

Water mass characteristics and estimation of turbulent mixing in Banggai Sea and Maluku Sea

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Abstract. Water masses can influence the mixing processes in the ocean. Temperature, salinity, and density data obtained from the CTD instrument during the BUDEE Expedition in September 2022 were used to identify the different water mass types and quantify their turbulence values. Turbulence was estimated using the Optimized Thorpe Method. The results revealed five types of water masses originating from the North Pacific, including NPSW and NPIW; from the South Pacific, including SPSW and SPLTW; and from the Antarctic, identified as AAIW. The highest vertical eddy diffusivity value was found in the Banggai region, reaching $1.5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$. In contrast, the Molucca and Seram seas showed much lower values, on the order of $10^{-4} \text{ m}^2 \text{ s}^{-1}$. The higher turbulence in the Banggai waters is likely due to its proximity to the Bote Strait and its relatively shallow topography. The lower turbulence in the Molucca and Seram Seas is attributed to deeper waters and limited interactions that induce water mass mixing. Overall, topography played a significant role in enhancing the mixing process by disturbing the stability of the water column.

Keywords: Banggai, BUDEE, Maluku water masses, optimized Thorpe method, vertical mixing

1 Introduction

Indonesia is located between two oceans: the Pacific Ocean and Indian Ocean. The current connecting these two oceans is the Indonesian Throughflow (Arlindo). Arlindo carries two main water mass components: the North Pacific and the South Pacific. North Pacific water masses include North Pacific Subtropical Water (NPSW), with high salinity in the thermocline layer, and North Pacific Intermediate Water (NPIW), with lower salinity in the deeper thermocline layer. A smaller contribution comes from the South Pacific [1], specifically the South Pacific Subtropical Lower Thermocline Water (SPLTW), which

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flows eastward at greater depths through the Halmahera Sea and Molucca Sea to the Seram Sea and then into the Banda Sea, with relatively high salinity [2]. Antarctic Intermediate Water (AAIW), located near the surface ($27.2 \sigma_\theta$), enters the northern Molucca Sea with slightly higher dissolved oxygen and much lower salinity [3]. Water masses are influenced by the transformation and mixing processes in the ocean. For example, the salinity of the NPSW changes from 34.90 psu to 34.54 psu, while the NPIW changes from 34.35 psu to 34.47 psu, indicating mixing in these waters [4]. Vertical mixing can also occur because sills restrict water flow in narrow or shallow straits, creating a higher current pressure compared to the open ocean.

Water mass mixing is caused by changes in density, temperature, salinity, and depth. The relationship between temperature and salinity can be used to observe the temporal and spatial mixing of water masses. The topography of the sill area affects the flow characteristics and mixing of water masses. This results in the flow of water masses being limited by the width or depth of the strait, resulting in a higher current pressure than in the open ocean. Internal waves blocked in the sill area result in high internal tidal energy in this region, allowing water masses from the Indonesian Ocean Rim to pass through several barriers, such as sills [5].

Water mass mixing plays an important role in heat transfer and nutrient distribution, and can affect the regional climate through heat and water transport to the thermocline. It can also generate nutrient fluxes that indirectly support phytoplankton growth [6]. This research focuses on identifying the characteristics of water masses at different depths and quantifying turbulent mixing in the Banggai Waters and Maluku Sea while also contributing to the scientific literature in this region.

2 Methods

2.1 Data and study area

Temperature, salinity, oxygen, and depth data were collected using a CTD SBE 911 instrument during the Widya Nusantara Expedition “Banggai Upwelling Dynamics and Ecosystem Experiment” (BUDEE 2022). The expedition was a collaborative research program between the National Research and Innovation Agency (BRIN) and several universities, conducted aboard the Research Vessel (RV) Baruna Jaya VIII in Banggai and Maluku Seas in September 2022. Six CTD stations were utilized in this study to analyze the water mass characteristics and estimate turbulent mixing. These stations were divided into three clusters: Station 3, located in the Seram Sea; Stations 11, 13, and 26, situated in the Banggai waters, representing shallow marine areas and potential upwelling zones; and stations 33 and 34, located in the Maluku Sea, representing deep-water regions (**Fig. 1**). Data processing and analysis were performed using Microsoft Excel, Microsoft Word, ArcGIS, ODV, MATLAB, SBE, and OTHORPE 1.2.

CTD SBE 911 Plus has a scanning rate of 24 Hz across all channels, indicating that the sensors can record 24 samples per second. The temperature sensor had a resolution of ± 0.0002 °C and an accuracy of ± 0.001 °C, while the conductivity sensor had a resolution of ± 0.00004 S/m and an accuracy of ± 0.0003 S/m.

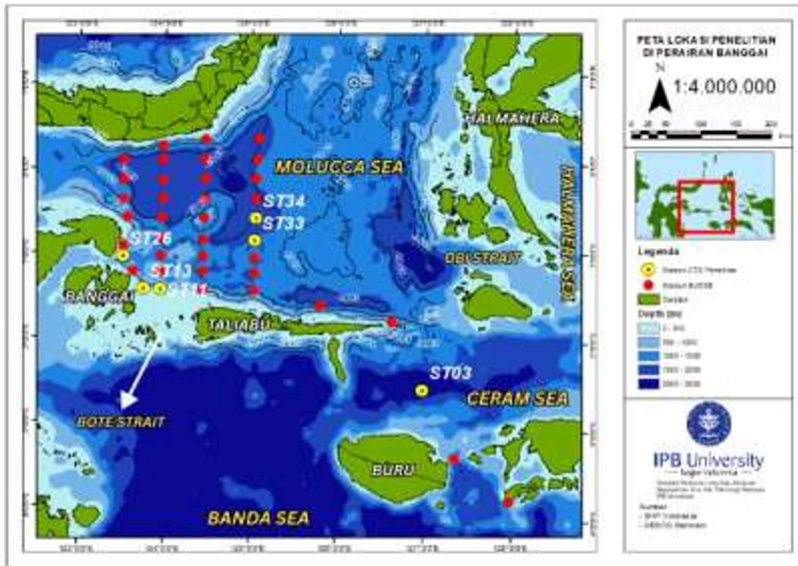


Fig. 1. Location of data observation and study areas at Banggai and Maluku Sea.

2.2 Data analysis

2.2.1 Determination of water layer

The water column layer was divided into three layers: mixer, thermocline, and deep. Water mass characteristics were determined by observing the temperature and density gradients. mixed layer can be identified by a temperature gradient $< 0.05^{\circ}\text{C}$, while a thermocline layer is $\geq 0.05^{\circ}\text{C}$ [7]. Water mass stratification analysis uses density gradients, with the determination of the mixed layer calculated using a gradient of $0.02 \sigma_{\theta}$, using the surface density as the reference point. If the density gradient is $\geq 0.02 \sigma_{\theta}$, the layer can be categorized as a thermocline layer [8].

2.2.2 Water mass characteristics

Water mass characteristic analysis used T-S, T-DO, and S-DO diagrams to identify the relationship between temperature, salinity, and oxygen. The water mass characteristic analysis provided an explanation for the types of water masses.

2.2.3 Thorpe analysis

Vertical mixing can be estimated by calculating vertical eddy diffusivity value (K_{ρ}) which is carried out through Thorpe scale analysis. The Thorpe scale represents the length scale of turbulent vertical overturns in stratified flows. In stratified flows, overturns are identified by the 'inverse' in density values, which is a condition of gravity. Overturn can be identified using the Thorpe method by calculating the Thorpe displacement [9].

$$d = z_a - z \quad (1)$$

The function of Thorpe displacement is to calculate the distance from depth Z_a to depth Z_b to reach a stable density. A positive value indicates that the water mass moves up to reach static stability, and vice versa. The value of the Thorpe displacement may originate from CTD noise, so it is necessary to filter again with several steps of density inversion selection related to vertical turbulence in the water column carried out through several stages of selection consisting of three parts: the value of the noise level of $\delta\rho = 2.09 \times 10^{-4} \text{ kg m}^{-3}$, inversion ratio (Ro) with a threshold of 0.2, and a T-S relationship of 0.66 [10]. These criteria eliminate the inversion of air parcels related to noise measurements, so they will not be involved in further delivery. Each Thorpe Scale value was obtained from the mean square of the Thorpe Displacement of n samples at the desired depth. Thorpe scale length value using Equation [9]

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

Turbulence produces kinetic energy from the breaking of surface and internal waves. This kinetic energy is broken down into smaller forms that transfer heat or energy to other media. Kinetic energy can be calculated using the following equation [11,10]:

$$\varepsilon = 0.64 L T^2 N^3 \quad (3)$$

when overturn is not detected, using the equation [11]:

$$\varepsilon_{background} = \max \left(1 \times 10^{-10}, \varepsilon_0 \frac{N^2}{N_0^2} \right) \quad (4)$$

N is the buoyancy frequency, $1 \times 10^{-10} \text{ W kg}^{-1}$ is the lowest kinetic energy dissipation rate value in Indonesian waters, $\varepsilon_0 = 7 \times 10^{-10} \text{ W kg}^{-1}$ and $N_0 = 3 \text{ cph}$ is the canonical dissipation value. By knowing the turbulent kinetic energy dissipation rate value, the vertical eddy diffusivity ($\text{m}^2 \text{ s}^{-1}$), which is a representation of the mixing level in the water column, is calculated using the following equation [12, 10]:

$$K_\rho = \Gamma \left(\frac{\varepsilon}{N^2} \right) \quad (5)$$

Γ is the mixing efficiency is an indicator of the conversion of turbulent kinetic energy to potential energy, so its value varies greatly depending on the dynamics of turbulence. Γ has a value of 0.2 [13]. This value of 0.2 is not an absolute value, but an average assumption that applies to stable stratified water conditions. N^2 is the Brunt–Väisälä frequency with units of cycle/h or S^{-2} .

3 Results and discussion

3.1 Vertical stratification of temperature, salinity, and density

Vertical temperature, salinity, and density profiles were used to determine the water column layers (**Fig. 2**). Oceanographic parameter data acquisition using the CTD was performed at depths of 0 – 1100 m.

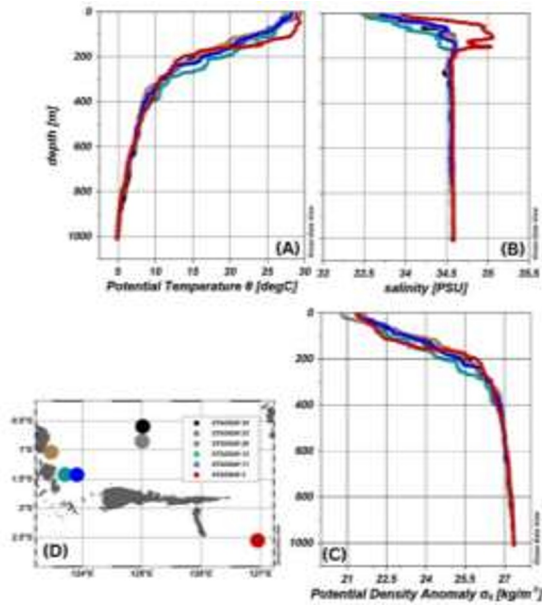


Fig. 2. Vertical profiles of (a) temperature, (b) salinity, (c) density, and (d) research map in Banggai and Maluku Sea.

Based on the vertical temperature profile (**Fig. 2a**), mixed layer at a depth of 27 – 60 m, with a temperature range of 26.52 – 29.22°C. After the mixed layer, which has a relatively high temperature, there is a thermocline layer with a temperature value that decreases significantly. The thickness of this layer ranges from 125 to 229 m, and the upper limit of the thermocline layer ranges from 28 to 61 m. The thermocline layer has a lower limit depth that ranges from 162 to 290 m, with a temperature range between 12.22 – 19.43°C. Variations in the depth of the lower limit of the thermocline layer are due to the North Equatorial Current (NEC) entering from the eastern Philippines, which can vertically press the water mass, resulting in the formation and shift of different thermocline depths [14]. The deep layer in the water is indicated by a homogeneous decrease in temperature values and a constant decrease in temperature with increasing depth. At the study site, the deep layer had a low temperature ranging from 4.77 to 11.80°C.

The vertical salinity profile is shown in **Fig. 2b**, with overall salinity values ranging from 33.46 to 35.06 psu. Station 3 had the highest salinity value of 35.06 psu. Station 3 is located in the Seram Sea. According to a previous study [15], salinity in the Seram Sea is higher than in other places in this research because highly saline water from Halmahera is found to be the dominant water flow from Indonesian Throughflow (Arlindo).

Vertical density profiles are shown in **Fig. 2c**. The mixed layer, based on density, has a depth ranging from 27 m to 58 m with a density of 20.81 22.03 kg m⁻³. Station 13 had the deepest mixed layer, at 58 m. In the pycnocline layer, the density value was in the range of 21.12 – 26.22 Kg m⁻³. The upper boundary pycnocline layer has a density profile with a value of 21.12 – 22.08 Kg m⁻³. Meanwhile, in the lower boundary pycnocline layer, the density profile showed a value between 24.83 – 26.22 Kg m⁻³. The deep-sea layer has a density value between 26.28 – 27.38 Kg m⁻³.

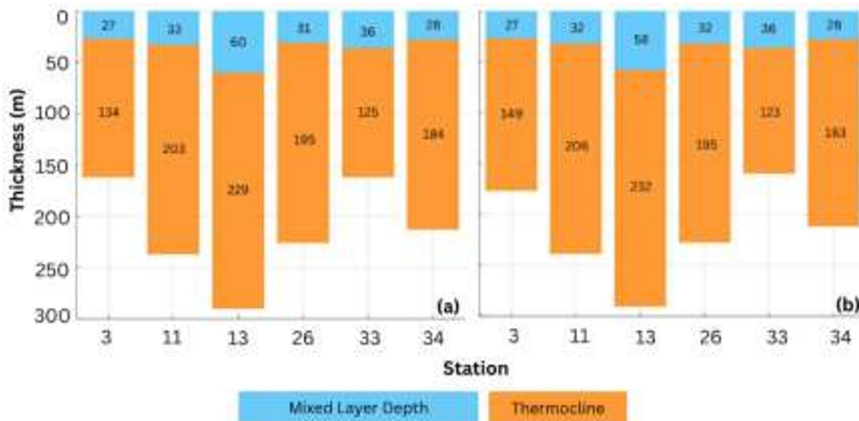


Fig. 3. Thickness of the mixed layer and thermocline based on (a) temperature gradient and (b) density gradient in the Banggai Waters and Maluku Sea.

Based on **Fig. 3**, water mass stratification in the waters showed results that did not differ significantly because density is influenced by temperature and salinity; however, in this study, salinity was relatively more constant than temperature. The temperature and density profiles at Station 13 showed a mixed surface layer and a thicker thermocline layer than at the other stations. This is because of the fairly strong mixing process of water masses, where warm water from the surface mixes with cooler water below. As a result, the mixed layer deepened, and the upper boundary of the thermocline was pushed deeper.

3.2 Water mass characteristics

Water mass was identified by analyzing the TS, TO, and SO diagrams (**Fig. 4**). There are two different sources of water mass at the research location: North Pacific and South Pacific water masses. The North Pacific water mass tends to be found in the Banggai waters, Maluku Sea, whereas the South Pacific water mass is found in the Seram Sea. Also supported research by [16] that the North Pacific water mass is not found in the Seram Sea but is filled by the South Pacific water mass. The characteristic of the South Pacific water mass is that it carries water masses with higher salinity than the North Pacific water mass.

South Pacific Subtropical Water Mass South Pacific Subtropical Water (SPSW) at $\sigma_\theta = 22 - 24 \text{ kg m}^{-3}$ with a maximum salinity of 35.06 psu. The SPSW water mass originated from the southern Pacific Ocean and entered Indonesian territory due to the influence of the North New Guinea Coastal Current (NGCC), which flows southeastward, originating from the branching of the Mindanao Current (MC) heading east as part of the North Equatorial Counter Current (NECC). A small portion of the NGCC flow turns into Indonesian waters, crossing the Halmahera Sea, East Maluku, and the northwestern region of Sulawesi, carrying the SPSW water mass with high salinity. This water mass was detected from the Seram Sea to the Banda Sea [17].

The salinity of the SPSW in this study was found to be much higher than the results obtained by [18] with a value of 34.85 psu, because when the BUDEE 2022 Expedition sailed, in western equatorial Pacific there was a strong anticyclonic circulation from the New Guinea Coastal Current (NGCC) during the period of June until September 2022. A positive phase occurred that coincided with La Niña conditions, which enhanced the intrusion of high salinity water masses from the South Pacific into the Maluku and Banggai Seas. It is suspected that there was a large leakage of the South Pacific water mass entering through Halmahera, resulting in water masses with high salinity at the research location (Seram Sea).

This is also in accordance with the research by [19] that showed that during the occurrence of La Niña, the Arlindo transport volume discharge is greater due to the strengthening of the hot spring pool around the waters of eastern Indonesia.

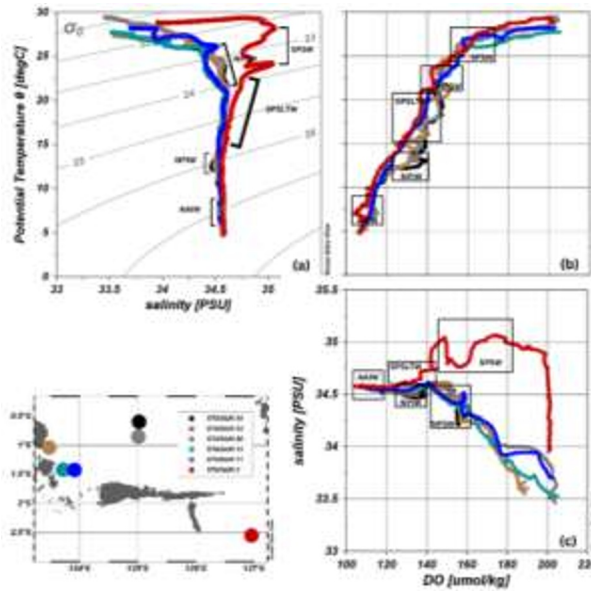


Fig. 4. Diagram of (a) T-S, (b) T-O, (c) S-O.

The North Pacific Subtropical water (NPSW) mass found in the Maluku Sea was identified at $\sigma_\theta = 22 - 23 \text{ kg m}^{-3}$ with a maximum salinity of 34.61 psu. The water mass identified in the deeper thermocline layer, it is South Pacific Subtropical Lower Thermocline Water (SPSLTW) at a density $\sigma_\theta = 23 - 25 \text{ kg m}^{-3}$ with a salinity value of 34.61 – 34.75 psu, a temperature of 15.31 – 22.45°C, and oxygen with a value of 128.42 – 142.61 $\mu\text{mol kg}^{-1}$. The identified water mass at density $\sigma_\theta = 25 - 26 \text{ kg m}^{-3}$ is a water mass originating from the North Pacific, namely North Pacific Intermediate Water (NPIW) with a salinity of 34.47 – 34.52 psu, 135.65 – 136.09 $\mu\text{mol kg}^{-1}$, and 12.35 – 13.84°C. The Antarctic Intermediate Water (AAIW) water mass was identified at isopycnal 26 – 27 kg m^{-3} with a salinity value of 34.55 – 34.54 psu, a temperature of 6.42 – 8.29°C, and oxygen of 112.51–113.78 $\mu\text{mol kg}^{-1}$. Based on research by [17], the New Guinea Coastal Under Current (NGCUC) transports AAIW into the Maluku Sea through the Talaud–Halmahera passage. Once inside, the water mass flowed southward along the western margin of Maluku, shifted eastward across the southern part of the basin, and finally moved northward along the eastern side, creating a large counterclockwise circulation pattern. A portion of this flow loops back to the Pacific Ocean through a weak cyclonic circulation in the eastern Maluku Strait, whereas the remaining flow continues toward the Seram Sea and Banda Sea through the Lifamatola Strait.

3.3 Analysis of turbulent mixing

Thorpe scale (L_T) analysis can be used to estimate the turbulent vertical mixing. The Thorpe Length Scale provides information on overturns occurring in the water column to determine static stability and can estimate the vertical eddy diffusivity [20]. The vertical profile of the Thorpe Length (L_T) Scale in Banggai Waters and Maluku Sea is presented in **Fig. 5**. Thorpe scale values at stations 11, 13, and 26 showed the highest values in the deep layer. This may be because of the high displacement level and low static stability of the deep layer.

Furthermore, according to [20], high Thorpe Length (L_T) scale values in the deep layer can also be caused by internal waves owing to interaction with the bottom topography of the waters. Furthermore, the increase in the Thorpe Length (L_T) scale in the deep layer is also associated with high Thorpe displacement, resulting in lower static stability and facilitating larger vertical water parcels.

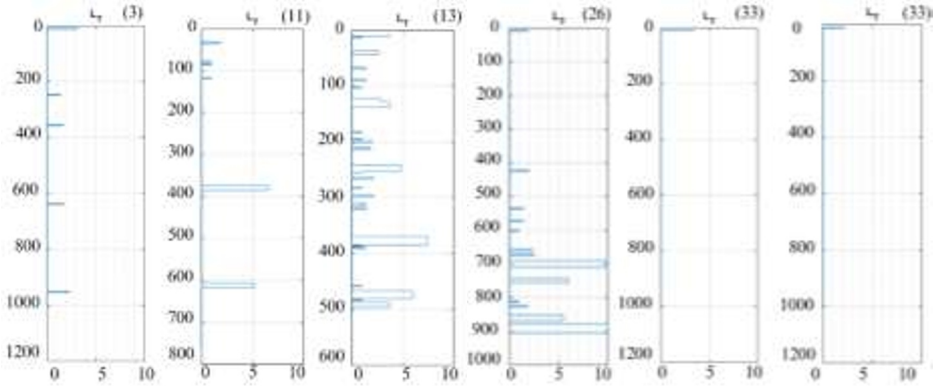


Fig. 5. Thorpe displacement profile after selection (dT_x) in Banggai and Maluku Sea.

Vertical mixing can be estimated by considering two parameters: turbulent kinetic energy dissipation (ϵ), and vertical eddy diffusivity ($K\rho$). Based on **Fig. 6**, the value of turbulent kinetic energy dissipation (ϵ) was high at stations located in the Bote Strait, such as Stations 11, 13, and 26. This indicates that the flow system in the strait resulted in a greater amount of kinetic energy in the turbulent flow than at other locations near the strait. In addition, this is related to the interaction of the flow with shallower waters, which results in an increase in the current shear. According to [20], the topography of the water plays a role in increasing the mixing value, especially in areas around the strait or threshold. Turbulent kinetic energy dissipation in the Seram Sea tends to be higher in the upper layers and decreases with increasing depth and In Maluku Sea. The conditions are increasingly stable and there is minimal turbulence at deeper depths.

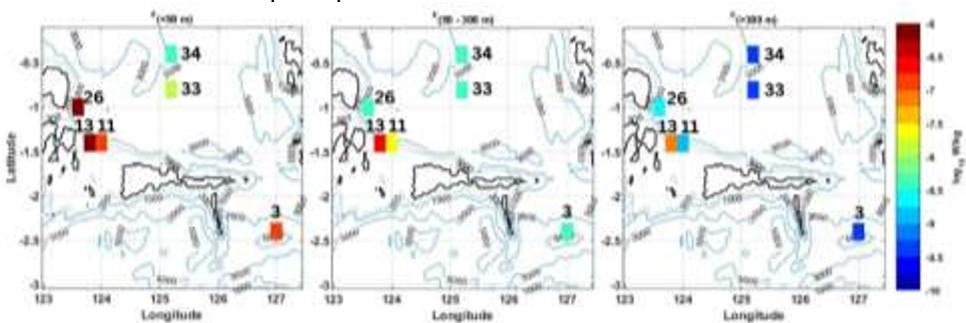


Fig. 6. Spatial distribution of turbulent kinetic energy dissipation rate at depths < 50 m, depths $50 - 300$ m, and depths > 300 m in the Banggai and Maluku Sea.

Based on **Fig. 7**, the highest vertical eddy diffusivity ($K\rho$) values at stations 11, 13, and 26 tend to be shallower and closer to the Bote Strait. The topography plays an important role in mixing. Studies examining the relationship between sills and vertical mixing in water have reported high $K\rho$ values in areas near sills and straits [6].

The vertical eddy diffusivity ($K\rho$) values at Station 13 were consistently higher at all depths than those at other stations. This indicated that strong mixing occurred at Station 13, resulting in the exchange of water masses between the lower and upper layers, indicating

nutrient enrichment. This triggered phytoplankton growth, which could indicate upwelling, making it a potential fishing ground for fishermen. This is also supported by research from [21] which explains that at Station 13 point is the point where upwelling occurs in the Maluku Sea because there is a current that moves northward above a depth of 60 m and moves in the opposite direction at the bottom at longitude 124° which is suspected to be the presence of upwelling that carries water masses from that depth.

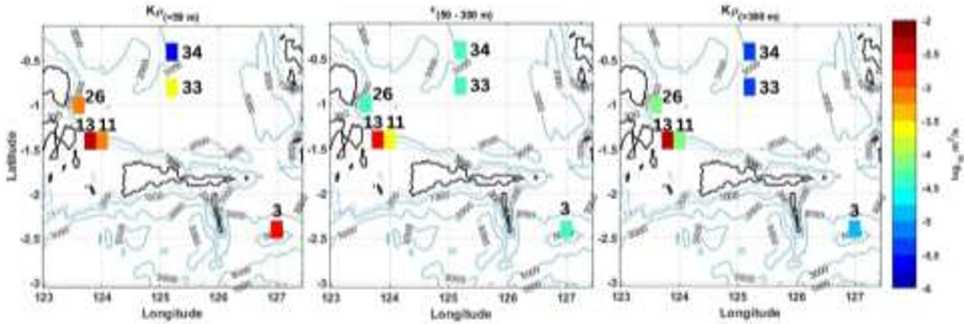


Fig. 7. Spatial distribution of diffusivity eddy vertical at depths < 50 m, depths 50 – 300 m, and depths > 300 m in the Banggai and Maluku Sea.

The spatial distributions of the turbulent kinetic energy dissipation rate (ϵ) and vertical eddy diffusivity (K_p) were visualized in temperature and salinity diagrams equipped with isopycnal lines (**Fig. 8**). Water mass mixing occurred isopycnal and diapycnal. Mixing that occurs between isopycnal surfaces or across densities is called diapycnal mixing, whereas mixing that occurs in isopycnal layers or the same density is called isopycnal mixing [6]. The distribution of ϵ and K_p values shows a relatively high value in the mixed layer up to the upper thermocline layer or in the isopycnal layer of < 22 – 26 kg m⁻³ which indicates the presence of intense turbulence in this layer. This region corresponds to the upper layer dominated by NPSW and SPSW water masses. In addition, according to research conducted by [19], there is a strong surface current in the Banggai region heading north, which results in high values of kinetic energy dissipation (ϵ) and vertical eddy diffusivity (K_p).

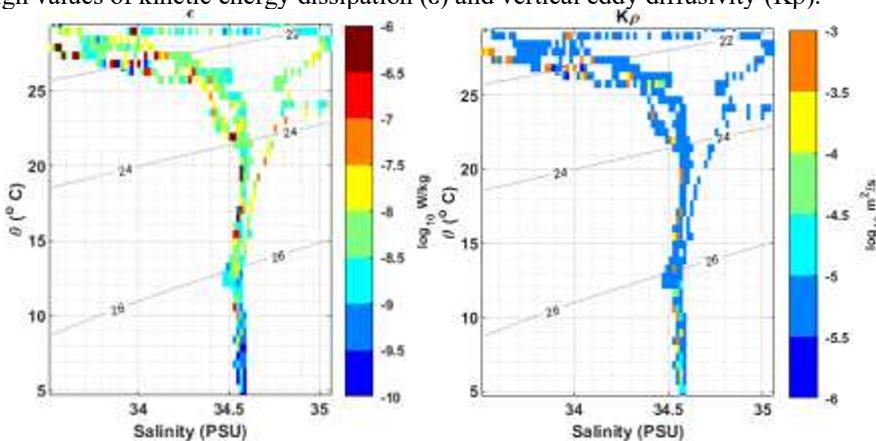


Fig. 8. T-S diagram overlap with turbulent kinetic energy dissipation and Vertical Eddy Diffusivity in Banggai and Maluku Sea.

The distribution of turbulent kinetic energy dissipation (ϵ) and vertical eddy diffusivity (K_p) in isopycnal layer > 26 kg m⁻³ appears to have decreased indicating that the layer is relatively stable and the level of turbulent energy in this layer is low, quantitatively the value of ϵ reaches the order 10⁻¹⁰ W Kg⁻¹ and value of K_p is 10⁻⁶ m² s⁻¹. Based on research by [6],

in the eastern route, namely the Halmahera Sea, the Maluku Sea, and the Banda Sea, the thermocline layer ($22\text{--}26\text{ kg m}^{-3}$) is characterized by a strong kinetic energy dissipation rate (ϵ) and vertical eddy diffusivity ($K\rho$). The deep layer (26 kg m^{-3}) was characterized by a low dissipation rate and less strong vertical eddy diffusivity.

4 Conclusion

Five water masses from different sources were identified in the study area, originating from the North Pacific and South Pacific. In the thermocline layer, South Pacific Subtropical Water (SPSW) and North Pacific subtropical Water (NPSW) were observed. In the intermediate layer, North Pacific Intermediate Water (NPIW) and South Pacific Subtropical Lower Thermocline Water (SPSLTW) are present. Below $27\text{ }\sigma\theta$ isopycnal Antarctic Intermediate Water (AAIW)

Turbulent mixing was stronger in the Banggai Waters due to their proximity to the Bote Strait, where the kinetic energy dissipation rate reached 10^{-7} W kg^{-1} and the vertical eddy diffusivity reached $1.5 \times 10^{-3}\text{ m}^2\text{ s}^{-1}$. This enhanced mixing is caused by the current interaction with the shallow topography associated with the strait flow.

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