

Water Mass Characteristics and Stratification Stability of the Flores Sea During the First Transition Season of 2023

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Abstract

The Flores Sea plays a critical role within the Indonesian Throughflow (ITF) system, functioning as a key transitional pathway where Pacific-derived water masses undergo significant transformation prior to entering the Banda Sea. Despite its importance, scientific understanding of the relationship between water-mass characteristics and water-column stability during the first transition season in this region remains relatively limited. This study was conducted to characterize the water masses present in the Flores Sea and to evaluate water-column stability using conductivity-temperature-depth (CTD) observational data collected from four sampling stations during the Jala Citra III-2023 "Flores" Expedition, carried out between April and May. Vertical profiles of temperature, salinity, and density were systematically analyzed to identify distinct water masses through the construction of temperature-salinity (T-S) diagrams, while water-column stability was assessed by calculating the Brunt-Väisälä frequency at each station. The results revealed a clearly defined vertical hydrographic structure, consisting of a surface mixed layer, a thermocline layer extending from approximately 40 to 300 meters in depth, and a deep layer situated below 300 meters. Analysis of the T-S diagrams identified three major water masses contributing to the hydrographic composition of the Flores Sea: North Pacific Subtropical Water (NPSW), South Pacific Intermediate Water (SPIW), and Antarctic Intermediate Water (AAIW). Furthermore, the highest Brunt-Väisälä frequency squared value, reaching $2.3 \times 10^{-2} \text{ s}^{-2}$, was observed at approximately 116 meters depth, indicating that the maximum stratification stability occurred within the thermocline layer. Overall, these findings demonstrate that combining water-mass characterization with Brunt-Väisälä frequency analysis offers a more comprehensive and integrated understanding of water-mass transformation processes and stratification dynamics along the Indonesian Throughflow pathway.

Keywords: Indonesian Throughflow, Flores Sea, water masses, Brunt-Väisälä frequency, stratification stability, CTD

Introduction

It is well known that the sea surface level in the western Pacific Ocean is higher than that in the eastern Indian Ocean, establishing a large-scale horizontal pressure gradient between the two ocean basins (Wyrtki, 1987). This pressure gradient drives the Indonesian Throughflow (ITF), which serves as the primary oceanic connection between the Pacific and Indian Oceans. Through this oceanic bridge, the ITF transports heat, freshwater, and water-mass properties while transmitting Pacific Ocean variability to the eastern Indian Ocean, thereby influencing upper-ocean thermal structure, thermocline variability, and regional climate (Ummerhofer et al., 2013). The ITF exhibits variability on seasonal to decadal timescales (Susanto et al., 2012; Sprintall

and Révelard, 2014; Gordon et al., 2019; Fritz et al., 2023; Lu et al., 2024). As a vital component of the global thermohaline circulation, the ITF regulates heat and freshwater budgets at low latitudes, modulates air-sea interactions across the tropical Indo-Pacific, and contributes to regional and global climate variability (Feng et al., 2018; Pujiana et al., 2019; Nagai et al., 2021; Santoso et al., 2022; Furue et al., 2023; Li et al., 2023).

The Flores Sea lies along the principal pathway of the ITF, receiving most of its inflow from the Makassar Strait, with an additional seasonal contribution from the Karimata Strait through the Java Sea (Gordon et al., 2012; Susanto et al., 2013; Sprintall et al., 2014; Gordon et al., 2019; Xu et al., 2021; Iskandar et al., 2023). Before entering the

Banda Sea and subsequently exiting to the Indian Ocean through the Ombai Strait and Timor Passage, these waters undergo substantial modification through vertical mixing and regional circulation (Sprintall *et al.*, 2009; Gordon *et al.*, 2010; Sprintall *et al.*, 2014; Gordon *et al.*, 2019; Guo *et al.*, 2023; Prastowo *et al.*, 2024). Seasonal atmospheric forcing further alters the thermohaline structure by modifying the depth and thickness of the thermocline, halocline, and pycnocline through variations in sea-surface heating (Rosdiana *et al.*, 2017; Silaban *et al.*, 2021). Consequently, the Flores Sea plays an important role in transforming Pacific-derived water masses into the Banda Sea and ultimately the Indian Ocean.

Previous studies have investigated the transport, vertical structures, and water-mass characteristics along the major ITF pathways, including the Makassar Strait (Gordon *et al.*, 2008; Susanto *et al.*, 2012; Gordon *et al.*, 2019), the Lifamatola Passage (Yuan *et al.*, 2018; Wang *et al.*, 2019; Tan *et al.*, 2020), the Lombok Strait (Hautala *et al.*, 2001; Potemra *et al.*, 2003; Atmadipoera *et al.*, 2009; Sprintall *et al.*, 2014; Guo *et al.*, 2023; Yuliardi *et al.*, 2021; Susanto *et al.*, 2024), the Makassar Strait and Flores Sea (Silaban *et al.*, 2021), and the Banda Sea (Kisnarti *et al.*, 2023). These studies consistently demonstrate that Pacific-derived water masses are modified by vertical mixing and regional circulation as they pass through the Indonesian seas, highlighting the importance of understanding water-mass transformation along the ITF pathway.

Although previous studies have improved our understanding of water-mass characteristics in the Flores Sea, they have primarily focused on identifying water masses from temperature-salinity (T-S) characteristics. Such analyses provide valuable information on the origin and distribution of water masses but do not quantify the vertical stability of the water column. Water-column stability is particularly important during the first transition season, when the reversal of the monsoonal winds modifies upper-ocean stratification, vertical mixing, and thermocline structure, potentially influencing the transformation of Pacific-derived water masses within the Flores Sea.

The Brunt-Väisälä frequency provides a quantitative measure of stratification stability and is widely used to evaluate the resistance of the water column to vertical displacement and mixing. When combined with conventional temperature-salinity (T-S) analysis, it enables a more comprehensive assessment of both water-mass characterization and stratification stability. Therefore, this study aims to characterize the water masses and evaluate the vertical stability of the water column in the Flores Sea

during the first transition season (April-May 2023) using CTD observations and Brunt-Väisälä frequency analysis. The results are expected to improve our understanding of oceanographic structure, water-mass transformation, and stratification processes along the ITF pathway before the waters enter the Banda Sea and ultimately the Indian Ocean.

Materials and Methods

The Flores Sea is a semi-enclosed basin located in the central Indonesian seas, bounded by Sulawesi to the north, Flores Island to the south, the Makassar Strait to the west, and the Banda Sea to the east. It constitutes one of the principal pathways of the ITF (Figure 1), transporting Pacific-derived waters towards the Banda Sea and subsequently the Indian Ocean (Gordon *et al.*, 2019). The regional circulation is primarily controlled by seasonal monsoonal forcing, complex bathymetry, and exchanges with adjacent basins, resulting in active water-mass transformation and vertical mixing (Liang, *et al.*, 2019; Ismail *et al.*, 2020; Xu *et al.*, 2021).

Oceanographic observations were conducted during the Jala Citra III-2023 “Flores Expedition aboard KRI Spica-934 in April-May 2023, corresponding to the First Transition Season between the Northwest Monsoon (December-March) and the Southwest Monsoon (June-September) in the Indonesian monsoon system. During this period, the weakening and reversal of monsoonal winds modify upper-ocean stratification and circulation, making it an appropriate time to investigate water-mass characteristics and vertical stability.

CTD observations

Oceanographic data were collected using four conductivity-temperature-depth (CTD) casts at for stations distributed across the Flores Sea (Figure 2). The stations were located from the northern part of the Flores Sea to its eastern sector near the Banda Sea and were selected to represent different oceanographic regions along the main ITF pathway (Figure 1) based on previously reported circulation patterns (Gordon *et al.*, 2019, Ismail *et al.*, 2020, Xu *et al.*, 2021).

Each CTD cast provided continuous vertical profiles of temperature, salinity, and density from the sea surface to a maximum depth of approximately 1,000 m. The geographic positions of all stations and the general ITF pathway are shown in Figure 2. Prior to analysis, all CTD profiles underwent standard quality control procedures. Obvious spikes and unrealistic measurements caused by sensor instability or ship motion were removed through visual inspections and despiking procedures. Mixing

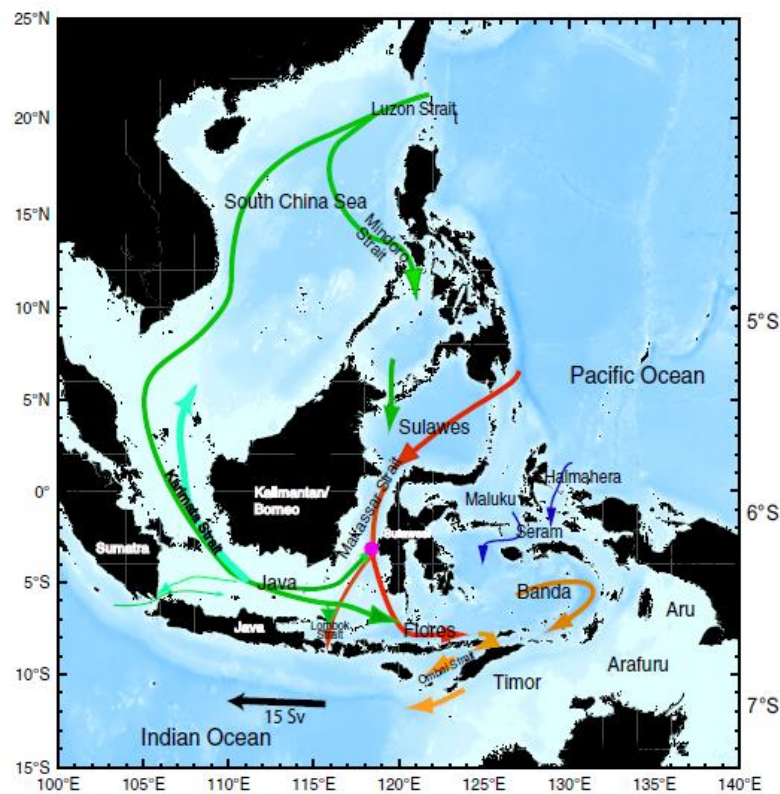


Figure 1. Map of the Indonesian Throughflow (IFT). Most of the IFT (red line) passes through the Makassar Strait. The IFT's path through eastern Indonesia/the Molucca Sea is shown in blue. The IFT's water masses mix in the Banda Sea before entering the Indian Ocean, with most exiting through the Timor Passage and Ombai Strait (orange). Currents from the South China Sea are shown in green (Source: Susanto and Song, 2015).

values and anomalous observations were excluded prior to subsequent analysis, and the cleaned profiles were interpolated to regular depth intervals to ensure consistency among stations. Descriptive statistics, including the minimum, maximum, and mean of temperature, salinity, and density, were calculated to summarise the observational dataset.

Water-mass analysis

Water masses were identified using temperature-salinity (T-S) diagrams, constructed from the processed CTD observations. The observed thermohaline characteristics were compared with published reference values for the principal Pacific water masses within the Indonesian seas, including the North Pacific Subtropical Water (MPSW), North Pacific Intermediate Water (NPIW), South Pacific Intermediate Water (SPIW), and Antarctic Intermediate Water (AAIW) (Natih *et al.*, 2020).

Based on the vertical distributions of temperature, salinity, and density, the water column was divided into three principal layers. Mixed layer: characterized by relatively homogeneous

temperature and salinity resulting from active surface mixing. Thermocline layer: identified as the depth interval exhibiting the strongest vertical temperature gradient, accompanied by pronounced changes in salinity and density. Deep layer: located beneath the thermocline where oceanographic properties vary only gradually with increasing depth. The thickness of each layer was determined directly from the observed vertical oceanographic profiles.

Water-column stability

Water-column stability was evaluated using the Brunt-Väisälä (buoyancy) frequency, which quantifies the resistance of a stratified water column to vertical displacement. The Brunt-Väisälä frequency was calculated from the vertical density gradient according to (Massel, 1999):

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

where N is the Brunt-Väisälä frequency (s^{-1}), g is the gravitational acceleration (9.81 m s^{-2}), ρ is the seawater density (kg m^{-3}), and z is depth (m). When

$N^2 > 0$, it represents a stratified environment, within which a fluid parcel oscillates vertically when it is displaced upward. This is only achieved when $\frac{d\rho}{dz} < 0$, corresponding to a situation where fluid parcels of higher densities are located below those of lower ones. In this case, when $\text{cap } N^2$ is less than 0, it indicates that the stratification is statistically unstable. This is true for $\frac{d\rho}{dz} > 0$, a sign of instability, corresponding to a top-heavy fluid configuration. These two possible values for N^2 suggest that the strength of the stratification increases with N . In other words, a larger value for N is found for a more stably stratified fluid. Positive values of the Brunt-Väisälä frequency indicate stable stratification, whereas lower values represent weaker stratification and greater susceptibility to vertical mixing.

Data processing and analysis

All oceanographic data were processed using MATLAB R2025b (MathWorks Inc, Natick, MA, USA) and Ocean Data View (ODV) version 5.7.1. MATLAB was used for quality control, interpolation, density calculation, and Brunt-Väisälä frequency was compared among the four CTD stations to evaluate the spatial variability of water-mass characteristics and water-column stability across the Flores Sea.

Results and Discussions

Oceanographic observations from the four CTD stations revealed distinct vertical variations in temperature, salinity, density, and Brunt-Väisälä frequency across the Flores Sea. These parameters exhibit characteristic stratification patterns that reflect the vertical structure and water-mass properties of the study area. The observed oceanographic characteristics at each station are presented in the following subsections, including temperature, salinity, density, and water-column stability, followed by comparisons with previous studies.

Temperature profile

It is apparent from Figure 3a that the vertical temperature profiles observed at all stations across the Flores Sea are similar, indicating a depth-dependent temperature variation. Table 1 summarizes temperature measurements of the mixed layer at each station during data collection.

Although the thickness of the mixed layer varies significantly from place to place (except Stations 2 and 4), temperature variations are apparently minor, measured between 29.25°C and 29.61°C. This finding suggests that a relatively constant temperature is characteristic of the mixed

layer, owing to vigorous turbulent mixing in the ocean's surface layer induced by wind stresses, particularly in tropical regions (Wyrki, 1961; Natih *et al.*, 2020). The results of temperature variation obtained from this study are significantly different from the values reported by Natih *et al.* (2020) for similar samples from the northern Lembata Island, where temperature varies from 25.67°C to 28.95°C during measurements in the second transition season between September and October. The apparent difference in the temperature range between the present study and the work of Natih *et al.* (2020) suggests differential heating on the surface, leading to a seasonal vertical distribution of temperature in the mixed layer. Meanwhile, the results of research conducted by Natih *et al.* (2020) in the surface layer at a depth of 3-80 m (77 m) in the transition season II of the northern waters of Lembata show that the temperature value ranges from 25.67 to 28.95 °C.

The thermocline layer in the Flores Sea during the first transition season (Figure 3a). At Station 1, the thermocline is located at a depth of 6-267 m (12-29.38°C), with a thickness of 261 m. Station 2 thermocline layer was found at a depth of 50-286 m (236 m) with a temperature value of 12.1-29.51 °C. The thermocline layer is at a depth of 30-289 m, found at Station 3, with a layer thickness of 259 m when the temperature value is 11.09-29.61 °C. The thermocline layer was observed at Station 4, ranging from 50 to 315 m (11.04-29.36°C) and having a thickness of 265 m. In contrast to the research results of Natih *et al.* (2020), the thermocline layer was found at a depth of 37-238 m, with a layer thickness of 201 m and a temperature value ranging from 25.67 °C to 28.95 °C. The upper layer of the thermocline in the Flores Sea is close to the mixed/homogeneous layer. The position of the thermocline layer typically begins at a depth of 10-500 m, whereas in tropical areas, it is often located near the mixed layer (Natih *et al.*, 2020).

The temperature in the deep layer decreases relatively steadily below the thermocline. The deep layer in the Flores Sea (Figure 3a) was found at Station 1 at a depth of >267 m when the temperature was 12.00-6.22 °C. Station 2 found the deep layer at 286-718 m (6.23-12.1 °C). The deep layer at Station 3 is at a depth of >289 m, with a temperature of 6.28-11.09 °C. Station 4 deep layer at Station 4 has a temperature value of 5.11-11.04 °C at a depth of >315 m. The deep layer extends to the seabed and has a relatively uniform temperature (Natih *et al.*, 2020).

Salinity

The layers in the vertical salinity profile show that low salinity values are found in the

mixed/homogeneous layer. Salinity in the surface layer (Figure 3b) at Station 1 was measured at a depth of 1.09-8 m, with a salinity value of 32.51-32.55 psu, and a layer thickness of 6.91 m. The mixed/homogeneous layer was found at a depth of 0.91-10 m with a layer thickness of 9.09 m (32.36-32.43 psu) at Station 2. Meanwhile, at Station 3, the mixed/homogeneous layer was located at a depth of 1.09-18 m (16.91 m) and had a salinity of 32.83-32.88 psu. Station 4 is at a depth of 0.92-30 m, with a thickness of 29.08 m for the mixed/homogeneous layer and a salinity of 33.07-33.17 psu. The salinity value is different from the research results of Natih *et al.* (2020), where at a depth of 3-80 m with a layer thickness of 77 m, the salinity value is 33.86-34.09 psu. The average salinity value is greater in the waters north of Lembata Island than in the Flores Sea.

Salinity (Figure 3b) for the halocline layer at Station 1 ranges from 8 to 130 m (32.55-34.51 psu) with a layer thickness of 128 m. The halocline layer at Station 2 is located at a depth of 10-150 m, with a layer thickness of 32.43-34.55 psu. The thickness of the halocline layer is approximately 140 m. Station 3 for the halocline layer is at a depth of 18-182 m with a layer thickness of 164 m (32.88-34.54 psu). The halocline layer is 180 m thick, while at Station 4 it occurs at depths of 30-210 m, with salinity values ranging from 33.17 to 34.55 psu. This result differs significantly from the findings of Natih *et al.* (2020), where the halocline layer is located at a depth of 37-238 m (201 m), and the salinity values range from 33.89 to 34.50 psu. The salinity value in the Flores Sea is smaller than in the waters north of Lembata Island.

Table 1. Temperature variations of the mixed layer, with corresponding thicknesses, measured at Stations 1-4.

Station	Thickness (m)	Temperature Variation (°C)
1	4.91	29.36–29.38
2	49.09	29.35–29.51
3	28.91	29.45–29.61
4	49.08	29.25–29.36

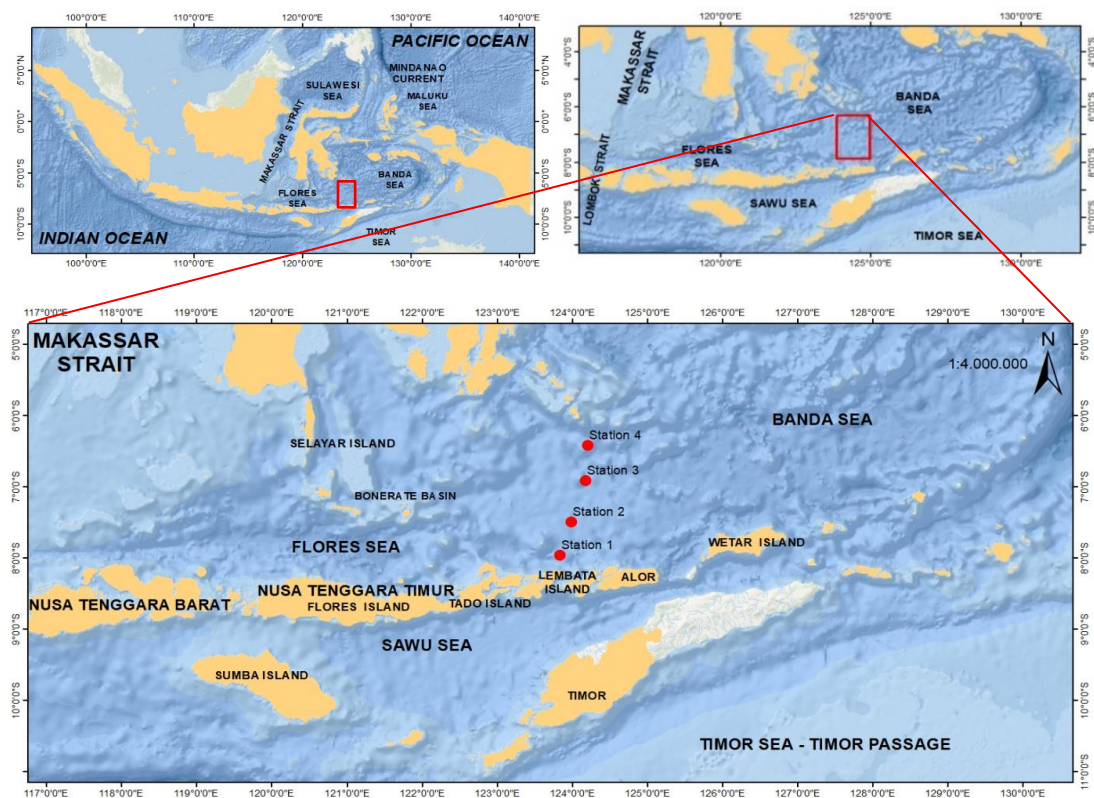


Figure 2. Study area showing the locations of the four CTD stations in the Flores Sea. The arrows indicate the general pathway of the Indonesian Throughflow (ITF) from Makassar Strait toward the Banda Sea based on previous observational and modelling studies.

The deep layer (Figure 3b) is in the Flores Sea during the first transition season. At Station 1, the deep layer is located at a depth of more than 130 m, with a salinity value of 34.51-34.53 psu. Station 2 for the deep layer is located at a depth greater than 150 m, with a salinity value of 34.49-34.55 psu. At a depth of >182 m is the deep layer with a salinity value of 34.54-34.55 psu at Station 3. The deep layer at Station 4, characterized by a salinity range of 34.55-34.58 psu, is located at depths of 210-884 m. In addition, the salinity in the Flores Sea increases with increasing depth. This differs from Webb (2020), who stated that at low latitudes, salinity decreases with increasing depth. This is also caused by the presence or absence of freshwater input from rivers leading to the estuary (Suhana, 2018).

Density

Vertical density profile in three layers: mixed layer, pycnocline layer, and inner layer (Figure 3c). The surface layer is located at a depth of 1.09-1.16 m at Station 1, with a thickness of 14.91 m and a density of 1,020-1,021 kg.m⁻³. At Station 2, the thickness of the mixed/homogeneous layer is 29.09 m at a depth of 0.91-30 m with a density value of 1,020-1,021 kg.m⁻³. Station 3 for this mixed/homogeneous layer is at a depth of 1.09-43 m with a layer thickness of 41.91 m and a density value of 1,020-1,022 kg.m⁻³. The mixed/homogeneous layer at Station 4 is at a depth of 0.92-69 m, with a density of 1,020-1,022 kg.m⁻³ and a thickness of 68.08 m.

The pycnocline layer in the Flores Sea at a depth of 16-279 m is at Station 1; the density is between 1,021 and 1,028 kg.m⁻³, and the layer thickness is 263 m. At Station 2, the pycnocline layer, with a thickness of 286.09 m, is located at a depth of 0.91-287 m, and the density value ranges from 1,020 to 1,027 kg.m⁻³. Station 3 for the pycnocline layer has a density value of 1,022-1,028 kg.m⁻³, a depth of 1.09-295 m, and a layer thickness of 293.91 m. The pycnocline layer, with a thickness of 299.08 m, is located at Station 4 at a depth of 0.92-300 m, and its density value ranges from 1,022 to 1,028 kg.m⁻³.

The density value for the deep layer in the Flores Sea during the first transition season is between 1,028 and 1,030 kg.m⁻³ at Station 1, at depths >279 m. Station 2 for the deep layer is located at a depth of greater than 287 m, with a density value of 1,027-1,030 kg.m⁻³. At Station 3, the deep layer is at a depth of >295 m with a density value of 1,028-1,030 kg.m⁻³. The deep layer at Station 4 has a density between 1,028 and 1,030 kg.m⁻³ at depths greater than 300 m.

Salinity and temperature stratification are indicated by density stratification, as evidenced by the high-density gradient in the pycnocline layer of the

Flores Sea (Figure 2c). Meanwhile, stratification is relatively lower near the surface and in deep waters, allowing water mass instability to occur, which can lead to turbulent mixing. The mixture of surface and pycnocline layer thicknesses in the density profile closely matches the temperature profile. This is because seawater density depends on temperature and salinity. Pond *et al.* (1983) explained that the relationship among density, salinity, and temperature is nonlinear; density is primarily influenced by temperature rather than salinity. The higher the temperature at constant salinity, the more water particles expand, increasing volume for the same mass and thereby decreasing density (Hermansyah *et al.*, 2021).

Based on observations of temperature, salinity, and density in the Flores Sea during the first transition season, layer thickness differed significantly at each station. Because Station 1 is near the coast, Stations 2 and 3 are in the open sea, and Station 4 is in the open sea leading to the coast. Additionally, it is predicted that the factor causing differences in thickness across stations is the time of data collection. With depth, the vertical and transverse distributions of salinity and density exhibit a linear pattern: the greater the depth, the higher the values. Temperature, salinity, and density are essential physical oceanographic parameters (Yuliardi *et al.*, 2022). In addition, the results of this study show that the thickness of the surface layer is thinner compared to the results of the study by Natih *et al.* (2020), while the thermocline, halocline, and pycnocline layers are thicker than the results of Natih *et al.* (2020) and Silaban *et al.* (2021).

Based on the thicknesses of the thermocline, halocline, and pycnocline layers, thicker layers indicate the influence of atmospheric forcing, particularly during wind-driven seasons. This is due to the presence of colder winds and ocean currents in the eastern waters of Indonesia in April and May, which result in relatively lower sea surface temperatures. Increasing thermocline thickness can prevent the upwelling and downwelling of seawater. Thus, plants that live in deep-sea waters (such as seaweed) find it difficult to rise to the surface to photosynthesize, which limits their ability to develop chlorophyll near the surface. Therefore, the fish population is predicted to decrease in April and May.

Characteristics of water masses

Based on the T-S diagram (Figure 4) for four stations in the Flores Sea, three water masses were identified as components of the ITF: North Pacific Subtropical Water (NPSW), South Pacific Intermediate Water (SPIW), and Antarctic Intermediate Water (AAIW). NPSW was found at a depth of 119.68-136.53 m, with a temperature of

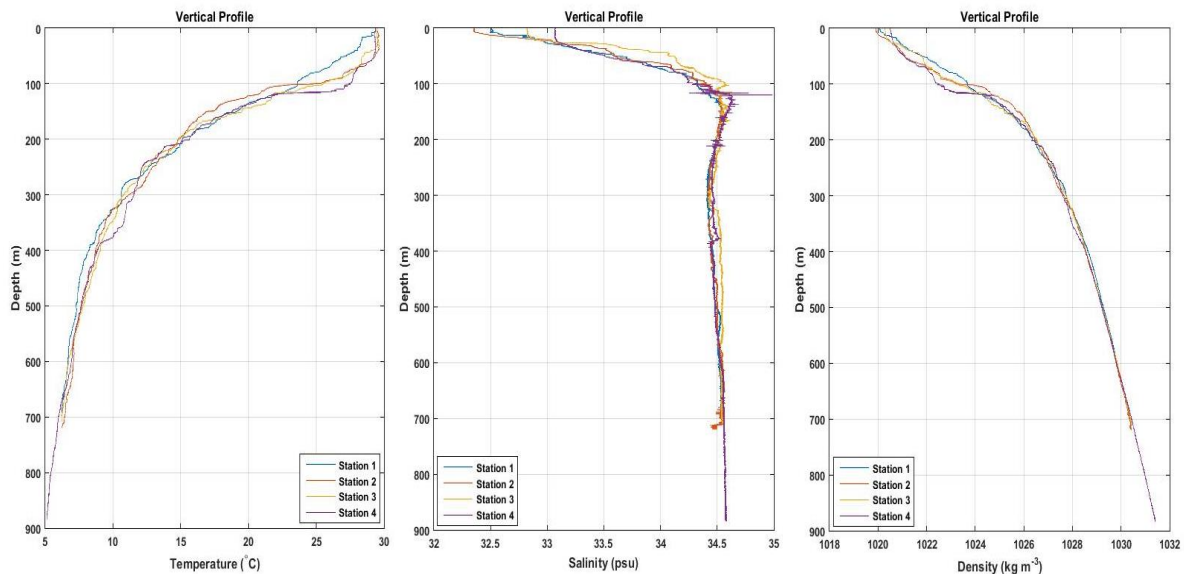


Figure 3. Thickness of the water mass layer vertically (a) temperature, (b) salinity, and (c) density.

20.05-22.16 °C and a salinity of 34.61-34.94 psu. NPSW occurs in the thermocline and halocline layers (layers with a very drastic gradient change with depth). SPIW is located at a depth of 607-766 m, with a temperature of 6-7.05 °C and a salinity of 34.55-34.56 psu in the deep layer. AAIW was found at a depth of 136-758 m, with a temperature of 5-6 °C and a salinity of 34.54-34.57 psu, in the deep layer.

Station 1 (Figure 4a), the water mass in the Flores Sea is located north of Lembata Island; no water mass was found flowing from the central Pacific Ocean (intermediate) or the subtropical part, which is influenced by the ITF. Station 2 (Figure 4b) found a dominant water mass flowing from the southern Pacific Ocean in the middle (intermediate) or South Pacific Intermediate Water (SPIW). Station 3 (Figure 4c) found a dominant water mass flowing from the central Antarctic (intermediate) or Antarctic Intermediate Water (AAIW). Station 4 (Figure 4d) found a dominant water mass flowing from the northern Pacific Ocean in the middle (intermediate) or North Pacific Subtropical Water (NPSW).

The results of the T-S diagram analysis (Figure 4) in the Flores Sea have different values from the results of research conducted by Ilahude *et al.* (1996), Gordon (2010), Natih *et al.* (2020), and Kisanarti *et al.* (2023) based on the influence of ITF. The discovery of the mass flow of water, which is a component of the ITF found by Ilahude *et al.* (1996), Gordon (2010), Natih *et al.* (2020), Kisanarti *et al.* (2023), indicates that there are four flows, which are divided into two: originating from the North Pacific and South Pacific. The water mass from the North Pacific consists of North Pacific Subtropical Water

(NPSW) and North Pacific Intermediate Water (NPIW). Additionally, the mass flow of water from the South Pacific comprises South Pacific Intermediate Water (SPIW) and Antarctic Intermediate Water (AAIW). The characteristics of the component water masses of ITF: (1) NPSW is found at an estimated depth of 100-150 m with an estimated temperature of 20-26 °C and salinity between 34.9-35.4 psu, (2) NPIW is found at a depth of 300-400 m with a temperature of 20-26 °C and salinity between 34.48-34.50 psu, (3) SPIW is found at a depth range of 500-800 m with a temperature of 6-8 °C and salinity of 34.55-34.65 psu, and (4) AAIW is found at a depth of >750 m with a temperature of 5-6 °C and salinity of 34.5-34.6 psu.

The water mass flowing from the north is identified only as NPSW, whereas from the south, two types of water mass flow are identified: SPIW and AAIW. NPSW is identified in the thermocline water mass layer, while those in the deep-sea layer are SPIW and AAIW. In addition, the results of the Ismail *et al.* (2020) trajectory model show that the water mass on the surface and thermocline that passes through the western ITF route comes from the northern Pacific Ocean, while the water mass in the deeper part is found to be mixed with water mass from the southern Pacific Ocean. This is related to the interaction between the very salty subtropical water mass (maximum) from the northern Pacific Ocean and the deep layer of the Flores Sea. The study's results also showed several salinity values at a temperature of 20 °C. This is due to the combination of different water masses, including NPSW with low salinity and intermediate-thermocline water with a salinity of 34.5 psu, obtained from SPIW (Figure 3).

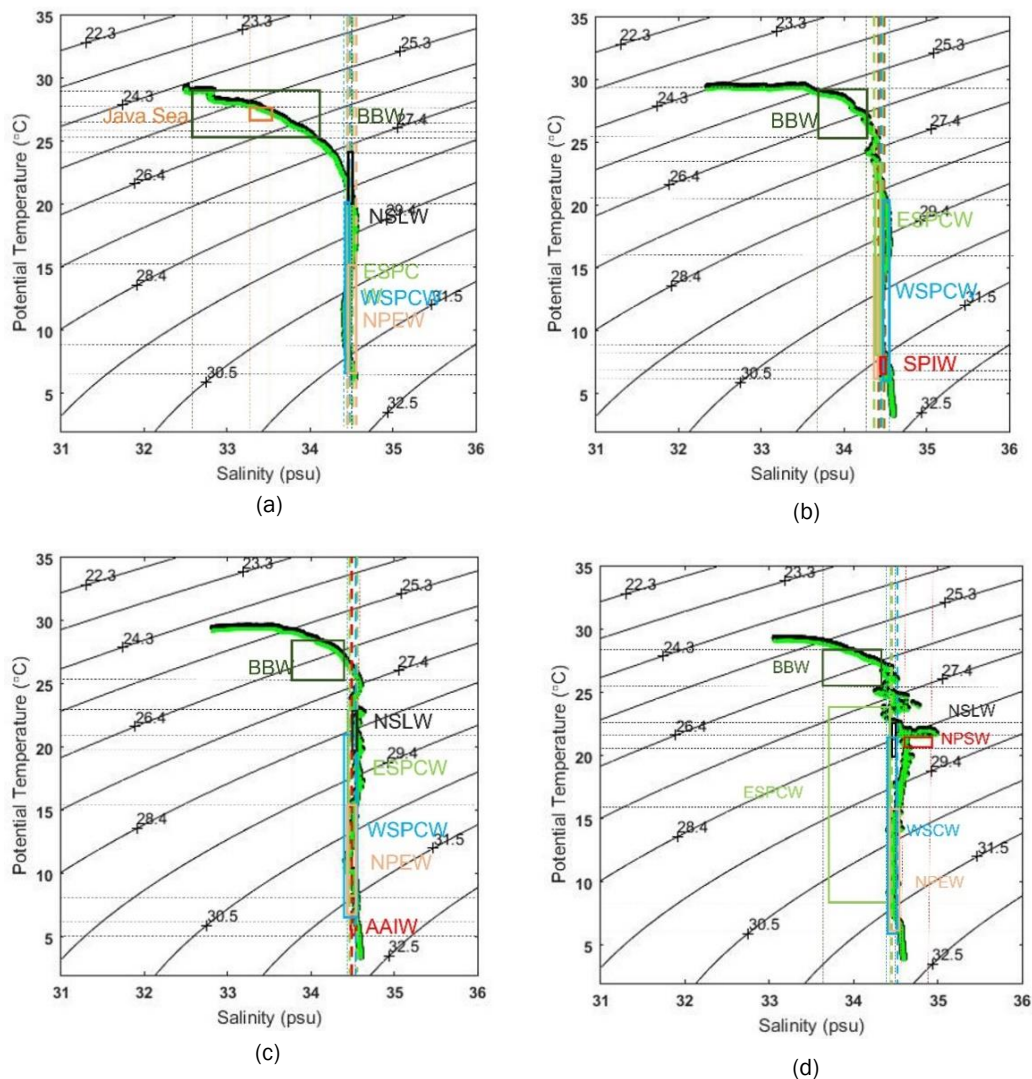


Figure 4. Distribution of water mass (a) Station 1, (b) Station 2, (c) Station 3, and (d) Station 4

In the Flores Sea, several water masses flow outside the ITF components, originating from the Bengal Bay Water (BBW) at the four Stations (Figure 4). The T-S diagram of Station 1 (Figure 4a) exhibits characteristics of temperatures between 25-29 °C and salinity of 32.7-34.1 psu, with a depth range of 14-80 m between the surface layer and the thermocline/halocline layer (Figure 3a and b). Station 2 (Figure 4b), BBW water mass has temperatures between 25-29 °C and salinity between 33.8-34.3 psu, with a depth of 59-99 m in the thermocline/halocline layer (a layer that changes drastically with depth), as seen in Figure 3a and b. Station 3 (Figure 4c), with temperature characteristics of 25-29 °C and salinity of 33.9-34.5 psu at a depth of 42-102 m, based on Figure 3a and b, indicates that the location of the discovery of this water mass is in the thermocline/halocline layer. In addition, at Station 4 (Figure 4d), the characteristics

of the BBW water mass with a temperature of 25-29 °C and a salinity of 33.7-33.4 psu at a depth of 59-114 m were observed in the layer (thermocline/halocline) seen in Figure 3a and b. The BBW classification is based on Agustinus et al. (2022), which describes the BBW water mass as having a temperature between 25 °C and 29 °C and a salinity between 28 and 35 psu. The BBW water mass is found from the surface to a depth of 70 m. Based on the analysis above, the characteristics of water masses are primarily found in the lower surface layer and in layers where there is a sharp gradient towards the depth of the thermocline/pycnocline.

The waters of the Flores Sea also contain the characteristics of the Eastern South Pacific Central Water (ESPCW) water mass. From the results of the T-S diagram analysis (Figure 4) for Station 1 (Figure 4a), the characteristics of the ESPCW water mass

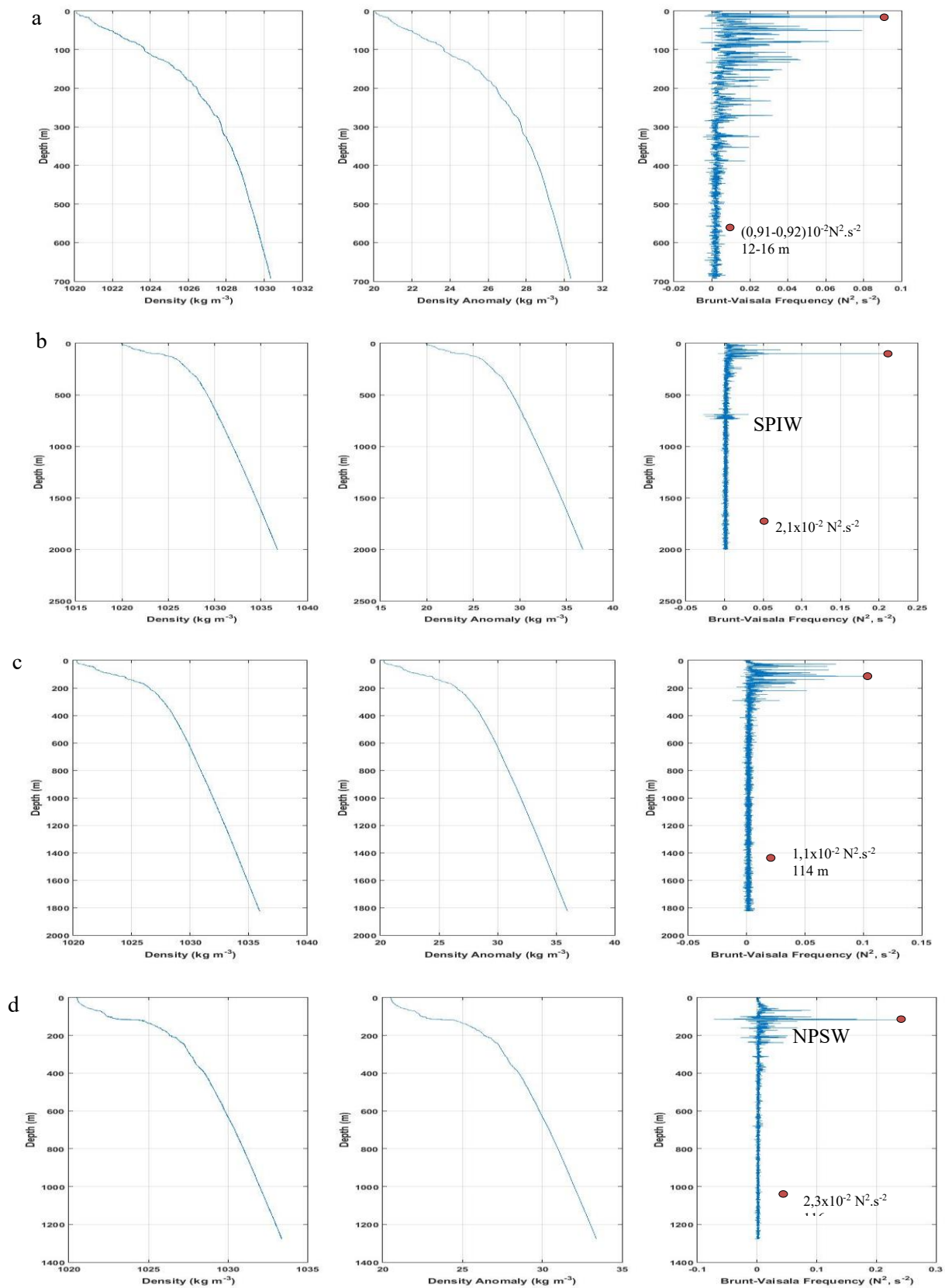


Figure 5. Water mass stability (a) Station 1, (b) Station 2, (c) Station 3, and (d) Station 4.

regarding the temperature between 8-22 °C and salinity of 34.4 psu are at a depth of 117-414 m, when in the thermocline/halocline layer to the inner layer (Figure 3a and b). Station 2 (Figure 4b) has the characteristics of the ESPCW water mass with a temperature of 8-23 °C and salinity between 34.4-34.5 psu at a depth of 101-463 m; this type of water mass is between the layers (thermocline/halocline) and the upper inner layer (Figure 3a and b). Station 3 (Figure 4c) is located between the thermocline/halocline layer and the upper inner layer (Figure 3a and b), with characteristics of temperature 8-23 °C and salinity 34.51-34.54 psu at a depth of 108-478 m. Station 4 (Figure 4d) found the characteristics of ESPCW water mass with a temperature between 8-23 °C and salinity between 34.4-34.5 psu at a depth of 116-466 m; this type of water mass is in the layer (thermocline/halocline) to the upper inner layer (Figure 3a and b). The classification of the characteristics of the ESPCW water mass above is based on the research results of Agustinus *et al.* (2022), which describe attributes of temperature ranging from 8.0 to 24.0 °C and salinity from 34.4 to 36.4 psu. The ESPCW water mass was found at depths of 80-165 m. The analysis of the characteristics of the dominant ESPCW water masses revealed the presence of these layers (thermocline/halocline) in the upper inner layers of the four stations.

The T-S diagram analysis revealed the characteristics of the Western South Pacific Central Water (WSPCW) water mass (Figure 4). The characteristics of the WSPCW water mass at Station 1 (Figure 4a) were found between temperatures of 6-20 °C and salinity of 34.51-34.53 psu at a depth of 130-693 m, which is between the thermocline/halocline layer and the deep layer (Figure 3a and b). Station 2 (Figure 4b), in the thermocline/halocline layer and between the deep layer, has found WSPCW between temperatures of 6-20 °C and salinities of 34.5-34.56 psu at depths of 121-776 m (Figure 3a and b). At Station 3 (Figure 4c), the type of WSPCW water mass was found between temperatures of 6-2 °C and between salinities of 34.54-34.57 psu, with a depth of 117-759 m, located between the (thermocline/halocline) layer and the deep layer (Figure 3a and b). In addition, at Station 4 (Figure 4d) the WSPCW water mass was found at a temperature of 6-22 °C and between salinities of 34.55-34.58 psu with a depth of 119-696 m; this type of water mass has been found between the thermocline/halocline layer and the deep layer (Figure 3a and b). The characteristics of the WSPCW water mass above are based on the classification results of Agustinus *et al.* (2022), with temperatures of 6-22 °C and salinities of 34.5-35.8 psu, and are found at depths of 135-500 m. The results of research conducted by Agustinus *et al.* (2022) show that the WSPCW water

mass is characterized by a temperature of 6-22 °C and a salinity of 34.5-35.8 psu. The WSPCW water mass is at a depth of between 135 and 500 m. Based on the analysis of the four stations above, the characteristics of the WSPCW water mass were found in the layer (thermocline/halocline) to the inner layer.

Characteristics of the Java Sea water mass were observed at Station 1 (Figure 4a): temperature 27.5-28 °C and salinity 33.2-33.4 psu, with a depth of 34-44 m, located in the surface and upper layers (thermocline/halocline) (Figure 3a and b). Atmadipoera *et al.* (2009) and Yuliardi *et al.* (2021) found that the surface layer to the thermocline layer shows salinity refreshment caused by excessive rainfall in the Java Sea, so that it moves eastward. The water mass in the Java Sea is considered a mixed water mass, characterized by both low and high salinity. This happens because the Flores Sea is the meeting point of the Java Sea and the ITF Route, whose flow comes from the Makassar Strait.

The North Pacific Equatorial Water (NPEW) water mass was found at Station 1 (Figure 4a) with characteristics between temperatures of 6.2-15.9 °C and between salinities of 34.51-34.53 psu at a depth of 188-693 m; this type of water mass is in the layer (thermocline/halocline) towards the inner layer (Figure 3a and b). At Station 2 (Figure 4b), the NPEW water mass was found with a temperature of 6.1-15.9 °C and a salinity of 34.51-34.53 psu at a depth of 169-735 m; the characteristics of this water mass are in the thermocline/halocline layer towards the inner layer (Figure 3a and b). The NPEW water mass was also found at Station 3 (Figure 4c) between temperatures of 6.1-15.9 °C and between salinities of 34.54-34.55 psu at a depth of 182-734 m; the characteristics of this water mass are in the layer (thermocline/halocline) towards the deep layer (Figure 3a and b). In addition, NPEW was also found at Station 4 (Figure 4d) with temperature characteristics between 6-16 °C and a salinity of 34.53-34.55 psu, with a depth of 187-696 m, found between the layer (thermocline/halocline) and the deep layer (Figure 3a and b). The analysis of the four Stations showed that the characteristics of the NPEW water mass were found between the thermocline/halocline and deep layers.

In addition, (Figure 4) there are characteristics of the North Subtropical Lower Water (NSLW) water mass. The results of the T-S diagram of the characteristics of the water mass are at Station 1 (Figure 4a), with temperature characteristics between 20.0-20.6 °C and salinity between 34.50-34.51 psu at a depth of 130-135 m, which is in the layer (thermocline/halocline) seen in Figure 2a and b. At Station 2, no NSLW water-mass characteristics were observed. At Station 3 (Figure 4c), NSLW water mass

was observed with temperatures between 20.4-23.9 °C and salinities between 34.50-34.57 psu at a depth of 109-139 m, within the thermocline/halocline layer (Figure 3a and b). The NSLW water mass was found at Station 4 (Figure 4d), with temperatures between 20.0-23.8 °C and salinities between 34.63-34.64 psu at a depth of 116-136 m. The water mass was found in the thermocline/halocline layer, as shown in Figures 3a and b. Research by Panjaitan *et al.* (2021) identified the characteristics of the North Subtropical Lower Water (NSLW) water mass at a depth of 94-140 m, with a temperature of 20-24 °C and salinity between 34.5 and 34.8 psu. Based on the analysis of the characteristics of the NSLW water mass at the four stations, it is in the thermocline/halocline layer. This NSLW water mass mainly enters Stations 3 and 4. The characteristics of this water mass begin to disappear at Stations 1 and 2.

Water mass stability

Of the four stations, high-frequency values were found on average at depths of 0-116 m (surface layer to upper pycnocline layer). The N results from all observation stations are shown in Figure 5 below. The results of all profiles show that the upper pycnocline layer tends to have a higher value: $(0.1-0.23) \cdot 10^{-4} \text{ N}^2 \text{ s}^{-2}$. The water column is in a very stable condition. Station 1 (Figure 5a) has a Brunt-Väisälä frequency value of $(0.91-0.92) \cdot 10^{-2} \text{ N}^2 \text{ s}^{-2}$, which is very stable at a depth of 12-16 m in the surface layer (Figure 3c) with an anomalous density value of $20.73 \text{ kg} \cdot \text{m}^{-3}$ and a density of $1,020 \text{ kg} \cdot \text{m}^{-3}$. The water column is also stable when the flow originates from the Makassar Strait, which is BBW (Figure 5a). The Brunt-Väisälä frequency value at Station 2 (Figure 5b), which is said to be stable, is a maximum of $2.1 \cdot 10^{-2} \text{ N}^2 \text{ s}^{-2}$ at a depth of 100 m, which is in the upper pycnocline layer (Figure 3c) and an anomalous density of $23.40 \text{ kg} \cdot \text{m}^{-3}$, and when the density is $1,023 \text{ kg} \cdot \text{m}^{-3}$. At Station 2, the stability of the water column comes from the Makassar Strait between the types of BBW and ESPCW water masses (Figure 5b).

Station 3 (Figure 5c) found a very stable water column in the upper pycnocline layer (Figure 3c) with a Brunt-Väisälä frequency value of $1.1 \cdot 10^{-2} \text{ N}^2 \text{ s}^{-2}$ at a depth of 114 m, when the anomalous density value was $24.03 \text{ kg} \cdot \text{m}^{-3}$, and the density was $1,024 \text{ kg} \cdot \text{m}^{-3}$. The stability of the water column is achieved when the mass flow of water comes from the Makassar Strait, with the water mass type ESPCW (Figure 5c). Then, for Station 4 (Figure 5d), a very stable water column was also found in the thermocline layer; it is known that the Brunt-Väisälä value is $2.3 \cdot 10^{-2} \text{ N}^2 \text{ s}^{-2}$ at a depth of 116 m when the anomalous density is $23.6 \text{ kg} \cdot \text{m}^{-3}$, and the density is $1,023 \text{ kg} \cdot \text{m}^{-3}$. At Station 4

(Figure 5d), the highest stability occurs when the water mass flow originates from the Makassar Strait with the water mass type being ESPCW and originates from the Sulawesi Sea with the water mass type NSLW (Figure 5d).

From the analysis of the stability level of the water column in the Flores Sea at four Stations, it was found to vary with depth but remained close together in the surface layer to the upper pycnocline layer. Based on the analysis of the Brunt-Väisälä (N) frequency value, an interesting thing was found from Stations 1 to 4: the N value was very high (stable) between the surface layer and the upper pycnocline layer at a depth of 0-116 m (Figure 5). The N values at Stations 3 and 4 are very high in the upper pycnocline layer. This condition indicates a threshold, and it is suspected that there is a high interval wave (Risiko *et al.*, 2017). The stable layer functions as a boundary (barrier) layer. This barrier layer becomes the boundary if water masses are mixed in the water column. Based on Figure 5, the stability of the Flores Sea water mass is in the mixed layer and the upper pycnocline between depths of 12-116 m. In particular, Station 4 (the northern part of the Flores Sea) shows greater stability than Station 1 in the northern part of Lembata Island. In addition, Station 4 Brunt-Väisälä Frequency has a very high N value (stable) at a depth of 116 m (upper thermocline/pycnocline layer). Brunt-Väisälä frequency not only shows the values of instability and stability. However, it can also indicate which water areas are close to neutral in water-column conditions (Figure 5).

The thermocline layer has a pycnocline, which is the main driver of the high-density gradient (Hermansyah *et al.*, 2021). The static stability condition in a layer is more favourable if the N value is higher. Conversely, the water column becomes unstable, or static instability occurs, if the N value becomes increasingly negative. In this case, the thermocline layer is the most stable compared with the surface and inner layers (Hermansyah *et al.*, 2021). Based on the analysis of the Brunt-Väisälä (N) frequency values, an interesting pattern was observed at Stations 1 to 4: the N value was very high (stable) between the surface layer and the upper pycnocline layer (Figure 5). The vertical profiles of temperature, salinity, and density strongly influence this water column's stability. In contrast, in the thermocline/pycnocline layer of Stations 1-4, the vertical profile of the water column looks irregular and zigzag (Figure 3a and c). This condition is thought to result from stirring in the thermocline/pycnocline layer, driven by strong internal wave activity (Hermansyah *et al.*, 2021). The thermocline layer can act as a barrier to vertical mixing between the mixed layer and the inner layer. In this barrier layer, BBW

water is massed from Station 4 to Station 1 (Figure 5). At Station 4, it appears very stable compared to other stations, and a small flow of NPSW water mass enters at a stable depth (Figure 5d).

It is predicted that NPSW can increase the stability conditions at Station 4. The conditions at Station 2 differ from those at other stations. Station 2, when in the inner layer, which was initially neutral, suddenly attains a stable condition, even though the Brunt-Väisälä frequency is not as significant as in the upper thermocline/pycnocline layer. This factor is predicted by the presence of water mass from SPIW entering from below. Station 3 Brunt-Väisälä frequency is quite large compared to Station 1; in these waters, the AAIW water mass entering from below is identified. Based on the water conditions at Stations 2 and 4, the presence of ITF water mass seepage: NPSW and SPIW, can increase water stability (Figure 5b and d). The Pacific Ocean is the largest ocean basin, with east-west variations in upper water masses, including central, eastern, and western waters in the northern and southern hemispheres. Pacific, there is a reasonably wide band in the Pacific Equatorial waters that is closely related to equatorial upwelling, which is unlikely to occur in El Nino years (Emery, 2001). Based on this, there is a slight possibility of mixing water and turbulence, especially in the Flores Sea during the first transition season.

Conclusions

The Flores Sea exhibits a well-defined vertically stratified water column during the first transition season (April-May 2023), confirming its important role as a transformation region along the Indonesian Throughflow (ITF). Temperature-salinity analysis identified three major Pacific-derived water masses: the North Pacific Subtropical Water (NPSW), South Pacific Intermediate Water (SPIW), and Antarctic Intermediate Water (AAIW), demonstrating that the Flores Sea modifies these water masses before they are transported into the Banda Sea. The Brunt-Väisälä frequency analysis revealed that the water column was consistently and stably stratified throughout the study area. Maximum stability occurred within the thermocline, reaching $2.3 \times 10^{-2} \text{ N}^2 \text{ s}^2$ at approximately 116 m, indicating that the strongest vertical density gradient controls the stability of the water column during the first transition season. Although oceanographic properties varied among the observation stations, the overall vertical structure remained remarkably consistent, suggesting that seasonal stratification dominates over local spatial variability. Integrating temperature-salinity analysis with Brunt-Väisälä frequency provides a more comprehensive understanding of both water-mass characteristics and stratification

stability than oceanographic analysis alone. These findings highlight the importance of considering water-column stability when investigating water-mass transformation and vertical mixing along the ITF. Consequently, this study contributes new observational evidence to our understanding of the oceanographic processes that regulate the transport and modification of Pacific-derived water before it enters the Banda Sea and ultimately the Indian Ocean.

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