Indirect estimation of turbulent mixing in western route of Indonesian throughflow

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Abstract. The Indonesian Throughflow (ITF) via its western path conveys mainly North Pacific water origin with Smax thermocline water and Smin intermediate water from its entry portal in Sangihe-Talaud arcs to the main outflow straits in Lombok, Ombai and Timor passage. Along its route, the throughflow water characteristics transforms significantly due to strong diapycnal mixing forced by internal tidal waves interaction along complex topography such as passages, sill, straits, and shallow islands chains. This paper reports a brief estimate of turbulent mixing profiles in Sangihe chains, and Makassar Strait. The CTD dataset are obtained from the year of maritime continent (YMC) Cruise in August 2019 on board the R.V. Baruna Jaya I. The Thorpe method is used to analysis dissipation energy (ε) and vertical diffusivity (Kz) from CTD dataset. It is shown that the highest ε epsilon 5.87 × 10⁻⁷ Wkg⁻¹ and Kz 4.42 × 10⁻³ m²s⁻¹ are found in the Sangihe area. In Labani Channel and Dewakang Sill the averaged vertical diffusivity is much weaker at the order of 10⁻⁴ m²s⁻¹. Thus, Sangihe Chains station have the highest values compared to other stations at depth 950-1000 meters.

Keyword: CTD dataset, dissipation energy, Indonesian throughflow, pasific water, thorpe analysis, vertical diffusivity

1. Introduction
The Indonesian Throughflow (ITF) is a main branch of global thermohaline circulation which directly transfers the properties of seawater in order to maintain the balance of heat and water volume between Pacific Ocean and Indian Ocean [1]. ITF carries a large mass of water through complex routes of Indonesian Maritime Continent, which impact on the nature of water in both oceans [2]. Indirectly, ITF variability plays a significant role in regional climate dynamics such as El Nino Southern Oscillation (ENSO), Walker Circulation, and monsoons [3]. The studies of [4] and [5] suggested that dynamics of ITF influences regional circulation patterns around it. The ITF enters Indonesian waters through two routes, namely through primary western route that enters through the Sulawesi Sea and continues to Makassar Strait, Flores Sea and Banda Sea which [6]. The main entry portal for Pacific water into the Indonesian sea is the Makassar Strait, conveying North Pacific water origin about 12.5 Sv (1 Sv = 10⁶ m³/s) or 77 % of total ITF [7]. Along its path within the internal Indonesian seas characteristics of these
water masses are changes due to diapycnal mixing with local water forced by internal tidal waves activities.

The vertical mixing process leading to transformation of physical properties can be caused by rough topography and internal wave activity. Indonesian waters are an area characterized by strong internal tidal values, as shown by a high energy transfer from barotropic to baroclinic tides of about 1.1 TW (10%) of total transfer over the world oceans [8]. ITF water mass undergoes a physical character transformation along its journey when it passes through Indonesian waters. This change in salinity 35 to 34psu indicates a strong vertical mixing process in Indonesian waters [9-11]. Thorpe scale method has been applied to historical CTD dataset to infer the spatial distribution of turbulent mixing in Indonesian Archipelago [12]. This paper aims to analysis a magnitude and distribution of vertical turbulent mixing using the Thorpe's method from several CTD casts in ITF western route from Sangihe-Talaud to Dewakang Sill is part of ITF main transport. In addition, it is able to complement information on ITF water mass transformation in internal Indonesia seas, especially ITF western route.

2. Materials and methods

2.1. Study area
This research was conducted in western route of ITF as shown in Figure 1, with 4 stations of CTD (Conductivity Temperature Depth) casts measurement at Sangihe Chains (Station 1), Makassar Strait (Station 2), Labani Channel (Station 3) and Dewakang Sill (Station 4). The CTD data acquisition was carried out from 9 to 16 August 2019. The geographical position, time, depth of CTD measurement, and bottom depth at each CTD station are presented in Table 1.

![Figure 1](image-url)  
*Figure 1.* A schematic ITF circulation in the western route. Color dots denote locations of CTD measurement during the YMC (Year of Maritime Continent) cruise Leg-2 in August 2019.
2.2 Data acquisition

The CTD SBE 9plus 24 Hz sampling resolution dataset are obtained from Year of Maritime Continent (YMC) Cruise Leg-2 in August 2019 on board the R.V. Baruna Jaya I. CTD data processing and analysis are performed using standard procedure of the SBE Data Processing Version 7.26.7. In this study, CTD datasets are selected for downcast measurement only. The CTD is lowered closed to the seabed with the deepest depth is in Station 1 of about 1058 m. The dataset of each parameter is bin averaged of 0.2 meter.

| Station | Location          | Lon (E)    | Lat (N)     | Date      | Bottom Depth (m) | CTD Depth (m) |
|---------|-------------------|------------|-------------|-----------|------------------|---------------|
| 1       | Sangihe Chains    | 125.5905   | 4.949333    | 9-Aug-19  | 1153             | 1058          |
| 2       | Makassar Strait   | 119.0997   | 0.399833    | 14-Aug-19 | 638              | 604           |
| 3       | Labani Channel    | 118.4193   | -3.1805     | 15-Aug-19 | 698              | 651           |
| 4       | Dewakang Sill     | 118.5195   | -5.34967    | 16-Aug-19 | 967              | 929           |

2.3 Data analysis

Analysis of CTD data to describe physical characteristics of water mass is carried out by plotting a temperature potential-salinity relationship (T-S diagram). This analysis is very useful and can provide the best explanation for recognizing water types, namely water masses with particular range of temperature, salinity, and density potential values; and water masses [13]. Specifically, this analysis is aimed at identifying the origin of the water mass according to the classification by [14]. Tracking and identification of water mass transformation are based on the T-S diagram profile.

According to [15] stratification of layer based on gradient is more realistic than using temperature, because the temperature profile does not always provide precise vertical stratification. The mixed layer was determined by calculating the gradient = 0.02 with a surface density reference point. If the gradient is more than 0.02 then the layer is categorized as a thermocline layer [16]. The boundary between the thermocline layer and the homogeneous inner layer can be seen visually from the density data which is cross-checked with the temperature data, the limit is area where the density value does not decrease sharply with depth. The depth of the mixed layer, the thermocline and the homogeneous layer in the interior were different at each CTD cast.

Static stability of water column can be influenced by the stratification conditions of waters which can modify the dynamics of turbulence. Turbulence will be suppressed under strong stratification conditions, so it takes greater turbulent energy to counter the vertical gradient of density [17]. The water mass stratification characteristics were identified from the value of Brunt Väisälä frequency ($N$). The value of $N$ which represents a measure of the static stability of the water mass is calculated using the equation from [19]:

$$N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}$$

CTD data analysis for estimating turbulent kinetic energy dissipation rate ($\varepsilon$) and vertical eddy diffusivity ($K_v$), first it is necessary to determine Thorpe displacement value, Galbraith and Kelley, Thorpe scale, and Ozmidov scale. Galbraith and Kelley identification is resolution limits on overturn detection as for the process is inversions and reordering regions, resolution of overturn thickness and resolution of dissipation rate. Based on the results of overturn and dissipation resolution obtained the value of $L_Z = 1$ and $\varepsilon = 1 \times 10^{-11} \text{Wkg}^{-1}$. The Overturn on density can be calculated with the Thorpe scale, sometimes containing spurious overturn. This can be caused by the unstable position of the ship when waves come or mismatch of conductivity and temperature sensors on the CTD instrument where time lag appears. Galbraith and Kelley there are two methods namely Run-Length Test and Watermass Test. However, in this research only used Watermass test (T-S Relationship tightness test) because the data screening has been carried out with a 0.2m bin average used SBE Data Processing. We use the
simplest models of smooth T–S covariation that is $\rho_S = a_S + b_S S$ and $\rho_T = a_T + b_T T$. The deviations between the observations and these lines are measured by computing the rms values of $\rho - \rho_S$ and $\rho - \rho_T$. The resultant ratios, denote $\xi_S$ and $\xi_T$ are positive-definite quantities that approach 0 for tight T–S relationships and that exceed 1 for rather loose relationships.

Thorpe fluctuations from density profiles are defined as difference between measured density value and reordered density value to be stable under the influence of gravity. This illustration uses the depth value function where depth $z_{re}$ (depth value that has been rearranged based on the density value) is moved to depth $z_{in}$ (depth value from the observation data) to form a static stability condition, then Thorpe displacement can be calculated by equation [19-21]:

$$d = z_{re} - z_{in}$$ (2)

After getting value of “$d$” (displacement), it is necessary to calculate estimated value of the minimum displacement thickness from the vertical resolution of CTD. It is intended that the value of “$d$” (displacement) is actual displacement value and not from CTD noise. The solution to resolve discrepancy is to allow for a vertical resolution to detect this reversal if not lower than [22]:

$$L_Z = 5 \times \partial Z$$ (3)

where $\partial Z$ is the vertical resolution of CTD data (dbar–meters). For this study, a bin average of 0.2 meters was used so that value $L_Z$ was 1 meter. This means that values less than 1 meter will be ignored and will not be included for further calculations. Thorpe scale calculation analysis was obtained using the equations of [19-20] [17, 22]:

$$L_T = \left( \frac{1}{n} \sum_{i=1}^{n} d_i^2 \right)^{1/2}$$ (4)

where $d_i$ is Thorpe's displacement at depth and $n$ is number of samples. Each value is obtained from the results of averaging sample at the desired depth. The average value in this study was carried out by dividing depth resolution into 50 meter. According to [19] explains that $L_T$ has a linear relationship with $L_O$ Ozmidov Scale. In a stratified fluid, a fluid parcel that moves a vertical distance in order to convert all of its kinetic energy into potential energy, Ozmidov scale [23]:

$$L_O = \left( \frac{\varepsilon}{N^3} \right)^{1/2}$$ (5)

where $\varepsilon$ is energy dissipation and $N$ is Brunt Vaisala frequency. Calculation analysis related to obtaining Thorpe scale values for each layer is used to calculate the Ozmidov scale using the equation [19]:

$$\frac{L_O}{L_T} = 0.8$$ (6)

$$L_O = 0.8 \times L_T$$ (7)

Turbulent kinetic energy dissipation rate per unit mass $\varepsilon$ is calculated using equation:

$$\varepsilon = L_O^2 N^3$$ (8)

Vertical eddy diffusivity rate ($K_Z$) was calculated using equation according to [17, 23]:

$$K_Z = \frac{\gamma \varepsilon}{N^2}$$ (9)

where is $\gamma$ mixing efficiency, representing the ratio of the buoyancy flux to dissipation viscosity rate. Over the last few years it has generally been chosen as a constant, $\gamma = 0.2$ which is the upper limit proposed by [24].
3. Results and discussion

3.1. Seawater properties and water mass stratification

Direct CTD data measurement at several locations along the western route of ITF provide dataset for observing water masses transformation. Potential temperature, salinity and potential density anomaly profiles from 4 CTD casts are presented in Figure 2. Temperature variation at the sea surface is about 2 °C where much warmer water is found at station 2 and 3 in Makassar. Furthermore, temperature profiles show significantly indicating instabilities of temperature profiles at thermocline and lower thermocline layers (Figure 2a). Salinity profiles reveal clearly salinity maximum (near 100 m depth) and minimum (near 300 m), which represent North Pacific water origin (NPSW S\text{max} and NPIW S\text{min}), as previously documented [11, 25, 26]. At Sangihe CTD station (blue line) where is the closest area to the sources of North Pacific water drawn by Mindanao Current, salinity S\text{max} and S\text{min} reaches their values about 34.94 psu and 34.35 psu, respectively. In Makassar stations (Station 2-3-4) salinity at this thermocline and intermediate layers changes drastically by about 0.35 psu at thermocline and 0.15 psu at intermediate depth. It is noted that at station Labani (yellow) is the strongest transformation of salinity profile compared to the salinity profile at Sangihe (blue) (Figure 2b). Potential density profiles show as similar to temperature profiles and the structure are much stronger at lower pycnocline layer, which are associated with internal tidal waves activities [27-28] (Figure 2c).

Stratification of water mass based on vertical temperature gradient exhibits the thickness of mixed layer depth between 45 m (at entry Makassar) and 65 m (at Dewakang) stations (Figure 3). Thermocline layer thickness varies between 145 m (at Labani) and 210 m (at Dewakang) stations. Highest vertical gradient of temperature at thermocline layer is found at station Labani, which may be associated with high shear flow in this narrow passage. In the southern part of Makassar, the Labani Channel Current area is increasing and the flow pattern has two partitions, one branch runs along the west canal and the other branch opens the east channel to the strait [29] and [30].

Instability of water column can cause mixing of water masses which can be determined by calculating the value of Brunt Vaisala frequency. Figure 4 shows profile value of Brunt Vaisala frequency on western route. The high Brunt Vaisala value in the thermocline layer corresponds to the pycnocline layer, which is a layer with a density value that increases significantly with depth [15] and [30]. In other words, the thermocline is the most stable layer compared to the mixed surface layer and deeper layer [29].
Figure 2. Vertical profiles of temperature (a), salinity (b) and density (c) from CTD casts at Sangihe (blue), stations Makassar (red, yellow, and black).

Figure 3. Layers The thickness (m) stratification of mixed layer depth, and thermocline depth at 4 stations in the ITF western path graph at stations 1-4 with description of layer.

Thorpe displacement (d) is related to density inversion or can be interpreted as displacement distance of density value point that adjusts to its stable condition. The close relationship between density inversion and turbulent mixing has been discussed in detail by [19] and [31]. Thorpe displacement values for each measurement station can be seen in Figure 5. Before getting thorpe displacement value, a Water Mass test was carried out to eliminate influence of noise from CTD instrument as done by [22] in order to obtain a valid and not ambiguous value. In general, thorpe displacement (Figure 5) value at each measurement station has the same pattern. In the mixed layer the displacement value is small, thermocline layer is very small or even absent and deep layer is large (following are criteria for very small, small and large value ±0-1, ±2-3 and ±4-6 m, respectively). When compared with the mixed surface layer and the thermocline layer, it appears that (d) value in deep layer is the highest. This condition is thought to be due to the low value of the stability of water mass in this layer.
Figure 4. Brunt Vaisala frequency (N2) profiles on western route Station 1 (a), Station 2 (b), Station 3 (c) and Station 4 (d).
Figure 5 Comparison of Thorpe Displacement Station 1-4 data before Galbraith and Kelley method (a) was applied and after was applied (d). Water mass test for temperature (b) and salinity (c).

Station 1 Thorpe Displacement values of mixed layer in range of -1 to 1 m, a positive (negative) value indicates that the water mass will move up (down). Thermocline layer 0 (zero) and deep layer with value of -3 to 3 m. This large Thorpe displacement value is related to the interaction effect. According to [32] stated that the high value of Thorpe displacement near bottom of water could be due to the interaction between the topography of the bottom of water and currents passing over it. Station 1 as the entry point for western route of ITF is influenced by Mindanao current from Pacific subtropics [33]. Station 2 has a small Thorpe displacement value in each layer. The difference in value is not too significant although it is still visible that small value reaches 0 (zero) in thermocline layer and mixed layer. The deep layer is -1 to 1 m. Station 3 Thorpe displacement values in mix layer 0 (zero) and value in thermocline and deep layer -2 to 2 m and deep layer reaches a maximum value of -4 to 5 m.

3.2 Water mass structure of western route
Distribution of water mass in the equatorial region is quite complex, especially in Indonesian waters. ITF passing through Indonesia experienced changes in physical characteristics, both temperature and salinity. This characteristic change is caused by topography of waters. The most significant change is salinity value because salinity is a fairly good conservative tracer, so its distribution is important to distinguish water masses. To see the characteristics of water mass using the T-S diagram which can be seen in Figure 6. The ITF that entered Indonesian waters carried NPSW and NPIW water masses. Pacific thermocline core layer (NPSW) and intermediate layer (NPIW) at isopycnal $\sigma_0$ 24-24.5 and $\sigma_0$ 25-26.5 [11, 34]. NPSW and NPIW water mass cores identified in this study can be seen in Table 2. Characteristic changes that occur where Station as a comparison, shows that mass of water entering Indonesian waters experiences a reduction in the salinity value in NPSW and an increase in NPIW because it adjusts to water conditions.
Table 2 Characteristics of NPSW and NPIW water masses from this study.

| Water mass Type | Station | Depth [m] | Pot. Temperature [°C] | Salinity [psu] | Pot. Density Anomaly [Kg/m³] |
|----------------|---------|-----------|------------------------|---------------|-------------------------------|
| NPSW           | 1       | 90 - 97.8 | 22.18 - 23.3           | 34.90 - 34.93 | 23.77 - 24.09                 |
|                | 2       | 94.8 - 117.6 | 19.17 - 20.55           | 34.61 - 34.64 | 24.32 - 24.70                 |
|                | 3       | 107 - 109.6 | 19.06 - 20.50           | 34.614 - 34.61| 24.33 - 24.71                 |
|                | 4       | 105.6 - 111.4 | 19.37 - 20.86           | 34.65 - 34.66 | 24.27 - 24.67                 |
| NPIW           | 1       | 227.8 - 320.4 | 9.38 - 11.59            | 34.36 - 34.42 | 26.22 - 26.58                 |
|                | 2       | 317.8 - 337.8 | 9.87 - 11.76            | 34.43 - 34.44 | 26.21 - 26.54                 |
|                | 3       | 223.2 - 289.6 | 9.98 - 11.90            | 34.45 - 34.46 | 26.20 - 26.54                 |
|                | 4       | 280.4 - 338   | 9.98 - 11.95            | 34.46 - 34.47 | 26.19 - 26.53                 |

Figure 6. Temperature-Salinity relationship (T-S diagram) from 4 CTD casts along the ITF western route, showing Smax and Smin of NPSW and NPIW water, respectively.

3.3 Estimates of turbulent kinetic energy dissipation and vertical eddy diffusivity
Profile of estimated range of turbulent kinetic energy dissipation (epsilon) and vertical eddy diffusivity at each station are shown in Figure 7. The high value of turbulent kinetic energy dissipation indicates release of a number of turbulent kinetic energy to modify the structure of the water mass that occurs in the mixing process [15, 26]. Missing of value Kz in thermocline layer on Makassar Strait due to the fact that thermocline layer is a stable layer that requires greater energy to disturb stability so that mixing occurs. The thermocline layer usually tends to coincide with the pycnocline layer, causing this layer to have the highest level of stability [30]. Based on the average value of epsilon and Kz between stations...
in (Table 3). The highest value is at Labani Channel station, which is $1.02 \times 10^{-7} W kg^{-1}$ and $6.49 \times 10^{-4} m^2 s^{-1}$ this is because entering the Labani Channel, ITF current is getting more intensive. The narrow and deep configuration of the Labani Channel is the main factor in the strong flow in the region causing high turbulent mixing [29]. Turbulent mixing in the water column occurs due to disturbances in vertical stability, among others caused by shear, wind friction and internal wave breaking. Internal wave breaking events can be caused by the narrowing of the bottom topography of the waters such as the Labani Channel, the presence of obstacles at the bottom of waters such as sills or hills on the seabed. If we look at the variations in current strength at depths below the pycnocline, it can be assumed that the shear stress of the ITF flow has the potential to trigger instability [30, 35].

**Table 3** Average value of Kinetic Energy Dissipation and Vertical Eddy Diffusivity at each station.

| Station              | Kinetic Energy Dissipation ($W kg^{-1}$) | Vertical Eddy Diffusivity ($m^2 s^{-1}$) |
|----------------------|----------------------------------------|-----------------------------------------|
| Sangihe Chains       | $3.54 \times 10^{-8}$                  | $5.82 \times 10^{-4}$                  |
| Makassar Strait      | $1.63 \times 10^{-8}$                  | $5.22 \times 10^{-4}$                  |
| Labani Channel       | $1.02 \times 10^{-7}$                  | $6.49 \times 10^{-4}$                  |
| Dewakang Sill        | $2.06 \times 10^{-8}$                  | $5.31 \times 10^{-4}$                  |

**Figure 7.** Profile vertical of dissipation energy and vertical difusivity in the ITF western route.
Sangihe chains station is the location that has the highest $\varepsilon$ and $K_z$ values compared to other stations due to energy from internal tidal waves interacting with topography, this is in accordance to [28, 36] which explains that strong mixing occurs in the area around Sangihe Island. Talaul due to internal tidal propagation. The local dissipation efficiency, the fraction of internal wave energy dissipated near the wave generation region, has been frequently used to parameterize tidal mixing [37]. The highest values of turbulent kinetic energy dissipation and vertical eddy diffusivity, respectively, were found at depth of 950-1000 meters at Sangihe Chains Station (Figure 7) $5.87 \times 10^{-7} \, Wkg^{-1}$ and $4.42 \times 10^{-3} \, m^2s^{-1}$ allegedly influenced by turbulence due to the interaction between internal tides with topography and sill, this value is also strongly correlated with [38]. This is explained by [37] that the Sulawesi Sea is an area that has the strongest internal tides in Indonesian waters and the Sangihe-Talaud region is a baroclinic tidal generating area. This area has a complex seabed topography, and shows a strong barotropic to baroclinic tidal energy transfer which is thought to be the trigger for turbulent mixing. Research results from [39] which also calculates vertical diffusivity distribution using the ROMS numerical model, at locations where strong mixing occurs in the area around Sangihe island with a vertical diffusivity value of $10^{-2} \, m^2s^{-1}$, even in areas far from the center generation, a vertical diffusivity of $10^{-4} \, m^2s^{-1}$, due to influence from dissipation of internal tidal propagation. Strong tidal currents approaching 0.5 m s$^{-1}$ be found in the Sangihe Island chain [37]. According to research [40] there was a very significant increase in the distribution of baroclinic energy dissipation in the area near the Sangihe-Talaud Islands, an area where there are sills. In this western route the lowest Vertical Eddy Diffusivity value occurs at Makassar Strait station with a range of values $3.66 \times 10^{-5} - 1.79 \times 10^{-3} \, m^2s^{-1}$. This value is also appropriate in [12]. The value of Vertical Eddy Diffusivity at stations located on Labani Channel and Dewakang Sill has increased from Makassar Strait, this is expected because of its influence and the presence of a sill that becomes a limiter causing an increase in [41] and Labani Channel presumably due to the strong internal tides in these waters. The strong internal tidal effect occurs during low tide conditions, ie when the water mass induces the inner layer and the internal waves that occur in Labani Channel are due to contribution of back propagation of internal waves from Dewakang Sill or are generated locally due to narrowing channel [30]. Added by [42] that the high value at the Dewakang Sill is caused by the presence of a very intense M2 current and the interaction between lee waves and surface waves. The high value in sill area (including Dewakang Sill) is thought to be due to the interaction of internal waves and shear with the bottom topography of the waters [43].

4. Conclusion
The throughflow passage via western route is categorized as a strong mixing region from Sangihe Chains to Dewakang Sill. The highest value of turbulent kinetic energy dissipation ($\varepsilon$) and vertical eddy diffusivity ($K_z$) estimation was found at Sangihe Chains station with $5.87 \times 10^{-7} \, Wkg^{-1}$ and $4.42 \times 10^{-3} \, m^2s^{-1}$ at depth 950-1000 meters, respectively. Mean values of $\varepsilon$ and $K_{rho}$ in Makassar Strait, Dewakang sea stations are $1 \times 10^{-8} \, Wkg^{-1}$ and $1 \times 10^{-4} \, m^2s^{-1}$. The highest average turbulent mixing estimate in Labani Channel station. The presence of NPSW water mass with maximum salinity is clearly visible at Sangihe Chains Station and has decreased salinity value as it enters Makassar Strait to Dewakang Sill.

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