Circulation dynamics of the Banda Sea estimated from argo profiles

M F A Ismail, A Taofiqurohman, A Purwandana

1) Research Centre for Oceanography, Indonesian Institute of Sciences, Jakarta, Indonesia
2) Fisheries and Marine Science, Padjadjaran University, Bandung, Indonesia

Email: mfur001@lipi.go.id

Abstract. The Banda Sea is a semi-enclosed marginal basin in the eastern tropical Indonesian waters. The circulation in the region displays strong seasonality in response to the seasonally reversing monsoon wind system. Yet, the basin is one of the least studied regions when it comes to the circulation dynamics – until now. Here, we present an analysis of an Array of real-time geostrophic oceanography (Argo) floats data during the period August 2017 to August 2019. The aim of the study is to investigate the spatial and temporal variability of circulation in the Banda Sea. Our study demonstrates the presence of cyclonic circulations, upwelling and downwelling with strong seasonal variability in the eastern part of Banda Sea off Maluku Island. It appears from the Argo temperature-salinity data that the subsurface cold and salty water shoals up during the southeast monsoon due to Ekman transport. Our study highlights the importance of Argo floats in elucidating the circulation in the Banda Sea.

1. Introduction

The Banda Sea is a semi-enclosed marginal basin located in the eastern tropical Indonesian waters hemmed by the 180° curvature of Banda arc islands flanking from the north to the south. On the west, the sea is restricted by Sulawesi Island adjacent to the Flores Sea. The region is part of the coral triangle region of the Indo-Pacific which has the humongous diversity of coral reef species [1]. The Banda Sea occupies mainly on the Banda oceanic plate. Oceanographically, the Banda Sea is part of the toll road of the interocean transport of tropical thermocline water from the low-latitude North Pacific Ocean into the Indian Ocean, called Indonesian Throughflow (ITF). There are two main ITF pathways to the Banda Sea: through the Makassar Strait into the Flores Sea and then the Banda Sea; via the Halmahera and Molucca Seas [2]. From the Banda Sea, the Pacific intermediate water then flows into the Indian Ocean by way of the Ombai Strait and Timor Passage [3]. The warm, low-salinity water of the North Pacific Ocean carried by the ITF has a significant role in maintaining heat and water balance between the Pacific Ocean and the Indian Ocean [2,4]. Thus, the ITF links to the regional ocean and climate dynamics such as El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Walker, and global thermohaline circulation [5].

Early studies by [6,7] suggest that water masses of the Banda Sea are influenced by the seasonal change of the Asian monsoon system. During the northwest monsoon (NWM) season, from November to March, low-salinity surface water which originated from the Java Sea flow across the Flores Sea...
into the Banda Sea. This surface low-salinity water accumulates in the region which depresses the thermocline [8] or exported to the Halmahera and Maluku Sea [6]. In addition, the low-pressure gradient between the Pacific and the Indian Ocean during the NWM season resulting in excess precipitation over evaporation [9]. In contrast, during the southeast monsoon (SEM) season the Banda Sea surface water is flush into the west and the Timor Sea which counterbalanced by upwelling of cooler and nutrient-rich waters in the eastern Banda Sea [7]. Consequently, the thermocline layer appears to be shallowing up to 30 to 40 m depth [10,11]. Further study by [12] suggests that upwelling events in the eastern Banda Sea extends from May to October and reaches a maximum in June-July. Despite the importance of the Banda Sea as an oceanographic link between the Pacific and the Indian Ocean, little is known about the circulation dynamics in the region. In this study, we investigate the circulation dynamics of the Banda Sea based on the Array of real-time geostrophic oceanography (Argo) autonomous profiling floats. The study aims to improve understanding of the circulation dynamics of the Banda Sea, in particular, the spatial and temporal variability of the circulation using the Lagrangian diagnostic and water masses analysis.

2. Material and methods
Data from Argo floats are analyzed to provide a high spatial and temporal resolution of surface circulation variability, as well as water mass dynamics in the Banda Sea. Two Argo profiler i.e. reference number 690746 and 690747 are available for the present analysis in the eastern Banda Sea. Argo 690746 was deployed on the longitude 130.99° E and latitude 5.00° S covering the period August 2017 to August 2019, while Argo 690747 was released on the longitude 131.00° E and latitude 4.88° S and operate between September 2018 to April 2019 (See Fig. 1). Both Argos are pre-programmed to descend to a certain depth at about 1000 to 2000 m and back rise to the surface while drifting freely. As it ascends, Argo measured temperature, salinity and pressure continuously. At the surface, the continuous measurements are averaged automatically and transmitted the data to the satellite. After the broadcast, the Argo dives again and initiates a new cycle. Argo profiles of temperature, salinity and pressure are publicly available in the form of delayed mode data and can be downloaded via the Global Data Assembly Centers (GDACs) after an automated scientifically quality control form [13]. The Lagrangian data analysis and the production of maps herein are generated using Matlab M_Map created by [14].

![Figure 1. Trajectories of the Argo floats deployed in the Banda Sea between August 2017 and August 2019, i.e. reference number 6901746 (a) and 6901747 (b). Black dotted arrows represent general schematic circulations pattern correspond to the Argo float’s trajectories. The 500 m isobaths are shown with thin black curves.](image-url)
3. Results and discussion

3.1. Lagrangian trajectories of Argo floats

The Argo floats trajectories in the Banda Sea for the period August 2017 to August 2019 are shown in Fig. 1. The Lagrangian trajectories are colour-coded to exhibit Argo’s real-time movement from initial deployment until become inactive. Furthermore, these trajectories provide a proxy for identifying the mean surface circulation pattern in the Banda Sea. In general, both Argo floats moved in a clockwise semi-circular motion indicative of a cyclonic recirculation cell (Fig. 1a and 1b). These cyclonic circulations have never been reported before in the Banda Sea and may correspond to the presence of cyclonic eddy or a gyre in the Banda Sea. Thus, our study is the first that reported the existence of cyclonic circulations in the Banda Sea. The trajectories also reveal that Argo floats 6901746 and 6901747 restrained in the eastern Banda Sea which covers the area of about 311 km² and 211 km², respectively. The Argo float 6901746 (6901747) moved with an average horizontal speed of 0.02 m s⁻¹ (0.03 m s⁻¹) or about 52.56 km month⁻¹ (78.84 km month⁻¹) during 24 months (8 months) of its life period. Therefore, the total horizontal distance travelled by Argo 6901746 and 6901747 in the Banda Sea is about 1,261 km and 631 km, respectively.

3.2. Seasonal variation of temperature and salinity

The sea surface temperature (SST) and sea surface salinity (SSS) variability in the Banda Sea varies both in space and time. Figure 2a and 2b show the spatial and temporal features of the SST gradient along the eastern Banda Sea estimated from Argo float 6901746 and float 6901747, respectively. The SST profiles clearly exhibit a seasonal cycle of SST cooling and warming. During the SEM season, i.e. August to October 2017, May to August 2018, and May to August 2019 (see Fig. 1), the SST is consistently ranging from 24°C to 27°C located off the coast of southern Maluku Island. The seasonal cycle of cooler SST appears to be associated with the upwelling of cold subsurface water driven by Ekman transport as previously reported by [7,12]. In contrast, during the NWM season i.e. November 2017 to April 2018 and November 2018 to April 2019 (see Fig. 1), the SST tend to increase significantly which range from 29°C to 31°C (Fig. 2a and 2b). Such SST increase during the NWM season is consistent with previous studies conducted in the Banda Sea [6–8]. Larger surface water imported from the Java-Flores Sea and Ekman-induced downwelling during the NWM is responsible for the warmer SST in the Banda Sea [12]. In accordance with the SST, the seasonal cycle of SSS salting and freshening also observed in the Banda Sea. The SSS values tend to increase during the SEM season which ranges from 34.25 psu to 34.5 psu. However, during the NWM season the SSS decline significantly and ranging from 33.5 psu to 33.75 psu (Fig. 2c and 2d).

A depth-time Hovmoller diagram of the temperature and the salinity are shown in Fig. 3 to examine the vertical structure of temperature and salinity distribution. The Hovmoller diagram of temperature from Argo float 6901746 and float 6901747 revealed seasonal ascend and descend of the 22°C to 24°C isotherm (Fig. 3a and 3b). During the SEM season from about August to October 2017, June to September 2018, and June to August 2019, the 22°C to 24°C isotherm appears shallow and reaching up to 50 m, and even the 24°C C isotherm can be seen to reach the surface and further shallowing the thermocline layer (Fig. 3a). [11] reported that the increased vertical mixing during the SEM season seems to reduce the depth of the thermocline layer. However, recent studies indicated that the turbulent kinetic energy dissipation rate and the vertical eddy diffusivity in the Banda Sea are very small [15–17]. They suggested that intense vertical mixing occurred in the entry passages and straits surrounding the Banda Sea, i.e. Halmahera, Buru and Lifamatola. During the NWM season, the 28°C to 32°C isotherm can be observed to deepen up to 300 m. Moreover, the 26°C even further deepens, reaches 700 m in February to March 2018 which depressed the thermocline layer. These seasonal shallowing and deepening of 22°C to 24°C isotherm could be a robust indication that upwelling and downwelling that take place in the eastern Banda Sea.
Figure 2. Spatial-temporal evolution of surface temperature (°C) and salinity (psu) estimated from Argo float 6901746 (a,c) and float 6901747 (b,d) in the Banda Sea. The black star and the black asterisk represent the initial and end location of the Argo floats, respectively. The 500 m isobaths are shown with thin black curves.

Figure 3. Depth-time Hovmoller diagram of the temperature in °C (a,b) and salinity in psu (c,d) from Argo float 6901746 and float 6901747 in the Banda Sea. The depth axis was restricted between 5 to 700 m and 200 m to highlight the layers where the uplift and deepening of temperature and salinity can be found.
The upwelling and downwelling events here are consistent with the aforementioned cooling and warming of SST in Fig. 2. Such patterns of seasonal vertical variability of 22°C to 24°C isotherm also present in the Hovmoller diagram of salinity (Fig. 3c and 3d). The temporal uplift and the deepening of 3.45 psu isohaline is nearly identical with the temporal shallowing and thickening of 22°C to 24°C isotherm. Our results of upwelling and downwelling event inferred from the vertical uplift and deepening of temperature and salinity complement the previous studies by [7,8,12] for the same region.

3.3. Water masses characteristic of the Banda Sea

Temperature-salinity (T-S) diagram of the study area was drawn with the temperature and salinity profiling data from two Argo floats i.e. 6901746 and 6901747. We plotted the TS diagram as a function of time to examine the water masses characteristic and its temporal variability (Fig. 4). In this diagram, the colour displays the time of T-S pairs in the profiles. The seasonal variation of the T-S diagram exhibits that the temperature and salinity variation in the mixed layer was evident in the Banda Sea. It can be visible from the T-S diagrams that the mixed layer characterized by the potential density (ρθ) range between 20 kg m$^{-3}$ to 22 kg m$^{-3}$, has a high temperature above 28°C and wider salinity range from fresh (32.75 psu) to medium salinity (34.45 psu) which occurred during NWM season (November to April). The high temperature (> 28°C) with fresh salinity (< 33.25 psu) is water masses that origin from the Java Sea, while the temperature above 28°C with medium to high-salinity value of 33.75 psu – 34.25 psu sourced from the North Pacific Surface Water (NPSW).

During the SEM season, the salinity range becomes narrow from 34 psu to 34.5 psu with temperature decrease to about 25°C to 26°C. Unlike the mixed layer, the variation of temperature and salinity in the thermocline layer is relatively homogenous with slight seasonal variation. The thermocline layer with ρθ between 23 kg m$^{-3}$ to 25 kg m$^{-3}$ marked by wider temperature range 23°C to 16°C and high salinity value ranging from 34.25 psu to 34.65 psu. The Pacific Thermocline Water (PTW) water masses signatures (> 34.5 psu) can be observed only during the SEM. In the deeper layer (> 25 kg m$^{-3}$), the water masses characterized by lower temperature (5°C to 15°C) and maximum salinity (> 34.5 psu) with no seasonal variation. These features of low temperature and maximum salinity correspond to the water the Pacific Intermediate Water (PWI). Our analysis of water masses characteristics which are described by the T-S diagram is consistent with the previous observation [7,12].

Figure 4. Observed temperature and salinity diagram of the Argo 6901746 and 6901747 in the Banda Sea.
4. Conclusion
A Lagrangian diagnostic and water masses analysis has been applied to the Argo float outputs in order to study circulation dynamics and water masses characteristics in the eastern Banda Sea. Two Argo floats i.e. reference number 690746 and 690747 were present in the region for two consecutive years starting from August 2017 to August 2019. We documented for the first time the appearance of cyclonic mean circulations in the eastern Banda Sea which may link to the presence of cyclonic eddy or gyre in the region. Our analysis also suggests that consecutive upwelling and downwelling occur seasonally in the region which would have important effects on thermocline stratification. Ekman-induced upwelling and downwelling are likely the main physical mechanism that leads to upwelling and downwelling in the Banda Sea. In general, the cyclonic circulations and upwelling in the Banda Sea are of great importance in controlling regional and seasonally high productivity and biodiversity. Lastly, our study highlights the significance of Argo floats in explaining the circulation in the least studied region like the Banda Sea.

References
[1] Spalding M D, Fox H E, Allen G R, Davidson N, Ferdaña ZA, Finlayson M 2007 Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience 57 573-83
[2] Feng M, Zhang N, Liu Q, Wijffels S 2018 The Indonesian throughflow, its variability and centennial change. Geosci Lett 5
[3] Molcard R, Fieux M, Ilahude A G 1996 The Indo- Pacific throughflow in the Timor Passage. J Geophys Res Ocean 101 12411–20
[4] Gordon A L 2005 Oceanography of the Indonesian Seas and their throughflow. Oceanogr 18
[5] Susanto R D and Song Y T 2015 Indonesian throughflow proxy from satellite altimeters and gravimeters. J Geophys Res Ocean 120 2844–55
[6] Wyrtki K 1958 The water exchange between the Pacific and the Indian Oceans in relation to upwelling processes. Proc 9th Pacif Sci Congr 61–6
[7] Wyrtki K 1961 Physical Oceanography of the Southeast Asian Waters. Naga Report, 2. (Scripps Inst Oceanogr) p 195
[8] Gordon A L, Ffield A, Ilahude A G 1994 Thermocline of the Flores and Banda seas. J Geophys Res Ocean 99 18235–42
[9] Spooner M I, Barrows T T, De Deckker P, Paterne M 2005 Palaeoceanography of the Banda Sea, and Late Pleistocene initiation of the Northwest Monsoon. Glob Planet Change 49
[10] Van Iperen J M, Van Bennekom A J, Van Weering T C E 1993 Diatoms in surface sediments of the Indonesian Archipelago and their relation to hydrography. Hydrobiologia 269 113–28
[11] Kinkade C, Marra J, Langdon C, Knudsen C, Ilahude A G 1997 Monsoonal differences in phytoplankton biomass and production in the Indonesian Seas: tracing vertical mixing using temperature. Deep Sea Res Part I 44 581–92
[12] Gordon A L and Susanto R D 2001 Banda Sea surface-layer divergence. Ocean Dyn 52 2–10.
[13] Argo 2020 Argo float data and metadata from Global Data Assembly Centre (Argo GDAC)
[14] Pawlowicz R 2020 M_Map: A mapping package for MATLAB
[15] Purwandana A, Cuypers Y, Bourret-Aubertot P, Nagai T, Hibiya T, Atmadipoera A S 2020 Spatial structure of turbulent mixing inferred from historical CTD datasets in the Indonesian seas. Prog Oceanogr 184 102312
[16] Bourret-Aubertot P, Cuypers Y, Ferron B, Dausse D, Ménage O, Atmadipoera A 2018 Contrast turbulence intensities in the Indonesian Throughflow: a challenge for parameterizing energy dissipation rate. Ocean Dyn 68 779–800
[17] Koch-Larrouy A, Atmadipoera A, van Beek P, Madec G, Aucan J, Lyard F 2015 Estimates of tidal mixing in the Indonesian archipelago from multidisciplinary INDOMIX in-situ data. Deep Res Part I 106 136–53
Acknowledgements
The authors would like to thank the international Argo Program and the national programs that made the data freely available via http://argo.jcommops.org. The publication of this research is supported by the funding scheme under the Deputy of Earth Sciences of the Indonesian Institute of Sciences (LIPI).