The effect of Ekman mass transport and Ekman pumping velocity on the variability of sea surface temperature in the Arafura Sea

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Abstract. Arafura sea is located between the southern part of Papua Island and Aru Island. Previous studies on Sea Surface Temperature (SST) have described that the SST is strongly affected by the upwelling, but the effect of Ekman Mass Transport (EMT) and Ekman Pumping Velocity (EPV) has not yet been studied. In other areas, it has been shown that EMT and EPV generated by the winds could affect the SST. Thus, further research is needed to better understand the role of the winds on the variability of SST through the mechanism of EMT and EPV in the Arafura Sea. This study used SST data from a high-resolution satellite image (GHRSST) and wind data from a scatterometer satellite image (MetOp A ASCAT). The data were processed using the composite and time-series correlation. This study shows that the higher the wind speed, causes the colder the SST in the Arafura Sea. In contrast, when the wind speed is lower, the SST tends to be warmer. The variabilities of the SST are mostly related to the mixing process associated with the magnitude of EMT. In the shallow water where the calculated Ekman depth is deeper than the actual depth, EMT is more influencing than EPV. On the deeper water at the northeast of the Island of Aru, the negative EPV induces upwelling, bringing the colder water to the sea surface. Statistically, the correlation between EMT (EPV) and the SST in the shallow water of the Arafura Sea is considered strong (weak). On the other hand, at the deep water of the Arafura Sea (northeast of the Island of Aru) offers a strong correlation between the EPV and the SST, whereas the EMT and the SST correlation is considered weak.

1. Introduction
The Arafura Sea is located between Torres Strait and Banda Sea. The primary productivity in the Arafura Sea is high, resulting the abundant fisheries resources. Previous study has shown that mackerel fish are widely available in Arafura Sea and offers high market value, and it is also shown that mackerel catch is strongly affected by both the chlorophyll-a and the SST [1]. However, there is no research about the effect of the wind on the variability of SST in the Arafura Sea. Therefore it is important to understand the effect of wind on the variability of SST which will be helpful for the management of abundant fisheries resources in the Arafura Sea.

Ekman Transport is the mass of water passing through a vertical plane one meter wide that is perpendicular to the transport and extending from the surface to depth, while the Ekman Pumping is the
vertical velocity generated by the curl of the wind stress [2]. Ekman Transport and Ekman Pumping velocity can generate mixing process that cools the sea surface temperature [3]. Previous studies on Sea Surface Temperature (SST) have described that the SST is strongly affected by the upwelling, but the effect of Ekman Mass Transport (EMT) and Ekman Pumping Velocity (EPV) has not yet been studied [4]. In other areas, it has been shown that EMT and EPV generated by the winds could affect the SST [5]. In the present study we investigate the mechanism and the effect of EMT and EPV to the variability of the SST in the Arafura Sea.

2. Materials and Methods

2.1. Data

The Level 3 ASCAT (MetOp) with 12.5 x 12.5 km resolution from 2011-2019 is used for the surface wind analysis. This product is measured by scatterometer sensor, which measured the backscatter of a wave to estimate the speed and direction of the wind at 10 m above the sea level. This product also has been tested and validated with 0.2 m/s bias [6]. The Level 4 GHRSSST with 1 x 1 km resolution from 2011-2019 is used for SST analysis. The SST is measured by microwave sensors and has been validated with 0.03 K bias [7]. The bathymetry data is obtained from ETOPO-1, one arc-minute global relief model of Earth’s surface.

2.2. Methods

The surface wind and SST data are sorted into monthly means and then monthly climatology using the equation below [8]:

\[ X(x, y) = \frac{1}{n} \sum_{i=1}^{n} x_i(x, y, t) \]  

(1)

Where: \( X(x, y) \) is monthly or monthly climatology means, \( x_i(x, y, t) \) is the \( i \)-th value of the data at \((x,y)\) position and time \( t \), and \( n \) is the number of data in the total period. If the \( x_i \) is NaN, then the data is not put into the equation.

Wind stress is used to calculate the EMT. The equation used for the wind stress is as follows [9]:

\[ \tau = \rho_a C_D |U_{10}| U_{10} \]  

(2)

Where \( \rho_a \) is the density of air, \( C_D \) is the coefficient of drag, and \( U_{10} \) is the wind speed at 10 m above sea level. The EMT is calculated using the following equation [9]:

\[ EMT = \frac{\tau}{\rho_w f} \]  

(3)

Where \( \tau \) is the wind stress, \( \rho_w \) is the water density, \( f \) is the Coriolis factor.

Ekman Pumping Velocity is calculated using curl from daily wind stress. EPV is calculated using the calculation below [10]:

\[ EPV = \frac{1}{\rho_w f} \nabla \times \tau \]  

(4)

3. Results and Discussion

The distribution of SST in December, January, and February tends to have a high temperature pattern, reaching maximum temperature during December. The temperature cools down during May and significantly lower during the East Monsoon, with the lowest temperature during August reaching 25°C. The warmest phase of the SST in the Arafura Sea occurred during December, with peak temperature reaching 30°C (Figure 1). During the west monsoon, the wind moves from the Seram Sea to Australia with the highest speed of around 4 m/s occurred in January and February. The wind speed increases during those two months. During March, the speed has minor difference compared to January and
February. During April, the wind direction has changed into northwestward wind with speed ranges from 1 to 3.5 m/s. During May, the wind speed increased to 8 m/s, with the wind direction similar to April. Wind speed continues to increase until July. The wind pattern during East Monsoon is northwest bound. During the East Monsoon, the wind speed increases compared to the previous month, with a peak of 9 m/s. During September, October, and November the wind speed decreased. The wind direction during September to November is similar to the East Monsoon. During December, the wind speed reaches the lowest, and the wind direction begins to change.

Figure 1. Wind and SST Overlay during 2011-2019.
In the study area, we choose 3 locations to represent each depth. A is shallow water, B is coastal water shallower than A, and C is deep water. Correlation between SST and wind in areas A, B, and C are shown in figure 3 (a), (b), and (c), respectively. The correlation between SST and wind shows a strong negative correlation at area A ($r = -0.76$), moderate negative at area B ($r = -0.59$), and moderate negative at area C ($r = -0.61$). According to the correlation result, it is known that SST has an inverse correlation with the wind. Higher wind speed causes lower SST.

**Figure 2.** The study area of A, B, and C.

**Figure 3.** (a) Correlation of SST and wind on area A, (b) Correlation of SST and wind on area B, (c) Correlation of SST and wind on area C.
The EMT during the west monsoon (December-February) is northeast bound, with the average transport magnitude reaches 4 m$^2$/s during January and February, an increase compared to 3 m$^2$/s during December. During March, the magnitude of transport and the direction is similar to January and February. During April, the direction has changed to Southwest bound with transport mass decreasing to 1 – 2 m$^2$/s. During May, the mass transport increased again, reaching 4 m$^2$/s with no change in direction. The magnitude of transport during East Monsoon shows a significant increase, reaching 10 m$^2$/s at East and West of the Aru Island. The magnitude of transport decreases during September-November, reaching 4 m$^2$/s in September and October, with a significant reduction to 2 m$^2$/s observed in November. During December, the mass transport reached its lowest point (1 m$^2$/s) (Figure 5).

![Figure 4](a) Correlation of SST, EMT and EPV on area A, (b) Correlation of SST, EMT and EPV on area B, (c) Correlation of SST, EMT and EPV on area C.
Figure 5. Climatology Composite of EMT during 2011-2019
Figure 6. The variability of EPV at Arafura Sea 2011-2019.

The distribution of EPV during the West Monsoon reaches $1.5 \times 10^{-5} \, \text{m/s}$ during January, with the direction of the vertical velocity downward. The EPV shows similar intensity and velocity to the previous month during March. The changes in EPV direction (upward direction) occurred in April, but
with weak intensity \((-0.5 \times 10^{-5} \text{ m/s})\). In May, the intensity of the EPV increases as the upward velocity reaching its peak at \(-1.5 \times 10^{-5} \text{ m/s}\). During the East Monsoon (June), the intensity of the EPV gets stronger and spreads throughout the Arafura Sea, while during July and August, the spatial distribution of the negative EPV is getting smaller. The velocity remains similar, and at the coast of Papua and west of the Aru Island, there are notable positive EPV. The intensity of the EPV declines during September-November and reaching its minimum during December (Figure 6).

Correlation between SST, EPV, and EMT in areas A, B, and C are shown in Figure 4 (a), (b), and (c), respectively. The correlation between EMT and SST is moderately negative in areas A, B, and C with the correlation values of -0.69, -0.48, and -0.42, respectively. The correlation between EPV and SST is weakly positive in area A \((r = 0.18)\), weakly negative in area B \((r = -0.15)\), and strongly positive in area C \((r = 0.76)\). Based on the correlation analysis, the intensity of the EMT at A and B leads to the variability of the SST, while in area C the variability of the SST is affected by the upward velocity of the EPV.

The distribution of SST in the Arafura Sea during the West Monsoon tends to be warmer throughout the Arafura Sea with low wind velocity, especially on the southern part of the Arafura Sea (Figure 1). The low SST value in the Arafura Sea is proportional to increasing wind speed (Figure 1). According to a previous study conducted in 2018, the variability of SST is affected by wind speed [3]. Higher wind speed will lead to stronger mixing. Hence the water mass from lower depth will move upward to the surface, causing the surface temperature to decrease [3]. Other studies showed that SST in the Arafura Sea is affected by the wind [4].

The results shown during March-May showed that the variability of the SST is increased slightly during April and decreasing during May, as shown in Figure 1. As previously explained that wind affects the SST during West Monsoon. During March-May, it is also clearly shown that weakening wind speed leads to the increasing SST and strengthening wind speed generates a stronger mixing mechanism that decreases SST. Previous studies showed that SST in the Arafura Sea reaches all-time low SST during the East Monsoon [4].

During September-November, it is shown that the wind velocity decreased, leading to the increased SST in the Arafura Sea and the decreased intensity of the mixing process (weaker wind leads to reduced water mass movement compared to the stronger wind). The mixing process was caused by the wind, which in turn generates the mixing process through EMT and EPV.

![Figure 7. Bathymetry of the Arafura Sea.](image-url)
that EPV has no or weak effect on the SST variability in the Arafura Sea. The situation is caused by the bathymetric condition of the Arafura Sea, as seen in Figure 7. The image showed that the water depth in the Arafura Sea is relatively shallow, i.e. the depth of area B is 10 – 20 m and the maximum depth at area A is 40 m. Only the C area has a deeper bathymetry reaching 80 m.

At area A, the correlation between EMT and SST is clearly shown during East Monsoon until December (June-December), while the correlation is quite weak during March-May. The peak period of EMT is proportional to the peak period of the wind, showing that the mixing process occurred was the direct result of the wind through EMT and it was the factor behind the variability of SST at area A. Higher wind speed will lead to more water mass displacement causing more intense mixing. The correlation between EPV and SST at area A is low. This is caused by the bathymetry of area A, which is shallow, therefore the water mass movement generated by the EPV alone is not enough to decrease the SST.

Area B showed the correlation between SST and EMT even weaker compared to area A. Figure 4 showed the EMT and SST are inversely correlated during June-February. A notable difference between areas A and B is the peak of the EMT, where the peak at area B is lower than area A by 1 m²/s. Another difference is that the maximum temperature is higher at area B (29.7°C) than area A (29.3°C), with a similar minimum temperature. This fact indicated that the mass transport needed to lower the SST value at Area B is lower than Area A. The correlation between EPV and SST at area B is weak, indicating the EPV has no effect on SST variability at area B. Therefore, the wind causes the variability of SST at area B through the mixing mechanism generated by the EMT.

Area C reveals the correlation between EMT and SST to be the weakest among other areas indicating that the variability of SST is less affected by the EMT. According to Figure 4c, area C is more affected by the EPV than EMT with a strong positive correlation value, showing a very distinguishable pattern compared to area A, which is strongly affected by EMT but less affected by EPV. This was caused by the bathymetry difference of both locations, as shown in Figure 7. The displacement of water mass to the surface through curl from EPV at area C will be more massive because the value of curl is bigger, therefore the SST will respond to the negative EPV occurring at area C. Negative EPV cause the water mass to surface via Ekman suction. Ekman Suction is the phenomenon that decreases the SST at area C, affecting more compared to the EMT. Previous studies at different locations also showed that EPV could displace cold-water mass from below to surface and cool the SST [5]. The peak of the negative EPV occurred during June (east monsoon), where the velocity of the EPV reached -0.21 m/s upward. When the velocity of the EPV is negative, the direction of the velocity is upward, and the SST will decrease, as shown in East Monsoon. Meanwhile, when the velocity is positive, the direction of the velocity is downward and the SST will increase, as seen in March, followed by the increasing SST in April.

4. Conclusion
The present study shows that EMT and EPV generated by the winds are responsible for the SST variability in the Arafura Sea. The mechanism of EMT that leads to the variability of the SST in the Arafura Sea is through mixing and the displacement of the water mass. Meanwhile, the EPV affected the SST through the upwelling process caused by the curl that generates the upward velocity. The magnitude of EMT in the Arafura Sea reaches 10 m²/s, while the velocity of the EPV ranges from -0.21 to 0.15 m/s. EMT is inversely correlated with the SST, therefore stronger EMT leads to lower SST. The EPV has no effect on the SST variability at the shallow water of the Arafura Sea, except at the northern part of the Arafura Sea, where upward velocity (negative EPV) leads to a low SST value.

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