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Vertical Mixing in The Onshore Region of The Northwestern Maluku Sea, Indonesia

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ABSTRACT

Spatio-temporal dynamics of vertical mixing in the northwestern Maluku Sea were quantified using the Thorpe Method from archived CTD datasets collected during the expedition of Baruna Jaya VIII RCO-LIPI on November 12–13, 2000. The turbulent kinetic energy (TKE) dissipation rate and vertical eddy diffusivity values inspected the variability of mixing properties. Higher values for both parameters were found at the shallower bathymetry, which is less than 1000 m deep. This suggests that the water column is vertically unstable as a result of being often subjected to internal solitary wave (ISW) breaking events. The strong temporal variability observed from the density profile also indicated a strong impact on internal tide activity. There was temporal fluctuation of the TKE dissipation rate as well as vertical eddy diffusivity values following semidiurnal periodicity, with typical variability up to one order of magnitude for both the dissipation and diffusivity. The range of fluctuation is [6.8×10^{-8} – 9.3×10^{-7}] W kg^{-1} and [1.5×10^{-5} – 5.4×10^{-3}] m^2s^{-1}, respectively in the upper 200 m depth. This water generated a high dissipation rate and vertical diffusivity when regularly exposed to internal solitary waves breaking from the Lifamatola Passage.

Keywords: *mixing properties, CTD data, turbulent kinetic energy, vertical eddy diffusivity*

ABSTRAK

Dinamika ruang-waktu percampuran vertikal di tenggara perairan pesisir Pulau Sulawesi dihitung dengan menggunakan Metode Thorpe dari data pengukuran CTD pada ekspedisi KR. Baruna Jaya VIII-LIPI pada tanggal 12-13 November 2000. Variabilitas karakteristik pencampuran diukur berdasarkan laju disipasi energi kinetik turbulen (TKE) dan nilai difusivitas eddy vertikal. Nilai yang lebih tinggi pada kedua parameter terlihat di area dengan batimetri yang lebih dangkal, yaitu kedalaman kurang dari 1000 meter. Hal ini menunjukkan ketidakstabilan kolom air secara vertikal yang disebabkan pecahnya gelombang internal soliter. Tingginya variabilitas temporal yang teramati dari profil densitas juga mengindikasikan pengaruh yang kuat dari aktivitas pasang surut internal. Terdapat fluktuasi temporal dari laju disipasi TKE serta nilai difusivitas eddy vertikal yang mengikuti periode semidiurnal, dengan variabilitas tipikal hingga satu orde besaran disipasi dan difusivitas. Kisaran fluktuasi masing-masing adalah [$6,8\times10^{-8}$ - $9,3\times10^{-7}$] W kg^{-1} dan [$1,5\times10^{-5}$ - $5,4\times10^{-3}$] m^2s^{-1}, pada kedalaman 200 m dari permukaan. Perairan ini mempunyai tingkat disipasi dan diffusivitas vertikal tinggi ketika secara teratur terkena gelombang internal soliter yang pecah dari Lifamatola Passage.

Kata kunci: percampuran vertikal, data CTD, energi kinetic turbulen, difusivitas eddy vertikal

1. Introduction

Numerous studies have been conducted following the Indonesian Mixing Experiment (INDOMIX) Project in 2010, focusing on the estimation of vertical turbulent mixing rates. The primary objective of these studies was to investigate the mechanisms involved in the transformation of Pacific water masses upon entering the Indonesian seas. These investigations have been carried out by researchers such as Nagai et al., (2021); Purwandana et al., (2020); Adhyatma et al., (2019); Bouruet-Aubertot et al., (2018); Nagai & Hibiya, (2015). One notable example of a thorough study is the Years of the Maritime Continent (YMC) program. This multinational

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initiative, encompassing the participation of 15 countries, aims to enhance our comprehension and forecasting capabilities of the local and global meteorological and climate systems on the Indo-Pacific Maritime Continent. The primary objective of this endeavor is to construct a comprehensive collection of observational data, foster the integration of observation and modeling techniques, and provide educational opportunities for aspiring scientists to pursue further research (Yoneyama & Zhang, 2020).

The Maluku Sea is one of the secondary Indonesian throughflow (ITF) entry passages that connect the Pacific Ocean and internal Indonesian seas and is creating a new branch of intermediate throughflow (Yuan et al., 2022). The interannual southward transport through this passage is up to 3.5 Sv (1 Sv = 10^6 m^3s^{-1}) between depths of 60 and 315 m (Yuan et al., 2018). This region is also influenced by monsoonal winds that control fisheries productivity and phytoplankton blooming events (Setiawan et al., 2022). Recently, image analysis of the Synthetic Aperture Radar (SAR) and Korteweg-de Vries (KdV) models (Purwandana & Cuypers, 2023) showed that the Maluku Sea is an active zone for internal solitary waves (ISWs) propagation, i. e., the Lifamatola Passage and Sangihe Passage waves which propagate northward and eastward, respectively. The existence of ISW was also revealed from direct observations using multi-channel seismic reflection (Firdaus, 2021).

In the Indonesian seas, the only study revealing the impact of internal solitary wave breaking was the one in the northern coastal waters of Sulawesi Island, Manado Bay (Purwandana et al., 2022). To date, there has been no confirming study on the dynamics of vertical mixing in the region of breaking ISW in other regions. Here, we estimate the vertical mixing characteristics in the northwestern coastal waters of the Maluku Sea. Heading directly to the front of ISWs generated from Lifamatola Passage (Purwandana & Cuypers, 2023), we hypothesized a greater dissipation rate and vertical diffusivity in the shallower waters than in the offshore region that was not impacted by breaking ISWs.

Understanding oceanographic physical processes, such as oceanic circulation, upwelling, ocean fronts, stratification of the water column, and vertical mixing, is essential for the assessment of primary productivity in the ocean (Platt & Sathyendranath, 1999). This also applies to Maluku Sea waters, which is part of the Indonesian Fisheries Management Area (WPP 715). This study's objective is to investigate the characteristics of the typical vertical mixing in the northwestern Maluku Sea, as well as the potential factors influencing it. The outputs from this study are needed, for example, to calculate the nutrient flux in the water column.

2. Material and Methods

A set of historical CTD Sea-Bird Electronics (SBE) 911 profiles collected in November 2000 by RV Baruna Jaya VIII in the Maluku Sea were processed to infer the mixing properties, i.e. turbulent kinetic energy (TKE) dissipation rate and vertical eddy diffusivity, in the water column. This is the first time that this CTD dataset has been used to examine vertical mixing using Thorpe analysis. The profiles consisted of 20 CTD casts, located mainly in the deep region (>100 m) of the coastal area of the northeastern part of Maluku Sea. Note that, the coast has typical steep topography. The profiles consisted of 20 CTD cast, located mainly in the deep region (>100 m) of the coastal area of the southeastern of the North Sulawesi. Since some CTD stations (St. 6-20) were performed relatively close to each other (<0.05^o) in geographical space, here we grid the TKE dissipation rate and vertical eddy diffusivity into 0.05^o space to represent the spatial averaged values. Considering that the sampling processes were conducted continuously over time and are in close proximity, we assumed these snapshot stations as a ‘time series’ mode in order to identify the degree of temporal variability of the parameters. We also assume that the tidal variability is highly related to seawater properties temporal variability as shown in Figure 4. The distribution of CTD stations and the existence of ISWs in the Maluku Sea as observed in SAR images (https://search.asf.alaska.edu), are shown in Figure 1. We show here the SAR image to prove the existence of ISW activity in the waters. Note that we have a lack of SAR images during the year of the observations. However, the ISWs formation is a tidal-driven phenomenon that occurs regularly in this region (Purwandana & Cuypers, 2023).

The CTD probe used in this study has a 24 Hz sampling rate capability. The temperature and salinity profiles were pre-processed using the SBE Data Processing module. Commonly, unstable profiles due to ship heaving were obtained, therefore we discarded the dataset in the first 5 m of depth and excluded them from

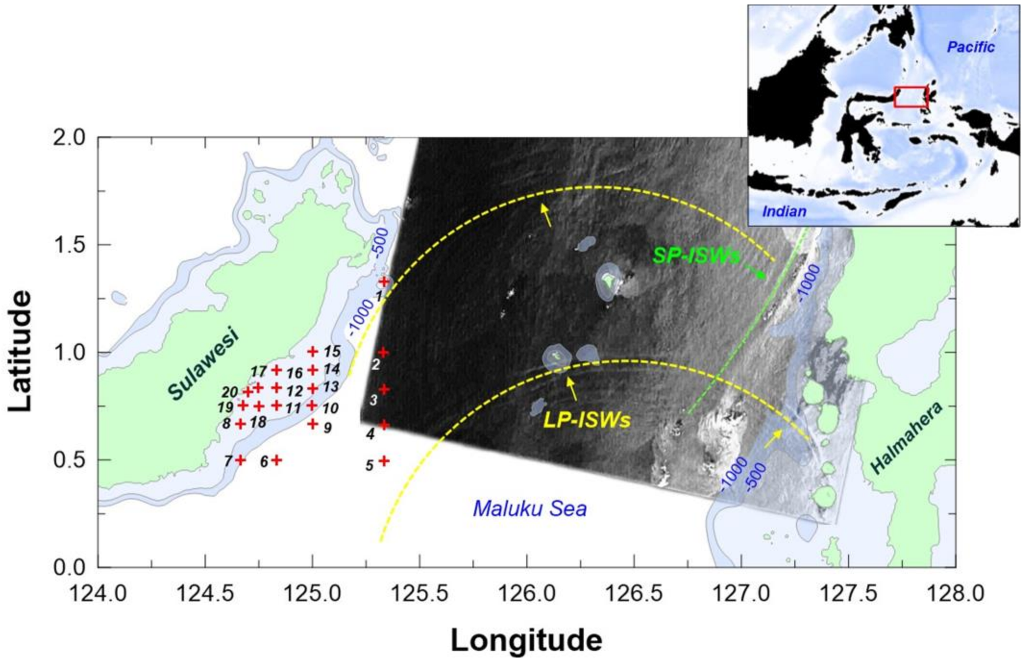

Figure 1. Map of Maluku Sea with topography from ETOPO (depth of >1000 m is presented in white colormap). The CTD casts collected on 12-13 November 2000 were presented in red plus signs. The measurements were conducted using the CTD SBE 911 on board of RV Baruna Jaya VIII. The yellow and green dashed curves denote the wave arc lines of the Lifamatola Passage internal solitary waves (LP-ISW) and Sangihe Passage internal solitary waves (SP-ISW), sketched from SAR image (the layer behind) which contained the signature of ISW events observed on 20 February 2015 (https://search.asf.alaska.edu).

the analysis. The density profile was derived from the temperature and salinity profiles. The vertical profiles of temperature and salinity are presented in Figure 3. Note that we put TKE dissipation rate and vertical eddy diffusivity also in the diagram.

This study's quantification of TKE dissipation rate and vertical eddy diffusivity relied on the perturbance observed in the density profile from each station, known as the Thorpe Method. This method has been categorized as an indirect method, different from the direct method which uses vertical current shear that is directly related to the turbulence. In this study, an improved Thorpe Method was used, which has been proven comparable to direct estimates in the Indonesian seas (Purwandana et al., 2020) and widely used in local waters (Purwandana, 2022; Purwandana, Cuypers, et al., 2021; Purwandana, Iskandar, et al., 2021; Sani et al., 2021).

External forcing coming from tidal-driven currents can lead to turbulent events due to the vertically sheared current profile. In the water column, this event is eventually manifested as a gravitationally unstable density profile. Simultaneously, this condition leads to a stabilizing effect, gained by a vertical displacement of the water column, namely an overturning event. This mechanism has been known as Thorpe displacement since it was first introduced in 1977 (Thorpe, 1977). Some filtering was applied for each density profile to distinguish the real overturn related to turbulent events from noise-related events (Purwandana et al., 2020; Frants et al., 2013; Gargett & Garner, 2008; Stansfield et al., 2001; Galbraith & Kelley, 1996). The TKE energy dissipation rate is defined as $\varepsilon = 0.64{L_T}^2N^3$ when overturn is detected and $\varepsilon = max\left(1\times10^{-10}, \varepsilon_0\left(N^2/{N_0}^2\right)\right)$ when no-overturn detected. Here, N is the buoyancy frequency, 1×10^{-10} is the lowest dissipation rate ever observed in the Indonesian seas (Bouruet-Aubertot et al., 2018; Koch-Larrouy et al., 2015); $\varepsilon_0 = 7\times10^{-10}m^2s^{-3}$ and $N_0 = 3cph$ are the canonical Garret and Munk dissipation rate and buoyancy frequency reference, respectively. Once the dissipation rate is defined, the vertical diffusivity can be estimated as $K_\rho = \gamma\,\varepsilon/N^2$, where $\gamma = 0.2$ is the mixing efficiency (Osborn, 1980).

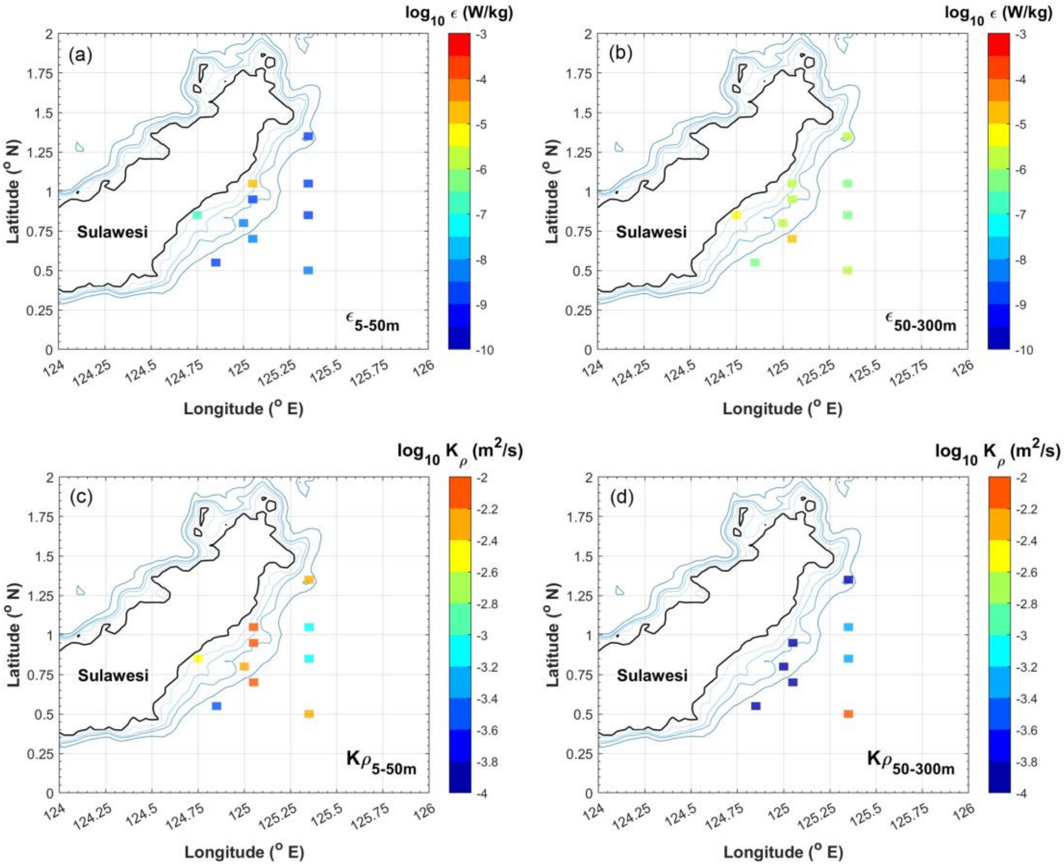

Figure 2. Spatial distribution of (a-b) TKE dissipation rate, ε and (c-d) vertical eddy diffusivity, Kρ in the onshore region of the northwestern Maluku Sea. Note that the original stations are gridded into 0.05^0 space.

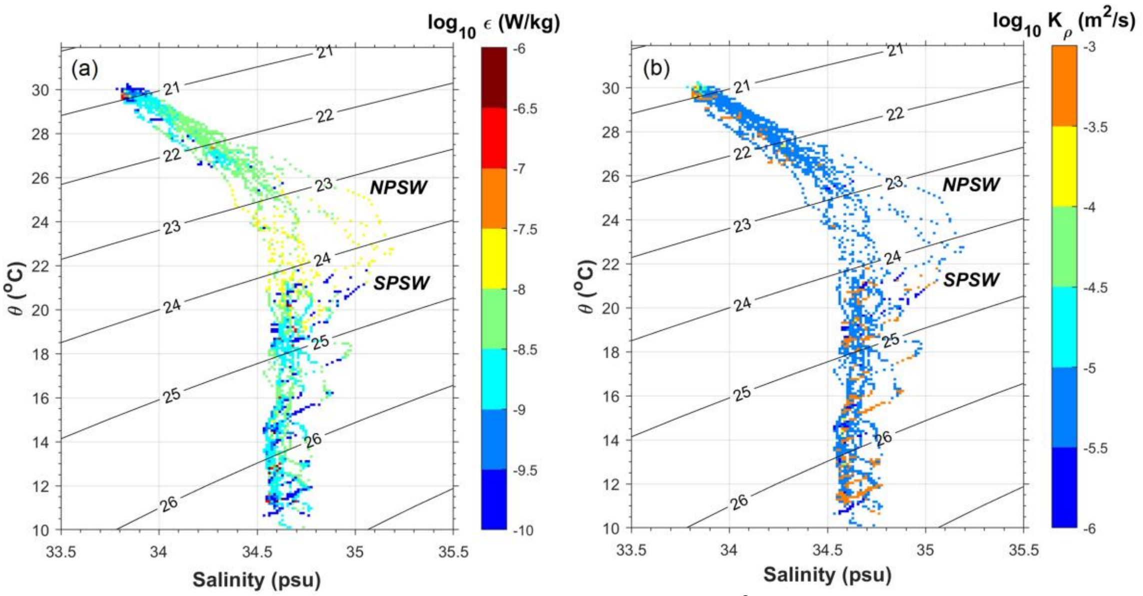

Figure 3. Temperature-Salinity (T/S) diagram gridded over 0.3^0 C × 0.05 psu space for: (a) TKE dissipation rate, ε and (b) vertical eddy diffusivity, K_ρ.

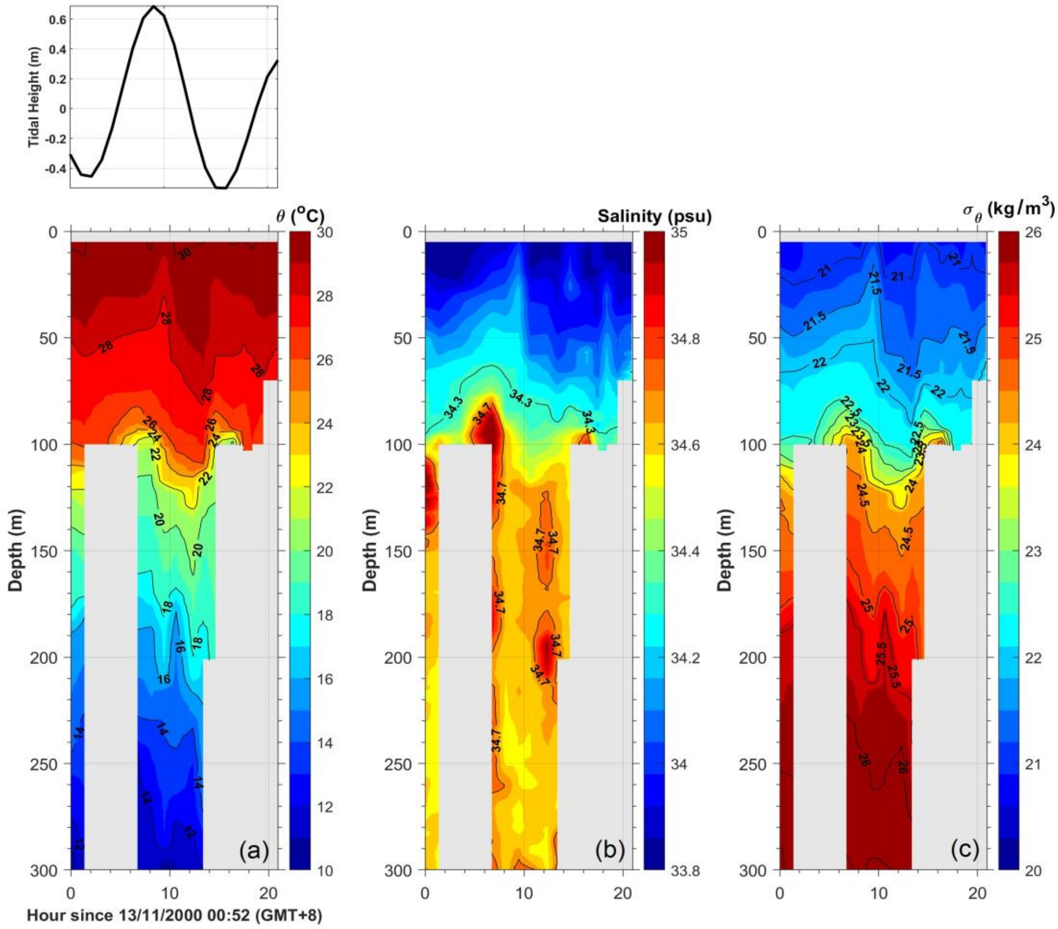

Figure 4. Temporal-mode plot of: (a) isothermal, (b) isohaline, and (c) isopycnal in the onshore region of the Maluku Sea which indicates a temporal fluctuation due to internal tide variability. The upper panels depict the predicted tidal height during CTD measurements.

3. Results and Discussion

3.1. Spatial variability

We focus this study on investigating the behavior of vertical mixing in the onshore region of the northwestern Maluku Sea waters or the southwestern coastal waters of the northern part of Sulawesi Island. The oceanographic CTD stations involved in this study were mostly cast in the topography area of ~1000 m depth (St. 6 – 20) with some other stations located in the deep sea waters of >3000 m depth (St. 1 – 5) (see Figure 1). Figure 2 shows vertically averaged values for two layers, i.e., 5 – 50 m and 50 – 300 m, representing the mixed layer and thermocline layer, respectively of TKE dissipation rate and vertical eddy diffusivity. We found a typical higher TKE dissipation rate in the onshore stations than in the deeper stations for the upper layer of 5 – 50 m depth (Figure 2a). In the deeper layer (Figure 2b), a homogenous pattern dominates the spatial variability, except for slightly elevated values at some deep sea stations (yellow plots).

Ocean vertical mixing is a complex process that is influenced by a variety of factors. In addition to ISW breaking events, vertical mixing is also influenced by wind stress at the ocean surface, tidal currents, density differences, and submesoscale topographic eddies (Srinivasan et al., 2017; Webb & Suginohara, 2001). The elevated values in the onshore/shallow region part are possible as the area is one of the hotspots for intensive vertical mixing in the Maluku Sea, according to the results of prior research conducted by (Yuan et al., 2022; Purwandana, Iskandar, et al., 2021; Ffield & Gordon, 1992). This hypothesis is reliable due to the fact that the southeastern coastal waters of northern Sulawesi Island are exposed regularly to ISW breaking events (Purwandana & Cuypers, 2023), which is a potential source of energy for mixing in the coastal waters (Purwandana et al., 2022; Bourgault et al., 2008). In the deep waters part,

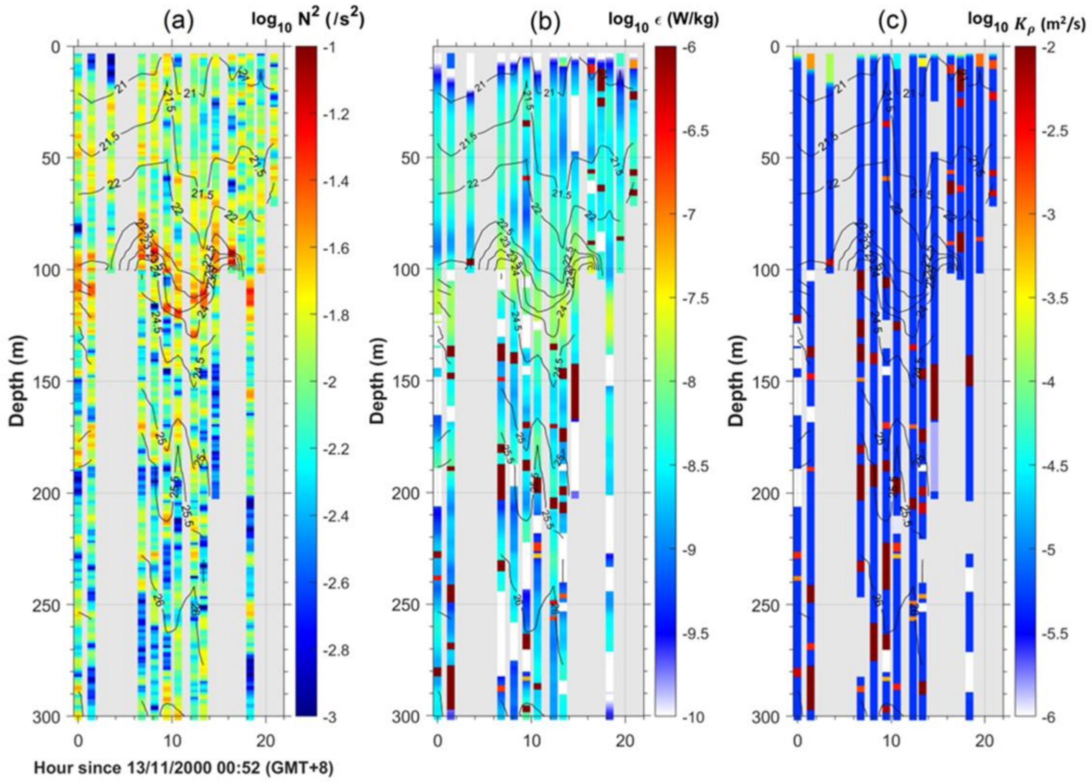

Figure 5. Temporal-mode plot of: (a) squared buoyancy frequency N, (b) TKE dissipation rate, ε and (c) vertical eddy diffusivity, K_ρ. The isopycnal contours are laid under to indicate the temporal variability of the parameters.

elevated values (St. 2 – 4) might be related to the shear currents variation in this area. The northern Maluku waters, especially the waters nearby to the eastern coast of Sulawesi Island are exposed to the regional circulations, influenced by forwarded Mindanao Current in the upper layer and New Guinea Coastal Under Current in the intermediate layer (Yuan et al., 2018, 2022). Maluku Sea waters are also influenced by Pacific water mass intrusions that were observed from an autonomous underwater glider and three moorings. The subsurface salinity maximum waters between 130 and 180 m were intermittently penetrating the Maluku channel, indicating the presence of North Pacific waters (Wang et al., 2023).

The waters of the northwestern Maluku Sea are influenced by the thermocline of Pacific water masses, possibly the mixture of North Pacific Subtropical Water (NPSW) and South Pacific Subtropical Water (SPSW), with a typical salinity of $S_{max} > 35\,psu$ at isopycnal 24 – 26 (see Figure 3). Nonetheless, we discovered a relative salinity decrease, which could be attributed to a strong TKE dissipation rate of 1×10^{-9} – 3×10^{-7} W kg^{-1} and vertical diffusivity on the order of 3×10^{-4} – 1×10^{-3} m^{-2}s^{-1}.

3.2. Temporal variability

The mixed layer of northwestern waters of the Maluku Sea is characterized by temperature, salinity, and density of 20 – 26 ^{0}C,

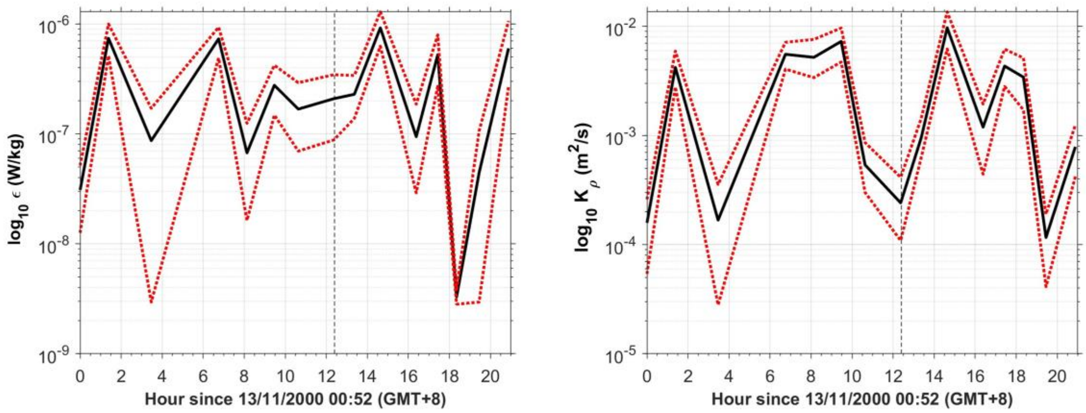

Figure 6. Temporal-mode variability in the upper 200 m layer of: (a) TKE dissipation rate, ε and (b) vertical eddy diffusivity, K_ρ. The dashed red plots are 95% confidence interval.

34.2 – 33.8 psu, and 20 – 21.6 kg m^{-3}, respectively; and below, the core of the thermocline layer is characterized by 28 – 30 ^{0}C, >34.8 psu and 22.5 – 25 kg m^{-3}, respectively. Occasionally, a pulse of high salinity of >34.7 psu appeared in the water column, i.e., the Pacific thermocline core layer. As shown by a temporal-mode plot in Figure 4, oscillating patterns of isotherm, salinity, and potential density were observed, following a period of semidiurnal internal tidal cycle, inferred from Oregon State University tidal inversion software (OTIS) (Egbert & Erofeeva, 2002). This strongly indicates the influence of internal tidal variability in the onshore area of the northwestern waters of the Maluku Sea.

We also inspected in more detail the temporal variability of stratification, TKE dissipation rate, and vertical eddy diffusivity as shown in Figure 5a, and found the strongest stratification occurred in the thermocline layer, as it should be in the order of ~0.2 s^{-1}. Interestingly, sporadic strong stratification also occurred in the upper and deeper layers amidst predominantly weaker stratification of ~0.06 s^{-1}. Strong stratification indicated a potency for strong vertical mixing if the energy for the activity was available. As shown in Figure 5b, sporadic strong TKE dissipation rate of ~10^{-6} W kg^{-1}, not only in the thermocline layer but also extending in the upper and deeper layers. This pattern is also a consequence as there were a lot of overturning events in the water column (not shown) hence increasing the TKE dissipation rate, ε. A similar sporadic pattern of high vertical eddy diffusivity, K_ρ, in the order of >10^{-3} m^2s^{-1} in the water column also occurred (Figure 5c). These occurrences are unlikely to be attributed to the direct breaking of internal waves, but rather to the interactions of internal waves generated, reflected, or modulated by the topography (Itoh et al., 2021; Waterhouse et al., 2014).

We found a cyclic pattern following the semidiurnal tidal period for both elevated ε and Kρ (Figure 6). The minimum (maximum) fluctuation for ε and Kρ reaches 6.8×10^{-8} (9.3×10^{-7}) W kg^{-1} and 1.5×10^{-5} (5.4×10^{-3}) m^2s^{-1}, respectively. This fluctuation signal of ε and Kρ is a common temporal variability as that found in previous studies (Purwandana, Cuypers, et al., 2021; Purwandana et al., 2020); strengthen the sensitivity of mixing properties measurements due to internal tidal variability. The range of dissipation rate observed in this area reached one order of magnitude, which is lower compared to the range observed in the Lombok Strait (two orders of magnitude range of tidal variability, located close to internal tide generating area) (Purwandana, Cuypers, et al., 2021); comparable to those observed in the Ombai Strait and Buru Strait (internal tide generating areas) (Purwandana et al., 2020); and higher than those observed in the northern Makassar Strait, northern and southern straits of the Halmahera Sea, and Labani Channel (Purwandana et al., 2020).

4. Conclusion

The northwestern waters of the Maluku Sea are typically influenced by South Pacific water masses. The mixing properties found in this study indicate that the study area is characterized by a strong TKE dissipation rate and vertical eddy diffusivity, with a wide range of tidal variability, that is even comparable to those observed in the internal tide-generating areas. We suggest that the impact of internal solitary waves was one of the factors responsible for the enhanced TKE dissipation rate and vertical eddy diffusivity in this area.

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Contribution statement

Bayu Priyono and Adi Purwandana are the main contributors to the manuscript, responsible for conceptualization, formal analysis, investigation, methodology, software, visualization, and writing – the original draft. Edi Kusmanto, Nuratmojo, and Muhadjirin are supporting contributors, participating equally in reviewing the manuscript.

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