Jurnal Teknologi Perikanan dan Kelautan Vol. 16 No. 4 November 2025: 440-452 ISSN 2087-4871
DOI: https://doi.org/10.24319/jtpk.16.440-452 EISSN 2549-3841

ESTIMATION OF MIXING AND TRANSFORMATION OF SOUTH PACIFIC WATER MASSES IN THE HALMAHERA SEA

ESTIMASI PERCAMPURAN DAN TRANSFORMASI MASSA AIR PASIFIK SELATAN DI LAUT HALMAHERA

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(Received October 13, 2025; Revised November 8, 2025; Accepted November 12, 2025)

ABSTRACT

The Halmahera Sea is part of the eastern pathway of Indonesian Throughflow and is a key area for water mass interaction and transformation. This study aims to estimate vertical mixing and analyze its implications for South Pacific water masses transformation in the Halmahera Sea. The data used are archived observational data from the National Research and Innovation Agency (BRIN), using CTD profilers and vertical current velocity measurements on February, 2021. Mixing estimation was using Thorpe analysis to calculate the turbulent kinetic energy dissipation rate (ε) and vertical eddy diffusivity ($K\rho$). Turbulent mixing areas were identified at depths of 50–300 m. The South Pacific water masses have a maximum salinity of 35.5 psu at the isopycnal σ_0 = 25.4, and a minimum salinity of 34.5 at the isopycnal σ_0 = 26.5. The Halmahera Sea near Obi Strait experiences a maximum salinity change at the isopycnal σ_0 = 25.5 with a value of 35.4 psu, while the minimum salinity at σ_0 = 26 is 34.8 psu. This layer (σ_0 = 24–26) exhibit a relatively high turbulent kinetic energy dissipation (10^{-6} W/kg) and vertical eddy diffusivity (10^{-3} m^2/s) that describe the transport of South Pacific Subtropical Water (SPSW). The isopycnal σ_0 = 26–27 show a decrease in minimum salinity, with ε on the order of 10^{-7} W/kg and $K\rho$ on the order of 10^{-3} m^2/s in the middle and deep layers near Obi Strait, indicating mixing driven by shear instability associated with internal wave energy dissipation zones.

Keywords: Halmahera Sea, South Pacific water mass, Thorpe analysis, turbulent mixing

ABSTRAK

Laut Halmahera merupakan bagian dari jalur timur Indonesian Throughflow dan adalah wilayah kunci untuk interaksi dan transformasi massa air. Penelitian ini bertujuan untuk memperkirakan pencampuran vertikal dan menganalisis implikasinya terhadap transformasi massa air Pasifik Selatan di Laut Halmahera. Data yang digunakan adalah data observasi arsip dari Badan Riset dan Inovasi Nasional (BRIN), menggunakan profiler CTD dan pengukuran kecepatan arus vertikal pada Februari 2021. Estimasi percampuran dilakukan menggunakan analisis Thorpe untuk menghitung tingkat dispersi energi kinetik turbulen (ε) dan difusivitas Eddy vertikal ($K\rho$). Area pencampuran turbulen diidentifikasi pada kedalaman 50–300 m. Massa air S. Pasifik Selatan memiliki nilai salinitas maksimum 35,5 psu pada isopiknal σ_0 = 25,4, dan salinitas minimum 34,5 pada isopiknal σ_0 = 26,5. Laut Halmahera di dekat Selat Obi mengalami perubahan salinitas maksimum pada isopiknal σ_0 = 25,5 dengan nilai 35,4 psu, sedangkan salinitas minimum pada σ_0 = 26 adalah 34,8 psu. Lapisan ini (σ_0 = 24–26), memiliki tingkat disipasi energi kinetik turbulen yang relatif tinggi (10^{-6} W/kg) dan difusivitas eddy vertikal (10^{-3} m^2/s) yang menggambarkan transportasi Air Subtropis Pasifik Selatan (SPSW). Lapisan isopiknal σ_0 = 26–27 menunjukkan penurunan salinitas minimum, dengan ε pada ordo (10^{-7} W/kg) dan Kρ pada ordo (10^{-3} m^2/s) di lapisan tengah dan dalam di dekat Selat Obi, menunjukkan pencampuran yang didorong oleh instabilitas geser yang terkait dengan zona disipasi energi gelombang internal.

Kata kunci: analisis Thorpe, Laut Halmahera, massa air Pasifik Selatan, percampuran turbulen

INTRODUCTION

The Indonesian Sea plays an important role in global ocean circulation, connecting the Pacific and Indian Oceans through the Indonesian Throughflow (ITF). This pathway is the primary mechanism for redistributing heat, salinity, and energy from high to low latitudes (Feng *et al.* 2018). The ITF flows through two main routes, the western route (Sulawesi Sea, Makassar Strait, Flores Sea) and the eastern which includes the Halmahera Sea and Maluku Sea (Ilahude dan Gordon 1996). The conditions of the Halmahera Sea are highly dynamic, as indicated, for example, by the meridional shifting of the Halmahera Eddy meridionally, which has a relatively stronger influence on fish catches in this region compared with zonal movements (Harsono *et al.* 2014).

In an ideal scenario, this dynamic process should occur through balanced convective and diffusive mechanisms, resulting in efficient transfer of water mass and energy from the Pacific Ocean to the Indian Ocean. However, the interaction of the ITF with complex underwater topography and current variability causes uneven vertical mixing. Energy from barotropic and baroclinic currents, especially those originating from internal tides, often results in energy dissipation around topographic features such as narrow straits, steep slopes, and undersea ridges (Klymak *et al.* 2012).

The dynamics of tropical currents from the western Pacific, equatorial currents, and the stratified nature of the water column create the potential for vertical shear and density instability that supports turbulent mixing (Purwandana and Cuypers 2023). Previous studies have shown that turbulent mixing in the Indonesian Sea is triggered by interactions between currents and topography, resulting in significant vertical fluxes and water mass transformation (Prihatiningsih *et al.* 2019). This process is controlled by the imbalance between buoyancy forces due to density stratification and vertical shear forces (Purwandana 2013). The Halmahera Sea is an active zone for internal wave generation, which influences the mixing of water masses. Detailed quantitative studies on the intensity of mixing and its triggering factors are still limited, particularly regarding their relationship with local oceanographic and topographic conditions.

The Pacific water mass flowing into Indonesia's internal waters has distinctive characteristics, as shown by its unique temperature-salinity (T-S) diagram. This is the result of vertical mixing and large freshwater inflows, as well as meteorological factors such as monsoon circulation that shape the seasonal characteristics of the water mass (Iskandar *et al.* 2021). The eastern route of the ITF is an area undergoing intense transformation due to the narrowing of topographic features (Nagai *et al.* 2017). Research conducted by Prasetyo *et al.* (2024) found that the kinetic energy dissipation rate reached 10^{-7} W/kg in the northern part, 10^{-8} W/kg in the inner and southern parts of the Halmahera Strait, and the vertical eddy diffusivity value was of the order of 10^{-3} m^2/s. These values are associated with the layer indicating the presence of subtropical South Pacific Water (SPSW). Another consistent study is from Iskandar *et al.* (2021), shows that the water mass in the Halmahera Sea in November (transition season) experiences more pronounced maximum salinity erosion in the northern waters of Halmahera than in the south. This indicates a transformation occurring as it passes through the narrow strait.

This study aims to estimate the mixing strength in the Halmahera Sea and analyze its effect on the transformation of water mass properties, focusing on changes in maximum salinity. This study is expected to explain the physical mechanisms that control changes in water mass properties, and clarify the role of the Halmahera Sea as an important zone for the transformation of Pacific water masses on their journey to the Indian Ocean.

METHODS

This study used conductivity, temperature, and depth (CTD) data from Sea-Bird Electronics (SBE) 911plus obtained from the observation archives of the National Research and Innovation Agency (BRIN). The CTD was operated at a sampling rate of 24 Hz on February 1–2, 2021, in the southern waters of Halmahera (-1.5°S to -0.5°S and 128°E to 129°E) (Figure 1). Three CTD stations were occupied along a transect crossing the Halmahera Sea, capturing fine-scale stratification and turbulent mixing. Raw CTD data were processed using the standard SBE Data Processing, including steps such as alignment, cell thermal mass correction, conductivity hysteresis removal, and edit loop filtering. The cleaned profiles were then averaged into 1 m intervals with uniform vertical resolution, allowing for high-fidelity vertical derivatives to be computed while minimizing high-frequency noise. Before analysis, the CTD measurement data were preprocessed prior to analysis. The data used were taken only from the downcast, which are profile measurements when the CTD was lowered to a depth (depth under increasing pressure). CTD data processing was carried out using SBE Data Processing-Win32 version 7.26.7. Current data from the ADCP were extracted using WINADCP to obtain depth data for zonal (u) and meridional (v) current components. This current data is supported by a hybrid ocean coordinate model (HYCOM) that provides global ocean output in the form of temperature, salinity, and depth across a 3D grid. The data can be downloaded for free from the official HYCOM website (https://www.hycom.org) by selecting the desired parameters, time range, and geographical area. These variables can be used to calculate the potential density field of seawater (σ_θ) and extract oceanographic properties at the isopycnal surface. In this study, the HYCOM model outputs of zonal (u) and meridional (v) currents, temperature, salinity, and depth were used. The gridded fields were loaded and interpolated onto isopycnic coordinates for mapping physical quantities such as salinity distribution and current patterns during the observation period (February 1–2, 2021).

The HYCOM used in this study provides three-dimensional data with a typical horizontal resolution of 0.08°. This resolution captures regional oceanographic features in sufficient detail across the Indonesian Sea and the Western Pacific, including narrow straits, continental slopes, and boundary currents. Vertically, HYCOM uses a hybrid coordinate system that adapts to the dynamic structure of the ocean. The version of HYCOM used in this study includes 40 vertical layers, allowing for a detailed representation of the vertical structure of temperature, salinity, and velocity from the surface to depths of more than 5,500 m. The thickness of the layers varies with depth: the surface layer is relatively thin, ranging from 1 to 5 m, in order to represent upper-ocean dynamics of the upper ocean, while the layers below become thicker with increasing depth. In this study, the temperature, salinity, and depth fields generated from HYCOM were used to calculate the potential density (σ_θ), which was then interpolated onto the surface of constant density (isopycnals).

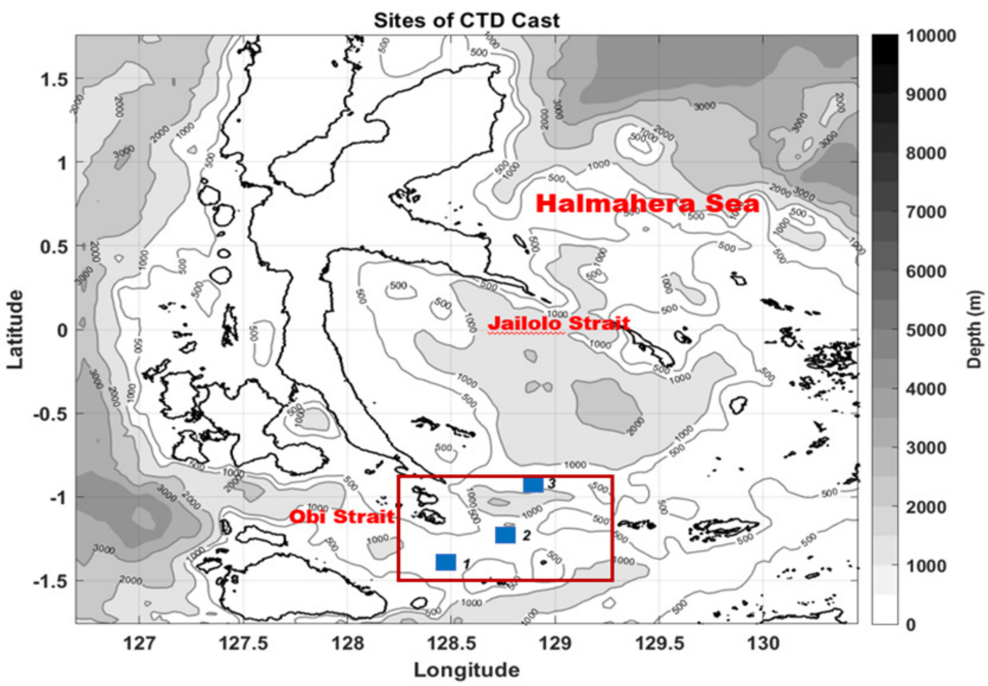

Figure 1. Research area (red box), CTD stations (blue dots), and ADCP transect (green line) in the southern waters of Halmahera.

Data analysis

The oscillatory movement of fluid to achieve equilibrium is called buoyancy frequency or the Brunt-Vaisala frequency (N^2), where fluid with high density is above low density and will move vertically to achieve equilibrium. This value is calculated using the following equation:

$$N^2 = \frac{g}{\rho_0}\frac{d\rho}{dz}$$

Next, the Thorpe displacement (Td) is calculated to identify water mass inversion. Td is obtained from the reordering of CTD data, where water masses with greater density are located below water masses with lesser density. All identified Td values are subsequently validated using the GK test (Galbraith and Kelley 1996). The threshold value used is 0.7 to minimize the possibility of the GK test rejecting some real overturns, which are usually small overturn areas (Stansfield *et al.* 2001; Naulita *et al.* 2014). The concept of Thorpe displacement calculation is illustrated in Figure 2 and calculated using the following equation (Dillon 1982):

$$Td = za - zb$$

The Td value is used to calculate the vertical displacement range of a water mass (Thorpe scale), which is calculated using the following equation:

$$L_T = \left(\frac{1}{n}\sum n^n i = 1\ Tdi^2 i\right)^2$$

Calculation of kinetic energy dissipation rate (W/kg) using the optimized Thorpe method by Purwandana and Cuypers (2023) as follows:

$$\varepsilon = 0.64 L_{T^2} N^3 (overturn\ detected)$$

After identifying the reversal of water parcels using the equation above, the following equation is used when no reversal is detected. In this case, N is the buoyancy frequency, 1×10^{-10} W/kg, and the lowest kinetic energy dissipation rate in Indonesian waters (ε_0 = 7×10^{-10} W/kg) and background stratification (N_0 = 3 cph).

$$\varepsilon = max\left(1\times10^{-10} m^2 s^{-3}, \varepsilon_0\left(\frac{N^2}{N_0^2}\right)\right)$$

$$(no\ overturn\ detected)$$

Then, using the turbulent kinetic energy dissipation rate, the estimated vertical diffusivity (m^2/s) reflecting the mixing rate in the water column is calculated using the following equation:

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

Identification of water masses using temperature and salinity (T-S) diagram analysis divides the water column into three layers: the mixed layer, the thermocline layer, and the deep layer. The definition of these layers s based on the temperature and density gradients within the water column. The surface mixed layer is characterized by a temperature gradient (ΔT) of <0.1 °C. Furthermore, the thermocline layer has a temperature gradient ≥0.1 °C and a density gradient ≥0.2 kg/m³ relative to the surface density reference (Prihatiningsih *et al.* 2019). The classification of layers based on density gradient is considered more realistic than using temperature alone, because temperature profiles do not always accurately depict vertical stratification. The boundary between the thermocline layer and the deep (homogeneous) layer is determined visually from density profiles and validated using temperature data. The boundary used is the depth range where the density value does not decrease sharply with depth (Purwandana *et al.* 2014).

RESULTS AND DISCUSSION

General circulation of the Halmahera Sea

It is necessary to observe the average salinity distribution and analyze the direction of ocean currents at several isopycnic layers to understand the dynamics of circulation and water mass distribution in the study area. These layers were selected to represent each layer in the water column. Sampling should be conducted over several days distributed within a month to represent average conditions during that period. To support the analysis of mixing on the day of data collection, it is necessary to visualize the average currents and salinity over the same time period as the data collection (February 1–2, 2021), taking into account the daily tidal cycle to identify tidal dynamics (Figure 3).

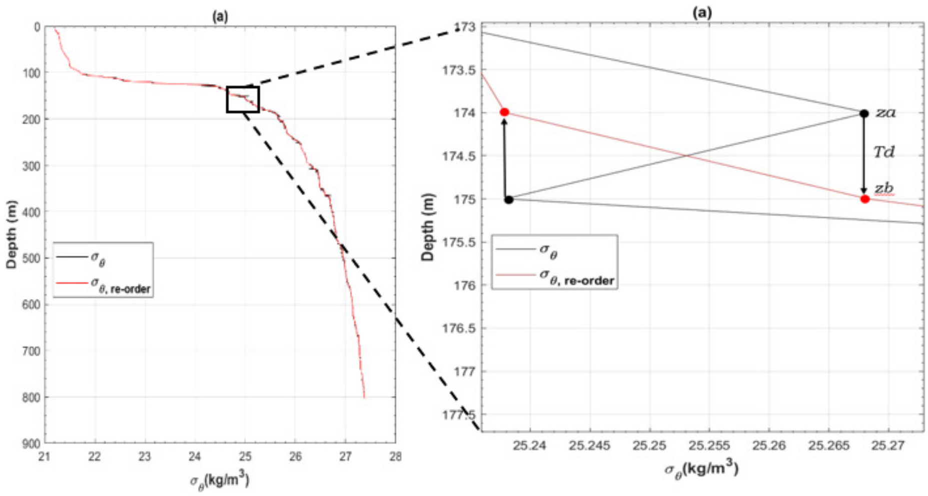

Figure 2. Concept of Thorpe displacement calculation.

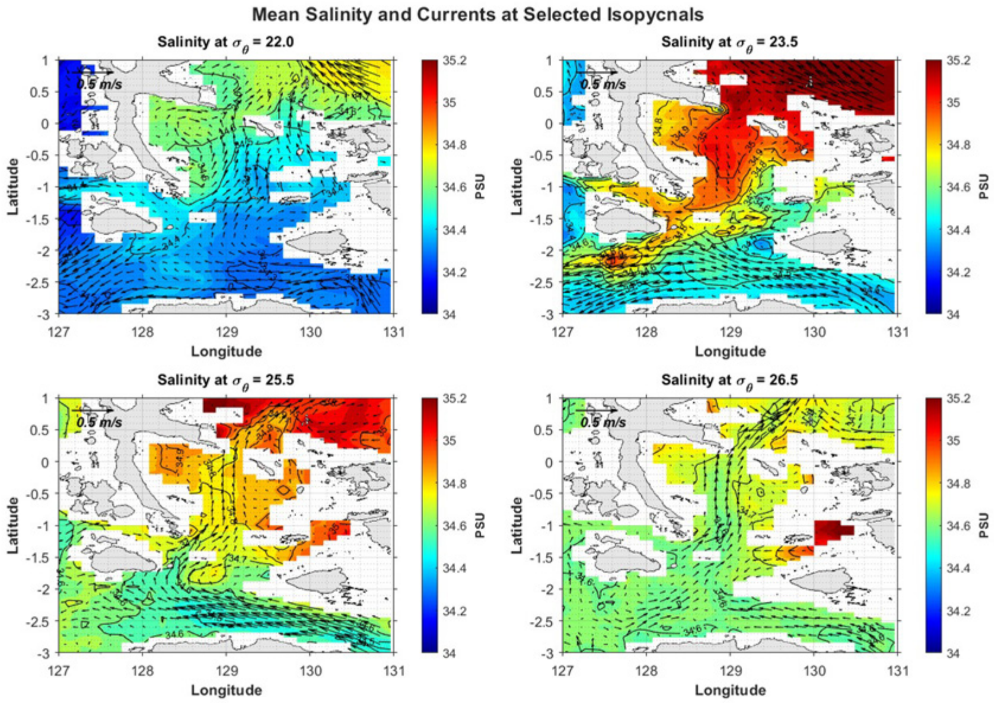

Figure 3. Spatial distribution of current and salinity during one tidal cycle in the southern waters of Halmahera in UTC time format on February 1–2, 2021.

The isopycnal layer σ_θ = 22.0, which represents the surface layer, it can be seen that water masses with relatively low salinity (<34 psu) dominate the southern and western parts of the study area. The current pattern indicates an inflow from the south to the north that follows the morphology of the Halmahera Strait. Furthermore, in the σ_θ = 23.5 layer, the intrusion of saltier water masses from the north becomes more pronounced with a salinity >35 psu (Figure 3) in the northeast, which is likely to originate from the intrusion of tropical water masses from the Western Pacific (South Pacific Subtropical Water). The layer σ_θ = 25.5, which represents the upper thermocline, shows high salinity extending from north to south through a narrow current pathway, indicating stable water mass transport from the north. This pattern is consistent with the easterly monsoon circulation, which strengthens the intrusion of salty water into the southern region. Meanwhile, in the deepest isopycnal layer analyzed, σ_θ = 26.5 (bottom), the salinity distribution begins to weakens with values ranging from 34.6 to

34.8 psu, and the current pattern becomes calmer and more dispersed. This indicates that the influence of surface dynamics is beginning to diminishes. This phenomenon is consistent with the characteristics of the lower thermocline layer, which is more vertically stable and less affected by surface turbulence.

This pattern is in line with the findings of Hadikusumah (2010), who reported that during the west monsoon season (December-January-February), currents move southward and are predicted to be part of the Indonesian throughflow, In addition Wattimena *et al.* (2018) reported that surface currents in the waters of Halmahera tend to move southward from the surface to a depth of 200 m with a current velocity of 0.3 m s^{-1}.

Water column stratification

The stratification profile of the Halmahera Sea is presented in Figure 4. The results of the Buoyancy Frequency (N^2) analysis show positive values, which indicate stable stratification conditions. These positive values were derived after the temperature and salinity profiles were reordered to ensure that the density distribution was stable relative to depth. At depths of 0–100 m, the N^2 value is relatively e low, while at depths of 100–200 m, the N^2 value is higher, indicating the presence of a strong thermocline layer. According to Harsono *et al.* (2023), the surface mixed layer tends to be thick due to the influence of internal factors such as surface winds and surface wave energy reaching a certain depth. When compared to the 400–800 m layer, the N^2 value is below 1–6 $\times 10^{-4}$ s^{-2}. This indicates that the mixed surface layer and the deep layer have weaker stability than the upper thermocline layer. All stations exhibit similar stability patterns, suggesting that significant vertical mixing is unlikely to occur without strong external forcing.

Estimation of turbulent mixing

The Td value is used to analyze the vertical mixing of water masses that occurs in the water column. The Td value indicates the distance traveled by a parcel of water from its initial position to a stable condition. The instability of the water column is indicated by positive and negative Td values. Negative (positive) values indicate that the water mass moves up (down) by a certain distance to reach a gravitationally stable condition (Harsono *et al.* 2023). The Thorpe displacement profile is shown in Figure 5, while the Thorpe scale is shown in Figure 6. The Td value near the Obi Strait at a depth of 0–100 m ranges from -5 to 5, while at a depth of 100–120 m it ranges from -7 to 3 m, and at a depth of 280–300 m, the Td value is close to 0 (Figure 5).

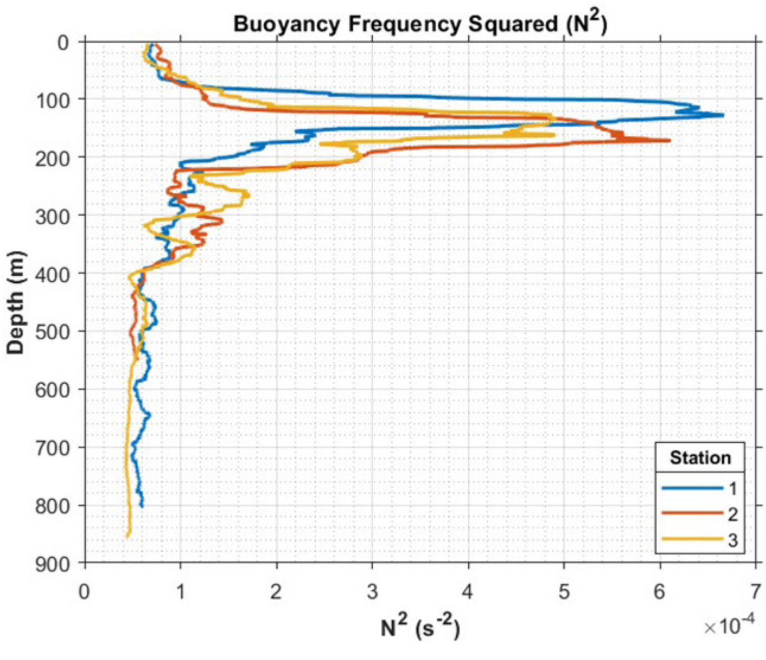

Figure 4. Stratification profile of the Halmahera Sea in February 2021.

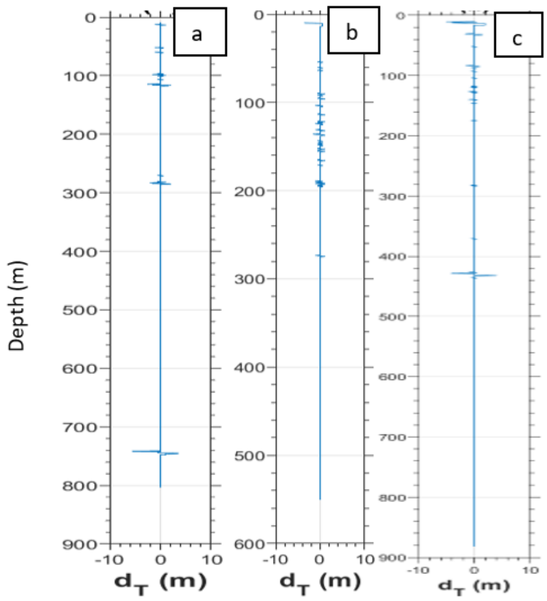

Figure 5. Thorpe displacement profile for Station 1 (a), Station 2 (b), and Station 3 (c) in the Halmahera Sea.

An interesting phenomenon occurs in the waters of Halmahera near the Obi Strait, where at depths of 100–300 m, high (stable) N^2 values are observed, which suppress turbulence and result in a small Thorpe scale. However, the Halmahera sea region also shows a fairly large Thorpe scale of around 2 m (Figure 6). Particularly in waters near the Obi Strait, this is most likely caused by intense vertical shear currents such as the Indonesian Throughflow or by strong internal wave energy, resulting in a source of turbulent energy that can disrupt the stability of the southern Halmahera waters. The instability caused by current faults can be explained by the Richardson number ($Ri = N^2/S^2$), where the value is less than 0.25. It appears that there are other mechanisms that support mixing with a Thorpe scale ranging only from 0.5 to 1 m. Previous research by Ostrovsky *et al.* (2024) evaluated small-scale turbulence parameters at large *Ri* values, and the results showed that turbulence processes can still occur when considering flow characteristics, topography, and changes in kinetic and potential energy. Therefore, further analysis was conducted by reviewing the relationship between the N^2 value and instability caused by shear.

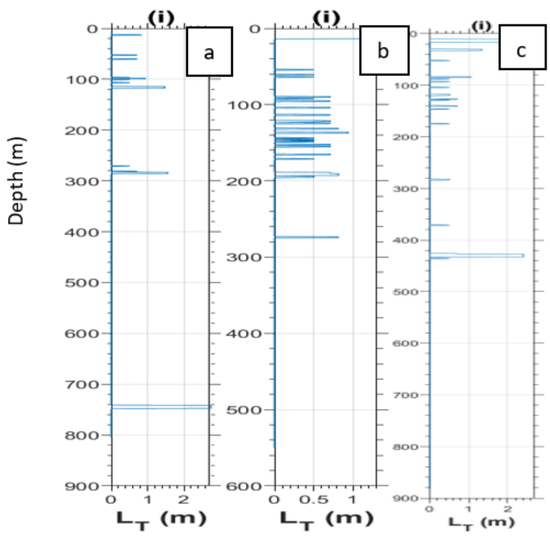

Figure 6. Length Thorpe (LT) profile for Station 1 (a), Station 2 (b), dan Station 3 (c) in the Halmahera Sea.

Spatial distribution of turbulent mixing

The spatial characteristics of turbulent mixing in the Halmahera Sea are shown based on observations at three CTD stations. The rate of kinetic energy dissipation and vertical eddy diffusivity with depth in the southern Halmahera waters are shown in Figure 7. The waters of Halmahera near the Obi Strait (128°E–128.4°E: ~1.4°S) show a TKE rate (10^{-6} W/kg) with a Kρ value close to (10^{-3} m^2/s), while the waters near Weda Bay (28.6°E–128.8°E: ~1.2°S) and the waters leading to Weda Bay (129.0°E–129.2°E) have TKE values that are relatively similar to those near Obi. The estimated Kρ in the area leading to Weda Bay is ($10^{-2.5}$ m^2/s) and in the waters near Weda Bay is (10^{-3} m^2/s), indicating a discrepancy between the ε and Kρ values due to dynamic anomalies.

The rate of kinetic energy dissipation (ε) represents the rate at which energy from currents or internal waves is transferred to small (micro) scale, while the vertical eddy diffusivity coefficient is a quantitative parameter that indicates the mixing capacity in transferring heat vertically (Osborn 1980). Spatial analysis of (ε) and (Kρ) and their correlation with the stability parameter Ri was performed to identify mixing zones and understand the role of internal waves in influencing the mixing process in the Halmahera Sea. The results of the analysis show that the spatial turbulent energy dissipation rate is consistent with the results of the previous Ri analysis. These values were then plotted into several depth layers, with depths >50 m representing the surface layer, 50–300 m representing the thermocline layer, and depths <300 m representing the deep layer.

The waters of Halmahera show relatively high kinetic energy dissipation rates ranging from (10^{-7}–10^{-6} W/kg) at depths of 50–300 m. This indicates the presence of concentrated energy that dissipates and propagates from the south, contributing to the vertical mixing of water masses. This finding is reinforced by the characteristics of the region at that depth, which feature narrow gaps and a steep topography (Prasetyo *et al.* 2024), while at depths <300 m, the ε value decreases in the waters near the Obi Strait. The high kinetic energy dissipation may indicate the presence of bottom-enhanced mixing occurring along the seafloor bathymetry (St. Laurent *et al.* 2002).

Overall, the distribution of ε and Kρ shows a pattern consistent with the vertical profile of potential density and water column instability (Ri), where Ri <0.25 dominates in the density range of 24–27 kg/m^3 (Figure 8). Isopycnal water mass mixing refers to mixing that occurs along layers of equal density or at isopycnal surfaces separating water masses of different densities. These conditions indicate vertical diffusion and exchange of physical properties between water layers. The southern part of the Halmahera Sea near the Obi Strait has complex topography that enhances kinetic energy dissipation, making it a regional mixing hotspot and contributing to water mass transformation. These results reinforce the role of Halmahera waters in transporting energy, heat, and nutrients (Kunze 2017).

Typical water mass

The identification of water masses in the Halmahera Sea is shown in Figure 9, while their characteristics based on specific isopycnal layers are presented in Table 1. The typical water mass of the South Pacific thermocline layer is the South Pacific Subtropical Water (SPSW), characterized by a maximum salinity of around 35.3–35.5 psu detected at a layer of 24–25.6 kg/m^3 (Figure 10). These results are consistent with the findings of Atmadipoera *et al.* (2022), who reported that S_{max} in the Seram Sea decreased from 35.5 psu to ~35.0 psu. SPSW is known to enter Indonesian waters through the South Equatorial Current (SSEC) and pass through the Halmahera Sea before being distributed to the Seram and Banda Seas (Sprintall *et al.* 2019). In The Halmahera Sea near the Obi Strait, a relative minimum salinity is observed at the 26.5 kg m^{-3} isopycnal layer at a depth of 200–400 m. This indicates the presence of South Pacific Intermediate Water (SPIW) that has transformed due to interaction with tropical water masses (Iskandar *et al.* 2021). SPIW originating from the South Pacific generally has a minimum salinity (~34.4–34.6 psu) at an isopycnic layer of 26–27 kg/m^3 (Guo *et al.* 2023). Water masses passing through the ITF enter low-latitude waters and undergo modification due to mixing or turbulent diffusion processes (Yuliardi *et al.* 2021). These results are in line with Prasetyo *et al.* (2024), who identified a maximum salinity of 35.2 psu due to vertical mixing along the southern Halmahera ITF. Water mass identification was also carried out using Argo float data to trace the South Pacific water mass. The results show that the typical South Pacific water mass has a maximum value of 35.5 psu at the isopycnal 25–26 kg/m^3. The 26–27 kg/m^3 isopycnal layer has a minimum salinity of 34.5 psu, characteristic of South Pacific Intermediate water (SPIW). The deep layer of the Halmahera Sea shows a decrease in the minimum salinity value, indicating a transformation of the water mass passing through the deep layer of the Halmahera Sea.

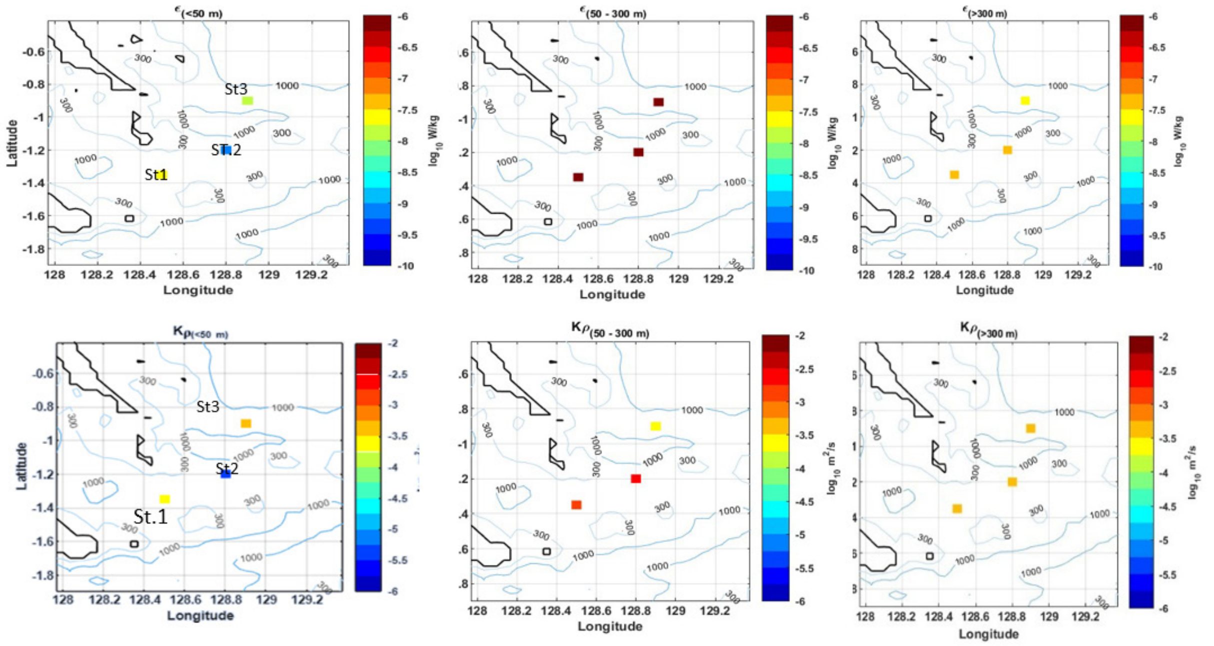

Figure 7. Spatial distribution of kinetic energy dissipation (top) and eddy diffusivity (bottom) in the Halmahera Sea.

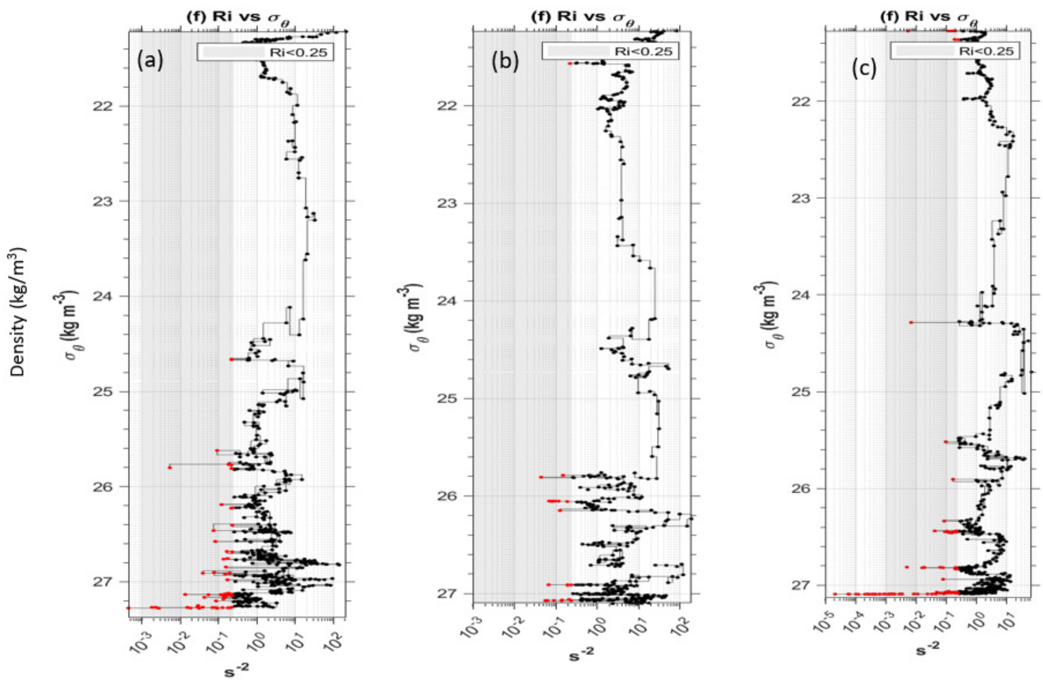

Figure 8. Vertical profile of potential density (σθ) relative to the unstable zone (Ri <0.25) at Station 1 (a), Station 2 (b), and Station 3 (c) in the Halmahera Sea.

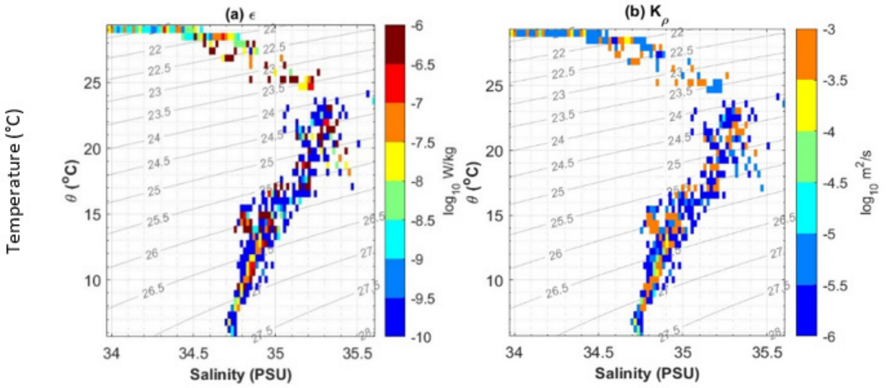

Figure 9. T-S profile diagram superimposed with kinetic energy dissipation rate values (left) and T-S profile diagram with vertical eddy diffusivity values (right) in the Halmahera Sea.

Table 1. Estimation of kinetic energy dissipation rate and vertical eddy diffusivity in the Halmahera Sea.

σθ (kg/m³)	Mean ε (W/kg)	Std Dev ε (W/kg)	Mean Kρ (m²/s)	Std Dev Kρ (m²/s)
<22	$3.5 \cdot 10^{-8}$	$2.2 \cdot 10^{-7}$	$2.0 \cdot 10^{-4}$	$7.4 \cdot 10^{-4}$
22–23	$2.2 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$	$2.2 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$
23–24	$4.6 \cdot 10^{-6}$	$7.7 \cdot 10^{-6}$	$1.9 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$
24–25*	$6.4 \cdot 10^{-7}$	$1.7 \cdot 10^{-6}$	$1.4 \cdot 10^{-3}$	$6.8 \cdot 10^{-3}$
25–26*	$7.1 \cdot 10^{-7}$	$3.2 \cdot 10^{-6}$	$1.5 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$
26–27**	$1.1 \cdot 10^{-7}$	$5.7 \cdot 10^{-7}$	$6.0 \cdot 10^{-4}$	$3.1 \cdot 10^{-3}$

*Middle layer ~ Subtropical South Pacific Water (SPSW) core layer

**Deep layer ~ Subtropical Intermediate South Pacific Water (SPIW) core layer

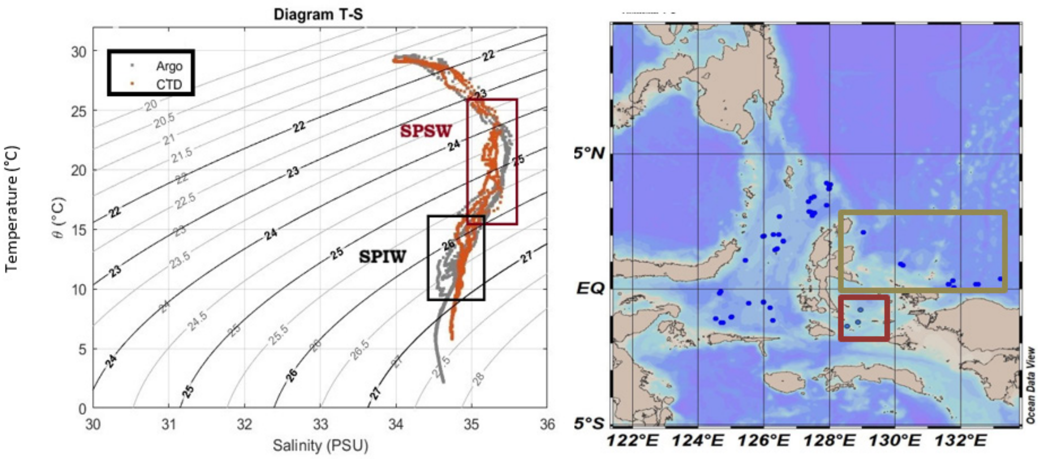

Figure 10. T-S diagram in the Halmahera Sea (left) and locations of temperature, salinity, and depth data collection (right), CTD data (orange boxes), data collection stations (blue dots), and Argofloat data (gray boxes).

Low-latitude waters such as the Halmahera Sea are characterized by complex topography consisting of steep ridges and narrow straits that act as triggers for internal tides, which, when interacting with the pycnocline layer, generate strong shear zones (Nash *et al.* 2007). This condition is consistent with the kinetic energy dissipation value and vertical eddy diffusivity rate in the thermocline layer, which are triggered not only by surface forcing but also by internal wave energy. A mixing study by Purwandana *et al.* (2014) in the Makassar Strait shows similar behavior, with an average eddy vertical diffusivity value of 2.4×10^{-3} m²/s in the deep layer triggered by internal tides due to channel narrowing.

Another study that also examined mixing in low latitudes, as reported by Sprintall *et al*. (2019), shows that mixing locations in Indonesia occur in areas with steep and narrow topography, where internal tide energy can produce turbulent kinetic energy dissipation in the range (10^{-7}–10^{-4} W/kg) and vertical diffusivity (10^{-4}–10^{-1} m^2/s). Characterization of mixing in selected isopycnal layers is conducted to identify the strength of turbulent kinetic energy dissipation that transports water mass. Isopycnal layers >27 represent the deep layer, while layers 22–25 w/kg^3 represent the intermediate layer (Moum *et al*. 2003). Analysis of each isopycnal layer allows recognition of the central mixing zone associated with the pycnocline layer. Estimates of the vertical eddy diffusivity and highest turbulent kinetic energy are in the isopycnal layer 22–26 kg/w reaching an order of 10^{-6} W/kg and Kρ reaching an order of 10^{-3} m^2/s (Table 1). Naulita *et al*. (2021) findings in the waters of the Lombok Strait show that kinetic energy dissipation ranges around (10^{-6} W/kg) and vertical eddy diffusivity is relatively high at 10^{-2} m^2/s in the isopycnal layer σ_θ = 25.5–26.5 in the area near the threshold. These conditions indicate the presence of large-scale energy sources such as internal waves that undergo shoaling and steepening before breaking.

CONCLUSION

Estimates of turbulent kinetic energy dissipation rate (ε) and vertical eddy diffusivity (Kρ) indicate that the most intense mixing in February 2021 occurred in the thermocline layer (50–300 m) with values of (10^{-7}–10^{-6} W/kg) and Kρ reaching (10^{-3} m^2/s). Vertical mixing shows that the thermocline layer is the main zone of water column instability compared to the upper and lower layers, which tend to be more stable. Vertical mixing in this region is greatly influenced by the dynamics of the Halmahera Sea as a cross-current route from the Pacific. The properties of the water mass in the southern Halmahera waters in February are characterized by the South Pacific Subtropical Water (SPSW) with a salinity range of 34.5–35.5 psu at an isopycnic layer of 25–26 kg/m^3 and the South Pacific Intermediate Water (SPIW). These findings confirm that the Halmahera waters act as a zone of vertical mixing that modifies the characteristics of water masses due to the influence of narrow straits and rough topography, and play an important role in the transfer of energy and nutrient fluxes that support the sustainability of the ITF circulation system.

ACKNOWLEDGMENTS

We would like to express our gratitude to the Education Fund Management Institution (LPDP), Ministry of Finance of the Republic of Indonesia, for the financial support provided for the master's thesis research project. We would also like to express our sincere gratitude to the National Research and Innovation Agency (BRIN) for their guidance in analyzing the data.

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