Horizontal Structure of Banda Eddies and The Relationship to Chlorophyll-a During South East Monsoon in Normal and ENSO Period on 2008-2010

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Abstract. Banda Sea is part of Indonesia Fisheries Management Area (WPP 714) which famous for Tuna fisheries. In addition to being influenced by Indonesian Through Flow (ITF), the Banda Sea also influenced by eddies. Banda eddies and the relationship to chlorophyll-a were studied by using the output of ocean circulation model produced by INDESO (Infrastructure Development of Space Oceanography) project in Ministry of Marine Affair and Fisheries. Data from 2008 to 2011 during normal phase of South East Monsoon period (June-August 2008), El Nino phase (June-August 2009), and La Nina phase (June-August 2010) were used. The model results showed two clockwise eddies in the northern of Banda Sea and three counterclockwise eddies in the southern of Banda Sea. The clockwise eddies were found at 20 meter depth and induced upwelling in south water of Buru Island, Ambon Island and Lease Island (Haruku, Saparua and Nusalaut Islands). Otherwise, counterclockwise eddies in the southern of Banda Sea (north of Wetar Island and Yamdena Island) generate the downwelling. High vorticity value of the eddy was found in the northern of Wetar Island. The presence of Banda Eddies on South East Monsoon period play an important role to maintain the water mass balance in the Banda Sea. Eddies also have strong influence on nutrient sinking from the surface of water. In addition, the eddies vorticity increased during the La Nina period and lead to low surface chlorophyll-a in the surface of the Banda Sea.

Keywords: Banda Eddie, ENSO, chlorophyll-a, upwelling, downwelling, INDESO.

1. Introduction

The Banda Sea is located in Eastern Indonesia Water and categorized as large and deep ocean with average depth of more than 3,000 meter. The sea is part of Indonesia Fisheries Management Area (WPP 714) which famous for Tuna fisheries and has the potential to become Indonesia’s national fish barn. This ocean is influenced by Indonesian Through Flow (ITF) water mass from the North and South of Pacific ocean, seasonal monsoon (northwest and southwest monsoon) and ENSO phenomena [1,2,3,4]. Furthermore, the Banda Sea dynamic is also influenced by eddies that play a role in water mass mixing in the Banda Sea [5,6].

Eddy is a smaller and temporary loop of swirling water that can travel long distances before dissipating. These swirling features can take the shape of warm-core (masses of warm water turning in colder ocean water) or cold-core (masses of cold water in warm) eddies and can travel for months
across hundreds or thousands of miles of open ocean. Banda Eddies have the clockwise and anticlockwise vortex which very fluctuating [6]. Another research using INDESO data model revealed that the Banda Anticlockwise Eddy (BAE) with radius of 300 km was found in the Northern Maluku Barat Daya Island and Wetar Island during Southeast Monsoon period. This eddy is permanent during South East Monsoon with energy and radius of area was influenced by ENSO [5].

Eddies transports water and heat long distance and help promote large-scale mixing of the ocean. It also transport nutrients and salt as well as regulate the climate and marine ecosystem. Ocean eddy has known to be the main source of variability on phytoplankton distribution, biogeochemical cycles and pelagic ecosystem [7]. Various types of pelagic fish in almost all waters are closely correlated with territorial waters where eddy is formed with relatively high Eddy Kinetic Energy. This eddies also causes a loss of nutrient in the surface depending on the direction of eddies [8]. In southern hemisphere, counterclockwise eddy lead to downwelling and clockwise lead to upwelling which influence the nutrient concentration.

Ocean Eddies play a major role in the transportation of water masses heat in some oceans. So, eddies modeling is needed for spatial climate studies [9]. This study was conducted to identify the structure and the formation of eddies in the Banda Sea and to find the correlation between the eddies and ocean productivity in the Banda Sea. It is hoped that this research can provide the latest information about Banda Eddies and the impact of eddies on the fertility of the Banda Sea.

2. Data and data analysis
2.1. Data Source

Numerical simulation data produced by INDESO (Infrastructure Development for Space Oceanography) project in Ministry of Marine Affair and Fisheries and satellite data were used in this research. Monthly average of three dimensional INDESO's data during South East Monsoon period (June to August) from 2008 to 2011 was downloaded with an area of study in the Banda Sea (see Figure 1). INDESO is a collaborative scientific program between Ministry of Maritime Affairs and Fisheries (MoMAF), Mercator Ocean International and Collecte Localisation Satellites (CLS). The spatial resolution of the model data is 1/12 degree (approximately 8 km). The parameters of model that used are Sea Surface Height (SSH), vertical profile of temperature, salinity, and ocean current (zonal and meridional direction). To see the relationship between eddies and ocean fertility, chlorophyll-a data was used and obtained from the Aqua MODIS satellite imagery which can be downloaded from https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMPchlAday.html.

Figure 1. Banda Sea
2.2. Data Processing

The occurrence of eddies can be interpreted from Sea Surface Height (SSH) data. In the southern hemisphere, combination of eddy current and coriolis force created low or high Sea Surface Height (SSH) due to divergence or convergence of the water mass. Clockwise eddy lead to water divergence in the southern hemisphere which produced low SSH and counterclockwise eddy created water convergence that lead to high SSH. Convergence lead to the downwelling phenomena and divergence lead to upwelling. Based on that mechanism, the mean SSH from 2008 to 2012 were depicted to see the distribution of eddies in the Banda Sea (see Figure 2).

To enhance our understanding about eddy mechanism, vertical profile of ocean current (zonal and meridional) were identified at each level of depth from surface to the depths where no eddies current were found. From that process, eddies depth and direction (clockwise or counterclockwise) information can be obtained and used to determine the strength of the eddies (see Table 1 and Figure 3). The relative vorticity ($\zeta$) value also used to analyze the strength and direction of Banda Eddies. Relative vorticity value was calculated by using horizontal ocean current data with formula as follow:

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Where $\zeta$ is vorticity (1/second), $u$ and $v$ are velocity components in $x$ and $y$ direction (meter/second). The results will give a positive or negative value which can be translated as eddies direction. In southern hemisphere, positive vorticity means eddies rotate in counterclockwise direction and negative vorticity mean eddies rotate in clockwise direction (Figure 3).

Vertical profile of temperature and salinity as well as surface chlorophyll-a were used to analyze the structure of water mass in the area around the eddies vortex which is very important in the distribution of chlorophyll in surface waters. Furthermore, the results of eddies analysis during normal and ENSO period will be compared with chlorophyll-a data to see the effect of ENSO to the vorticity of eddies and their impact on the Banda Sea fertility.

3. Results and Discussion

3.1. The presence of Banda Eddy during South East Monsoon (SEM) Period

The presence of eddies during the South East Monsoon (SEM) period in Banda Sea can be seen from INDESO’s Sea Surface Height (SSH) data. Figure 2 and Table 1 shows the mean SSH from INDESO’s data (Figure 2.A) and mean SSH from AVISO satellite data (Figure 2.B) [10]. Due to the coarse resolution of AVISO (0.25 degree, approximately 27 km) compared to INDESO data (approximately 8 km), only the eddies in north of Wetar Island (the bigger eddies) can be detected from AVISO data. In INDESO’s data, some eddies with difference characteristic (the size and direction of swirling) was detected.

Sea Surface Height (SSH) is lower in the northern of Banda Sea, especially in the south of Buru and Seram Island and higher SSH was found in the southern of Banda Sea (north of Wetar Island and Yamdena Island). The high SSH in the southern Banda Sea are due to the counterclockwise eddies (A, B and C in Figure 3), while the lower SSH that marked with D and E are due to the clockwise eddies. In the southern hemisphere, combination of eddies rotation and coriolis force can be presumed that eddies D and E is an upwelling area [5,11,12,13]. Otherwise, counterclockwise eddies in the southern of Banda Sea (A,B,C) create the downwelling area [13].

The presence of 5 eddies during South East Monsoon period is thought to be an important factor in maintaining water masses balance system, promote large-scale mixing of the ocean, transport
nutrients and salt as well as regulate the climate and marine ecosystem in Banda Sea. This area is also a spawning location during October and November based on PERMEN-KP NO 4 2015 (Figure 2C).

Table 1. Eddies location in Banda Sea during South East Monsoon (SEM)

| No | Eddy ID | Eddy Location       | Type of Eddy (see Figure 3) | Depth  |
|----|---------|---------------------|----------------------------|--------|
| 1  | A       | ~ 122.8°E, 7°S      | Counterclockwise           | 0-200 m|
| 2  | B       | ~ 125.4°E, 6.7°S    | Counterclockwise           | 0-300 m|
| 3  | C       | ~ 130.4°E, 6.9°S    | Counterclockwise           | ~ 50 m |
| 4  | D       | ~ 127.3°E, 4.5°S    | Clockwise                  | 25-150 m|
| 5  | E       | ~ 130.5°E, 4.6°S    | Clockwise                  | 25-150 m|

Figure 2. The INDESO’s data Mean SSH from 2008 to 2012 (a), The AVISO’s data Mean SSH from 2002 to 2012 [10] (b) and spawning ground of Tuna which closed from fisheries activities during October and December based on PERMEN-KP NO 4 2015 (c).

The previous research revealed that existence of counterclockwise eddies have observed around the north of Wetar Islands and Yamdena Island at the surface depth with a radius of about 300 km during the Southeast Monsoon Period [5]. In this study, we mark that eddies from previous study
as eddies B and we found another eddies on the west side of the eddies B which named as eddies A (see Figure 3).

Eddies A and B was formed due to interaction of wind induced current in Banda Sea and strong Indonesia Through Flow (ITF) that flow at Flores Sea. On South East Monsoon period, southeasterly wind produces westward transport in some area and depth (mostly in mixed layer) of Banda Sea. At that moment, the transport of ITF is stronger which flow eastward at Flores Sea in the upper thermocline layer and influence the mixed layer to flow at same direction with the ITF. The junction area of the currents produced the counterclockwise eddies that will triggers downwelling. Counterclockwise eddy pattern in at Eddies A, B and C becomes a sign of downwelling area [5]. Furthermore, these three eddies have positive relative vorticity value that mean the rotation is counterclockwise.

![Figure 3](image)

**Figure 3.** Relative vorticity overlay with current vector at 0, 55 and 155 meter in Banda Sea during South East Monsoon (June, July and August) on 2008,2009 and 2010.

Clockwise eddies were form at northern of Banda Sea (Eddies C and D) from the depth of 25 meter. Previous researcher [6] named these two eddies as Buru Eddies (BuE) for eddies at location E and Banda Eddies (BaE ) for eddies at location D. This eddies has a negative vorticity value which mean it has clockwise rotation. This eddy is an extension of the current from the Lifamatola Strait down to the Buru Strait and some part of the current circling Buru Island from the west then along the southern part of Buru Island and joined by eddy formed in the south of Seram Island. These two eddies, which have a fairly large radius of almost the size of eddy B and formed at depths from 55 to 155 m, but with the weaker of kinetic energy.
The presence of eddies A, B, and C during SEM period of 2008, 2009 and 2010 had different sizes and vorticity characteristic. During the normal period (June to August of 2008) and El Nino (June to August 2009), trade winds were not too strong (weaker in El Nino condition) compare to the La Nina condition, so that the ITF transport from the Flores Strait was less strong than westward Ekman transport that leaving the Banda arcs. This condition make the eddies vortex is not well-formed [5]. This is can be seen from the small value of vorticity in eddies B (Figure 3). However in La Nina condition (2010), eddies B has a perfectly circle shape and large vorticity value. In this period, the strength of trade wind increased [17,18] which increased Indonesian Through-Flow transport at Flores Sea [19,20,21]. Water mass transport that leaving the Banda Islands arc is relatively smaller than the other years (2008 and 2009) at 1.24 Sv (1 sv = 1 x 10^6 m^3/second) [5]. The presence of eddy B coincides with the counterclockwise eddy (Eddy A) on the west side of eddy B in the Banda Sea. Eddy A is formed due to the junction of currents that pass through the strait between Buton Island and the Wakatobi Islands, with currents from the Flores Sea.

3.2. Characteristic of Water Mass

The presence of eddies in the north and south of Banda Sea caused a differences in the characteristics of surface water mass. Water mass in the north of the Banda Sea characterized by high salinity and low temperature, while in the south is characterized as low salinity and high temperatures (Figure 4).

![Figure 4](image)

Figure 4. Sea Surface Salinity (SSS) and Sea Surface temperature (SST) distribution in the Banda Sea during South East Monsoon (June, July and August) on 2008, 2009 and 2010.

The Sea Surface Salinity in 2008 is generally higher with lower temperature compare to the others. This condition is due to the high Sea Surface Salinity of the ITF water masses which flow to the Banda Sea from the Halmahera Sea. Banda Sea Surface Salinity during SEM period on 2008 ranged from 34.06-34.63 PSU, in 2009 it ranged from 33.87-34.40 PSU while in 2010 it ranged from 33.55-34.16 PSU. The average Sea Surface Temperature of the Banda Sea during normal years (2008) is between 26.7 - 29.1°C, during the El Nino year (2009) it tends to be higher than the normal year which is between 28.8 - 29.4 °C, while in La Nina year (2010) the average Sea Surface Temperature was found to be higher with the value of 28.8 - 29.5°C. The characteristic of water masses in the eddies core can be seen in Table 2.
Table 2. Surface Water Mass Characteristics in the Eddies Core in the South of Banda Sea.

| Year | Latitude | Longitude | Temperature | Salinity |
|------|----------|-----------|-------------|----------|
| Eddies A | 7.3 | 123 | 27.61 | 34.12 |
| 2008 | 7.3 | 123 | 28.33 | 34.00 |
| 2010 | 7.3 | 123 | 28.66 | 33.57 |
| Eddies B | 7.2 | 126.5 | 27.14 | 34.11 |
| 2008 | 7.2 | 126.5 | 27.77 | 33.99 |
| 2010 | 7 | 125 | 28.32 | 33.55 |
| Eddies C | 6.9 | 130.2 | 27.05 | 34.29 |
| 2008 | - | - | - | - |
| 2009 | - | - | - | - |
| 2010 | - | - | - | - |

The cross section plot was made along the latitude of 4.6 ° S and 7 ° S to depict the vertical structure of temperature and salinity under the eddies formation (figure 5). In the north of the Banda Sea (cross section along latitude 4.6 ° S), where eddies E and D were formed, it seem deep water mass rises in the east side of the eddies which was marked by an increase in salinity and a decrease in temperature (Figure 5 left). This is due to a water mass transport from the northeast to the southwest (Figure 3, depth 0 m) which lead to upwelling in the east side of the Banda Sea. The upwelling phenomena is also seen from chlorophyll-a distribution in the north of Banda Sea especially south of Buru Island, Ambon Island and Lease Island (see figure 6). High concentration of chlorophyll-a can be seen in the coastal waters to open ocean. However in the 2010, the water mass characteristic is difference and chlorophyll-a concentration is low. Another phenomena influence the upwelling on 2010.

The cross section along latitude 7 ° (Figure 5 right) shows the salinity distribution which overlay with temperature (contour) in the southern of Banda Sea. Low salinity value was seen deeper at the eddies A, B and C locations. In 2008 (normal period), the low salinity values was seen to the depth of 75 meter in Eddies A location, 109 meter in Eddies B and 55 meter in Eddies C. It is indicated that counterclockwise eddies in A, B and C induced downwelling and bring the low salinity water from the surface to the deep layer. In 2009 (El Nino period) and 2010 (La Nina), low salinity depth decrease compared to the depth in 2008. It seem that the strength of downwelling was decreased due to the change of wind induced current and ITF current during each period.

The difference in the depth of a downward water mass also influenced by the characteristic of water masses in the core of eddies. In a normal year (2008), the water masses were cooler and saltier, so that the density of water became heavier, which caused the water mass easy to sink. Compared to 2010 (La Nina), the density of water mass was lighter due to higher temperatures and lower salinity. Moreover, the sinking process was also depends on Indonesian Through Flow (ITF) transports during the season. The ITF transport in the east season in the normal year is 1.84 Sv (1 sv = 1 x 10⁶ m³/second), which greater than in El Nino phase (1.58 Sv) and La Nina phase (1.24 Sv) [5]. The strength of ITF transport influence the strength of the eddies and downwelling process in the southern of the Banda Sea that causes the water mass to sink.
Figure 5. Cross-section (red line) of salinity distribution overlay with contour of temperature in the Banda Sea during South East Monsoon (SEM) Period on 2008, 2009 and 2010

3.3. Chlorophyll-a in the Banda Sea.

The distribution of chlorophyll-a appeared evenly in all area in 2008, with ranged from 0.31 - 0.56 mg / m³ with an average of 0.39 mg / m³. In 2009, chlorophyll-a values were high in the northern Banda Sea, especially in the southern of Buru Island with ranged from 0.2 - 0.8 mg / m³ with an average of 0.35. Low coverage of chlorophyll-a was found during the La Nina period (2010) with a range between 0.16 - 0.35 mg / m³ and an average of 0.22 mg / m³.
Figure 6. Distribution of mean chlorophyll-a during June, July and August (JJA) on 2008 (A), on 2009 (B) and on 2010 (C).

Figure 7. Meridional mean of Chlorophyll-a (123°E to 132.5°E, red box) along latitude 3° – 8°S during June-July-August (JJA) on 2008 (blue line), 2009 (red line) and 2010 (green line) (A), and monthly climate mean of chlorophyll-a on 2008 (blue line), 2009 (red line) and 2010 (green line) (B).

The chlorophyll-a concentration in 2008 appeared to be distributed evenly with higher concentration at latitude 4°S near the coastal area. This is due to weaker counterclockwise eddies that lead to weaker downwelling at southern of Banda Sea in 2008 (compare to 2010), and a strong transport of water mass that push the nutrient from upwelling region to spread across the entire Banda Sea. In El Nino condition (2009), chlorophyll-a was higher at around 3.5°S and low in the southern part. Nutrient are concentrated in the coastal area in the south of Buru Island and Ambon Island. In this period, weaker trade wind and make the nutrient concentrated near the upwelling zone. Furthermore in La Nina conditions, chlorophyll-a concentration is low in all area of Banda Sea. Strong counterclockwise eddies (eddies B, see Figure 3) was produce strong downwelling area which causes the sink of nutrient from the surface.
4. Conclusion

In this research, five eddies in the Banda Sea were found during South East Monsoon (SEM) period (June, July and August). Two eddies (E and D) in the north of Banda Sea that have clockwise rotation that trigger the upwelling phenomena which can be identified from low Sea Surface Height (SSH), high Sea Surface Salinity (SSS) and low Sea Surface Temperature (SST) value. It also can be seen in high surface chlorophyll-a concentration during the SEM period in coastal area in Buru Island, Ambon Island and Lease Island. The other three eddies (A, B, and C) were found in southern of Banda Sea that have counterclockwise rotation which the biggest is eddies B that located in north of Wetar Island. In the southern hemisphere, counterclockwise eddies collect the water mass to the core which created the downwelling area that can be detected from high SSH value, deep penetration of surface salinity and temperature to the deep layer and the disappeared of the chlorophyll-a due to the sinking caused by downwelling.

ENSO have a role to strengthening or weakening the Indonesian Through Flow (ITF) and monsoon that lead to eddies occurrence. In 2009, El Nino event weakening the ITF and monsoon that lead to chlorophyll-a concentration only concentrated in north of Banda Sea and chlorophyll-a in the southern of Banda Sea was sinking due to downwelling. Furthermore in 2010 (La Nina), strong eddies in the north of Wetar Island lead to low concentration of chlorophyll-a in Banda Sea due to intensive sinking caused by downwelling.

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