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Seasonal Variation of Ekman Transport in the Southern Waters of West Sumatra

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Abstract

Seasonal Variation of Ekman Transport in the Southern Waters of West Sumatra

This study examines seasonal variations in Ekman transport in the southern waters of western Sumatra using wind, ocean current, and sea level data from the Copernicus Marine Service for the period 2023–2024. Data analysis was conducted spatially and temporally using Panoply, Python, and ArcGIS software. The results show that Ekman transport dynamics are significantly influenced by changes in the direction and intensity of the Asian–Australian monsoon winds. Maximum transport values were identified in the East Season at 4-5 m^3/s due to strengthening southeasterly winds, while minimum values occurred in the West Season at 1-2 m^3/s when westerly winds dominated the region. These seasonal variations show a close relationship with changes in surface currents and sea level, reflecting the dynamic response of the oceanographic system to the influence of wind friction. These results reinforce the understanding that Ekman transport plays an essential role in controlling regional ocean circulation patterns and provides an important scientific basis for marine resource management in the waters west of Sumatra.

Keywords: *Wind; Current; Sea Level; Ekman Transport*

INTRODUCTION

Ekman transport is a fundamental mechanism in physical oceanography that describes the movement of surface water masses in response to wind stress and the Coriolis force, resulting in water transport that is directed perpendicular to the prevailing wind (to the left in the Southern Hemisphere). The magnitude of Ekman transport is primarily controlled by wind stress, the Coriolis parameter, and local oceanographic conditions (Bravo *et al*., 2016; Jacox *et al*., 2018). This process plays a critical role in regulating ocean circulation, sea surface temperature distribution, sea level variability, and the vertical supply of nutrients to the euphotic layer, thereby influencing primary productivity, particularly in coastal and tropical regions (Strutton *et al*., 2015; Wei *et al*., 2024).

Numerous studies have demonstrated that seasonal variability in surface winds is the dominant driver of both the intensity and direction of Ekman transport. In the tropical Indian Ocean, fluctuations in Ekman transport have been shown to significantly modulate chlorophyll-a distribution and primary productivity (Strutton *et al*., 2015). Strengthening of seasonal winds enhances surface water divergence, which is closely associated with sea surface temperature cooling and increased nutrient input from subsurface layers (Jacox *et al*., 2018). Furthermore, Ekman transport anomalies contribute substantially to the variability of surface currents and sea level on seasonal to interannual time scales in the eastern Indian Ocean (Wei *et al*., 2024).

In the waters west of Sumatra, Ekman transport dynamics are strongly governed by the Asian–Australian monsoon system. During the West Monsoon (December–February), west to northwesterly winds carrying moist air masses dominate the region, driving coastal currents southeastward and promoting the accumulation of water masses along the coastline. In contrast, during the East Monsoon (June–August), stronger southeasterly winds prevail and induce pronounced surface water divergence, triggering upwelling processes from the Bengkulu to Lampung regions (Narayana *et al*., 2021; Wirasatriya *et al*., 2020; Xu *et al*., 2021). Recent studies indicate that the intensification of

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southeasterly winds over the past decade has enhanced the strength of upwelling along the Sumatra–Java coast and led to its earlier seasonal onset (Horii *et al*., 2023; Zhang *et al*., 2023).

Previous investigations in southern Java waters reveal that maximum Ekman transport intensity typically occurs during the East Monsoon, coinciding with intensified upwelling and a marked decrease in sea surface temperature (Horii *et al*., 2023; Wirasatriya *et al*., 2020). Given the similarities in coastal morphology, monsoon forcing, and oceanographic characteristics between southern Java and western Sumatra, comparable mechanisms are expected to operate in the Bengkulu–Lampung region (Narayana *et al*., 2021; Horii *et al.*, 2020). However, studies specifically addressing the seasonal variability of Ekman transport in the southern sector of western Sumatran waters remain limited, particularly for recent periods with higher temporal resolution.

This region plays a strategically important role in regional circulation, as it lies along the pathway of the *Indonesian Throughflow* (*ITF*), which connects the Indian Ocean with the Pacific Ocean and the South China Sea (Makarim *et al*., 2019). Seasonal variations in Ekman transport in this area have the potential to influence heat redistribution, vertical mixing intensity, and nutrient supply to the euphotic zone, thereby affecting biological dynamics such as primary productivity and chlorophyll-a concentration (Varela *et al*., 2015). In addition to monsoonal forcing, Ekman transport variability in the eastern Indian Ocean is also modulated by large-scale climate phenomena such as the *Indian Ocean Dipole (IOD)* and *El Niño–Southern Oscillation (ENSO),* which can amplify or suppress seasonal wind responses (Jayaram, 2022; Roxy *et al*., 2016; L. Zhang *et al*., 2022). Positive *IOD* conditions, for instance, are known to strengthen southeasterly winds and enhance offshore Ekman transport, leading to more intense upwelling along the Sumatra–Java coast (Horii *et al*., 2023; Narayana *et al*., 2021).

Based on the description above, this research aims to analyze the role of Ekman transportation in controlling the dynamics of coastal and open sea waters, especially in relation to the upwelling process which contributes to increasing water fertility. This research specifically aims to examine the seasonal variability of Ekman transport and the dynamic response of air masses which are influenced by wind patterns, to identify areas that have the potential to experience increased water fertility. In addition, this research is aimed at understanding the relationship between wind-induced water mass transport and nutrient distribution and ocean dynamics, to provide a more comprehensive picture of the mechanisms controlling water fertility in the study area.

MATERIALS AND METHODS

This study focuses on the southern part of the West Sumatra Waters, stretching from Muko-Muko to Lampung. The data used includes wind parameters, ocean currents, and sea surface height obtained from *Copernicus Marine MyOcean Viewer* for a two-year period, from 2023 to 2024. The data was analyzed in the form of monthly averages and seasonal averages with a 3-month interval in accordance with the monsoon season division in the study area. Data processing and analysis were carried out using *Panoply* software, *Python* software, and *ArcGIS* software to support the visualization and spatial and temporal interpretation of the oceanographic variables studied.

The research location was mapped in advance using *ArcGIS* to obtain a spatial representation of the study area. This location map shows the geographical boundaries of the observation area, which covers the southern waters of the west coast of Sumatra, as shown in Figure 1.

The mapping results map serves as the main reference in interpreting the spatial distribution of oceanographic parameters studied in this research. The distribution map is then analyzed using descriptive and quantitative approaches. Descriptive analysis was used to identify and describe the general patterns of wind, ocean currents, and sea surface height distribution during the observation period, while quantitative analysis was applied to obtain numerical values for each parameter in order to strengthen spatial interpretation in a more in-depth and objective manner.

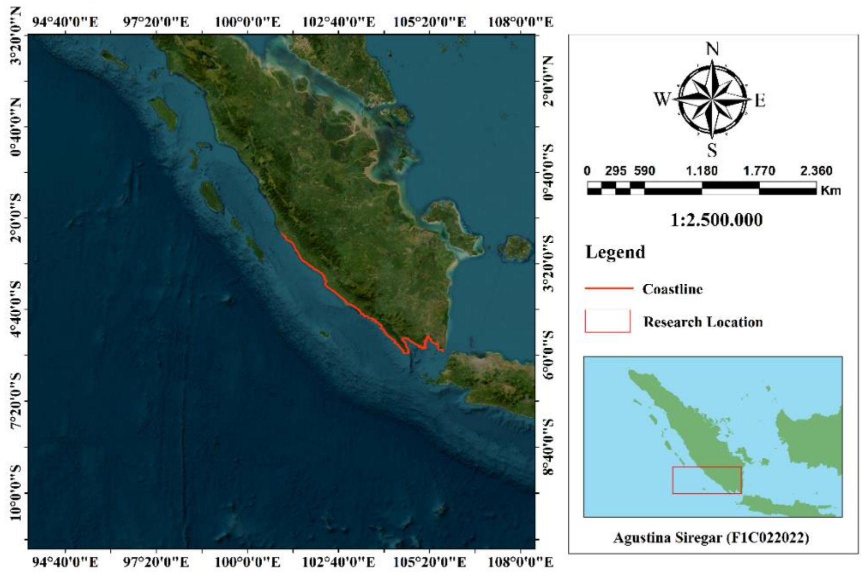

Figure 1. Research Location

Data processing in this study was carried out using average wind, ocean current, and sea surface height data for a two-year period, from 2023 to 2024. Wind data was processed using two software programs, *Panoply* and *Python,* for the purpose of comparing results. In *Panoply*, the data was processed in the form of monthly averages, while in *Python*, it was processed in the form of three-monthly (seasonal) averages representing the variations in atmospheric and ocean dynamics during the two-year observation period. The ocean current data was then analyzed by correlating it with sea level height to identify current distribution patterns from offshore to coastal areas. The processing of currents and sea level height was carried out using Panoply, while additional seasonal-based analysis was performed using *Python* through quarterly average calculations to observe dynamic inter-seasonal changes.

Next, the processed wind data was used to calculate wind friction force, which was analyzed in the form of a three-month seasonal average during the 2023–2024 period. Wind friction force was calculated along the southwestern waters of Sumatra to identify its effect on surface water mass movement. Based on Fikra *et al.* (2025), the data used is the average seasonal wind speed component during the observation period:

$$\tau_x = \rho_{udara}\, C_D\, U^2$$

$$\tau_y = \rho_{udara}\, C_D\, V^2$$

with ρ_{udara} (*air density*) = 1.3 kg/m^3; *CD (drag coefficient)* = 1.4×10-3; and *U* and *V* are the seasonal average wind speeds (m/s). The seasonal average Ekman transport toward the open sea due to wind friction is calculated using (Ganguly *et al*., 2024):

$$M_{xE} = \frac{\tau_x}{f}$$

$$M_{yE} = \frac{-\tau_y}{f}$$

where f is the *Coriolis* parameter (2 Ω sin θ, $\Omega = 7.29\times10^{-5}$ s^{-1}; θ = latitude). The Ekman transport value is converted into Sverdrup units (1 *Sverdrup (Sv)* = 10^6 m^3/s) by calculating the Ekman transport per unit of seawater density, ρ_{water}(kg/m^3) using equations (Ganguly *et al*., 2024) :

$$M_{xE} = \frac{\tau_x}{\rho_{air} f}$$

$$M_{yE} = \frac{-\tau_y}{\rho_{air} f}$$

To calculate the Ekman transport magnitude in the southern waters of western Sumatra, (Ma *et al.*, 2017):

$$\text{mag} = \sqrt{{M_{xE}}^2 + {M_{yE}}^2}$$

These calculations were performed by applying Ekman transport equations using scripts developed in Python software. The results were then compared with ocean current distributions and sea level heights to assess the relationship between atmospheric dynamics and oceanographic responses in the southern waters of western Sumatra.

RESULTS AND DISCUSSION

Seasonal wind patterns in the waters south of western Sumatra show varying dynamics in direction and intensity throughout the year. The color gradation represents wind speed, while the direction vectors illustrate seasonal changes in wind orientation, as shown in Figure 2.

The analysis results show that seasonal wind variations in the southern part of the western Sumatra waters are strongly related to changes in seasonal wind patterns throughout the annual cycle. Spatially, the study area covers coordinates around 95°E–110°E and 2°S–11°S, which are open waters with tropical atmospheric circulation characteristics that are strongly influenced by the Asian Australian monsoon system. During the West Season (December–February), wind patterns are dominated by flows from the southeast to the west–northwest with relatively weak intensities of around 1–3 m/s. This northwesterly wind direction reflects the dominance of the western monsoon system, which brings moist air masses from the western Indian Ocean to the Indonesian region (Wirasatriya *et al*., 2020).

During Transition Period I (March–May), the wind direction shifts from southeast to northwest with speeds increasing to 4–5 m/s. This shift marks the transition from the west monsoon to the east monsoon. The increase in wind speed increases friction on the sea surface, thereby significantly increasing Ekman transport in the southern region (Kurniawati *et al*., 2021).

During the East Monsoon (June–August), strong and stable winds blow from the southeast to the northwest at speeds of 7–9 m/s, especially at latitudes 6°S–11°S. These conditions result in maximum Ekman transport along the west coast of Sumatra. Spatially, the wind pattern parallel to the coastline around the southern part of the West Sumatra Sea produces strong friction forces, thereby also strengthening Ekman transport in the southern part. The spatial distribution of wind speed shows an increasing gradient towards the south, indicating greater transport intensity at low latitudes. This phenomenon is in line with the results of studies (Kurniawati *et al*., 2021; Wirasatriya *et al*., 2020), which confirm the dominance of the east monsoon on the dynamics of sea surface circulation in the region.

Upon entering Transition Period II (September–November), the wind direction shifted from east–southeast to west–northwest, accompanied by a decrease in speed to a range of 3–5 m/s. This weakening caused a reduction in friction at the sea surface and a decrease in Ekman transport intensity.

Overall, seasonal wind variations in the southern waters west of Sumatra exhibit a consistent annual pattern, with maximum values during the East Monsoon and minimum values during the West Monsoon. This distribution, which exhibits greater intensity in southern latitudes, confirms that seasonal changes in wind speed and direction are the primary factors controlling Ekman transport dynamics in this region. This pattern also aligns with recent studies in the eastern Indian Ocean, which report increased surface transport activity due to strengthening easterly winds in recent years (Horii *et al*., 2023; Kurniawati *et al*., 2021; Wirasatriya *et al*., 2020)

Seasonal variations in oceanographic conditions in the southern waters of western Sumatra can be demonstrated by the distribution of sea currents and changes in sea level. Based on Figure 3, differences in surface elevation are visualized through color variations, while water mass movement patterns are indicated by current vectors that illustrate the response to seasonal wind influences.

Spatial analysis of average surface currents and sea level in the waters south of western Sumatra during the 2023–2024 period reveals a consistent pattern of seasonal variability in response to monsoon dynamics in the eastern Indian Ocean. During the West Season (December–February), the distribution of sea level shows a prominent positive anomaly along the coast, with values reaching 0.50–0.55 m, while offshore areas show lower values, ranging from 0.55–0.35 m. Surface currents move predominantly southeastward parallel to the coastline, indicating the occurrence of Ekman transport towards the coast due to the influence of westerly winds. This condition triggers the accumulation of air masses in the western coastal area of Sumatra and an increase in sea level relative to offshore areas, potentially strengthening coastal circulation during the peak rainy season.

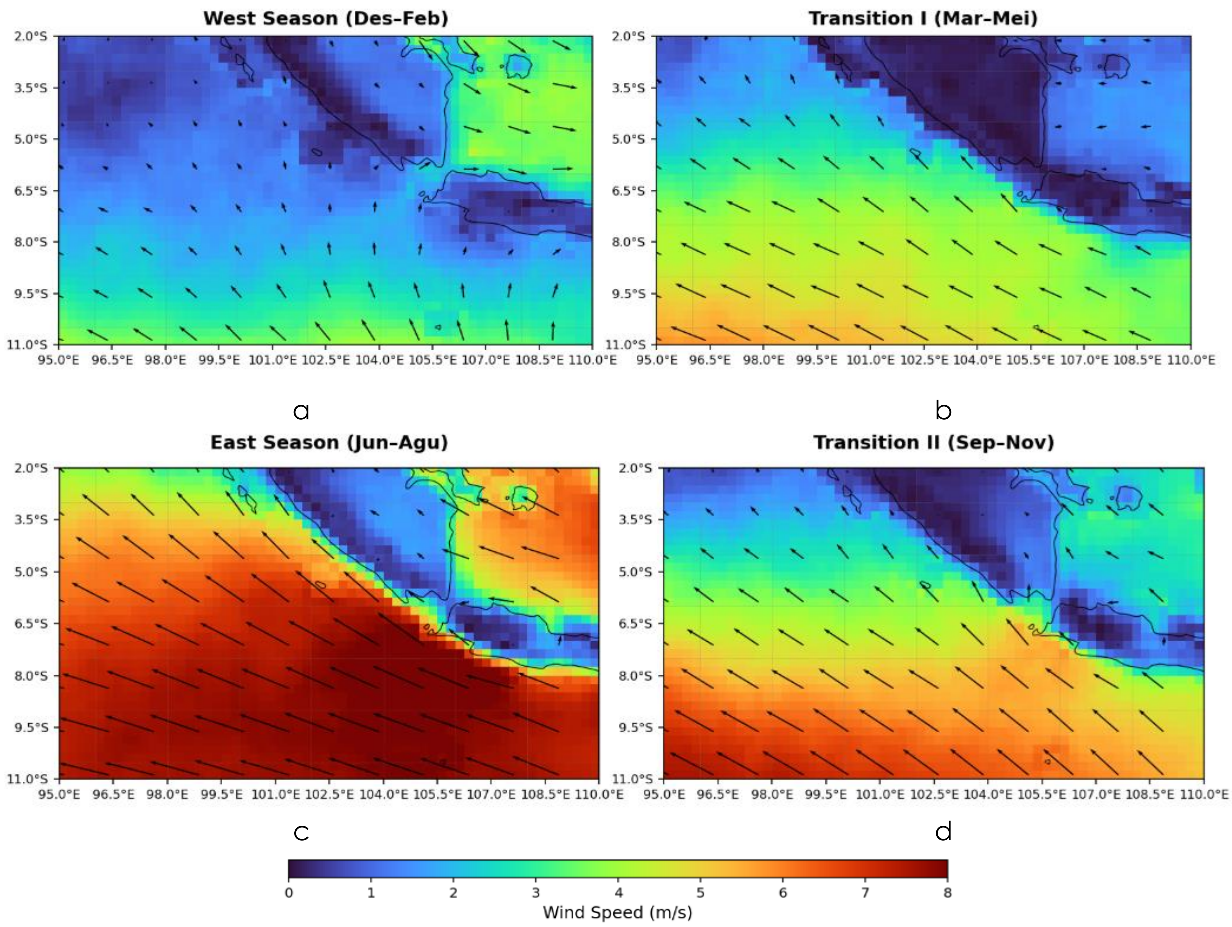

Figure 2. Distribution of average seasonal winds over 2 years (2023-2024) in the southern part of the West Sumatra Sea, (a) West Season, (b) Transition Season I, (c) East Season, and (d) Transition Season II in 2023-2024.

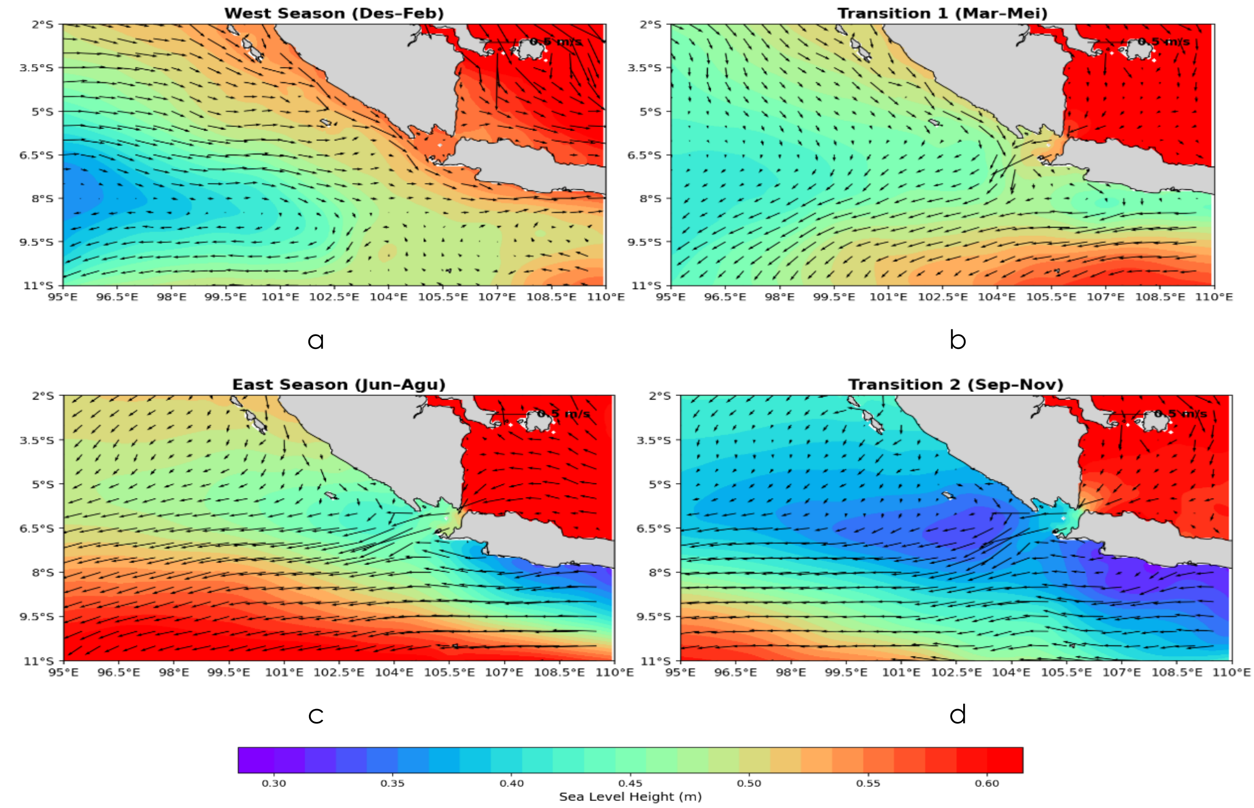

Figure 3. Distribution of current (vector) and sea level (color) seasonal averages for 2 years (2023-2024) in the southern part of the West Sumatra Waters, (a) West Season, (b) Transition Season I, (c) East Season, and (d) Transition Season II in 2023-2024.

During Transition Season I (March–May), the sea level gradient is still apparent, although its distribution becomes more even, ranging from 0.35 to 0.50 m. Surface currents begin to show more diverse patterns, with flows from the northwest in the north and from the west in the south. This pattern reflects the weakening of wind friction forces associated with the shift from the west monsoon to the east monsoon.

Entering the East Monsoon (June–August), high sea levels along the west coast of Sumatra decreased to around 0.40–0.50 m, while the western offshore area showed an increase of up to 0.45–0.60 m. Surface currents are not entirely oriented to the southwest, but move west to northwest along the coast and southwest in the southern part. This pattern indicates Ekman transport away from the coast, which is in line with the dominance of southeasterly winds. The divergence of water masses formed is closely related to the upwelling process in the southwestern region of Sumatra, as reported by (Wirasatriya *et al*., 2023; Zhang *et al*., 2023).

During Transition Season II (September–November), sea level declined again, especially in the central to southern regions, ranging from 0.30 to 0.40 m, while sea level values in coastal areas were lower. Surface currents showed irregular patterns with relatively low speeds, although there was still a tendency for westward and southwestward flows in some locations. These conditions described the transition stage before the west monsoon strengthened again, when the intensity and direction of wind friction began to change but had not yet reached their maximum.

Overall, sea level variations and surface current patterns show that changes in the direction and intensity of seasonal winds are the main drivers of Ekman transport dynamics in the waters west of Sumatra. During the West Monsoon, wind pressure generates transport towards the coast, increasing water mass accumulation, while during the East Monsoon, transport away from the coast causes divergence and supports upwelling. The relationship between sea level variability and surface current orientation confirms the strong link between wind friction, sea surface pressure gradients, and coastal circulation configurations in the eastern Indian Ocean tropics. These findings are consistent with those of Kurniawati *et al*., (2021) and Setiawan *et al*., (2022), which indicate that monsoon dynamics play a dominant role in controlling coastal current patterns and sea level fluctuations along the west coast of Sumatra, with important implications for regional circulation, primary productivity, and sea surface temperature distribution in the region.

The distribution of Ekman transport shows seasonal fluctuations in the intensity and direction of water mass movement. Transport values are displayed using a color scheme, while direction vectors illustrate the movement patterns that arise from the interaction of wind friction forces with the sea surface layer, as shown in Figure 4.

The spatial distribution of Ekman transport in the southern waters of western Sumatra shows significant changes throughout the year, in line with the seasonal dynamics that develop in the region. Each monsoon period exhibits different characteristics in terms of transport direction and intensity, representing the response of surface water mass to annual atmospheric variability. During the West Monsoon (December–February), the magnitude of transport along the southern coast of Sumatra is relatively low, generally below 2 m^3/s. The direction of transport during this period tends to be northward, marking the movement of surface water masses from the southern region toward higher latitudes, albeit with weak intensity in most offshore areas.

Entering Transition Season I (March–May), there was an increase in Ekman transport values ranging from 1–2 m^3/s, especially at mid to southern latitudes between 6°–10ºS. The direction of transport shifted to the southwest, indicating a change in the orientation of surface water movement from the previous seasonal pattern. The increase in transport intensity is also evident in the spatial distribution, which shows greater values in offshore areas. During the East Season (June–August), Ekman transport reached its maximum intensity of 4-5 m^3/s, characterized by strong and relatively uniform transport across most of the region. The direction of transport during this season remained southwest, while longer vectors indicated a much stronger surface water mass push compared to other seasons.

In the Second Transition Season (September–November), there was a decrease in intensity from its peak in the East Season, with transport values in the medium range of around 2–4 m^3/s. The direction of transport shifts to the west, reflecting a reorganization of water mass movement patterns from a southwest orientation to a direction more parallel to the latitudinal line. The spatial distribution during this period also shows more dynamic directional variability, particularly in the southern coastal region, as this area enters a transition phase towards the next seasonal system.

Overall, the seasonal variability of Ekman transport in this region shows a consistent pattern of change in both intensity and direction of transport. The lowest transport values occur in the West Season, increase in the Transition Season I, reach a maximum in the East Season, and then decrease again in the Transition Season II. The shift in transport direction from north → southwest → southwest → west throughout the annual cycle confirms that the dynamics of surface water mass in the southwestern waters of Sumatra are strongly influenced by seasonal atmospheric conditions in the region.

The analysis results reveal that seasonal fluctuations in Ekman transport in the southern waters of western Sumatra are strongly influenced by changes in the direction and intensity of the Asian–Australian monsoon winds. These variations have a direct impact on the distribution of surface currents and sea surface height, which collectively regulate water mass dynamics in both coastal and offshore areas. During the East Season (June–August), the intensity of the southeast wind increases significantly, resulting in a maximum Ekman transport value of 4-5 m^3/s moving offshore. This condition reflects the occurrence of strong surface water mass divergence along the coast of Bengkulu to Lampung. The results of this study are in line with research Horii *et al*., (2023) and Wirasatriya *et al*., (2023), which shows that the strengthening of easterly winds in the eastern Indian

Ocean plays a role in accelerating surface circulation and increasing primary productivity through more intensive water mass movement. Thus, Ekman transport plays an important role in regulating the ocean–atmosphere energy balance in the eastern tropical Indian Ocean.

Conversely, during the West Season (December–February), the weakening of westerly winds causes a significant decrease in the minimum Ekman transport value of 1–2 m^3/s. Water masses tend to move towards the coast (*onshore*), which results in water accumulation in coastal areas and an increase in local sea level. These findings are consistent with the results of a study (Setiawan *et al*., 2022), which emphasizes the relationship between regional atmospheric pressure variability and sea level fluctuations in Indonesian tropical waters. The spatial shift in sea level gradients between seasons indicates an oceanographic response to changes in wind friction, where sea surface pressure gradients are a key parameter in assessing the intensity of horizontal transport. During Transition Periods I and II, atmospheric-ocean dynamics exhibited complex characteristics due to changes in wind direction from westerly to easterly and vice versa. In this phase, Ekman transport exhibits spatially non-uniform variations, reflecting the interaction between regional wind patterns and local circulation. The irregularity of surface currents and sea pressure fluctuations that arise signify a transition phase towards dominant monsoon conditions. This phenomenon demonstrates the important role of temporal friction forces in maintaining the stability of the tropical ocean circulation system (Simanjuntak & Lin, 2022).

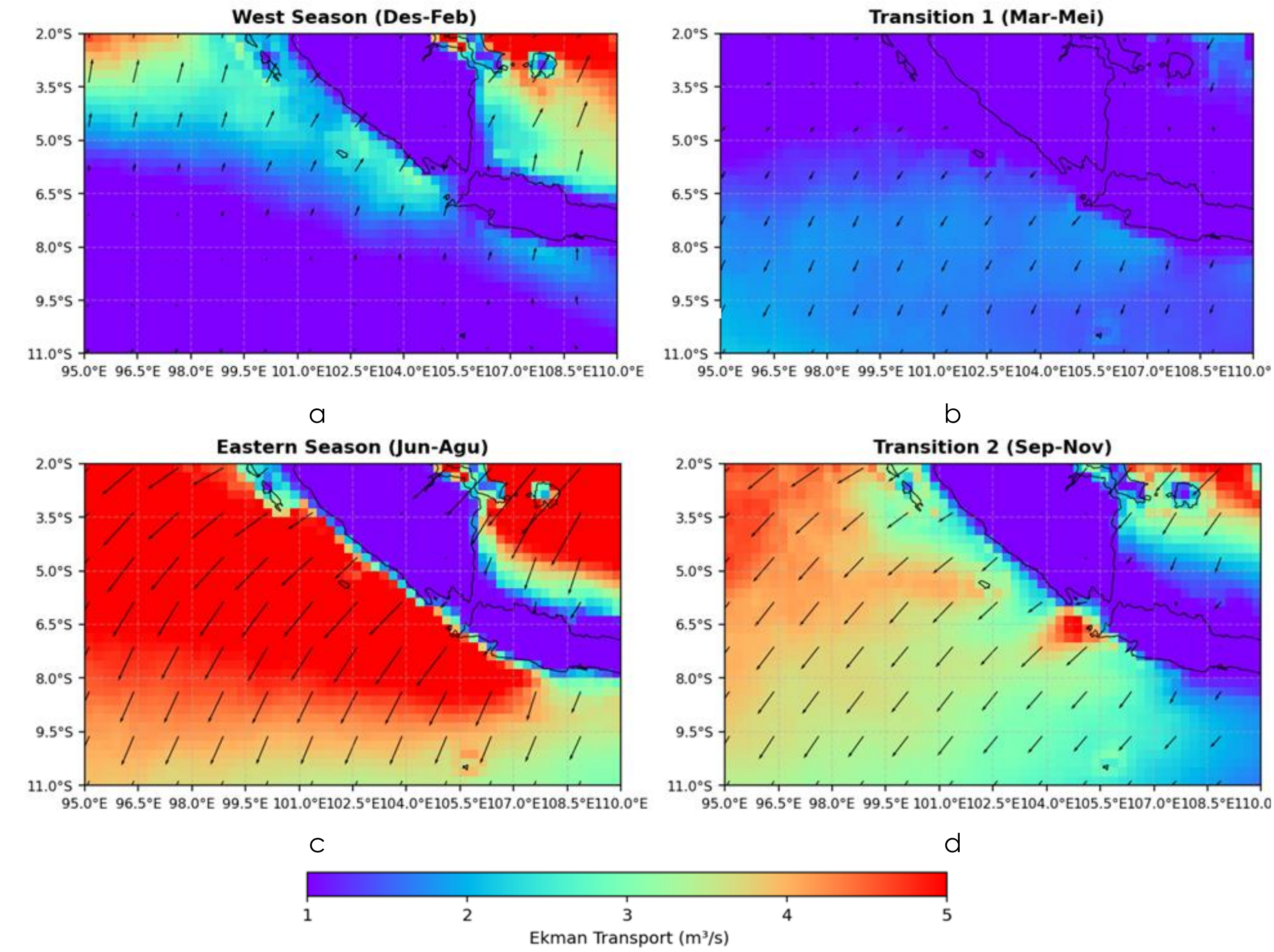

Figure 4. Distribution of average seasonal Ekman transport for 2 years (2023-2024) in the southern part of the West Sumatra Waters, (a) West Season, (b) Transition Season I, (c) East Season, and (d) Transition Season II in 2023-2024.

Overall, the relationship between wind, ocean currents, and sea level shows that seasonal winds are the main controller of Ekman transport dynamics in this region. The strengthening of southeasterly winds during the East Season increases transport away from the coast and lowers coastal sea levels, while the dominance of westerly winds during the West Season results in transport towards the coast, contributing to an increase in sea level. This annual variability has direct implications for *sea surface temperature (SST*) distribution and marine biological productivity. Changes in surface transport affect thermal equilibrium and nutrient distribution in the euphotic layer (Himawa *et al*., 2025; Silaban *et al*., 2025). Furthermore, Ekman transport patterns in the waters west of Sumatra also show a close relationship with large-scale phenomena such as the *Indian Ocean Dipole (IOD)* and *El Niño–Southern Oscillation (ENSO*), which can strengthen or weaken the influence of regional monsoons (Wei *et al*., 2024; L. Zhang *et al*., 2022). Positive *IOD* conditions, for example, have the potential to strengthen southeasterly winds and increase the intensity of Ekman transport along the west coast of Sumatra. These cross-scale interactions confirm that local dynamics in the region cannot be separated from the broader global circulation system. Thus, the results of this study confirm that seasonal variations in Ekman transport in the southern part of the western Sumatran waters are not only controlled by seasonal wind dynamics, but are also the result of complex interactions between regional *atmospheric* forces and local oceanographic conditions. A comprehensive understanding of these mechanisms is essential to support marine resource management and improve the ability to predict future regional climate variability.

CONCLUSION

Seasonal variations in Ekman transport in the southern part of the western waters of Sumatra show a strong correlation with the dynamics of the Asian–Australian monsoon winds, with maximum values occurring in the East Season of 4–5 m^3/s due to the strengthening of southeasterly winds and minimum values of 1–2 m^3/s in the West Season when westerly winds weaken. These changes in wind direction and intensity directly affect surface current patterns and sea level height, resulting in differences in water mass distribution between coastal and offshore areas. In general, the findings of this study indicate that wind friction plays a dominant role in regulating seasonal ocean circulation dynamics in the region. These conditions have significant consequences for oceanographic variability patterns, water productivity levels, and coastal resource management strategies oriented towards sustainability.

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