Analysis of turbulent mixing in the Eastern Path of Indonesian Throughflow

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Abstract. Several studies confirmed that strong transformation of Indonesian Throughflow (ITF) water appears along the eastern ITF pathway from Maluku to Ceram to Banda Seas. This is, presumably, caused by energetic internal tidal activities that generate turbulent mixing. This study was aimed to analysis the turbulent mixing using Thorpe method from CTD data set acquired during the STOKAS 2015 cruise onboard R.V. Baruna Jaya 7 in the eastern ITF region. The study area was divided into four regions: Sulawesi Sea (SUL), Maluku Sea (MAL), Ceram Sea (CER), and Banda Sea (BAN). Thorpe method provides an approach to quantify the overturn of water mass using Thorpe displacement validated using Galbraith and Kelley (GK) test and to calculate the kinetic energy dissipation ($\varepsilon$) and vertical diffusivity ($K_p$). From diagram T-S, the transformation of ARLINDO waters was identified in the gateway. This is supported by a current pattern in which the ARLINDO water mass recirculated in SUL, then moved southward to MAL. The vertical diffusivity eddy ($K_p$) varied in the order of $10^{-5}$ to $10^{-2}$ m²s⁻¹ and its kinetic energy dissipation ($\varepsilon$) varied in the order $10^{-11}$ to $10^{-5}$ W/Kg in all regions. This mixing was indicated to be driven by internal tide.

Keywords: ARLINDO, internal tide, ITF, turbulent mixing

1. Introduction

The Indonesian Archipelago has a unique oceanographic characteristic, a mixture of strong water mass and varied in the current circulation, including monsoon currents that are affected by the monsoon winds and Indonesian Throughflow (ITF). The circulation of ITF enters through the main portal between Mindanao and Papua and then extends into two paths, the western path (Makassar Strait) and the eastern path (Lifamatola Strait). It plays an important role in global circulation and in the changes of heat flux and sea surface temperature (SST) [1].

Based on the observations by the International Nusantara Stratification and Transport (INSTANT) program [2-4] over 2004-2006, the ITF transport through the Makassar Strait at a depth of 0 - 700 m was 11.6 Sv in average and that through the Lifamatola Strait at a depth near the bottom (2050 m) was 2.5 Sv. The ITF that flows in the Lombok Strait at 0 - 300 m was 2.6 Sv, in Ombai Strait at 0-1150m was 4.9 Sv and in the Timor exit (Timor Passage) at depth of 1890 m was 7.5 Sv. Hence, the total flow of the ITF transport entering its eastern path were 14.1 Sv and and that leaving the eastern path was 15 Sv. There was an enhancement in ITF exit for 25-30% from early 2000 in the observation year with
insignificant differences in mooring observation between weak El-Nino-La-Nina phase conditions and a positive IOD (Indian Ocean Dipole Mode) phase in 2006 [2].

In addition to the study of ITF water mass transport, the water mass stratification was also reviewed using CTD measurement data from the INSTANT expedition. The eastern path of ITF (Halmahera and Maluku Seas), South Pacific water mass in the interior layer enters through the route. This is evidenced by potential sigma-t value ($\sigma_t$) between 26 and 27. However, high salinity from South Pacific Subtropical Lower Thermocline Water (SPSLTW) is indicated to be strongly mixed by tides along the eastern path of ITF with changes in maximum salinity from 34.60 to 34.25 psu [5].

Turbulent mixing can also influence to the dynamics of water mass. As numerically stated in [6], the increase in vertical water mass mixing on seamounts cools the Indonesian waters, in average, is less than 0.30°C through Ekman transport and coastal upwelling. In addition, tidal vertical mixing also contributes to the change in ITF's water mass [6] and [7] so that the intensity and distribution of tidal mass mixing is important in predicting large-scale ocean circulation and atmospheric circulation globally [8]. The first microstructure measurement (related to the value of water mass mixing) in the Indonesian Archipelago was carried out by [9] in the middle of the Banda Sea. A weak vertical water mass mixing value ($K_\rho$) O (10$^{-5}$ m$^2$s$^{-1}$) only occurred above 300 m depth. This results is different from the results of the advection-diffusion model conducted by [10] where the transformation of water mass in Indonesian waters requires an average vertical diffusivity value of $K_\rho$ O (10$^{-4}$ m$^2$s$^{-1}$). Based on the dynamics of the water mass and the identified mixing value, further research is needed to analyze the turbulent mixing considering that the turbulence has an important role in the mixing of water masses.

Several studies on the mixing of water mass and their transformation in Indonesian waters were also carried out by [11] in Makassar Strait. Additionally, a research on the vertical turbulence of the Pacific Ocean water mass into isohaline water mass was carried out in Indonesian waters [12]. Therefore, this research needs to be conducted because the recent information on turbulent mixing in the Eastern Indonesia regions is limited which needs to be analyzed using Thorpe method. In this study, the area of study constituted Eastern Indonesia waters, i.e. Sulawesi Sea, Maluku Sea, Ceram Sea and Banda Sea.

2. Materials and Methods

2.1. The data and study area

Data were collected in Maluku Sea, eastern Sulawesi Sea and Halmahera from May to June 2015, Banda Sea in February 2016 and Ceram Sea in June 2016 using Research Vessel (RV) Baruna Jaya VII. This cruise was a part of National Fisheries Stock Assessment (STOKAS) program by the Center for Fisheries Research – Ministry of Marine Affairs and Fisheries. The study area and locations of data collection are shown in figure 1. CTD data were processed using SBE Data Processing software before the analysis process. Four study areas were selected in this research: Sulawesi Sea (SUL), Maluku Sea (MAL), Ceram Sea (CER) and Banda Sea (BAN).

2.2. Thorpe analysis

Estimation of vertical diffusivity ($K_\rho$) was carried out by calculating the Thorpe Scale (L_T) value. The Thorpe scale states the turbulent vertical overturn length scale in a stratified flow [13]. In stratified flow, overturn will be identified from the 'inverse' on the value of density, which is a gravity condition that has an unstable density gradient [14].

Technically, the inversion caused by unstable density is reordered to obtain a potential density profile ($\sigma_\rho$) which is more stable. Thorpe's fluctuations in density data are defined as the difference between the measured density values and the reorder density and gravitational stability. The Thorpe displacement ($d_T$) as $d_T' = z_m - z_n$ is the distance that must be reached at the depth of $z_n$ to $z_m$ to achieve a stable density [15], or the depth which has a Thorpe scale fluctuation equal to zero. A positive (negative) value indicates that the water mass moves up (bottom) to reach for static stability. This condition occurs if the water mass of low (high) density is below the water mass of high (low) density.
Each Thorpe Scale value was obtained from the average of Thorpe Displacement quadratic of $n$ samples at the desired depth. The average of Thorpe Displacement in this study was carried out in two layers: mixed surface layer and thermocline layer. The Thorpe Scale value was then calculated by the equation:

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

The existence of vertical diffusivity is closely related to energy dissipation as stated in [16]. This indicates an equilibrium between energy transfer and transformation of the water mass. In continental runways, where there is a seabed cliff, the formation of internal waves can be caused by the enhancement of current intensity to seabed cliff [17]. The constant $a$ was used to obtain the diffusivity coefficient value of the Thorpe scale from the semi-empirical equation. Then the rate of turbulent kinetic energy dissipation per unit mass ($\varepsilon$) [18]:

$$\varepsilon = L_0^2 N^3$$ (2)

However, not all turbulent kinetic energy is used to mix water mass. Most of this turbulent kinetic energy will be dissipated by viscosity and friction [19]. Then a few of fractions $\gamma$ are used to mix fluid density vertically and raise the center of mass. Thus, the vertical diffusivity coefficient was calculated as [18]:

$$K_\rho = \frac{\gamma \varepsilon}{N^2}$$ (3)

where the local buoyancy frequency or Brunt-Vaisala ($N^2$) was derived from the density profile of the reorder results. Variable $\gamma$ or mixing efficiency represents the conversion efficiency of the turbulent kinetic energy to the potential energy system. This value can be varied, depending on the turbulence dynamics. [20] states the value of $\gamma = 0.15$ from the calculation, while [21] states the value of $\gamma = 0.2$.

### 2.3. Galbraith and Kelley (GK) test

The overturn in density can be calculated by Thorpe scale, sometimes contains spurious overturn or mixing of water mass. This can be caused by the unstable position of the vessel when the wave comes or the mismatch of conductivity and temperature sensors in CTD instrument where the time lag appears. Then, it is necessary to do further tests to confirm the existence of water mass mixing. According to
[14], there are two methods that can be done: Run-Length Test and Watermass Test. However, we only used Watermass Test in this research.

The water mass test was carried out using a simple model to smooth the T-S covariation. The model equation used was:

\[ \rho_s = a_s + b_s S \quad \text{and} \quad \rho_T = a_T + b_T T \] (4)

Where \( a_s, b_s, a_T, \) and \( b_T \) are the coefficients of the line equation for salinity and temperature data. These coefficients were obtained by plotting the salinity and temperature data on the x-axis (\( \rho_s \)) and y-axis (\( \rho_T \)). We then looked for the linear equation that is most suitable with the distribution of data. The values of \( \rho_s \) and \( \rho_T \) were the density derived from salinity and temperature. The above equation is a linear equation which will produce a straight line on a vertical density profile. The deviation between the observation data and this line was obtained by calculating the root mean square (rms) values of \( \rho - \rho_s \) and \( \rho - \rho_T \). This deviation value has no dimensions when it is divided by Thorpe scale value.

The comparison between the deviation of \( \rho_s \) and \( \rho_T \) with Thorpe Scale will produce the values \( \xi_s = \frac{\rho_s}{L_T} \) and \( \xi_T = \frac{\rho_T}{L_T} \). These variables must be positive and have the value ranging between 0 and 1. If the value of \( \xi_s \) and \( \xi_T \) is close to zero, it indicates the closest T - S relationship. Meanwhile, the value of \( \xi_s \) and \( \xi_T \) more than 1 indicates that there is no T - S relationship. The critical values \( \xi_c \) of \( \xi_s \) and \( \xi_T \) are obtained from correlation coefficient between the visual observation score and the calculation from \( \xi_s \) and \( \xi_T \). The values that get reordering individually were given a score of 0 to 1, depending on the T-S relationship. The results of the scoring were compared with the value of \( \xi_s \) and \( \xi_T \) from the calculated results as a rough calibration of the test. Based on [14], the reordering region which had a value of \( \xi_c \) below 0.5 was considered to have a vertical density overturn. However, this research used \( \xi_c \) below 1 to reveal the small overturn (figure 2).

![Figure 2. Results of thorpe displacement before GK test (left), after GK test (middle), and the inversion of unstable density (right).](image)

3. Results and Discussion

3.1. Evolution of water mass characteristic

This research focused on the analysis of ITF flow that passed through the eastern path. Sulawesi Sea (SUL) area had high salinity water mass or was identified as North Pacific Subtropical Water (NPSW). Based on figure 3, there was a change in salinity from 34.75 psu to 34.5 psu in SUL to MAL area at depth 100 – 150 m. This reduction in salinity indicated 3 possibilities: 1. existence of recirculation in MAL that brought back the NPSW water mass to SUL, 2. strong mixing was caused by internal tide, and 3. low-volume of ARLINDO transport dissipated by turbulent mixing.
This result was in agreement with [23] that the character of maximum salinity found in this water mass is reduced, even not found in some locations. Based on its current pattern (figure 4), the recirculation of water mass was existed in SUL then moves to south (MAL). Hence, the NPSW is not brought back to SUL and this attenuation of salinity maximum is caused by turbulent mixing. In particular, NPSW is strongly eroded from its entrance in MAL area and the transformation is occurred at the area that has sub-basins, eroding the subtropical salinity maximum of the eastern path.

![Figure 3](image1.png)

**Figure 3.** Vertical section of salinity overlayed with the bathymetry which shows the reduction of salinity in ITF eastern path.

![Figure 4](image2.png)

**Figure 4.** Vector of currents from model (GLORYVS24): (a) June 2015, (b) February 2016, and (c) June 2016. The current at 100 m depth along transect moved southward during the observation period.

The evolution of water mass from SUL to MAL area was quite large which reduced the high salinity from 34.75 psu to 34.5 psu. The MAL water mass was quite mixed and stratified. Then CER and BAN water mass were well mixed. This transformation of water mass characteristic in the SUL to BAN areas indicated the turbulent mixing process. The T-S diagram for all regions indicated the impact of internal tide mixing (figure 5).
3.2. Analysis of vertical turbulent mixing

The profile of turbulent mixing can be identified from Thorpe scale calculation ($L_T$) and Thorpe displacement ($d_T$). Thorpe scale values are shown vertically that explain the $L_T$ distribution based on the water depth. On the figure 7, the value of $L_T$ at SUL has ranged from 0 to 12 m at a depth of 150 - 1000 m. The enhancement of $L_T$ value in SUL occurred at depth of 200 - 400 m, then the values decreased at depths of 400 m to 1000 m ($L_T \sim 0 - 5$ m). The profile of $L_T$ at MAL showed a different pattern from SUL where in MAL at depth of 200-1000 m with value of L ranged from 0 to 15 m. For all depths, these range values were almost similar. The profile of $L_T$ in CER had a slight different with the profile of $L_T$ at MAL with a shorter range of values (0 - 11 m). Finally, the profile of the $L_T$ in BAN had the shortest value ranges (0 - 7 m) than other regions. If we compare these $L_T$ patterns in each region with T-S diagrams, their patterns were looked quite similar that there was weakening values from the SUL to BAN.

Quantification of turbulent mixing in this study was calculated using Thorpe analysis on the value of $L_T$ produced. However, this Thorpe method only detects the maximum value of kinetic energy dissipation of O (10$^{-11}$ W/Kg) [11]. The results of calculation was averaged per 50 m (figure 7). In general, the values appeared on the surface to a depth of 50 m are still strongly influenced by wind. Profiles of $\varepsilon$ and $K_p$ varied among regions due to depth, i.e. the values were lower as the sea layer was deeper. The profile values of $\varepsilon$ in the SUL region has a value range O (10$^{-11} - 10^{-5}$ W/Kg) and the value range of $K_p$ O (10$^{-4} - 10^{-2}$ m$^2$s$^{-1}$). The range of the values was greater at depths of 100 - 500 m than at
Meanwhile, the range of the values in the MAL region was slightly different from the range of the values in SUL. In the MAL, the range was narrow for $\varepsilon$ value O $(10^{-11} - 10^{-8} \text{ W/Kg})$ and for $K_p$ value O $(10^{-5} - 10^{-2} \text{ m}^2\text{s}^{-1})$. The range was found wide at depth of 200 – 400 m but slightly narrow at depth below 400 m. The mixing profile in CER was weaker than that in the MAL; the range of the value range was narrower except for $K_p$ ($\varepsilon \sim O=(10^{-11} - 10^{-9} \text{ W/Kg})$ where those values were only detected at depth of 250 – 600 m. Then, the BAN has the weakest mixing profile compared to other regions ($\varepsilon \sim O=10^{-11} - 10^{-9} \text{ W/Kg}$, $K_p \sim O=10^{-5} - 10^{-4} \text{ m}^2\text{s}^{-1}$) where those values were only detected at depth of 250 -750 m.

The result of vertical diffusivity calculation in the BAN was also compared with the $K_p$ values of INDOMIX microstructure in the Banda Sea [25]. Microstructure results show the values with range from $10^{-6} - 10^{-4} \text{ m}^2\text{s}^{-1}$, this value is quite similar to the results of Thorpe calculations.

Turbulent mixing in the studies area is also described spatially in figure 9 with parameters of kinetic energy dissipation ($\varepsilon$). The value of $\varepsilon$ at a depth of 150 m was identified only in the SUL and one half part of the MAL. Then at a depth of 250 m, the SUL has the highest $\varepsilon$ (i.e., $10^{-10} - 10^{-8} \text{ W / Kg}$) while $\varepsilon$ was lower in the BAN (i.e., $10^{-11} - 10^{-10} \text{ W/Kg}$). The similar north-south pattern was identified at a depth of 500 m where $\varepsilon$ in the SUL was higher (i.e., $10^{-11} - 10^{-10} \text{ W/Kg}$) than the other regions (i.e.,$10^{-11} \text{ W/Kg}$) although the range was narrower. Finally, at depth of 1000 m, $\varepsilon \sim O (10^{-11} \text{ W/Kg})$ was only identified in the MAL.
Internal tide plays an important role in determining turbulent mixing. Vertical mixing is generated by tidal activity because tidal currents occur rapidly in the Indonesian Sea and are dominated by $M_2$ components with a speed up to 0.5 ms$^{-1}$ [26]. As the existence of the sill, the tidal propagation changes direction where the water mass moves upward following the topography. In stratified seas, this vertical movement generates waves or can be referred to as internal tide. The internal tide can dissipate or produce vertical diffusivity in the water column to the bottom of the water. In this study, the internal tide was able to transform the ARLINDO water mass. Thus, the role of sill or topography feature becomes important in tidal barotropic conversion being baroclinic [28].

The investigation conducted by [28] related to the propagation of simulation of internal tide at depth of 142 m with the EXPL simulation showing internal tide propagation occurred in several locations, namely Sangihe Islands (H1), Sulawesi Sea (H1), Lifamatola Strait (V2), and Sea Halmahera (V2), as shown in figure 9. The high value of kinetic energy dissipation is seen in the area around the sill.
4. Conclusion

The T-S diagram and vertical section of the salinity distribution indicated a transformation of ARLINDO water mass at depths of 100-150 m from the SUL to BAN regions. This transformation was supported by the recirculation in the SUL region, then the current moved southward (MAL). The ARLINDO transport was small that turbulent mixing activities can dissipate its water mass. The vertical diffusivity ($K_\rho$) was found high in the MAL and SUL regions ($10^{-5} - 10^{-2}$ m$^2$ s$^{-1}$) and low in the BAN region ($10^{-5} - 10^{-4}$ m$^2$ s$^{-1}$). Therefore, the Maluku sea plays an important role in the transformation of ARLINDO water mass. The vertical diffusivity from Thorpe analysis was in a good agreement with intensified dissipation at the bottom produced by numerical analysis. The transformation of ARLINDO water mass was also due to the presence of internal tide caused by sill or topographic configuration so that barotropic tidal conversion becomes baroclinic. This conversion promoted vertical diffusivity or turbulent mixing.

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