The Ocean Heat Content of Lombok Strait Water Masses in 2011 – 2015

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Abstract. The Lombok Strait that located between the island of Bali and Lombok is one of the seas in Indonesia that connects the Pacific Ocean and the Indian Ocean. Therefore, the characteristics of the Lombok Strait waters get influence from those oceans. In this research, the analysis of water masses in the Lombok Strait waters are investigated and analysed by using T-S diagram. The main data used are temperature and salinity from the HYbrid Coordinate Ocean Model (HYCOM) model in 2011 – 2015 with 1/12° x 1/12° horizontal resolution and vertical resolution up to 1500 m. The T-S diagram was used to identify the water masses contribution in the Lombok Strait and the ocean heat content (OHC) was calculated for each water mass. The Timor Sea Water (TSW) and Australasian Mediterranean Water (AAMW) contributed maximally in thermocline layer with 65.85% of the total heat content (1.12 x 10¹³ J/m²) and 24.46% (4.16 x 10¹² J/m²). Then, The Antarctic Intermediate Water (AAIW) and Banda Intermediate Water (BIW) contributed maximally in intermediate layer (500 – 1500 m) with 8.17% of total heat content (1.39 x 10¹² J/m²) and 1.52% (2.59 x 10¹¹ J/m²). In addition, the ocean heat content of each water mass was influenced by El-Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). The ocean heat content of TSW and BIW increased when El-Niño and positive of IOD appeared and decreased during La-Niña and negative of IOD. Conversely, the ocean heat content of AAMW and AAIW decreased when El-Niño and positive of IOD appeared and increased during La-Niña and negative of IOD.

Keywords: Water Masses, TS diagram, Ocean Heat Content, El-Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Lombok Strait.

1. Introduction

The Lombok Strait that located between the island of Bali and Lombok is one of the seas in Indonesia that connects the Pacific Ocean and the Indian Ocean. In addition, The Lombok Strait is one of the biggest exit way for the Indonesian Throughflow (ITF) which connects the Pacific Ocean to the Indian Ocean, so that the characteristics of the Lombok Strait waters get influence from those oceans as display in figure 1.
According to Wyrtki (1961), the water masses in Indonesian waters from the North Pacific Ocean are NPIW (North Pacific Intermediate Water) and NPSW (North Pacific Subtropical Water), while the water masses from the South Pacific Ocean are SPSW (South Pacific Subtropical Water) and SPIW (South Pacific Intermediate Water). Furthermore, specific studies of water masses have been carried out in the Lombok Strait and two water masses from the Indian Ocean were identified, namely North Indian Subtropical Water (NISW) and Australasian Mediterranean Water (AAMW) [4]. On the other hand, Wijffels et al. (2002), Wyrtki (1961), Emery et al. (1986) explained that there were local water masses, namely Indonesian Intermediate Water (IIW) or Banda Intermediate Water (BIW) and Indonesian Upper Water (IUW) or Timor Sea Water (TSW) in the Ombai Strait and Timor Strait that were carried by the South Equatorial Current (SEC) and ITF to the Indian Ocean (14° LS - 10° LS). The characteristic of those water masses could be seen in Table 1.

Table 1. Water Masses Characteristic (Source: Wijffels et al., 2002; Wyrtki, 1961; Emery and Meincke, 1986; You et al., 1993)

| Water Masses                                | Salinity (ppt) | Temperature (°C) |
|---------------------------------------------|----------------|------------------|
| North Pacific Subtropical Water (NPSW)      | 34.8 – 35.2    | 20 – 24          |
| South Pacific Subtropical Water (SPSW)      | 34.6 – 35.3    | 13 – 24          |
| North Pacific Intermediate Water (NPIW)     | 34.1 – 34.5    | 7 - 11           |
| South Pacific Intermediate Water (SPIW)     | 34.45 – 34.66  | 5 – 7            |
| Antarctic Intermediate Water (AAIW)         | 33.8 – 34.5    | 2 – 10           |
| Timor Sea Water (TSW)                       | 34.4 – 35.0    | 8 – 23           |
| North Indian Subtropical Water (NISW)       | 34.6 – 36.0    | 16 – 19          |
| Banda Sea Intermediate Water (BIW)          | 34.5 – 34.9    | 4.5 - 6          |
| Australasian Mediterranean Water (AAMW)     | 34.5 – 34.7    | 5.5 – 15         |

The presence of the Lombok Strait that located between the Pacific and Indian Ocean caused this area is being affected by phenomena that occur in those oceans such as El-Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) [8]. ITF regulates the hot pools position in the Indian Ocean and controls the depth of the thermocline, which will indirectly affect the climate in the tropics and middle latitudes. One of the factor that might influence the current climate change is the heat content inside the water [9].
ITF plays a major role on the contained heat content and the pattern of sea surface temperatures which are closely related to the events of ENSO, IOD, and the Monsoon system in Asia.

The ocean-atmosphere interactions control the climate on earth. Transport of heat energy from the atmosphere and the oceans is important in controlling the climate. Most of the heat absorption occurs in the oceans due to 70% of the earth's surface is covered by sea water. Global seawater warming in layers between 0 - 2000 m has increased around 0.09 °C and in layers between 0 - 700 m has increased around 0.18° C as display in figure 2 [10]. The warming of sea water caused expansion in seawater and if accompanied by melting ice on land it will cause a sea level rise, which can make a disruption for natural marine ecosystems and will also threaten the human life.

![Figure 2. Time Series of World Ocean Heat Content (10^{22} J) in 1995-2006 for 0 – 2000 m depth (red line) and 700 – 2000 m depth (black line) based on WOD 2009 Data (Source: Levitus et al., 2012)](image)

In addition, most of the research that has been done only examines the type of water mass in an area and its volume transport, whereas the research that related to the ocean heat content for each water mass is still limited. Therefore, this study will examine the heat content for each water mass which is influenced by atmospheric-oceanographic phenomena such as ENSO and IOD, especially in the Lombok Strait. Then, this study was conducted to determine the composition of the water masses and to determine the ocean heat content that carried by each water mass, so that the origin of the water masses in the Lombok Strait and the water mass with dominant heat content can be known.

2. Data and Method

The main data used in this study are temperature and salinity from the HYbrid Coordinate Ocean Model (HYCOM) model in 2011 – 2015 with 1/12° x 1/12° horizontal resolution and vertical resolution up to 1500 m depth. The location of the data used is located in one meridional transect in the Lombok Strait waters with coordinates 7.92° - 9.12° of South Latitude and 115.76° of East Longitude with a total of 16 stations as displayed in Figure 3.
To find out what water masses occupy Lombok Strait, we set up one meridional transect (red line) to draw the T-S Diagram. The processed data were summed for each season, which is divided into two seasons namely the boreal winter represented by December-January-February (DJF) and the boreal summer represented by June-July-August (JJA). Firstly, The T-S Diagram were drawn to identify the water masses and the ocean heat content (OHC) of each water mass were calculated by a formulation from Kumar et al. [11]:

$$OHC = C_p \sum_{k=2}^{n} \rho_k (T_{h1} - T_k) (Z_k - Z_{k-1})$$

where $C_p$ is the specific heat of sea water which has a value of 4184 J kg$^{-1}$K$^{-1}$, $\rho_k$ is the density of sea water at a depth ($k$) (kg / m$^3$) and $T_{h1}$ is the temperature at the surface for each water mass and $T_k$ is the temperature at the depth ($k$) (°C), $Z_k$ is the depth ($k$) and $Z_{k-1}$ is the depth ($k-1$) (m). The data to calculate this OHC is from all stations occupies the whole study area as in the meridional transect in figure 3.

3. Result and Discussion
a. Water Masses

In this research, in the waters of Lombok Strait were found four types of water masses: TSW (Timor Sea Water), AAMW (Australasian Mediterranean Water), AAIW (Antartic Intermediate Water), and BIW (Banda Intermediate Water). Those water masses were carried by the currents that move around the Lombok Strait. AAIW that is formed in the Atlantic was carried out by Thermohaline Circulation (large-scale ocean circulation) to Indonesian Waters through the Pacific Ocean. Then, AAIW entered Indonesian Waters through the Makassar Strait and Halmahera Sea due to ITF and goes to Lombok Strait waters. In addition, TSW, AAMW, and BIW that were found in Indian Ocean were carried to Lombok Strait due to SEC, SJC, and ITF at the south of Lombok Strait [8].
We can see in table 2 that the thermocline layer was identified around 80 – 400 m depth. The water masses that play a major role in the thermocline layer were TSW and AAIW at 70 – 500 m depth. Then, the water masses that contributed maximally in the intermediate layer (below the thermocline layer) are AAIW and BIW at 500 – 1500 m depth.

Table 2. Types of Water Masses in Lombok Strait and it’s Characteristic

| No | Type of Water Mass | Depth (m)   | Temperature (°C) | Salinity (ppt) |
|----|--------------------|-------------|------------------|---------------|
| 1  | TSW                | 70 – 500 m  | 8 – 23           | 34.4 – 35.0   |
| 2  | AAMW               | 150 – 800 m | 5.5 – 15         | 34.5 – 34.7   |
| 3  | AAIW               | 450 – 1000 m| 2 – 10           | 33.8 – 34.5   |
| 4  | BIW                | 1000 – 1500 m| 4.5 – 6         | 34.5 – 34.9   |
b. Ocean Heat Content (OHC) of The Water Masses

Each water mass carried the heat content from the formation area and had a different magnitude. The water mass that had the biggest volume (thickest) would also have the biggest ocean heat content. We already had calculated for the total ocean heat content from the entire water masses in the Lombok Strait in 2011 – 2015, that was $1.7 \times 10^{13} \text{J/m}^2$. In Figure 5, we can see that the TSW had the largest contribution among other water masses with a total heat content around 65.85% ($1.12 \times 10^{13} \text{J/m}^2$) of the total heat content. TSW had the biggest temperature and salinity range, so the TSW had a larger and thicker volume among other water mass and would have the biggest heat content also. Then, the AAMW around 24.46% ($4.16 \times 10^{12} \text{J/m}^2$), AAIW about 8.17% of total heat content ($1.39 \times 10^{12} \text{J/m}^2$) and BIW around 1.52% ($2.59 \times 10^{11} \text{J/m}^2$) based on their thickness of the layer.

The Lombok Strait is one of the Indonesian seas that connects the Pacific Ocean and the Indian Ocean, consequently this area was being affected by phenomena that occurred in these two oceans such as ENSO and IOD. The effect on ENSO and IOD could be seen in the 100 m depth temperature as displayed in figure 6. When El-Niño and Positive IOD occurred (September 2015), the 100 m depth temperature decreased. Conversely, when La-Niña and Negative IOD occurred, the 100 m depth temperature increased (Mei 2013).
Furthermore, we can see from figure 7 (a) and (b) that the heat content of TSW and BIW had a positive correlation with ONI and DMI. This correlation showed that when El-Niño and Positive IOD occurred, the heat content of TSW and BIW increased, but it decreased during La-Niña and negative IOD. We know that when El-Niño and positive IOD occurred, the ITF would have weaker contribution to Indonesian seas, specifically to Lombok Strait. This caused the contribution of TSW and BIW that was from the Indian Ocean would increase due to declining contribution from AAIW and AAMW.

![Figure 7. Ocean Heat Content of (a) TSW, (b) BIW, (c) AAMW, (d) AAIW and its Correlation with ONI and DMI in 2011 – 2015](image)

On the other hand, in figure 7 (c) and (d) we know that the heat content of AAMW and AAIW had a negative correlation with ONI and DMI. This correlation showed that when El-Niño and positive IOD occurred, the heat content of TSW and BIW would decrease, while increasing during La-Niña and negative IOD. The volume of ITF was stronger when La-Nina and Positive IOD occurred, so that the contribution of AAIW that was from the Pacific Ocean would also be stronger. Then, the AAMW that was carried by ITF also getting stronger when ITF was stronger.

4. Conclusion

Based on the results of data processing in 2011 – 2015 from HYCOM, four types of water masses had been identified in Lombok Strait waters, namely Timor Sea Water (TSW), Australasian Mediterranean Water (AAMW), Antarctic Intermediate Water (AAIW) and Banda Intermediate Water (BIW). The TSW and AAMW contributed maximally in thermocline layer, while the AAIW and BIW contributed maximally in intermediate water. On the other hand, the total value of ocean heat content of each water mass is \(1.7 \times 10^{13} \text{J/m}^2\). The TSW (biggest water volume thickness) had the highest heat content around 65.85% in Lombok Strait waters, while BIW is the lowest (smallest water volume thickness) with 1.52% of the total heat content. Furthermore, the heat content of TSW and BIW had a positive correlation with ONI and DMI, however the heat content of AAMW and AAIW had a negative correlation with ONI and DMI.
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