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Characteristics and Analysis of Water Mass Structure in the Waters of the Haruku Strait, Indonesia

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ABSTRACT

The Haruku Strait, on the Maluku Islands, Indonesia, lies between Haruku, Pombo, and Ambon Islands, forming a dynamic marine passage. This study analyzed the physical characteristics and stratification of water masses during the Southeast Monsoon (August–September 202 2) to understand their role in nutrient distribution, heat dispersion, and circulation. Due to its geographic and oceanographic conditions, the strait is an ideal site to examine monsoon-driven mixing processes. Data were collected at 16 stations across multiple depths using a CTD Rinko ASTD 101, measuring temperature, salinity, and density. Results showed significant vertical and horizontal variations. In August, peak upwelling in the Banda Sea and strong Southeast Monsoon winds led to notable changes in water characteristics. By September, both upwelling and wind intensity weakened, reducing stratification differences. Water mass analysis identified North Pacific Subtropical Water (NPSW) in the thermocline layer at all depths. Stratification analysis using Brunt-Väisälä frequency (N^2) calculations indicated higher stability in the thermocline layer, with N^2 values greater than those in surface layers across the northern, central, and southern regions. These findings highlight the seasonal monsoon's influence on water mass stratification, emphasizing its role in sustaining marine ecosystems under varying monsoon intensities.

INTRODUCTION

The Maluku Islands waters, Indonesia, are characterized by diverse island configurations and seabed topography, influencing water mass exchange dynamics and circulation patterns. The Haruku Strait, located within the Maluku Islands between Haruku Island, Pombo Island, and Ambon Island, is a highly dynamic strait. Geographically, its northern boundary is influenced by water masses from the Seram Strait, while its southern boundary is directly affected by water masses from the Banda Sea **(Tubalawony *et al.*, 2023)**. This region is strategically significant for shipping, capturing fisheries, transportation, and conservation **(Latuconsina, 2010; Sangadji, 2014; Sangadji & Sofyan, 2019; Lestaluhu, 2022; Sangadji, 2022)**. Such activities and uses, both directly and indirectly, can impact the area's physical and chemical oceanographic parameters.

The characteristics of Haruku Strait waters are influenced not only by local winds and tidal currents but also by monsoon winds. The Southeast Monsoon winds, in particular, cause surface water to move offshore, creating a water mass deficit that initiates upwelling in the Banda Sea. Upwelling is a process where colder, high-salinity, nutrient-rich waters from deeper layers rise to the surface, representing an important oceanographic dynamic connecting deep and shallow waters. Additionally, variations in seabed topography influence water mass dynamics, contributing to mixing processes **(Purwandana, 2013)**.

In addition to the upwelling dynamics in the Banda Sea, the Haruku Strait is affected by coastal input from rivers discharging into the strait. Several rivers, such as those at Waai, Tulehu, Haruku, and Rohomoni, influence the characteristics of water masses near coastal regions **(Tubalawony *et al.*, 2024)**. Riverine input can affect coastal water mass properties, impacting mixing, nutrient distribution, and heat dispersal, with potential climate implications. **Tomczak and Godfrey (1994)** noted that analyzing circulation patterns and water mass mixing provides insights into understanding deep-sea circulation.

Given the complex dynamics of Haruku Strait waters, this study aimed to investigate the structure and stratification of water masses in the Haruku Strait during the Southeast Monsoon (August–September 2022). This research focused on the mixing processes impacting nutrient distribution, heat dispersal, circulation, and currents, which, in turn, influence the adaptation of marine organisms in the Haruku Strait.

MATERIALS AND METHODS

This study was conducted in August and September 2022, encompassing 16 sampling stations distributed across the waters of Haruku Strait, Indonesia (Fig. 1) **(Pello *et al.*, 2024; Tubalawony *et al.*, 2024)**. The selection of stations considered several aspects, including water movement patterns (water mass circulation), land input (runoff), coastal ecosystems, and the topography of Haruku Strait. Detailed sampling station information is presented in Table (1). *In-situ* measurements of temperature and salinity of water masses in Haruku Strait were conducted using the conductivity, temperature, and depth (CTD) instrument, Rinko ASTD 101, manufactured by JFE Advantech Co., Ltd., Japan. Data on temperature and salinity recorded by the CTD at each transect were tabulated and analyzed. Vertical distributions of temperature, salinity, and density, along with the temperature-salinity (T-S) diagram, were visualized using Ocean Data View (ODV) version 5.7.0 – 2024, while horizontal distribution patterns were visualized using Surfer version 12.

Water mass layers were divided into the mixed surface layer and thermocline layer, analyzed based on the water mass temperature and density gradient, known as the threshold gradient method. The mixed surface layer was characterized by a temperature gradient (ΔT) <0.1°C, while the thermocline layer had a temperature gradient of ≥0.1°C and a density gradient of ≥0.02kg·m⁻³ **(Thomson & Fine, 2003; Cisewski *et al*., 2005)**.

Physical properties of the water mass were analyzed using the potential temperature-salinity (T-S) diagram, created with ODV software. The T-S diagram illustrates the relationship between temperature and salinity observed at various depths in the water column. It aids in identifying the character and origin of a water mass based on specific temperature and salinity values and is instrumental in revealing water mass structures resulting from water mixing **(Emery, 2001; Thomson & Emery, 2014)**.

The stability of water masses in Haruku Strait was further analyzed using the Brunt–Väisälä frequency (N^2), also known as buoyancy frequency. When a higher-density fluid is positioned above a lower-density fluid, vertical movement occurs until a stable equilibrium is reached. The Brunt–Väisälä frequency was calculated using the equation proposed by **Stewart (2002)** as follows:

$$N^2 = -\frac{g}{\rho_0}\frac{dp}{dz}$$

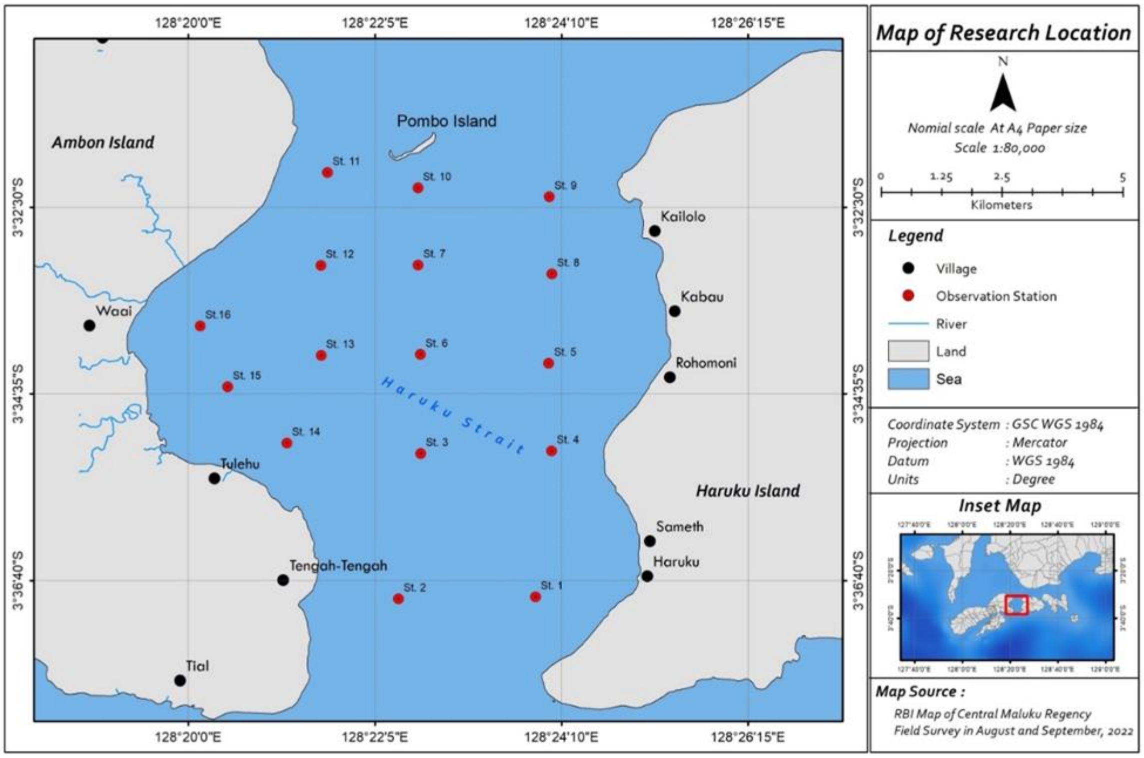


Fig. 1. Map of sampling locations in the waters of the Haruku Strait, Indonesia (Modified from **Pello *et al*. (2024)** and **Tubalawony *et al.* (2024)**

Table 1. Sampling station position

Station	Longitude (°E)	Latitude (°S)
St. 1	128.39796	-3.61419
St. 2	128.37246	-3.61454
St. 3	128.37659	-3.58750
St. 4	128.40093	-3.58701
St. 5	128.40043	-3.57070
St. 6	128.37652	-3.56909
St. 7	128.37610	-3.55243
St. 8	128.40102	-3.55406
St. 9	128.40053	-3.53970
St. 10	128.37609	-3.53808
St. 11	128.35925	-3.53523
St. 12	128.35801	-3.55251
St. 13	128.35807	-3.56924
St. 14	128.35170	-3.58556
St. 15	128.34125	-3.57018
St. 16	128.33071	-3.56267

In addition to field measurement data, the average monthly rainfall data for 2022 were also used as secondary data. The rainfall data were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) at the Pattimura Station in Ambon. The average rainfall data are presented in Fig. (2).

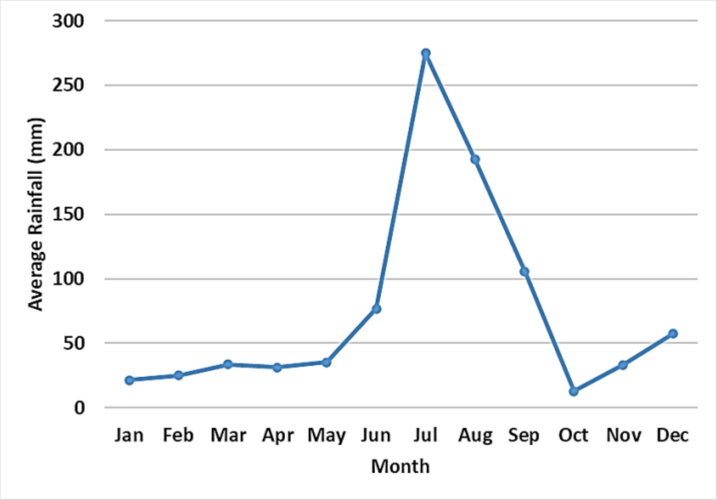


Fig. 2. Graph of average rainfall during 2022 from BMKG Pattimura Ambon station

RESULTS AND DISCUSSION

1. Vertical distribution of water mass in the Haruku Strait

The stratification patterns of water masses in Haruku Strait can be observed through the vertical profiles of temperature, salinity, and density based on measurements taken in August and September 2022 (Figs. 3, 4, and 5). The vertical distributions of temperature, salinity, and density vary across all measurement stations. The vertical temperature profile shows maximum values at the surface layer, with fluctuations within the thermocline layer (Fig. 3). In August, surface layer temperatures down to a depth of 100m ranged from 24.5 to 27.5°C, while in September, temperatures ranged from 25.5 to 28.5°C.

The temperature measurements in August in the mixed surface layer (surface to the upper boundary of the thermocline) ranged from 27 to 27.5°C, while the thermocline layer (± 50m to maximum measurement depth) ranged from 24.5 to 27.4°C. In contrast, the September measurements for the mixed surface layer (surface to the upper boundary of the thermocline) ranged from 27.5 to 28.5°C, with thermocline layer temperatures (± 60m to maximum measurement depth) ranged from 25.5 to 27.4°C.

The depth of the mixed layer in August was shallower than in September. The mixed layer was also found to be thicker in the northern part of the strait (Stations 8, 9, 10, and 11) compared to the southern part (Stations 1 and 2) in August, whereas, in September, the mixed layer was thicker in the southern part of the strait compared to the northern part.

Vertical temperature variation within the mixed surface and thermocline layers in Haruku Strait in August and September reflects the influence of strong Southeast Monsoon winds, shallow waters, rainfall intensity, and the upwelling phenomenon in the Banda Sea. Water temperatures in Haruku Strait were cooler in August than in September due to the peak of the Southeast Monsoon winds, which intensifies mixing alongside peak upwelling activity in the Banda Sea. **Qu *et al*. (2005)** stated that the seasonal reversal of Monsoon winds drives upwelling in several Indonesian waters, including the southern coast of Java, the Flores Sea, and the eastern Banda Sea. The semi-annual monsoon wind reversals impact the physical characteristics of seawater, stratification, and circulation in the upper thermocline layer of the Banda Sea **(Gordon & Susanto, 2001; Moore *et al*., 2003)**. **Sprintall and Liu (2005)** noted that the strong wind stress during the Southeast Monsoon (June-September) significantly cools Banda Sea surface temperatures.

Gordon and Susanto (2001) and **Tubalawony *et al*. (2016)** also indicated that upwelling generally occurs in the waters of the Maluku Islands due to the Southeast Monsoon winds. These winds drive water transport along the southern side of the islands, causing water to move away from the coast and triggering Ekman pumping. This mechanism brings cooler, deeper water to the surface. Due to the connectivity between Haruku Strait and the Banda Sea, physical changes in sea temperature, stratification, and circulation in the upper thermocline layer of the Banda Sea also influence conditions in Haruku Strait and surrounding waters.

Another factor that contributes to surface cooling in the mixed layer in August is high rainfall (precipitation). Warmer temperatures in the surface and thermocline layers observed in September are likely due to increased solar intensity, the weakening of Banda Sea upwelling, and the diminishing Southeast Monsoon winds. Research by **Titaley *et al.* (2024)**, based on 10-year average SST data in the waters of Seram and Buru Islands, found that SST remains stable during the second transition season (September-November), rises during the west monsoon (December-February) and first transition season (March-May), and decreases during the east monsoon (June-August). **Titaley *et al.* (2024)** found, based on 10-year average monthly SST data in the waters of Seram and Buru Islands, that SST remains stable during the second transition season (September-November). SST increases during the west monsoon (December-February) and the first transition season (March-May) and decreases during the east monsoon (June-August). Low SST during the east monsoon is associated with the peak of southeast monsoon wind speeds and the upwelling phenomenon.

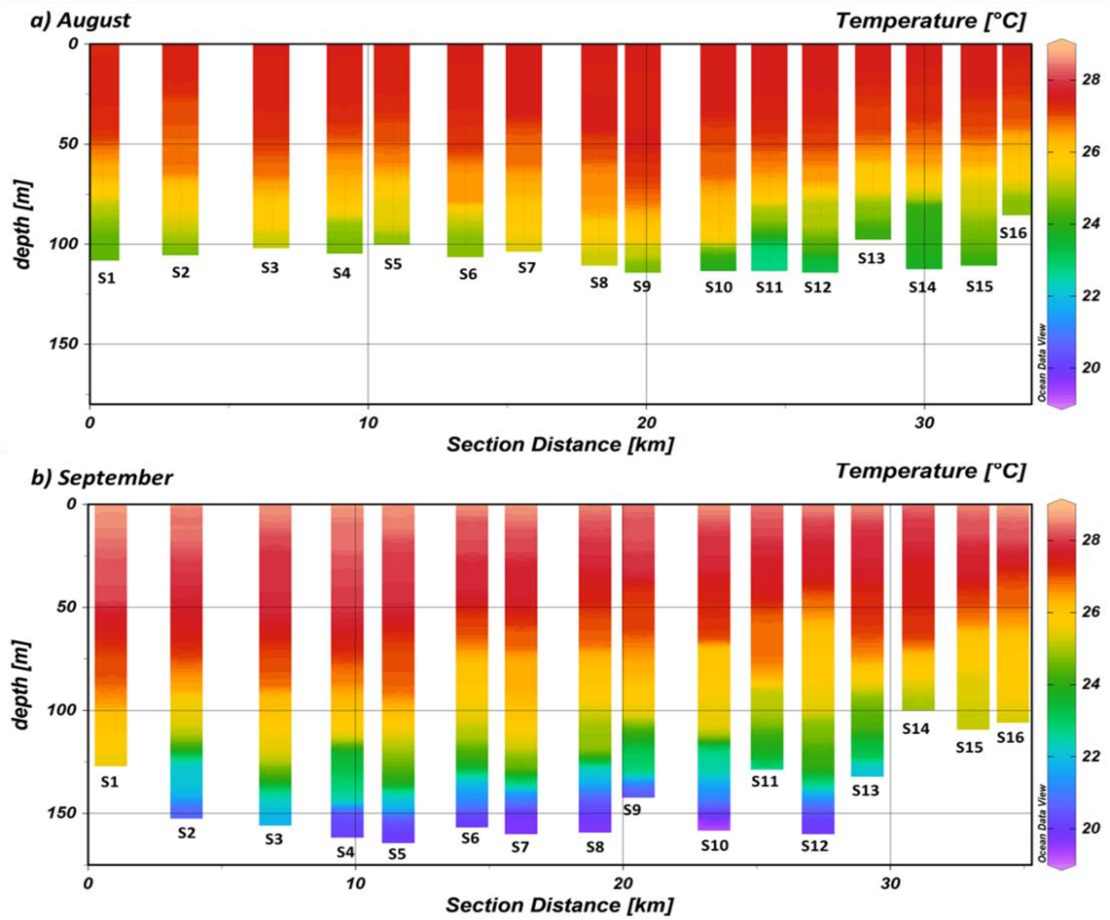


Fig. 3. Vertical distribution of temperature in the Haruku Strait, **a)** August 2022; **b)** September 2022

The vertical distribution of salinity across all measurement stations in Haruku Strait shows an increase with depth (Fig. 4). In August, salinity within the surface layer down to a depth of 100m ranged from 34.08 to 34.73psu, while in September, it ranged from 34.10 to 34.83psu. Lower surface salinity was observed near river mouths in Waai and Tulehu (Stations 12, 15, and 16) as well as around Pombo Island (Stations 9, 10, and 11) in August, and similar low surface salinity was also found near the river mouths in Waai and Tulehu in September.

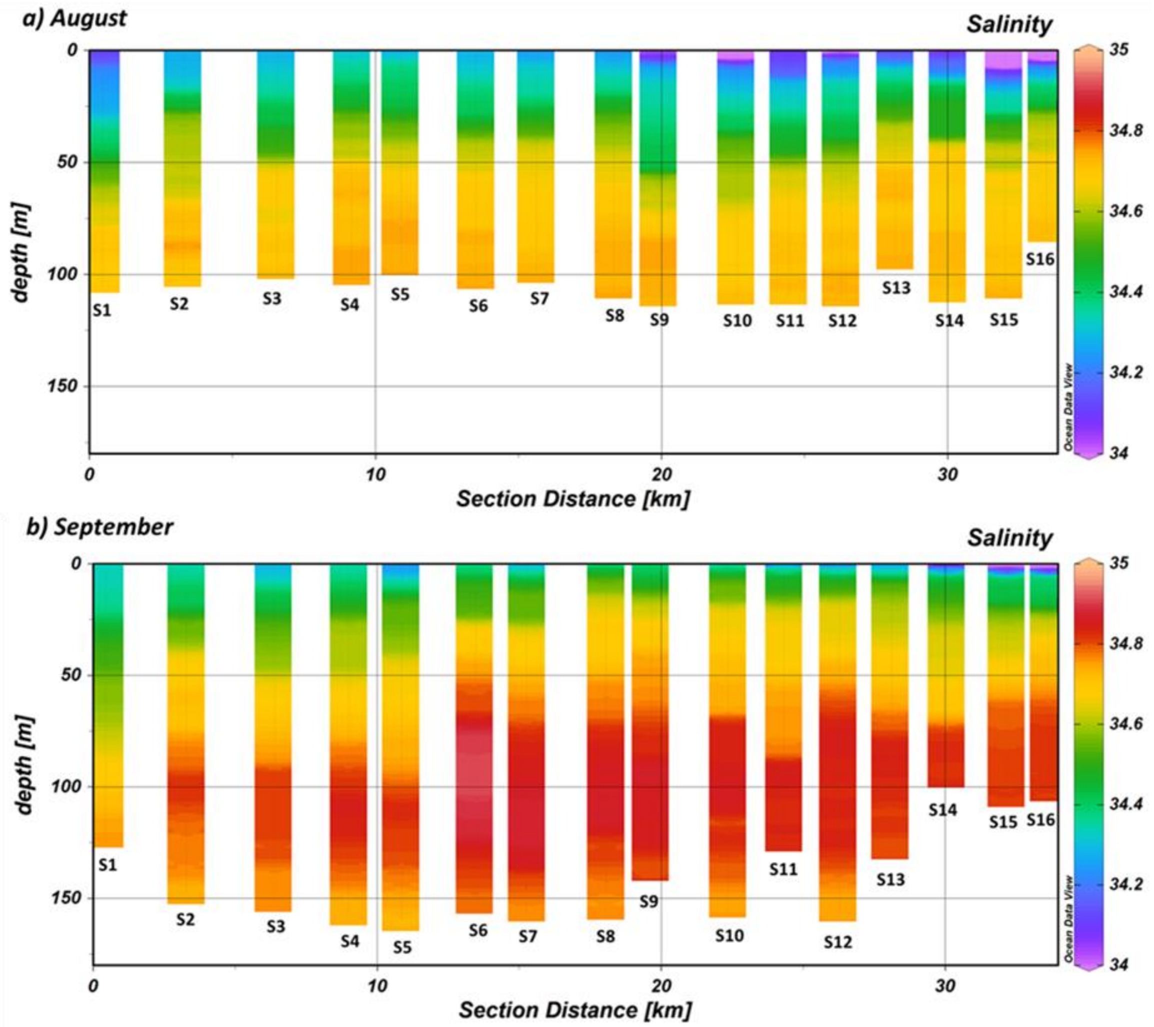


Fig. 4. Vertical distribution of salinity in the Haruku Strait, **a)** August 2022; **b)** September 2022

High rainfall in August and freshwater input from rivers discharging into Haruku Strait contribute to reduced salinity values **(Rugebregt *et al*., 2019)**. In the halocline layer, salinity increases due to the upwelling of deeper, high-salinity water. However, salinity within the halocline in August was lower than in September, influenced by high rainfall and the strong mixing of water masses driven by Southeast Monsoon winds

(Tubalawony *et al.*, 2023). Similar to the vertical temperature distribution, the salinity distribution pattern in Haruku Strait is also influenced by water masses from the Banda Sea. The maximum surface salinity range observed in Haruku Strait in August aligns with findings by **Wouthuyzen *et al.* (2020)**, who reported an average surface salinity (Sea Surface Salinity - SSS) in the Banda Sea during the East Monsoon (June, July, August) of 33.929psu (±0.245), with a maximum of 34.230psu.

The vertical density distribution in Haruku Strait (Fig. 5) varies by depth from the surface to the pycnocline layer. Lower density values are observed in the mixed layer, with an increase in the pycnocline. In August, density from the surface down to 100m depth ranged from 21.87 to 23.22kg/ m³, while in September, it ranged from 21.51 to 23.04kg/ m³.

Density distribution in Haruku Strait is influenced by temperature and salinity conditions. The upwelling phenomenon in the Banda Sea affects the horizontal density gradient near the surface, driving a strong geostrophic current along the coast.

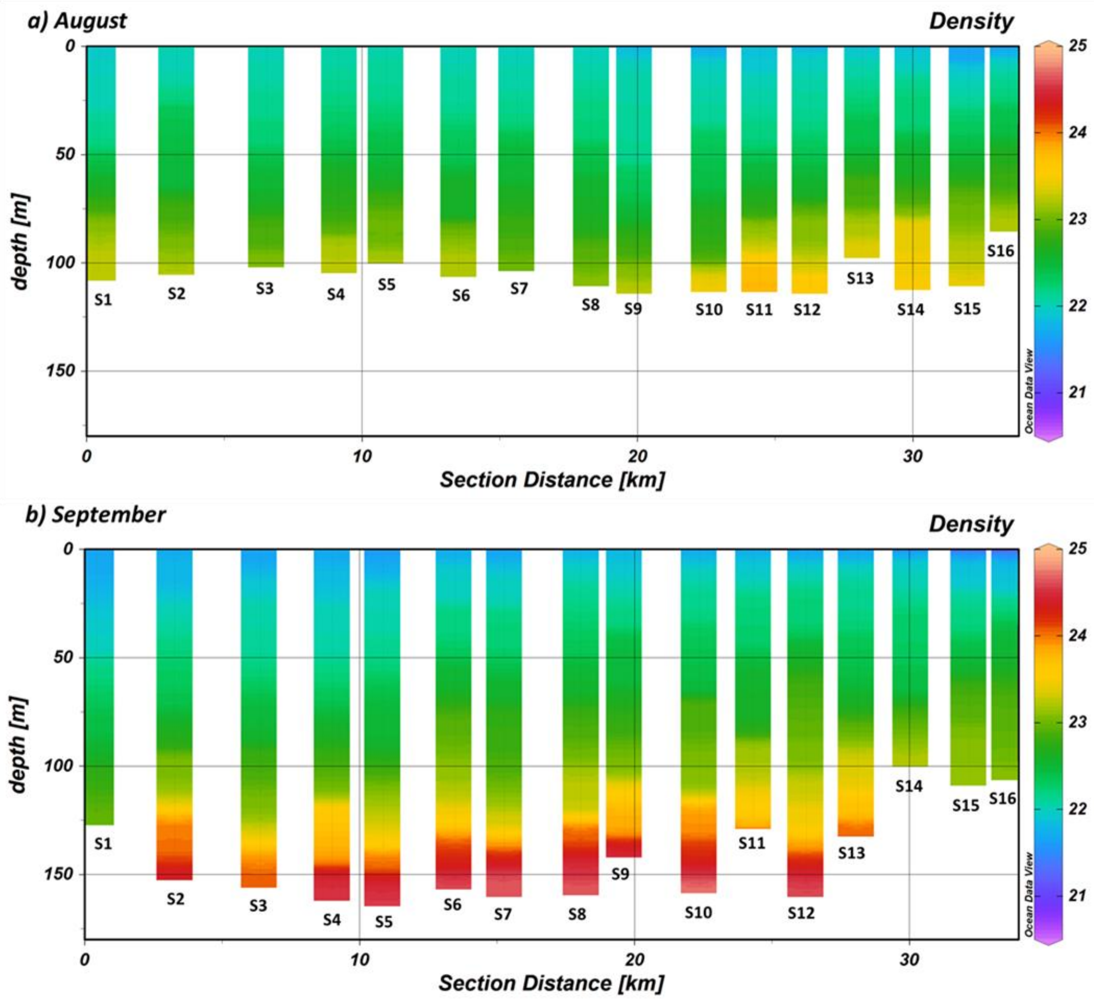


Fig. 5. Vertical distribution of density in the Haruku Strait, **a)** August 2022; **b)** September 2022

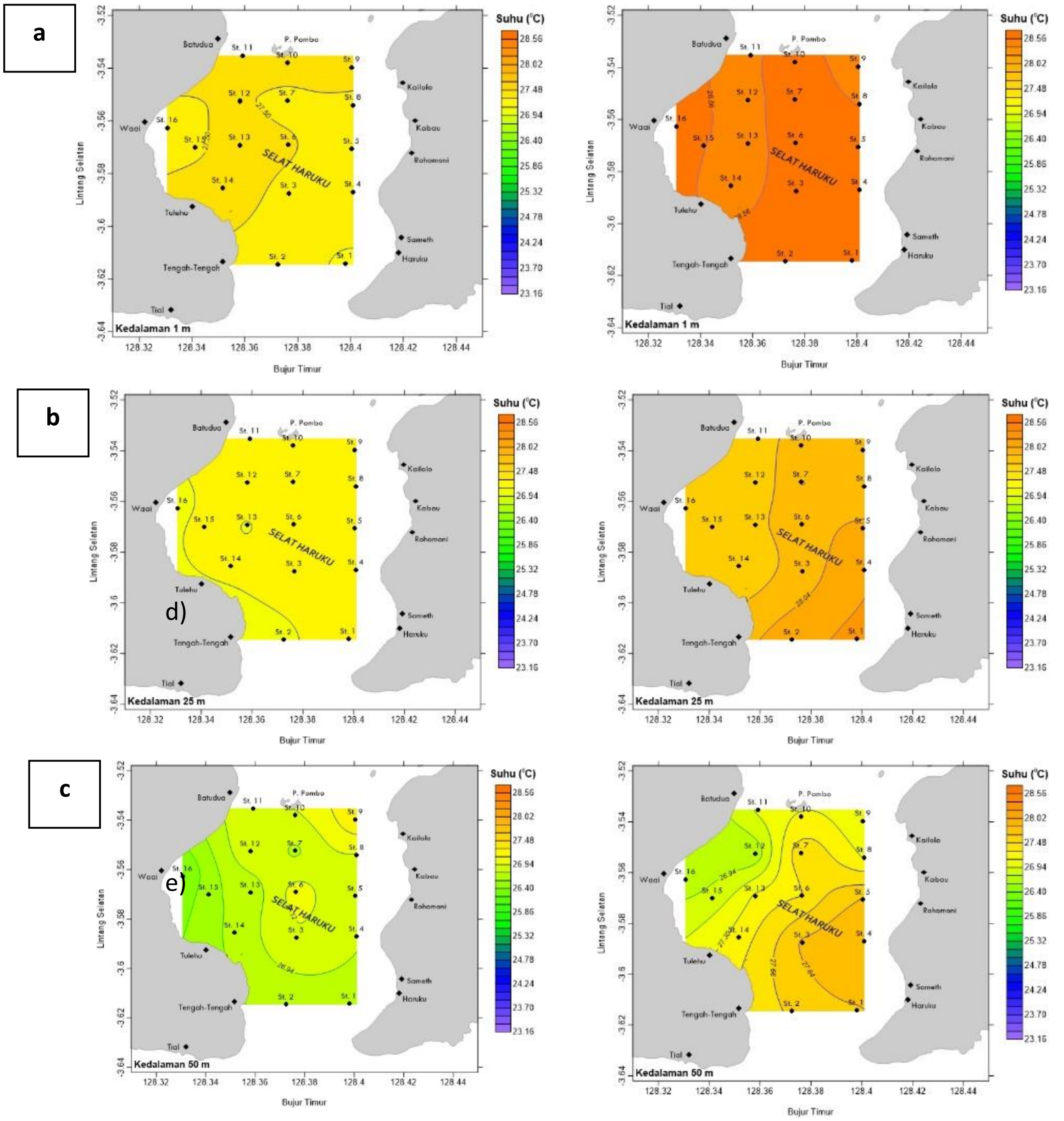
Previous research on the physical characteristics of water mass in Haruku Strait was reported by **Tubalawony *et al.* (2023)**, which described temperature and salinity profiles in May. In that study, temperatures ranged from 28.71 to 29.6°C in the surface layer down to 25m, and from 24.68 to 28.11°C at depths of 50 to 100m. Salinity values ranged from 33.12 to 33.60psu from the surface to 25m, and from 33.83 to 34.38psu at depths of 50 to 100m. The differences in temperature and salinity characteristics reported by **Tubalawony *et al.* (2023)** and those observed in this study indicate that the water mass characteristics in Haruku Strait vary seasonally.

2. Horizontal distribution of water mass in the Haruku Strait

Based on the horizontal distribution of temperature, salinity, and water mass density at depths of 1, 25, 50, 75, and 100m (Figs. 6, 7, and 8), it was found that Haruku Strait exhibits a unique pattern of water mass distribution from the surface layer to the thermocline depth during August and September 2022. This distribution pattern indicates spatial-temporal differences in water mass characteristics. The spatial-temporal characteristics of water temperature in Haruku Strait reveal that the average temperature is cooler in August at each depth (1, 25, 50, 75, and 100m) compared to September (Fig. 5). Spatial temperature distribution also shows distinct water mass conditions in the northern and southern parts of Haruku Strait during August and September at each depth (1, 25, 50, 75, and 100m). In August, water mass temperature in the northern part of Haruku Strait is warmer than in the southern part, with cooler temperatures in the south influenced by upwelling dynamics in the Banda Sea. Conversely, in September, water mass temperatures in the southern part are warmer than in the northern part. Horizontal distribution in the surface layer indicates differences in water mass characteristics between the northern part of Haruku Strait, which is influenced by Seram Strait, and the southern part, dominated by water masses from the Banda Sea. The impact of upwelling during the Southeast Monsoon season contributes to lower surface and thermocline temperatures in August and September 2022.

The spatial dynamics of salinity in Haruku Strait in August from the surface down to 50m depth show higher salinity in the southern waters of the strait compared to the northern waters around Pombo Island (Fig. 7A-C). The elevated salinity in the southern waters is due to vertical mixing of water masses, leading to an increase in salinity. Additionally, at the surface (1m), salinity in the waters around Waai Bay is notably low (Stations 13-16), influenced by freshwater input from rivers (Wairutung, Wainusa, Waitasoi, and Waiatua) that flow into the coast of Waai, Ambon Island. This condition is also a result of high rainfall. Salinity at the halocline depth (75 and 100m) in August and September (Fig. 7C-D) indicates that the water mass in the northern part of the strait has higher salinity than in the southern part during these months.

Spatially, water density in Haruku Strait varies at depths of 1, 25, 50, 75, and 100m in August and September 2022 (Fig. 7). Density values increase with depth. Surface density (1m) is lower on the side of the strait bordering Ambon Island compared to the side bordering Haruku Island. This distribution pattern is consistent in both August and September, although surface density values are higher in August than in September. Density is nearly uniform across the waters at depths of 25 and 50m in both August and September. At 100m depth, a higher density distribution pattern is observed on the side of the strait bordering Ambon Island compared to the side bordering Haruku Island in both months. Spatially, the water mass characteristics in Haruku Strait differ from other straits, influenced by seasonal variations, wind speed, solar radiation, water topography, and geographic location **(Hussein *et al*., 2024; Kamel *et al*., 2024)**.



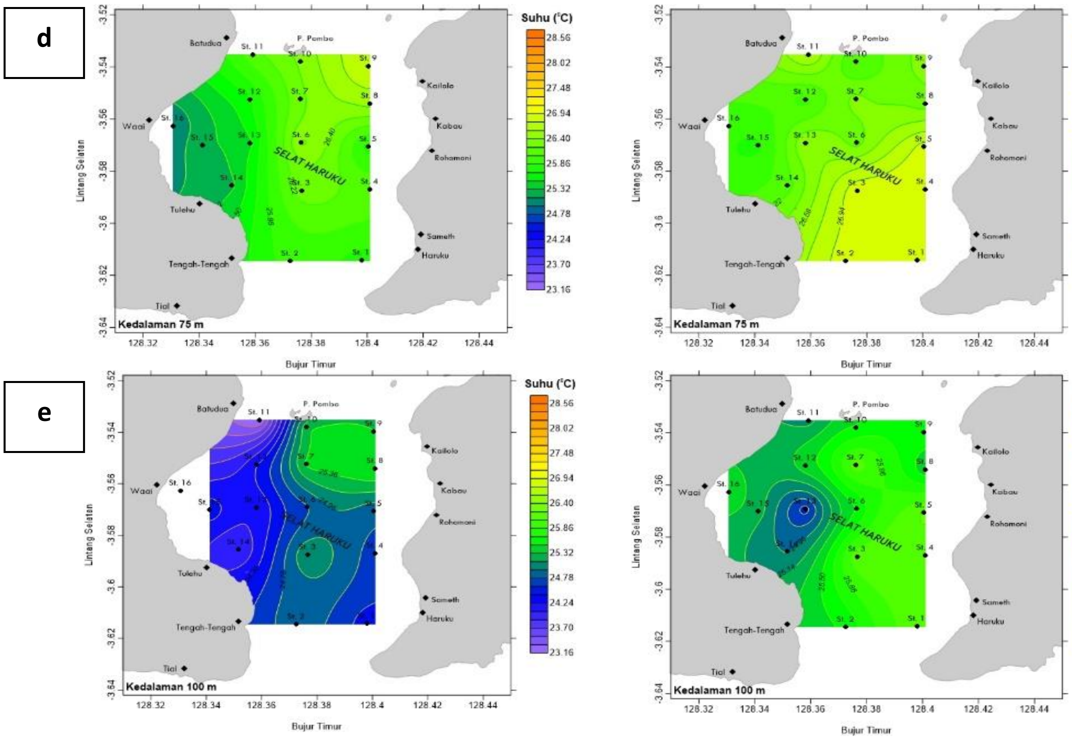
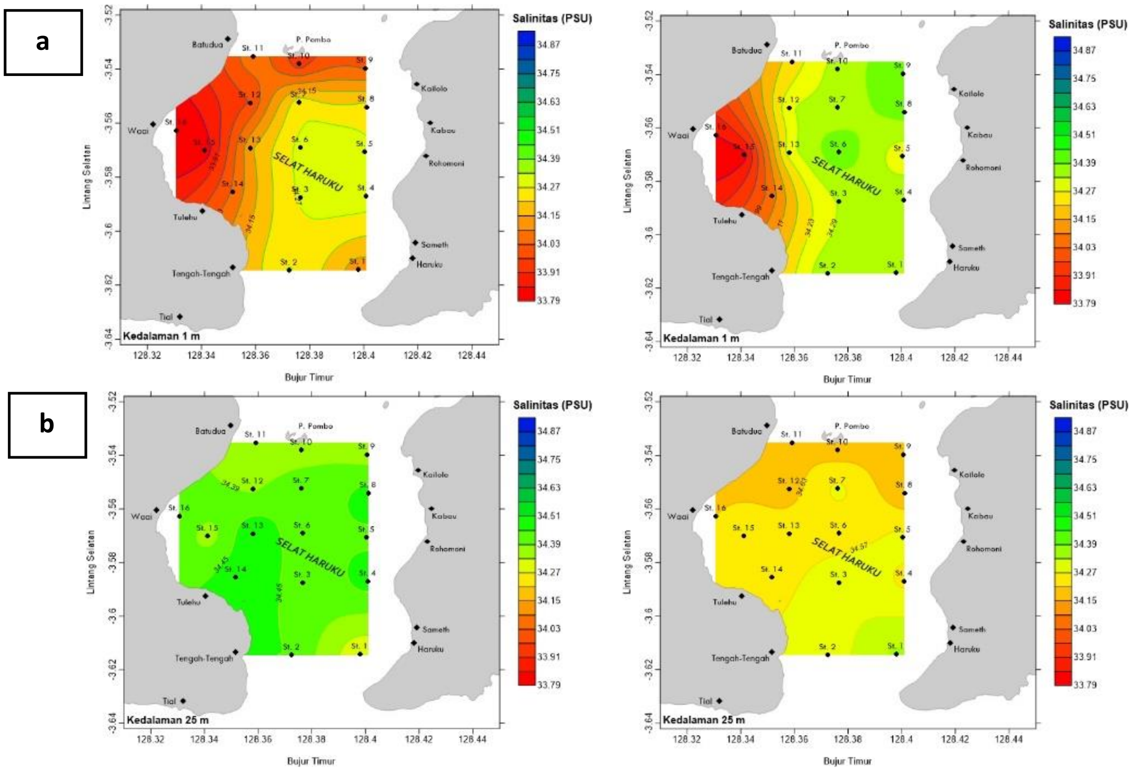


Fig. 6. Horizontal distribution of temperature at depths of **(a)** 1m, **(b)** 25m, **(c)** 50m, **(d)** 75m, and **(e)** 100m in the Haruku Strait in August 2022 (left) and September 2022 (right)



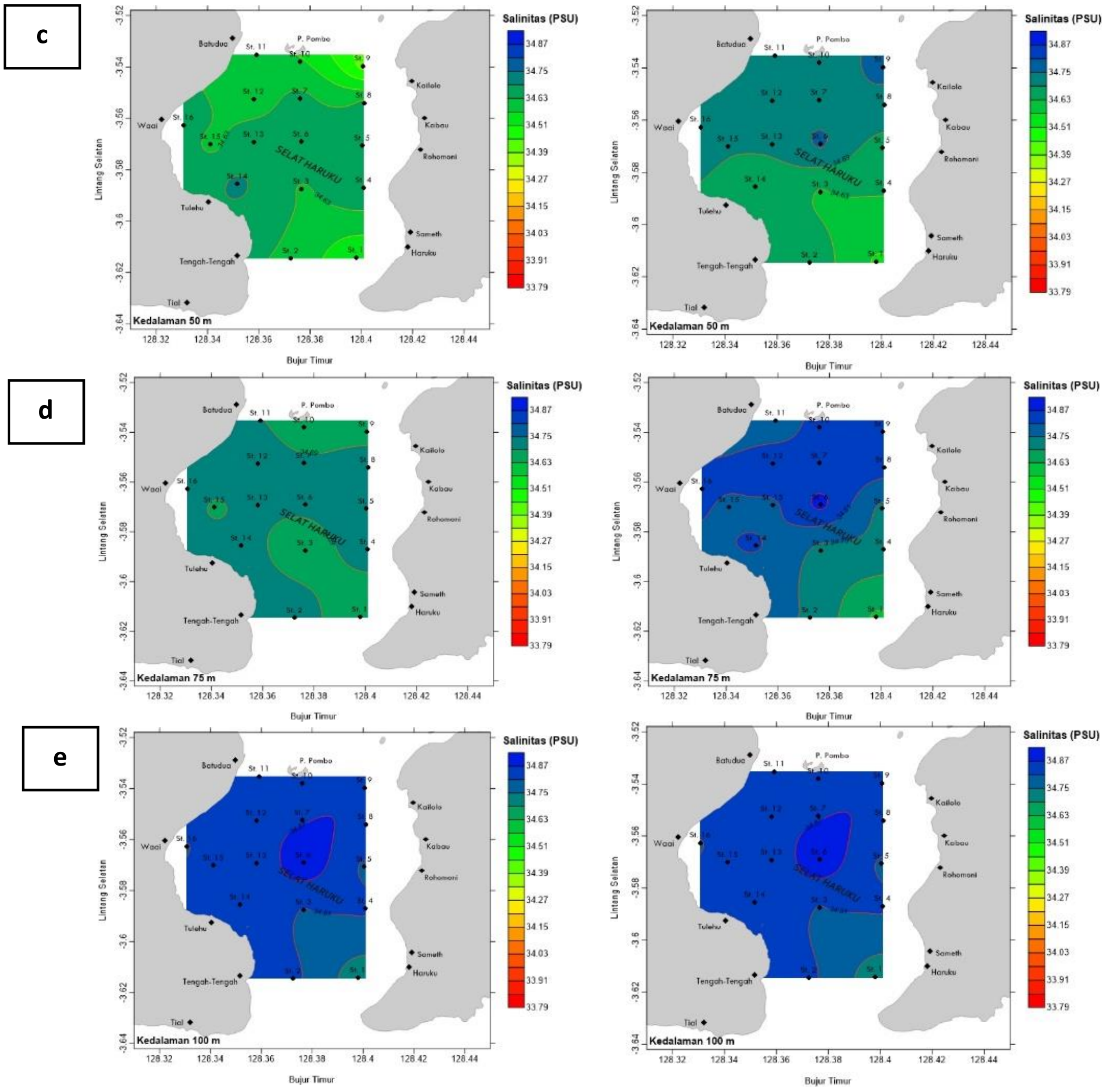
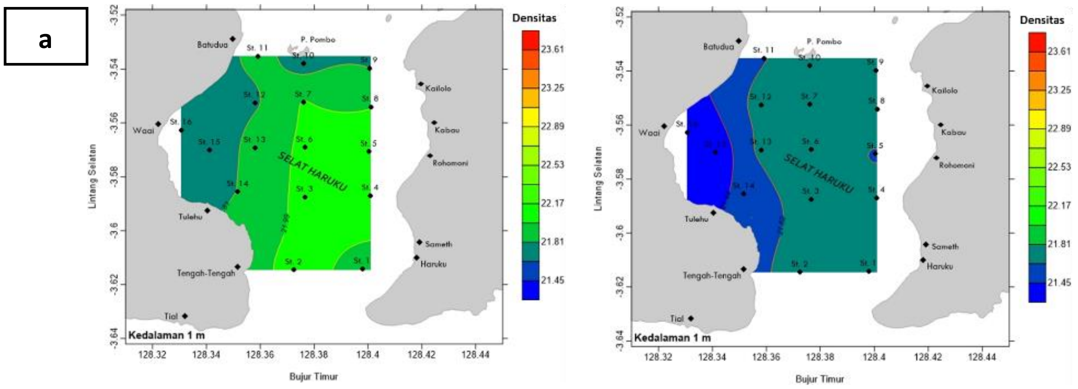


Fig. 7. Horizontal distribution of salinity at depths of (**a**) 1m, (**b**) 25m, (**c**) 50m, (**d**) 75m, and (**e**) 100m in the Haruku Strait in August 2022 (left) and September 2022 (right)



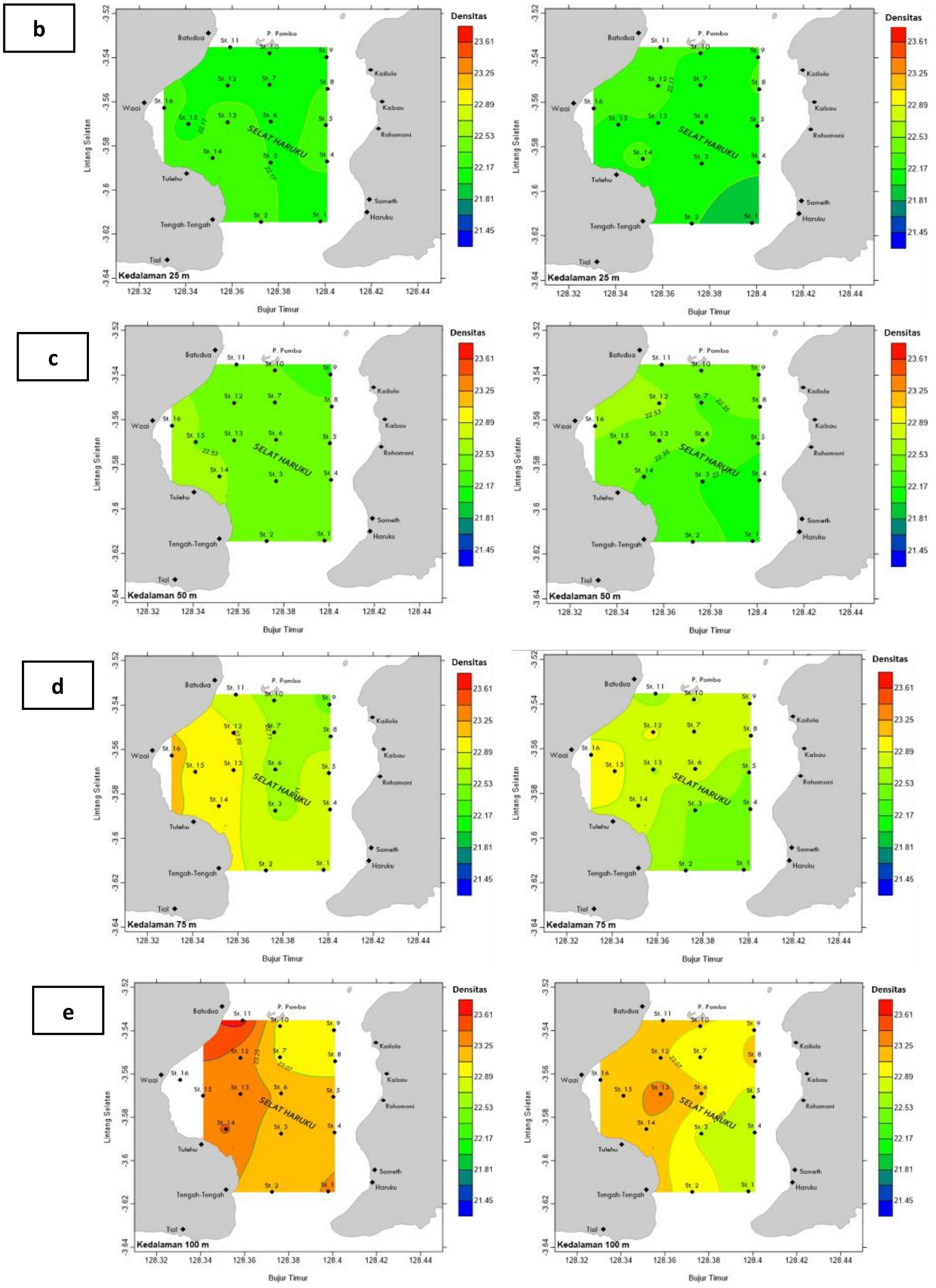


Fig. 8. Horizontal distribution of density at depths of (**a**) 1m, (**b**) 25m, (**c**) 50m, (**d**) 75m, and (**e**)100m in the Haruku Strait in August 2022 (left) and September 2022 (right)

3. Identification of water masses in the Haruku Strait

The results of the water mass identification analysis at 16 measurement stations in the Haruku Strait are presented in the T-S diagram (Fig. 9). The analysis identified North Pacific Subtropical Water (NPSW) in the thermocline layer, extending to the maximum measured depths of 100–120m in August and 115–160m in September. This water mass is characterized by a maximum salinity (Smax) of up to 34.79psu, occurring at isopycnals of 23.99–25.45kg/ m^3, with temperatures ranging from 17.09 to 23°C.

Hadikusumah (2010) reported that NPSW, with an initial maximum salinity of 35.576psu, is found north of Papua, Indonesia. Due to mixing processes, its salinity decreases to 35.394psu in the Halmahera Strait, 34.721psu in the central Seram Sea, and 34.663psu in the Banda Sea at depths of ~120–160m.

The water mass in the Haruku Strait is influenced by mixing processes involving water masses from the Banda Sea, the Seram Strait, and freshwater inflows from major rivers discharging directly into the strait. Additional factors affecting water mass mixing include the region's complex seafloor topography.

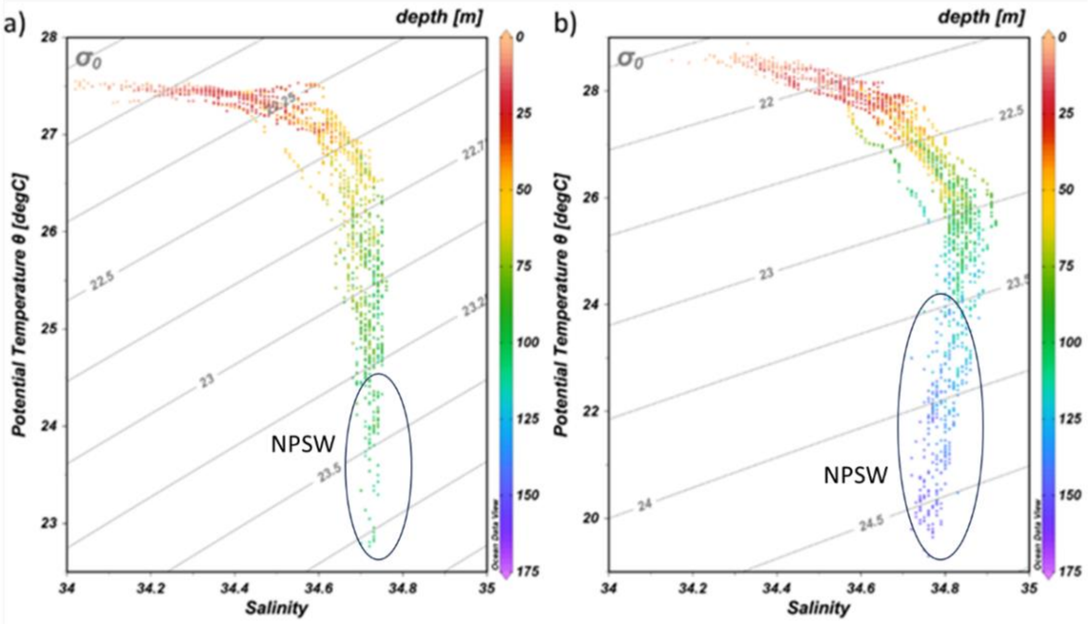


Fig. 9. T-S diagram profile of water masses in the Haruku Strait; **a)** Measurements in August 2022; **b)** Measurements in September 2022

4. Stability of water mass in the Haruku Strait

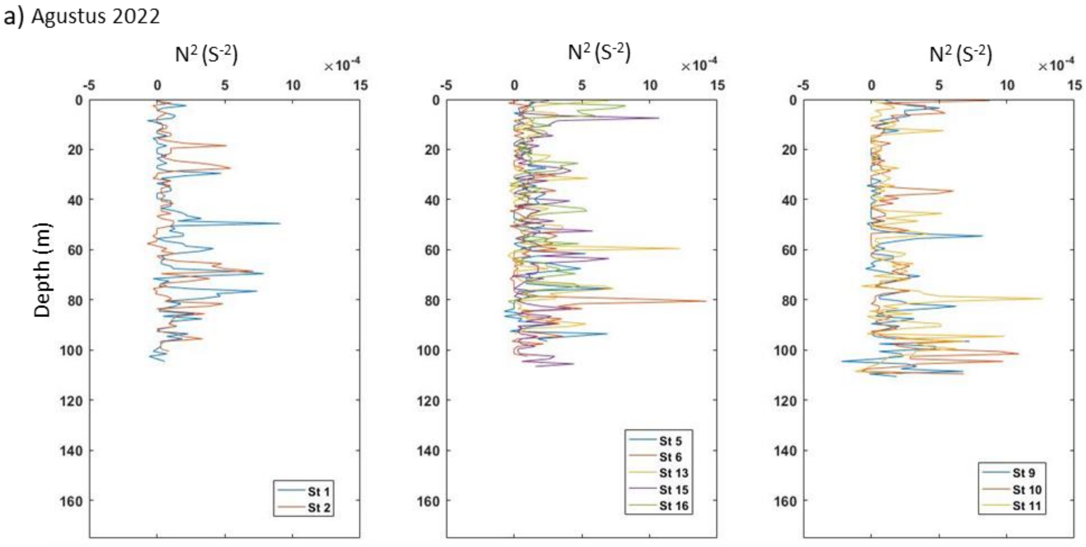
Water stability plays a role in the distribution of water masses within the water column **(Purwandana, 2013)**. A water column is considered stable when water mass density increases with depth **(Roseli *et al.*, 2015)**. The stability of water masses in the Haruku Strait was analyzed using Brunt-Väisälä frequency (N^2) calculations, as shown in Fig. (10). The waters of the Haruku Strait were divided into three segments: Segment 1 in the southern part of the strait (Stations 1 and 2), directly connected to the Banda Sea;

Segment 2 in the central part of the strait (Stations 5, 6, 13, 15, and 16); and Segment 3 in the northern part of the strait (Stations 9, 10, and 11).

In August, Brunt-Väisälä frequency (N^2) calculations across all three segments showed that the average tendency of water mass stability was relatively higher in the thermocline layer compared to the mixed layer. This indicates that the mixed layer has a low vertical density gradient, resulting in less stable water masses that could facilitate vertical mixing. The high wind speeds in August likely generated currents and waves, leading to mixing processes **(Tristianto *et al*., 2021)**. This finding aligns with **Pond and Pickard (1983)**, who noted that N^2 values in the mixed layer are lower compared to those in the thermocline and deeper layers.

Unlike in August, Brunt-Väisälä frequency calculations for September revealed varying levels of water mass stability across the three segments. In Segments 1 and 3, water mass stability tended to be relatively high at the surface, decreased in the homogeneous layer, and then increased again in the thermocline. This pattern suggests that the weakening wind in September allowed N^2 values to remain relatively high at the surface. In Segment 2, however, water mass stability was relatively high at the surface but low in the thermocline. This instability in the thermocline layer is likely due to a low vertical density gradient, promoting vertical or turbulent mixing within this layer. **Pond and Pickard (1983)** observed that vertical mixing of water masses is limited by the water column layering system, which closely relates to water mass stability levels.

Water column layering is inherently dynamic and influenced by factors such as current-generating energy, water depth, bathymetric conditions, upwelling and downwelling events, suspended solids, latitude, rainfall, and global climate variability **(Tomczak, 2000; Tang *et al*., 2006)**.



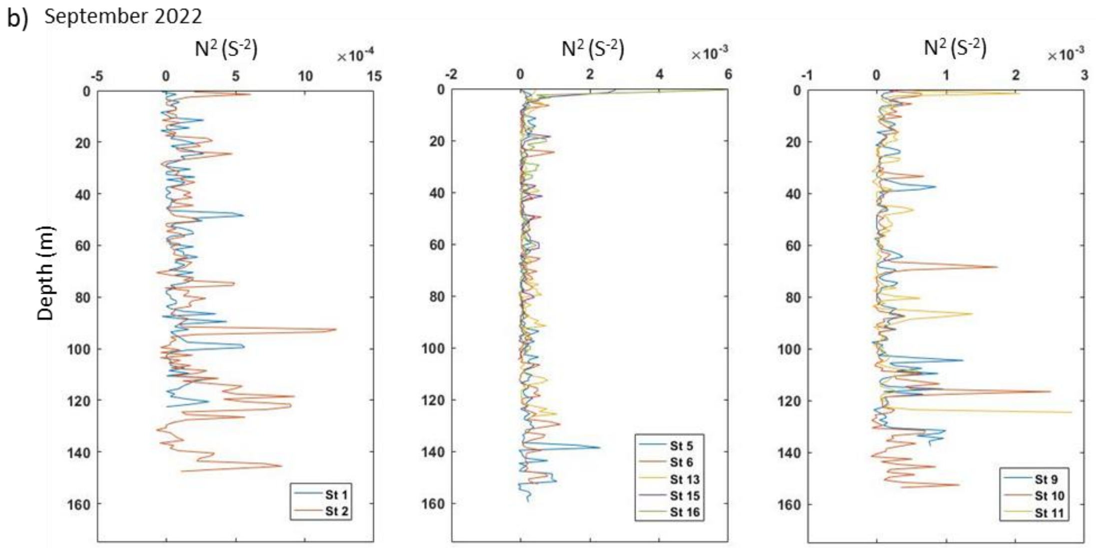


Fig. 9. Brunt-Väisälä frequency graph of water masses in the Haruku Strait, divided into three segments: the southern part of the strait (left), the central part of the strait (center), and the northern part of the strait (right)

CONCLUSION

The characteristics and stratification of water masses in the Haruku Strait exhibit seasonal variations. In August, surface temperatures down to 100m ranged from 24.5 to 27.5°C, while in September, they increased to 25.5–28.5°C. Salinity in this layer varied from 34.08–34.73psu in August and 34.10–34.83psu in September. Density ranged from 21.87–23.22kg/ m³ in August and 21.51–23.04kg/ m³ in September.

Due to its connectivity with the Banda Sea, physical changes, stratification, and circulation in the upper thermocline of the Banda Sea influence conditions in the Haruku Strait. The spatial-temporal variations of water masses, both vertically and horizontally, are driven by Southeast Monsoon wind intensity, upwelling, river inflow, rainfall, and seafloor topography.

T-S diagram analysis identified North Pacific Subtropical Water (NPSW) in the thermocline layer, extending to depths of 100–120m in August and 115–160m in September. Brunt-Väisälä frequency calculations indicate that the mixed layer has the lowest stability, promoting vertical mixing, while the thermocline layer is the most stable, exhibiting the highest frequency values.

This study enhances the data from previous research by providing insights into the seasonal variation of water masses in the Haruku Strait. The findings contribute valuable information for fisheries resource management and climate change impact mitigation.

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