ILMU KELAUTAN: Indonesian Journal of Marine Sciences *June 2024 Vol 29(2):261-272* *e-ISSN 2406-7598*

The trend of Halmahera Eddy and Mindanao Eddy

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Abstract

Global warming, due to increasing greenhouse gases, has increased the frequency of El Niño Southern Oscillation events and influenced ocean dynamics. This research determined the trends of Mindanao Eddy's and Halmahera Eddy's over 28 years (1993–2020). The data used in this research consist of sea surface currents, surface wind, sea surface height, and NIŇO3.4 index. Determination of eddy currents was done using the Automated Eddies Detection method. The results showed that the Asian-Australian monsoon and El Niño Southern Oscillation events influence the characteristics of the Mindanao Eddy and Halmahera Eddy. During the Asian monsoon, the position of the Mindanao Eddy and Halmahera Eddy shifts southward, while during the Australian monsoon, it shifts northward. During El Niño, the position of the Mindanao Eddy turns eastward with a smaller diameter, but the position of the Halmahera Eddy does not shift. Conversely, during La Niña, the position of the Halmahera Eddy turns northwestward with a smaller diameter, while the position of the Mindanao Eddy remains unchanged. The shift of the Mindanao Eddy during the El Niño event is closely related to the weakening of the North Equatorial Current and the strengthening of the North Equatorial Countercurrent. On the other hand, the shift of the Halmahera Eddy during the La Niña event is related to the strengthening of the South Equatorial Current as a source of water masses for the New Guinea Coastal Current. The velocity of the Mindanao Eddy and Halmahera Eddy experienced an increasing trend in 1993-2020.

Keywords: *Mindanao Eddy, Halmahera Eddy, trend, El Niño, La Niña*

Introduction

The western tropical Pacific Ocean has received a lot of attention because it plays an important role in the Earth's climate system, modulating ENSO, and thermohaline circulation through the Indonesian Throughflow (Lukas *et al.*, 1991; Gordon, 1995; Kashino *et al.*, 1998). The dynamics of the western tropical Pacific Ocean between Mindanao and New Guinea are influenced by the Northern Equatorial Current flowing westward, the Mindanao Current flowing southward, the North Equatorial Countercurrent flowing eastward, and the New Guinea Coastal Current flowing along the northern coast of New Guinea. Interactions between the North Equatorial Current, the Mindanao Current, the North Equatorial Countercurrent, and the New Guinea Coastal Current cause the cyclonic Mindanao Eddy and the anticyclonic Halmahera Eddy to be formed (Wrytki, 1961). The Mindanao Eddy and Halmahera Eddy are more significant than most eddies in the ocean (Arruda and Nof, 2003).

Mesoscale eddies have an important role in the distribution of ocean circulation, transport and mixing of heat, salt and biogeochemical tracers on a global scale (Dong *et al.*, 2014; Zhang *et al.*, 2014; Chiang *et al.*, 2015; Faghmous *et al.*, 2015; Ding *et al.*, 2020; Yang *et al.*, 2020). In addition, mesoscale eddies have significant role in regulating the distribution and transport of primary productivity (Chelton *et al.*, 2011; Gruber *et al.*, 2011; Hu *et al.*, 2014; Coria-Monter *et al.*, 2014; Yu *et al.*, 2019; Zhang *et al.*, 2023). The Halmahera Eddy transfers a mixture of water masses from the northern and the southern hemispheres to the eastern route of the Indonesian Throughflow (Kashino *et al.*, 2013). Therefore, the variability of the Halmahera Eddy affects the transport of the Indonesian Throughflow (Kashino *et al.*, 1998). Research on the Mindanao Eddy and Halmahera Eddy has been carried out by other researchers. These studies mostly discuss the center and diameter of eddy currents, shifts in eddy currents, and the relationship between eddy currents and chlorophyll-a, sea surface temperature, and salinity (Harsono *et al.*, 2014; Simanungkalit *et al.*, 2018; Suharyo *et al.*, 2020; Wang *et al.*, 2021).

The dynamics of the western tropical Pacific Ocean are influenced by the El Niño Southern Oscillation phenomenon (Bolliet *et al.*, 2011). The frequency of the El Niño Southern Oscillation events

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https://ejournal.undip.ac.id/index.php/ijms
DOI: 10.14710/ik.ijms.29.2.261-272

Received : 29-02-2024
Accepted : 11-04-2024

has increased due to the impact of global warming (Cai *et al*., 2014; Marjani *et al*., 2019; Li *et al*., 2021). In addition, global warming also causes an increase in the acceleration of ocean surface currents (Toggweiler and Russell, 2008; Hu *et al*., 2020; Peng *et al*., 2022). Based on this, it is indicated that the characteristics of the Mindanao Eddy and Halmahera Eddy also experience changes. The research aims to determine the interannual trends of the Mindanao Eddy and Halmahera Eddy.

Materials and Methods

The research utilized data from 1993 to 2020, which included real-time daily ocean surface current analysis, weekly sea surface height, and monthly surface winds, along with the NIŇO3.4 index. The ocean surface current analysis data was obtained from http://apdrc.soest.hawaii.edu/data/data.php?discipline_index=2 and has a spatial resolution of 0.25º x 0.25º. The source of this data is The Physical Oceanography Distributed Active Archive Center, NASA's Jet Propulsion Laboratory. The sea surface height data was obtained from https://www.aviso.altimetry.fr/en/home.html and has a spatial resolution of 0.25° x 0.25°. The surface wind data was obtained from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form and has a spatial resolution of 0.25° x 0.25°. The NIŇO3.4 index data was obtained from https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/.

The daily and weekly data were processed into seasonal and climatology categories, with seasonal variations split into DJF (December-February), MAM (March-May), JJA (June-August), and SON (September-November). The zonal and meridional components of the surface currents and surface winds were processed into vectors to obtain the direction and velocity of surface currents and surface winds. Eddy currents were determined using Automated Eddies Detection (Nencioli *et al*., 2010). Eddies are identified based on sea surface height contours and rotation of surface currents that are separate from the primary currents. The eddy center must have a minimum local velocity.

This study analyzed seasonal variations, the impacts of ENSO, and the shifting trends of the Mindanao Eddy and Halmahera Eddy. ENSO and IOD events were identified based on monthly values of the NIŇO3.4 index from 1993-2020, as shown in Figure 1. An analysis of the impact of ENSO on the Mindanao Eddy and Halmahera Eddy characteristics was carried out in 1997 and 2015 (El Niño) and 1998 and 2010 (La Niña) based on Figure 1. The trends of the Mindanao Eddy and Halmahera Eddy velocities were analyzed using linear regression.

Result and Discussion

Figure 2 shows seasonal variations of the Mindanao Eddy and Halmahera Eddy. The dynamics of the Mindanao Eddy and Halmahera Eddy change every season. Seasonal changes of the center point of the Mindanao Eddy and Halmahera Eddy are shown in Figure 3. The Mindanao Eddy moves counterclockwise, with a sea level decrease at its center. In the DJF season the Mindanao Eddy center point is located at 7.15^{0} N and 128.5^{0} E and shifts northward at 7.5^{0} N and 128.8^{0} E in the MAM season. The Mindanao Eddy center point shifts northward at 7.65^{0} N and 129^{0} E in the JJA season and shifts back southward at 7.5^{0} N and 128.8^{0} E in the SON season. The velocity and diameter of the Mindanao Eddy in the DJF season are around 11 cm.s^{-1} and 132 km, respectively, and in the MAM season, they are about 19 cm.s^{-1} and 165 km. The velocity and diameter of the Mindanao Eddy increase to about 24 cm.s^{-1} and 242 km in the JJA season and about 21 cm.s^{-1} and 220 km in the SON season.

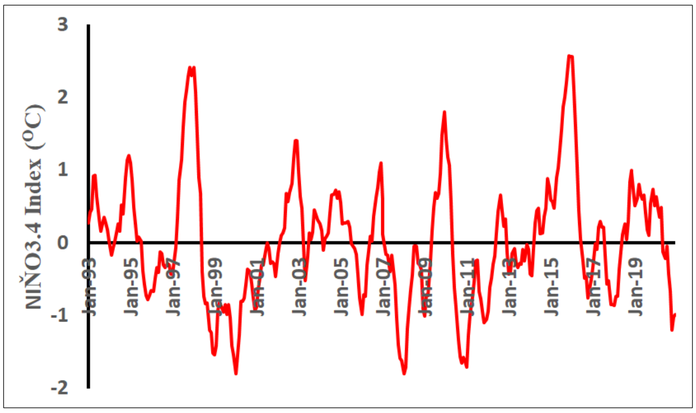

Figure 1. NIŇo3.4 index from 1993-2020

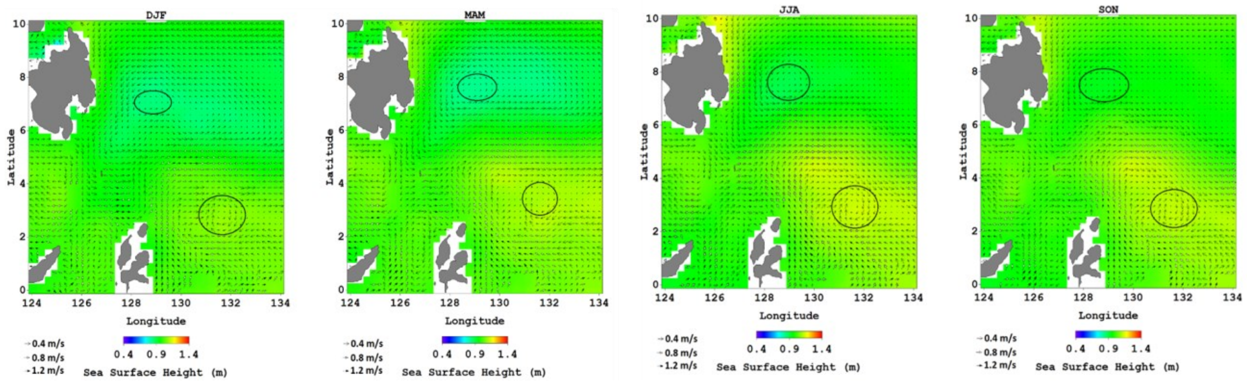

Figure 2. Seasonal variation of the Mindanao Eddy and Halmahera Eddy. Sea surface height (colors) and ocean surface current (arrows)

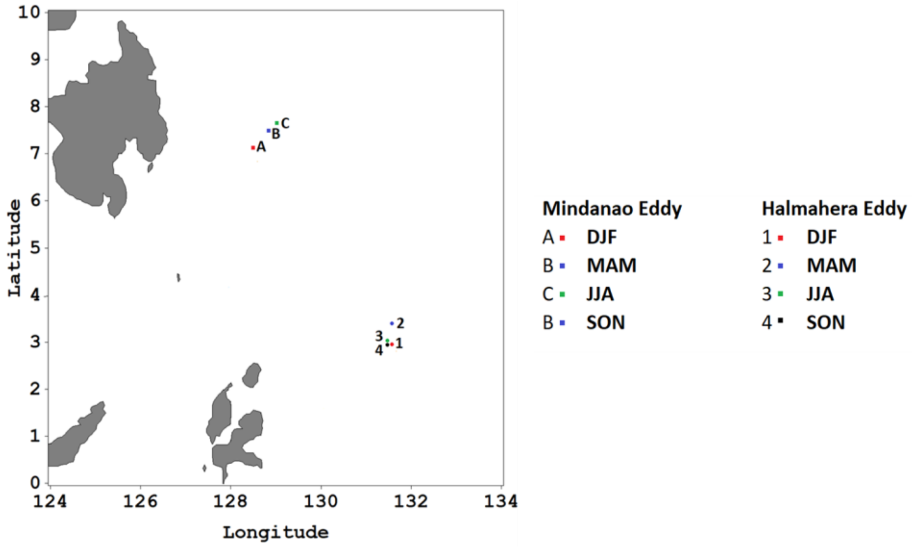

Figure 3. Seasonal center point of the Mindanao Eddy and Halmahera Eddy

On the other hand, the Halmahera Eddy moves clockwise accompanied by an increase of sea level at its center. The Halmahera Eddy center point is located at 2.9^{0} N and 131.65^{0} E in the DJF season and shifts northward at 3.4^{0} N and 131.65^{0} E in the MAM season. In the JJA season, the Halmahera Eddy center point shifts back to the southward at 3^{0} N and 131.5^{0} E and shifts again to the southward at 2.9^{0} N and 131.5^{0} E in the SON season. The velocity and diameter of the Halmahera Eddy in the DJF season are around 27 cm.s^{-1} and 253 km and it is smaller around 21 cm.s^{-1} and 187 km in the MAM season. Then, the velocity and diameter of the Halmahera Eddy are greater around 29 cm.s^{-1} and 275 km during the JJA season and in the SON season around 28 cm.s^{-1} and 220 km.

Figure 4 shows the Mindanao Eddy and Halmahera Eddy patterns in the JJA-SON season during El Niño (1997 and 2015). The characteristics of the Mindanao Eddy and Halmahera Eddy experience significant changes when El Niño occurs. Changes in the center point of the Mindanao Eddy and Halmahera Eddy during El Niño are shown in Figure 5. The Mindanao Eddy position generally shifts eastward with a smaller diameter than an average year. In the JJA season, the Mindanao Eddy center point shifts eastward at 7.5^{0} N and 129.15^{0} E (1997) and 7.5^{0} E and 131.8^{0} E (2015). The Mindanao Eddy center point shifts eastward at 8^{0} E and 133.4^{0} (1997) and 7.9^{0} N and 129^{0} E (2015) in the SON season. In contrast to the Mindanao Eddy, in general, the position and diameter of the Halmahera Eddy do not change during El Niño. Vice versa with the Mindanao Eddy, the velocity of the Halmahera Eddy during El Niño is more significant than normal year conditions. Changes in the velocity and diameter of the Mindanao Eddy and Halmahera Eddy during El Niño are shown in Table 1 and Table 2.

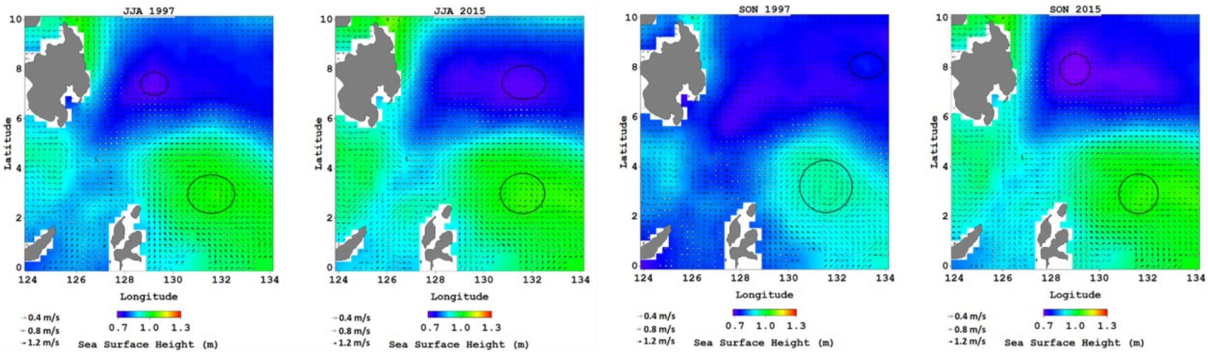

Figure 4. Seasonal variation of the Mindanao Eddy and the Halmahera Eddy during El Niño (left: 1997 and right: 2015). Sea surface height (colors) and ocean surface current (arrows).

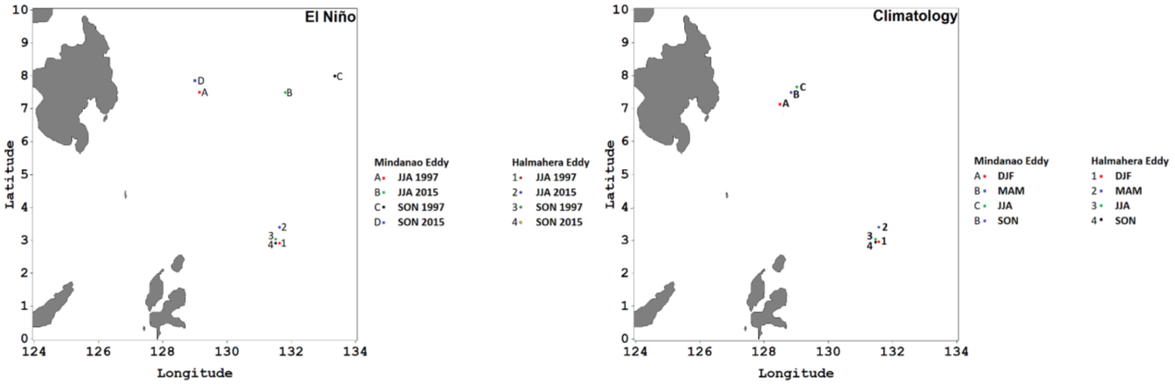

Figure 5. Change of the center point of the Mindanao Eddy and Halmahera Eddy during El Niño (left) and climatology (right)

Table 1. Velocity of the Mindanao Eddy and Halmahera Eddy during El Niño

Season	Mindanao Eddy			Halmahera Eddy		
	Climatology ($m.s^{-1}$)	El Niño 1997 ($m.s^{-1}$)	El Niño 2015 ($m.s^{-1}$)	Climatology ($m.s^{-1}$)	El Niño 1997 ($m.s^{-1}$)	El Niño 2015 ($m.s^{-1}$)
JJA	24	15	8	29	47	43
SON	21	10	14	28	35	34

Table 2. Diameter of the Mindanao Eddy and Halmahera Eddy during El Niño

Season	Mindanao Eddy			Halmahera Eddy		
	Climatology (km)	El Niño 1997 (km)	El Niño 2015 (km)	Climatology (km)	El Niño 1997 (km)	El Niño 2015 (km)
JJA	242	187	220	275	275	275
SON	220	220	220	220	220	220

Figure 6 shows the patterns of the Mindanao Eddy and Halmahera Eddy in the JJA-SON season during La Niña (1998 and 2010). The characteristics of the Mindanao Eddy and Halmahera Eddy change significantly when La Niña occurs. During La Niña 1998 events, the Mindanao Eddy was not formed. Changes in the center point of the Mindanao Eddy and Halmahera Eddy during La Niña are shown in Figure 7. In La Niña 2010, the Mindanao Eddy center points at 8.15^0 N and 128.9^0 E in the JJA season and is located at 7.8^0 N and 129.15^0 E in the SON season. In general, the Halmahera Eddy position shifts northwestward when La Niña occurs with a smaller diameter than the normal year. In the JJA season, the Halmahera Eddy center point shifts northwestward at 5^0 N and 128.3^0 E (1998) and 4.5^0 N and 129.8^0 E (2010). In the SON season, the Halmahera Eddy center point still shifts northwestward at 4.9^0 N and

128.3^0 E (1998), but in 2010 the Halmahera Eddy center point did not shift. Changes in the velocity and diameter of the Mindanao Eddy and Halmahera Eddy during La Niña are shown in Table 3 and Table 4.

Inter-annual variations of the Mindanao Eddy and Halmahera Eddy velocities from 1993-2020 are shown in Figure 8 and Figure 9. In general, inter-annual variations of the Mindanao Eddy and Halmahera Eddy fluctuate. The range of the velocity fluctuation of the Mindanao Eddy is between 8 cm.s^{-1} – 44 cm.s^{-1}, while the Halmahera Eddy velocity ranges between 9 cm.s^{-1} – 48 cm.s^{-1}. The average velocity of the Halmahera Eddy is greater than the Mindanao Eddy. From 1993 to 2020 years, the trend of the inter-annual velocity of the Mindanao Eddy and Halmahera Eddy has increased.

Based on the results, it is known that the seasonal and inter-annual positions of the Mindanao Eddy and Halmahera Eddy experience strong meridional shifts. The meridional shift of the Mindanao Eddy and Halmahera Eddy positions is closely related to the Asian-Australian monsoon pattern (Kashino *et al*., 1998; Harsono *et al*., 2014). Figure 10 shows the seasonal pattern of the surface wind in the western tropical Pacific Ocean. In the DJF season, the surface wind moves to the southwest and south at a velocity of around 3.8 m.s^{-1}. The push of the surface wind causes the Mindanao Eddy and Halmahera Eddy positions to shift southward. The surface wind direction in the MAM season still moves to the southwest and south but the velocity weakens to around 2.3 m.s^{-1}. This weakening causes the surface wind to decrease so that the positions of the Mindanao Eddy and Halmahera Eddy begin to shift northward. In the JJA season, the surface wind movement changes to the north and northeast with a velocity of around 2.9 m.s^{-1}, so that the Mindanao Eddy position increasingly shifts northward. In the SON season, the direction of surface wind movement is still to the north and northeast with surface wind velocity weakening to around 1.4 m.s^{-1}. This weakening of surface wind velocity causes the positions of the Mindanao Eddy and Halmahera Eddy to shift back southward.

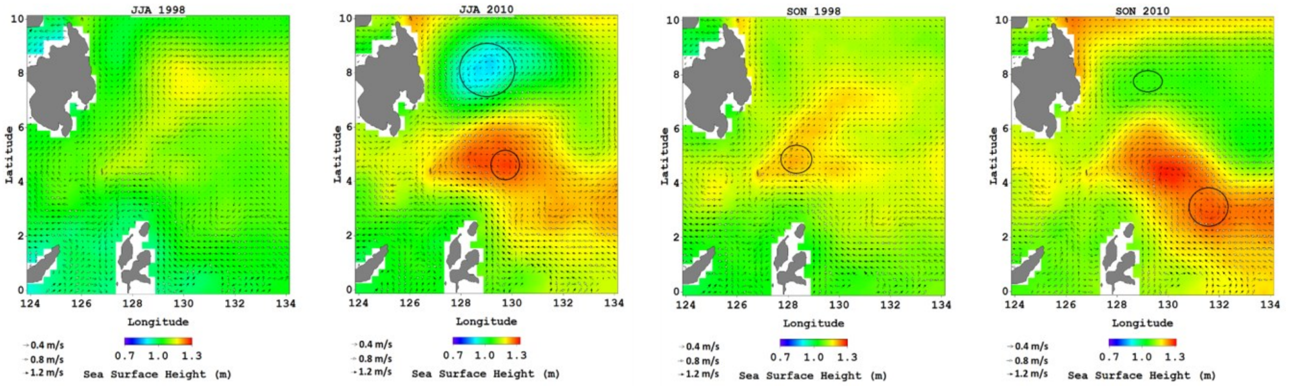

Figure 6. Seasonal variation of the Mindanao Eddy and the Halmahera Eddy during La Niña (left: 1998 and right: 2010). Sea surface height (colors) and ocean surface current (arrows)

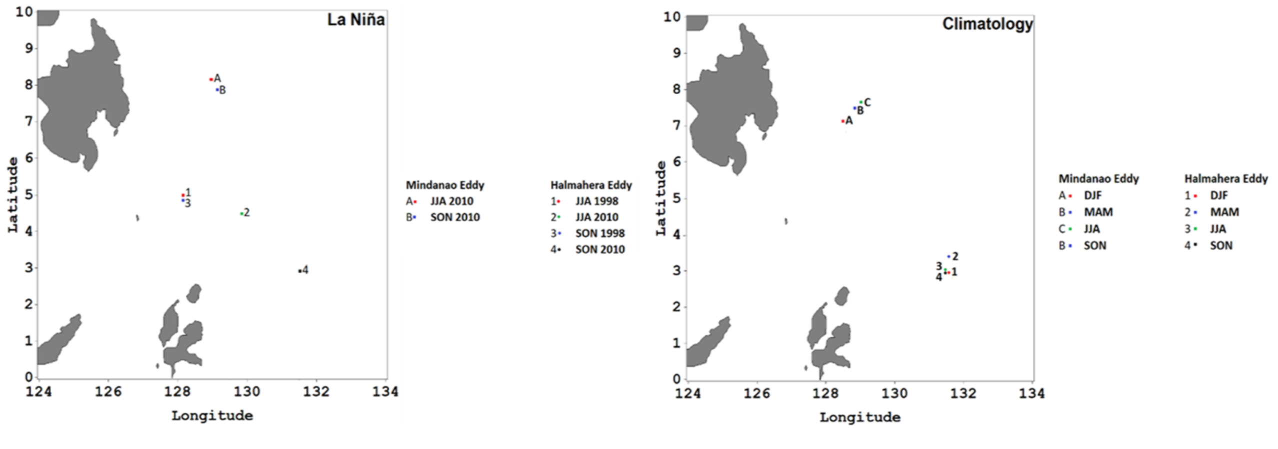

Figure 7. Change of the center point of the Mindanao Eddy and Halmahera Eddy during La Niña (left) and climatology (right)

Table 3. Velocity of the Mindanao Eddy and Halmahera Eddy during La Niña

Season	Mindanao Eddy			Halmahera Eddy		
	Climatology ($m.s^{-1}$)	La Niña 1998 ($m.s^{-1}$)	La Niña 2010 ($m.s^{-1}$)	Climatology ($m.s^{-1}$)	La Niña 1998 ($m.s^{-1}$)	La Niña 2010 ($m.s^{-1}$)
JJA	*24*	*not formed*	*36*	*29*	*Not formed*	*20*
SON	*21*	*not formed*	*16*	*28*	*20*	*33*

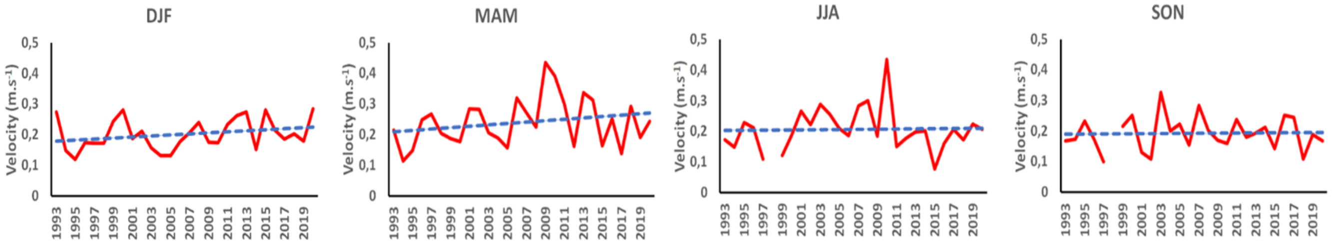

Figure 8. Interannual variation of the Mindanao Eddy velocity

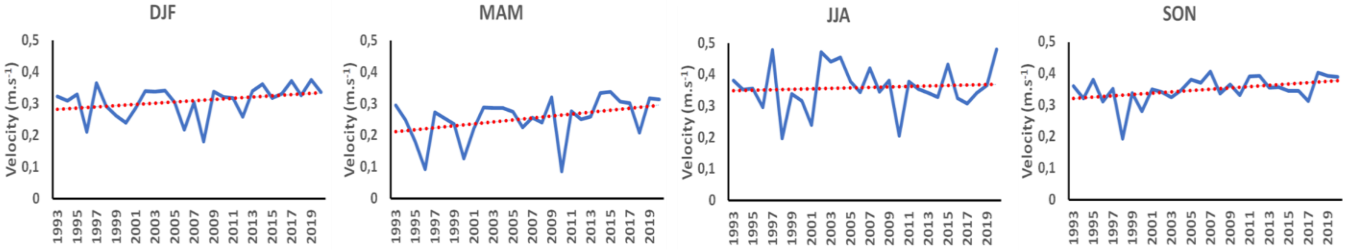

Figure 9. Interannual variation of the Halmahera Eddy velocity

The variability of the Mindanao Eddy and Halmahera Eddy is influenced by the conditions of the surrounding main currents, namely the North Equatorial Current, the Mindanao Current, the North Equatorial Countercurrent, and the New Guinea Coastal Current (Zhang *et al*., 2012; Kashino *et al*., 2013). Figure 11 shows the surface current patterns in the western tropical Pacific Ocean in the JJA-SON season during the El Niño events (1997 and 2015). In the JJA season, the North Equatorial Current intensity weakens as indicated by a decrease in velocity from 24 $cm.s^{-1}$ (climatology) to 17 $cm.s^{-1}$ (1997) and around 19 $cm.s^{-1}$ (2015). Meanwhile, the North Equatorial Current velocity decreases in the SON season from 20 $cm.s^{-1}$ (climatology) to around 18 $cm.s^{-1}$ (1997) and around 17 $cm.s^{-1}$ (2015). Previous studies also stated that the North Equatorial Current intensity weakens during the El Niño (Kashino *et al*., 2009).

In contrast, the coverage and intensity of the North Equatorial Countercurrent becomes wider and stronger during El Niño. In the JJA season, the North Equatorial Countercurrent coverage extends north-south from 583 km (climatology) become around 1078 km (1997) and about 968 km (2015) with the velocity increasing from 25 $cm.s^{-1}$ (climatology) to 44 $cm.s^{-1}$ (1997) and 49 $cm.s^{-1}$ (2015). The North Equatorial Countercurrent coverage in the SON season extends from 440 km (climatology) become about 891 km (1997) and 880 km (2010). Meanwhile, the North Equatorial Countercurrent velocity increased from 28 $cm.s^{-1}$ (climatology) to about 40 $cm.s^{-1}$ (1997) and around 36 $cm.s^{-1}$ (2015). This is consistent with the results of other studies which stated that the North Equatorial Countercurrent intensity increases during the El Niño and weakens during the La Niña (Webb, 2018; Wijaya and Hisaki, 2021). The weakening of the North Equatorial Current accompanied by an increase in the coverage and intensity of the North Equatorial Countercurrent causes the Mindanao Eddy position to shift eastward during El Nino.

In general, the Halmahera Eddy position does not change during El Niño, but the Halmahera Eddy intensity increases. The existence of the Halmahera Eddy is influenced by the New Guinea Coastal Current whose water mass comes from the South Equatorial Current (Lukas *et al*., 1991; Qu *et al*., 1999; Arruda and Nof, 2003; Kashino *et al*., 2013). The South Equatorial Current intensity increases during El Niño. The South Equatorial Current velocity in the JJA season is around 14.5 $cm.s^{-1}$ (climatology) becoming around 15.2 $cm.s^{-1}$ (1997) and 16.2 $cm.s^{-1}$ (2015). In the SON season, the South Equatorial Current velocity is around 11 $cm.s^{-1}$ (climatology) becomes 16.2 $cm.s^{-1}$ (1997) and around 13.7 $cm.s^{-1}$ (2015). An increase in the South Equatorial Current intensity will strengthen the New Guinea Coastal Current intensity. The increase of the North Equatorial Countercurrent and the South Equatorial Current intensity is indicated as the cause of the Halmahera Eddy position not changing and the Halmahera Eddy intensity being greater.

Figure 12 shows the patterns of the surface current in the western tropical Pacific Ocean in the JJA-SON during La Nina (1998 and 2010). When La Niña occurs the coverage of the North Equatorial Current becomes wider from 15^0 N – 5^0 S, whereas the coverage of the North Equatorial Countercurrent is very small. With the wider coverage of the North Equatorial Current, it will affect the existence of the Mindanao Eddy and Halmahera Eddy. In JJA 1998, in eastern Mindanao there was a change in current movement where the coverage of the Mindanao current and the North Equatorial Countercurrent were very small. The reduced coverage of the Mindanao current and the North Equatorial Countercurrent is indicated as the reason why the Mindanao eddy did not form. In the SON 1998 the Mindanao Eddy still had not formed, but the Halmahera Eddy formed with a position shifted northwestward. The Halmahera Eddy shifts northwest is indicated as a result of the push from a stronger North Equatorial Current and a weakening of the North Equatorial Countercurrent intensity. When La Nina 2010, the Mindanao Current and the North Equatorial Countercurrent are formed so that the Mindanao Eddy formed in the same position as a normal year, but the Halmahera Eddy shifts northwestward in the JJA season. In the SON 2010, the Mindanao Current and the North Equatorial Countercurrent formed so that the Mindanao Eddy and the Halmahera Eddy positions were the same as normal year conditions.

Surface wind is the main driving force of the ocean surface current circulation (Wilson *et al*., 2016; Dohan, 2017; Röhrs *et al*., 2023). Therefore, the intensity of the North Equatorial Current and the South Equatorial Current in the tropical Pacific Ocean is influenced by the northeast trade wind north of the equator and the southeast trade wind south of the equator. Figure 13 and Figure 14 show the velocity anomalies of the northeast trade wind and southeast

Table 4. Diameter of the Mindanao Eddy and Halmahera Eddy during La Niña

Season	Mindanao Eddy			Halmahera Eddy		
	Climatology (km)	La Niña 1998 (km)	La Niña 2010 (km)	Climatology (km)	La Niña 1998 (km)	La Niña 2010 (km)
JJA	*242*	*not formed*	*242*	*275*	*not formed*	*110*
SON	*220*	*not formed*	*165*	*220*	*132*	*187*

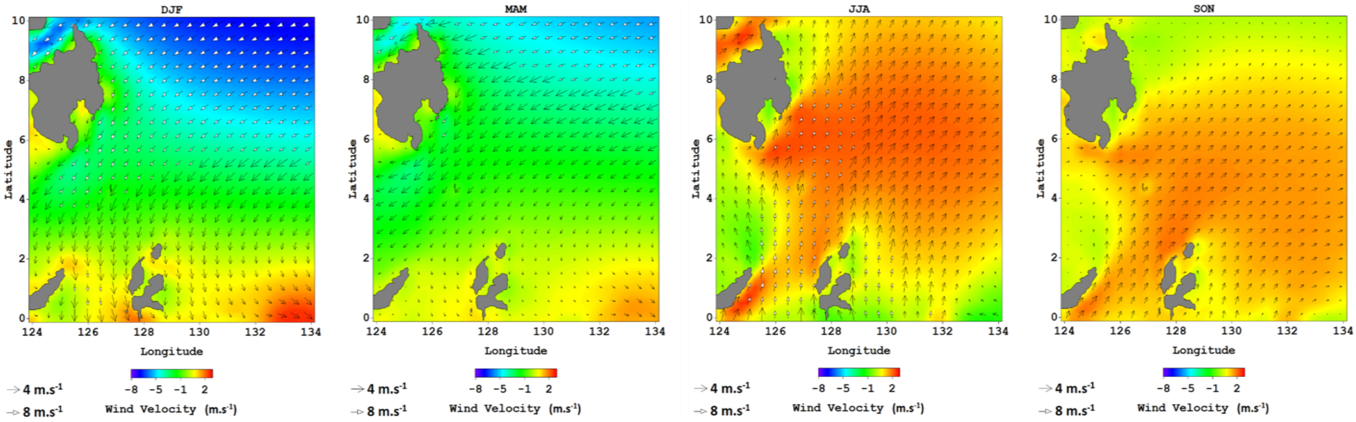

Figure 10. Seasonal variation of the surface wind circulation

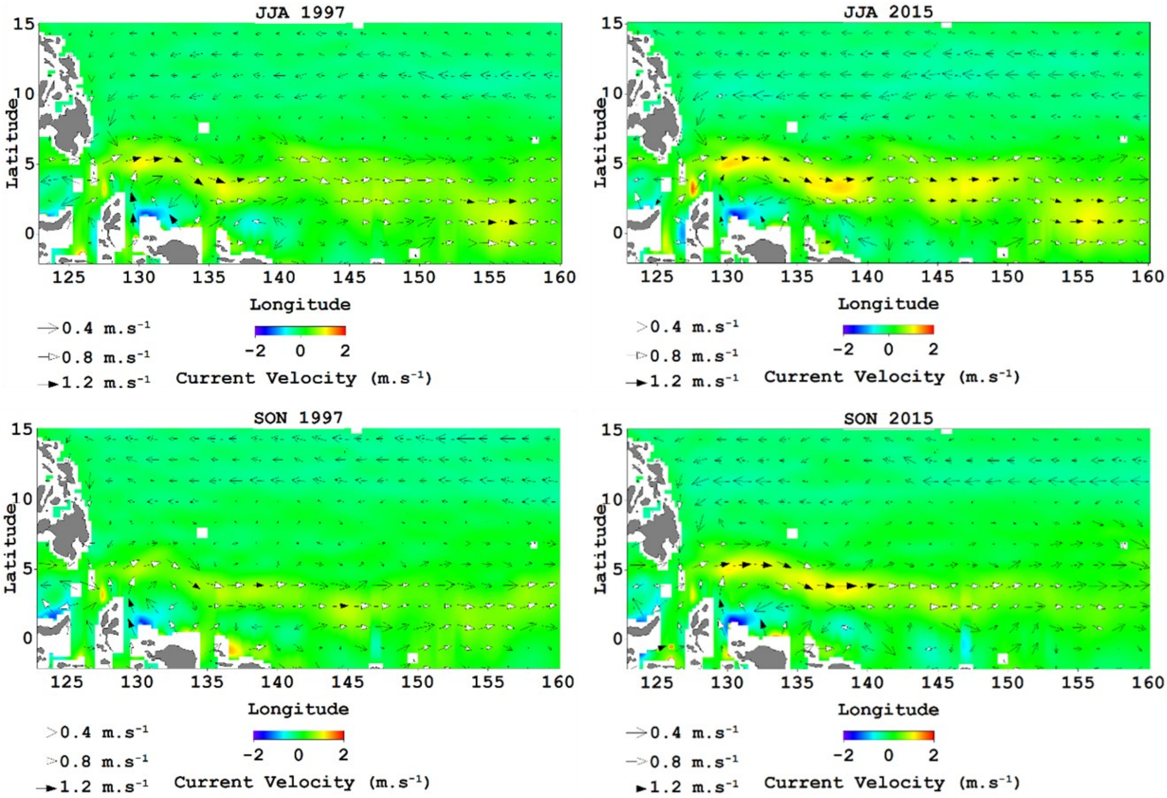

Figure 11. Pattern of ocean surface current during the El Niño

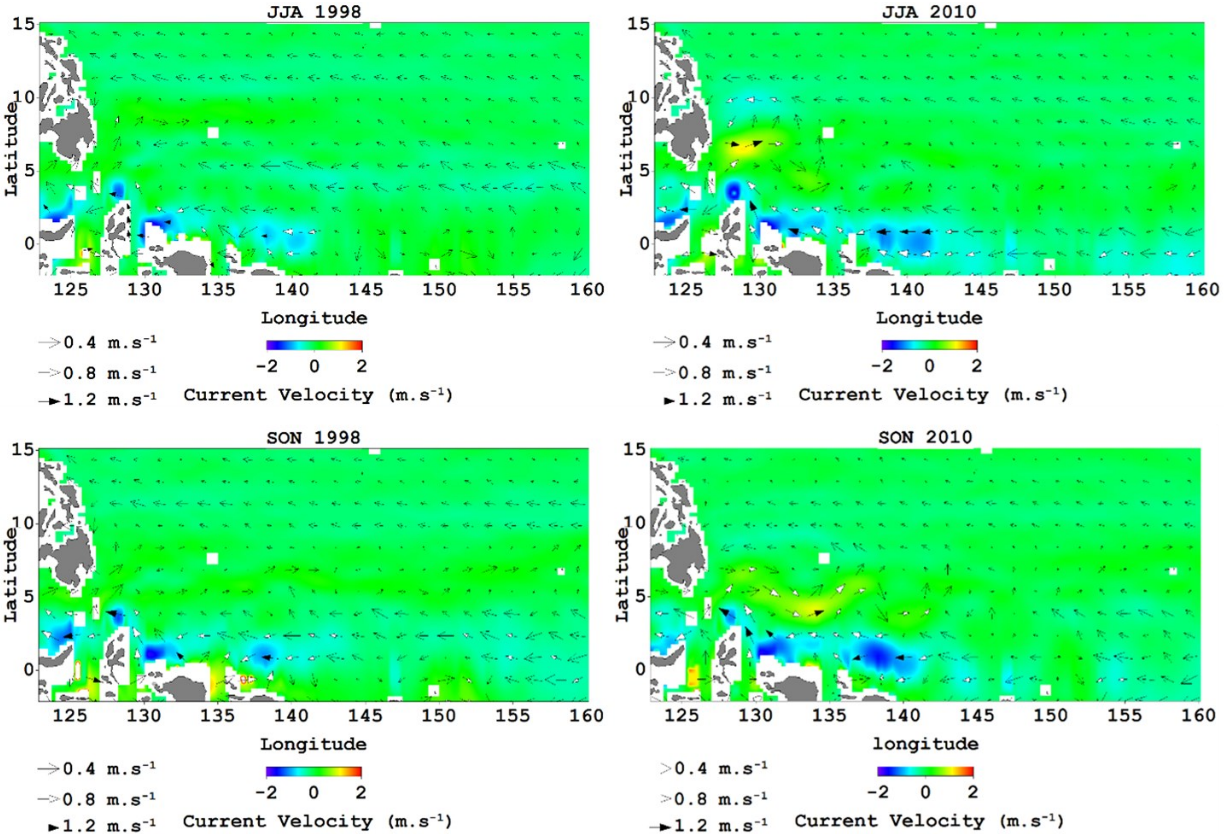

Figure 12. Pattern of ocean surface current during La Niña

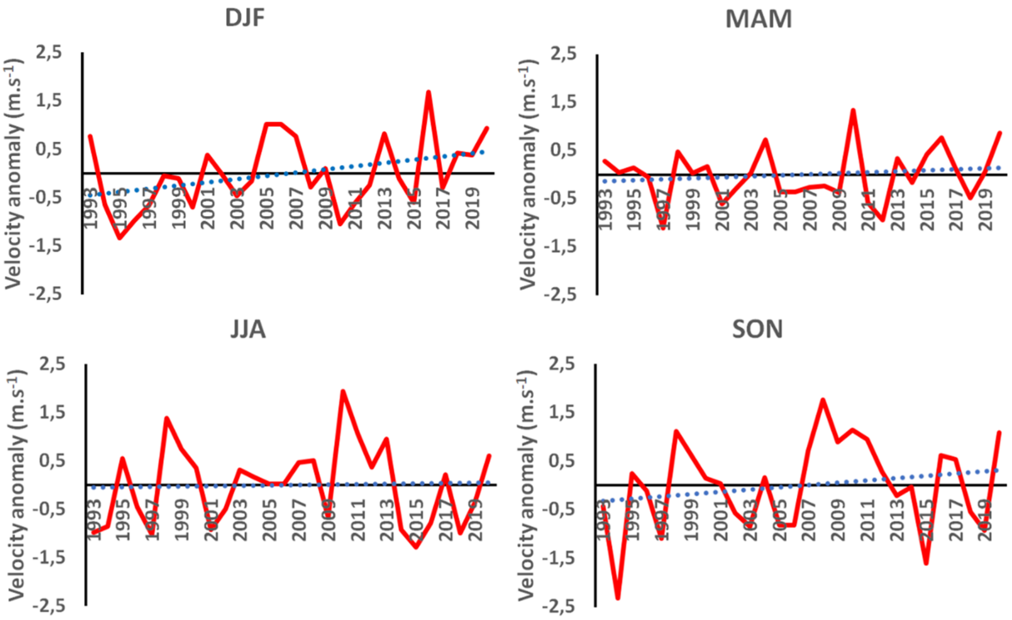

Figure 13. Interannual anomaly of the northeast trade wind velocity

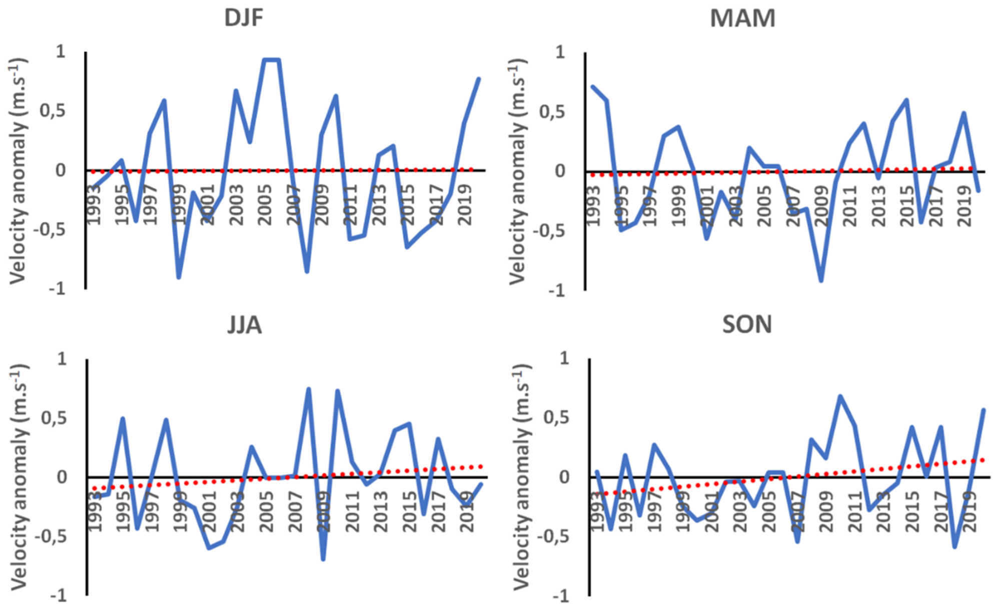

Figure 14. Interannual anomaly of the southeast wind trade velocity

trade wind in the tropical Pacific Ocean (20⁰ N – 20⁰ S). From 1993 to 2020, the inter-annual variations of the trade wind velocity in the tropical Pacific Ocean experienced an increasing trend. An increase in the trade wind velocity will increase the velocity of the North Equatorial Current and the South Equatorial Current. Therefore, an increase in the velocity of the North Equatorial Current and South Equatorial Current is indicated as the cause of the increasing trend of the velocity of the Mindanao Eddy and Halmahera Eddy.

Conclusion

Based on the results that have been carried out, it can be concluded that the positions of the Mindanao Eddy and Halmahera Eddy experience shift every season. The shifting of the Mindanao Eddy and Halmahera Eddy positions is influenced by the Asian-Australian monsoon. When it is cold in the northern hemisphere (Asian monsoon) the position of the Mindanao Eddy and Halmahera Eddy shifts southward, whereas when it is hot in the northern hemisphere (Australian monsoon) the position of the Mindanao Eddy and Halmahera Eddy shifts northward. When El Niño occurs, the Mindanao Eddy position shifts eastward but the Halmahera Eddy position does not change. On the other hand, when La Niña occurs, the Halmahera Eddy position shifts northwest but the Mindanao Eddy position does not change. In La Niña 1998, the Mindanao Eddy did not form when the coverage of the Mindanao Current and the North Equatorial Countercurrent were very small due to the increasing of the North Equatorial Current intensity. The influence of El Niño and La Niña on the Mindanao Eddy and Halmahera Eddy is closely related to the increasing and weakening of the North Equatorial Current as a source of the Mindanao Current water mass and the South Equatorial Current as a source of the New Guinea Coastal Current water mass. From 1993 to 2020 period, the velocity of the Mindanao Eddy and Halmahera Eddy experienced an increasing trend.

Acknowledgement

The authors would like to thank the National Research and Innovation Agency (BRIN), which has provided financial support and material assistance for the authors to complete this research.

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