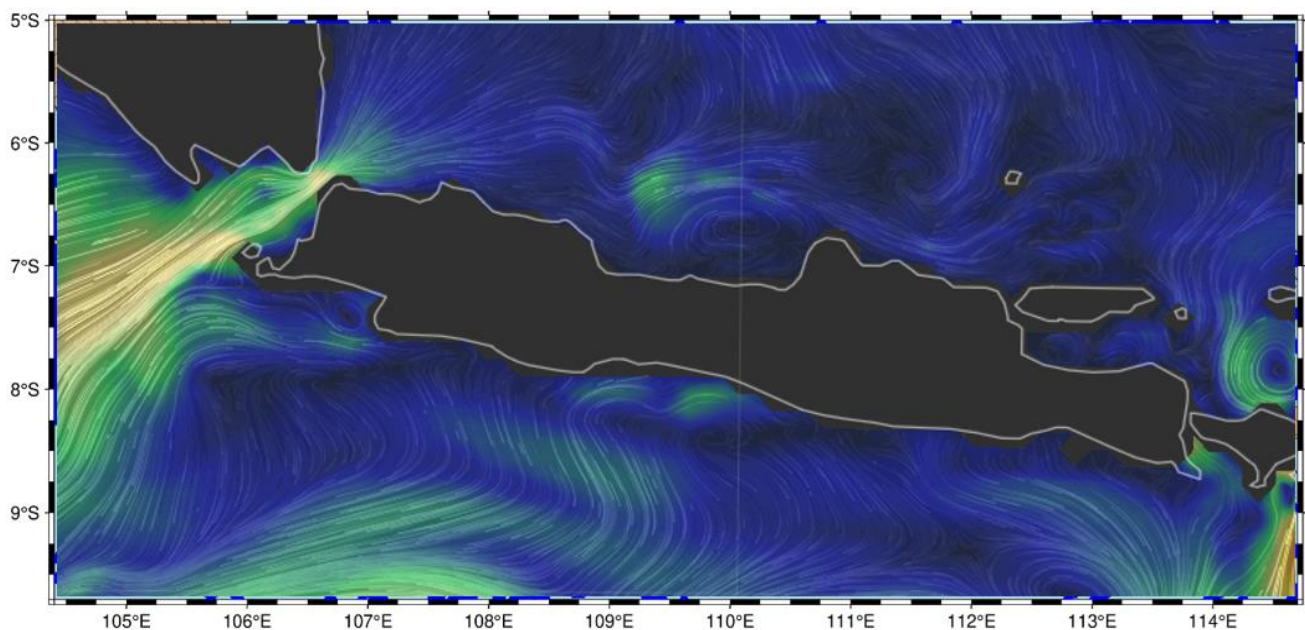


Figure 4. October (Second Transition Season)

From a physical oceanographic perspective, the circulation characteristics observed during October represent a recovery and adjustment phase following the period of intense upwelling and strong alongshore flow associated with the East Monsoon. During this Second Transition Season, the gradual weakening of southeasterly monsoon winds leads to a significant reduction in wind-driven offshore transport. As Ekman transport diminishes, upwelling processes along the southern coast of Java become progressively weaker, allowing surface waters to remain longer in the upper ocean layer. This process facilitates a gradual warming of the sea surface and promotes the re-establishment of vertical stratification in the water column. The weakening of upwelling during October has important implications for nutrient dynamics in the Southern Java waters. Reduced upward transport of nutrient-rich subsurface waters can lead to declining nutrient concentrations in the euphotic zone, potentially limiting primary productivity compared to the East Monsoon period. However, the transitional nature of circulation during this season may also enhance horizontal mixing and localized nutrient redistribution, resulting in spatially heterogeneous biological responses. Such conditions can create transitional ecosystem states, where productivity and biological activity vary across coastal and offshore regions.

Surface current variability observed during the Second Transition Season further underscores the sensitivity of the Southern Java circulation system to seasonal shifts in atmospheric forcing. As large-scale monsoonal winds weaken, local oceanographic processes—including coastal geometry, bathymetry, and mesoscale circulation features—play an increasingly important role in shaping surface current patterns. This leads to more complex and less organized circulation structures, particularly in nearshore areas, compared to the highly coherent flow observed during the peak monsoon seasons. Transitional periods such as October play a critical role in modulating the annual cycle of surface circulation by redistributing water masses and gradually resetting oceanographic conditions prior to the onset of the West Monsoon. These adjustments influence not only physical properties such as temperature and stratification but also ecological connectivity, sediment transport pathways, and the dispersal of marine organisms. Consequently, a detailed understanding of surface circulation dynamics during the Second Transition Season is essential for interpreting seasonal variability in marine productivity and ecosystem processes along the southern coast of Java, as well as for supporting sustainable marine resource management in the region.

5. CONCLUSION

This study provides a comprehensive overview of the seasonal patterns and characteristics of surface ocean currents in the Southern Java sea based on global reanalysis data visualized through the Earth Nullschool platform. The results demonstrate that surface circulation in the region exhibits strong seasonal variability, primarily controlled by the Asian–Australian monsoon system. Distinct differences in current

direction, intensity, and spatial coherence are evident between monsoonal and transitional periods, highlighting the dominant role of atmospheric forcing in shaping near-surface ocean dynamics along the southern coast of Java. The East Monsoon emerges as the most influential seasonal phase, characterized by intensified and well-organized alongshore currents that promote offshore transport and coastal upwelling. These conditions are closely associated with enhanced nutrient availability and increased marine productivity, underscoring the importance of monsoon-driven circulation for fisheries and ecosystem processes in the region. In contrast, the West Monsoon exhibits moderate alongshore flow with relatively stable circulation patterns, while the transitional seasons (April and October) are marked by weaker currents and higher spatial variability, reflecting the adjustment of the ocean surface layer to changing wind regimes.

Overall, the use of global reanalysis data through a web-based visualization platform proves to be an effective approach for examining regional surface current dynamics, particularly in areas with limited in-situ observations. The findings of this study contribute to improved understanding of seasonal circulation variability in the Southern Java sea and provide a useful baseline for future oceanographic research, marine resource management, and coastal planning. Further studies incorporating quantitative current measurements and longer temporal analyses are recommended to refine and expand upon the insights presented in this work.

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