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North-south difference of water mass properties across the Lembeh Strait, North Sulawesi, Indonesia

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Abstract

Two field observations were conducted around the Lembeh Strait in September 2015 and 2016, respectively. Evidences indicate that seawater around the Lembeh Strait is consisted of North Pacific Tropical Water (NPTW), North Pacific Intermediate Water (NPIW), North Pacific Tropical Intermediate Water (NPTIW) and Antarctic Intermediate Water (AAIW). Around the Lembeh Strait, there exist some north-south differences in terms of water mass properties. NPTIW is only found in the southern Lembeh Strait. Water mass with the salinity of 34.6 is only detected at 200–240 m between NPTW and NPTIW in the southern Lembeh Strait, and results from the process of mixing between the saltier water transported from the South Pacific Ocean and the lighter water from the North Pacific Ocean and Sulawesi Sea. According to the analysis on mixing layer depth, it is indicated that there exists an onshore surface current in the northern Lembeh Strait and the surface current in the Lembeh Strait is southward. These dramatic differences of water masses demonstrate that the less water exchange has been occurred between the north and south of Lembeh Strait. In 2015, the positive wind stress curl covering the northern Lembeh Strait induces the shoaling of thermocline and deepening of NPIW, which show that the north-south difference of air-sea system is possible of inducing north-south differences of seawater properties.

Key words: water mass, Lembeh Strait, north-south difference

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1 Introduction

The coral triangle (CT) is so named as it refers to a roughly triangular area of the tropical marine waters of Indonesia, Malaysia, Papua New Guinea, the Philippines, the Solomon Islands, and Timor-Leste (Barber, 2009; Castruccio et al., 2013; White et al., 2014). While only covering 1.6% of the planet's oceanic area, the region has 76% of all known coral species in the world (Hoegh-Guldberg et al., 2009). As a habitat for 52% of Indo-Pacific reef fishes and 37% of the world's reef fishes, it encompasses the highest diversity of coral reef fishes in the world (Hoegh-Guldberg et al., 2009). The CT is recognized as the global center of marine biodiversity (Barber, 2009; Kleypas et al., 2015) and a global priority for conservation (Castruccio et al., 2013).

The oceanographic complexity and importance on preserving the CT, however, present challenges for understanding the roots of this spatial variability. Several importance field observations funded by Western Equatorial Pacific Ocean Circulation Study (WEPOCS) and Arus Lintas Indonesia (Arlindo) were implemented and provided large amounts of hydrographic data to discuss the characteristics of water masses (Fine et al., 1994; Hautala et al., 1996; Kashino et al., 1996), stratification isopycnal mixing and vertical mixing (Hautala et al., 1996). In recent years, the International Nusantara Stratification and Transport program (INSTANT) was established to directly measure the dependent ITF from the intake of Pacific water at Makassar Strait and Lifamatola Passage, to the Nusa Tenggara exit channels into the Indian Ocean (Susanto et al., 2007; Gordon et al., 2010; Metzger et al., 2010). A joint investigation on the air-sea interaction between US and China (1985–1990) was conducted to investigate the hydrographic features and equatorial current system in the western equatorial Pacific Ocean (Du and Fang, 2011). Whereas, the investigation on the variation of the water mass properties entering into the Indonesia seas is rare.

Within the upper 300 m, observations indicated that the Indonesia Through Flow (ITF) (Fig. 1) consists mostly of North Pacific thermocline and intermediate water (McCreary et al., 2007; Mayer and Damm, 2012) carried by Mindanao Current from the North Pacific Ocean (Gordon and McClean, 1999; Ffield and Robertson, 2008). In the deep channels east of Sulawesi, South Pacific water carried by New Guinea Coastal Current infiltrates isopycnally into the lower thermocline and dominates the deeper layers, including the overflow into the deep Banda Sea (Mayer and Damm, 2012; Sprintall et al., 2014). The incoming stratified Pacific thermocline waters altered by strong air-sea fluxes, monsoonal wind-induced upwelling and extremely large tidal forces (Ffield and Gordon, 1996; Schott and McCreary, 2001; Gordon, 2005; Ffield and Robertson, 2008; Kartadikaria et al., 2011; Sprintall et al., 2014), such that the distinctive salinity maximums originating from the North Pacific (salinity of 34.8 at 100 m) and the South Pacific Ocean (salinity of 35.4 at 150 m) disappear while

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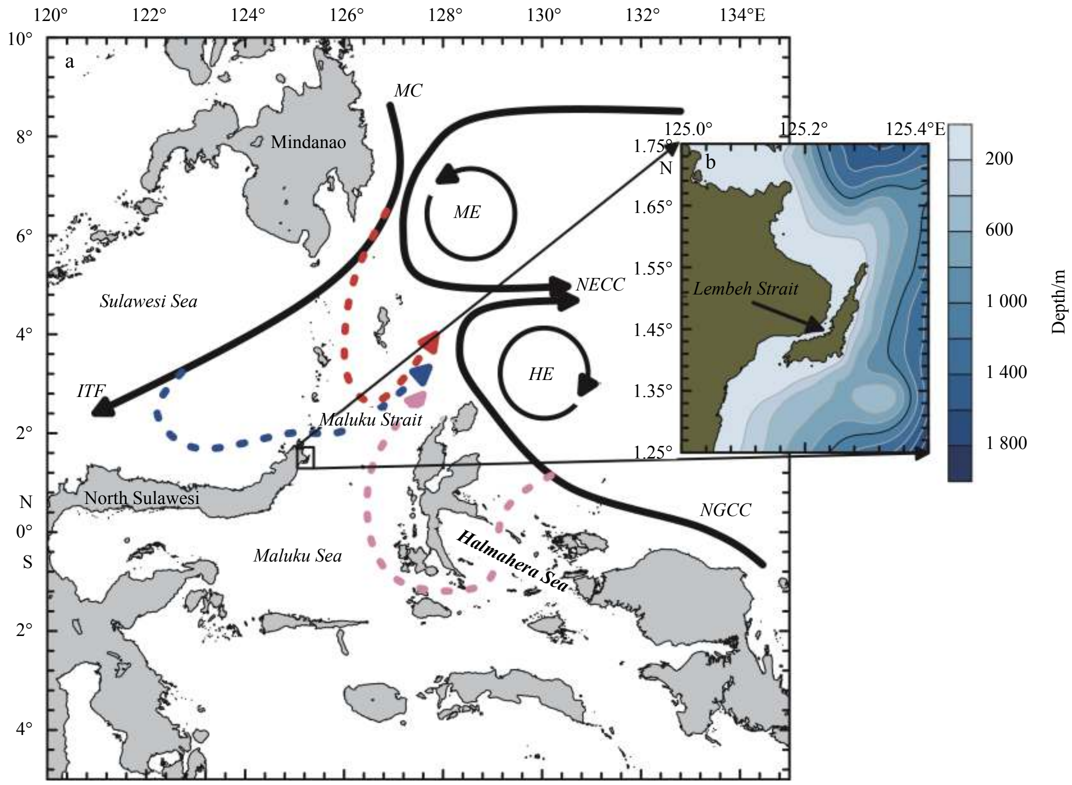

Fig. 1. Schematic of the surface-subsurface current pattern between Mindanao and New Guinea (a), based on Kashino et al. (1999) and Susanto et al. (2007), i.e., Mindanao Current (MC), North Equatorial Countercurrent (NECC), New Guinea Coastal Current (NGCC), the Mindanao Eddy (ME), the Halmabera Eddy (HE), and Indonesia Through Flow (ITF). The observation region (b) around the Lembeh Strait is marked by black rectangle.

within the Indonesian seas (Hautala et al., 1996). Meanwhile, some evidences indicated that the hydrological environment in the Maluku Strait is able to be influenced by the water mass originated from Sulawesi Sea, North Pacific Ocean and South Pacific Ocean together (Susanto et al., 2007).

Desiring to promote the deeper understanding of marine biodiversity conservation and ecosystem management, marine environmental protection and monitoring technology, and development and utilization of marine bio-resources on CT, the "China-Indonesia Bitung Ecological Station Establishment" project was signed and conducted between Research Center for Oceanography, Indonesian Institute of Sciences (RCO-LIPI) and Third Institute of Oceanography, Ministry of Natural Resources (TIO-MNR). The field observation region is off the extreme northern coast of Sulawesi Island, and near the channel between the Sulawesi Sea and Maluku Sea, as shown in Fig. 1. Evidences indicated that there is a dramatic north-south difference in biodiversity around the Lembeh Strait. The few hydrological data limit the understanding of north-south differences. In 2015, in the context of the "China-Indonesia Bitung Ecological Station Establishment" project successfully cooperated three years, there is a need to deploy subsurface mooring system (SMS) in the Lembeh Strait to understand the interior oceanic circulation and to provide plausible explanations for the north-south differences in biodiversity. Therefore, TIO-MNR and RCO-LIPI agree to conduct the "Subsurface Mooring System (SMS) and Physical Oceanography in Lembeh Strait" project together, in which RCO-LIPI is responsible for the scheduling of the research vessel and TIO-MNR is responsible for the SMS deployment. Under the consideration of the north-south difference in marine biodiversity, CTD observations have also been implemented before the deployment and retrieving of SMS. The field observation region is chosen around the Lembeh Strait.

2 Materials

2.1 *The details of topography at the north and south of Lembeh Strait*

In the middle of Lembeh Strait (Fig. 1b), the seabed is shallower and flatter than those in the north and south side of Lembeh Strait, and has the average depth of 30 m. At the northern Lembeh Strait, from the mouth of Lembeh Strait to a distance of about 1 000 m following the direction of Section NT2 in Fig. 2, the seabed is flat with the depth between 125 m and 150 m. Beyond 1 km, the seabed morphology has a slope about 8° and the water depth varies from 150 m to about 500 m. When the distance exceeds 6 km, the slope of seabed reaches 11°. The seabed in the southern Lembeh Strait is even flatter than that in the northern Lembeh Strait. Following the direction of Section ST3, the depth changes from 70 m to 750 m with a slope of about 5° within the distance of 6 km.

2.2 *The details of the observation stations*

In 2015, the CTD observation was conducted on September 27–29 and consisting of 15 and 7 stations at northern and southern Lembeh Strait respectively, as shown in Fig. 2a. In 2016, the field observation was carried out on September 17–19, consisting of 14 and 11 stations at the northern and southern Lembeh Strait respectively, as shown in Fig. 2b. Measurement of the characteristics of water masses with CTD 911 Plus installed on Research

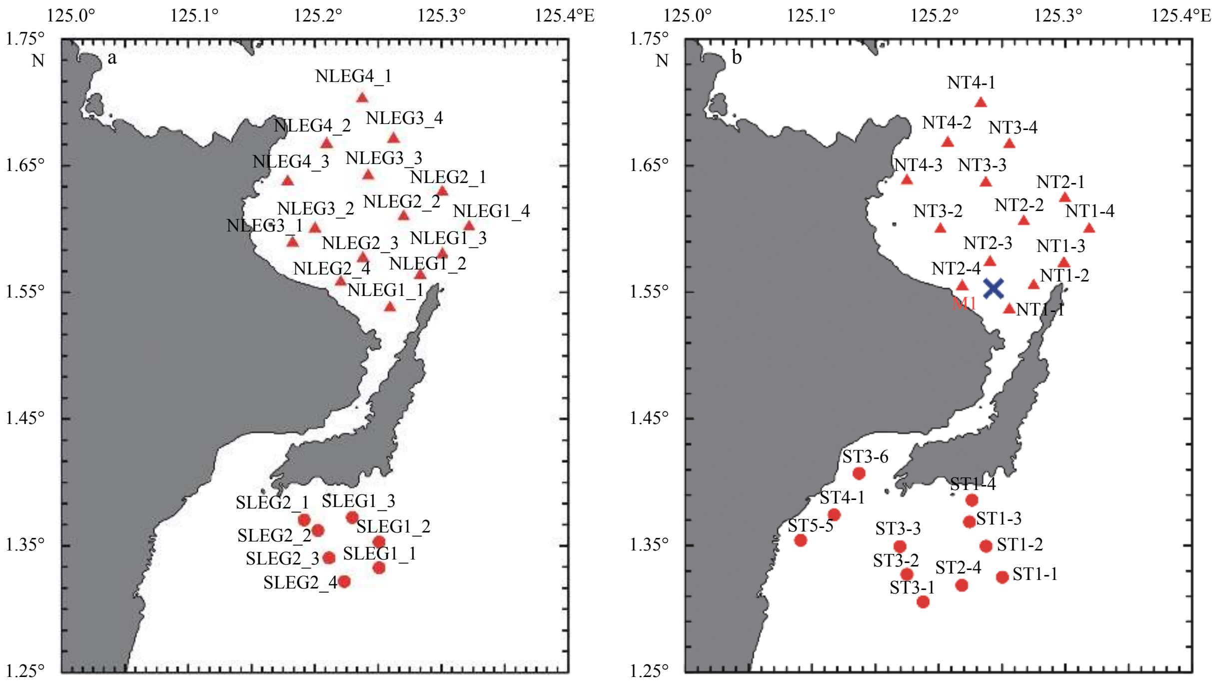

Fig. 2. Map of CTD stations observed in 2015 (a) and 2016 (b). The red triangles represent the northern station of Lembeh Strait, and the red dots are the southern station of Lembeh Strait. The blue cross is the location of Subsurface Mooring System (SMS, M1).

Vessel Baruna Jaya VIII. The collected parameters include temperature, conductivity, density and chlorophyll.

A mooring system marking by cross in Fig. 2b is successfully retrieved in the northern Lembeh Strait on September 17, 2016. The SMS designing to acquired long-term ocean currents profiles, was deployed at 1°33.194′N, 125°14.36′E at 359 m on October 1, 2015. A 75 kHz ADCP is mounted at 40″ glass floats locating at the depth of about 250 m. Two JFE CTD with the type of A7CT-USB are mounted at the depth of 272 m and 314 m respectively and acquire the temperature and salinity of sea water. Another two RBR with the type of TDR–2050 are mounted at the depth of 291 m and 331 m respectively and acquire the temperature and pressure of sea water.

2.3 *Argo floats*

From January 2015 to October 2016, the profiles of Argo floats in Pacific Ocean and Sulawesi Sea are chosen to make a comparison of the profiles on the properties of water mass around the Lembeh Strait. The quantity and location are detailed in Section 3.2.

3 Water mass properties around the Lembeh Strait

In field observation region, also called as "a water mass crossroads" (Fine et al., 1994) because of the thermocline and intermediate waters from the northern and southern Pacific Ocean, there exist several water masses (Wyrtki, 1987; Kashino et al., 1996), as shown in Table 1. Here, the CTD data in 2016 was analyzed to examine the seawater properties in the southern and northern Lembeh Strait respectively.

3.1 *Water mass properties*

In the northern Lembeh Strait, the listed water masses in Table 1 are able to be identified in Fig. 3a. Water mass with the maximum salinity around σ_θ=24.5 kg/m^3 is identified as the North Pacific Tropical Water (NPTW) at the 100–200 m depth layer. Water mass with the minimum salinity around σ_θ=26.5 kg/m^3 is the North Pacific Intermediate Water (NPIW) with the range of 240–320 m. Under NPIW, there exists a salinity minima at σ_θ= 27.2 kg/m^3, which is identified as Antarctic Intermediate Water (AAIW). At the NPIW layer, the two stations with the anomaly of salinity are NT1–4 and NT2–1, both of which locate at the most east in all northern stations.

In the southern Lembeh Strait (Fig. 4), we can see the similar T-S diagram with Fig. 3a. The water mass with the maximum salinity is NPTW, but which is around σ_θ=24 kg/m^3. The water mass with the minimum salinity is NPIW, whose isopycnal is consisted with the stations in the northern Lembeh Strait. Under NPIW, water mass which presents salinity maxima is different from in the northern Lembeh Strait. Bingham and Lukas (1995) identified it as North Pacific Tropical Intermediate Water (NPTIW). The limit of observation depth less than 500 m in southern stations causes the absence of AAIW.

Table 1. The main water mass properties, listed by Hautala et al. (1996) and Wyrtki (1987)

Core layer		T/°C	S	σ_θ/kg·m^{-3}
North Pacific Tropical Water (NPTW)	S_{max}	15–23	34.6–35.1	24.5
South Pacific Tropical Water (SPTW)	S_{max}	13–24	34.6–35.3	24.5
North Pacific Intermediate Water (NPIW)	S_{min}	7–11	34.1–34.5	26.5
Antarctic Intermediate Water (AAIW)	S_{min}	5–7	34.45–34.6	27.25

Note: S_{max} and S_{min} represent the existence of the maximum and minimum of salinity respectively.

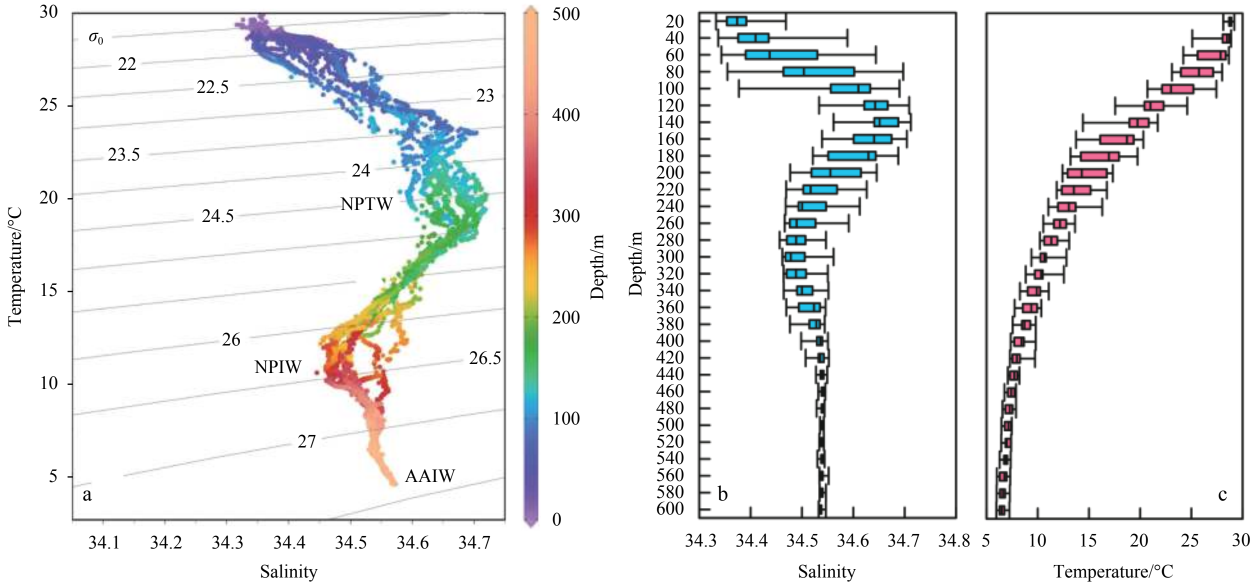

Fig. 3. T-S Map (a) in all northern stations and the box-plot for salinity profiles (b) and temperature profiles (c) of all northern stations.

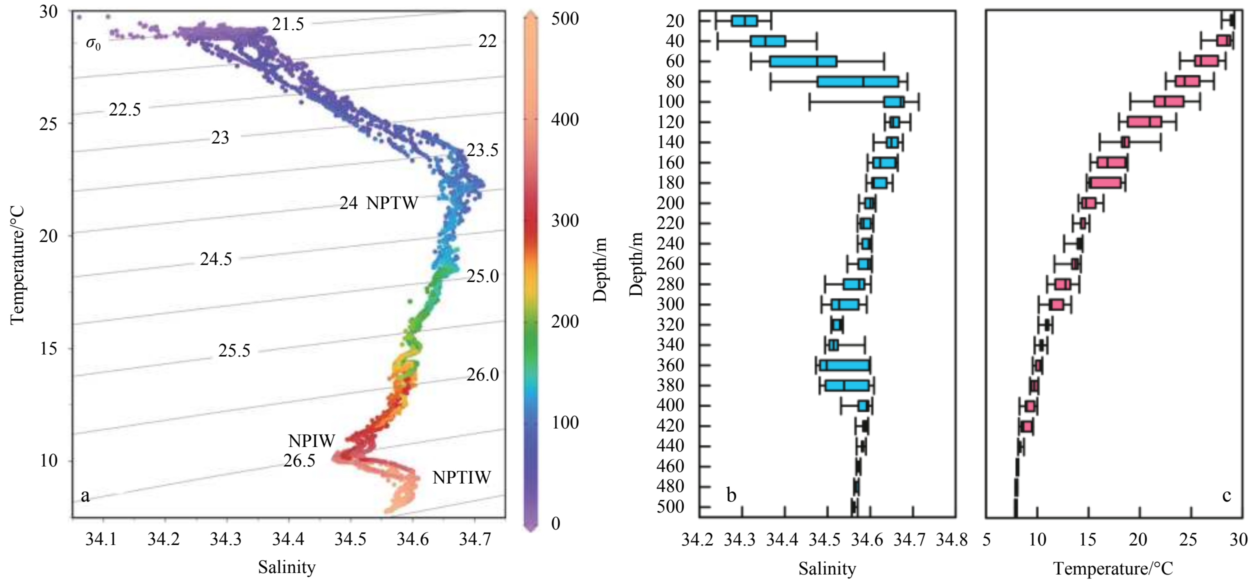

Fig. 4. T-S Map (a) in all southern stations and the box-plot for salinity profiles (b) and temperature profiles (c) of all southern stations.

3.2 *The north-south difference of water mass properties*

The comparison on the properties of water mass between the north and south of Lembeh Strait unveils the following differences.

(1) Mixed layer depth (MLD)

Mixed layer depth is calculated according to the criterion which is a threshold value of temperature or density from a near-surface value at 10 m depth (ΔT=0.2°C or $\Delta\rho_\theta$=0.03 kg/m^3), as shown in Fig. 5a. The criterion is detailed in de Boyer Montégut et al. (2004).

Among observation stations, the maximum value of MLD, equal to 72 m, is at NT3–3. The minimum value of MLD, equal to 30 m, is at ST1–1. In the north of Lembeh Strait, the closer the station is to the coast of Sulawesi Island, the greater the value of MLD is. MLD along Section N3 is deeper than in other section. In the southern Lembeh Strait, MLD is less than in the northern Lembeh Strait. The maximum value of MLD is close to the south mouth of Lembeh Strait. The minimum value of MLD is far from the coast.

In terms of the average salinity of MLD (Fig. 5b), it is decreasing gradually from north to south. The maximum value lies the most east which is far from the northern coast. The minimum value is at most southern station. In the northern Lembeh Strait, due to the effect of terrestrial freshwater, the salinity at the mouth of Lembeh Strait is smaller than other area. In the southern Lembeh Strait, because of the influence of river in the east of southern observation region, the spatial difference of salinity is smaller than in the north.

In the northern Lembeh Strait, from the dramatic difference of MLD, it is deduced that a strong current from open ocean

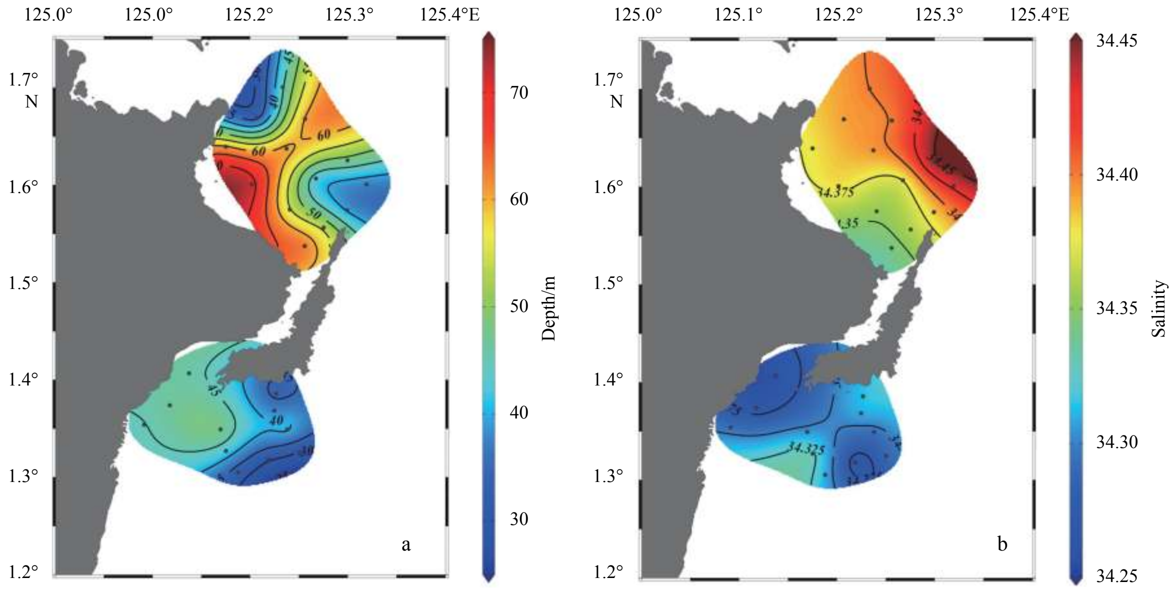

Fig. 5. The distribution of mixed layer depth (a) and the average salinity (b) in MLD in 2016.

should pour into the northern Lembeh Strait along Section N3 and the sea water is stacked off the coast. Because of the limit of the topography, the sea water only in upper 45 m pass through the Lembeh Strait southward, which are verified by the SMS as well.

(2) NPTW

In the northern Lembeh Strait, the maximum salinity reaches 34.7 which is much smaller than 35.1 in the north Pacific Ocean. In Fig. 3, around 23.5 kg/m^3<σ_θ<25 kg/m^3, the difference of salinity become small and the difference of temperature is evident, which indicates that when the NPTW moves along thermocline (the isothermal line of 20°C), the core layer of NPTW has been receded as a result of the vertical mixing or isopycnal mixing. Contrary to the characteristic of NPTW in the northern Lembeh Strait, the core layer of NPTW in the southern Lembeh Strait is more evident.

(3) NPIW

In the northern Lembeh Strait, except for NT1–4 and NT2–1, around 26 kg/m^3<σ_θ<26.5 kg/m^3, the salinity of sea water is uniform in vertical, equal to ~34.48. In the southern Lembeh Strait, the minimum salinity is only along the 26.5σ_θ, of which the value is similar with that in the northern Lembeh Strait.

In addition, it is worth noting that within 250–350 m, the salinity profile of NT1–4 and NT2–1, both of which locate the most east of the northern Lembeh Strait, are notable exception in the northern Lembeh Strait.

(4) NPTIW

The dramatic north-south difference of seawater properties is the presence of NPTIW only in the southern Lembeh Strait. In Fig. 4, the core salinity in NPTIW is ~34.58, which is along 26.8σ_θ.

(5) The water mass between NPTIW and NPTW in southern Lembeh strait

According to the statistic box-plot in Figs 4b and c, a water mass with the homogeneous salinity equal to ~34.6, ~14°C of temperature and along the isopycnal of 26σ_θ, covering southern Lembeh Strait is identified between NPTIW and NPTW with the range of 200–250 m. Whereas, it is not found in the northern Lembeh Strait. The six profiles of temperature (Fig. 6b) and salinity (Fig. 6a) acquired by Argo floats (Fig. 6a) is chosen to make a comparison with the southern observation data.

According to the distribution of salinity from 200 m to 260 m, the salinity in the field observation is greater than the value in Sulawesi Sea and Maluku Sea, and less than the value in the South Pacific Ocean, which indicates that the water mass is the result of sea water from the South Pacific Ocean entering into Maluku Sea through Halmahera Sea mixing the sea water from the North Pacific Ocean and Sulawesi Sea.

4 The interannual variation of sea water mass properties

Due to the same observation date, the two field observations provide a choice of comparison on the properties of water masses. The observation region is divided into the northern Lembeh Strait and the southern Lembeh Strait because of the significant difference of water mass properties. It is possible to acquire the mean profile of temperature and salinity for all northern or southern station in 2015 and 2016 respectively to illustrate the interannual variation of water mass.

4.1 *The interannual variation of water mass properties around the Lembeh Strait*

In the north of Lembeh Strait (Fig. 7a), the properties of water masses such as NPTW, NPIW and AAIW in 2016 are different from in 2015. In mixing layer, the water in 2015 is colder and saltier than in 2016. The difference of temperature is ~2°C and the salinity is ~0.3. There is a salinity minima beneath the mixing layer in 2015 caused by the decreased rainfall and increased evaporation. The salinity maxima of NPTW in 2015 is greater than in 2016, of which the depth in 2015 becomes shallow. The corresponding temperature in 2015 is colder than in 2016. Similarly, the salinity minima of NPIW and AAIW in 2015 are greater than in 2016 as well. The core of NPIW become deepening. The corresponding temperature of NPIW in 2015 is greater than in 2016. The temperature of AAIW, however, also appears an increase in 2015.

In the south of Lembeh Strait (Fig. 7b), the temperature of surface water at the range of 0–50 m in 2015 is colder than in 2016, and the difference is beyond 3°C. In thermocline, different from the northern sea water, the salinity in 2015 is less than in

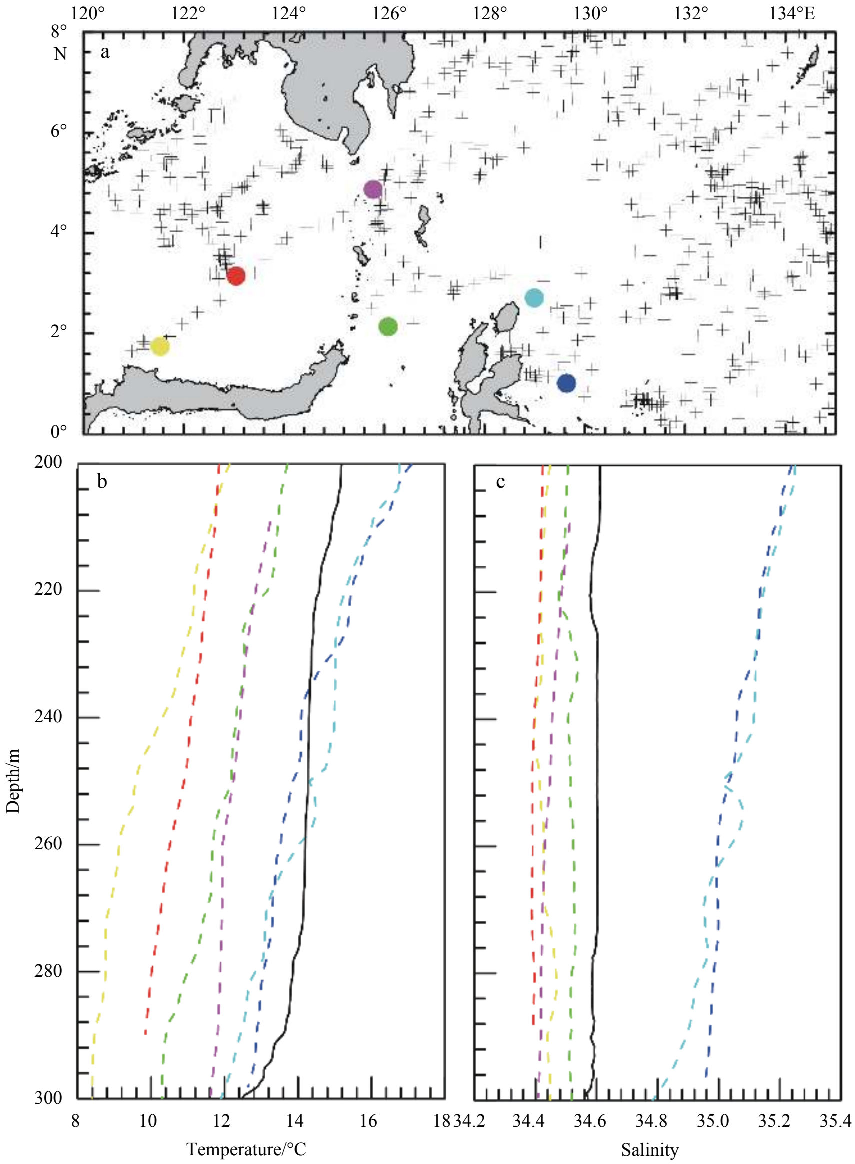

Fig. 6. The profiles of temperature (b) and salinity (c) acquired by Argo floats (show the location of single Argo profile) (a). The color of profiles in Figs 6b and c corresponds to the location of Argo floats, and the black line shows the profile of ST2-4.

2016. In NPIW layer, the salinity in 2015, similar with in northern Lembeh Strait, is greater than in 2016. Remarkably, the depth of salinity maxima, unlike the change in the northern Lembeh Strait, does not get changed.

4.2 *The north-south difference of the interannual variation of water mass properties*

The evident differences of interannual variations of water masses between the southern and northern Lembeh Strait are the shoaling of thermocline and the deepening of NPIW in the north of Lembeh Strait in 2015.

We calculate the magnitude/direction of wind stress and the wind stress curl covering the northern and southern Lembeh Strait respectively (Fig. 8). Although the difference of the magnitude and direction of wind stress between the south and north of Lembeh Strait is small in 2015–2016, the wind stress curl has a dramatic difference. In the northern Lembeh Strait, there exists the positive wind stress curl in September 2015. It, however, becomes negative in September 2016. In September 2015–2016, the wind stress curl covering the southern Lembeh Strait is always positive.

Zhong and Zhao (2014) deduced the relationship between the surface stress curl ($\triangle\tau$) and depth of Atlantic Water (AW) for explaining the phenomena of the deepening of AW core from using a 2.5-layer reduced gravity model, which is

$$\Delta h \approx \frac{fL\Delta\tau}{k_1 g_1'}, \tag{1}$$

where f is Coriolis parameter, k_1 is the friction coefficient, L is the scale of basin, and g_1' is the reduced gravity. In their paper, the $\triangle h$ is the variation of the thickness of upper ocean, which also presents the variation of the depth of upper boundary of AW.

Assumed that the first model layer is the upper ocean above NPIW (in the northern Lembeh Strait, the depth is about 200 m) whose thickness is h, the second layer represents the thickness of NPIW, and the deeper layer is assumed to be motionless. In that way, $\triangle h$ represents the variation of upper boundary of NPIW.

In Eq. (1), the variation of the thickness of upper ocean has a positive correlation with the wind stress curl. In the case of positive wind stress curl in 2015, the NPIW layer become deepening. With regard to the shoaling of thermocline in 2015, it is caused by Ekman pumping induced from cyclonic wind field.

5 Conclusions

The two field observations in the north/south of Lembeh Strait are implemented to investigate the difference of water mass properties between the north and the south of Lembeh Strait. Evidences indicate that the structure of sea water is consisted of

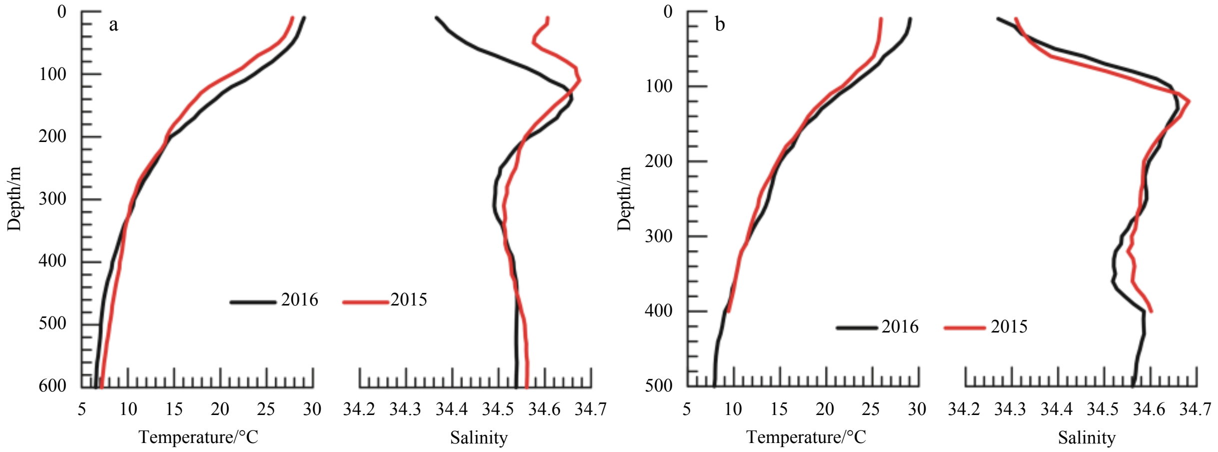

Fig. 7. The comparison of the profiles of mean salinity and mean temperature between 2015 (red lines) and 2016 (black lines). a. The comparison of northern stations and b. the comparison of southern stations.

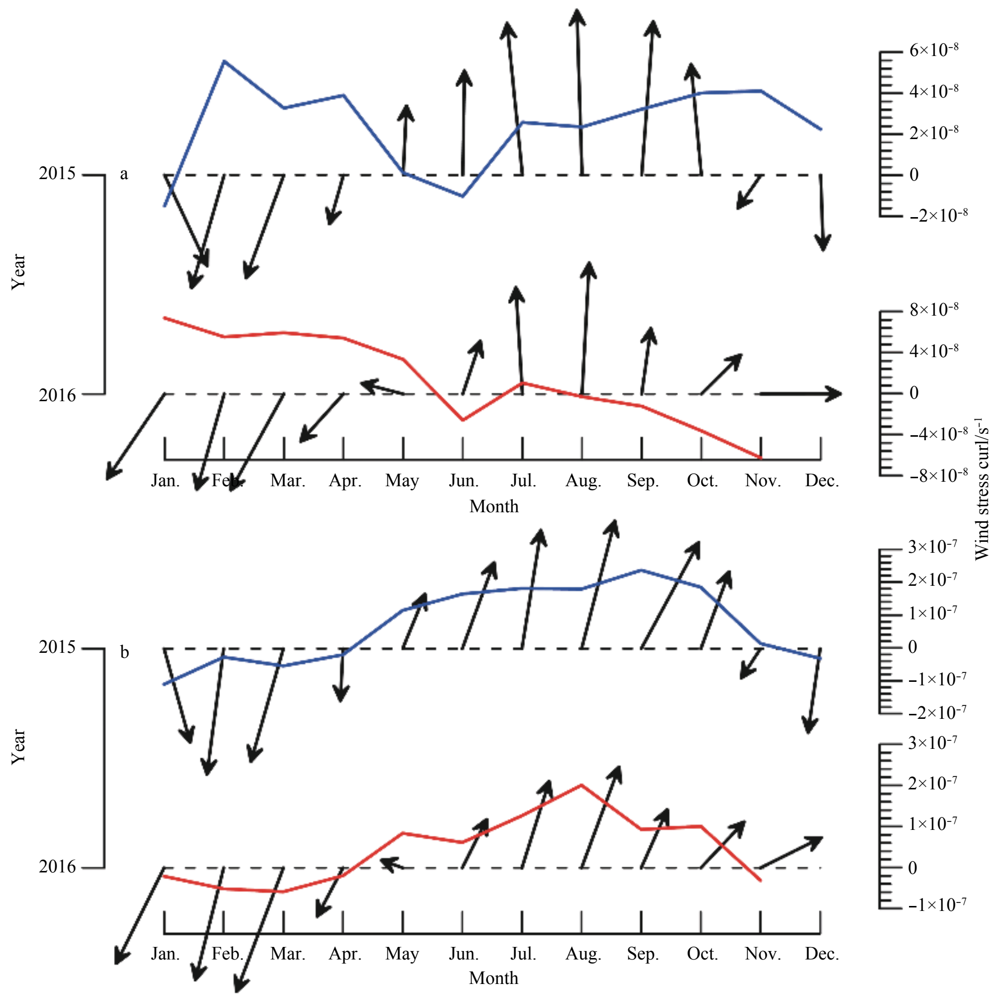

Fig. 8. The monthly wind direction of the north (a) and south (b) of Lembeh Strait and the monthly wind stress curl of covering the north and south of Lembeh Strait in 2015 (blue) and in 2016 (red).

NPTW, NPIW, NPTIW and AAIW in sequence. Because the maximum observation depth is less than 500 m at the southern Lembeh Strait, the AAIW was not found.

In the north, the surface water in 2015 is colder and saltier than in 2016. NPTW and NPIW in 2015 present the characteristic of high salinity. In the south, different from the north, the temperature of NPTW in 2016 is higher. The salinity of NPIW in 2016 is smaller. In the north of Lembeh Strait, the NPTIW is absent. In the southern Lembeh Strait, a water mass is observed at 200–240 m, which is absent in the northern Lembeh Strait. The dramatic difference of water masses indicates that the less water exchange has been occurred between the north and south of Lembeh Strait.

In the northern Lembeh Strait, the shoaling of thermocline and the deepening of NPIW in 2015 is caused by the positive wind stress curl. The depth of thermocline and NPIW in the southern Lembeh Strait, however, have not been changed in 2015. Evidences indicate that the great difference of the interannual variation of water mass properties between in the northern and southern Lembeh Strait are caused by the difference of local air-sea system as well.

It is important that the dramatic differences of water mass properties around the Lembeh Strait play an important role in the difference of biological diversity between the northern and southern Lembeh Strait. The difference of north-south local air-sea system is also possible to influence on the properties of water mass and indirectly affect biological diversity.

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