

The Effect of ENSO on the Upwelling Intensity in the Seas along the Northern Coast of Papua: A Case Study of the 2015–2016 El Niño and the 2010–2011 La Niña Events

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ABSTRACT

The seas along the Northern Coast of Papua constitute a region with complex oceanographic conditions as they are situated within the Indo-Pacific warm pool (IPWP). The geographical location in the southern hemisphere induces upwelling during the west monsoon season (December-January-February). Additionally, interannual phenomena such as the El Niño Southern Oscillation (ENSO) can impact the intensity of upwelling in these waters. This study aimed to compare the upwelling intensity in the seas along the Northern Coast of Papua during neutral phases and ENSO phases. The main indicators of upwelling are sea surface temperature (SST) and Ekman mass transport (EMT). The data utilized in this study include SST from GHRSSST and surface wind from ASCAT. The data processing employed the monthly composite method with spatiotemporal analysis based on anomaly results derived from monthly climatology. The analysis results reveal that El Niño 2015–2016 led to an increase in upwelling intensity ranging from 1.82 to 4.00 m/s², while La Niña 2010–2011 resulted in a weakening of upwelling intensity ranging from 4.95 to 6.56 m/s² in the seas along the Northern Coast of Papua. On the basis of correlation and regression analysis, it can be concluded that offshore EMT significantly influences upwelling anomalies in the southeastern waters, whereas the northwestern waters are more influenced by the shifting IPWP during ENSO.

Keywords: ENSO, upwelling, Northern Coast of Papua, Indo-Pacific warm pool, Ekman mass transport.

INTRODUCTION

The Indo-Pacific Maritime Continent constitutes a group of islands situated in the western part of the equatorial Pacific Ocean, characterized by intricate interactions among land, atmosphere, and ocean dynamics. Encompassing various countries in Oceania and Southeast Asia, including Indonesia, this region is specifically part of the

Indo-Pacific warm pool (IPWP). With an annual average sea surface temperature (SST) exceeding 28 °C (Deckker, 2016), IPWP plays a pivotal role in global climate and ocean circulation.

As part of Indonesian seas, the seas along the Northern Coast of Papua is located at the western edge of the equatorial Pacific. Designated as an upwelling area, it experiences this phenomenon during the west monsoon season (December,

January, February) (Wirasatriya et al., 2021). The upwelling phenomenon is notably influenced by climate variability, primarily through monsoons and the El Niño Southern Oscillation (ENSO). Under normal conditions, monsoons predominantly influence the upwelling intensity in these seas. Conversely, ENSO can displace warm water pools in a zonal motion, contributing to the complexity of upwelling intensity in these waters (Hartanto, 2011). Hence, this study addresses the challenge of discerning differences in upwelling intensity due to the ENSO phenomenon along the Northern Coast of Papua.

Upwelling is defined as the ascent of water masses from deeper layers to the sea surface due to offshore Ekman mass transport (Wirasatriya et al., 2020, 2021). Consequently, SST cooling serves as an indicator of upwelling occurrence. In this study, the impact of ENSO on SST variability as a proxy for upwelling in the seas along the Northern Coast of Papua was explored. These seas directly border the Indo-Pacific warm pool, exerting a major influence on the shift of the warm pool during ENSO. To quantify upwelling intensity, EMT was employed, which remains unaffected by the movement of the Indo-Pacific Warm Pool. The conducted investigation focused on case studies during the strongest El Niño (2015–2016) and the strongest La Niña (2010–2011), identified by the strong Oceanic Niño Index (ONI) as depicted in Figure 1 (Varotsos et al., 2016).

DATA AND METHODS

The study was carried out in the seas along the Northern Coast of Papua, spanning coordinates 4°S – 2°N and 130°E – 145°E. Three plots were employed for data conversion across all variables (indicated in red boxes). The research location is visually represented in Figure 2. Secondary data, in the form of SST data, were obtained from the group for high-resolution sea surface temperature (GHR SST) with a spatial resolution of 9 km. Wind data were acquired from the advanced scatterometer (ASCAT) with a resolution of 12.5 km. The observation period spans from January 2007 to December 2020.

Red boxes denote the sampling plots for the analysis in Table 1 and Table 2. The yellow angle represents the angle between the equator and the coastal line for calculating offshore EMT.

Data analysis relies on monthly anomaly data derived from its respective monthly climatology. The calculation of the monthly climatology employs the formula outlined in Wirasatriya et al. (2017), expressed as follows:

$$X(x, y) = \frac{1}{n} \sum_{i=1}^n xi(x, y, t) \tag{1}$$

where: $X(x, y)$ – monthly average or climatology;
 $xi(x, y, t)$ – data value at position x, y and time t ;
 n – amount of data.

To derive EMT values from wind speed, the equations by Hsieh and Boer (1992) were

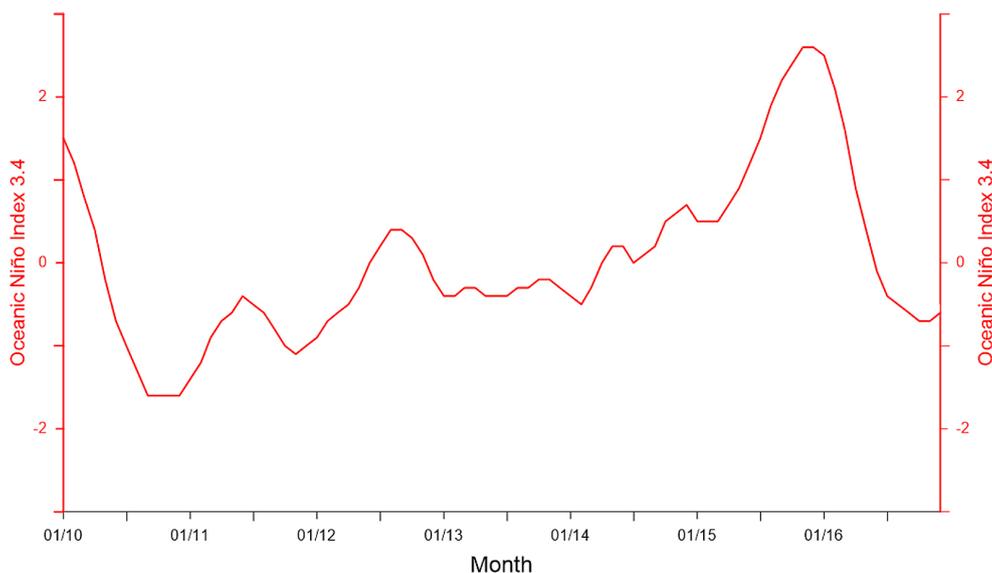


Figure 1. Oceanic Niño index 2010–2016

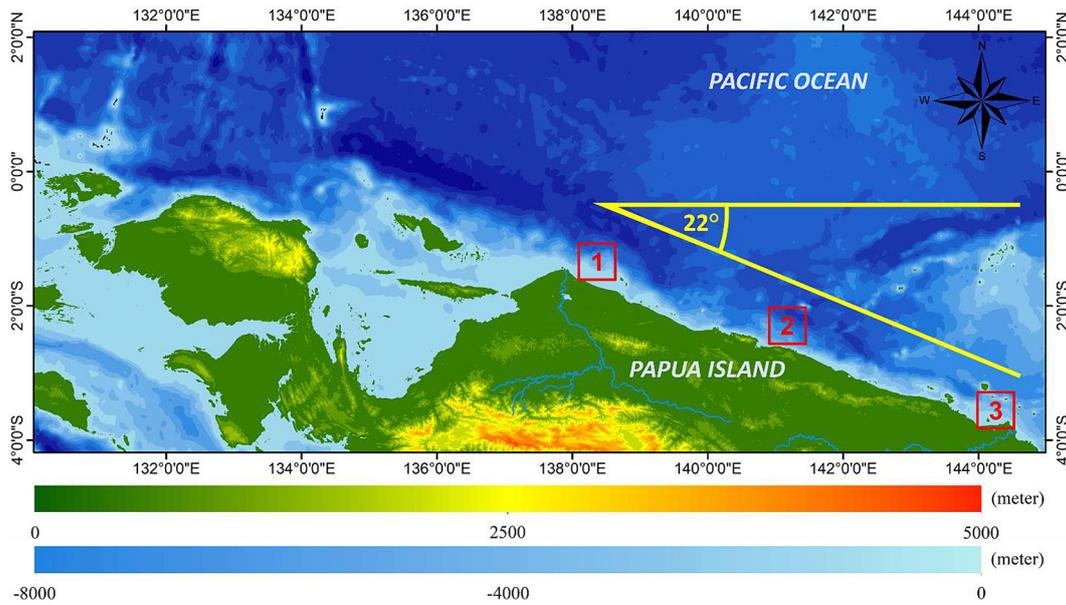


Figure 2. The study area of the seas along the Northern Coast of Papua

employed. These equations, tailored for EMT calculations near the equator, were previously utilized by Wirasatriya et al. (2019) in the Northern Maluku Sea. The equation is expressed as follows:

$$Q_x = \frac{\delta\tau_x + f\tau_y}{\rho_w(f^2 + \delta^2)} \quad (2)$$

$$Q_y = \frac{\delta\tau_y + f\tau_x}{\rho_w(f^2 + \delta^2)} \quad (3)$$

where: Q_x – zonal EMT;
 Q_y – meridional EMT;
 δ – frictional dumping parameters (480^{-1} day);
 τ_x – zonal wind stress;
 τ_y – meridional wind stress;
 f – Coriolis factor ($\Omega = 7.292 \times 10^{-5} \text{ rad s}^{-1}$);
 ρ_w – density of water (1025 kg m^{-3}).

To ascertain offshore EMT, it is essential to account for the angle between the coastline and the equator. The calculation formula employed in this study was derived from the research by Kok et al. (2017) and is expressed as follows:

$$EMT = -\left(\sin\left(\varphi - \frac{\pi}{2}\right)Q_y + \cos\left(\varphi - \frac{\pi}{2}\right)Q_x\right) \quad (4)$$

where: Q_x – zonal EMT;
 Q_y – meridional EMT;
 φ – angle between the equator and the coastline (22°).

This study employed the Pearson correlation analysis technique, encompassing all variables.

Pearson correlation establishes linear connections between two variables, providing a correlation value (r). In this study, Pearson correlation was utilized to investigate the relationships between ONI, offshore EMT, and SST. Additionally, regression analysis was conducted to analyze the relationships among parameters serving as indicators of upwelling. The output of the regression equation includes the coefficient of determination (R^2) and the regression equation, offering insights into the effects between the examined variables.

RESULTS AND DISCUSSION

Monthly climatology analysis

The SST in the seas along the Northern Coast of Papua exhibits higher values compared to the surrounding waters, primarily attributed to their location within IPWP. IPWP, situated in the western part of the Pacific Ocean, is characterized by elevated water temperatures influenced by the Walker circulation and Hadley circulation (Li et al., 2018). These circulations collectively form a warm pool in the West Pacific Ocean. The Hadley circulation directs the northeast and southeast trade winds toward the intertropical convergence zone (ITCZ). Strengthened by the Walker circulation, these winds persistently blow from America to Asia along the Pacific Ocean, leading to the accumulation of warm water masses in the west. The warm water mass in the West Pacific Ocean

exhibits zonal movement influenced by the two monsoon systems in the region. During the east monsoon, the winds from the southeast intensify the southeast trade winds, thereby strengthening the movement of the South equatorial current

(SEC) and New Guinea coastal current (NGCC) towards IPWP. Consequently, cooler water masses are transported towards IPWP, suggesting an eastward shift of IPWP (Siedler et al., 2013). This is notably observed in June–August, marked by

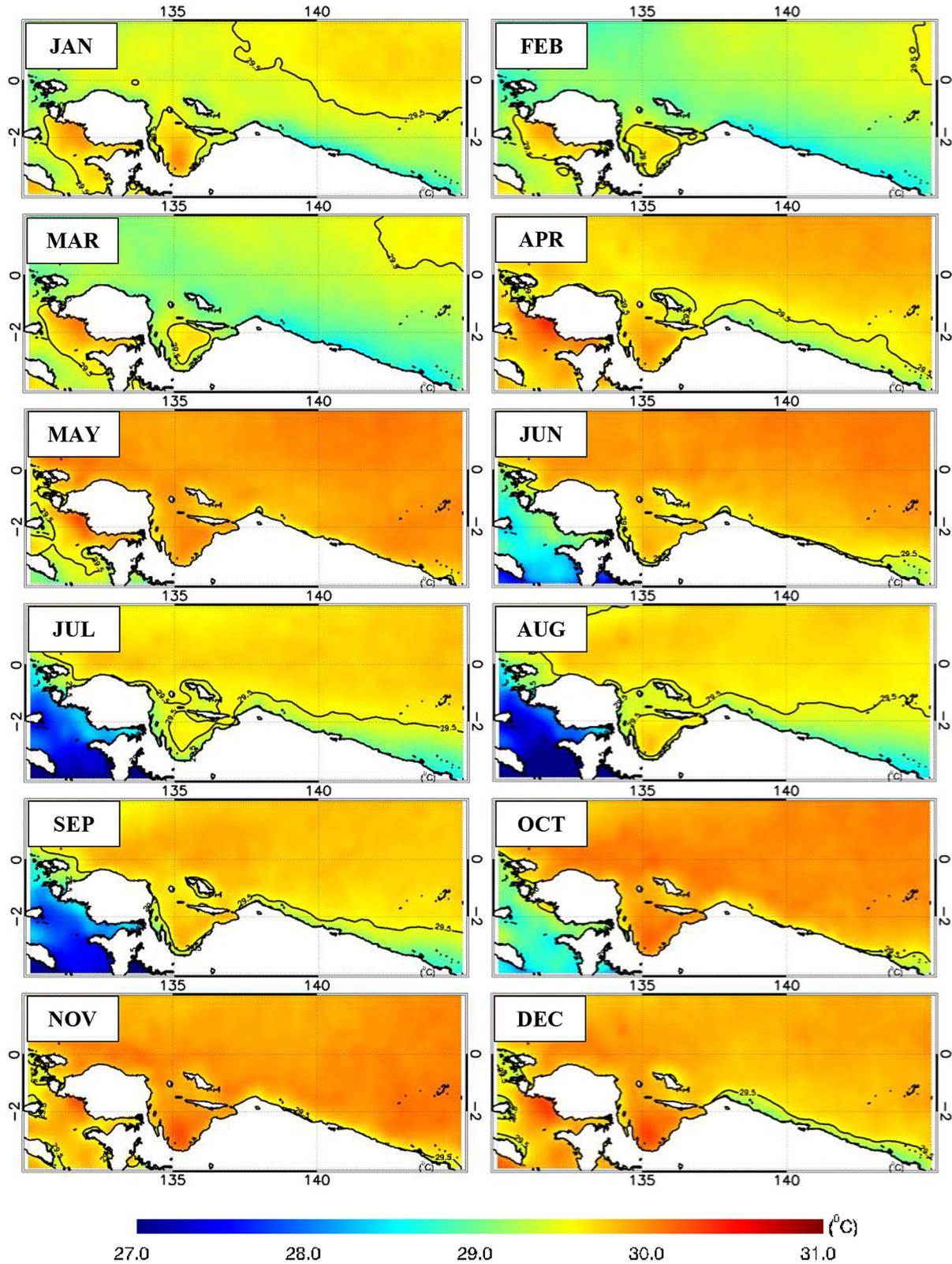


Figure 3. Monthly climatology of SST in the seas along the Northern Coast of Papua

a decrease in SST in the seas along the Northern Coast of Papua, particularly in coastal areas. Conversely, during the west monsoon, there is an increase in wind speed from the northwest,

known as westerly wind burst (WWB). The WWB movement is directly linked to the equatorial under current (EUC), moving eastward from the IPWP (Hartanto, 2011). Consequently,

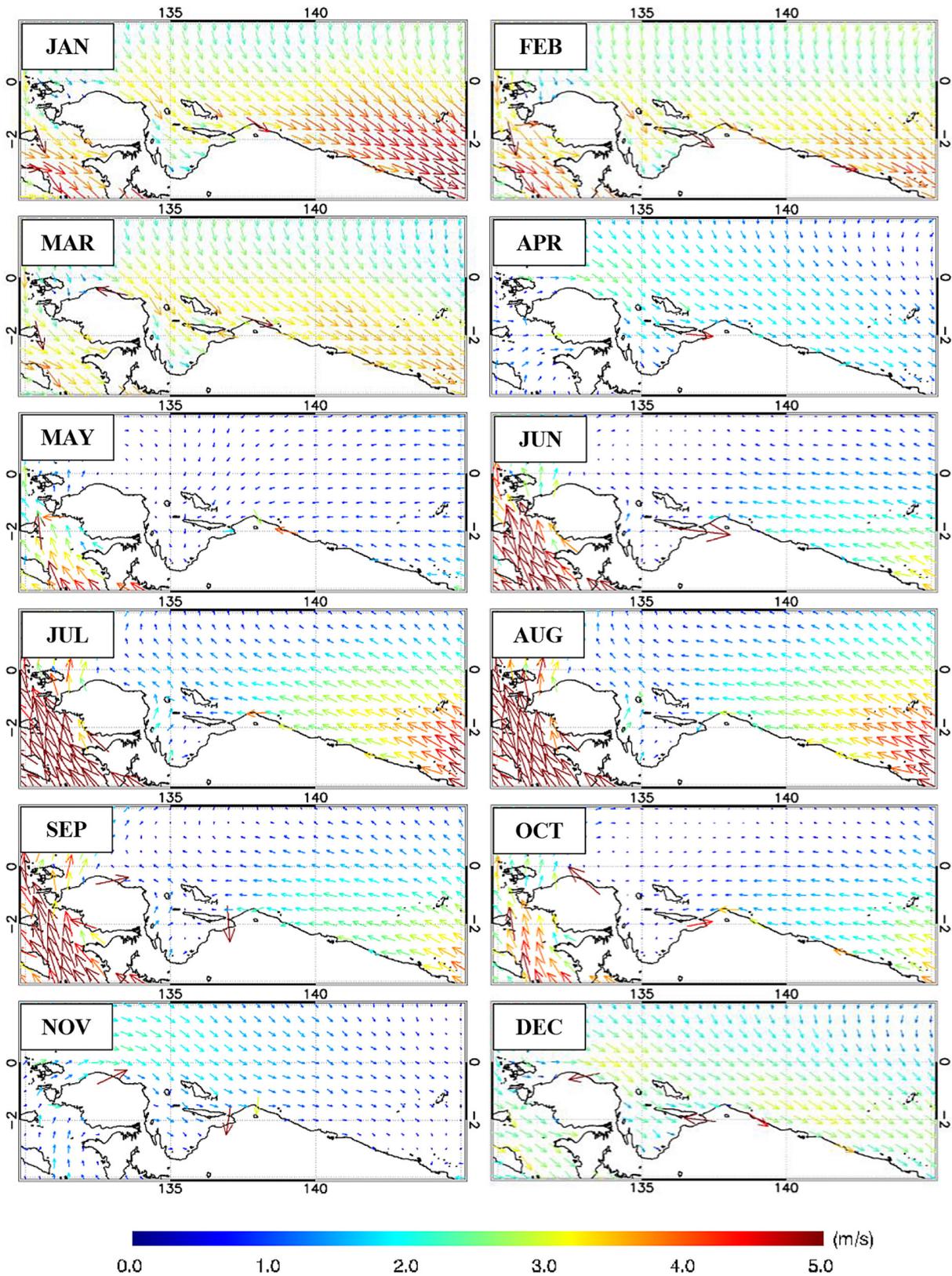


Figure 4. Monthly climatology of sea surface wind in the seas along the Northern Coast of Papua

during the west monsoon, the IPWP experiences a zonal shift to the east due to the addition of water mass from the EUC. This shift is evident in December–February, indicated by a decrease in SST in the seas along the Northern Coast of

Papua. The monthly climatology of SST is presented in Figure 3.

The seas along the Northern Coast of Papua function as estuaries for various rivers, making the intensity of river runoff a significant factor

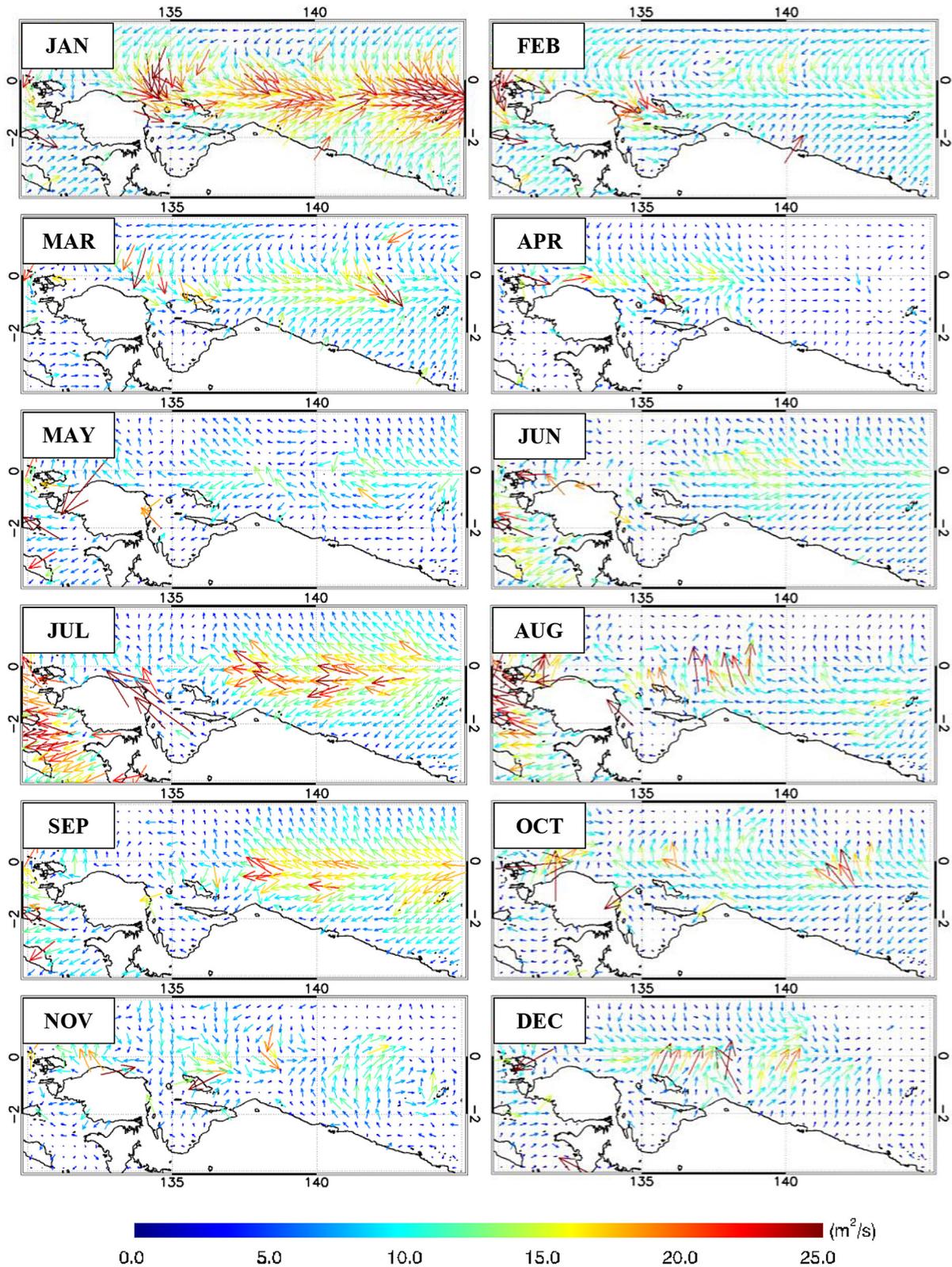


Figure 5. Monthly climatology of EMT in the seas along the Northern Coast of Papua

influencing the chlorophyll-a abundance in the waters. Land precipitation contributes to increased runoff in rivers, leading to elevated levels of chlorophyll-a due to heightened nutrient supply (Kunarso et al., 2019). Two noteworthy plots are associated with the watersheds of the Mamberamo River and the Sepik River, both of which discharge into the seas along the Northern Coast of Papua. During the west monsoon season, prevailing monsoon winds carry warm air masses from the northwest, resulting in high rainfall intensity on Papua Island (Webster, 2020). The areas with notable rainfall intensity are concentrated in coastal waters and the northern foothills of the mountains. A daytime convergence area forms on the mainland, causing sea breezes to carry air masses towards the center of the island. Upon reaching the Jayawijaya Mountains, orographic rainfall occurs at the northern foothills. At night, the convergence area shifts towards the sea, prompting air masses to move and induce rain in coastal waters (Christianto, 2014). Conversely, during the eastern season, there is minimal rainfall in the seas along the Northern Coast of Papua or on the mainland, except for Cenderawasih Bay. The topography of Cenderawasih Bay, surrounded by high mountains such as the Weyland Mountains (Alfahmi et al., 2019), forms a basin that intensifies convergence, resulting in consistently high rainfall throughout the year. The monthly climatology of wind is presented in Figure 4.

EMT represents the movement of water masses and serves as an indicator of upwelling in marine environments. The upwelling induced by EMT is contingent upon wind intensity and the direction of EMT movement towards the coast (Stewart, 1997). The monthly climatology of EMT is depicted in Figure 5. In the seas along the Northern Coast of Papua, EMT exhibits an offshore movement (offshore EMT) from November to April, indicating the occurrence of upwelling during this period. Positive EMT values, with the highest intensity observed in January, support this conclusion. Additionally, the results reveal instances of EMT with very high intensity around the equator. This heightened intensity can be attributed to the Coriolis factor, which has a smaller value at the equator. A smaller Coriolis factor enhances EMT, as it serves as a dividing factor for EMT (Wyrтки and Eldin, 1982).

Upwelling can be discerned through the examination of SST and EMT parameters. The climatological average of SST and EMT values

across the three plots suggests the potential occurrence of upwelling during the west monsoon. During this period, SST reaches its lowest values, while EMT attains its highest values. The upwelling observed in the west monsoon can be elucidated by the movement of wind as a generator of EMT. In the west monsoon, winds flow from the northwest, propelling the EMT towards the northeast. This displacement of EMTs away from the North Coast of Papua creates a void in the water mass along the coastal areas. Consequently, the water masses from deeper layers move upward to fill this void, instigating upwelling, as evidenced by low SST in coastal regions.

Parameter anomalies during the ENSO period

The periods of El Niño in 2015–2016 and La Niña in 2010–2011 were among the most significant ENSO events observed over the last two decades (Varotsos et al., 2016). An ENSO period is defined when the index exceeds 0.5 for three consecutive months. Typically, ENSO periods commence in boreal summer (JJA) and conclude in boreal spring (MAM), with the anomaly peak occurring in boreal winter (DJF) (Zhang et al., 2016). ENSO is characterized by the Oceanic Niño Index (ONI), reflecting SST anomalies in the NIÑO 3.4 region. The ONI values increase during El Niño, decrease during La Niña, and subsequently decrease further after reaching the peak in boreal winter. Therefore, ENSO research is concentrated on boreal winter, where ONI attains its highest values (Behera, 2021). The spatial distribution of anomalies for each parameter during the El Niño 2015–2016 and La Niña 2010–2011 phases is illustrated in Figure 6.

Spatial anomalies during the El Niño period (2015–2016) reveal a notable increase in coastal upwelling in the seas along the Northern Coast of Papua. This is evident in Figure 6, showcasing negative anomalies in SST and positive anomalies in offshore EMT. The heightened offshore EMT intensity is attributed to an increase in WWB during the peak of the El Niño period (Webster and Lukas, 1992). The intensified WWB contributes to elevated offshore EMT, reinforcing upwelling in the seas along the Northern Coast of Papua. Additionally, the strengthened upwelling is manifested by a decrease in SST in coastal waters. Nur'utami and Hidayat (2016) propose that El Niño induces a zonal movement of the IPWP to the east due to reduced equatorial trade wind

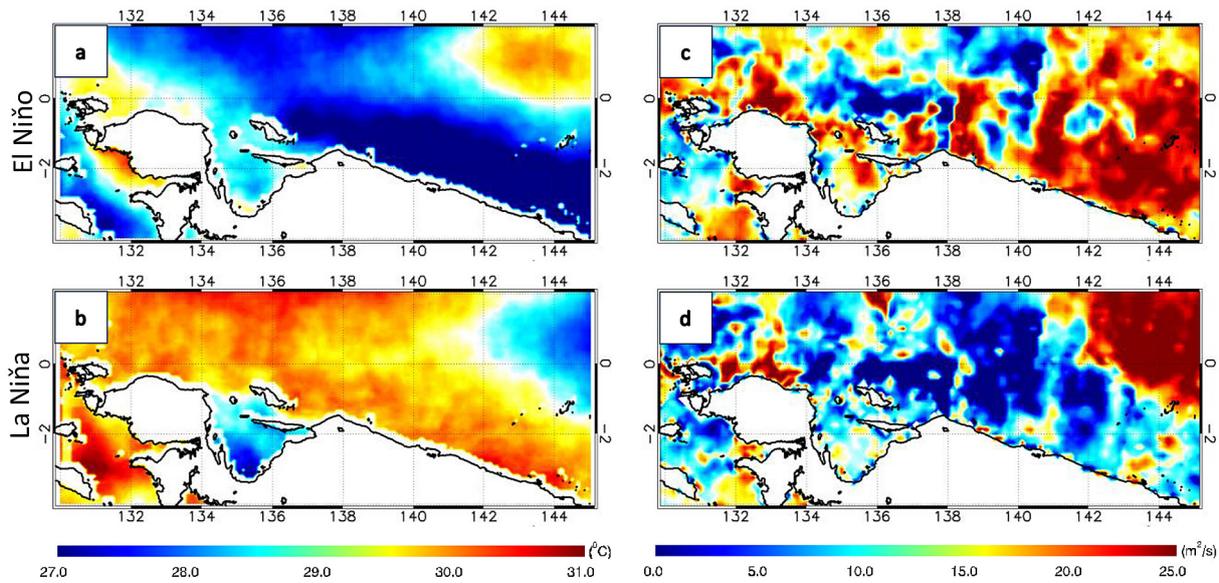


Figure 6. Anomalies during El Niño 2015–2016 (upper) and La Niña 2010–2011 (lower) for (a, b) SST, (c, d) offshore EMT in DJF

intensity, impacting the decrease in SST in the seas along the Northern Coast of Papua. Hasegawa et al. (2009) further note that the SST decline is linked to the intensified northwestern winds during the peak of the El Niño period, expanding areas with low SST to the northeast, signifying upwelling strengthening.

Conversely, during the La Niña period (2010–2011), the seas along the Northern Coast of Papua exhibited anomalies opposite to those of the El Niño event. Coastal waters generally experience a significant decrease in offshore EMT intensity, indicating a weakening of upwelling during La Niña. This reduction in offshore EMT is attributed to La Niña inducing a weakening of WWB (Nurafifah et al., 2022), leading to a decline in upwelling intensity in the waters. In contrast to offshore EMT, SST values in the seas along the Northern Coast of Papua increased during the La Niña period. This rise in SST is linked to accelerated trade wind speeds during La Niña, caused by differences in sea level altimetry on the east and central coasts. The result is a gathering of warm water to the west (Boening et al., 2012). During the La Niña period, an SST increase is observed on the coast to the northeast, signifying a weakening of upwelling intensity during La Niña.

Upwelling intensity during the ENSO period

ENSO induces variations in upwelling intensity compared to neutral conditions, primarily driven by anomalies in the offshore EMT during

both El Niño and La Niña events. The assessment of upwelling intensity in the seas along the Northern Coast of Papua employs the Upwelling Index based on offshore EMT (UIEMT) as the primary index, supplemented by the Upwelling Index based on SST (UISST). The Upwelling Index based on SST (UISST) is not employed as the primary reference for upwelling intensity due to the complex SST variability in the waters along the Northern Coast of Papua, which reside in IPWP. The intricate SST variations, influenced by IPWP movements, render temperature differences between coastal and open waters unsuitable as a basis for determining upwelling (Kok et al., 2017). Tables 1 and 2 present upwelling intensity anomaly statistics for the El Niño 2015–2016 and La Niña 2010–2011 periods, respectively. The chosen months for analysis correspond to the strongest Oceanic Niño Index (ONI) for El Niño (December 2015) and La Niña (December 2010).

The El Niño period is characterized by an increased upwelling intensity, evident in the rise of offshore EMT and a simultaneous decrease in SST across all plots. Conversely, during La Niña, upwelling intensity weakens, marked by a reduction in offshore EMT and a rise in SST across all plots. Tables 1 and 2 highlight that Plot 1 exhibits a larger offshore EMT anomaly than the other plots. This discrepancy is attributed to the proximity of Plot 1 to the equator, resulting in higher offshore EMT and a more substantial anomaly. Additionally, Plot 1 records the lowest SST anomaly compared to other plots due to

Table 1. Upwelling intensity for the El Niño period in December 2015

Parameter	Offshore EMT (m ² /s)			SST (°C)		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
El Niño	13.15	8.82	5.45	29.05	28.86	28.72
Climatology	9.15	6.76	3.63	29.61	29.62	29.38
Anomaly	4.00	2.05	1.82	-0.56	-0.76	-0.65

Table 2. Upwelling intensity for the La Niña period December 2010

Parameter	Offshore EMT (m ² /s)			SST (°C)		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
La Niña	2.59	0.95	-1.32	29.84	29.88	29.70
Climatology	9.15	6.76	3.63	29.61	29.62	29.38
Anomaly	-6.56	-5.81	-4.95	0.23	0.25	0.32

its direct connection to IPWP. Consequently, the temperature in Plot 1 tends to remain constant with lower anomalies. These findings align with Wyrтки’s assertion (1961) that the oceanographic conditions in the seas along the Northern Coast of Papua are predominantly influenced by IPWP, especially in the areas close to the equator.

The correlation between offshore EMT and SST exhibits a strong negative value during the west monsoon (DJF) and transition 1 (MAM), ranging from -0.433 to -0.779. In contrast, the correlation between offshore EMT and SST shows a weak positive value during the east monsoon (JJA) and transition 2 (SON), with a range of 0.079 to 0.389. This observation suggests that offshore EMT effectively triggers upwelling only during the west monsoon. Furthermore, the correlation values across the three plots differ. In the west monsoon, the correlation values for Plots 1 to 3 are -0.433, -0.510, and -0.687, respectively. These values lead to the conclusion that offshore EMT

predominantly influences upwelling in Plot 3, situated at the edge of IPWP. In contrast, offshore EMT does not exert a major influence on upwelling in Plots 1 and 2, both located within the IPWP. This is attributed to the strong influence of the warm pool on SST in these plots, resulting in a low correlation between offshore EMT and SST (Alexander and Scott, 2007).

Regression analysis was conducted between offshore EMTs and SSTs to establish a causal relationship between the two datasets (Kustitunto and Badrudin, 1994). The results of the scatter plot regression analysis are presented in Figure 7. The regression lines indicate negative regression for all three plots, signifying that higher offshore EMT values correspond to lower SST values. Consequently, regression analysis is deemed suitable for upwelling analysis in all three plots. For Plot 1, the regression yields a coefficient of determination of 0.187 with the equation $y = -0.0296x + 29.615$, while Plot 2 has a

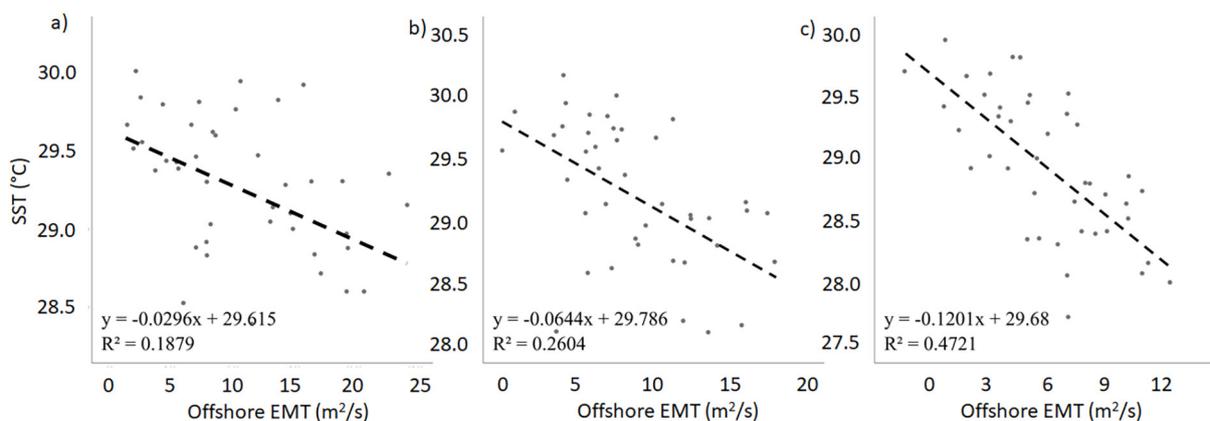


Figure 7. Scatter plot of offshore EMT against SST during DJF 2007–2020 for Plot 1 (a), Plot 2 (b), and Plot 3 (c)

coefficient of determination of 0.260 with the equation $y = -0.0644x + 29.786$. Plot 3 exhibits the highest coefficient of determination at 0.472, with the equation $y = -0.1201x + 29.68$. This implies that offshore EMT has the strongest effect on SST in Plot 3, aligning with the correlation analysis that also indicates the highest correlation between offshore EMT and SST in Plot 3. Therefore, the impact of offshore EMT on SST in Plot 3 is substantiated.

CONCLUSIONS

The study revealed notable variations in upwelling intensity in the seas along the Northern Coast of Papua during the El Niño period (2015–2016) and the La Niña period (2010–2011). In the El Niño phase, the upwelling intensity increased by 4.00 m²/s, 2.05 m²/s, and 1.82 m²/s across the respective plots. Conversely, during the La Niña period, upwelling intensity exhibited a decrease of -6.56 m²/s, -5.81 m²/s, and -4.95 m²/s in each plot. A consistent trend emerged concerning SST during these contrasting ENSO phases. SST decreased across all plots during the El Niño period, while a converse pattern was observed during La Niña, with SST registering an increase in all plots. The correlation analysis between EMT and SST demonstrated values of -0.433, -0.510, and -0.687 for each plot, indicative of a negative relationship between offshore EMT and SST. Further, the determination coefficient values were 0.187, 0.260, and 0.472 for each respective plot. These analyses collectively underscore the influence of EMT on upwelling, particularly in the southeastern part of the waters. Meanwhile, the northwestern region continues to be predominantly influenced by IPWP. In conclusion, this study enhances the understanding of the complex dynamics of upwelling in the seas along the Northern Coast of Papua, shedding light on the distinct impacts of El Niño and La Niña events on the upwelling intensity and SST patterns in different regions of the study area.

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