Physical Oceanography Condition and the Turbulent Mixing in Mid-upper Layer of the Eastern Indian Ocean during the InaPRIMA Cruise 2019

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Abstract. Turbulent mixing in the ocean has a significant role in weather and climate, especially concerning flux between the ocean and atmosphere. This research aims to study physical oceanography conditions and quantify the turbulent mixing in the Eastern Indian Ocean during the InaPRIMA cruise in November 2019. The CTD data from five meridional stations were processed to determine the oceanographic condition. Water mass stratification was determined by a temperature gradient of 0.05°C/m for thermocline boundaries, and turbulent mixing was calculated using the Thorpe method. The results showed that the mixed layer depth (MLD) varied between 16.41-45.74 m, while the depth of the thermocline layer ranged from 178.3-237.0 m. The MLD was getting deeper to the north, while thermocline depth tends to be shallower associated with the wind speed. The Thorpe analysis for all CTD showed that overturn with size varies between 2.5-30 m was identified. The turbulent kinetic energy was ranged from an order of 10^{-8} to 10^{-6} Wkg^{-1}, while the turbulent diffusivity was ranged from an order of 10^{-4} to 10^{-2} m^{2}s^{-1}. Turbulence mixing in MLD suggests driving by wind stress, while in thermocline because of shear instability and double-diffusive salt fingering and in deep layer because of topography.
1. Introduction

The Indian Ocean has a vital role in global climate through the global overturning circulation and carbon budget [1]. For the Regional scale, the Indian Ocean influences climate and weather variability in the Indonesian Maritime Continent through Indian Ocean Dipole, Monsoon system, Madden-Julian Oscillation (MJO), Kelvin waves, etc. Multiscale variability in the Indian Ocean was reported to influence by turbulence mixing. [2] reported that inaccuracy of ocean-atmosphere model for monsoon prediction may generate by poorly constrained surface fluxes as the representation of mixing. The heat and momentum exchange from the mixing process also affects the MJO ocean response in the Indian Ocean. [3] report that mixing was contributed to systematic errors in numerical models of MJO evolution. Ocean turbulence has a significant impact on the atmospheric moisture budget of MJO evolution [4].

Turbulence is defined as random and irregular motion from an order of 0.01 to 100 m [5]. Turbulence has an important role in the ocean and atmosphere dynamics, especially in terms of the distribution of heat, salt, and nutrients [6]. Diapycnal mixing is essential to understand ocean stratification and meridional overturning circulation [7]. Turbulence near the seabed affects the deposition and transport of inorganic matter and sediment transport [8].

Several mechanisms are responsible for generating vertical mixing. At the surface, turbulence may be generated by interaction with the atmosphere through heat and momentum transport because of the wind stress and ocean waves (Langmuir circulation) [7]. In the ocean interior, turbulence may generate by double-diffusive processes such as salt fingering, a condition when the temperature and salinity stratification are unstable. Shear instability of strong current and internal waves is also responsible for turbulence in the ocean interior [7]. The topography effect (sill-like topography) can also cause turbulence when the water mass flows in it [8].

There are many instruments used to measure mixing in the ocean, such as microstructure profiling [7,9] and the Conductivity-Temperature-Depth (CTD) [10,11,12]. The microstructure is more general to use in mixing measurement than CTD because of the CTD limitation [13]. Despite its limitation, CTD using a 24 Hz frequency sampling rate still get a valid mixing estimation if processed with a proper processing method [8]. This research aims to determine the overturn region and estimate the turbulent mixing by using Thorpe analysis during the InaPRIMA cruise in November 2019. The InaPRIMA (Indonesia Program Initiative on Marine Observation and Analysis) is a joint ship-time BMKG-NOAA collaboration for collecting met-ocean data and maintaining the RAMA mooring buoy in the Eastern Indian Ocean. This study is limited to using CTD data to estimate turbulent mixing only in November 2019 to describes the conditions at that time (snapshot).

2. Data and Method

2.1 Data

The data used in this research are physical properties of water column such as temperature, salinity, and oxygen data acquired by using Conductivity-Temperature-Depth (CTD) SBE 911 plus at sampling rate 24 Hz from the surface to depth of 1000 m and meteorological data such as wind data from Portable Automatic Weather Station (PAWS). This data was collected during the Indonesia Initiative Program on Maritime Observation and Analysis (InaPRIMA) cruise in November 2019 for 29 days since 12 November 2019 using Research Vessel (R/V) Baruna Jaya I. The data was conducted at five locations in the Tropical Eastern Indian Ocean near 90 degree east at the latitude of 0, 4 N, 8 N, 12 N, and 15 N (Figure 1). The average ocean current Mercator Model from 11-30 November 2019 was download from Copernicus environment monitoring service (CMEMS) (www.marine.copernicus.eu).
2.2. Data processing and analysis
CTD data were processed using standard procedure according to [14] including conversion, align CTD, wild edit, filter, cell thermal mass, loop edit, derived variable, and bin average. The water column stratification was divided into three layers: the mixed layer depth (MLD), thermocline layer, and deep layer. The stratification is based on a temperature gradient of 0.05°C m⁻¹ for the upper and lower boundary of the thermocline [15,16]. The temperature gradient can be calculated by the following formulation:

$$\frac{\Delta T}{\Delta z} = \frac{T_i - T_{i+1}}{z_i - z_{i+1}}$$  \hspace{1cm} (1)

The schematic diagram for water column stratification is illustrated in figure 2.

![Schematic of stratification based on temperature gradient of 0.05°C/m for thermocline layer](image)
2.2.1 Overturn identification and turbulent quantification  

The density was derived from temperature, salinity, and pressure data based on The Unesco Equation of seawater:

\[
\rho = \frac{\rho(S,T,0)}{K(S,T,p)}
\]  \hspace{1cm} (2)

The overturn occurred when there is vertical instability of water mass, the condition when less dense water is located beneath more dense water [17]. To identify the overturn, the density data is reordered to a stable condition. The Thorpe displacement is defined as the distance of unstable density at a depth of \(z_a\) to its stable condition depth at \(z_b\),

\[
d = z_a - z_b
\]

as illustrated by [10]. The overturned is defined if Thorpe displacement greater than 2.5 m [11].

Figure 3. Schematic diagram how to determine the Thorpe displacement as illustrated by [10]

The [17] test is applied to Thorpe displacement to ensure that no false overturn is identified. The [17] used a non-zero criterion for temperature and salinity data to identified the overturn [11]. After calculating the Thorpe displacement (\(d\)), the Thorpe scale (\(L_T\)), which is the RMS of Thorpe displacement, is calculated using the following equation [18]:

\[
L_T = \left(\frac{1}{N}\sum_{n=1}^{N} d_n^2\right)^{1/2}
\]  \hspace{1cm} (3)

Estimation of turbulent intensity in overturn region is defined by the value of turbulent kinetic energy dissipation (\(\varepsilon\)) and the turbulent vertical diffusivity (\(K_z\)). The turbulent kinetic energy indicated the amount of kinetic energy release to media by the mixing process [A]. The turbulent kinetic energy is calculated using the equation below [18]:

\[
\varepsilon = L_0^2 N^3
\]  \hspace{1cm} (4)

Where the \(L_0\) is the Osmidov scale [19]

\[
L_0 = 0.8L_T
\]  \hspace{1cm} (5)

\(N\) is the Brunt Vaisalla frequency or buoyancy frequency. \(N^2\) is also used to define the stability of water mass. \(N^2\) is calculated using equation:

\[
N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}
\]  \hspace{1cm} (6)

Where \(g\) is the gravity acceleration (9.8 m s\(^{-1}\)), \(\rho\) is density (kg m\(^{-3}\)), and \(z\) is the depth (m). Density value equation (6) is the reorder density (density in stable condition).
The turbulent diffusivity rate at each overturn is obtained using equation (7):

\[ \kappa_z = \frac{\gamma \varepsilon}{N^2} \]  

(7)

\( \gamma \) is the mixing efficiency, generally 0.2 [20].

3. Result and Discussion

3.1. Temperature, salinity, and oxygen profiles

The temperature profiles show the water column stratification among the CTD stations. Mixed layer depth (MLD) is defined as a layer that has small temperature gradients. The mixed layer depth in this research varies from 16 to 45 m (Table 1). In the equator, the MLD is shallowest and tends to be deeper for the northern CTD stations. Comparison between wind speed and MLD of all CTD stations (Figure 5) shows a strong positive relationship between wind speed and MLD with an R-square value more than 0.7. The wind stress causes mixing that will distribute temperature over several meter depth. The MLD also depends on water mass stability. The more stable the water mass, the harder the mixing occurred. Figure 5 shows the stability of the water mass of all CTD stations. In station 1 (latitude 0 degrees), the stable layer shallower than others made the MLD in the station near the equator shallower than other stations. The thermocline depth, when temperature gradient >0.05°C, has a range of 178-218 m. This research in November 2019 at the same time with strong positive IOD occurred in the Indian Ocean. This thermocline has similar to [16]. They found the average thermocline depth when positive IOD occurred was 208 m. The thermocline has a strong negative correlation with the depth of the thermocline [16].

| CTD station | MLD (m) | Thermocline depth (m) | Thermocline thickness (m) |
|-------------|---------|-----------------------|---------------------------|
| 90 E, 0     | 16.41   | 216.7                 | 200.29                    |
| 90 E, 4 N   | 45.74   | 237.0                 | 191.36                    |
| 90 E, 8 N   | 34.79   | 207.2                 | 169.71                    |
| 90 E, 12 N  | 37.78   | 203.2                 | 165.42                    |
| 90 E, 15 N  | 41.28   | 178.4                 | 137.14                    |

Table 1. Depth of MLD, thermocline, and the thermocline thickness

![Figure 4](image-url)  

Figure 4. Profiles of Brunt Vaisalla Frequency (blue line) overlaid with temperature (red line) and density profiles (black line) in latitude: (a) 0; (b) 4 N; (c) 8N; (d) 12 N; (e) 15 N
Salinity in Figure 4(b) showed the low salinity in the surface layer (33-33.5 psu) then increased to thermocline layer (34-35.8 psu) and tended to be constant up to the depth of 1000 m (34.8-35 psu). The salinity value varies in the thermocline layer. In the equator, at a depth of 100 m, there is the intrusion of high salinity (35.75 psu), which indicates the presence of Arabian Sea Water (ASW), a water mass that has salinity between 35.5-36.8 psu [21]. In the latitude of 12 N, at a depth of 100 m, there is low salinity intrusion (34.15 psu) detected, which indicated the presence of Bay of Bengal water mass [21]. The meridional variation of salinity possibly because the distribution of water mass meridionally different.

Dissolve oxygen concentration in Figure 4(c) showed a similar pattern with temperature profiles. At the MLD, the oxygen concentration was ~5.5 mg/l, slightly higher (5.6 mg/l) in the upper thermocline boundary, then rapidly decrease until 3 mg/l at a depth of 250 m and continue to decrease slowly until the depth of 1000 m. High oxygen concentration in MLD because absorbed from the atmosphere and also produced by plankton. Decreasing oxygen concentration in the thermocline layer until 1000 m depth is because far from the atmospheric exchange and there is not enough light for the photosynthetic process [22].

Figure 5. Relationship between wind speed and the depth of mixed layer

3.2. Stability of water mass
Overturn occurred because of unstable stratification. The stability of water mass is represented by Brunt Vaisalla Frequency ($N^2$). The higher $N^2$ value, the more stable the water mass. The $N^2$ calculation result in Figure 6 showed the low value in the mixed and deep layer, while the high value in the thermocline layer. In MLD, the maximum value of $N^2$ was $0.4 \times 10^{-3}$ s$^{-2}$, while in the mixed layer up to $2.9 \times 10^{-3}$ s$^{-2}$, and $0.025 \times 10^{-3}$ s$^{-2}$ in lower thermocline until the depth of 1000 m. The high value of $N^2$ in the thermocline indicated that this layer is the most stable. The high value of $N^2$ in the thermocline is because in this layer the density gradient very high as the manifestation of pycnocline layer [23]. High stability near the surface in station 1 probably made the MLD in the latitude of 0 degrees shallower than others. The low value of $N^2$ in the lower thermocline boundary up to 1000 m depth could make mixing occurred easily.
Figure 6. Profiles of Brunt Vaisalla Frequency (blue line) overlaid with temperature (red line) and density profiles (black line) in latitude: (a) 0; (b) 4 N; (c) 8 N; (d) 12 N; (e) 15 N

3.3. Overturn detection and quantification

The presence of mixing in the water column could detect by calculated Thorpe Displacement. Thorpe displacement calculates the difference between in situ density and reordered stable density, and it can be used to estimate the size of the overturn. The positive (negative) value in Thorpe displacement indicated the water mass move up (down) to reach its stable condition.

Thorpe displacement value in figure 7 showed a higher value in MLD and deep layer than in the thermocline layer. It is because the thermocline layer was the most stable layer that will be hard to mix. In CTD station 1 and 2 (latitude of 0 and 4 N), the Thorpe displacement is higher at a depth of>700 m than MLD, while in the rest station in the latitude of 8 N, 12 N, and 15 N, the higher Thorpe displacement is located at the surface indicated the different mechanism that caused the mixing.

The size of mixing can describe by the vertical size of overturning. The vertical size of the overturn in figure 8 was calculated from Thorpe displacement. The minimum size overturns of CTD 24 Hz,
according to [11] was 2.5 m. The displacement that has vertical size <2.5 will be ignored. The vertical size of the overturn from all stations varies between 2.5-29 m.

In MLD, the overturn was identified in all CTD stations with a size vary from 7.5 to 17 m. Because it was identified in all latitudes, it can be assumed that mixing in the MLD because of wind stress. [10] showed that there was a high correlation between wind stress and mixing in MLD. In the thermocline, overturn occurred in equator (at a depth of ~200 m) and latitude 15 N (at a depth of ~100 m) with size ranging from 2.5 to 9 m. The overturn in the thermocline layer possibly by the shear instability of a strong equatorial undercurrent. The average current velocity model from 11-30 November 2019 in the equator (Figure 9) showed a high eastward current speed at a depth of 100 m. This strong current could generate shear instability at 200 m to induce mixing at that depth. [7] reported that in the equator, shear instability from strong current could generate turbulent mixing. Moreover, salt fingering (more salty water located above less salty water) as in the equator at 100 m depth (as seen in Figure 4(b)) could trigger the turbulent mixing through the double-diffusive phenomena [7]. For the deep (homogenous) layer, the overturn was identified in the equator (at a depth of ~700 m and 950 m) and in latitude 4 N (at a depth of ~990 m). The overturn in the homogeneous layer is assumed due to topography effect. CTD stations of latitude 0 and 4 in Figure 1 are located above the Ninetyeast ridge, the interaction between water mass flow and the ridge could generate turbulence mixing. [24] showed that vertical diffusivity is high near the sill topography.

![Thorpe displacement profiles](image)

**Figure 7.** Profiles of Thorpe displacement in latitude: (a) 0; (b) 4 N; (c) 8 N; (d) 12 N; (e) 15 N
3.4. Turbulent kinetic energy and turbulent diffusivity

The intensity of turbulent mixing is represented by turbulence kinetic energy and turbulent diffusivity. These mixing parameters of every single overturn were calculated using equations (4) and (7). The turbulence kinetic energy ($\varepsilon$) of all stations in Figure 10(a) ranges from an order of $10^{-8}$ to $10^{-6}$ W kg$^{-1}$. In MLD, the $\varepsilon$ was ranging from $1.78 \times 10^{-8}$ to $6.93 \times 10^{-6}$ W kg$^{-1}$ ($2.5 \times 10^{-7}$ W kg$^{-1}$ on average). This result is similar to [9]. They found that the average $\varepsilon$ at a depth of 0.75 m of tropical Indian ocean was from an order of $10^{-7}$ to $10^{-6}$ W kg$^{-1}$. But this value is one order higher than [7]. They found that in the thermocline layer, $\varepsilon$ was ranging from $2.66 \times 10^{-8}$ to $2.34 \times 10^{-7}$ W kg$^{-1}$ ($1.22 \times 10^{-7}$ W kg$^{-1}$ on average), and in the deep layer from $1.65 \times 10^{-8}$ W kg$^{-1}$ to $7.5 \times 10^{-8}$ W kg$^{-1}$ ($4.5 \times 10^{-8}$ W kg$^{-1}$).

The $\varepsilon$ value tends to be higher in the MLD than thermocline and deep layer. This pattern was similar to [13, 24]. The high $\varepsilon$ value in the MLD indicates the high energy released during the mixing process. $\varepsilon$ value has a linear relationship with the size of overturning and stability of water mass. Although the deep layer (990 m) overturn in the equator has a larger size than overturn in the MLD, but the Brunt Vaisalla ($N^2$) in the deep layer one order smaller than in the MLD. This condition is resulting in a higher $\varepsilon$ value in the MLD than the deep layer. The layer with high stability will need more energy to mixed than the unstable layer.

The vertical diffusivity rate ($\kappa_z$) in Figure 10(b) is ranging from $O (10^{-4}-10^{-2}$ m$^2$ s$^{-1})$. This result similar to [7]. They found the $\kappa_z$ in the tropical Indian Ocean was also varies from $O (10^{-4}-10^{-2}$ m$^2$ s$^{-1})$. The average vertical diffusivity in MLD, thermocline, and deep layer in this research is $6.1 \times 10^{-3}$ m$^2$ s$^{-1}$, $5.6 \times 10^{-3}$ m$^2$ s$^{-1}$, and $1.2 \times 10^{-3}$ m$^2$ s$^{-1}$, respectively. The highest value of $\kappa_z$ at a depth of 990 m indicated that intense mixing occurred in that depth because its location is near the ridge of Ninetyeast. The $\kappa_z$ value does not only depend on the size of the overturn but also static stability. In MLD, the vertical size of overturning at latitude 12 N is more extensive than at latitude 15 N, but the $\kappa_z$ value of 12 N smaller than 15 N. It is because of water mass stability ($N^2$) of MLD in 12 N larger ($2.5 \times 10^{-5}$ s$^{-2}$) than 15 N ($2.5 \times 10^{-6}$ s$^{-2}$), the more stable water mass, the harder the water mass to mixed.
4. Conclusion

Physical oceanography such as temperature, salinity, and dissolved oxygen of the Eastern Indian Ocean during the cruise is meridionally variated. Turbulent mixing is more intense in the mixed layer and deep layer than in the thermocline layer. Turbulent kinetic energy in the overturn region varies from O \(10^{-8}\) to \(10^{-6}\) W/kg, while the vertical diffusivity rate varies from O \(10^{-4}\) to \(10^{-2}\) m\(^2\)/s. The data indicated that mixing in MLD is because of the stress of sea surface wind, while the thermocline because of shear instability of strong equatorial undercurrent and salt fingering and for the deep layer is because of the topography of ridge.

Acknowledgments

We would like to thanks BMKG, BPPT, NOAA, and all crews of R/V Baruna Jaya I for the facilities to conduct this research.

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