Geostrophic currents in the Northern Lembata Waters: from OTEC Cruise observation in September–October 2017

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Abstract. The Northern Lembata Waters (NLW) is located in the Flores Sea that its dynamics is strongly affected by Monsoon Current and the Indonesian Throughflow (ITF). This study aims to describe the physical characteristics of the waters and geostrophic current, using observation CTD data from OTEC Cruise 2017. The type of water mass is identified using T-S diagram, and geostrophic currents is determined using a reference level at 600 dbar. From its characteristics such as temperature, salinity, and density it can be deduced that the waters vertically stratified. It is revealed a strong geostrophic flow due to water density differences. In the upper layer (0–300 dbar) geostrophic velocity ranged from 12.59 to 343.93 cm s⁻¹ flowing eastward and in the deeper layer (300–600 dbar) geostrophic velocity (in section B) ranged from 7.66 to 49.19 cm s⁻¹ flowing westward. The eastward flow is considered to be part of the ITF, and the westward flow at deeper layer may be associated with density-driven flow between Banda and Flores Seas.

1. Introduction

The Northern Lembata Waters (NLW) is located in the eastern side of Flores Sea, and at the southwest side of Banda Sea. Both waters play an important role because it is the main path of the monsoon current system, thus forming a strong monsoonal current conditions [1]. During the northwest monsoon, the current flows from South China Sea towards the Java Sea, Flores Sea, and Banda Sea. In contrary, during the southeast monsoon, the current flows from Banda Sea towards the South China Sea. This current also known as Indonesian Monsoon Current (Armondo) [2]. Flores Sea is also crossed by the Indonesian Throughflow from Makassar Strait [3].

The currents in the ocean can be measured directly using the measuring device such as current meter or a moored buoy that was anchored in the water column. Undirect current measurement, using the geostrophic method is also used to describe the current that formed in the ocean. The current can be calculated using this method, but requires information on water density distribution in the ocean that can be obtained from measurements of temperature, salinity, and depth [4][5].

Geostrophic currents is formed from the balance between horizontal pressure gradient and Coriolis force that results from horizontal currents. It is assumed away from the top and bottom ekman layer, and at the distance of a few tens of kilometers horizontally and times for a few days [5]. Current is determined with the approach that fluid acceleration and friction effect is relatively small, and the horizontal velocity component is dominant than the vertical component, and affected by gravity as external force [4][5].
OTEC Cruise 2017 is an observation aimed at revealing OTEC potential as a renewable energy source in the East Nusa Tenggara. This study is part of the cruise program, which is to describe stratification and geostrophic flows. In Flores and Banda Sea, the study of ocean currents has been carried out. But in NLW it has not been studied. Therefore, this study aims to describe the physical characteristics of the seawater properties and geostrophic currents in NLW.

2. Data and data analysis

2.1. Study area
Research site is located in the north of Lembata Island (Figure 1). The two lines perpendicular to the coastline is used to describe the profile of physical characteristics such as temperature, salinity, density, and geostrophic currents. This study was conducted from March–November 2018 in Ocean Data Processing Laboratory and Physical Oceanography Laboratory, Department of Marine Science and Technology (ITK), Faculty of Fisheries and Marine Science, IPB University.

2.2. Data

2.2.1. OTEC cruise
The data used in this study are temperature, salinity, and depth from Conductivity, Temperature and Depth (CTD). This data is obtained from OTEC Cruise in 2017, a joint program between Marine Geological Institute (P3GL) and ITK. Data retrieval held on September 24–October 2, 2017 in NLW using the research vessel Geomarin III-P3GL. There are 30 CTD casts in this survey. However, only 9 CTD casts (in section A dan B) are used in this study. Length of section A is 8.7 km and section B is 12 km [6].

2.3. Research equipment
Equipment used to measure the temperature, salinity, and depth i.e. CTD SBE 19plus V2 profiler SeaCAT (Table 1) [6].
Table 1. CTD SBE 19plus V2 SeaCAT Profiler specification.

| Specification                        | Temperature (°C) | Conductivity (S/m) | Pressure (strain gauge sensor) |
|--------------------------------------|------------------|--------------------|-------------------------------|
| Measurement capability               | -5–35            | 0–9                | 0–7000 dbar                   |
| Sampling speed                       | 4 Hz (4 sample/s) |                    |                               |
| Communication                        | Baud rate 9600, 8 bits data |            |                               |
| Communication connectivity           | P/N 171883 Y-Cable |                    |                               |
| Memory                               | 64 Mbyte         |                    |                               |
| Conductivity frequency               | 2521.701 Hz      |                    |                               |

2.4. Data analysis

Temperature, salinity, and depth data used to describe the profile of physical characteristics of the waters and calculate the geostrophic currents in NLW in September–October 2017. Profile distribution of temperature, salinity, and density are presented to illustrate the water characteristics. This results describe the thickness and value of each layer. T-S diagram is used to identify the type of water mass in the study area [7].

Geostrophic currents is determined by assuming the depth is at reference level at 600 m [4]. To obtain geostrophic currents, it takes long distance horizontally. The distance between 2 station on section A is 8.7 km and section B is 12 km. The following equation for geostrophic currents (1):

\[
(V_1 - V_2) = \frac{1}{2\Omega sin \theta L} \int_{p_1}^{p_2} \delta_{B} dp - \int_{p_1}^{p_2} \delta_{A} dp
\]

Where, \((V_1 - V_2)\) is the difference between the velocity at pressure \(p_1\) and \(p_2\), averaged value between 2 station; \(\Omega\) = rotation degree of the earth of 7.29 x 10^{-5} rad/s; \(\delta\) = specific volume anomaly; \(L\) = distance between 2 station; and \(\theta\) = geographic latitude.

To obtain transport volume, it can be computed with the following formula [8]:

\[
10^6 T_y = \frac{10^{-4}}{L} \left( \int_{p_1}^{p_2} \delta dp \left| \int_{z_n}^{z_o} \left[ \int_{p_1}^{p_2} \frac{d \delta_{B}}{dz} \right] dz \right| A \right) + \frac{10^{-4}}{L} \left( \int_{p_1}^{p_2} (z_0 - z) \delta dp \right) A
\]

Where, \(A\) and \(B\) are the limits of the horizontal; \(z_0\) and \(z_n\) is vertical limit; \(z_0\) is located on the surface above \(p_1\); \(z_0 - z\) is depth observations. Volume transport (\(T_y\)) has sverdrups unit (1 Sv = 10^6 m^3 s^{-1}) and is not affected by the distance \(L\) between 2 station.

3. Results and discussion

3.1. Temperature and salinity distribution

Temperature and salinity changes with depth. It can be divided into 3 layers vertically, surface mixed layer, thermocline layer, and deep layer [9]. Surface mixed layer in section A has a depth is ranged from 3–80 m and section B is 3–68 m. For temperature, section A (Figure 2a) is ranged from 26.39–28.95 °C and section B is ranged from 25.67–28.76 °C. And each salinity is ranged from 33.86–34.02 and 33.89–34.09. Surface mixed layer thickness range from 10–200 m in the tropics region, where temperature is relatively constant due to turbulence that generated by wind, and salinity is more lower because affected by rainfall [1][5].

Change in temperature and salinity is relatively large below the surface mixed layer. This layer known as thermocline layer. Thermocline layer in section A has a depth is ranged from 42–238 m and section B is 37–237 m. For temperature, section A is ranged 10.39–28.13 °C and section B is ranged from 10.81–28.50 °C. And each salinity is ranged from 33.90–34.50 and 33.89–34.46. In thermocline
layer, temperature gradient more than 0.1 °C m⁻¹. Layer position usually starts from the depth of 10 m to 500 m, while for the tropics near the surface [9]. The upper layer is at 37 m. This indicates that the thermocline layer position is near the surface.

Temperature and salinity decreased relatively constant below the thermocline layer. This layer is deep below the water, known as deep layer. In section A, the depth is ranged from 196–1133 m and section B is 166–1417 m. Some stations have a thickness more than 1000 m (>1 km). For temperature, section A is ranged 4.21–12 °C and section B is 3.68–13.76 °C. And each salinity is ranged from 34.40–34.60 and 34.42–34.61. This layer is formed down to the bottom of the sea with its temperature and salinity relatively uniform [9].

3.2. Potential density anomaly distribution and T-S diagram
Density changes increasingly with depth. The value of density is affected by temperature, salinity, and pressure [10]. Density increases with increasing salinity and pressure, and decreasing temperature. Surface mixed layer density in section A (Figure 4a) is ranged from 21.62–22.43 kg m⁻³ and section B (Figure 4b) is 21.69–22.69 kg m⁻³. Density changes rapidly in thermocline layer, in section A it is ranged from 21.83–26.46 kg m⁻³ and section B is 21.74–26.41 kg m⁻³. The large density difference indicates the stability of thermocline layer in separating the surface and deep layer effectively [9]. But it does not mean that the two layers interaction is disconnected, at the particular time and place, there was a vertical transport connecting both [11]. In deep layer, each density is ranged from 26.13–27.47 kg m⁻³ and 25.85–27.53 kg m⁻³.

Figure 2. (A) Temperature distribution in section A and (B) section B.
Figure 3. (A) Salinity distribution in section A and (B) section B.

Figure 4. (A) Density distribution in section A and (B) section B.
Figure 5. T-S diagram in section A (left) and section B (right).
T-S diagram is used to identify water mass in NLW. The ITF might pass NLW because if its location near the Flores and Banda Sea. Water mass is identified using its salinity maximum (S-max) and salinity minimum (S-min). Range of salinity (S-max) at range near 14 °C shows the characteristics of North Pacific Subtropical Water (NPSW), and salinity range (S-min) about 34.40 at 10 °C shows the characteristics of North Pacific Intermediate Water (NPIW) [7]. S-max can be found in section A (Figure 5) at 169 m with salinity about 34.51 and temperature at 14.77 °C. And S-min can be found in section A and B (Figure 5) at a depth of 252–263 m with salinity about 34.45 at 9.98–10 °C. Some research in the Flores Sea indicates that the value of S-max can be found at 150–200 m with salinity of 34.50 and S-min is at 200–400 m with salinity of 34.46 [1][12]. S-max changes from 34.90 to 34.53 and S-min changes from 34.35 to 34.47 near the ITF outflow [13]. This changes is affected by strong vertical mixing along the ITF pathway [7].

3.3. Geostrophic currents and transport volume

Geostrophic currents which has a negative value shows the flow is westward and the positive is eastward. It velocity in section A ranged from 1.24 to 132.52 cm s⁻¹ and section B is 7.66 to 343.93 cm s⁻¹. The highest velocity are 132.52 cm s⁻¹ at 66 m in section A and 343.93 cm s⁻¹ at surface (0 m) in section B. Its velocity become relatively very small near the reference level from 0.04x10⁻¹² to 1.25x10⁻¹² cm s⁻¹.

Flow direction can be devided into 2 parts, the eastward flow at 0–300 m (upper layer) and the westward flow at 300–600 m (deeper layer). Water mass transport that flows easward is 3.35 Sv in section A. For section B, the eastward flow is 5.14 Sv and the westwards is 1.4 Sv. Geostrophic currents showed a considerable result that the highest velocity is 343.93 cm s⁻¹. To calculate the geostrophic currents required a horizontal distance above 50 km [5]. This is necessary to minimize the internal waves and tidal effect [14].

In general, the eastward flow in section A and B is ranged from 12.59 to 343.93 cm s⁻¹. Section B which is located on the west side has a higher velocity than section A on the east side. It is thought to be affected by the ITF that flows from Sulawesi Sea to Makassar Strait and turn east towards the Banda Sea [13]. Other study indicate that water mass transport that flows through Flores Sea at 300 m is part of North Pacific Waters [14]. In this study, the results indicate that NPSW and NPIW were found in NLW. For the westward flow, it can be inferred that there is water mass from Banda Sea entering NLW.
below 300 m [14]. Its velocity is ranged from 7.66–49.19 cm s\(^{-1}\) in section B. However, further study in NLW needed to determine the water mass that flows from Banda Sea.

4. Conclusion
Stratification of water masses in the NLW is indicated vertically with 3 layers, i.e. surface mixed layer, thermocline layer, and deep layer. North Pacific water masses origin (NPSW and NPIW) are found here. Section A which is located on the east side is affected by the ITF that transport NPSW and NPIW. Then, section B which is located on the west side is also affected by Banda Sea transport at the deeper layer. Geostrophic flow in section B has a higher velocity than section A. Transport volume in section A is 3.35 Sv (flows eastward). In section B, transport volume at the upper layer is 5.14 Sv (flows eastward) and at the deeper layer is 1.4 Sv (flows westward). Total transport volume which flows eastward has greater volume than the westward.

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