Ocean current signals propagation along the Outer Banda Arcs

V C Masoleh*, A S Atmadipoera2, M Purba2

1Graduate Program in Marine Sciences, Bogor Agricultural University, Bogor, Indonesia
2Physical Oceanography Laboratory, Dept. of Marine Science and Technology-IPB, Bogor, Indonesia

*E-mail: vanessamasoleh@yahoo.com

Abstract. Equatorial Pacific Rossby waves may enter into the interior of the Indonesian Throughflow (ITF)'s eastern pathway, such as along the Outer Banda Arcs (OBA). This study aimed to investigate the dynamics of the ITF along the OBA channel from Ceram Sea to Aru Basin to Western Timor Passage. This is necessary because it can provide information about the physical oceanographic conditions, especially the dynamics of the current in the study area. Based on the Hovmoller diagram, a propagation of the signal from kinetic energy was found along the OBA which its phase speed theoretically appears to be trapped in Rossby waves, because of the similarity of the speed phase. The normal mode analysis shows that the oscillation in Ceram Sea, Aru Basin, and Timor Passage has the same pattern based on the potential density and Brunt-Vaisala frequency profiles. The transport’s coherence between Indo-Pacific meridional winds and transport volume in Aru Basin shows a strong coherence value (0.94) which is dominated by an annual variability with a period of 341 days. The results suggest that zonal winds along the equator Pacific Ocean act as a remotely forced Rossby waves that propagate westward, entering the interior of Indonesian Seas.

Keywords: current, ocean, signals

1. Introduction

Indonesian seas connect the Pacific Ocean and the Indian Ocean which leads it being called the Indonesian Throughflow (ITF), which plays an important role in regulating the patterns of oceanic and atmospheric circulation [1, 2]. The ITF occurs due to the difference in pressure gradients between the Western Pacific Ocean and the Eastern Indian Ocean [3] as a result of the blowing of the Southeast Trade Winds toward the equator. The ITF circulates seawater from the western Pacific Equator to the Indian Ocean and its water mass originates from the North Pacific and South Pacific [4]. The currents move along the western boundary - known as the Western Boundary Current (WBC) - in the tropical side of the Pacific Ocean passing through the Equator which then become the ITF [5, 6]. The ITF enters the Indonesian seas and carries the North Pacific Subtropical Water (NPSW) mass in the thermocline layer, characterized by maximum salinity, and North Pacific Intermediate Water (NPIW) mass in the lower layer of the thermocline, characterized by minimum salinity [7, 8]. ITF water mass transforms when it enters Indonesian seas before it exits the Indian Ocean. The total salinity of NPSW when
entering Indonesian seas was 34.90 psu and decreased to 34.63 psu in the exit, while the minimum salinity for NPIW was 34.35 psu and changed to 34.47 psu in the exit [9].

The transformation of the Pacific Ocean water mass to Indonesian seas mostly occurs in the Banda Sea through a mixing process, warm water flux and cold water flux, and upwelling. Seasonal cycles of upwelling and downwelling is generated by Ekman currents in Banda Sea which produce seasonal oscillations at 40 m depth and form a thermocline layer 0.33 m from the sea surface [9]. Ocean currents signal propagation were found in deep waters in the eastern part of Timor Sea that flow from Banda Sea to Timor Trench in 1250 m depth [10]. This paper aims to investigate the dynamics of the ITF along the Outer Banda Arcs (OBA) channel from Ceram Sea to Aru Basin to Western Timor Passage. The existence of signal propagation of the Rossby wave crosses along the Other Banda Arcs, which is influenced by the dynamics (remote forcing) of the Pacific Ocean, so this study can provide a better understanding of the physical oceanographic conditions especially the dynamics of currents in the Outer Banda Arcs.

2. Materials and Methods

2.1. Study area

This study took place along the Outer Banda Arcs (OBA), restricted to areas between 2.5°S-11°S and 125.5°E-134°E (figure 1). Data analysis and processing were conducted at the Laboratory of Physical Oceanography, Department of Marine Science and Technology, Bogor Agricultural University.

![Figure 1. Study area along OBA consisted of three transects: A) normal mode analysis in Ceram Sea (2.5°S and 130.2°E), B) normal mode analysis in the Basin Aru (6.2°S and 133.7°E), and C) normal mode analysis in Timor Passage (8.9°S and 127.4°E).](image)

2.2. The data

2.2.1. INDESO model outputs. This study used the output from the Ocean General Circulation Model (OGCM) with configuration of Infrastructure Development for Space Oceanography (INDESO) from January 2008 to December 2014 (7 years). The model has a horizontal resolution of 1/12° (~9.25 km) and 50 depth levels. The data were developed by Mercator Ocean in collaboration with Collecte Localization Satellites (CLS) to provide data to the Ministry of Marine Affairs and Fisheries of Indonesia for oceanographic development in the Marine Observation and Research Institute (BROL) Perancak - Bali. Data output consists of daily zonal and meridional components of currents, temperature and salinity. INDESO data can be accessed through the website http://www.indeso.web.id/.
2.3. Data analysis

Data were processed and analysed by a Hovmoller diagram which was calculated from the Kinetic Energy (KE) of zonal and meridional components to see the circulation patterns along OBA, with the following equation:

\[ KE = \frac{1}{2} \rho V^2 \]  

(1)

Notes: \( \rho \) is seawater density and \( V \) is total current of zonal and meridional components.

Normal mode analysis was used to see the oscillations of wave propagation. It was assumed that the pressure components, density and velocity components \( (u, v) \) and \( w \), respectively, can be separated into vertical and horizontal variables [11]. The vertical Eigen function \( \psi_n(z) \) of \( n \) mode number refers to [12];

\[ \frac{d}{dz} \left( \frac{1}{N_b^2} \frac{d\psi_n(z)}{dz} \right) = -\frac{1}{c_n^2} \psi_n(z) \]  

(2)

Notes: \( N_b = \left[ -(g/\rho)\frac{d\rho}{dz} \right]^{1/2} \) is Brunt-Vaisala frequency and \( c_n \) is phase speed for \( n \) mode, where the Eigen function \( \psi_n(z) \) is normalized so that \( \psi_n(z) = 1 \).

The equation to obtain the horizontal Eigen function is as follows;

\[ (u, v) = \sum_{n=0}^{N} (u_n(x, y, t), v_n(x, y, t))\psi_n(z) \]  

(3)

In this calculation, the barotropic mode \( (n=0) \) is ignored with respect to the baroclinic response. Each Eigen function expresses the oscillation type of the wave propagation system, and the Eigen function is the solution of the system which is known as the normal mode oscillation of the system.

Furthermore, Cross-Power Spectral Density (cross-PSD) was applied to analyse the periodicity of significant energy of two data of time series, for example time series of transport volume in Aru Basin and time series of meridional winds in Indo-Pacific. The correlation between them can be analyzed from the coherence and phase values. The results of the cross-PSD are the co-spectrum of energy which shows the amount of energy fluctuations at the same frequency between two data, coherence that shows correlation value on the same frequency between two data, and phase difference which shows the time lag between two variables. Cross-PSD calculation follows the equation in [13].

3. Results and Discussions

3.1. Signal propagation of kinetic energy along OBA

The Hovmoller diagram found a strong signal of Rossby wave propagation from kinetic energy along the OBA (figure 2). It was estimated that the phase speed of wave propagation at 5 m depth ranged between 3.1 cm s\(^{-1}\) to 23.7 cm s\(^{-1}\) with the average phase speed of around 8.7 cm s\(^{-1}\). Phase speed of wave propagation at 155.9 m depth was about 3.1 cm s\(^{-1}\) to 17.4 cm s\(^{-1}\) while the average phase speed was around 11.1 cm s\(^{-1}\) (table 1). This, theoretically, appeared to be trapped Rossby waves, which is consistent with previous study [14], which obtained an estimated phase speed of Rossby waves ranging around 5-60 cm s\(^{-1}\).
Figure 2. Hovmoller diagram along OBA at (a) 5 m and (b) 155.9 m.

Table 1. Phase speed signal of wave propagation from kinetic energy along OBA.

| No | Year | At 5 m depth | At 155.9 m depth |
|----|------|--------------|-----------------|
|    |      | Phase speed (m s\(^{-1}\)) | Phase speed (cm s\(^{-1}\)) | Phase speed (m s\(^{-1}\)) | Phase speed (cm s\(^{-1}\)) |
| 1  | 2008 | 0.237        | 23.7             | 0.174           | 17.4           |
|    |      | 0.061        | 6.1              | 0.125           | 12.5           |
| 2  | 2009 | 0.129        | 12.9             | 0.122           | 12.2           |
|    |      | 0.039        | 3.9              | 0.070           | 7.0            |
| 3  | 2010 | 0.058        | 5.8              | 0.142           | 14.2           |
|    |      | 0.044        | 4.4              |                 |                |
| 4  | 2011 | 0.169        | 16.9             | 0.071           | 7.1            |
|    |      | 0.031        | 3.1              | 0.022           | 2.2            |
| 5  | 2012 | 0.163        | 16.3             |                 | 0.189           | 18.9           |
|    |      | 0.034        | 3.4              | 0.142           | 14.2           |
| 6  | 2013 | 0.079        | 7.9              | 0.091           | 9.1            |
|    |      | 0.046        | 4.6              |                 |                |
|    | 2014 | 0.094        | 9.4              |                 |                |
| 7  |      | 0.035        | 3.5              | 0.127           | 12.7           |
|    |      |              |                  | 0.031           | 3.1            |
| Total | 1.219 m s\(^{-1}\) | 121.9 cm s\(^{-1}\) | 1.567 m s\(^{-1}\) | 156.7 cm s\(^{-1}\) |
| Average | 0.087 m s\(^{-1}\) | 8.7 cm s\(^{-1}\) | 0.111 m s\(^{-1}\) | 11.1 cm s\(^{-1}\) |

3.2. Oscillation of ITF along OBA

The results of the normal mode analysis show that the oscillation of wave propagation in the Ceram Sea, Aru Basin, and Timor Passage has almost the same pattern based on the potential density profiles and Brunt-Vaisala frequency. The first vertical mode did not have a crossing point so that the current in the first mode flows southward in Ceram Sea and Timor Sea, while the current in Aru Basin headed northward (figure 3 & figure 5). The second vertical mode had a zero-crossing point of around 187 m in depth, with the current direction to the north was over 187 m in depth and to the south less than 200 m in depth. The third vertical mode had two zero-crossing points; one was around 133 m in depth and another crossing around 266 m in depth with the current direction to the south at over 130 m in depth and to the north around 150 – 260 m in depth and to the south at over 266 m in depth.
Horizontal velocity structure shows that the first horizontal mode has a zero-crossing point of around 210 m in depth. The currents in the Ceram Sea and Timor Passage had the same direction to the west at over 200 m in depth and to the east less than 230 m in depth, while the Aru Basin showed the opposite direction (figure 4). The second horizontal mode had two crossing points; one was around 100 m in depth and the second was around 320 m in depth. The third horizontal mode had the first zero-crossing at around 70 m in depth, the second around 200 m in depth and the third around 400 m in depth.

Figure 3. Profiles of potential density, Brunt-Vaisala frequency, vertical velocity structure and horizontal velocity structure in Ceram Sea (2.5°S and 130.2°E).

Figure 4. Profiles of potential density, Brunt-Vaisala frequency, vertical velocity structure and horizontal velocity structure in Aru Basin (6.2°S and 133.7°E).
3.3. Coherence between zonal winds in Indo-Pacific and transport volume in Aru Basin

The results of cross-PSD analysis of the coherence between zonal winds in Indo-Pacific and transport volume in Aru basin display a strong coherence value (0.93) (figure 6). It is dominated by annual variability with a period of 341 days, showing that the signal fluctuation of the zonal winds in Indo-Pacific occurs before the Aru Basin’s transport signal, in accordance with previous study [15] where fluctuations of variability in Aru Basin were dominant in annual time-scale with average transport of -0.61 Sv to the south. High coherence areas in the Pacific Ocean were found in the Northern Pacific Subtropical and Equatorial, indicating that zonal winds become the driving force of currents in Aru Basin. The presence of zonal wind along the Pacific Ocean plays a role as a surface force generator that produces a Rossby wave response that propagates along the Western Pacific equator [16].

4. Conclusion

Signal of the ITF propagation was detected along OBA, that was found using a Hovmoller diagram with the estimated average phase speed of Rossby waves. Oscillation of wave propagation in Ceram Sea,
Aru Basin and Timor Passage has almost the same pattern based on potential density profiles and Brunt-Vaisala frequencies. For this reason, it is believed that the oscillation is due to the arrival of Rossby waves. Fluctuation of currents in the study area is remotely forced by subtropical and equatorial Zonal winds in central Pacific Ocean through the Equatorial Rossby waves. This is interesting for mankind because it provides information to fishermen that the ITF signal propagation that can detect upwelling was revealed in the study area, meaning that the waters are rich in fishery resources.

Acknowledgments

The Authors would like to thank BPOL Perancak Bali and CLS Toulouse France and also thank INDESO Project, especially to Dr. Phillipe Gaspar, Dr. Benoit Tranchant, Dr. Ariane Koch-Larrouy and Berny Subki MSc. Suggestions from Reviewers for the refinement of this article are greatly appreciated.

References

[1] Sprintall J, Gordon A L, Koch-Larrouy A, Lee T, Potemra J T, Pujiana K and Wijffels S E 2014 The Indonesian seas and their role in the coupled ocean–climate system Nat. Geosc. 7 487-492
[2] Miyama T, Awaji T, Akitomo K and Imasato N 1995 Study of seasonal transport variations in the Indonesian Seas J. Geophys Res. 100 20517-20541
[3] Wyrtki K 1987 Indonesian throughflow and the associated pressure gradient J. Geophys Res. 92(C12) 12914-12946
[4] Hasanudin M 1998 Arus lintas Indonesia (ARLINDO) Ocean. 23 1-9
[5] Lee T, Fukumori I, Menemenlis D, Xing Z and Fu L 2002 Effect of the Indonesian throughflow on the Pacific and Indian Oceans J. Phys Oceanogr. 32 1404-1429
[6] Kashino Y, Watanabe H, Herunadi B, Aoyama M and Hartoyo D 1999 Current variability at the Pacific entrance of the Indonesian throughflow J. Geophys Res. 15 11021-11035
[7] Hautala S L, Reid J L and Bray N 1996 The distribution and mixing of Pacific water masses in the Indonesian Seas J. Geophys Res. 101 375-389
[8] Atmadipoera A, Molcard R, Madec G, Wijffels S, Sprintall J, Koch-Larrouy A, Jaya I and Supangat A 2009 Characteristics and variability of the Indonesian throughflow water at the outflow straits Deep-Sea Res. I. 56 1942-1954
[9] Gordon A L 2005 Oceanography of the Indonesian seas and their throughflow Oceanogr. 18 14-27
[10] Van Bennekom A J 1988 Deep-water transit times in the eastern Indonesian basins, calculated from dissolved silica in deep and interstitial waters Nether. J. Sea. Res. 22 341-354
[11] Emery W J and Thomson R E 2014 Data Analysis Methods in Physical Oceanography (Waltham: Elsevier)
[12] Iskandar I, Tozuka T, Sasaki H and Masumoto Y 2006 Intraseasonal variations of surface and subsurface currents off java as simulated in a high-resolution ocean general circulation model J. Geophys. Res. 3 1-15
[13] Bendat J S and Piersol A G 2010 Random Data Analysis and Measurement Procedure (New York: John Wiley and Sons Inc)
[14] Meyers G 1979 On the annual rossby wave in the tropical North Pacific ocean J. Phys. Oceanogr. 9 663–674
[15] Masoleh V C and Atmadipoera A S 2018 Coherence of transport variability along Outer Banda Arc IOP. Conf. Ser.: Earth. Environ. Scienc. 176 012012
[16] Wijffels S and Meyers G 2003 An intersection of oceanic waveguides: variability in the Indonesian throughflow region J. Phys. Res. 34 1232-1253