Observed of Equatorial Currents in the Indian Ocean during Two Contrasting IOD Events: 2006 and 2010

P A Utari
Research Center for Deep-Sea, Indonesian Institute of Sciences, BRIN, Indonesia.

E-mail: putriadiautari91@gmail.com

Abstract. The evolution of Indian Ocean Dipole (IOD) events in 2006 and 2010 is investigated using observational data products that are made to understand several processes in the positive (negative) phase of IOD events. Two Acoustic Doppler Current Profiler (ADCP) moorings mounted at 90°E and 80.5°E along the equator were used to evaluate the zonal current variation during two contrasting Indian Ocean Dipole (IOD) events. Westward anomalies of the zonal current were observed at 0°, 80.5°E during the peak phase of the positive IOD event from October to December 2006. Meanwhile, the observed zonal currents at 0°, 90°E only showed the short-term westward anomalies during October 2006. On the other hand, during the negative IOD event in 2010, the observed zonal current at both mooring locations indicated strong intraseasonal variations of the eastward anomalies from August to December 2010. Strong easterly (westerly) anomalies of the surface zonal winds were observed during the peak phase of the positive (negative) IOD event in 2006 (2010). These easterly (westerly) anomalies forced upwelling (downwelling) equatorial Kelvin waves indicated by the negative (positive) sea surface height anomalies. Strengthening (weakening) of upwelling (downwelling) along the equatorial Indian Ocean would be a significant factor for further understanding of IOD evolution.

1. Introduction
The circulation atmosphere-ocean in the tropical Indian Ocean is an active player that influences climate variability on seasonal to interannual timescales [1-2]. This condition can affect the anomalous that happen in the tropical Indian ocean especially the current propagations. The dynamic of equatorial surface currents in the tropical Indian Ocean is the main aspect to be observed that correlates with the seasonal monsoonal winds. The equatorial ocean can respond to westerly winds and generate equatorial currents known as Wyrtki Jets [3-4]. Previous studies have widely described that the Wyrtki Jets in the Indian Ocean were mainly forced by the local equatorial zonal winds during the transition season between Asian summer monsoon and Asian winter monsoon [5-8].

In the normal condition, Wyrtki jets appear in boreal spring (April – May) and boreal fall (October – November) that moves in the equatorial Indian Ocean between 2°N and 2°S [9-10]. This jet is influenced by strong westerly winds along the equator which occurs very fast around 60°E - 90°E and 2°N - 2°N. The jet is slowing down in the depth of 80 m and reverses direction below 120 m [8]. It has been known that Indian ocean Dipole (IOD) depends on a seasonal cycle that correlates with Wyrtki jets.
The IOD phenomenon is a symptom of the anomaly of the sea surface temperature (SST), that caused by the interaction of the ocean surface and the atmosphere, especially in the Indian Ocean and south of Java [11-13]. The anomaly of SST causes a pressure difference in the western region (50°E - 70°E, 10°S - 10°N) and the eastern Indian Ocean (90°E - 110°E, 10°S - 10°N). The wind moving from the east to the west of the Indian Ocean will push the cooler and higher density masses of ocean water from seabed onto the surface (upwelling) and vice versa. These processes have accumulated seawater and raised sea surface temperatures in the western part of the Indian Ocean. While in the eastern part of the Indian Ocean, SST has decreased quite dramatically especially on the southern coast of Java and the western coast of Sumatra. The decrease of the SST in the eastern part of the Indian Ocean is known as a negative anomaly whereas the increase of SST in the western part of the Indian Ocean is known as a positive anomaly [14]. These combined two events are called the formation of two poles [15-17]. Table 1 shows that the year of positive and negative IOD in Indian Ocean.

Table 1. Positive and negative IOD event based on the Dipole Mode Index

| Classification | Years |
|----------------|-------|
| Positive IOD  | 1961, 1963, 1967, 1972, 1976, 1982, 1983, 1987, 1991, 1994, 1997, 2002, 2003, 2006, 2008, 2011, 2012 |
| Negative IOD  | 1954, 1956, 1958, 1959, 1960, 1964, 1980, 1989, 1992, 1996, 2010 |

The study of the IOD phenomenon is very important for climate prediction. For example, one of the IOD phenomena has been documented in early 2006 was suspected as a major cause of drought disaster especially in Indonesia. On the contrary, another IOD phenomenon that happened in 2010 was suspected as a cause of flood disaster. Since these IOD events affected different disasters, we need to study closely the major component which one of the events would be leading to the flood or drought. As long as the author has the knowledge, the previous research has not compared the dynamic of equatorial currents as an indicator of the different IOD events before. Therefore, the purpose of this research is aimed to analyze each type of IOD event as a function of dynamic equatorial currents.

In this paper, we used the data sets as follows. In section 2, we describe the data and methods to analyze each type of IOD events. In section 3, we illustrate not only the anomalous currents during 2006 and 2010 but also the dynamic of equatorial currents during 2006 and 2010. The mean equatorial west-minus-east sea surface temperature (SST) gradients are affected by the characteristic of an extreme positive IOD [18]. On the other research, it has described the huge impacts of eddy-like sea surface height anomalies (SSHAs) on the strong intraseasonal variability of Meridional currents [19]. The different goals of this paper with the previous studies are to analyze and describe the evolution of positive IOD and negative IOD in the equatorial current with mooring data from ADCP at 80.5°E and 90°E.

2. Data and Methods

In this study, we use the surface wind data was taken from European Centre for Medium-Range Weather Forecasts Interim Reanalysis which is retrieved from http://www.ecmwf.int/. This product was retrieved from January 1st, 2002 till December 31st, 2012. This data is available for daily data on a 0.25°x0.25° grid. The surface wind data is used to determine the mechanism of zonal transport variations which lies at 30°W-100°E and 20°S – 20°N.

The data of sea currents were obtained by ADCP (Acoustic Doppler CurrentProfiler) mooring in the equatorial Indian Ocean which is part of the program RAMA buoys network. The current data, depth resolution from 25m until 350m, was used in this research at 80.5°E for the period October 27th, 2004 till August 17th, 2014 with daily resolution. In the previous research, the ADCP data was used to observe
currents at 80.5°E and 90°E as background for a more focused discussion of intraseasonal variability (Iskandar, et al. 2011). In addition, we also used current data at 90°E with the depth resolution from 40 m until 410 m depth. The data provides daily current velocity from the period November 14th 2000 till June 7th 2012.

The observed of surface current analysis is from October 21st 1992 till 31st December 2016. We retrieved from Ocean Surface Current Analyses Real Time (OSCAR) to observe the dynamic of surface currents. The available surface current datasets are on the global grid every 5 days. It represents the average current at 15 m depth with resolution of $1° \times 1°$. This product is derived from satellite altimetry measurements which could be accessed from http://apdrc.soest.hawaii.edu.

The Sea Surface Height (SSH) data were retrieved from Asia-Pacific Data-Research Center (APDRC), which could be accessed from http://apdrc.soest.hawaii.edu. This product is available for the period January 2nd 2002 till January 2nd 2013. This data set is merged data from all altimeter missions (Jason-1 and 2, TOPEX/Poseidon, Envisat, and several other missions). The data set has a horizontal resolution of $0.25° \times 0.25°$ and a temporal resolution of 7 days. The DMI data was retrieved from Ocean Observations Panel for Climate, which could be accessed from http://stateoftheocean.osmc.noaa.gov. This product is available for the period November 4th 1981 till April 5th 2017. The DMI is an indicator of the east-west temperature gradient across the tropical Indian Ocean, correlated to the Zonal Mode. The DMI data is calculated as the difference of the West tropical Indian Ocean and South-East tropical Indian Ocean. All of the data sets which are used in this study were summarized in Table 2.

Table 2. Summary of data used in this study

| Data          | Interval | Record Length          |
|---------------|----------|------------------------|
| ADCP (80.5°E) | Daily    | 27 Oct 2004 – 17 Aug 2012 |
| ADCP (90°E)   | Daily    | 15 Nov 2000 – 7 Jun 2012 |
| SSH           | Weekly   | 2 Jan 2002 – 2 Jan 2013 |
| OSCAR         | weekly   | 22 Oct 1992 – 31 Dec 2016 |
| ECMWF         | Daily    | 1 Jan 2002 – 31 Dec 2012 |
| DMI           | weekly   | 4 Nov 1981 – 31 Aug 2016 |

By using data sets of sea currents, wind surface, SSH, and DMI, the anomaly pattern was found in the equatorial Indian Ocean. The prominent occurrences of this pattern provide the basis for analyzing the dynamics of currents associated with different IOD evolutions. Using mean calculation was done to observe the regularity of current climatology in the Indian Ocean with other observational datasets. Consequently, the basic calculation of climatology was summing up the data for each of the same months from January to December. All variables of the mean climatology that used to calculate the anomalies fields. We get the anomalies of surface wind, surface currents, and zonal currents by constructing based on deviations from their mean climatology. The data of wind, currents, and SSH were processed by the low-pass filter method, a method of smoothing an image of the original data. This method is accomplished in the frequency domain with high-frequency attenuation to eliminate noise caused by high-frequencies (Kondo, et al. 2016). To remove seasonal signal, the current data was low-pass filtered on 7 days suggested on (Watts, et al, 2016) and wind surface and SSH was low filtered on 15 days suggested on (Kanzow, et al. 2007).

3. Results and Discussions

3.1 Anomalous Equatorial Currents In 2006

In this section, we consider by proving the dynamic of equatorial currents based on the time series of Dipole Mode Index (DMI) to illustrate the evolution of Positive IOD in 2006. The important thing to analyze positive IOD is characterized by strongly phase-locked with the seasonal cycle. DMI, the surface current anomaly at 80.5°E and zonal current anomaly at 80.5°E was shown in Figure 1a. DMI in 2006 indicates the temperature anomalies $\geq 1.5°C$ which happened during boreal fall (September-October).
Figure 1. Time series of (a) Dipole Mode Index (DMI), (b) near-surface current anomaly at 80.5°E, and (c) zonal current anomaly at 80.5°E during 2006.

The surface current dynamic at the position of 80.5°E was not significance during boreal fall. From the Figure 1b, the velocity was weak and was not consistent with the positive IOD event during boreal fall. It was similarly with the zonal current at 80.5°E which was not significant velocity during boreal fall. The red (blue) contour indicates the direction of current eastern (western). In boreal spring, the zonal currents move at the upper depth 100 m to the western with speed 20 m/s. At the depth below 100 m was not a significant movement. The uniqueness of positive IOD in the position of 80.5°E was not affected by the surface current and zonal current.

Figure 2. Time series of (a) Dipole Mode Index (DMI), (b) near-surface current anomaly at 90°E, and (c) zonal current anomaly at 90°E during 2006.
As shown in Figure 2(a), DMI indicates the evolution of positive IOD events during boreal fall. It was different from the surface current at 90°E. The dynamic of surface current was decreased during monsoon breaks. In contrast, the zonal current at 90°E was strong in the depth around 60 m-180 m during the boreal fall. It showed long-term eastward during boreal falling but the westward anomalies were short-term. At the upper depth 180 m was not movement zonal current which shown zero velocity in that location like Figure 2c.

Based on the result of 80.5°E and 90°E, the positive IOD was characterized that the velocity of zonal current was stronger in 90°E than in 80.5°E. It showed that the 90°E locations developed at the end of August and matured during boreal fall (September-October) to mid-December. Accordingly, the positive IOD event is indicated by anomalous cooling near the Java coast in response to the intensified southeasterly trade winds in boreal spring [23]. It then manifested as a basin-wide dipole mode marked by opposite anomalies, particularly in sea surface temperature (SST) on either side of the tropical Indian Ocean. The uniqueness of positive IOD in the position of 80.5°E wasn't affected by the surface current and zonal current.

3.2 Anomalous Equatorial Currents In 2010
Contrasting with positive IOD event, the evolution of negative IOD event was illustrated with significance DMI during boreal fall in Figure 3a. The negative IOD is signed by lower temperature (≤ 1.2°C) which happened in 2010. On the other hand, the surface current anomaly at 80.5°E was increased during boreal fall. There was a dynamic current in the surface with the velocity ≤ -1.2°C which was not consistent with DMI evolution in this period Figure 3a.

Figure 3. Same as Figure 2 except during 2010.

The evolution of negative IOD 2010 was seen by DMI Index on Figure 3a. The normal condition was denoted by DMI Index at the beginning of 2006. Consequently, the peak phase occurred on September and decayed on November which was pointed out by blue contour. In Figure 3b, the dynamic of surface currents on 80.5°E was invisible its anomalies on boreal fall (September – November). On other conditions, it would be interesting to see that the pattern of zonal current anomalies captured on
the surface during September marked by red contour on Figure 3c. The red contour indicates the eastward anomalous on boreal fall. These eastward anomalous are only seen at the below 100m depth. The zonal currents at the upper 100m depth occurred westward which was signed by blue contour. From these results, we now argue that there was the evolution of negative IOD in the position of 80.5°E but it was unseen clearly through eastward in the surface currents and subsurface currents.

Figure 4. Same as Figure 3 except during 2010.

The surface current at 90°E didn’t show clearly the significant velocity in boreal spring (March – May) and boreal fall (September – November) shown by Figure 4b. Associated with the negative IOD arose in subsurface currents as Figure 4c, the intraseasonal perturbations were found at the depth 40 m – 180 m in boreal fall. During boreal spring, the subsurface currents was significant at depth ≥ 80 m and found eastward anomalous which was signed by the red contour. It was not the same with the subsurface dynamics in boreal fall that the westward was weak in the depth 80 m till 180 m. In boreal fall, there was propagation current to the east with high velocity in the depth 40 m till 120 m and was not movement of current in the depth upper 120 m. It means that the movement of current was accelerated for 30 days before boreal fall which caused the current shift to the west.

3.3 Dynamic of Equatorial Waves During 2006 And 2010

In this part, we analyze the basin-scale surface layer variability associated with the positive IOD 2006 and negative IOD 2010, which is becoming the main observation in the dynamic of equatorial waves. The hovmuller diagram of wind surface, SSH, and surface currents are shown in Figure 5. Wind surface indicates anomalous that easterly wind generated zonal current and large negative SSH anomalies (upwelling Rossby waves) along the equator during January-March Figure 5b-c. In this period, wind surface anomaly shows consistent with the equatorial wave theory.
Figure 5. Hovmöller diagram of a). wind surface anomaly; b). sea surface height (SSH) anomaly; and c). surface current anomaly.

The space–time evaluation of wind surface, SSH, and surface current anomalies was denoted by the Hovmöller diagram which is used to visualize the equatorial current anomalies. Figure 5a shows the Hovmöller diagram along equator which denotes the space–time evaluation of original and reconstructed wind surface. Figure 5b shows the Hovmöller diagram of original and reconstructed sea surface height (SSH) along equator Indian Ocean. In Figure 5c, the Hovmöller diagram represents the surface current. The pattern of equatorial currents is exactly seen the evolution of positive IOD 2006. The negative SSH (upwelling Rossby wave) and positive SSH (downwelling Kelvin wave) along the equator as shown Figure 5b-c. Easterly wind was significance during boreal fall (September–October) to last December 2006. It was affected strong negative SSH anomaly) which generated upwelling Rossby wave.

Figure 6. Same as Figure 5 except during 2010
The evolution of negative IOD event in 2010 was shown by Figure 6 which has the same calculation with positive IOD event 2006. In boreal winter (January-February), westerly wind ruled and generated the positive SSH anomaly as Figure 6a-b. It affected downwelling Kelvin wave during boreal winter with the velocity around 0.4 m/s. The westerly wind still occurred during boreal spring which generated the positive SSH anomaly (downwelling Kelvin wave). In contrary, easterly wind dominated during boreal summer and generated positive SSH anomaly (downwelling Rossby wave). During boreal fall, easterly was strong along the equator especially at 80°E-90°E which generated positive SSH anomaly (downwelling Rossby wave).

4. Conclusion
In this study, we report the analysis of observation for contrasting IOD phenomenon related to currents dynamic in Equatorial Indian Ocean (EIO). The results indicate abnormally currents and the correlation seasonal monsoonal winds during 2006 and 2010. Firstly, the exceptional boreal spring (April – May) and boreal fall (September – October) at 80.5°E was weak though DMI indicates that the positive IOD was strong in boreal fall than boreal spring during 2006. Uniquely, at 90°E was strongly zonal current anomaly in boreal fall but surface current shown the decreased velocity. It means that the strongly dynamic current happened in zonal current around the depth of 40 m till 180 m. Thirdly, the evolution of DMI in 2010 was weak but it was opposite with the dynamic of surface current at 80.5°E. The surface current has decreased the velocity at this location but the enhancement of current occurred at 90°E. Fourthly, the Easterly wind was weak which also affected negative SSH anomaly and generated upwelling Rossby wave during boreal fall in 2006. However, Westerly wind dominated along the equator that generated positive SSH anomaly and downwelling Kelvin wave during boreal fall in 2010. This suggests that the variables of wind, SSH and current have influence to the both of IOD events in 2006 and 2010.

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