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Seasonal variation of the upper-layer seawater properties in the Banda Sea: observed from an autonomous CTD Argo float

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Abstract. An autonomous CTD (conductivity-temperature-depth) Argo float was deployed in the deepest Weber Basin of Banda Sea to investigate seasonal changes of the upper-layer seawater properties from the first year of CTD time-series data between August 2017 and July 2018. It is found that the float trajectory formed distinct elliptical-shapes, exhibiting a new picture of deep clockwise circulation of the float parking depth at 1000 m. On seasonal scale, large fluctuation of properties, mixed-layer depth, and thermocline thickness, were associated with seasonal alternating Ekman upwelling and downwelling dynamics. Upwelling "colder" event (July-September) was characterized by outcrops of 27°C isotherm, 34 psu isohaline and 22 kg/m^3 isopycnal at sea surface and large lateral variation of salinity in the upper 50 m. In contrast, these properties lines deepen down to about 100 m depth during downwelling "warmer" event (December-February). Amplitude of seasonal temperature change in the upper-layer was about 3°C. The very fresh water episode in the upper-layer was found during the monsoon break in April.

Keywords: Banda Sea, CTD, upper-layer dynamics.

1. Introduction

Being the only inter-ocean connection at low-latitude between the tropical Pacific Ocean and the Indian Ocean, Indonesian Sea provides pathways of upper-layer ocean current system as a branch of global thermohaline circulation (known as the Indonesian Throughflow, ITF). This water mass transfers tropical Pacific's heat and freshwater fluxes into the Indian Ocean. The ITF plays a significant role in controlling physical setting of marine ecosystem, ocean-atmosphere interaction and climate variability in Indonesian Sea and Indo-Pacific region [1-3].

Complex features geographical configuration of interior seas, passage, and straits in Indonesian Sea the ITF brings both northern and southern Pacific water origin through different pathways from the

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inflow portal seas between Mindanao and Papua to the outflow the straits between Nusa Tenggara and Timor. These transfered Pacific water masses origin together with local near-surface freshwater arrive in a confluence region of the Banda Sea, and stay temporarily in the deep Banda basin, before exiting into the Indian Ocean via outflow straits of Ombai Strait and Timor Passage [2, 4] (figure 1).

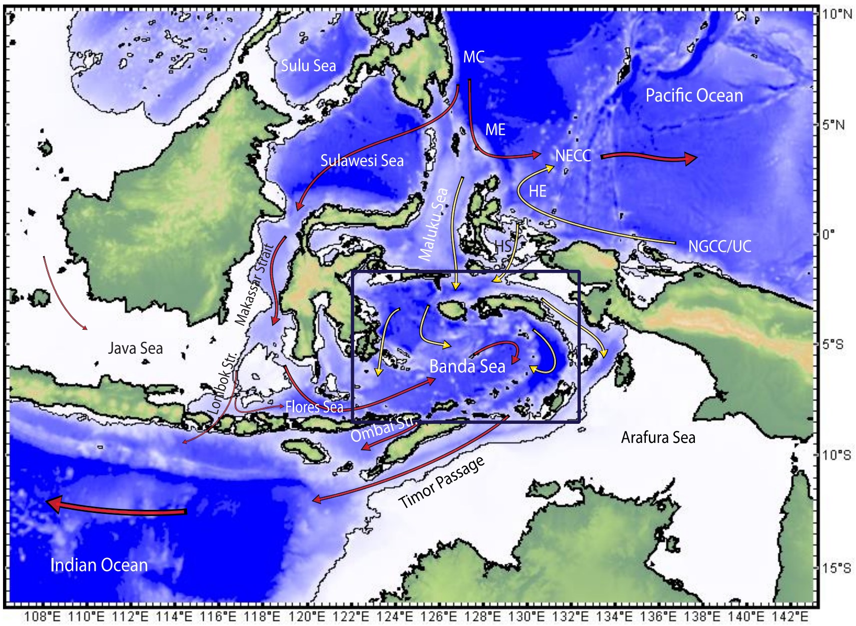

Figure 1. A schematic flow of the Indonesian Throughflow from the Pacific to the Indian Oceans through the interior Indonesian Seas. A deep Banda Sea (rectangle) is a confluence region of different Pacific water origins.

The Banda Sea (BS) functions as a large deep basin where its upper-layer dynamics and variability on seasonal time-scale are significantly controlled by monsoon winds, which indicate alternating seasonal convergence and divergence of upper-layer flows associated with upwelling and downwelling dynamics [3, 5, 6, 7]. On interannual time-scale ocean variability in the BS is also affected by anomaly of climate variability of Pacific El Nino Southern Oscillation (ENSO) and Indian Dipole Mode (IOD) [3, 5]. Furthermore, on intraseasonal (Madden-Julian Oscillation MJO) time-scale coupled upper-layer ocean-atmosphere dynamics and variability in the BS influence significantly local ocean-climate variability [8].

Physical setting of the BS provides high biodiversity of marine organisms such as coral reefs and associated coral fishes [9, 10]. High marine primary productivity is found during the southeast monsoon “upwelling” period which is correlated with high pelagic fish stock density. Nutrient and chlorophyll-a concentration in upper 25 m depth is maximum during “upwelling” period, and nursery ground and migratory of large pelagic fishes such as tuna and skipjack [11-14].

Ocean observation with in-situ time-series data of temperature-salinity-depth (CTD) with high spatial-temporal resolution is still a challenge in Banda Sea. However, for the first time since late July 2017 an autonomous CTD Argo float was deployed in deep Weber basin in eastern Banda Sea. Time-series CTD data from surface down to 1000 m depth with 2-days cycle between July 2017 and August 2018 have been acquired. The objective of this paper was to investigate stratification and seasonal variation of water masses in the eastern Banda Sea.

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2. Materials and Methods

2.1. Study area

The study area was located in the deepest Weber basin - Banda Sea (figure 1). A passenger motor vessel departed from Ambon to Tual in the late July 2017. The CTD Argo float (ID 6901746) was deployed at initial position of 131°E and 5 °S around the deep Weber basin on the mid-course of the vessel.

2.2. Data

The CTD operation was set during upcast profiling from 1000 m depth to the sea surface, and stayed at 1000 m parking depth during idle-mode. Temporal resolutions for autonomous profiling of conductivity-temperature-depth (float cycle) was set to daily in the first 3-months, but then it was changed to be 2-days cycle. Vertical resolution of CTD profiling was set to 1 m in the first 400 m, and 5 m for remaining depth. Since early November 2017 to present, vertical resolution was set to 1 m in the upper 300 m depth (except from surface to 200 m depth for one month between October and November 2017) and the remaining depth was 2 m (figure 2). The data used in this study was one year from 29 July 2017 to 5 August 2018.

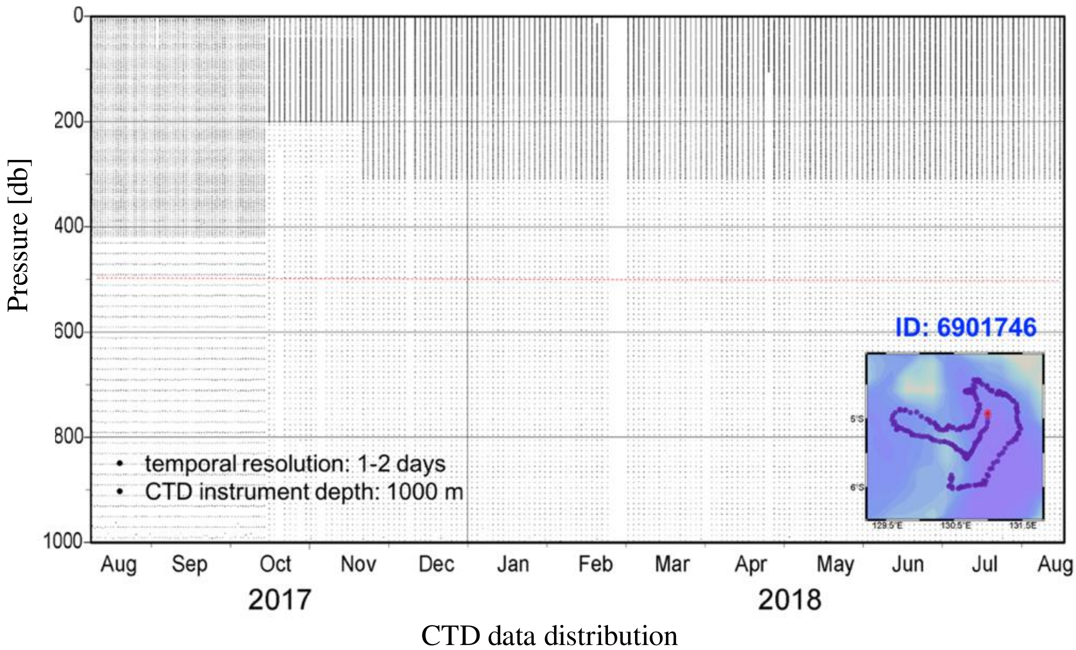

Figure 2. Depth-time distribution of the CTD Argo float data (ID 6901746) in Banda Sea from 29 July 2017 to 5 August 2018. Time resolution (float cycle) was set to 2-days (except during the first 3-months, 1-day), and vertical resolution is set to 1 m for the first 300-m and 2 m between 300 m and 1000 m depth (except during the first 3-months). Inset denotes float trajectory during a year. Red line at 500 m depth denotes CTD data series used in this study.

2.3. Data Processing and Analysis

Time-series CTD data from surface to 1000 m depth were processed interpolated to obtain standard temporal and vertical spatial resolutions. Temporal resolution (time interval) was interpolated to 2-days and vertical resolution is set to 1 m in the upper 300 m depth and 2 m below 300 m depth. In this paper, we focused to analyze time-series CTD data only from surface to 500 m depth.

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3. Results and discussion

3.1. Distinct clockwise deep circulation at 1000 m depth
Trajectory analysis of the float at 1000 m parking depth reveals a complex clockwise circulation pattern which has not been described before in this area. From its initial position in July 2017 to the last position, the float drifted southwestward, then it turned sharply northwestward from August to September exiting Weber basin, then it turned again to the southeastward-eastward to Weber basin (figure 3). It almost covered six months to make one cycle. The float continued to encircle southward and southwestward and turned westward in June-July 2018.

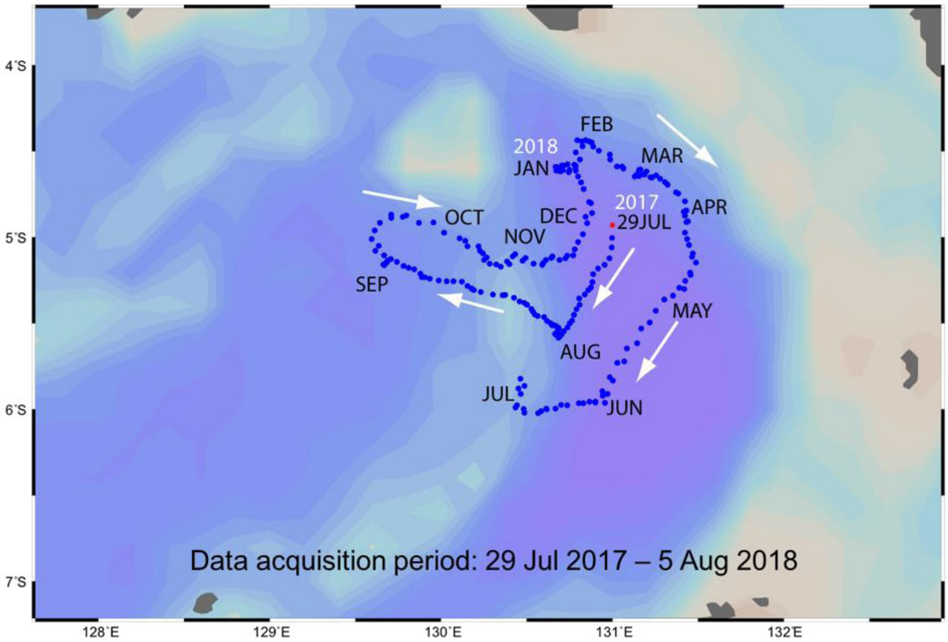

Figure 3. Trajectory of the CTD Argo float (ID6901746) from 29 July 2017 to 5 August 2018, indicating a clockwise circulation in eastern Banda Sea at 1000 m (parking) depth.

The first six-month period trajectory of the float formed an ellipse which oriented almost east-west, then six-month later orientation of the trajectory was north-south. It is considered that complex clockwise eddy revealed from the float trajectory might be persistent in this deepest Weber basin in Banda Sea. From another Argo float trajectory advected from Maluku Sea to Banda Sea a strong southward flow was observed directly passing Lifamatola Strait to Seram Sea to western Buru Island then traversed southward in central Banda Sea to southern islands (not shown). This means that flow pattern in central Banda Sea with a strong southward flow is different to those observed in Weber basin where relative slow-moving deep circulation is found here.

3.2. Stratification of Banda Water
Stratification of seawater properties from surface to 500 m depth in Banda Sea was found clearly a strong seasonal fluctuation as fundamental period of oscillation (figure 4 – 6). Seasonal oscillation of potential temperature was indicated by a warmer episode (temperature > 28°C) in the upper 50 m depth, e.g., during the peak of Northwest Monsoon (NWM) period from December to February, but cooler episode (temperature < 27°C) appeared during the peak of Southeast Monsoon (SEM) period from July to September (figure 4 left panel). Maximum (>30°C) and minimum (<27°C) temperature in the upper 50 m were found during the peak of NWM and SEM period, respectively. Fluctuation of temperature on higher frequency is also found from the data. In the upper 50 m depth, isotherm of 27°C is outcropped during the SEM period (e.g., between August-September 2017 and July-August 2018), but it deepens to about 100 m depth during peak of the NWM period. Accordingly, isotherm of 25°C and 20°C which may represent lower base of mixed layer and middle thermocline layer,

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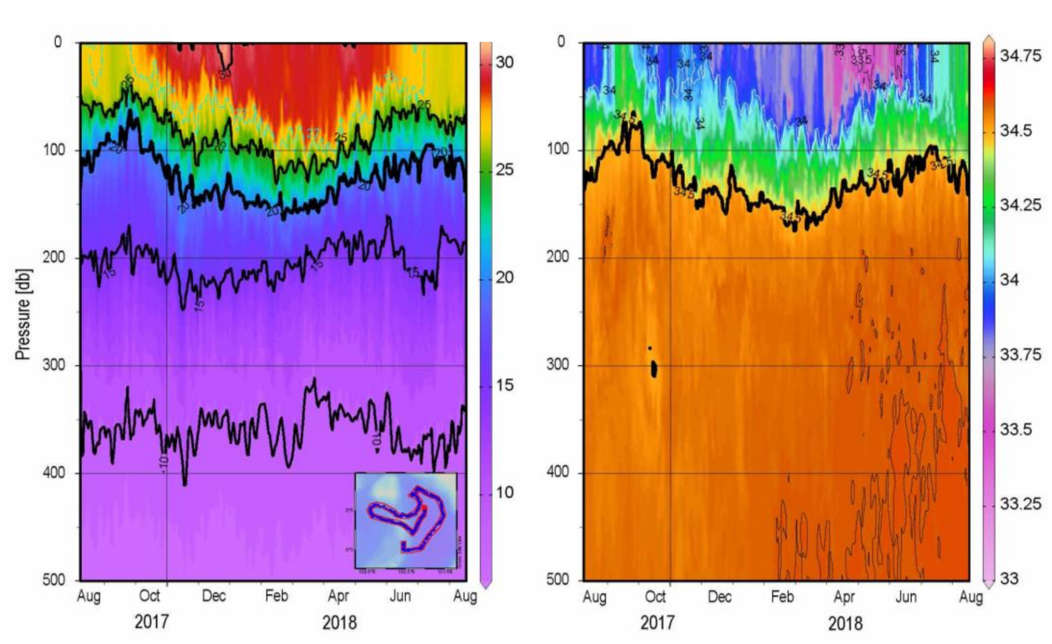
respectively (figure 4) shallow to 50-75 m depth during the SEM and deepens to 100-150 m depth during the NWM. Fluctuation of isotherm of 10°C in deeper layer (300-400 m depth) showed a fluctuation on higher frequency.

Seasonal variation of salinity was indicated by freshening episode (salinity <33.5 psu) during the Monsoon Break (MB) from the NWM to the SEM period (e.g., between April and June) and salty episode (salinity >34 psu) during the peak of SEM period. Fluctuation of isohaline of 34 psu was almost identical with fluctuation of isotherm of 27°C, where it deepened during the NWM period and outcrops during the SEM period (figure 4 right panel). Isohaline of 34.5 psu which represented a thermocline layer was also similar with isotherm of 20°C, where it deepened during the NWM period and shallow during the SEM period. Below 300 m depth, salinity was relatively homogenous (about 34.55 psu), but slightly higher salinity water mass (about 34.55 psu) appeared from February 2018 to the end of measurement.



(a) (b)

Figure 4. Depth-time section of potential temperature (a) and practical salinity (psu) (b) between 0-500 m depth and from 29 July 2017 to 5 August 2018.

For the first time, large seasonal variation of temperature and salinity in the upper 150 m depth was obviously revealed from time-series CTD Argo float data in Weber basin. There were an alternating deepening/shallowing mixed layer base (isotherm of 25°C) and mid-thermocline layer (isotherm of 20°C) during opposite monsoon period, and outcropping of isotherm of 27°C and isohaline of 34 psu in mixed layer base and isohaline of 34.5 psu in mid-thermocline layer. Those were some characteristics of distinct stratification related to alternating warming episode (downwelling) and cooling episode (upwelling) in Banda Sea, which was identified first time from limited hydrographic data [15-19]. The time-series CTD Argo float data showed that these fluctuations of alternating downwelling and upwelling were revealed much more detail. For example, we found that near-surface freshwater appeared during the transition monsoon rather during the peak of monsoon period. Furthermore, outcropped temperature and salinity was found on isothermal 27°C and 34 psu, respectively which had not been reported.

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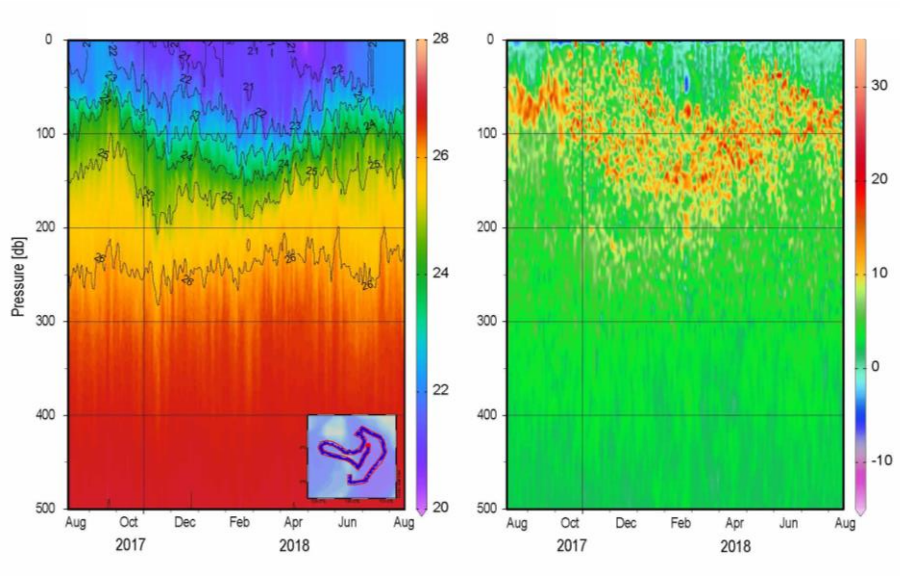
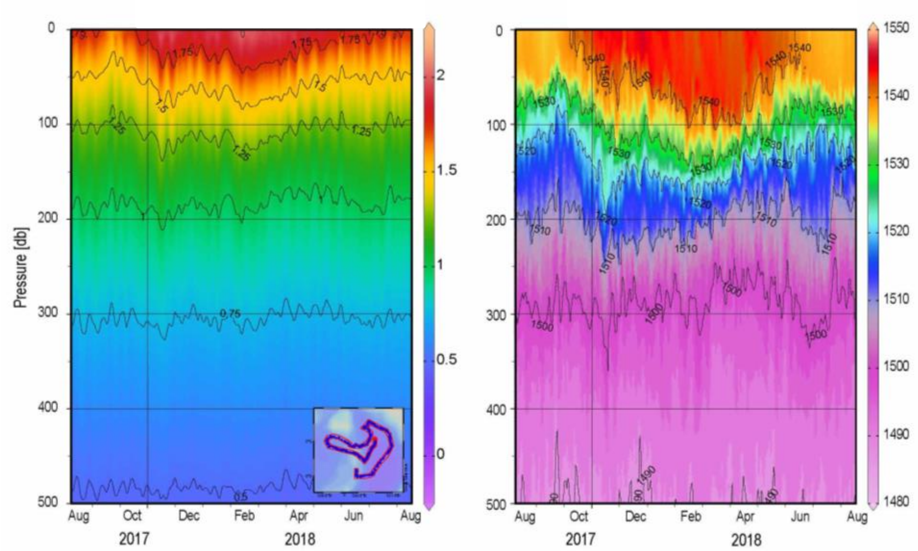


(a) (b)

Figure 5. Depth-time section of potential density anomaly (kg/m^3) (a) and Brunt-Vaisala frequency (b).

Stratification of potential density anomaly (figure 5a) was characterized by lighter density (<21.5 kg/m^3) that appeared during the NWM 'rainy' period, but the lightest density (<21 kg/m^3) was found during the monsoon break (April-May). Outcropped density of >22 kg/m^3 and shallowing density of 23 kg/m^3 were found during the SEM period associated with the upwelling episode, but it deepened to about 125 m depth during the NWM period. Pycnocline layer, as it represented by isopycnal 24-25, showed a large amplitude (about 100 m) of seasonal fluctuation, compared to pycnocline of 26 at lower layer (50 m). Distribution of high Brunt-Vaisala frequency that indicates a static stability of water mass appeared in the upper 200 m depth since seasonal pycnocline exists in this layer (figure 5b). High static stability (BVF) deepened during the NWM and shallows during the SEM period. Relatively small static stability was found near surface layer during the peak of monsoon period and in deeper layer.



(a) (b)

Figure 6. Depth-time section for dynamic height anomaly (a) and sound speed (b).

Stratification of dynamic height anomaly (DHA) relative to 1000 m depth confirms alternating downwelling and upwelling dynamics in the study area. During the SEM ‘upwelling’ period a low DHA was found associated with low sea level. For example, isopleth of 1.75 was outcropped to sea surface layer during this upwelling period. In contrast, high DHA was seen during the NWM ‘downwelling’ period, where isopleth of 1.75 deepened to about 50 m depth. Fluctuation of DHA in the upper thermocline layer (for example isopleth of 1.5) was also consistent to the fluctuation of DHA in mixed layer (figure 6a).

Stratification of sound speed showed high sound speed (>1540 m/s) in the upper thermocline during the NWM period, where its outcropped in sea surface during the SEM period. Sound velocity (<1535 m/s) decreased during the SEM period. Sound speed in the thermocline layer (represented by contour line of 1530 m/s) showed a large seasonal fluctuation, which its sound speed deepened and lessened during opposite monsoon period (figure 6b).

3.3. Structure of water masses

Structure of water masses in Weber basin Banda Sea was confirmed a relatively homogenous in salinity of Banda water in thermocline layer (between isopycnal 24.0 and 25.5) and intermediate layer (below isopycnal 26), but relatively large seasonal fluctuation of salinity in upper-layer (above isopycnal 23.5). Homogeneous water mass in salinity of 34.6 below isopycnal 25 was seen clearly (figure 7). However, a weak signature of salty South Pacific Subtropical Lower Thermocline Water (SPSLTW), as well as North Pacific Intermediate Water, was also seen between isopycnal 26 and 27. There was a weak spatial variation of salinity.

When the float traversed 130.5°E westward to central Banda Sea, signature of North Pacific water origin (thermocline and intermediate water) was much stronger. In contrast, when the float remained in the Weber basin, relatively homogeneous in salinity of water mass was dominant below 25 isopycnal, but SPSLTW becomes visible. Salinity in near-surface layer (above isopycnal 23.5) showed a relatively large variation between 33.6 and 34 psu, particularly above isopycnal 22.

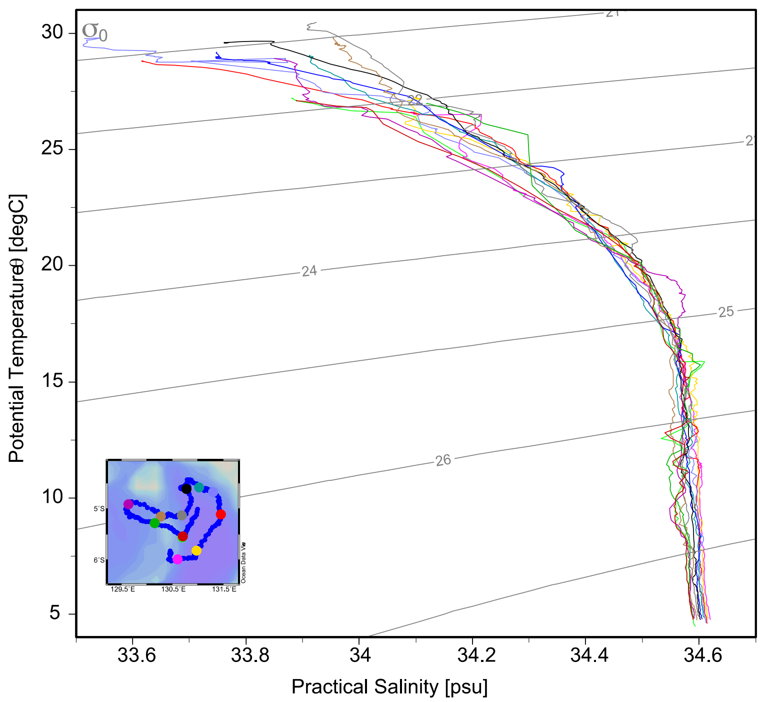


Figure 7. Temperature-Salinity relationship (T-S diagram) from CTD Argo profiles in Banda Sea, plotted only for every mid of month.

3.4. Seasonal evolution of seawater properties

Seasonal evolution of seawater properties was indicated by a significant change of properties in the upper 100 m depth (figure 7). During peak of the SEM period (August 2017), temperature reached its minimum of about 25.5°C with large variation of salinity (33.8-34.2 psu) and density anomaly near 22 kg/m^3 and mixed layer depth (MLD) of about 40-50 m (figure 8a). During the Monsoon break I (Nov 2017) temperature increased to about 30°C, salinity shifted to about 33.8-34 psu, and density anomaly decreased to about 21.5 kg/m^3 with small MLD thickness indicating strong stratification of water mass (figure 8b).

During the peak of the NWM period (Jan 2018) temperature was maximum of about 30°C, salinity decreased to about 33.9 psu, density anomaly of 21.5 kg/m^3, and MLD thickness of 40 – 75 m (figure 8c). During the Monsoon break II (Apr 2018) seawater temperature was still warm near 30°C, but freshening surface water from surface down to 100 m depth was clearly observed during this period, in which salinity varied between 33.5 and 33.7 psu. Density anomaly decreased to about 21.5 kg/m^3 with MLD thickness of about 40 m. Return to the peak of SEM period (Jul 2018) temperature shifted to its minimum of about 26°C with large salinity variation (33.9 – 34.3 psu) and density anomaly increased to about 22 kg/m^3 with thickness of MLD of about 50 m (figure 8e). Evolution of seawater properties can be summarized in table 1.

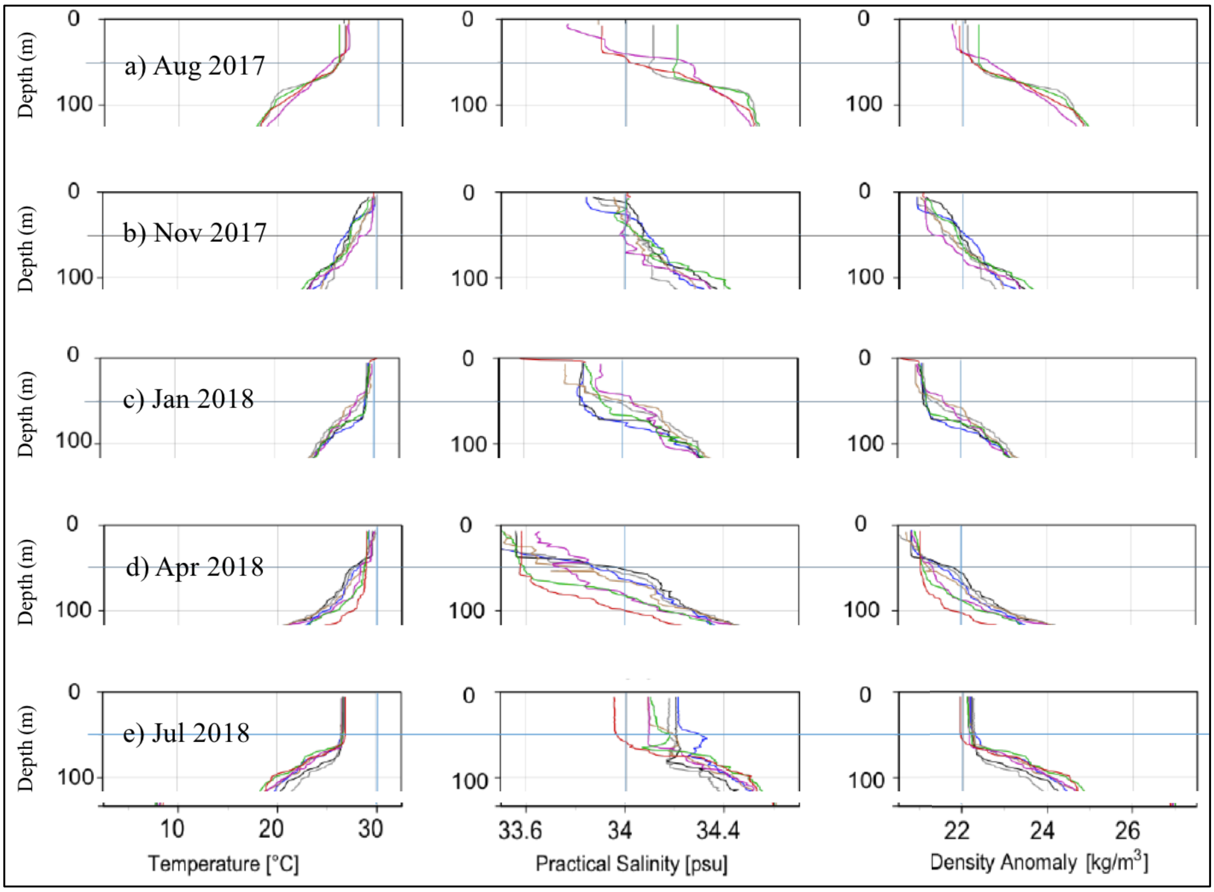


Figure 8. Seasonal evolution of seawater properties (temperature, salinity and density anomaly) in the upper 100 m depth from August 2017 to July 2018 along the trajectory of the float.

Table 1. Seasonal evolution of seawater properties in the upper 100 m depth in Banda Sea.

Month	Temperature range (°C)	Salinity range (psu)	Density anomaly range (kg/m^3)	Mixed Layer Depth range (m)
Aug 2017	25.0 – 26.0	33.8 – 34.2	21.8 – 22.4	40 – 50
Nov 2017	28.0 – 30.0	33.8 – 34.0	21.3 – 21.5	25 – 50
Jan 2018	29.0 – 30.0	33.8 – 33.9	21.4 – 21.5	40 – 75
Apr 2018	28.0 – 29.0	33.5 – 33.7	21.0 – 21.5	25 – 50
Jul 2018	26.0 – 26.0	33.9 – 34.2	21.8 – 22.4	50 – 75

3.5. Discussion

For the first time in the Weber basin of Banda Sea, time-series CTD data from surface to 1000 m depth, from the Argo float data revealed an interesting result that had not been reported before. Deep clockwise circulation around the Weber basin was a novel perspective, showing a complex deep flow which was not straight southward as inferred previously [1]. Here, north-south and east-west elliptical shape of the circulation was found.

Derived satellite surface winds, sea surface temperature and chlorophyll-a are well studied in Banda Sea, which shows large seasonal changes of surface parameters [1, 5, 11, 16, 20]. However, seasonal pattern in the water column such as in the upper 100 m depth was still less described. Our data showed seasonal changes that relate to upwelling (SEM period) as indicated by outcropped isotherm of 27°C, isohaline of 34, isopycnal of 22, isopleth of 1.5 dyn.m, and sound velocity of 1530 m/s. Those parameters were deepened to about 100-150 m depth during the opposite NWM monsoon period. Furthermore, it was found that freshening upper layer appeared not during NWM 'rainy' season but during monsoon break in April. Alternating Ekman upwelling and downwelling were clearly seen from the time-series data, associated with discharge and recharge of upper-layer heat flux, respectively.

Seasonal evolution of seawater properties shows that mixed layer depth deepens during peak of monsoon period, in good agreement with [5, 20]. However, near-surface salinity variation was found during peak SEM period, and strong vertical stratification was found during monsoon breaks in April and November.

Previous studies showed that Banda Sea provides high primary productivity of pelagic fishes, nutrient, chlorophyll-a, and larvae and micro nekton during upwelling period, for example [8, 9, 10, 11, 20, 21]. Air-sea interaction in this deep interior basin plays a significant role in regulating local climate variation [14]. Continuous time-series observation is needed to better understand ocean and climate variability in this region.

4. Conclusion

The first year CTD time-series data from an autonomous Argo float revealed a novel view of deep circulation and detailed large seasonal changes of upper-layer seawater properties in Webber basin of Banda Sea. The float trajectory at 1000 m parking depth demonstrated a clockwise deep circulation with several elliptical-loops, which had not been reported before. Response of upper-layer properties to the strong reversal monsoonal winds was indicated by alternating Ekman upwelling (downwelling) during the opposite monsoon periods. Upwelling event was clearly marked by outcrops of 27°C isotherm, 34 psu isohaline, and 22 kg/m^3 isopycnal at the sea surface. However, these properties lines deepened to about 100 m depth during downwelling period. It was also noted that very fresh upper-layer appeared here during monsoon break in April rather during rainy season in January.

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