Coherence of transport variability along outer Banda Arcs

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Abstract. Previous study hypothesized that the Pacific equatorial waves could enter into the interior Indonesian Seas and influenced the Indonesian Throughflow (ITF) along its eastern pathway. Here we investigate the variability of volume transport in the upper 500 m depth and its coherency along the outer Banda Arcs (OBA) channel from Ceram Sea (CS) to Aru Basin (AB) to western Timor Passage (TP) using daily INDESO model output (2008-2014). As expected, mean volume transport along OBA is in clock-wise direction: +1.04 (±1.54) Sv eastward in CS, -0.61 (±0.79) Sv southward in AB, and -8.42 (±2.05) Sv westward in TP, respectively. The vertical structure of currents is prominently intensified in the upper 300 m layer. Scales of transport variability in CS and AB are dominated by annual period with secondary in intraseasonal (ISV) period. In contrast, TP dominant periodicities are on the semiannual and ISV scales. Transport variability on ISV 30-43 days period among CS - AB - TP shows a significant coherence (>0.8) and phase difference (2-5 days) with signal in CS leading to AB and TP. This suggests a presence of Pacific equatorial waves which propagate along OBA channel.

1. Introduction
The Indonesian Throughflow (ITF) is a current system influenced by the thermocline of the North Pacific Ocean, which flows into Indonesian waters through two main routes, namely, the west path through the Sulawesi Sea and the eastern path through the Halmahera Sea and the Maluku Sea, where the components of ITF comprise water masses from the North Pacific and South Pacific [1, 2]. The ITF current system plays an important role in the formation of ENSO, which affects the global climate in channeling the Pacific Ocean to the Indian Ocean, where the stronger ITF transport occurs in the La Nina period (West Pacific is warmer) and weakens in the El Nino period (West Pacific is cooler) [3, 4]. The ITF varies seasonally, with the highest transport rates being found during the Southeast Monsoon (SEM, June to August) while the lowest transport during the Northwest Monsoon (NWM, December to February) [5, 6, 7].

The North Pacific water mass flow into Indonesian waters from Mindanao Current through the Sulawesi Sea to the Makassar Strait and then 20% of the water mass passes through the Lombok Strait and the rest follows the Flores Sea and Banda Sea [8]. Previous studies show that upon entering Indonesian waters, characteristics of ITF's water masses are changed into a considerable transformation, in areas closed to Sangihe undergoing a transformation of 40%, in Makassar Strait and the Flores Sea 30%, in the Halmahera Sea, Maluku Sea and Ceram Sea at 26 %, and in the Strait of Ombai and Timor by 26% while in the Banda Sea, Java Sea, and in the Indian Ocean, the masses are transformed in the opposite direction with the total transformation of each region are -15%, -2%, and -3%, respectively [9, 10]. According to [11], the propagation of the Rossby Pacific wave signal trapped offshore from the western tip of New Guinea spreads, which propagate poleward along west coast of Australia, in response to the Pacific zonal winds. Also visible is the propagation of the Rossby wave to the west across the
Banda Sea and into the subtropical south Indian Ocean within of 1500 km, in response to the Equatorial Pacific wind energy. This paper aims to investigate the variability of volume transport in the upper 500 m depth and its coherence along the outer Banda Arcs (OBA) channel from Ceram Sea (CS) to Aru Basin (AB) to western Timor Passage (TP).

2. Data and data analysis

2.1. Study area
This study was conducted in Banda Sea and its adjacent seas, which focused on outer Banda Arcs (Ceram Sea, Aru Basin, and Timor Passage) (figure 1). Data processing and analysis was carried out in Physical Oceanography Laboratory, Marine Science and Technology Department, Bogor Agricultural University.

2.2. The data

2.2.1. INDESO model outputs. The data source of this research was obtained from the INDESO (Infrastructure Development for Space Oceanography) project of the Ministry of Fisheries and Marine Affairs. The INDESO model used the NEMO ocean general circulation model with specific configuration within the domain model in Indonesian Seas and adjacent waters (90°E-145°E; 25°S-20°N), including detailed bathymetry, explicit tidal forcing and mixing parameterization. Model simulation was performed at the Marine Observation and Research Institute (BPOL) Perancak Bali and at CLS (Collecte Localisation Satellites) Toulouse France. Model configuration was described in [12]. The model output data consist of daily zonal and meridional current components, seawater temperature, and salinity time-series data spanning from January 2008 to December 2014 (7 years). The data could be accessed through the website http://www.indeso.web.id/. The INDESO data is averaged daily simulation data results with horizontal resolution 1/12° (9.25 km) and 50 depth levels.

2.2.2. Model validation. The validation of INDESO model output with satellite observation and field current measurement data in the study area (Banda Sea) was performed by [13, 14]. They reported that correlation between model sea surface temperature (SST) and satellite SST data was reasonably high (r=0.95). Fluctuation of model SST and the satellite data was in phase [13]. Comparison of model current vector and observed shipboard Acoustic Doppler Current Profiler (ADCP) data during the INDOMIC cruise in July 2010 showed a good agreement between the model and observation, where upper-surface eddies in Banda Sea and strong persistent Indonesian Throughflow current vectors in Ceram and Ombai
Straits were well reproduced by the model [14]. In addition, general model validation of INDESO model output was also described in [12].

2.3. Data analysis

Analyses of time-series data of zonal and meridional components at each section in Ceram, Aru and Timor Passage were performed using Cross-Power Spectral Density (Cross-PSD) method [15], and Continuous Wavelet Transform (CWT) method [16] to examine periodicity from current component and volume transport time-series.

Volume transport estimate at each section (A, B and C in Fig.1) was calculated using the equation below [17]:

\[
Q_{u_A} = \int_A^B \int_0^L u \, dy \, dz
\]

(1)

\[
Q_{v_B} = \int_B^C \int_0^L v \, dx \, dz
\]

(2)

\[
Q_{u_C} = \int_C^A \int_0^L u \, dy \, dz
\]

(3)

where \(Q_{u_A}, Q_{v_B}, \) and \(Q_{u_C}\) are volume transport estimates (in Sverdrup Sv; 1Sv=10\(^6\) m\(^3\)/s) at Ceram section (A), Aru section (B), and Timor section (C) by integral operation taking account of a length of section (m), depth integration (0-500 m), and zonal and meridional current components (u and v).

The wavelet analysis aims to find out time-frequency or time-period distribution within time-series data, i.e. how the power changes over [16]. In this research, CWT analysis was applied to volume transport times-series data in Ceram, Aru and Timor sections. Following [17], the CWT equation is expressed as follows:

\[
C(\text{scale}, \text{position}) = \int_{-\infty}^{\infty} f(t) \psi(\text{scale}, \text{position}, t) \, dt
\]

(4)

which \(C\) is wavelet coefficients; \(f(t)\) is time series data; \(\psi\) is mother wavelet. The CWT Analysis is using wavelet as band pass filter which grouped in time and scale, so \(\eta = s, t\) and normalized in unit of energy.

Power Spectral Density (PSD) Analysis was used to find out the significant energy peaks for respective periods within times-series data with 95% confidence interval. In this research, length of the time-series data (N) is 2557 and segment length used for PSD calculation is 1024. Following [15], the PSD of each volume transport time-series was estimated using the equation, as follows:

\[
X_i(f_k) = \Delta t \sum_{n=0}^{N-1} x_{in} \exp\left[-\frac{j2\pi kn}{N}\right]
\]

(5)

Which \(X_i(f_k)\) is Fourier components; \(x_{in}\) is data values, \(n = 0, 1, ..., N-1, i = 1,2, ..., n_d; k = 0,1, ..., N/2\).

The cross-PSD (cross-Power Spectral Density) analysis method was used to find out shared periodicity from both time-series data. Their degree of correlation is indicated by its normalized coherence value, which varies from minimum (0) to maximum (1). In this research, cross-PSD analysis was used to obtain correlation between time-series data of volume transport in Ceram Sea (Q\(_{a}\)) vs Aru (Q\(_{a}\)); in Aru (Q\(_{a}\)) vs in Timor (Q\(_{a}\)); and in Ceram (Q\(_{a}\)) vs in Timor (Q\(_{a}\)).

The result of cross-PSD analysis is co-spectrum energy that shows magnitude of energy fluctuations at specific frequency within both of times-series data; coherency and phase show correlation and phase difference (lag or lead) at specific frequency within both of time-data series. Positive phase means one time-series leads (or proceed) to another series in contrary to negative phase to be lag to another series. According to [15], co-spectrum estimate is calculated by using equation:

\[
G_{XY}(f_k) = \frac{2\Delta t}{T} \left| X(f(k)) * Y(f(k)) \right|
\]

(6)
where $G_{XY}(f_k)$ is density spectrum of cross energy in frequency to-$k$ ($f_k$); $f_k$ is the discretized frequencies, where $f_k = k/Nh; k = 0, 1, 2, ..., N-1$; $X(f_k)$ is Fourier component from ($xt$); $Y(f_k)$ is Fourier component from ($yt$); $\Delta t$ is time cross sampling data (1 day); $T$ is data period. 

Coherence value is calculated by using this equation [15]:

$$y^2_{XY}(f_k) = \frac{|S_{xy}(f_k)|^2}{S_x(f_k)S_y(f_k)}$$

(7)

where $y^2_{XY}(f_k)$ coherence is value in frequency to-$k$ ($f_k$); $S_{xy}(f_k)$ is density spectrum of cross energy in frequency to-$k$ ($f_k$); $S_x(f_k)$ is density spectrum energy $X(f_k)$; $S_y(f_k)$ is density spectrum energy $Y(f_k)$ in frequency to-$k$ ($f_k$). 

Phase different value is calculated by using this equation [15]:

$$\theta_{XY}(f_k) = \tan^{-1}\left[\frac{Q_{xy}(f_k)}{C_{xy}(f_k)}\right]$$

(8)

where $Q_{xy}(f_k)$ imaginer is value from $G_{XY}(f_k)$; $C_{xy}(f_k)$ is real value from $G_{XY}(f_k)$.

3. Results and discussion

3.1. Mean structure of ITF along outer Banda Arcs

Figure 2 shows the circulation pattern of ITF average transport along the outer Banda Arcs within the three study areas: Ceram Sea, Aru Basin, and Timor Passage. In the Ceram Sea, the average flow of ITF is dominant to the East with a current velocity of about 0.20 m/s at depth above 150 m. The average flow rate of ITF in Aru Basin is about 0.12 m/s at depth above 110 m, with the dominant flow direction to the South.

According to [5], the flow of ITF at depth above 200 m is caused by the strong gradient pressure difference between the Pacific and Indian Oceans. The circulation pattern in Timor Passage has a unique pattern in which the average speed of ITF is about 0.40 m/s flowing Westward from the surface (0 m) to the depth of 380 m, and the reversal of the current flow direction to a depth below 400 m with the average current velocity by 0.04 m/s (figure 2c). The reversal of the currents to the East is the response of Kelvin wave occurring due to the zonal wind anomalies in the equatorial Indian Ocean [18, 19].

Figure 2. Mean structure of ITF along outer Banda Arcs; (a) mean structure in Ceram Sea at 130°E, (b) mean structure in Aru Basin at 6°S, (c) mean structure in Timor Passage at 126°E.
3.1.1. Annual cycle. The annual cycle of marine circulation in the study area varied on a seasonal basis. In the Northwest Season (December-February), the direction of current flow in the Ceram Sea is predominantly Westward with a current velocity of about 0.28 m/s at depth above 200 m (figure 3) while in the transition season I (March-May), there is a reversal of the current direction at a depth below 100 m to the East, so that in the Southeast (June-August) the direction of the dominant current flow to the East with the current velocity is stronger than that of in the Northwest Season which is about 0.40 m/s. In addition, water mass propagation is indicated in South Pacific flowing into the Banda Arcs through Ceram Sea by bringing in high-energy water mass [1].

The direction of current flow in the Aru Basin in the Northwest Season is dominant to the North at a depth above 200 m, with a current velocity by 0.08 m/s. This is expected due to the mass water input from the Indian Ocean while in the Southeast, the current flow is dominant to the South with a current velocity by 0.16 m/s (figure 4). In the Southeast Season, the mass of Northern Subtropical Lower Water is indicated in the Pacific through the Ceram Sea and Irian Jaya [20].

In the Timor Passage, the flow of currents tends to have the same pattern, with a current velocity of about 0.40 m/s continuously moving westward (figure 5). However, in the Southeast Season, there is a reversal of current flow with a current velocity of 0.80 m/s at a depth below 400 m in accordance with previous research [21]. The direction of maximum ITF flow occurs during the Southeast Season as a response of local winds occurring in the study area.

**Figure 3.** Annual cycle of zonal component (Ceram Sea at 130°E).

**Figure 4.** Annual cycle of meridional component (Aru Basin at 6°S).
3.2. Transport variability of ITF along outer Banda Arcs

The ITF volume transport of Ceram Sea (CS) from January 2008 to December 2014 is presented in figure 6a. The transport fluctuation ranges between -3 Sv to + 2 Sv, with a mean of 1.04 Sv and a standard deviation of 1.54 Sv. In general, the volume transport of CS indicates its direction to be dominant to the West. Alindo transport dominant to the West occurs during the Southeast Season period, while in the North West Seasons the transport of ITF changes to the East (figure 6b).

In the Aru Basin (AB) area, the volume transport of ITF shows the range of fluctuations between -2 Sv to +1.5 Sv, with a mean of about -0.61 Sv and a standard deviation of about 0.79 Sv (figure 7a). In general, the maximum transport of ITF is more dominant to the South, with fluctuations in transport on an annual time-scale (figure 7b). The volume transport of ITF Timor Passage (TP) shows the range of -13 Sv to -3 Sv, with transport rate of around -8.42 and standard deviation of 2.05 Sv (figure 8a). The transport movement of ITF ST is dominated by an intra-seasonal time-scale, transport to the South.

Figure 5. Annual cycle of zonal component (Timor Passage at 126°E).

Figure 6. Time series of volume transports in the Ceram Sea with band-pass filter 31 days (a), and volume transport climatology (b).
Figure 7. Time series of volume transports in the Aru Basin with band-pass filter 31 days (a), and volume transport climatology (b).

Figure 8. Time series of volume transports in the Timor Passage with band-pass filter 31 days (a), and volume transport climatology (b).

The results of time series analysis using continuous wavelet transform (CWT) method for transport of ITF CS, AB, and TP from 2008 to 2014 show 3 periodicities of variability with intra-seasonal time-scale (20-90 days), semi-annual time-scale (180 days) and annual time-scale variability (360 days) (figure 9). The results of the CWT analysis in the CS region show that transport variability is dominated by annual time-scale fluctuations occurring from January 2008 to December 2014, with relatively high CWT coefficients (figure 9a). The CS transport variability also occurs on the semi-annual, which occurred in 2009, 2010, 2013 and 2014 with relatively small coefficient CWT.

The transport variability of ITF AB shows fluctuations on a more dominant annual time-scale in the region, starting from 2008 to 2014, with high CWT coefficient values occurring in 2010 to 2013 (figure 9b). AB transport fluctuations on a semi-annual scale appear in the first 3 years of 2008-2010 with relatively small CWT coefficients. AB transport variability on inter-seasonal time-scales occurs in the transitional period 2 (September-November).

The transport variability of ITF TP is dominated by fluctuations at semi-annual time-scales, with fairly strong CWT coefficients (figure 10c) while fluctuations in the intra-seasonal time-scales occurred during the Southeast of the period of 2008 to 2014.
3.3. Power spectral density time-series of transport ITF along outer Banda Arcs

Spectrums of the energy densities for the zonal and meridional components in the three study areas are presented in figure 10. Visually, the signal propagations among the Ceram Sea, the Aru Basin and the Timor Passage can be seen from the peak of the spectrum of significant energy densities found in the periods of 20, 24, 26, 43, 171, 341 days, where the current time-series data are dominated by annual, semi-annual, and intra-seasonal fluctuations.

3.4. Coherence and phase time-series transport variability ITF along outer Banda Arcs

3.4.1. Coherence and Phase Time-Series Transport Variability between Ceram Sea and Aru Basin. The analysis results of Cross-PSD time series of ITF transport between the Ceram Sea and the Aru Basin show that the significant coherence values occurred on annual, semi-annual, and intra-seasonal time-scales, in 341 days, 171 days, 43 days, 26 days, 24 days, and 20 days (figure 11). The highest coherence value (0.9689) occurs in a 341 day period with a 26.5 days different phase difference, which means the signal fluctuation of the Ceram Sea appears earlier than the Aru Basin signal. The second largest coherence value is 0.9127 with a phase difference of 2 days. Furthermore, for the coherence value from
the periods of 171 days, 43 days, 24 days and 20 days respectively is 0.8168 with a phase difference of 13.8 days, 0.8373 (2.5 days).

**Table 1.** Coherence and time series phase of transport variability between the Ceram Sea and the Aru Basin.

| Period (days) | Coherence | Phase (days) |
|---------------|-----------|--------------|
| 341           | 0.9689    | 26.5         |
| 171           | 0.8168    | 13.8         |
| 43            | 0.8373    | 2.5          |
| 26            | 0.9127    | 2            |
| 24            | 0.8089    | 1.3          |
| 20            | 0.8624    | 1.3          |

3.4.2. Coherence and phase time-series transport variability between Aru Basin and Timor Passage.

Figure 12 shows the results of Cross-PSD analysis of the ITF transport time series between Aru Basin and Timor Passage having significant coherence values occurring on an intra-seasonal, semi-annual and annual time-scales. The highest coherence value of 0.8682 occurs in a period of 43 days with a 5-days phase difference. This suggests that the Aru Basin propagation signal emerged earlier than that of the Timor Passage. In the periods of 341 days, 171 days, 26 days, 24 days and 20 days, coherence values of 0.8285 (2.6 days), 0.6214 (8.4 days), 0.7025 (3 days), 0.7962 (2.7 days) and 0.7931 (2.3 days) were obtained. This means that the Aru Basin signal flowing into the Timor Passage takes 2.3 days to 8.5 days (table 2).

**Figure 11.** Coherence and phase time-series volume transport between the Ceram Sea and the Aru Basin.

**Figure 12.** Coherence and phase time-series volume transport between the Aru Basin and Timor Passage.
Table 2. Coherence and time series phase of transport variability between the Aru Basin and Timor Passage.

| Period (days) | Coherence | Phase (days) |
|---------------|-----------|--------------|
| 341           | 0.8285    | 2.6          |
| 171           | 0.6214    | 8.4          |
| 43            | 0.8682    | 5            |
| 26            | 0.7025    | 3            |
| 24            | 0.7962    | 2.7          |
| 20            | 0.7931    | 2.3          |

3.4.3. Coherence and phase time-series transport variability between Ceram Sea and Timor Passage.

The coherence analysis of zonal component shows the highest coherence value (0.8917) in the 20 days period (table 3), in which the propagation signal in Timor Passage preceded the Ceram Sea with a difference of 1 day phase. The coherence values on the intra-seasonal scale in the periods of 43 days, 26 days, and 24 days respectively are 0.6798 (1.8 days), 0.8537 (1.5 days), and 0.5969 (0.7 days). This indicates that the Timor Passage signal is earlier than that of the Ceram Sea.

Table 3. Coherence and time series of transport variability between the Ceram Sea and the Timor Passage.

| Period (days) | Coherence | Phase (days) |
|---------------|-----------|--------------|
| 341           | 0.8696    | 28.5         |
| 171           | 0.8253    | 19.4         |
| 43            | 0.6798    | 1.8          |
| 26            | 0.8537    | 1.5          |
| 24            | 0.5969    | 0.7          |
| 20            | 0.8917    | 1            |

4. Conclusion

The annual cycle of ITF along the Banda Sea bow is characterized by a stronger flow rate in the Southeast Season compared to that of the North West Season. The volume of transport of ITF of the Ceram Sea ranges from -3 Sv to +2 Sv, with an average of 1.04 Sv (± 1.54 Sv) to the East. In the Aru Basin, the average volume transport is about -0.61 Sv and the standard deviation is about 0.79 (± 0.79) Sv Southward and -8.42 (± 2.05) Sv Westward in the Timor Passage.

Transport variability in the Ceram Sea and the Aru Basin is dominated by fluctuations in semi-annual and annual time-scales, whereas in the Timor Passage, it is dominated by intra-seasonal and semi-annual
time-scales. A significant coherence exists between the Ceram Sea and the Aru Basin occurring over a 1.3 day period up to 26.6 days, with the a high coherence value of 0.9127 between the Ceram Sea and the Aru Basin with a phase difference of about 2 days.

The highest coherence value between the Aru Basin and Timor Passage is 0.8682 occurring in the 43 day period with 5 days phase difference. In the period of 20 days, the highest coherence value between Ceram Sea and Timor Passage with phase difference about 1 day was obtained. This indicates that there is an indication of the propagation of the equatorial wave signal from the Ceram Sea to the Timor Passage along the outer Banda Arcs.

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