OSEANOLOGI DAN LIMNOLOGI DI INDONESIA
Online ISSN: 2477-328X
Akreditasi RISTEKDIKTI No. 200/M/KPT/2020
http://oldi.lipi.go.id

Vertical mixing in the deep region of the Sunda Strait, Indonesia

Adi Purwandana

Research Center for Oceanography - National Research and Innovation Agency (RCO-BRIN),
Jakarta, Indonesia
Jl. Pasir Putih I Ancol Timur, Jakarta 14430

*e-mail: adip003@brin.go.id

Submitted 14 December 2021. Reviewed 17 December 2021. Accepted 10 February 2022.
DOI: 10.14203/oldi.2022.v7i1.397

Abstract

The characteristics of mixing properties in the Sunda Strait waters were revealed using indirect method, employing the archived CTD datasets of the RCO-BRIN. The mixing properties represented by turbulent kinetic energy dissipation (TKE) rate and vertical eddy diffusivity were inferred using an improved Thorpe Method from gravitationally unstable density profiles measured by CTD in July 2001. This study is aimed to reveal the rate of water mass mixing quantitatively. Vertically, the region was characterized by three distinctive regimes of TKE dissipation rate, i.e. 8.2×10^{-8} W/kg in the near-surface and upper thermocline layer, 2.6×10^{-7} W/kg in the lower thermocline layer and 9.1×10^{-9} W/kg in the intermediate and deep layer. The spatial variability of the dissipation rate is likely related to topography roughness pattern where enhanced dissipation rate mainly occurred in the steep topography region. No specific regime can be clustered from the vertical diffusivity value due to its intermittent pattern, possibly due to the impact of topography roughness and stratification variability in space and time. The maximum enhanced values reached 3×10^{-4} m^2/s. It was suggested that strong shear due to interaction between sharp changing topography, the strait throughflow and tidal currents controls the mixing rate in this region. This indirect estimates need to be validated against microstructure measurements via a continuously profiling which covers at least one tidal cycle to investigate possible temporal variability.

Keywords: vertical mixing, Thorpe Method, dissipation rate, vertical diffusivity.

Abstrak

Percampuran vertikal di bagian perairan dalam Selat Sunda, Indonesia. Karakteristik properti pencampuran massa air di wilayah perairan dalam Selat Sunda diungkap dengan metode tak langsung dari arsip data CTD Pusat Riset Oseanografi BRIN. Properti percampuran yang direpresentasikan oleh laju disipasi energi kinetik turbulen dan difusivitas eddy vertikal dihitung menggunakan Metode Thorpe yang telah diperbarui, diidentifikasi dari ketidakstabilan profil densitas secara gravitasi dari data CTD bulan Juli 2001. Studi ini bertujuan mengungkap laju percampuran massa air secara kuantitatif di wilayah perairan dalam Selat Sunda. Secara vertikal, wilayah perairan ini dicirikan oleh tiga rezim lapisan laju disipasi yang berbeda, yakni $8,2\times10^{-8}$ W/kg pada lapisan dekat permukaan dan lapisan termoklin atas, $2,6\times10^{-7}$ W/kg pada lapisan termoklin bawah dan $9,1\times10^{-9}$ W/kg pada lapisan menengah dan dalam. Variabilitas spasial disipasi tampak mengikuti pola kekasaran topografi, nilai yang tinggi umumnya terjadi pada topografi yang curam. Tidak ada rezim difusivitas secara spesifik yang dapat dikelompokkan karena peningkatan nilai yang tidak beraturan, yang dapat diakibatkan oleh pengaruh kekasaran topografi dan variabilitas stratifikasi secara spasial dan temporal. Ditemukan nilai maksimum difusivitas hingga 3×10^{-4} m^2/s. Diduga, sesar arus yang kuat akibat interaksi antara topografi yang berubah drastis, aliran selat dan arus pasang surut mengendalikan laju pencampuran di wilayah ini. Estimasi tidak langsung ini perlu divalidasi dengan pengukuran mikrostruktur dengan metode profil secara kontinyu yang mencakup setidaknya satu siklus pasang surut untuk menyelidiki kemungkinan variabilitas temporalnya.

Keywords: percampuran vertikal, Metode Thorpe, laju disipasi, difusivitas vertikal.

Introduction

Indonesian seas are characterized by two different depth regions. The western part has been known as the Sunda Shelf region with typical depth of less than 50 m, constructed post Pleistocene era around 250,000 years ago (Voris, 2000). The eastern part is characterized by deep waters of more than 50 m depth until more than 7000 m depth in the Banda Sea. Located between two oceans, i.e. the Pacific and Indian, the Indonesian seas are the connecting waters allowing the throughflow, namely the Indonesian throughflow (ITF) from Pacific to Indian Ocean due to sea level gradient (Wyrtki, 1961).

The topography of the Sunda Strait is characterized by shallow waters in the northern part, connected to the Java Sea; and deep waters in the southern part, connected to the Indian Ocean. The Sunda Strait is a connecting passage allowing the South China Sea water entering the Indian Ocean via its shallow water throughflow. The throughflow counts only around 2.5% from the total of ITF transport or 0.25 Sv (1 Sv = 1×10^6 m^3/s) (Xu et al., 2018). The Strait allows the transport of the Java Sea water and South China Sea water.

The Sunda Strait throughflow which flows toward the Indian Ocean is driven seasonally by monsoonal winds, maximum/minimum during the Northwest/Southeast Monsoon period. As part of the southern Java waters, the southern Sunda Strait is also exposed to seasonal upwelling during Southeast Monsoon period, from June to November; maximum in July-August (Silubun et al., 2015). Upwelling event will supply the upper layer with colder-nurient rich below water hence is an important natural mechanism which supports fisheries productivity. The Sunda Strait has also been influenced by semidiurnal tide M_2 variability from Indian Ocean (Egbert et al., 2002; Purwandana, 2019).

Many features occurred in the Sunda Strait have been explored, such as seasonal throughflow, tides and seasonal upwelling. However, no study focusing on vertical turbulence and related mixing has been conducted in this strait due to lack of interest as well as expertise on small scale processes. The interaction between complex topography and tidal current can be an effective source of vertical mixing due to sheared currents. The presence of throughflow from the strait and upwelling event occurred during the Southeast Monsoon months spanning from along the western coastal waters of the Sumatra and along the southern coastal waters of Java (Susanto et al., 2001) are additional phenomena that potentially amplify the vertical turbulent event in the upper layer and giving benefits from supplying nutrients into the upper layer, respectively.

Vertical turbulent mixing and related events are the least observed oceanography phenomena in the Indonesian seas. Understanding the characteristics of vertical mixing is important to assess our ecosystems in term of their potency naturally as well as their vulnerability from being exposed by anthropogenic pressures.

The Sunda Strait is part of Fisheries Management Area (*Wilayah Pengelolaan Perikanan, WPP* 572). This waters is featured by well-known interesting oceanographic phenomena, the seasonal upwelling occurred during Southeast Monsoon months. Yet, there is still limited study related to the potency from vertical mixing phenomena in this area. This study is a baseline research which will support the assessment of the potency in this waters. The quantification of mixing properties in this study can be used directly, for example to estimate the nutrient flux in the water column (Law et al., 2003). The study on vertical mixing is also important from climatic perspective as the parameters gained from this study (TKE dissipation rate and vertical eddy diffusivity) are usefull input to adjust regional climate models in the Indonesian seas hence will help us to better predict seasonal and climatic events, such as rainfall periods (Koch-Larrouy et al., 2010).

Above mentioned conditions and needs lead this study to use the indirect method by optimizing an archived CTD measurements datasets stored at the Laboratory of Physical Oceanography – Research Center for Oceanography (RCO) BRIN. Note that, RCO – BRIN as the oldest oceanographic research institution in the Indonesia, has a very long history in collecting the CTD casts entire the Indonesian seas. This study is aimed to quantify, for the first time, the vertical turbulent mixing in the Sunda Strait deep waters.

Methods

An archived CTD *Sea-Bird Electronics* (SBE) 911 datasets collected in July 2001 by RV Baruna Jaya VIII were analyzed to infer the properties of vertical mixing, i.e. the turbulent kinetic energy dissipation rate and vertical eddy diffusivity. The variability of vertical mixing properties depends on the field of flow characteristics, which is mainly driven by the interaction between regular barotropic tidal currents and topography hence generating instability in the water column. Therefore, the using of archived CTD datasets to characterize the mixing properties has been a common method widely used in oceanic mixing physics (see Purwandana et al., 2020; Yang et al., 2014). There were 12 CTD casts involved in this study, sampled in the deep region of the Sunda Strait waters (**Figure 1**a). The CTD has a typical 24 Hz sampling rate, and were previously preprocessed using SBE Data Processing module, and only downcast profiles were considered due to frame-related noise in the upcast profile. The upper 10 m profiles were also discarded since potentially disturbed by ship heaving and atmospheric forcing turbulence, as the focus of vertical turbulence analysis is to identify the impact of internal tides and spatial topography. The vertical instability related to mixing in the water column can be easily inspected from shaking features in the density profile (Park et al., 2014; Yang et al., 2014). The density profiles derived from temperature and salinity profile of the CTD cast from all stations are presented in **Figure 1**a.

Firstly introduced by Thorpe (1977), the method is started by inspecting the vertical distance that should be traveled by two water mass parcels which has gravitationally unstable condition (light/low density under the weight/high density) to gain stable condition (light/low density above the weight/high density). The squared root of this distance is defined as Thorpe length scale (L_T). Before defining the L_T, the density overturns should be screened carefully since they may contain spurious overturns. Some filter settings are defined, i.e. the density noise level ($\delta\rho$ = 5.24x 10^{-4} kg m^{-3}), T-S tightness relationship ξ = 0.7; and overturn ratio Ro = 0.2. The detail of each filtering parameter is explained in some studies (Frants et al., 2013; Galbraith et al., 1996; Gargett et al., 2008; Purwandana et al., 2020; Stansfield et al., 2001).

Under stratified condition of the water column, the occurrence of vertically unstable water mass parcels can vary since the high stratification tends to limit the turbulent event. In the meantime, the vertical current shear will enhance the turbulent event. Dillon (1982) defined a relationship between L_T and previously estimated turbulent measurements from current shear, the Ozmidov length scale (L_O) as L_O/L_T = 0.8. The stratification and L_T from all stations are presented in **Figure 1**c and **Figure 1**d, respectively. Later, since Thorpe Method defines the turbulent event observed from CTD which detects only large overturning water mass parcels, the lower instability will set to zero. Therefore, a background dissipation rate should be defined as no detected overturning event from density profile of the CTD (due to low vertical resolution of the measurements) does not mean no dissipation in the water column. The turbulent kinetic energy (TKE) dissipation rate is calculated as (Purwandana et al., 2020),

$$\varepsilon = \begin{cases} 0.64{L_T}^2N^3, & \text{overturn} \\ \max\left(1\times10^{-10}\ \text{W/kg}, \varepsilon_0\left(\dfrac{N^2}{{N_0}^2}\right)\right), & \text{no overturn} \end{cases} \quad (1)$$

N is the buoyancy frequency, 1×10^{-10} W/kg is the lowest resolved dissipation rate in the Indonesian seas (Bouruet-Aubertot *et al.*, 2018; Koch-Larrouy *et al.*, 2015); ε_0 = 7×10^{-10} W/kg and N_0 = 3 cph are the canonical Garret and Munk dissipation rate and buoyancy frequency reference, respectively. Then, the vertical diffusivity is calculated as:

$$K_\rho = \Gamma\frac{\varepsilon}{N^2} \quad (2)$$

Γ = 0.2 is the mixing efficiency (Osborn, 1980). The ε and K_ρ from all stations are presented in **Figure 1**e and **Figure 1**f, respectively.

The CTD stations were irregularly in space, where there were two stations located at a relatively close distance, separated by less than

0.05° (**Figure 1**a). Therefore, the spatial pattern of the mixing properties are inspected in a gridded horizontally maps over 0.05°. This setting produces 11 gridded stations as shown in **Figure 2**a. Hereinafter, the station mentioned in the text refers to this gridded station. Vertically, the values are also averaged with depth intervals of 50-300 m (thermocline layer), 300-500 m (intermediate layer), and 500-1000 m (deep layer), and are averaged by the density ranges to assess their values related to the water mass characteristics, and are presented in the temperature-salinity (T-S) diagram.

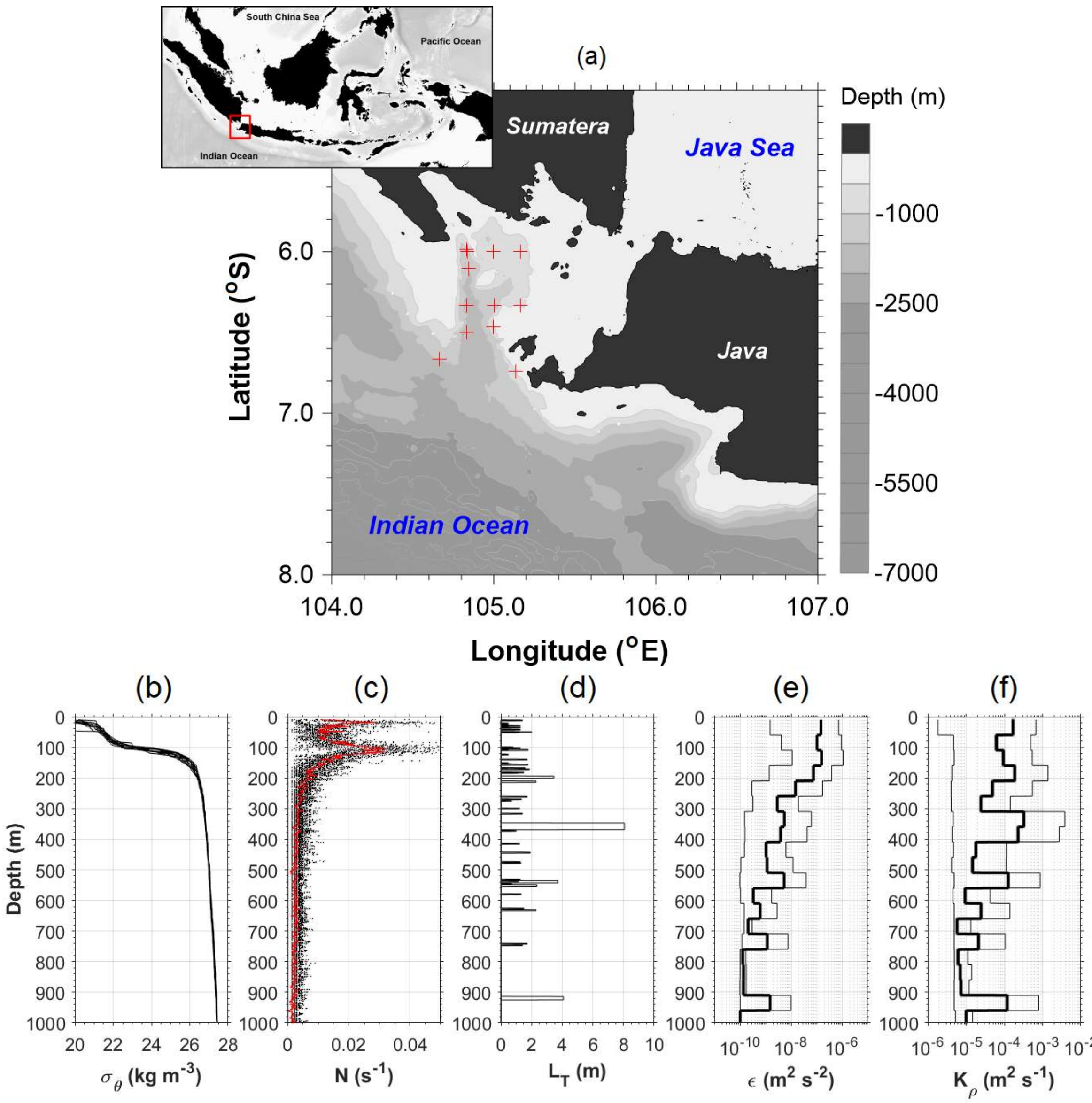

Figure 1 (a) Map of Sunda Strait waters with topography inferred from ETOPO. The CTD casts sampled in July 2001 are presented in red plus signs. The measurements were conducted using the CTD SBE 911 on board of RV Baruna Jaya VIII; (b) density profiles inferred from salinity and temperature measurements, (c) stratification represented by buoyancy frequency profiles from all CTD casts, (d) Thorpe length identified from instabilities in the density profiles, (e) turbulent kinetic energy dissipation rate (mean-bold line, minima and maxima-thick lines), (f) vertical diffusivity (mean-bold line, minima and maxima-thin lines).

Gambar 1 (a) Peta perairan Selat Sunda dengan topografi dari ETOPO. Penurunan CTD dilakukan pada bulan Juli 2001, disajikan dengan tanda *plus* merah. Pengukuran dilakukan dengan menggunakan CTD SBE 911 Kapal Riset Baruna Jaya VIII; (b) profil densitas yang diturunkan dari data salinitas dan suhu, (c) stratifikasi yang direpresentasikan dengan nilai frekuensi apung, (d) skala panjang Thorpe yang diidentifikasi dari ketidakstabilan pada profil desnitas, (e) disipasi energi kinetik turbulen (rerata-plot tebal, minimal dan maksimal-plot tipis), (f) difusivitas vertikal (rerata-plot tebal, minimal dan maksimal-plot tipis).

Results

The Sunda Strait deep waters region is characterized by stratified water column with two typical pycnocline (~thermocline) layers, the upper thermocline in the upper 100 m and lower thermocline below, down to ~300 m depth (**Figure 1**b). Such structures can be clearly indicated from the buoyancy profiles, with a typical core value of 0.03/s in the ~25 m and ~175 m for the first and the second layer of the thermoclines (**Figure 1**c). Instabilities represented by Thorpe length (L_T) were observed in the density profiles, more frequent in the upper 300 m and intermittent in the lower layer (**Figure 1**d).

This research is a baseline study on vertical turbulent mixing in the Sunda Strait waters. Spatially, the deep waters region of the Sunda Strait is characterized by predominantly high dissipation rate in the upper layer (50-300 m, Ø 10^{-7} W/kg) and decreasing trend of dissipation rate below. The lowest dissipation rates were observed in the deep layer (50-300 m, [10^{-10} – 10^{-9}] W/kg) (**Figure 2**a-c). Note that elevated dissipation rate observed in the 50-300 m depth were identified at Station 1, 3, 5, 7, 8, 9, 10 and 11. These stations are located in the steep topography. An elevated vertical diffusivity [1.0×10^{-4} – 3.2×10^{-4}] m^2/s were also identified near steep topography (50-300 m, Station 5, 8, 9) (**Figure 2**d-f).

The deep region of the Sunda Strait is characterized by Indian Ocean water masses, i.e. the North Indian Subtropical Water (NISW), North Indian Intermediate Water (NIIW) and North Indian Deep Water (NIDW) (**Figure 3**). The influence of low salinity of the Java Sea Water (JSW) was observed in the upper layer. Density anomaly based averaging of the dissipation rates and vertical diffusivity are shown in

Table 1 in order to investigate the water mass characteristics in each layer of density in the strait region. Representation of these values in the T-S diagram is shown in **Figure 3**. As shown in **Figure 3**a, three different regime of dissipation rates are identified, i.e. the upper thermocline/density range layer of $\sigma_\theta < 23$ kg/m^3 is characterized by the dissipation rate of [3.2×10^{-9} – 1.0×10^{-8}] W/kg; the lower thermocline/density range of $\sigma_\theta = 23 – 25.5$ kg/m^3 is characterized by dissipation rate of [1.0×10^{-8} – 3.2×10^{-7}] W/kg; the intermediate layer/density range of $\sigma_\theta = 25.5 – 26.5$ kg/m^3 is characterized by dissipation rate of [1.0×10^{-9} – 3.2×10^{-9}] W/kg; and the deeper layer/density range of $\sigma_\theta > 26.5$ kg/m^3 is characterized by dissipation rate of less than 1.0×10^{-9} W/kg.

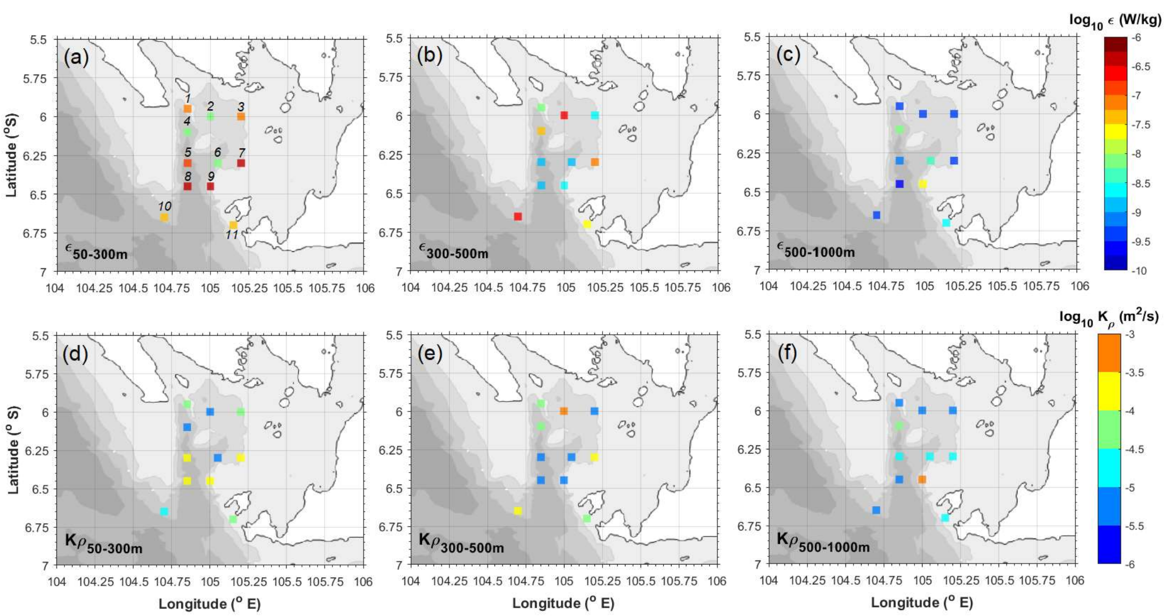

Figure 2 Horizontal mapping of turbulent kinetic energy dissipation rate (in $\log_{10}$ scale, W/kg) averaged at three depth ranges: (a) 50 – 300 m (thermocline layer), (b) 300 – 500 m (intermediate layer), (c) 500 – 1000 m (deep layer); and vertical diffusivity at the same depth range (in $\log_{10}$ scale, m^2/s): (d) 50 – 300 m (thermocline layer), (e) 300 – 500 m (intermediate layer), (f) 500 – 1000 m (deep layer). Note that the data is presented in 0.05^o grid spacing. The topography is provided by ETOPO (the depth scale refers to Fig. 1a).

Gambar 2 Pemetaan horizontal disipasi energi kinetik turbulen (dalam skala $\log_{10}$, W/kg) dirata-ratakan pada tiga rentang kedalaman: (a) 50 – 300 m (lapisan termoklin), (b) 300 – 500 m (lapisan menengah), (c) 500 – 1000 m (lapisan dalam); and rata-rata difusivitas vertikal (dalam skala $\log_{10}$, m^2/s) pada rentang kedalaman: 50 – 300 m (lapisan termoklin), (b) 300 – 500 m (lapisan menengah), (c) 500 – 1000 m (lapisan dalam). Data disajikan dalam grid 0,05^o. Topografi disajikan oleh ETOPO (skala kedalaman merujuk pada Gambar 1a).

Table 1 Mean and standard deviation of the dissipation rate (ε, W/kg) and vertical eddy diffusivity (K_ρ, m^2/s) for specified density anomaly range (σ_θ, kg/m^3).

Tabel 1 Rata-rata dan simpangan baku disipasi energi kinetik turbulen (ε, W/kg) dan difusivitas eddy vertikal (K_ρ, m^2/s) pada berbagai rentang anomali densitas (σ_θ, kg/m^3).

σ_θ (kg/m^3)	ε, W/kg		K_ρ, m^2/s	
	mean	**stdev**	**mean**	**stdev**
21.0-22.0	$1.3\cdot10^{-7}$	$9.3\cdot10^{-7}$	$1.1\cdot10^{-4}$	$7.4\cdot10^{-4}$
22.0-23.0	$3.3\cdot10^{-8}$	$2.5\cdot10^{-7}$	$3.7\cdot10^{-5}$	$2.9\cdot10^{-4}$
23.0-24.0	$5.9\cdot10^{-7}$	$2.9\cdot10^{-6}$	$3.0\cdot10^{-4}$	$1.5\cdot10^{-3}$
24.0-25.0	$1.8\cdot10^{-8}$	$3.4\cdot10^{-9}$	$4.9\cdot10^{-6}$	$2.0\cdot10^{-20}$
25.0-26.0	$1.7\cdot10^{-7}$	$1.5\cdot10^{-6}$	$8.1\cdot10^{-5}$	$7.2\cdot10^{-4}$
26.0-27.0	$1.7\cdot10^{-8}$	$2.2\cdot10^{-7}$	$1.3\cdot10^{-4}$	$1.2\cdot10^{-3}$
>27.0	$8.7\cdot10^{-10}$	$1.1\cdot10^{-8}$	$2.9\cdot10^{-5}$	$2.8\cdot10^{-4}$

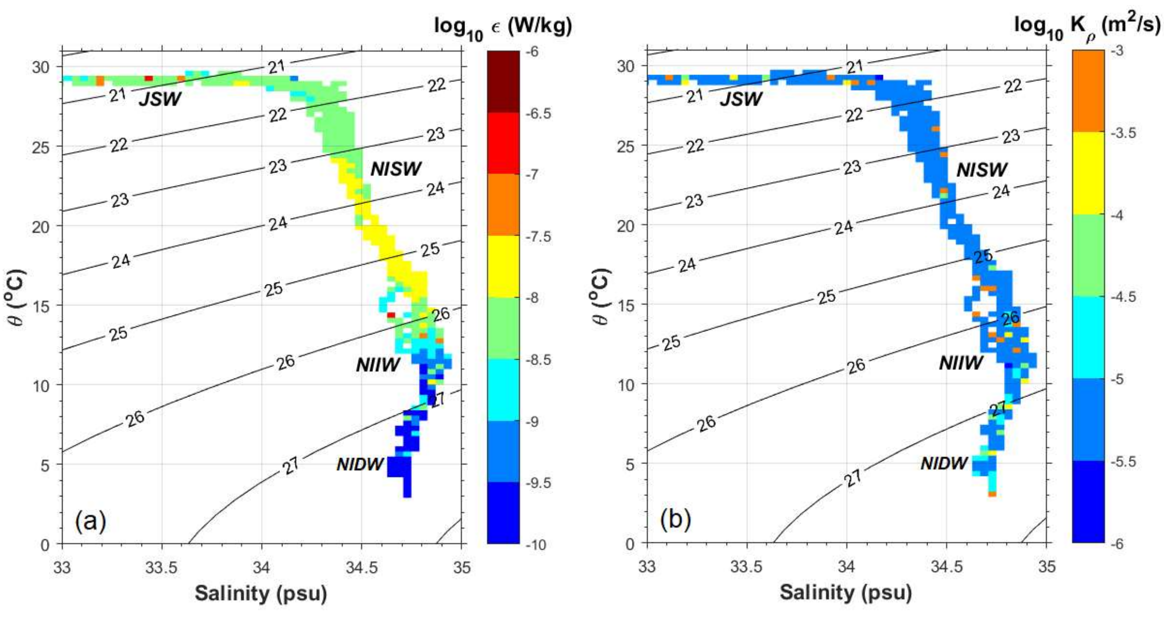

Figure 3 Grid averaged T-S diagram in 0.5 $^oC \times 0.1$ psu space involving all CTD stations with overlaid colors: (a) turbulent kinetic energy dissipation rate (in $\log_{10}$ scale, W/kg), (b) vertical eddy diffusivity (in $\log_{10}$ scale, m^2/s). The JSW, NISW, NIIW and NIDW denote the Java Sea Water, North Indian Subtropical Water, North Indian Intermediate Water and North Indian Deep Water, respectively.

Gambar 3 Grid rata-rata 0,5 $^oC \times$ 0,1 psu diagram suhu-salinitas (T-S) dari semua stasiun CTD dengan tumpang susun warna: (a) disipasi energi kinetik turbulen (dalam skala $\log_{10}$, W/kg) dan (b) difusivitas vertikal (dalam skala $\log_{10}$, m^2/s). JSW, NISW, NIIW dan NIDW berturut-turut adalah adalah massa air Laut Jawa, massa air Samudera Hindia lapisan pertengahan dan massa air Samudera Hindia lapisan dalam.

Discussion

The water masses in the Sunda Strait have a typical Indian Ocean characteristics in the thermocline and deeper layer, with less influence of fresh water masses in the mixed layer from the Java Sea throughflow. Although featured by less influence of Java Sea water in the mixed layer yet a relatively high dissipation rate and high vertical diffusvity in this layer (σ_θ < 22 kg/m^3) are potential to freshen the upper layer. In general, high dissipation rates in the order of 10^{-8} to 10^{-7} W/kg observed in the waters are not surprising since the stations are located in the narrow passage/strait. Another possible mechanism occurred is the hydrolic jump that is often occurred down stream in the narrow passages, the same mechanism as working in the Lifamatola Passage (Tan et al., 2020). However, the values are lower compared to the maximum values observed in other straits, i.e. Ø [10^{-7} - 10^{-6}] W/kg in the Halmahera Straits and Ombai Strait (Bouruet-Aubertot et al., 2018; Nagai et al., 2021), the Lombok Strait (Purwandana et al., 2021a) and Maluku-Talaud waters (Purwandana et al., 2021b).

As can be indicated from vertical profiles shown in **Figure 1**e, an enhanced dissipation rates occurred in the upper layer, which is likely related to the active circulations, as has been suggested from observation and modeling of surface currents study by Mujiasih et al. (2021) which indicated strong mainstream currents of ~0.7 m/s in the observation area. Spatially, a closer look to each station as shown in **Figure 2**a-c, indicated that there is a spatial trend horizontally of the enhanced dissipation rate in the steep topography stations (~high bottom roughness, i.e. the standard deviation of the bathymetry over a specified cell size); and also vertically, decreasing trend towards depth. Enhanced dissipation values were also observed in the intermediate layer at Station 2, and in the deep layer at Station 4 and 6, where located in the non steep topography (~low bottom roughness). Basically, the pattern of dissipation rate can be variably not only in space but also in time (Purwandana et al., 2021a; Purwandana et al., 2020). As we do not have a daily station from the archived datasets to investigate the temporal variability of the dissipation rate in this area, we put a possibility that there can be the influence of tidal variability.

There is an intermittent pattern of eddy diffusivity vertically as can be seen in **Figure 1**f, yet still can be observed a decreasing trend towards depth. The vertical diffusivity is sensitive to the stratification through inversely proportional relationship hence the deeper layer is potential to have elevated diffusivity even with a small amount of TKE dissipation rate, as long as the stratification is low. Therefore, it is common that enhancement of the diffusivity value will increase in the elevated dissipation rate area such as above the steep topography, as can be confirmed in **Figure 2**d-f. Intermittency pattern showed in the vertical diffusivity also suggests the importance of continue measurements which covers at least one tidal cycle to look over the temporal variability of stratification as well as current shear.

A low salinity in the upper layer of σ_θ < 21 kg/m^3 in the southern Sunda Strait as shown in the T-S diagram in **Figure 3** indicated the existence of shallow water throughflow from the Java Sea. This low salinity contributes to the 'pseudo' pycnocline layer formation in the upper 50 m depth hence producing highly stratified layer. Three different regimes of TKE dissipation rate clustered in the T-S diagram as shown in **Figure 3**a indicate the most dissipative layer is in the lower thermocline layer (σ_θ = 23-26 kg/m^3), followed by the upper thermocline layer (σ_θ < 23 kg/m^3), and the lowest dissipation rate occurred in the intermediate and deep layer (σ_θ > 26 kg/m^3). This trend, i.e. dissipative in the thermocline layer and near surface layer is related to high shear instability formed due to stronger current structures there. Less dissipative in the deeper layer is occurred due to less strong current shear and less stratified water column, a typical condition in the deep layer.

Conclusions

The typical values of dissipation rate observed in this study is 1-2 order higher than the typical deep sea dissipation rate such as in the Banda Sea yet compared to other narrow passages, such as to those in the Halmahera Straits and Ombai Strait, the dissipation rate in the deep region of the Sunda Strait is one order lower. The CTD stations involved in this study are located in the narrow passage/strait, the place where barotropic tidal currents will be converted into internal tide and generate local mixing. High dissipation rates occurred in the upper 300 m layer, which is a clear evidence of enhanced values related to shear instability due to possibly strong currents. This study highlighted the importance of comprehensive project in the future which involves more parameters, such as current measurements and microstructure profiler and also involves other aspects such as biogeochemistry hence the impact of vertical mixing to the oceanic productivity can be directly assessed.

Acknowledgment

The author thanks the Crew and Captain of the RV Baruna Jaya VIII for helping the data acquisition during the observations, Pak Hadikusumah and all staffs of Laboratory of Physical Oceanography for preserving the archived CTD datasets processed in this study.

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