Indonesian Throughflow (ITF) variability in Halmahera Sea and its coherency with New Guinea Coastal Current

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Abstract. The Indonesian Throughflow passing through the Halmahera Sea (H-ITF) is supposed to be supplied by the western boundary current system, particularly from the New Guinea Coastal Current (NGCC). However, characteristics of H-ITF and NGCC is not well understood yet. This paper aims to investigate vertical structure, transport volume estimate, and transport variability of H-ITF and its coherency with NGCC in the upper 200 m depth. The dataset are obtained from daily INDESO model output (2008-2014). H-ITF across latitude of 0.3\(^\circ\)S is indicated by a strong intensified southward flow in upper 150 m with 67.2 km width, and mean transport volume 2.35 (±1.94) Sv (southward). Furthermore, NGCC across 134\(^\circ\)E is characterized with 291.2 km width, strong velocity core (>0.4 m/s) in the upper 200 m depth, and transport volume 13.47 (±6.6) Sv (westward). The model indicated that H-ITF is supplied by 17.45% of NGCC. Variability of H-ITF is dominated by intraseasonal period. High coherence (0.85) between H-ITF and NGCC transport is revealed on intraseasonal (45-day) period, with NGCC signal is 4.86 days leading to H-ITF. This signal may be associated with a passage of westward equatorial Pacific waves into Halmahera Sea.

1. Introduction
The main inflow of ITF is known as the western path from the Mindanao Current (MC) that flows over the top of the thermocline carrying North Pacific Subtropical Water (NPSW) and the North Pacific Intermediate Water (NPIW). This branch fills the Indonesian Sea through the Sulawesi Sea and then flows through the Makassar Strait. This ITF branch flows out to the Indian Ocean through the Lombok Strait and eventually reaches the Flores Sea and the Banda Sea to finally exit through the Ombai Strait or the Timor Passage [1,2].

In addition to the western path, the ITF inflow also passes the eastern path with two routes available. The first route is via Maluku Sea, bringing the South Pacific Intermediate Water (SPIW) from the Maluku Sea to the Lifamatola Strait to the Banda Sea and then through the Ombai Strait or the Timor Passage to the Indian Ocean. The second route via Halmahera Sea (H-ITF) brings the South Pacific Subtropical Water (SPSW) through Halmahera and the Seram Sea and eventually joins the first eastern route of the Banda Sea. Shallower waters from the South Pacific enter through the passages that line the Halmahera Sea [3,4]. Water mass in Halmahera Sea (HS) is different from other Indonesian waters because it is influenced by the presence of equatorial currents dynamics and warm pools that have a major effect on ocean-atmosphere interactions. Warm pools are caused by a year-round blowing Trade winds that drags the masses of tropical warm water to the western tropical Pacific Ocean and then accumulates in the Tropical Western Pacific region covering the waters of Halmahera and Northern Papua. These territorial waters also have complex current dynamics that may be caused by complex configuration of bathimetry. There are several currents that play a role in transporting water masses in this area such as...
Mindanao Current (MC), New Guinea Coastal Current (NGCC), New Guinea Under Current (NGCUC), North Equatorial Counter Current (NECC), Halmahera Eddies (HE), and Mindanao Eddies (ME) [5, 6, 7, 8, 9].

The circulation and transport within the Indonesian seas has a large seasonal variation due to the influence of the reversing annual winds filed associated with the Asian-Australian monsoon system [10,11,12]. Several studies of the ITF transport which pass through the HS from the measurement and modeling have been reviewed previously. The results of measurements made by [6] noted of 1.5 Sv (1 Sv=10⁶ m³ s⁻¹) transport volume leads to the south from the average measurement of one year mooring. Measurement results by [13] in Lifamatola showed that this path brings about 2.5 Sv mass of water coming from the Southern Pacific Ocean from the deeper layers (South Pacific Subtropical Lower Thermocline Water / SPSLTW) through the Maluku Sea to the Banda Sea.

However, it is not yet possible to estimate the amount of water mass carried through this eastern path due to other water mass inputs on the eastern path, through the HS [14,15]. Apart from the measurement results, the estimated transport passing through the HS from the modeling analysis is also done by Morey et al. [16] using the Navy Layered Ocean Model (NLOM), found the 3 Sv transport within the thermocline and the intermediate layer; [17] using the Parallel Ocean Climate Model (POCM), 2.2 Sv flow to the south in the HS; [18] using NEMO Ocean General Circulation Model, 0.8 Sv.

Although there is already a study of transport in the HS, there is no specific study of the dynamics and variability of Halmahera ITF (H-ITF) and its relation to NGCC/NGCUC. The purpose of this study is to investigate the structure and characteristics of H-ITF, and the variability of the H-ITF transport and its coherence with NGCC.

2. Data and data analysis

2.1. Study area
This study was conducted from March to June 2017 in the Physical Oceanography Laboratory, Department of Marine Science and Technology (ITK) - FPIK IPB Bogor. The study area includes one transect in HS (0.3°S, 128°E- 132°E) and one transect in the North of New Guinea (134°E, 2.2°N - 0.6°S) (figure 1).

![Figure 1. Study area in the Halmahera Sea and its adjacent waters in western equatorial Pacific Ocean. Lines that perpendicular (A) and parallel (B) denote sections for NGCC/NGCUC and H-ITF transport calculations. The location of the vertical current profiles (denoted by the star symbols).](image)

2.2. The data
2.2.1. INDESO model outputs. Model outputs from a series of simulation of NEMO ocean general circulation model of Infrastructure Development of Space Oceanography (INDESO) configuration,
performed by the CLS France & BPOL Bali, were used in this study. The outputs of data-series span from January 1st 2008 to December 31st 2014. INDESO is a scientific cooperation program at the Ministry of Marine Affairs and Fisheries with a consortium of joint European Marine Research Institute (MERCATOR-Ocean and Collecte Localisation Satellites - CLS) France. Daily average of 3-dimensions ocean current fields were used for this study.

2.3. Data analysis
Characteristics of circulation and current variability in the study area were assessed by applying time-series analysis, i.e. calculating the mean value of zonal component current (134°E, 0.6°S - 2.2°N) and meridional (128°E – 132°E, 0.3°S) from 2008-2014, Continuous Wavelet Transform (CWT) transformation analysis, cross-PSD (Power Spectrum Density) analysis, and EOF (Empirical Orthogonal Function) analysis, according to [19] and [20]. The mean flow aims to analyze general circulation patterns in the study area in spatial form. The climatological method is used to analyze the annual cycle of variable current and temperature. The EOF method is used to analyze the spatial and temporal variability of H-ITF and NGCC/NGCUC.

The estimated transport volume (0-200 m) of H-ITF passing the transect line of east Halmahera and estimated transport volume of NGCC were calculated by integrating the velocity of the zonal component current ($u$) for the estimated transport volume of NGCC ($Q_{u}$) and meridional components ($v$) to estimate the transport volume of H-ITF ($Q_{v}$) against transect length and depth, following [19].

$$Q_{uNGCC} = \int NGCC \int_{z}^{0} udydz$$

$$Q_{vHalma} = \int Halma \int_{z}^{0} vdxdz$$

where $Q_{uNGCC}$ is the total volume of NGCC that intersects line A (transect line in North Papua); $Q_{vHalma}$ (Sv unit) is the total transport volume of H-ITF cutting line B (line in eastern Halmahera); $z$ (200 m) is a lower limit of integration velocity to surface depth (0 m), and $u$ is zonal current component, while $v$ is meridional current component (m/sec).

2.4. Data validation
To assess a performance and reliability of the model results, a snapshot of current vector data from shipboard acoustic Doppler current profiler (SADCP) data from the INDOMIX cruise 2010 and the INDESO model output is overlaid on July 06 and July 10, 2010 at 50 m depth level (figure 2).

![Figure 2](image-url)

**Figure 2.** Comparison between observed current vectors from INDOMIX data (red) and modeled current vectors of INDESO model (black) at 50 m depth level on July 6, 2010 (left) and July 10, 2010 (right) in Halmahera Sea and adjacent waters.
SADCP measurements at 50 m depth level in along the northern coast of New Guinea show NGCC flows northwestward and turns eastward to Halmahera Island. Current vectors of INDESO model (black) similar with the observed current vectors from INDOMIX data (red), although model velocities being generally slightly weaker than observations. At some locations, magnitudes of current vector amplitude of INDESO model look a little weakened compared with observations such as the northern coast of New Guinea and the eastern of Halmahera. This is allegedly due to the difference in the resolution of the data where the INDESO model is the average spatial resolution of 9 km x 9 km, but the current observation INDOMIX data is the average 1 km. It can be said that INDESO model output can reproduce pretty good current vector of a the spatial pattern, so that the quality of the outcome a simulation model indeso can be used to further analysis in this study.

Evaluation of an operational ocean model configuration at 1/12 degrees spatial resolution for the NEMO (NEMO2.3/INDO12) physical ocean model covering the whole Indonesian Exclusive Economic Zone (IEEZ) in the framework of the INDESO has also been done through comparisons with various data sets including outputs of the parent model, climatologies, in situ temperature and salinity measurements, and satellite data [4].

3. Results and discussion

3.1. Characteristics of H-ITF
The averaged vertical structure of the meridional current component (v) of INDESO model from 2008-2014 at 0.3°S in the Halmahera Sea is presented in figure 3. ITF Halmahera is indicated by a southward strong current. The existence of H-ITF is characterized by a southward flow that is found from the surface to a depth of 200 m, with a speed magnitude exceeding 0.3 m/s, and it weakened as it approached the deeper depth (0.1 m/s). The magnitude velocity of the ITF within its core layer is 0.3 m/s, confined between the surface layer and a depth above 100 m. The width axis of ITF Halmahera was 72 km in the surface and narrowed further reaching a depth of 200 m. The southward flow in the Halmahera Sea was found from the surface to a depth of 700 m. The main driving force of the ITF flow in the upper 200 m layer was the differences in the strong sea level pressure between the Pacific Ocean and Indian Ocean so that the ocean current flows to the south throughout the year [21].

Figure 3. The cross-section of the averaged meridional current component (v) of H-ITF at 0.3°S; 129°E. The colors in meridional currents show the speed scale (m/s). The location of the current transect (figure 1).
3.2. The Annual Cycle of Meridional Component Current of H-ITF
The annual cycle of the meridional current component of ITF Halmahera (figure 4) shows that the current velocity became much stronger during the Southeast Monsoon-SEM (Jul-Aug-Sept) than that of Northwest Monsoon-NWM (Nov-Dec-Jan) period. In September, the intensification of ITF strengthens in the surface layer to almost 200 m (> 0.4 m/s). At a depth of 300 m - 650 m, the movement of current towards the south with the speed magnitude of 0.04 - 0.12 m/s in Halmahera Sea is found. The fluctuations of ITF during the NWM shows clearly a weaker intensity of ITF (on the surface to a depth of 200 m) when compared to that of the SEM.

The main current of ITF flowing during the SEM shows a stronger current velocity when compared to that of NWM. This implies that the transport volume of ITF was greater in the SEM compared to that in NWM, which is in good agreement with previous studies [22, 17, 12]. In the Transition Monsoon Break-TMB 2 (Oct-Nov), the current velocity of ITF Halmahera weakens. This is due to the reversal of the direction of the SEM winds fields into the northwest winds, so that Ekman transport was heading to the north [23].

The description of physical characteristics of water masses (temperature, salinity and current) from the observational data sources in the Halmahera Sea is still challenging. Previous research conducted in the Halmahera Sea [6], after measuring with the mooring current meter at a depth of 400 m, 700 m and 900 m revealed that currents at each depth have different velocities and directions. However, current changes in the Halmahera Sea were dominantly controlled by NGCC and NGCUC [6].

![Figure 4](image_url)

**Figure 4.** The annual cycle of meridional current component of H-ITF (0.3°E). Negative (positive) values indicate southward (northward) flows.

3.3. Spatial Structures and Temporal Variations of H-ITF
The spatial structure of H-ITF can be interpreted from the EOF analysis results for meridional current component, expressed by the four largest percentage of explained variances (EOF Mode 1 - Mode 4 (figure 5).

The largest signal amplitude of EOF Mode 1 was found at the entrance of ITF in the northeastern Halmahera Sea with a value of 0.58 and a 75% explained variance. The pattern in EOF mode 1 shows
that the main flow of ITF Halmahera dominantly flowed towards the south indicated by a positive value, while the negative value indicates the recirculation of the flow to the north. EOF Mode 2 with a 7% explained variance revealed a smaller variability with a positive coefficient on the surface, but below surface, the dominance was negative. EOF 3 with a 5% explained variance had a positive coefficient value on the surface, but with the increasing depth, the variance value was more dominantly negative. The pattern in EOF Mode 4 with 3% explained variance showed a negative coefficients. Spatially, the surface EOF value was higher at the middle and west branches of the eastern HS. Surface flow tended to pass through the central and western branches while in the western branches, fluctuations were quite significant due to seasonal changes.

The temporal variation of the time-series data corresponding to EOF Mode 1 - Mode 4, and the results of the wavelet transformation and power spectral density (PSD) analysis are presented in figure 6. EOF Mode 1 shows high intraseasonal variability (25 and 78 days) with a CWT coefficient > 0.6. Based on the result of density energy analysis, some dominant peaks occurred during the period of intraseasonal (i.e. 25 - 78 days), in addition to the peaks period of 14 day and 214 days. High intraseasonal variability was found approximately in January 2008, June 2008, January 2009, August 2009, April 2010 and July 2012.

Based on the temporal spectral analysis of EOF Mode 1 on the surface (figure 5), it is shown that the intraseasonal period of 25 and 78 days had greater energy density values of 63 and 60 (m/s)$^2$/cpd. The 78-day period is thought likely to be influenced by the arrival of Rossby waves which has a period of 70-100 days [24, 25]. The signals propagated southwards through the HS into the Seram Sea and then southwestward around the Banda Sea to pass through Ombai Strait in the annual period (214 days) and biweekly period (14 days) were also found and had a reasonably strong energy of 53 (m/s)$^2$/cpd, but they were weaker than the intraseasonal period.

![Figure 5](image-url)

**Figure 5.** Four largest EOF modes, showing vertical structures of H-ITF, acrossing 0.3°S in Halmahera Sea.
EOF Mode 2 in the surface depth has a spatial distribution with a positive predominant value. Temporally, through CWT analysis, it is known that intraseasonal and biweekly periods (14 days) are still visible but with lesser CWT coefficients than the semi-annual (180 days) period. The temporal variability of EOF Mode 3 of the CWT and PSD coefficients shows the fluctuations of meridional current with the peaks of annual period (373 days). In EOF Mode 4, the opposite site was found. In spectral analysis, the intraseasonal peak with the periods of 18, 41 and 84 days becomes more visible.

Visually, the fluctuations of ITF Halmahera are dominated by the fundamental periods of intraseasonal time-scales. The expedition result of Internal Tides and Mixing in Indonesia Throughflow (INDOMIX) in a moored bottom ADCP for about 2.5 years in the Halmahera Sea revealed fluctuations in current flows on the intraseasonal, seasonal and interannual periods [25]. On the intraseasonal scale of near-bottom current in the Halmahera Sea, power spectral density energy of current peaks at 14, 21, 23 and 27 days periods [26]. Period of 14 days scale is expected to be influenced by the tide at dominant components lunar monthly (MM) and diurnal fortnightly (MF). Moreover, 27 days periods is expected to be driven by remotely equatorial zonal winds through the propagation of Rossby waves in the tropical Pacific Ocean.

![Figure 6](image1.png)

Figure 6. The principal component of EOF mode 1-mode 4 (left panel), showing temporal variation of meridional component of H-ITF from the results of EOF analysis. Middle and right panels are related to CWT and PSD analysis of time series.

3.4. Characteristics of the NGCC and NGCUC

The averaged cross-section of the zonal component (u) of the INDESO model output 2008-2014 accrossing 134°E in Northern Papua shows the presence of three layers of core of NGCC and NGCUC, indicated by a strong westward flow with magnitude exceeds 0.4 m/s was near 0.4°N - 1.0°N and could be identified until a depth of 200 m. The NGCC and NGCUC width dimension that intersected at 134°E is 291.2 km. Vertical extent of NGCC was seen down to a depth of 200 m. In fact, NGCUC was found beneath the NGCC at about 0.4°N - 2.0°N to a depth of 1142 m with a current magnitude of about 0.1 m/s (figure 7a).

The NGCC and NGCUC flow along the New Guinea (Papua) coast, and they are part of the South Equatorial Current. NGCC flows northwestward [11], and NGCUC flows northwestward and then turns eastward to Halmahera Island, joining the Mindanao Current and flows eastward as the North Equatorial Counter Current. The cyclonic ME and anticyclonic HE were found at the confluence region of Mindanao and NGCUC [8].
NGCC is a surface current caused by seasonal influences [27]. In the boreal summer characterized by the southeasterly monsoon, westward currents of over 60 cm/s were dominant in the surface layer. In the boreal winter, an eastward surface current developed to 100 cm/s extending down to 100 m depth in response to the northwesterly monsoonal winds. During the Southeast Monsoon, NGCUC flows strongly northwestward [8].

3.5. Annual Cycle of Zonal Component Current of NGCC and NGCUC

The annual cycle of NGCC/NGCUC during the NWM period was characterized by strong mainstream velocity in December, but it began to weaken in January to February (figure 8). In the transitional period I (March, April, May), NGCC was still visible with a strong amplitude of speed. However, NGCUC magnitude of velocity became weaker, and shallower. The main current velocity of the NGCC and NGCUC was weakening towards the West, and part of the current entered the Halmahera Sea. This is because the direction of the wind changed from the northwest monsoon to the southeast. Thus, surface circulation patterns in the northern waters of Papua have a strong seasonal variability [23].

During the SEM period (JJA), the magnitude of NGCC was on the surface and NGCUC beneath NGCC began to increase. In the second Transitional Monsoon Break periods (October - November), the NGCC mainstream velocity was intensified, reaching a current velocity of 0.45 m/s in almost all depth levels and still visible until the end of Monsoon Break.

![Figure 7](image)

**Figure 7.** The average cross section of the zonal component current (u) of NGCC and NGCUC (a). The color in the zonal current shows the speed scale (m/s). The location of the current transect (figure 1).
Figure 8. Annual cycle of NGCC and NGCUC (across 134°E). Negative (positive) values indicates westward (eastward) flow direction.

3.6. Spatial Structures and Temporal Fluctuations of NGCC/NGCUC

The spatial structure of NGCC/NGCUC can be interpreted from the results of EOF analysis for the zonal current expressed by the largest percentage of explained variances for EOF Mode 1, Mode 2, Mode 3 and Mode 4 (figure 9).

Amplitude of the largest signal of EOF Mode 1 with a value reached 0.62 and percentage of variance 53%. This is in line with the higher standard deviation of the zonal current (u) in the region. EOF Mode 2 with a 15% variance percentage had a smaller variability on the surface to a depth of 30 m. EOF Mode 3 with a 7% percent variance percentage had a negative dominant variance value. The pattern in EOF Mode 4 with a 4% variance percentage had a negative dominant variance value on the surface, but with the increasing depth, the variance value is more dominantly positive.

The temporal variation of time series data corresponding to four largest EOF Modes and the results of the wavelet transformation and power spectral density (PSD) analysis are presented in figure 10. EOF Mode 1 shows the high intraseasonal variability (84 days) with a CWT coefficient value of > 0.8 (figure 10). Based on the result of density energy analysis, some dominant peaks occurred during the intraseasonal periods of 24, 39 and 84 days (figure 10). High intraseasonal variability was found in June 2008, August 2009, November 2010 and July 2012.
Temporally, through the CWT analysis (figure 10), it is known that intraseasonal periods were still visible but with a considerable greater coefficient of CWT (> 0.8). The distributions of the CWT coefficient and the temporal graph of EOF Mode 2, Mode 3 and Mode 4 shows the fluctuations of meridional currents have an annual dominant cycle (figure 10). Meridional current become strong during the Southeast monsoon, and weaken during the Northwest Monsoon. The process occurring during the annual period was described earlier in figure 9. Using the 1,024 segment length on the spectral analysis, it is clear that the annual period with the peak period was 387 days in EOF Mode 2, 361 days in EOF Mode 3, and 373 days in EOF Mode 4.

Figure 9. Four largest EOF modes, showing vertical structures of NGCC and NGCUC, across 134°E in northern New Guinea (Papua).

Figure 10. The principal component of four largest EOF modes (left panel), showing temporal variation of zonal component of NGCC and NGCUC at 134°E from the results of EOF analysis. Midle and right panels display results of CWT and PSD analysis of time series.
3.7. Variability of Transport Volume at the H-ITF and the NGCC and NGCUC

The average time series data of ITF Halmahera transport volume from January 2008 to December 2014 show the ranges of transport fluctuations between -7.8 Sv (to the south) and 4.0 Sv (to the north), with an average value of approximately -2.2 Sv and standard deviation of approximately 1.8 Sv (figure 11a). The annual cycle of transport of ITF Halmahera shows the transport strengthened during the Southeast Monsoon toward the south and obtained its maximum in October (3.4 Sv) in the final period of the Season, whereas it became relaxed at 0.4 Sv in January in the Monsoon period (figure 11b). Visually, fluctuations in the transport of ITF Halmahera are dominated by fundamental periods of intraseasonal time scales.

In the northern region of Papua, the average transport time series of NGCC and NGCUC shows fluctuations in the high range between -77 Sv (toward the west) and 10 Sv (towards the east), with an average of approximately -27.5 Sv and a standard deviation of approximately 16 Sv (figure 11c). The annual cycle of NGCC and NGCUC transport shows the ITF transport became strong during the Southeast Monsoon and reached its maximum in November (50 Sv), and subsequently, it relaxed to 3 Sv in May during the first transitional season (figure 11 d). Visually, NGCC and NGCUC transport fluctuations show an annual fundamental period. This means the annual variation of transport becomes dominant in this region.

![Figure 11. Time-series of transport volume in the upper 1000m in the H-ITF regions and its annual cycle (upper panels), and at NGCC and NGCUC region (lower panels).](image)

3.8. Coherence of Transport Fluctuation between H-ITF and NGCC

The relationship between ITF Halmahera transport and NGCC transport (above 200m) can be seen from the time-transport data of ITF Halmahera transport and NGCC transport from January 2008 to December 2014 (figure 12).
The mean transport volume of ITF Halmahera is around 2.35 (± 1.94) Sv (southward), while the mean transport volume of NGCC is about 13.47 (± 6.6) Sv (westward). The annual cycles of the average transport of ITF Halmahera and NGCC transport show similar fluctuation pattern with the maximum transport was found from October to November, and the minimum transport was found in January. NGCC is found along 134°E 0.4°N - 2.0°N (figure 2 and 7a) with a strong flow intensity westward across northern Halmahera with an average transport 13.47 Sv. The mean transport volume of ITF Halmahera is around 2.35 Sv. In regards to the similarity of fluctuation pattern of ITF transport and NGCC transport and based on the ratio calculation, the percentage of NGCC entering through the Halmahera Sea above 200 m depth was 17.45% from the total transport volume of NGCC. This shows that NGCC transport contributes by about 17.45% to the ITF transport entering through the Halmahera Sea.

The result of cross-PSD analysis between the ITF Halmahera transport time series and the NGCC transport time series revealed significant coherence over several periods, i.e. 28 days, 38 days, 45 days, 79 days, 128 days and 341 days periods (figure 13). The highest coherence value (0.85) occurred in the 45-day period, with a positive phase difference (4.86 days). This indicates that the NGCC signal fluctuation at the 45-day periods appeared first in transect of 134°E (in Northern Papua) and 4.86 days later, the signal propagation appeared in transect of 0.3°S of ITF Halmahera. The values and phase differences between the NGCC signals at transect of 134°E of Northern Papua with the signal of ITF Halmahera at transect of 0.3°S are presented in table 1.

Figure 12. Time-series of transport volume in the upper 200 m in the H-ITF regions and its annual cycle (upper panels), and at NGCC and NGCUC region (lower panels).
Figure 13. Coherence (a) and phase (b) between the H-ITF transport and the NGCC transport series.

Coherence analysis results revealed that the phase difference between signal fluctuations in NGCC and ITF Halmahera ranged from 2.56 days to 15.4 days. This indicates that NGCC at the transect of 134°E (in Northern Papua) flowing into the ITF Halmahera region at transect of 0.3°S needs between 2.56 days to 15.4 days, indicating the presence of propagation of the Rossby wave signal entering the HS.

Table 1. Period, coherence and phase between H-ITF transport and NGCC transport.

| No | Period (day) | Coherency | Phase (day) |
|----|--------------|-----------|-------------|
| 1  | 28           | 0.6835    | 2.56        |
| 2  | 38           | 0.8474    | 4.25        |
| 3  | 45           | 0.8519    | 4.86        |
| 4  | 79           | 0.8256    | 8.8         |
| 5  | 128          | 0.8192    | 15.4        |
| 6  | 341          | 0.3826    | 5.46        |

The oceanic response to wind forcing is often accomplished through wave processes that propagate along the equatorial and coastal wave guides within the Indonesian Archipelago, and impact the water properties, thermocline and sea level on all timescales. The equatorial winds that produced free equatorial Rossby waves whose signals indicated reached the study region. Equatorial Pacific Rossby waves excited coastally trapped waves off the western tip of New Guinea that propagated poleward along the Arafura/ Australian shelf break. As well, Pacific energy radiated westward into the southeast Indian Ocean via the Banda Sea [29, 30].

4. Conclusion
The circulation pattern in the eastern part of the Halmahera Sea is characterized by the strong axis of ITF Halmahera on the middle lane of the Halmahera Sea. The average of ITF Halmahera transport at transect of 0.3° SL is -2.2 (± 1.8) Sv (negative: southward). On the northern side of Papua, NGCC/NGCUC transport is approximately -27.5 (± 16) Sv (positive: westward).

The upright structure of ITF Halmahera at 0.3° LS transect is characterized by the wide size of around 67.2 km, the depth of the current from the surface to the depth of 150 m with a maximum
current layer of >0.3 m/s from the surface to 100 m. The annual cycle of ITF Halmahera shows the width and speed of ITF Halmahera are fully developed in the Southeast Season with transport of about 3.4 Sv, which is in contrast to the minimum ITF Halmahera (about 0.4 Sv) in the Northwest season. The size of the NGCC NGCUC cross section of the transect at 31°BT is 291.2 km in width, 0-1142 m in depth with the maximum speed of > 0.4 m/s in the depth of 50-200 meters.

Variability of ITF Halmahera is dominated by fluctuations with the subsequent ISV of annual and biweekly periods where as variability of NGCC/NGCUC is dominated by annual period. Significant coherence between NGCC and ITF Halmahera occurs between 28 days to 341 days. The highest coherence (0.85) occurs in the 45-day period with a phase difference of about 4.86 days. This means that the propagation of the Rossby wave signal from NGCC into the Halmahera Sea region take approximately 4.86 days.

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