Water mass along eastern pathway of Indonesia Throughflow from a CTD Argo Float

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Abstract. Eastern pathway of the Indonesia Throughflow (ITF) conveys a secondary ITF inflow that brings North/South Pacific water entering interior Indonesian Seas. The transformation occurred along the Pacific water mass journey towards the Indonesian sea. For the first time since 2016, CTD Argo float measurement is available following the ITF path – along Maluku-Seram-Banda Seas, providing prime datasets to be able seen change of ITF water. This paper aims to investigate transformation of ITF water masses and the percentage of water mass contribution (with Optimum MultiParameter method) along its eastern path of ITF between Maluku – Seram and Banda Seas. The result shows that along the path, North Pacific water origin is predominant in Southern Banda Sea, but lower thermocline water of South Pacific water origin in South Maluku and Seram Sea. Large transformation of ITF water is indicated with salty upper-thermocline water in Maluku-Seram Seas, but fresh thermocline water in Banda Sea. Spatial variation of mixing layer depth and thermocline depth is also found. The percentage of the water mass contribution of the North Pacific water NPSW and NPIW gets bigger along the journey to the Banda Sea, while the dominant of SPSLTW was found in Maluku Sea and Seram Sea.

1. Introduction
The water mass that moves from the Pacific Ocean to the Indian Ocean through Indonesia, known as Indonesian Throughflow (ITF). Indonesian Throughflow (ITF) has an important role in global circulation, where the water mass increases due to vertical mixing along its trajectory [1][2].

The ITF water mass have two water mass source, that is in the thermocline and the intermediate water masses of the North Pacific and South Pacific. The water mass from the North Pacific consists of the North Pacific Subtropical Water (NPSW) maximum salinity in the thermocline layer and the North Pacific Intermediate Water (NPIW) minimum salinity mass in the intermediate layer. About 90% of ITF water mass comes from the North Pacific [1]. The South Pacific water mass consists of South Pacific Subtropical Lower Thermocline Water (SPSLTW) maximum salinity and Lower Thermocline Water (SPSLTW) relatively high salinity below the thermocline layer of the eastern path through the Halmera Sea and the Maluku Sea to the spooky Sea, and then to the Banda Sea [3].

There are 3 main entrance of the North Pacific and South Pacific water masses into Indonesian waters. the first, which is also the dominant route, pushes the north pacific water mass with high salinity characteristics (34.8 psu), through the Sulawesi Sea and the Makassar Strait, and exits through Lombok and the Ombai Strait then through the Timor Sea. This route is called the Western route. The second route, bring subthermocline water in the south pacific through the Maluku Sea and the Lifamatola Strait. then it flows through the third or final route that is passed by Halmahera, Seram and the Banda Sea [4]. The second and third are known as the Eastern route.
Water mass flow that passes through Indonesian waters will having water mass transformation such as salinity, temperature, dissolved oxygen and density depending on the entrance and residence time in Indonesian waters [3]. The water mass from the western and eastern routes will join the Banda Sea. The water mass that flows through ITF from these two route will having character modification along its journey to Indonesia. We will show that there has been a transformation of water mass along the ITF route, especially in the eastern pathway from the south Maluku Sea to the Banda Sea by looking the stratification and contribution of water mass in the Maluku-Seram-Banda Sea.

2. Method

2.1. Study area
This research was carried out in the southern part of the Maluku Sea, the Seram Sea and the Banda Sea. CTD profile data was obtained from trajectories using data from several Argo float CTD tracking stations throughout the region.

![Figure 1. Map of research location.](image)

2.2. The data
Data is accessed from the French Maritime Center portal IFREMER (http://www.argodatamgt.org/Access-to-data Description-of-all floats2). 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.

The data used in this study is the temperature-salinity-depth profile data in the South Maluku Sea to the Banda Sea from the Argo float CTD. Data used from September 25, 2017 to June 7, 2018. From the surface to a depth of 500 m.

2.3. Data analysis
The Transformation of ITF in the study area uses analysis of water mass stratification, water mass structure, and water mass contribution. Stratification of water mass by making a cross-section distribution of temperature, salinity, vaisala brunt, density, and temperature and salinity based on density. The cross section used to identify the stratification of the water column which is divided into three layers, mixing layer, thermocline layer, and deep layer. The Thermocline Layer determine using...
temperature gradient that refers to \[5\] > 0.05°C/m as the upper and lower limits. The stability frequency can be referred to as the floating frequency or Brunt-Väisälä (N) frequency. This frequency can be interpreted as the frequency of movement of a vertical fluid parcel. The amount of N can be expressed in units of cycles per hour. The value of N which represents a static stability measure of water mass that can be calculated using the following equation \[6\]:

\[ N_l = \left( -\frac{g}{\rho_0} \frac{d\rho}{dz} \right)^{1/2} \]  

(1)

Water mass structure using T-S diagram Analysis is a diagram that shows the relationship of salinity and temperature to determine the density conditions in waters. This TS diagram will be used in identifying the characteristics of the water mass that occurs and also the mixing that occurs. The TS diagram is used to illustrate the relationship between temperature and salinity that is observed simultaneously, at various vertical depths of the seawater column. This analysis is very useful and is able to provide the best explanation to recognize the types of water, namely the mass of water with certain temperature and salinity values and the mass of water.

Calculate the water mass contribution using OMP which is implemented using python by \[7\] based on the principle of triangle mixing by \[8\] which can be accessed https://ocefpaf.github.io/python4oceanographers/blog/2014/03/24/watermass/. The principle used in this study is triangle mixing, which is to calculate the percentage of mixing of three masses of water with a linear equation. The Equation used is:

\[ T1m1 + T2m2 + T3m3 = T \]  

(2)

\[ S1m1 + S2m2 + S3m3 = S \]  

(3)

\[ m1 + m2 + m3 = 1 \]  

(4)

Where \(T\) and \(S\) are the temperature and salinity data used to find the mixing ratio, while \(T_n\) and \(S_n\) are the temperature and salinity values in the core mass of water 1, 2, and 3. \(M_n\) is the value of the percentage of the mass mixing of water.

The types of water masses included are North Pacific Subtropical Water (NPSW), North Pacific Intermediate Water (NPIW), and South Pacific Subtropical Lower Thermocline Water (SPSLTW).

3. Result and discussion

3.1. Water mass stratification of Maluku Sea to Banda Sea

The temperature and salinity profiles of the waters of the Maluku Sea to the Banda Sea are shown in Figure 2. The temperature profile can be divided into 3 layers, surface layers, thermocline layers, and inner layers (homogeneous). The Maluku Sea, the Seram Sea, and the Banda Sea have a range of temperatures and salinity of 7.3 - 30.5 °C and 32.17 - 34.66 psu, with the range of each sea in table 1.

The temperature in the mixed layer in the Maluku Sea is warmer than the Seram Sea and the Banda Sea, where the highest temperature is 30.55 °C. The thermocline layer along the Maluku Sea to the Banda Sea has values ranging from 11.8 - 29 °C. In this layer there was a significant decrease in temperature with a temperature gradient> 0.05 °C \[5\]. Under the thermocline layer there is a gradual change in temperature with depth, which in this homogeneous layer along the Maluku Sea to the Banda Sea has a range of values of 11.7 - 13.2 °C.

Based on the figure 2(b) the mixed layer has a lower salinity value than other layers, the salinity range of the surface layer is 32.17 - 34.39 psu. There is a very low salinity of water masses in the Banda Sea to reach 32.17 psu which is thought to be due to the low mass salinity of the Java Sea due to moonsons to the east of the Java Sea \[3\]. Under the surface layer the salinity value has increased to a range of 34.2 - 34.66 psu, the finding of extreme salinity values in the Maluku Sea and the Seram Sea has reached more than 34.6 psu. This is presumably due to the presence of NPSW and SPSLTW water masses which are characterized by maximum salinity (S-max).

Mixed layers of each station have different depth and thicknesses. The Banda Sea has the thickness of the thickest surface layer, while the surface layer that has the thinnest thickness is in the Maluku Sea. The depth of the thermocline layer is in the range of 36-100 m. The lower limit of the thermocline layer
is at a depth of 142-274 m. Thermocline layers in the Maluku Sea, Seram Sea and Banda Sea have different thicknesses. The Maluku Sea has the thickest thermocline layer thickness, while the thinnest thermocline layer is in the Banda Sea. The inner layer or homogeneous layer is in the range of depth of 143 - 275 m. Maluku Sea has the thickest thickness in the deep layer.

![Temperature and Salinity Cross-Section in Maluku Sea to Banda Sea](image)

**Figure 2.** Temperature (a) and salinity (b) Cross-Section in Maluku Sea to Banda Sea.

**Table 1.** Temperature and salinity in Maluku Sea to Banda Sea.

| Sea     | Temperature (°C) | Salinity (PSU) |
|---------|------------------|----------------|
| Maluku  | 7.52 - 30.55     | 33.45 - 34.66  |
| Seram   | 7.29 - 29.76     | 33.32 - 34.63  |
| Banda   | 7.27 - 29.96     | 32.17 - 34.60  |

Brunt Vaisala frequency values based on the results obtained range from -12.5 to 29.6 cycl / h. A negative Vaisala brunt value indicates high instability in this layer [9]. Low N values are dominant negative values found in the mixed and inner layers. The highest N value is found in the thermocline layer, this is because in the thermocline layer there is a pycnocline layer which is a layer where the density gradient increases sharply with respect to depth.

The density contour is similar to the potential temperature contour. The results of the transverse density from the Maluku Sea to the Banda Sea are presented in figure 4. Density in the waters of the Maluku Sea to the Banda Sea with depths reaching 500 m has a range of 19.6 kg / m³ to 27 kg / m³. According to [5] the layer mixed density value in a waters in the tropics is /g148 22.0 kg / m³ but at the station in the Maluku Sea there is a density that reaches 22.8 kg / m³. Differences in density can occur due to differences in temperature and salinity. The range of density values in this layer is 22-26 kg / m³ [2]. In this layer the density from the Maluku Sea to the Seram Sea has decreased. From the Seram Sea
to the Banda Sea the density has increased. Density in the inner layer has a range of 26-27 kg / m$^3$ with increasingly homogeneous contour line changes.

Figure 3. Brunt-vaisala frequency (a) and density cross-section (b) in Maluku Sea to Banda Sea.

Figure 4 shows temperature changes based on density tend are homogeneous from the Maluku Sea, Seram to Banda. The temperature contours in the mixed layer tend to follow changes in density. Surface temperature layers tend to be warm. Minimum salinity is at densities <20 kg / m$^3$ which is a mixed layer. Temperature changes from the Maluku Sea, the Seram Sea, and the Banda Sea based on density are not too large, but changes in salinity are more significant seen in the Maluku Sea which has high salinity to the Banda Sea with low salinity. This causes the salinity to influence the density changes that occur along the Maluku Sea to the Banda Sea. Changes in salinity that occur from the Maluku Sea, Seram Sea, and the Banda Sea along the way are still clearly visible until the thermocline and deep layers.
Figure 4. Temperature (a) and salinity (b) based on density in Maluku Sea to Banda Sea.

3.2. Water mass structure of Maluku Sea to Banda Sea

S-max is a characteristic of NPSW in the thermocline and SPSLTW in the lower thermocline, while S-min is a characteristic of NPIW. S-max in the thermocline layer is found in the Maluku Sea at a depth of 130-200 m reached 34.66 psu with a temperature range of 16-20.7°C, while S-max in the Seram Sea is 34.62 at depth 140-220 m with a temperature range of 15.5 - 19.3°C. While in the Banda S-max it was found at depth 150-220 m of 34.59 psu with a temperature range of 15.5 – 18.4°C. S-max in the Banda Sea is lower than in the Maluku Sea and the Seram Sea, this might be because the thermocline structure in the Banda Sea has similarities with the Makassar Sea and the Flores Sea, which is the western route to the Banda Sea [10].

S-max in the lower thermocline layer in S-max under the thermocline layer in the Maluku Sea and the Seram Sea is 34.63 psu. In the Maluku Sea the S-max is in the depths of 280 - 490 m with a temperature range of 8.4 - 13.5°C. In the Seram Sea the S-max is at a depth of 340-500 m with a temperature range of 8.2 - 11.5°C. S-max in Banda Sea at depth 370 – 470 m reached 34.6 psu with temperature range 8.1 - 9.1°C. Gordon and Fine (1996), in a depth range from 200 to 600 m in Maluku, Seram and to the northern boundary of the Banda Sea, the maximum salinity greater than 34.6 psu is the mass of the South Pacific low thermocline water entering the Indonesian ocean via the Halmahera Sea. Spread north in Maluku and south to the Banda Sea. According to [11], after entering eastern Indonesian waters there was a decrease from the maximum salinity of the SPSLTW water mass due to vertical mixing. In the central and southern Banda Sea, the South Pacific low thermocline water began to be replaced by the North Pacific low salinity thermocline water taken through the Makassar [12].
The S-min value in the Maluku Sea and Seram Sea reached 34.55 psu and Banda Sea is 34.5 psu with varying depths. Maluku Sea S-min is found at a depth of 230 - 290 m with a temperature range of 10.5 - 12.1°C. While the Seram Sea is at a depth of 230 - 360 m with a temperature range of 8.4 - 11.6°C. The Banda S-min Sea is at a depth of 270 - 380 m with a temperature range of 7.8 - 12.3°C. S-min in the Maluku Sea at an intermediate depth of 34.55 psu and in the Banda Sea of 34.5 psu with a mass of north pacific water in the Banda Sea is input from the Flores Sea [4].

**Figure 5.** T-S Diagram in Maluku Sea to Banda Sea.
3.3. Water mass contribution in Maluku Sea to Banda Sea

The results of the analysis of the contribution of water mass percentage from the Maluku Sea, the Seram Sea, and the Banda Sea use the North Pacific reference water mass value entering from the Maluku Sea and the South Pacific reference water mass value entering through the Obi Strait. NPSW, NPIW, and SPSLTW contributions in each sea have different values. NPSW contributions in the Maluku Sea, Seram Sea and Banda Sea are presented in table 4. The highest NPSW contribution was in the Maluku Sea at 130 m a depth at 91%. The lowest NPSW contribution was in the Seram Sea at 220 m depth at 58%. Overall, the changes in the contribution of the NPSW in the Maluku Sea and the Seram Sea have similarities and are increasingly higher towards the Banda Sea. The high contribution of NPSW in the Banda Sea is probably due to the inclusion of a mass of north pacific water other than through the Maluku Sea namely via the Flores Sea / Western route.

### Table 2. Percentage contribution of NPSW in Maluku Sea to Banda Sea.

| Depth (m) | Maluku | Seram | Banda |
|-----------|--------|-------|-------|
| 130       | 91     | -     | -     |
| 140       | 88     | 88    | -     |
| 150       | 86     | 87    | 90    |
| 160       | 77     | 77    | 89    |
| 180       | 68     | 67    | 77    |
| 200       | 59     | 61    | 73    |
| 220       | -      | 58    | 63    |

Note: - : Excludes the depth of type of water mass in the study area.

The Contribution of NPIW in Maluku Sea, Seram Sea, and Banda Sea are presented in Table 3.

### Table 3. Percentage contribution of NPIW in Maluku Sea to Banda Sea.

| Depth (m) | Maluku | Seram | Banda |
|-----------|--------|-------|-------|
| 230       | 80     | 93    | -     |
| 240       | 77     | 92    | -     |
| 260       | 75     | 90    | -     |
| 270       | 74     | 90    | 93    |
| 280       | 72     | 86    | 91    |
| 290       | 71     | 83    | 88    |
| 300       | -      | 78    | 90    |
| 320       | -      | 73    | 85    |
| 330       | -      | 71    | 85    |
| 340       | -      | 70    | 86    |
| 360       | -      | 58    | 78    |
| 380       | -      | -     | 76    |

Note: - : Excludes the depth of type of water mass in the study area.

The highest NPIW contribution was in the Banda Sea with a 270 m depth of 93%. The lowest NPIW contribution of 58% was in the Seram Sea with a depth of 360 m. The contribution of NPIW is low in the Maluku Sea and is increasing when entering the Banda Sea. The contribution of NPIW in the high Banda Sea is probably due to input from other routes namely the Makassar Strait and the Flores Sea,
this is supported by the research of Ilahude and Gordon (1996), the presence of a mass of low salinity NPIW water originating from the Makassar Strait and the Flores Sea which replaced the water mass from the South Pacific.

The Contribution of SPSLTW in Maluku Sea, Seram Sea, and Banda Sea are presented in Table 4. The SPSLTW contribution in the Maluku Sea has the highest value of 93% at a depth of 450 m. The lowest SPSLTW contribution was in the Seram Sea at 340 m depth of 21%. SPSLTW contribution is high in the South Maluku Sea, and has decreased as it heads to the South Seram Sea and Banda Sea. This is in accordance with the study of [12], the mass of the South Pacific water while in the Central Banda Sea has decreased and was replaced by the mass of the north Pacific water originating from the Makassar Strait.

According to [14], the North Pacific water mass in the South Maluku Sea and the Seram Sea has been replaced by the maximum thermocline salinity originating from the South Pacific, while the Banda Sea is more similar to the Flores Sea with the dominant North Pacific water mass as a source the mass of water. This is what might have caused the overall contribution of the North Pacific water mass to be greater in the Banda Sea than in the Maluku Sea and the Seram Sea.

Table 4. Percentage contribution of SPSLTW in Maluku Sea to Banda Sea.

| Depth (m) | Maluku (%) | Seram (%) | Banda (%) |
|----------|------------|-----------|-----------|
| 280      | 28         | -         | -         |
| 300      | 41         | -         | -         |
| 325      | 54         | -         | -         |
| 340      | 62         | 21        | -         |
| 350      | 73         | 28        | -         |
| 370      | 79         | 39        | 24        |
| 400      | 83         | 50        | 36        |
| 425      | 87         | 61        | 47        |
| 450      | 93         | 68        | 54        |
| 470      | 90         | 72        | 58        |
| 490      | 88         | 72        | -         |
| 500      | -          | 74        | -         |

Note: - : Excludes the depth of type of water mass in the study area.

4. Conclusion
The Maluku Sea, the Seram Sea, and the Banda Sea have different thicknesses of mixed layers, thermocline and inner layers. In the mixed layer the Banda Sea has the thickest thickness. Maluku Sea has the thickness of the thermocline layer and the thickest inner layer. NPSW, NPIW, and SPSLTW water masses were found in the Maluku Sea and the Seram Sea. While the Banda Sea, NPSW and NPIW water masses were more dominant.

NPSW, NPIW, and SPSLTW contributions in Maluku Sea, Seram Sea, dan Banda Sea have different values. The largest NPSW and NPIW contributions are in the Banda Sea, while the dominant SPSLTW contributions are found in the South Maluku Sea and the Seram Sea. Water mass transformation occurs along the Maluku Sea to the Banda Sea, in the form of changes in temperature and salinity along the water mass journey.
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