Variability of ITF front at 115°E in the Eastern Indian Ocean: from 15-years Gridded CTD Argo Float Data

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Abstract. This study aims to investigate a depth-latitude spatial and temporal variability of ITF front at 115°E, using 15-years (2004–2018) of monthly gridded CTD Argo float dataset in the Indo–Australia Basin. The Empirical Orthogonal Function method was performed to analysis these time-series data. It is shown that mean meridional extent of ITF front is established between 14°S and 10°S. The ITF front can be described by the first five modes of potential temperature and salinity EOF’s, which accounted for 88.6% and 80.7% of the total variance, respectively. The first EOF mode (67.9%) of depth-latitude temperature reveals spatial pattern which is out-of-phase between near-surface layer (<100 m) and thermocline layer, for example, during the northwest monsoon period, warmer and saltier water in the upper-layer and colder and fresher thermocline water are frequently observed, which differ to those observed during the southeast monsoon period. EOF principal components of temperature and salinity exhibit strong annual variation, followed by intraseasonal and interannual scales. On inter-annual scales, fluctuation of temperature and salinity is well correlated with ENSO and IODM, as previously expected.

1. Introduction
The Indonesian Throughflow (ITF) is a current system in the Indonesian seas that has importance role which carries warm and fresh waters from the Pacific Ocean to the Indian Ocean. This circulations drive by prevailing trade winds over the tropical oceans that cause an increase of sea level on the western Pacific Ocean and a lowering on its eastern Indian Ocean. The different of pressure gradient between the two oceans flows with strong seasonal and interannual variability. The ITF is supposed to represent warm water route as the upper part of the global water mass circulation. The ITF transport also has contribution to redistribute heat budget on controlling regional and global climate variability.

ITF flows to Indian archipelago through different pathways in the western path and eastern path. The main inflow of ITF is the western path from the Mindanao Current that flows through the Sulawesi sea and then flows through the Makassar strait. This ITF branch flows out the Banda Sea to finally exit through the Lombok Strait eventually reach the Flores Sea and the Banda Sea to finally exit through the Ombai Strait or the Timor Passage.

The eastern path of ITF inflow with two routes via 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 and the Seram Sea and eventually joins the first eastern route of the Banda Sea. ITF water mass from western path carrying North Pacific Subtropical Water (NPSW) and the North Pacific Intermediate Water (NPIW), and in addition the eastern path of ITF carrying South Pacific Intermediate Water (SPIW) in the first route and the South Pacific Subtropical Water (SPSW) in the second route.

The Indo – Australian Basin is an interets region to study because it influence by the ITF water mass from Lombok Strait outflow in the northern side and Indian Ocean water mass in the southern side. The
ITF water exits from Lombok Strait in the 350 m depth and characterized by the fresher salinity in the thermocline layer in the northern side near south of Bali from upper layer to 400 m [1]. The total transport by [2] noted of 2.6 Sv (Sverdrup) (1 Sv = 10^6 m/s) transport volume leads to the Indian Ocean from the Lombok Strait. ITF water mass strongly influence by monsoon in the thermocline layer (around 100-150 m) and Indian Ocean water masses intrusion in the above of the thermocline layer [2]. This conditions make the region at 115°E of the Indo-Australian basin has potential to shape clearly boundary (front) between ITF water mass and Indian Ocean water mass.

Front define as any region in the ocean with large of change in any variable, such as temperature and salinity. The hydrological front in study area separate ITF water mass and Indian Ocean water mass characterized from temperature and salinity parameters. The ITF front variability studied by Fieux et al. [3] found the front in the 13°S in southeast monsoon in the upper layer to 700 m depth. This front separate Subtropical South Indian Water (STW) characterized by maximum salinity and the Central Water (CW) characterized by the maximum oxygen. These two water mass flow from Indian Ocean shape front in the southern side with the Intermediate Indonesain Water (IIW) in the northern side characterized by the homogen salinity in the 1300 m depth [3].

Although there is already a study of ITF front in the Indo – Australian basin, there is no specific study of the variability of spatial pattern and temporal variability at the 115°E transect from the gridded field Argo Float data. The purpose of this study is to describe ITF front including vertical structure, spatial pattern, and temporal variation at 115°E transect in the Indo – Australian basin with Empirical Orthogonal Function analysis.

2. Method

2.1. Study area

This study was conducted in the Indo – Australian basin area, which focused on South of Bali – Western Australia sea at 115°E from 8°S - 20°S (Figure 1). Data processing and analysis was carried out in Physical Oceanography Laboratory and Data Processing Laboratory, Marine Science and Technology Department, IPB University and took the time from March – June 2019. Transect 115°E was choose as the region of considered as the outflow zonally region of ITF water mass from Indonesia seas.

![Image](https://www.argo.ucsd.edu/Gridded_fields.html)

**Figure 1.** Study area in the Indo – Australian Basin, South Bali to Western Australia and its adjacent waters in eastern Indian Ocean.

2.2. The data

Observational data outputs from CTD Argo Float accessed in https://www.argo.ucsd.edu/Gridded_fields.html were used in this study. Argo is an international project as an effort to collect high quality temperature and salinity profile from the upper 2000 m of global ocean. The data come from battery-
powered autonomous floats that drift mostly at depth and typically 10-day intervals while measuring temperature and salinity. On surfacing, satellites position the floats and receive the transmitted data. Work principle of CTD Argo Float presented in Figure 2a. The outputs of data-series are temperature and salinity parameters and span from January 16th 2004 to October 16th 2018 (15 years). This monthly gridded data has horizontal grid for 1° and vertical resolution of 58 depth level with the maximum depth at 1978 m in the cross section of 115°E from 8°S - 20°S. The Argo Float data type that use in this study is Global Gridded Net CDF Argo only dataset produced by optimal interpolation from Scripps Institution of Oceanography. The procedure of Argo Float data processing to produce gridding data of temperature and salinity used with optimum interpolation method. Argo Float data has interpolated toward 58 depth level from 0 to 2000 dbar. Each levels has 10 to 100 dbar intervals with narrow sampling value above 15 m depth assumed as the represent of surface layer. The distribution pattern of Argo Float data presented in Figure 2b captured from https://www.jcommops.org/board. Gridded field Argo float data has horizontal resolution for 1° or equal with 111 km, and vertical resolution consist of 58 depth level with maximum depth for 1987 m.

![Figure 2. (a) Work schematic of CTD Argo Float in one cycle data measurement according to [4]; (b) Data distribution of CTD Argo Float measurement before gridding method has applied.](image)

2.3. Data analysis

The variability of ITF front in the study area were assessed by applying time series analysis, i.e. calculating the mean value of temperature and salinity in the cross section from 2004-2018, EOF (Empirical Orthogonal Function) analysis according to [5] with the 5 biggest mode, and PSD (Power Spectral Density) analysis according to [6]. Hovmoller analysis also applied to analyze the response of ITF front by temperature and salinity inter-annual pattern corresponding with ENSO and IOD Index. The water mass characteristics in the Indo – Australian basin has been analyzed with the TS Diagram. The mean of temperature and salinity pattern aims to analyze general characteristics of the water masses in the study area. The climatological method is used to analyze the annual cycle of ITF front by the temperature and salinity. The EOF method is used to to describe vertically spatial pattern and temporal variability. The PSD analysis used to measure the dominant periodic of the EOF temporal time series.

3. Result and discussion

3.1. Water mass characteristics of Indo-Australian Basin

The averaged vertical structure of the temperature and salinity in the cross section at transect 115°E and 8°S - 20°S from 2004-2018 is presented in Figure 3. The fifteen years average pattern describe the temperature and salinity characteristics as the initial steps to identify ITF front. The temperature pattern of this region show in figure 3(a) characterized with the shallower thermocline in the northern side near the South of Bali. The thermocline layer found in the depth of 50 m – 120 m. The shallower thermocline
layer in the northern side to around 15°S caused the effect of upwelling. Isoterm contour in northern side at the depth of 50 – 200 m show intensive temperature changes to the depth and it’s correspond with another characteristics of upwelling with trends of temperature decreasing [7]. The upwelling in this region affected by monsoon phenomenon.

The salinity mean pattern in the transect 115°E; 8°S - 20°S from 2004-2018 (figure 3b) revealed two different cores which represent different salinity value between northern side and southern side in the upper layer to the thermocline layer. The fresher salinity was found in the northern core about 33.8 – 34.6 psu in the depth of surface layer to 200 m. The saltier salinity was found in the southern core about 34.7 – 35.4 psu in the surface layer to 450 m. The different of salinity core used as the initial steps to identify water mass vertical structure that shape ITF front. The fresher salinity near South of Bali in the surface layer is recognized as the ITF water mass from outflow channel in the Lombok Strait corresponding with the [8] found salinity characteristic of ITF-water mass in this region has value around 34.4 psu.

Water mass type in this region show by the TS Diagram (figure 4). The maximum salinity was found in the southern near Australia with the value > 34 psu. This water mass correspond to Subtropical South Indian Water (STW) [3] in the thermocline layer in the depth about 220 – 270 m. In the northern side near South of Bali, water mass with minimum salinity correspond to the Indonesian Through flow Water (ITW) characterized by the fresh water in the surface layer to 400 m [2]. This ITF water mass is the flow out from western route in the Lombok Strait.

Figure 3. (a) The cross-section of the averaged temperature and (b) salinity pattern at 8°S - 20°S; 115°E. The colors in meridional currents show the temperature value (°C) and salinity value (psu).
3.2. The annual cycle of temperature and salinity

The annual cycle of the temperature presented in Figure 5 and the annual cycle of salinity presented in Figure 6. The annual cycle of temperature shows strongly seasonal variations in the upper layer above 100 m and the thermocline layer. But, this pattern has out of phase, if the upper layer dominated with the positif anomaly then the thermocline layer show the opposite. In the northwest monsoon (DJF) to the transitional I (MAM) positif anomaly dominated the upper layer with temperature anomaly about 0.3°C – 2.4°C while the thermocline layer dominated with cold temperature. Pattern of this period mentioned as the warmer episode. Colder negative core found in the February at the depth of 100 – 200 m.

Southeast monsoon (JJA) to the transitional II (SON) shows the opposite pattern which upper layer dominated with negative anomaly about -0.3°C to -1.8°C. This period mentioned as the colder episode. Positive anomaly core was found from May and more intensive in the August. This warmer core found at the 100 – 300 m with the center of core found at the 10°S - 15°S in the 150 m. This core represent as ITF water mass from outflow strait as mentioned by [2] that the ITF water mass exits through Lombok Strait characterized by the warmer temperature about 28.77°C. The upper layer of temperature variability cause by the upwelling in the southeast monsoon in the Southern of Java until Arafura Sea.

The annual cycle of salinity anomaly presented in Figure 6 and divide as the Salty Episode in the northwest monsoon (DJF) to the transition I (MAM) and the freshening episode in the southeast monsoon (JJA) to the transition II (SON). In the freshening episode revealed fresh water in the northern side on the upper layer to 100 m. This salinity anomaly is about -0.11 psu to -0.17 psu. This water mass correspond Java Sea water in the upper of 100 m which flows through Lombok Strait. The unique discovery of this study was found the water mass intrusion with lower salinity from the Indian Ocean flowing to north in the 100 – 300 m depth. Intrusion appeared because the weakness of ITF transport in the northwest monsoon, and this water mass describe as Subtropical South Indian Water (STW) from Indian Ocean.
Figure 5. The annual cycle of temperature anomaly (115°E). Negative (positive) values indicate temperature below the mean value and (higher).
Figure 6. The annual cycle of salinity anomaly (115°E). Negative (positive) values indicate salinity below the mean value and (higher).
3.3. Spatial pattern and temporal variations of temperature

The spatial pattern of temperature anomaly can be described by the EOF analysis results, expressed by the five largest percentage of explained variance (Figure 7). EOF temperature has 88.6% of total variance with the five biggest mode (EOF Mode 1 – Mode5). The largest signal amplitude of EOF temperature mode 1 has a value of 67.9% explained variance. The pattern in EOF temperature mode 1 shows intensive variability in the upper layer to thermocline layer. EOF mode 1 with a value of 67.9% explained variance revealed the dominantly of negative value in the upper layer to 100 m. It also has out of phase with the thermocline layer with the appearance of positive core in the 100 – 300 m with the center at 13°LS. This positive core show the same pattern with annual cycle in the southeast monsoon and it highly predict as ITF water mass. Negative coefficient value in the upper layer represent of Java sea water while the positive core in the thermocline layer represent the ITF. The result of spatial pattern from EOF mode 1 in the ITF front region present in Table 1 to describe the ITF front characteristics.

EOF mode 2 with a 12% explained variance revealed more complex pattern in this layer and show the opposite condition with EOF mode 1. EOF mode 2 spatial pattern correspond and represent the warmer episode phase of annual cycle with the dominantly positive value in the upper layer above 100 m and negative value in the thermocline layer. EOF mode 3 with a 4.2 % explained variance had a positive coefficient value on the 100 – 400 m in the southern side. The pattern in EOF Mode 4 and Mode 5 with 2.5% and 2% explained variance show the smaller variability in the upper layer and tend to homogen to the depth. Spatially, the surface EOF value was higher at the thermocline layer and it has out of phase.

Figure 7. Five largest EOF modes, showing vertical structures of Temperature, acrossing 115°E in the Indo-Australian Basin.

The temporal variation of the time-series data corresponding to EOF Mode 1- Mode 5, and the results of the power spectral density (PSD) analysis are presented in Figure 8. EOF Mode 1, Mode 2, and Mode 3 shows high annual variability (8-12 month). Based on the result of density energy analysis, mostly
dominant peaks occurred during the period of annual scale. Based on the temporal spectral analysis of EOF Mode 1, it is shown that the annual and intra-seasonal period of 12.1 and 5.9 month days had greater energy density values of 21.2 and 8.7 (m/s)^2/cpd. The 12.1-month period is thought likely to be influenced by the monsoon [2]. Eof Mode 2 also has the greatest peak of spectral density of annual period (11.6 month), and EOD Mode 3 with 12.1 month.

Figure 8. The principal component of EOF mode 1-mode 5 (left panel), showing temporal variation of temperature anomaly from the results of EOF analysis. Right panels are related to PSD analysis of time series.

3.4. Spatial pattern and temporal variations of salinity
The spatial pattern of the salinity anomaly expressed by the five largest percentage of explained variance (Figure 9) with the total variance value of 80.7%. EOF Mode 1 has the largest explained variance with a value of 54.6% and shows the salinity above 200 m dominantly by negative coefficient. The lowest
salinity in the surface shape core with the center at 12°S - 15°S. This core expanded to northern and southern side and increase to the depth. It strongly thought that the fresh water in the surface is Java sea water that flowing to Indian Ocean through Lombok Strait.

EOF Mode 1 shows the salinity pattern in the sub surface layer shows changes in that are dominated by negative values about -0.1 psu until -0.02 psu at the 100 – 200 m. Under the 200 – 450 m depth from southern side about 11°S - 20°S shows the pattern of water mass intrusion with maximum value of salinity anomaly. This intrusion center has 0.02 psu value as the core at 19°S. In the same depth, northern side has dominated of lower salinity. The result of spatial pattern from EOF mode 1 salinity in the ITF front region also present in Table 1.

**Figure 9.** Five largest EOF modes, showing vertical structures of Salinity, acrossing 115°E in the Indo-Australian Basin.

The water mass intrusion of high salinity also appeared from EOF mode 2 and move upward from 100 – 400 m and flow expand to the north. EOF Mode 2 with the value of 13.6% explained variance also apperaed the contribution of high salinity water mass in the 8°S - 13°S. EOF mode 2 shows the different pattern in the north, middle, and south of region area in the same depth from surface to 400 m. Dominantly positive value shape core in the 8°S - 12°S in the surface about 100 m while the southern side dominated by negative value of salinity EOF from 12°S - 20°S. This pattern show of annual cycle period in the November until March while the upper layer are more salin.

In the EOF mode 3 with 5.8% explained variance show the pattern of water masses intrusion flowing to northern side clearly appeared. The intrusion also flowing to the surface from 0 – 300 m. In addition, northern side from 8°S - 14°S shows the pattern of negative value of salinity core until 100 m depth. This meeting of different salinity value strongly taught as the potential to shape salinity front in the
Water mass intrusion strongly describes the Subtropical South Indian Water (STW) from the Indian Ocean characterized by maximum salinity in the thermocline layer.

EOF Mode 4 and Mode 5 has the smaller value of explained variance of 4% and 2.7%. It shows a more complex pattern in the surface to thermocline layer but has very small explained variance. But, this mode clearly describes the variability in the deep layer with homogenous salinity. EOF mode 4 and mode 5 are thought as the representatives of annual cycle in the April and September which have complex salinity patterns due to the transition period.

The temporal variation of the time-series data corresponding to EOF salinity Mode 1 - Mode 5, and the results of the power spectral density (PSD) analysis are presented in Figure 10. EOF Mode 1, Mode 2, and Mode 3 show high annual variability. Based on the result of density energy analysis, mostly dominant peaks occurred during the period of annual scale. Based on the temporal spectral analysis of

![Figure 10](image-url)
EOF Mode 1, Mode 2, and Mode 3, it is shown that the annual period of 12.1 month days had greatest energy density values of 15.6, 19.1, and 14.5 (m/s)²/cpd.

Table 1. Characteristic of ITF Front from temperature and salinity parameter.

| Parameter                        | Information                                                                 |
|----------------------------------|-----------------------------------------------------------------------------|
|                                  | Upper Layer | Thermocline Layer | Intermediate Layer |
| Temperature                      |             |                  |                   |
| Temperature Range (°C)           | 26-28       | 16-26            | 10-16             |
| Depth Range (m)                  | 0-70        | 70-200           | 200-600           |
| Latitude Range (°S)              | 11-14       | 10-13            | 10-14             |
| Anomaly Range from BOF Mode 1 (°C) | Negative Anomaly (0.1-1.3) | Positive Anomaly (0.1-0.9) | Positive Anomaly (0.1-0.4) |
| Annual Cycle                     | DJF/MAM Warming | JJA/SON Cooling | DJF/MAM Cooling | JJA/SON Warming |
| Salinity                         |             |                  |                   |
| Salinity Range (psu)             | 34-34.5     | 34.6-35.2        | 34.6-34.65        |
| Depth Range (m)                  | 0-100       | 100-200          | 200-700           |
| Latitude Range (°S)              | 11-15       | 10-13            | 10-13             |
| Anomaly Range from BOF Mode 1 (°C) | Negative Anomaly (0.07-0.21) | Positive Anomaly (0.01-0.07) | Negative Anomaly (0.01-0.02) | Positive Anomaly (0-0.01) |
| Annual Cycle                     | DJF/MAM Saltier | JJA/SON Fresher | DJF/MAM Saltier | JJA/SON Fresher |

3.5. Hovmoller analysis of temperature and salinity

Hovmoller salinity shows the response of the temperature and salinity in the upper layer represent at the 50 m (Figure 11) and the thermocline layer represent at the 150 m depth (Figure 12). Hovmoller analysis are adjust with the ENSO and IOD index to describe how the ITF front propagation in the ENSO and IOD period. This depth was chosen as the layer which became the main route of the Indonesian archipelago with zonal movement. Hovmoller analysis of temperature show the strongly annual and inter-annual variability.

According to Nino 3.4 index shows that strong El Nino phenomenon occurred in 2010 and 2015, which the strong of El Nino period present in Table 2. IOD index also shows the positive IOD in the same year as the strong El Nino occurred. The Temperature pattern in the upper layer has different phase with the thermocline layer. In 2015 when strongly El Nino occurred, temperature anomaly pattern did not show the change significantly at the upper layer. El Nino condition affect the thermocline layer and cold the temperature around -0.1°C until 0°C. El Nino in the 2015 increased until the beginning of 2016 which the lower temperature about 0.4°C. This colder temperature also caused by upwelling which take water masses from the bottom to the upper layer and carrying colder water masses.

La Nina occurred in the 2008 and 2011 as the Nino 3.4 index and did not really show the difference between the two depths. Strong La Nina in 2011 affected temperature pattern in the thermocline layer increase along year. Warm temperature in the Indonesian seas due to westerlies wind that constantly blowing along year moving warm pool flowing more intens. This condition push the warm pool in the western Pacific moving to Indonesia seas. It could affect the thermocline layer shallower and temperature warmer.

Salinity anomaly from hovmoller analysis show the pattern which did not really responsive with ENSO and IOD in the upper and thermocline depth. Strong El Nino occurred in the 2010 and it affected salinity in the upper layer more positive while in the 2015 shows the thermocline layer was lower. Strong
La Nina in the 2008 and 2011 shows the upper layer did not show the clearly difference while the thermocline has colder temperature.

Table 2. The event period of El Nino and La Nina based on the Nino 3.4 index.

| The Event | Period               | Peak  | Temperature Anomaly | Category |
|-----------|----------------------|-------|---------------------|----------|
| El Nino  | JUL 2009-APR 2010 (9 month) | DES 2009 | 1.3 | Strong |
| El Nino  | AUG 2014-MAY 2016 (21 month) | DES 2015 | 2.4 | Strong |
| La Nina  | JUL 2007-JUN 2018 (11 month) | DES 2009 | -1.6 | Strong |
| La Nina  | JUN 2010-MAY 2011 (11 month) | DES 2015 | -1.5 | Strong |

Figure 11. Hovmoller analysis of the temperature at 50 m and 150 m depth adjusted with ENSO and IOD index.
Figure 12. Hovmoller analysis of the salinity at 50 m and 150 m depth adjusted with ENSO and IOD index.

4. Conclusion
ITF Front in the Indo –Australian Basin especially at transect 115°E from monthly gridded Argo Float Data show the high variability in the upper layer and the thermocline at the 0-400 m. The vertical structure of the water mass contributing to the front formation is the ITF water mass from the outflow through Lombok Strait and the South Indian Water Subtropical (STW) water mass from the Indian Ocean. Annual cycles of the ITF front by temperature and salinity parameters show that ITF front has strongly seasonal variability and more intense in the southeast monsoon.

Spatial pattern of the temperature parameters is separated from the results of the EOF mode 1 analysis with an explained variance of 67.9% characterized by positive coefficient core in the thermocline layer. The ITF front by spatial pattern of the salinity parameter is divided from EOF mode 1 with a explained variance of 54.6% which shows the intrusion from the Indian Ocean in the thermocline layer.

The temporal variation ahead of ITF front strongly influence by phenomenon with dominant periodicity is an annual scale and inter-annual scale. The annual scale period of this variability strongly describe as monsoon and inter-annual scale period strongly describe as the impact of ENSO and IOD. Temperature anomaly has strong responsive due to ENSO and IOD found at the 150 m, while the salinity anomaly did not really shows the different response.

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