Eddies spatial variability at Makassar Strait – Flores Sea

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Abstract. This study was aimed to get the distribution of eddies spatially and temporally from Makassar Waters (MW) to Flores Sea (FS), as well as its relations with the upwelling, the downwelling, and chlorophyll-a concentration. The study area extends from 115°–125° E to 2.5°–8° S. The datasets were consisted of monthly geostrophic currents, sea surface heights, sea surface temperatures, and chlorophyll-a from 2008 – 2012. The results showed that eddies which found at Makassar Strait (MS) has the highest diameter and speed of 255.3 km and 21.4 cm/s respectively, while at the southern MW has 266.4 km and 15.6 cm/s, and at FS has 182.04 km and 11.4 cm/s. From a total of 51 eddies found, the majority of eddies type was anticyclonic. At MS and FS, eddies formed along the year, whereas at southern MW were found missing in West Season. Moreover, the chlorophyll-a concentration was consistently higher at the eddies area. Even though, the correlation among eddies and the upwelling downwelling phenomena was not significantly as shown by sea surface temperatures value.

1. Introduction

Makassar-Flores Sea was the area with dynamic condition of oceanography. The water masses in this region are highly influenced by two systems of main current through it, the Indonesian through flow (ITF) and Indonesia monsoonal flow (IMF) [1]. Arlindo is a current flowing through Indonesian waters from the pacific ocean to the Indian ocean caused by differences in the sea level of height [2]. Through Arlindo, some waters get influenced by El Nino Southern Oscilation (ENSO), one of them is the southern ocean of Makassar – Flores Sea which located at the center of Indonesian waters. Furthermore, this phenomenon can affect the other oceanography events such as eddies and upwelling.

IMF in the west season is characterized by water mass that moves from west to east along with west monsoon wind which lead to the accumulation of water masses in Banda Sea and resulted the downwelling events. In the east season, water mass move in the reverse direction so that the water mass in Banda Sea is empty and the upwelling occurred [1]. Primer productivity in this region can be determined based on concentration of chlorophyll-a [3], because chlorophyll-a is an important pigment which is found in phytoplankton for photosynthesis, as well can be used to identifying upwelling and downwelling phenomenon [4].
Upwelling is a phenomenon when a cold water goes up from the deep layer to the surface caused by emptiness of water mass in the surface. Downwelling is a phenomenon where warm water goes down from the surface to the deep layer caused by an accumulation of water mass in a surface that must be distributed to the deep layer. Upwelling brings nutrients that required by phytoplankton, while downwelling brings a great oxygen saturation [5]. One of the cause of upwelling is eddies [6].

Eddies is a circular current that have scale of spatial ranged from dozens to hundreds of kilometers and temporal scale ranged from weekly to monthly. Eddies is one of the phenomena attracting a lot of attention for oceanography expertise because eddies have influences to biological aspect, physics and the dynamics of the atmosphere such as affecting the abundance of phytoplankton and the transfer of heat into the atmosphere [7].

Mc Gillicuddy et al. (1998) adduced that temperature, salinity, sea surface height, chlorophyll-a in eddies can changing based on the criteria of eddies itself [8]. On southern Makassar, water moving westward in May until September and moving eastward in November until March. In April and October the direction of water changed and eddies were occurred [9]. Then according to Nontji (2005), in April eddies were occurred from Karimata Strait until Flores Sea [10]. Martono (2010) has been proving by using hydrodynamics modeling of baroclinic three dimensions method and the results shown that eddies occurred in April and October in Java Sea and Flores Sea [11]. Then Kartadikaria (2010) who used in situ data that has been through several processes of analyses has found three eddies in the north of Lombok Island [12].

2. Study area, material and method

2.1. Study area

This study was conducted in December 2014 to January 2015 with study area located in 2°30’–8°S 115°–125°E (Figure 1). Data processing carried out in National Institute of Aeronautics and Space (LAPAN) Bandung and computer laboratory at Fisheries and Marine Science Faculty, Padjadjaran University.

![Figure 1. Study Area](image-url)
2.2. Material and method
Software used in this research shown at table 1.

| No  | Software     | Utility                                      |
|-----|--------------|----------------------------------------------|
| 1   | Surfer 10    | Create ocean current pattern map             |
|     |              | Create spatial map of SSH, SST, and Wind     |
| 2   | ArcGis       | Create study area map                        |
|     |              | Create distribution of chlorophyll-a spatial map |
| 3   | ODV          | Data conversing from .NC format to excel worksheet |
| 4   | SeaDas       | Data extracting from .TIFF format            |
| 5   | Microsoft Excel | Data control process                        |
| 6   | Microsoft Word | Writing paper                              |

Materials used in this research shown at table 2.

| No  | Dataset (2008-2012) | Data Resolution | Data Level | Source                                      |
|-----|---------------------|-----------------|------------|---------------------------------------------|
| 1   | Sea Surface Temperature | 0.08° or ±9km | 3          | Terra/MODIS http://coastwatch.pfeg.noaa.gov/erdda |
| 2   | Geostrophic Current | 0.08° or ±9km | 3          | NOAA/AVHRR http://atoll-motu.aviso.altimetry.fr/ |
| 3   | Sea Surface Height | 0.08° or ±9km | 3          | JASON2 http://atoll-motu.aviso.altimetry.fr/ |
| 4   | Chlorophyll-a      | 0.08° or ±9km | 3          | Aqua/MODIS http://oceancolor.gsfc.nasa.gov   |

2.3. Eddies Spatial Distribution
Geostrophic current obtained from data processing and identified the existence of eddies by observing whether there are circular pattern on vector plot. It could be concluded as an eddies when circular pattern at vector plot is out or separate from the main flow. To strengthen the analysis, geostrophic current was compared with sea surface height in the same month and year.

Moreover, eddies were analyzed from its rotation direction, diameter, core, and geostrophic current velocity on each month and divided into three areas represent Makassar Strait (2.5° – 5° S and 116° – 119° E), Southern Makassar Waters (5° – 8° S and 116° – 120° E) and Flores Sea (5° – 8° S and 120° – 125° E). The direction of rotation was analyzed clockwise (cyclonic eddies) or counter clockwise (anticyclonic eddies). Eddies diameter could be known by counting longest distance between the circle [14]. The calculated longest distance could be reflected to the position of the latitude or longitude, simply written into the formula .
\[ D = \frac{||b| - |a|| \times 111 \text{ km}}{1 \text{ derajat}} \]

Where:
- \( D \) = Eddies diameter (km)
- \( b \) = Easternmost edge of the circle of longitude or lower latitude edge of the circle (degree)
- \( a \) = Westernmost edge of the circle of longitude or high latitudes edge of circle (degree)

Eddies core was determined by identifying the midpoint of the circular current visually and reflected on the position of latitude and longitude to obtain the eddies center point. Average geostrophic velocity in eddies could be calculated using the Pythagorean formula where in

\[ c = (u^2 + v^2)^{1/2} \]

Where:
- \( c \) = The resultant speed of geostrophic current (cm/s)
- \( u \) = Geostrophic current U component (cm/s)
- \( v \) = Geostrophic current V component (cm/s)

2.4. Eddies relationship with upwelling and downwelling

Furthermore, in order to see eddies relationship with SSH, SST, and chlorophyll-a concentration as an indicator of upwelling and downwelling phenomenon. SSH, SST, and the concentration of chlorophyll-a in every month of which occurred in the formation of eddies analyzed with the surrounding area. At the time of eddies were formed or not formed was compared to the SSH, SST, and its concentration of chlorophyll-a. Also we analyzed the relationship between SSH, SST, and the concentration of chlorophyll-a with the direction of eddies.

3. Results and discussion

3.1. Eddies spatial distribution

Based on the results of data visualization, geostrophic currents and sea surface height on a monthly dataset, it is known that during the years 2008 - 2012 has happened 52 events of eddies in the study area that represent Makassar Strait, South Makassar Waters and Flores Sea. Within one month, eddies could formed up to four events, but the eddies is not always formed on each month.

3.1.1. Eddies Spatial Distribution at Makassar Strait

Eddies at Makassar Strait is formed due to the topography of the sea and coastline complexity. These waters have a depth of over 2000 meters [12] and is located between the two islands that flank. During the years 2008 - 2012 in Makassar Strait eddies were formed 29 events, which is 17 cyclonic eddies and 8 anticyclonic eddies. In Makassar Strait, eddies was formed in June 2010 and has the longest diameter 255.3 km, which is included into the mesoscale eddies criteria [8]. Then the fastest flow velocity on the Makassar Strait was within the eddies formed in March, which is 21.4 cm/s.

In the Makassar Strait, eddies formed in January of 2009 have a central point around 117.88° E and 4.89° S. Eddies has a diameter along 132.09 km and geostrophic velocity average reached 10.4 cm/s, while in February 2011 had a central point around 118.74° E and 3.80° E with geostrophic velocity average of 5.2 cm/s with a diameter of 147.63 km.
Eddies formed in January 2009 was a cyclonic eddies (indicated by black circles) whereas eddies formed in February 2011 was an anticyclonic eddies (indicated by the red circle). It can be seen that in January 2009 in line with the direction of clockwise eddies (cyclonic) and in February 2011 rotates counter-clockwise (antisiklonik). Based on the map of the current pattern of geostrophic, the formation of cyclonic eddies in January 2009 were due to the dominance or strong currents forming a major which originated from the Java Sea, while anticyclonic eddies in February 2011 were due to the interaction with the mainland [14] as shown in (Figure 2).

In March of 2008, 2009 and 2012, there were formed eddies. Each point of the center of the eddies were 117.3° E and 4° S in 2008, 117.9° E and 4° S in 2009, 117.1° E and 4° S, 115.65° E and 4.8° S in 2012. Diameter of each eddies in March 2008 and 2009 were 177.6 km and 137.64 km, while the diameter in March 2012 was 164.28 km. The central point in 2009 is shifted, seen from the previous year which shifted about 0.6° eastward. This is presumably due to the mass of water that entered through the Makassar Strait in March 2008 stronger (8.5 cm/s) compared to the March 2009 (3 cm/s). Visually, it can be seen that the sea surface temperature of water masses that coming from the Pacific Ocean in March 2008 were colder than in March 2009. The differences could reach to 1.4° C, it could influence the position and size of the eddies [11].

Eddies that formed in April 2008 moved counter-clockwise with the center point that was around 117.6° E and 3.4° S. Diameter of the eddies in April of 2008 reached 139.86 km and geostrophic velocity average up to 10.6 cm/s. In 2009 and 2012 in the same month was also formed an eddies with a center point approximately 117° E and 3° S and diameter of 133.2 km, as well as 4.1° S and 117,1° E with a diameter of 124.32 km.

At Makassar Strait in May 2008 formed an eddies and its center in 117.9° E and 3.9° S with a diameter reached 155.4 km. In the same month in 2009, 2011 and 2012 were also formed an eddies in 117.2° E and 4° S with a diameter of 172.05 km, 117.1° E and 4.9° S with a diameter of 138.75 km, 118.3° E and 4.1° S diameter 142.08 km. Eddies in May 2008 and 2012 was a cyclonic eddies (indicated by black circles), while in May 2009 and 2011 was the anticyclonic eddies (marked by red circle). The cyclonic and anticyclonic types occurred because of differences in the density of the water masses that form the eddies. Eddies formation in May 2008, the water mass in these locations tend to be of low density, forming a cyclonic type of eddies, whereas in May 2009 tend to be high-density waters. Based on visualization, sea surface height at a central point eddies May 2008 is lower than the center point of eddies May 2009 (Figure 3).
Figure 3. SSH Differences (A) May 2008 and (B) May 2009 That Shows Cyclonic and Anticyclonic Eddies

On June there were formed the eddies in 2008, 2009, 2010, and 2011. The focal point of each event is located in 117.9° E and 4° S, 117.8° E and 3.4° S, 118.4° E and 3.7° S, 118.3° E and 4.7° S with a diameter in the range of 179.8 - 255.3 km. The highest geostrophic velocity on this month was found in 2009 which is 23.5 cm/s.

Eddies formed in these waters in July of 2009 and 2010 have a central point in 117.9° E and 3.7° S, 118.6° E and 4° S. These both eddies diameter reached 155.4 km and 144.3 km. While the eddies in August 2008 and 2010 center point 117.9° E and 3.7° S, 4.5° S 118.1° E and with a diameter 187.59 and 213.2 km and geostrophic velocity average is 14.1 and 11.8 cm/s.

3.1.2. Eddies Spatial Distribution at South Makassar Waters

A total of 20 events eddies formed in the waters of South Makassar to limit 116° - 20° and 5° E - 8° S. A total of 15 events during the year 2008-2012 move anticlockwise and just five events that move clockwise. The most eddies found in one month occurred in May 2008 by three events with the center point 116.7° E and 5.7° S, and 6.3° S 119.4° E, 119.1° E and 7.6° S. With eddies diameter is 241.98 km, 166.5 km and 250.86 km.

In SMW, the center point is shifted in April and May 2008. Both of this eddies center point is 117.1° E and 5.4° S, 118.4° E and 5.6° S, diameter is 168.72 km and 210.9 km. Both eddies is moving anticyclonic (indicated by the red circle). According to Gordon et al. (2003), the waters of Indonesia got a very strong influence coming from NINO3 area in the Pacific Ocean on the west monsoon season and the transition period that goes through the Makassar Strait. This is evident through data visualization of geostrophic current, its shown that the center point shifted 0.4° southeastern (Figure 4).

Figure 4. Geostrophic Current Pattern (A) April 2008 And (B) May 2008
SMW eddies formed in June of 2008, 2009, 2010, and 2012. These eddies central point is around 118.6° E and 6.6° S, 119.3° E and 7.7°S, 119.3° E and 6.3° S, 117.8° E and 6.4° S. In this month the highest diameter was found, its reached 228.66 km in 2009.

SMW in July formed an eddies in 2008 and 2010. The diameter of each eddies is 157.62 km and 166.5 km. Geostrophic velocity reach 9.1 cm/s and 4.6 cm/s. The speed differences of these eddies caused by its center point location. In July 2008 the central point of the eddies is in 118.4° E and 5.4° S whereas in July 2010 is 118.6° E and 7.1° S. The speed differences of these eddies caused by the proximity of eddies which formed closer to the major current from Arlindo and South China Sea. This is consisted with the statement from Mann and Lazier (2006), speed of geostrophic in eddies nearer the major current tends to be higher than the eddies that far from major current [14].

Two eddies found in August 2009 and 2012. Each eddies has a central point at 119.4° E and 7.7° S, 119.6° E and 6.4°S. Then in October formed an eddies in 2008 and 2012 that has a central point at 118.7° E and 6.3° S, 117.7° E and 5.6°S. Furthermore, in November eddies occurred in 2009 and 2011 with the center point at 118.6° E and 6.3° S, 119.4° E and 5.8° S.

Figure 5. SSH Differences at Eddies Core (A) September 2010 And (B) September 2011

In September eddies was formed in 2010, 2011, and 2012. The center point of these eddies started at 118.2° E and 5.8° S, then shifted southeastern to 119.3° E and 6.3° S, then returns to 118.4° E but the latitude still at 6.9° S. Its happen because of the differences in the speed and direction of the major current of the years during 2008 - 2012. Then there are differences in sea level at the center of the eddies. The year 2011 had higher sea levels were lower compared by year 2010 and 2012 is 1.04 cm and 0.94 cm. Based on sea level at the center point eddies, eddies formed in September 2011 was a cyclonic eddies (indicated by black circles), while in September 2010 and 2012 is an anticyclonic eddies (marked by red circles) (Figure 5).

Eddies in these waters has a direction of rotation is counter clockwise except in June of 2011, which has a central point around 120.1° E and 7° S with a diameter of 129.87 km. Based on data processing of geostrophic currents and sea surface height on a monthly basis, the general direction of the rotation is counter clockwise (marked by red circle) which has a higher sea level at its center than the surrounding area. Otherwise when the direction of rotation is clockwise, the high sea level in its center point will be lower (indicated by the black circle) (Figure 6). This is consistent with the theory by Stewart (2008) that the level of sea surface height at the center point indicate the type which is cyclonic eddies or anticyclonic eddies [15].
3.1.3. Eddies Spatial Distribution at Flores Sea

Eddies in the waters of the Flores Sea is the least formed. During the years 2008 - 2012 eddies formed only seven times, even in the year 2010 in these waters did not formed an eddies in throughout the year. It’s possible because these waters are more open than in the other study area as well as away from the main water mass that can form eddies.

At Flores Sea in February 2011, March 2012 and April 2008 formed an eddies with a center point at 121.2° E and 5.4° S, 6.1° S and 124°E, 121° E and 5.4°S. The diameter of each eddies is 150.96 km, 182.04 km and 175.38 km with geostrophic speed average 4.1 cm/s and 11.4 cm/s and 10.6 cm/s. In December 2008 and October 2012 (Figure 7) also formed an eddies in Flores Sea this. Each of these events has a center point around 124.7° E and 5.7° S, 5.6° S and 123.8° E and with a diameter of 166.5 km and 157.62 km and geostrophic speed average is 8.9 cm/s and 8.5 cm/s.

4. Conclusion

Spatially, eddies formed at Makassar Waters – Flores Sea during 2008 – 2012 up to 52 events that spread to MS, SMW and FS. There was 29 events of eddies with 17 cyclonic eddies and 8 anticyclonic eddies. At SMW, there was 20 eddies formed with 15 cyclonic eddies and 5 anticyclonic eddies, whereas at FS there was 7 eddies with 5 cyclonic eddies and 2 anticyclonic eddies. Diameter of eddies can shrinking or developing by 5 until 100 km and the core of eddies can shifting by 0.1° until 1.0° to east-south-west in every month.
References

[1] Ilahude A G and Nontji A 1999 Oseanografi Indonesia dan perubahan iklim global (El Nino dan La Nina) Lokakarya AIPI Puslitbang Oseanologi-LIPI Jakarta p 12
[2] Hasanudin M 1998. Arus Lintas Indonesia (ARLINDO) Oseana 23 2 p 1-9
[3] Kunarso S, Hadi N S, Ningsih M S, Baskoro 2011 Variabilitas suhu dan klorofil-a di Daerah Upwelling pada variasi kejadian ENSO danIOD di perairan selatan Jawa sampai Timor Jurnal Ilmu Kelautan 16 3 p 171-180
[4] Azis M F 2006 Gerak Air di Laut Oseana 31 4 p 9-21
[5] Martono S, Hadi N S, Ningsih. 2008b. Studi Eddies Mindanao dan Eddies Halmahera Jurnal Penelitian Perikanan 11 2 p 204-210
[6] Robinson A R 1983 Eddies in Marine Science (Berlin: Springer) p 609
[7] McGillicuddy D J, Robinson A R, Siegel DA, Jannasch H W, Johnson R, Dickey T D, McNeil J, Michaels A F, and Knap A H 1998 Influence of mesoscale eddies on new production in the sargasso sea Nature 394 p 263-265.
[8] Wyrtki K 1961 Physical Oceanography of the South East Asian Waters (San Diego: The Scripps Institution of Oceanography University of California)
[9] Nontji A 2005 Laut Nusantara (Jakarta: Djambatan) p 368
[10] Martono 2010 Pengaruh fenomena El Nino dan La Nina terhadap arus eddies di Laut Jawa dan Laut Flores
[11] Kartadikaria A R Y, Miyazawa K, Nadaoka A, Watanabe 2011 Existence of eddies at Crossroad of The Indonesian Seas Springer-Verlag in T Ezer (Ed.) Ocean Dynamics 62 31-44.
[12] Mann and Lazier 2006 Dynamics of Marine Ecosystem Blackwell Publishing Ltd 3 285-336
[13] Pranowo et al. 2005
[14] Vaillancourt R D et al. 2003 Impact of A cyclonic eddies on phytoplankton community structure and photosynthetic competency in subtropical North Pacific Ocean (Columbia: Pergamon)
[15] Aulia A 2013 Variabilitas arus eddies di perairan Selatan Jawa-Bali berdasarkan data Satelit Jurnal Perikanan Kelautan (Jatinangor: Universitas Padjadjaran)