Transformation of South Pacific Water Masses in the Halmahera Sea

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Abstract. The Halmahera Sea is part of the eastern entry route of the Indonesian throughflow (ITF) passages. The characteristics and transformation of the South Pacific water masses are presented based on the HYCOM model (Hybrid Coordinate Ocean Model) and direct observations of CTD (Conductivity, Temperature, Depth) acquired during the East Indonesian Expedition in October 2017 using RV Baruna Jaya VIII. This study is aimed at characterizing the typical water masses observed in the Halmahera Sea and tracking the transformation of the South Pacific water masses in the region. The results show that there was an indication of strong vertical mixing of maximum salinity of the South Pacific thermocline water masses, i.e., South Pacific Subtropical Water (SPSW), from ~35.2 PSU at isopycnal 24 – 25 kg m^{-3} becomes ~34.8 PSU in the Southern Halmahera Strait (around 200 km from the entry passage, the Northern Halmahera Strait), and rapidly decreases from the Southern Halmahera Strait and Obi Strait to become 34.6 PSU in the Maluku Sea. These preliminary findings suggest a strong mixing in the southern Halmahera Strait and Obi Strait.

Keywords: *Halmahera Sea, Water masses, Transformation, SPSW*

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1. Introduction

The Indonesian maritime continent links two oceans, the Pacific Ocean and the Indian Ocean [1], [2], via its throughflow, known as the Indonesian throughflow (ITF). The throughflow transports water masses from the Pacific into the Indian Ocean via two entry passages, the western and eastern routes. Throughflow from the Mindanao Strait can enter the Sulawesi Sea, Makassar Strait, Flores Sea, and Banda Sea via the western route of the Indonesian throughflow (ITF)[3]. While the eastern route transports Pacific water masses through the Halmahera Sea [4][5][6,], it contributes approximately 2.44 Sv (1 Sv = 10 6 m3 s-1) to the ITF [7]. The ITF is the key of the global thermohaline belt [8], where around 89% and 11% of Indonesian waters enter the Indian Ocean, respectively characterising the western and easternIndian Oceans [9].

The typical water masses in the western Pacific Ocean originate in the northern and southern hemispheres, specifically the North Pacific Subtropical Water Mass (NPSW) in the thermocline layer, flowing from the North Pacific with maximum salinity at a depth of around 100-400 m and a temperature of around 20°C; and the North Pacific Intermediate Water (NPIW) in the intermediate layer with minimum salinity at a depth of around 500-1500 m and a temperature of around 10°C; South Pacific Subtropical Water (SPSW) flows from the South Pacific, with maximum salinity at a depth of 500-1000 m and a temperature of 7-16°C; Antarctic Intermediate Water (AIW) flows from the South Pacific, with minimum salinity at a depth of 500- 1500 m and a temperature of 6°C [10].

Changes in the character of the Pacific water masses occur along the passages in the Indonesian waters [11], [12]. Previous measurements carried out in the Halmahera Sea showed that the South Pacific thermocline layer, i.e., the South Pacific Subtropical Water (SPSW), has a typical salinity of 34.99-34.72 PSU in the isopycnal σ_θ 25-26 [13]. In the northern waters of Papua, the SPSW water mass has a typical salinity of 35.0 to 35.4 PSU. This water mass will be the source of the water mass entering the Halmahera Sea. Some studies indicated that there is a strong vertical mixing responsible for salinity reduction in the Halmahera waters [13], [14],[16], [17]. This strong vertical mixing in the Indonesian sea has been cited as a possible mechanism due to interaction between strong tidal current with rough topography such as sills, straits [11].

The chemical and physical properties of water masses, such as temperature, salinity, and mineral content, can be used to identify their characteristics. Temperature and salinity are important indicators of the state of water masses. They both have an impact on the distribution of aquatic organisms [18]. The Halmahera Sea is known as a hotspot for vertical mixing, which has the potential to change the properties of the South Pacific water masses [5], [19]-[22].

This research focuses on characterizing and quantifying the water masses transformations in the Halmahera Sea, represented by their salinity changes. This study is aimed to inspect the salinity changing of the eastern route of the ITF via the Halmahera Sea, from the Pacific Ocean towards the Obi Strait and Maluku Sea based on CTD (conductivity, temperature, depth) observations. This study also compares the widely used hybrid oceanography dataset, the Hybrid Coordinate Ocean Model (HYCOM), with direct observation.

2. Methods

The observation was carried out in the Halmahera Sea (Figure 1). The datasets were obtained during the Eastern Indonesia Expedition using RV the Baruna Jaya VIII in October 2017. The CTD casts were carried out at 10 stations (Figure 1), sampled using Sea Bird Electronics (SBE) 911 plus CTD. The sensor temperature resolution is 0.001°C and ±0.0003 S m^{-1} for conductivity of the CTD sampling rate is 24 Hz [23]. We also involve the hybrid datasets obtained from the HYCOM (https://ncss.hycom.org/thredds). The HYCOM datasets have a

spatial resolution of 1/2° (~9 km) yet with no tidal forcings. The water masses characteristics are identified based on its appearance in T-S diagram and its spatial cross-section variability.

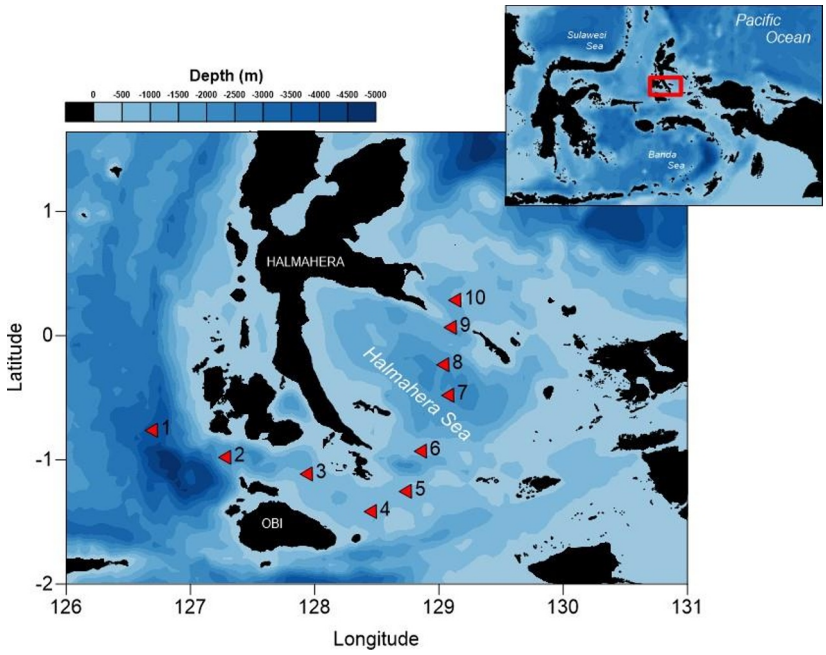

Figure 1. The CTD cast stations during the field observations in October 2017 in the Halmahera Sea.

3. Results and Discussion

3.1 Typical Watermasses Characteristic

The spatial distribution of T-S diagram shown by the HYCOM datasets indicated no strong monthly variability and is relatively the same with the CTD observations in term of the detectability of the typical maximum salinity of the SPSW. However, in absence of tidal current forcing the HYCOM datasets produced a less salinity erosion of the SPSW in the Halmahera Sea, hence the mixing effect is weak [19][24]. The absence of internal tidal mixing in the HYCOM datasets is also can be seen by the presence of outlier data in the deeper layer.

From the CTD observations, we found the typical South Pacific thermocline water masses (SPSW) with a maximum salinity of ~35.2 PSU at σ_θ = 24 – 25 kg m^{-3}. The strongest maximum salinity is found in the entry strait of the Halmahera Sea (the northern strait). Maximum salinity penetration begins to disappear when entering the Obi Strait to the Maluku Sea. A drastic decrease in salinity occurred from the Southern Halmahera Strait to the Obi Strait and eventually becomes 34.6 PSU in the Maluku Sea (Figure 3). The SPSW water masses enters the Halmahera Sea due to the forcing currents of the New Guinea Coastal Current [18], [25] [26], [27]. The typical of the water masses obtained from CTD observations has been shown in Table 1.

From the HYCOM datasets, we inspect monthly variability of water masses using T-S Diagram analysis of the HYCOM datasets as shown in Figure 2. The maximum salinity in January is ~35.2 PSU at σ_θ = 24 – 25 kg m^{-3} (Figure 2a), and decreases in February of ~35 PSU at σ_θ = 24 – 25 kg m^{-3} (Figure 2b). The maximum salinity in March is ~35.2 PSU at σ_θ = 24 kg m^{-3} (Figure 2c), slightly increases in April of ~35.3 PSU at σ_θ = 24 – 25 kg m^{-3}

(Figure 2d). The maximum salinity in May is ~35.2 PSU at $\sigma_\theta = 23 – 25$ kg m^{-3} (Figure 2e), and ~35.2 PSU at $\sigma_\theta = 24 – 25$ kg m^{-3} in June (Figure 2f). The maximum salinity in July is ~35.2 PSU at $\sigma_\theta = 24$ kg m^{-3} (Figure 2g). We found decreasing maximum salinity in August is ~34.8 PSU at $\sigma_\theta = 24 – 25$ kg m^{-3} (Figure 2h). The maximum salinity in September is ~34.9 PSU at $\sigma_\theta = 23 – 24$ kg m^{-3} (Figure 2i), ~35.2 PSU at $\sigma_\theta = 24 – 2\ 5$ kg m^{-3} in October (Figure 2j), ~35.3 PSU at $\sigma_\theta = 24$ kg m^{-3} in November (Figure 2k), and ~35.2 PSU at $\sigma_\theta = 24$ kg m^{-3} in December (Figure 2l).

The availability of CTD observations datasets allows us to confirm the validity of the HYCOM datasets. We compare the typical water masses in October 2017 from observation and from HYCOM (Figure 3). The core layer of SPSW water mass was identified at isopycnal $\sigma_\theta = 24\text{-}25$ kg m^{-3}, identified firstly from the northern Halmahera Strait (Station 10), i.e. the source of SPSW water masses before entering the Halmahera Sea. The depletion of the core layer of SPSW is suspected to be impact of strong vertical mixing at isopycnals $\sigma_\theta = 24 – 25$ kg m^{-3}. Traces of maximum salinity of the SPSW begin to disappear at Station 6 in the Southern Halmahera Sea with a typical salinity of ~34.8 PSU. A drastic decrease in salinity occurred in the South Halmahera Strait and Obi Strait, remaining the salinity of ~34.6 in the Maluku Sea (Stations 1). Recent studies also indicated that this water masses are the South Pacific Subtropical Water (SPSW) [17], [28], [27]. Even though the characteristic salinity range is not the same as in the area where it was formed, the maximum salinity characteristics are still visible in the Halmahera Sea [29]. This is due to the formation of SPSW water masses in the eastern part of the tropical South Pacific Ocean, where evaporation is greater than rainfall, and when it penetrated into the Halmahera Sea, the maximum salinity will be eroded due to physical process [30], [31].

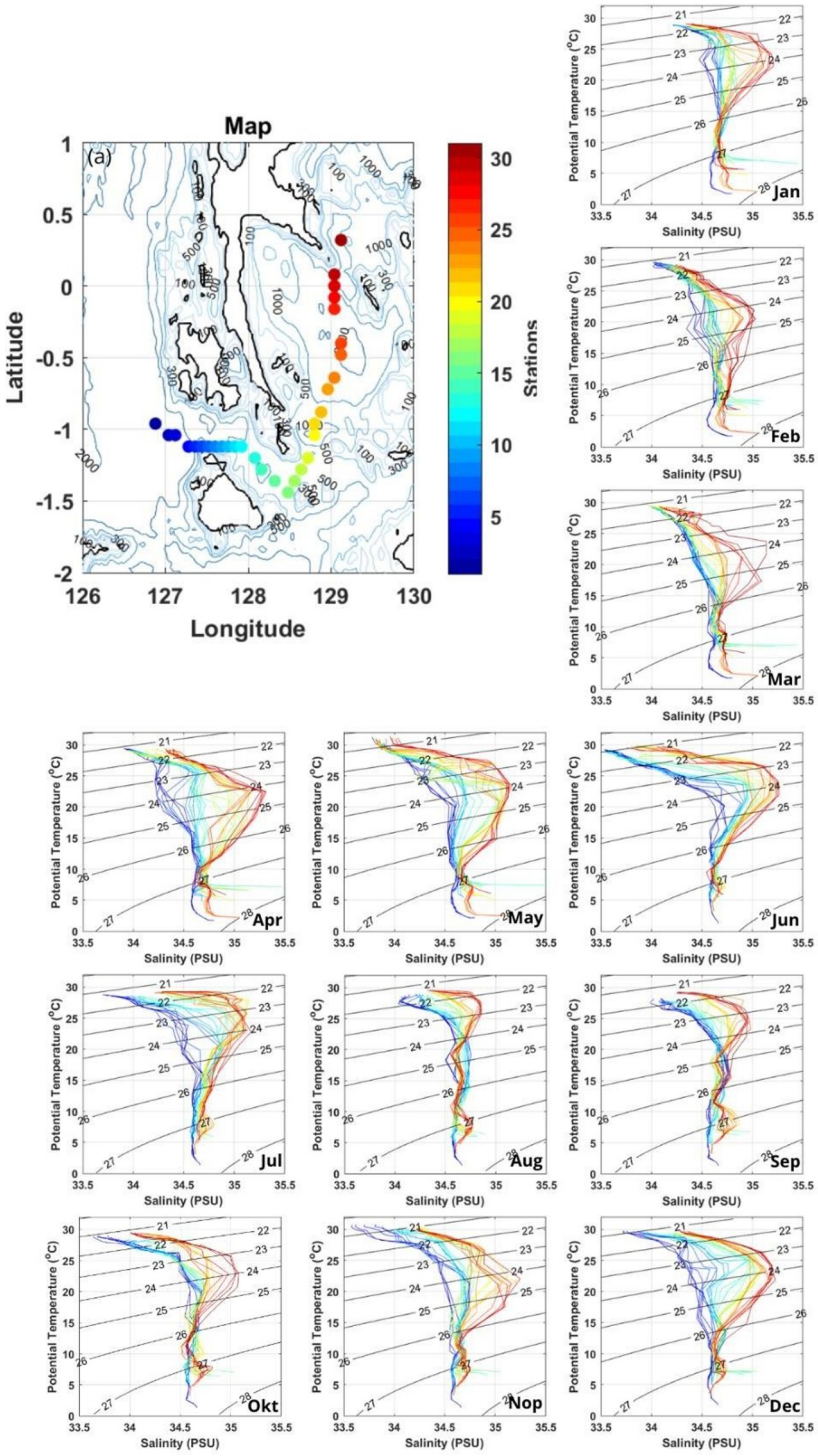

Figure 2. T-S Diagram from various months from January to December, 2017.

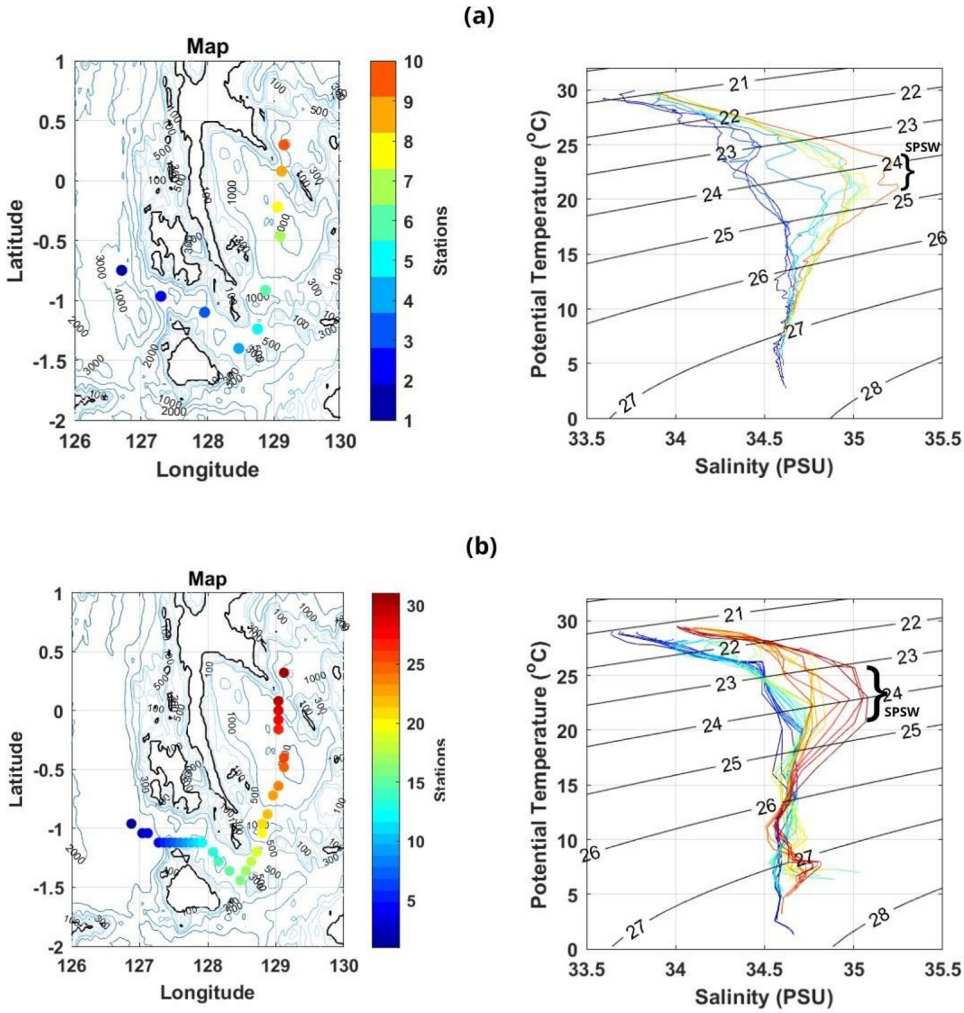

Figure 3. T-S Diagram: (a) CTD Observations in October 2017 (b) HYCOM in October 2017.

Table 1. Characteristics of water masses based on certain isopycnals in the Halmahera Sea derived from CTD observations datasets

σ_θ (kg m^{-3})	θ (°C)	Salinity (PSU)	Water Masses
21 – 22	27.59 – 29.57	34.0 – 34.31	-
22 – 23	25.84 – 27.51	34.4 – 34.75	-
23 – 24	23-51 – 25.7	34.78 – 35.2	-
24 – 25*	20.27 – 23.24	35.17 – 35.2	*South Pacific Subtropical Water* (*SPSW*)
25 – 26	14.33 – 19.07	34.74 – 35.12	-
26 – 27	10.26 – 13.86	34.67 – 34.76	-
27 – 28	2.83 – 9.58	34.61 – 34.66	-

**Core layer thermocline* ~ Core layer thermocline water mass of South Pacific (SPSW-South Pasific Subtropical Water)

3.2 Transformation of salinity

The salinity maximum of ~35.2 PSU of the SPSW was found at Station 10, in the northern Halmahera Strait (Figure 4). The water masses are located at isopycnal 24 – 25 kg m^{-3}, thinner compared to that shown by the HYCOM. It is suspected that there is strong vertical mixing, i.e. cross isopycnal mixing in this area. Maximum salinity penetration of ~35.2 PSU from Station 10 is ~200 km to the south of the Halmahera Sea and Obi Strait. The signature of SPSW begin to disappear at Stations 1 to Station 6 in the Obi Strait towards the Maluku Sea, which is characterized by the decreasing of maximum salinity of ~34.6 – 34.8 PSU.

The SPSW maximum salinity disappears when entering the Obi Strait, with typical salinity reduction from ~35.2 PSU to ~34.8 PSU. Salinity reduction occurred at Station 4 in the Obi Strait due to suspected strong vertical mixing in this area. Previous research, regarding the influence of tides on vertical mixing in Halmahera waters, found that the simulated salinity distribution without tides did not experience maximum salinity changes and would penetrate southward into the Banda Sea waters, while the simulated salinity distribution with tides shows a significant dilution in maximum salinity from the of Halmahera sea when it passes through the Halmahera Sea (Obi Strait) [32]. Other factors that can influence vertical mixing and transformation are rough topography such as sills [33], [34], stratifications [35], straits, and internal wave activity [11], [36], [37].

This research is also in accordance to previous findings, i.e. the characteristics of the South Pacific subtropical water mass begin to disappear when they are in the Obi Strait. The Halmahera Sea is the location where the strong mixing occurred, as can be seen in the vertical cross section. Water masses in the Maluku Sea show relatively low salinity because fresh water dominates in these waters.

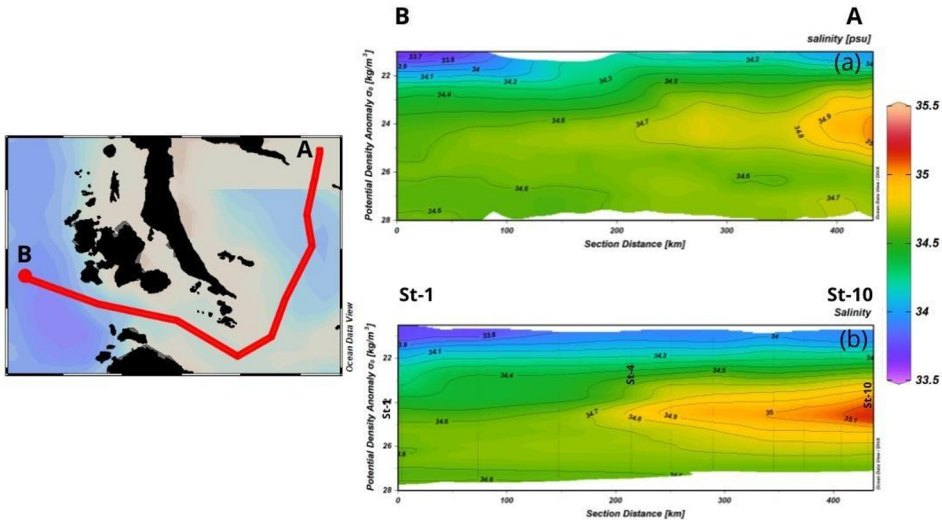

Figure 4. Vertical cross section: (a) HYCOM in October 2017, (b) CTD observations in October 2017.

4. Conclusions

It was confirmed by direct CTD observations that the South Pacific water masses in the Halmahera Sea is characterized by a typical maximum salinity of 35.2 PSU and exposed to strong salinity erosion. However, we found no significant monthly variations shown by the hybrid model datasets as they ignored the tidal forcing. SPSW maximum salinity in the thermocline layer penetrated southward from the northern Halmahera Strait as far as ~200 km towards the Obi Strait. The drastic decrease in salinity suggests the strong vertical mixing in the southern Halmahera Strait and the Obi Strait.

Acknowledgment

We would like to thank the RV Baruna Jaya VIII crew for helping the data acquisition. All authors contributed equally as the main contributors to this manuscript.

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