Seasonal Variability of The Mixed Layer Depth in The Sulawesi Sea

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Abstract

The Sulawesi Sea is a semi-enclosed basin located in the Indonesian Seas and considered as the one of location in the west route of Indonesian Throughflow (ITF). There is less attention on the mixed layer depth investigation in the Sulawesi Sea. Concerning that the mixed layer plays an important role in influencing the ocean in air-sea interaction and affects biological activity, the estimation of mixed layer depth (MLD) in the Sulawesi Sea is important. Seasonal variation of the mixed layer in the Sulawesi Sea between 115°-125°E and 0°-8°N is estimated by using World Ocean Atlas 2013. Forcing elements on the mixed layer in terms of surface-forced turbulent mixing from mechanical forcing of wind stress and buoyancy forcing (from heat flux as well as freshwater flux) in the Sulawesi Sea is provided by using a reanalysis dataset. The MLD is estimated directly on grid profiles with interpolated levels based on chosen density fixed criterion of 0.03 kg.m^{-3} and temperature criterion of 0.5°C difference from the surface. The results show that mixed layer depth in the Sulawesi Sea varies both spatially and temporally. Generally, the deepest MLD was occurred during the southwest monsoon (JJA), and the lowest MLD was occurred during the first transition (MAM) and second transition monsoon (SON). Strengthening and weakening MLD are influenced by mechanical forcing from wind stress and buoyancy flux. In the Sulawesi Sea, the mixed layer deepening coincides with the occurrence of a maximum in wind stress, and low buoyancy flux at the surface. This condition is the opposite when mixed layer shallowing occurs.

Keywords: mixed layer depth, Sulawesi Sea, seasonality, wind stress, buoyancy flux.

Abstrak

Variabilitas Musiman Kedalaman Lapisan Tercampur di Laut Sulawesi. Laut Sulawesi merupakan laut semi tertutup yang terletak di perairan Indonesia dan merupakan salah satu lokasi dari rute barat arus lintas Indonesia (Arlindo). Penyelidikan kedalaman lapisan tercampur di Laut Sulawesi masih kurang mendapat perhatian. Mengingat lapisan tercampur berperan penting dalam interaksi udara-laut serta mempengaruhi aktivitas biologis, maka pengukuran kedalaman lapisan tercampur di Laut Sulawesi merupakan hal yang penting. Variasi musiman lapisan tercampur di Laut Sulawesi yang terletak antara 115°-125°BT dan 0°-8°LU diestimasi menggunakan *World Ocean Atlas* 2013. Elemen-elemen yang memengaruhi lapisan tercampur permukaan dari gaya mekanis tekanan angin dan gaya apung (dari fluks bahang serta fluks air tawar) di Laut Sulawesi diperkirakan menggunakan data reanalisis. Pengukuran kedalaman lapisan tercampur dihitung secara langsung pada setiap profil dari grid pada level interpolasi berdasarkan kriteria perbedaan densitas 0,03 kg.m^{-3} dan kriteria perbedaan suhu 0,5°C dari permukaan.

Hasil penelitian menunjukkan bahwa kedalaman lapisan tercampur di Laut Sulawesi bervariasi secara spasial maupun temporal. Secara garis besar, kedalaman lapisan tercampur terdalam terjadi selama monsun barat daya (JJA), dan kedalaman lapisan tercampur terendah terjadi pada musim transisi pertama (MAM) dan musim transisi kedua (SON). Penguatan dan pelemahan kedalaman lapisan tercampur dipengaruhi oleh gaya mekanis dari gaya tekan angin dan fluks daya apung. Di Laut Sulawesi, pendalaman lapisan tercampur bertepatan dengan terjadinya gaya tekan angin maksimum, dan fluks daya apung yang rendah di permukaan. Kondisi ini berbanding terbalik ketika terjadi pendangkalan lapisan tercampur.

Kata kunci: kedalaman lapisan tercampur, Laut Sulawesi, musiman, gaya tekan angin, fluks daya apung.

Introduction

The upper ocean is marked by a homogeneous layer, in which temperature, salinity, and density are nearly uniform (Kara et al., 2000). The deepest layer of this homogenous layer is often called mixed layer depth (MLD). MLD is typically tens of meters deep (Bessa et al., 2018; Hosoda et al., 2010; Kara et al., 2000). This homogeneous layer is caused by turbulent vertical mixings (Ezer, 2000; Kara et al., 2000; Pollard et al., 1973). The turbulence mixing is primarily shear-driven by the wind stress at the surface, and another significant convective mixing is driven by the heat loss to the atmosphere, and freshwater flux from the atmosphere (Anderson et al., 1996; Ezer, 2000; Kara et al., 2000; Li et al., 2016; Pollard et al., 1973; Ushijima & Yoshikawa, 2019). Freshwater flux from precipitation and surface heating increase surface buoyancy forming a relatively warm and fresh thin MLD (Anderson et al., 1996; Pollard et al., 1973; Ushijima & Yoshikawa, 2019; Yoshikawa, 2015). MLD has spatial-temporal variability, and it varies on different time scales (Abdulla et al., 2016; Brainerd & Gregg, 1995; Carton et al., 2008; D'Ortenzio et al., 2005; Lim et al., 2012; Abdulla et al., 2018). Changes in MLD have an impact on biological activity, and it plays an important role in influencing the ocean in air-sea interaction (Costoya et al., 2014; Garwood Jr., 1979; Jang et al., 2011; Srivastava et al., 2018). This layer reflects the width of the upper ocean that interacts with the atmosphere (Carton et al., 2008; Garwood Jr., 1979). MLD is the basis of heat and freshwater exchanges between the ocean and the atmosphere and affects other processes, such as the water masses formation (James & Talley, 2009; Yu et al., 2020), the quantity of subduction from the surface layer to greater depths (Marshall et al., 1993), blooming of phytoplankton (Calbet et al., 2015; Obata et al., 1996; Schofield et al., 2018; Smith Jr & Jones, 2015), primary production (Itoh et al.,

2015; Jang et al., 2011), regulating seasonality ecosystem (Xue et al., 2021), and also replenishes near-surface nutrient stocks (Diehl et al., 2002). In addition, the surface oceanic mixed layer stored the heat that provides a source for drives global variability such as El-Niño (Guan et al., 2019; Yeh et al., 2009). Thus, the depth of the MLD is very important for determining the temperature range both in oceanic and coastal regions.

The Sulawesi Sea is a semi-enclosed area located in the Indonesian Seas between 115°-125°E and 0°-8°N. The oceanic part of the Sulawesi Sea is influenced by the Indonesian Throughflow (as the initial region in the western route of ITF) (Gordon, 2005), internal wave (Nagai & Hibiya, 2015), and characterized by intra-seasonal mesoscale eddies (Masumoto et al., 2001). A distinctive feature in this sea is one of the wide areas in the Indonesian Seas with a maximum depth of about 6000 m (Figure 1). Sulawesi Sea is bordered by the Sulu Sea and Mindanao Island in the north, the western tropical Pacific Ocean in the west, Makassar Strait and Sulawesi Island in the south, and Kalimantan (Borneo) Island in the west (Figure 1). Various studies in the Sulawesi Sea focus on the analysis of water masses and circulation in relating to the influences of the Indonesian Throughflow and tidal mixing (Gordon, 2005; Gordon et al., 2011; Masumoto et al., 2004; Nagai & Hibiya, 2015; Susanto et al., 2000). However, there is less attention to the mixed layer depth study in the Sulawesi Sea. The investigation of MLD in this sea is important, considering that this location is one of the widest oceanic areas in the Indonesian Seas that could influence various aspects such as air-sea interaction, determination of the temperature range in oceanic and coastal regions, and marine organisms (Itoh et al., 2015; Jang et al., 2011; Srivastava et al., 2018)).

A recent study of MLD in the Indonesian Seas (including Sulawesi Sea) is provided by (Radjawane et al., 2015), they suggest the

seasonal variation of MLD in Indonesian Seas is closely related to seasonal monsoonal wind patterns. However, there is a limitation in the previous studies on mixed layer depth in the Indonesian Sea or Sulawesi Sea i.e., the relation of buoyancy forcing to the formation of MLD. Nonetheless, the MLD is not only forced by the mechanical forcing from the prevailing wind but also with other parameters such as buoyancy flux that affect the thickness of MLD. Most importantly, the MLD in the Sulawesi Sea needs to be well understood on how the factors influencing the seasonal MLD. Thus, this study will relate mixed layer variability to surface-forced turbulent mixing from mechanical forcing of wind stress, as well as buoyancy forcing (from heat flux, and freshwater flux) in the Sulawesi Sea. The seasonal variability of mixed layer depth is investigated by using high-resolution global ocean climatology of temperature and salinity from the World Ocean Atlas 2013.

Methods

The main data used in the study is the World Ocean Atlas 2013 (WOA 13). The World Ocean Atlas (WOA) is a set of gridded fields of oceanographic variables based on in-situ measurements from a wide variety of sources. Global or decadal averages of temperature and salinity are provided at monthly, seasonal, and annual averaging periods on standard depth levels from 0 to 5500 m. The averaging period in WOA13 is from 1955 to 2012. The horizontal resolution used in this study is 0.25° for temperature and salinity data (Locarnini et al., 2013; Zweng et al., 2013). The geographic extent use in this study is 115°-125°E and 0°-8°N; The monthly WOA is used for the analysis, and it is interpolated onto the 1db vertical grid using Akima interpolation (Akima, 1970).

The MLD is estimated in this study directly on grid profiles at interpolated levels. MLD is defined through the threshold method with a finite-difference criterion from a near-surface reference value (Kara et al., 2003; Monterey & Levitus, 1997). Linear interpolation between levels is used to estimate the exact depth at which the difference criterion was reached. Similar to (Kara et al., 2003; Monterey & Levitus, 1997) by using the gridded climatological dataset, the chosen fixed criterion in density is 0.125 kg m^{-3} and the fixed criterion

in temperature is 0.5°C from the surface as shown in Equations (1) and (2) (Kara et al., 2003; Monterey & S. Levitus, 1997). Different from (Radjawane et al., 2015) that only use temperature threshold criteria, in this study, the smallest value between MLD criteria from density and temperature is considered as the MLD. This analysis is used, since the MLD from the two thresholds calculations are different, and each temperature and density profiles have s different mixed layer depth estimation. Figure 2 shows the example of temperature and density (as well as salinity) profiles from one grid point in the Sulawesi Sea, it shows that the MLD from temperature threshold criteria is deeper than MLD from density threshold criteria because the density is derived from temperature and salinity, thus the density profiles reflect both temperature and salinity characteristics (on Figure 2, the salinity profile has a shallow mixed layer that shows only in a few meters from the surface, and it is reflected into the density profile). The implication of this criteria is that the MLD will be different (or even smaller) than the calculation from (Radjawane et al., 2015).

MLD density = depth where

$$(\sigma_0 = \sigma_{0 \text{ at surface}} + 0.125 \text{ kg m}^{-3}) \quad\quad (1)$$

MLD temperature = depth where

$$(T = T_{\text{at surface}} + 0.5°C) \quad\quad (2)$$

To examine mechanisms that are responsible for seasonal variations of the MLD, the mechanical forcing from wind stress and buoyancy forcing (from heat and freshwater fluxes) are utilized in this study. The amount of energy transferred from the atmosphere to the mixed layer is proportional to the wind friction velocity and surface buoyancy fluxes. These two quantities will be used to qualitatively infer the respective contribution of mechanical and buoyancy forcings to the seasonal MLD variations. Zonal and meridional winds are provided by the reanalysis ERA-interim daily (Dee et al., 2011) from January 1979 to 2012 with a spatial resolution of 0.75° x 0.75°, and the spatial coverage is the same as in WOA selection. The monthly climatology of wind stress on each grid points are estimated from these dataset ($\tau = \rho_{air} C_D u^2$, where ρ is the air density, C_D is wind drag coefficient that is set as 0.0015, and u is the velocity).
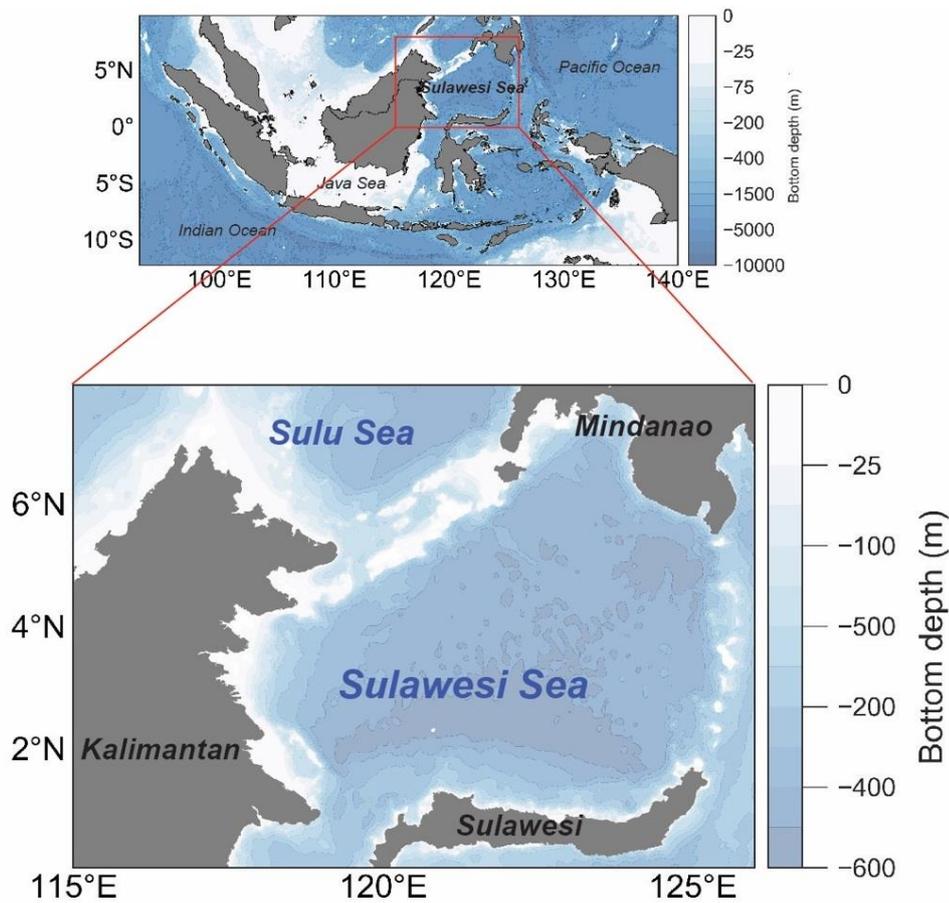
Figure 1. Map of Indonesian archipelago (upper panel) and its magnification in the Sulawesi Sea (bottom panel) bordered by Sulu Sea, Kalimantan, Sulawesi and Mindanao Island.

Gambar 1. Peta kepulauan Indonesia (atas) dan perbesarannya di Laut Sulawesi (bawah) yang berbatasan dengan Laut Sulu, Pulau Kalimantan, Sulawesi dan Mindanao.
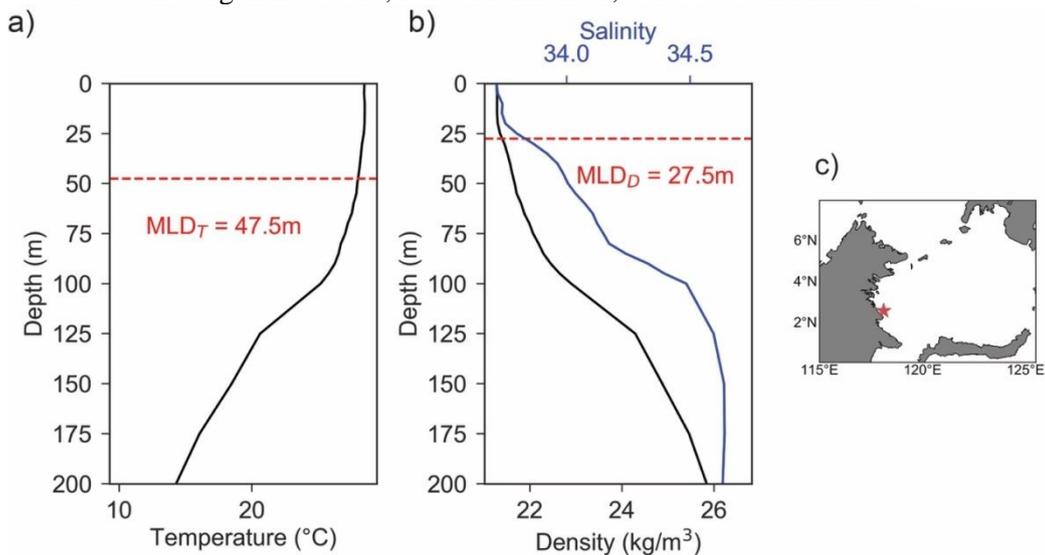

Figure 2. Profiles of (a) temperature, (b) density and salinity from one example grid of WOA in Sulawesi Sea at 118.125°E, and 2.625°N in January, and (c) point location in the Sulawesi Sea. Red dash lines indicate MLD calculated from temperature threshold criteria (0.5°C, MLD_T) in Figure a, and from density threshold criteria (0.125 kg m^{-3}, MLD_D) in Figure b.

Gambar 2. Profil (a) suhu, (b) densitas dan salinitas dari salah satu contoh grid WOA di Laut Sulawesi pada 118.125°BT, dan 2.625°LU pada bulan Januari, dan (c) lokasi titik di Laut Sulawesi. Garis putus-putus merah menunjukkan kedalaman lapisan tercampur yang dihitung dari kriteria ambang suhu (0,5°C, MLD_T) pada Gambar a, dan dari kriteria ambang densitas (0,125 kg m^{-3}, MLD_D) pada Gambar b.

To investigate the buoyancy forcing, European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5) data are used to compute surface buoyancy flux climatology over 1979–2012 with a spatial resolution of 0.1° × 0.1°. We construct the monthly climatology of surface buoyancy flux in the Sulawesi Sea from evaporation, precipitation, net shortwave radiation, net longwave radiation, sensible heat flux and latent heat flux data from ERA5. Net surface heat flux (Q_{net}, W m^{-2}) is defined as (Cronin et al., 2019),

$$Q_{net} = Q_{SW} - Q_{LW} - Q_{lat} - Q_{sen} \quad (3)$$

Where Q_{SW} is the shortwave radiation, Q_{LW} is longwave radiation, Q_{lat} is latent heat flux and Q_{sen} is sensible heat flux. The net surface buoyancy (B_o, kg s^{-1} m^{-2}) is computed as follows (Gill, 1982; Keerthi et al., 2013),

$$B_o = B_h + B_w \quad (4)$$

$$B_o = \frac{\alpha Q_{net}}{C_p} + \beta \rho (P - E) S_o \quad (5)$$

where B_h is the buoyancy due to heat flux, B_w is the buoyancy related to fresh water flux, α and β are the coefficients of thermal and haline expansion respectively, Q_{net} is the net heat flux, C_p is the specific heat of water, $(P – E)$ is the freshwater flux from precipitation (P) and evaporation (E), and S_o is the surface salinity from WOA that re-grided by linear interpolation in the ERA5 resolution. The estimation of α and β follows the calculation from (McDougall, 1987).

Note that, the estimation of wind stress and buoyancy flux are covered in the WOA period from 1955 to 2012, thus the estimation is still reliable to analyze the seasonal variation compare to WOA. (Lim et al., 2012; Radjawane et al., 2015) also use different time ranges of dataset to compare MLD with another atmospheric forcing in the seasonal time scale variation. The seasonal climatology is divided based on the monsoon system i.e., northeast monsoon at December-January-February (DJF), first transition monsoon at March-April-May (MAM), southwest monsoon at June-July-August (JJA), and second transition monsoon at September-October-November (SON).

The cross-correlation coefficient analysis is performed to find the correlation and lag between the monthly wind stress and MLD, and buoyancy flux and MLD, the methodology followed by (Emery & Thomson, 2001). We use partial regression to isolate signals purely associated with wind stress and buoyancy flux spatially in the Sulawesi Sea (Keerthi et al., 2013). This technique has already been applied in several studies to separate MLD signals from different atmospheric forcing, i.e., (Keerthi et al., 2013). Before applying the partial regression, we re-grid both wind stress and buoyancy flux into the WOA grid by using the linear interpolation method (Meijering, 2002).

Result

A. Seasonal variations of mixed layer depth

To examine the basin-scale spatial distribution of MLD in the Sulawesi Sea, by averaging the monthly means, we produced the annual mean-field of MLD (Fig. 3a). The most distinct feature of the distribution is that the MLD is greater (>20 m) near the western tropical Pacific Ocean, Central Sulawesi Sea in 120°E-125°E, until it reaches the north of Makassar Strait, and smaller (10-18 m) near the Sulawesi, Kalimantan and Mindanao Island. Annual-mean MLD averaged over the Sulawesi Sea is around 20 m.

Latitudinal distribution (Figure 3b) of the MLD along 123°E clearly shows the pattern of shallower mixed layer near the Mindanao and Sulawesi coasts and deeper mixed layer in the middle of Sulawesi Sea. Meanwhile, the longitudinal distribution (Figure 3c) of the MLD along 4°N shows the deepest Mixed layer in the eastern side near the western Pacific Ocean and becomes shallower until it reaches near the Kalimantan coast. Generally, the MLD at greater longitude is deeper than the lower longitude, and exists almost in all seasons, that is probably because of its location near the open seas in the western tropical Pacific Ocean whereas the wind stress is relatively high.
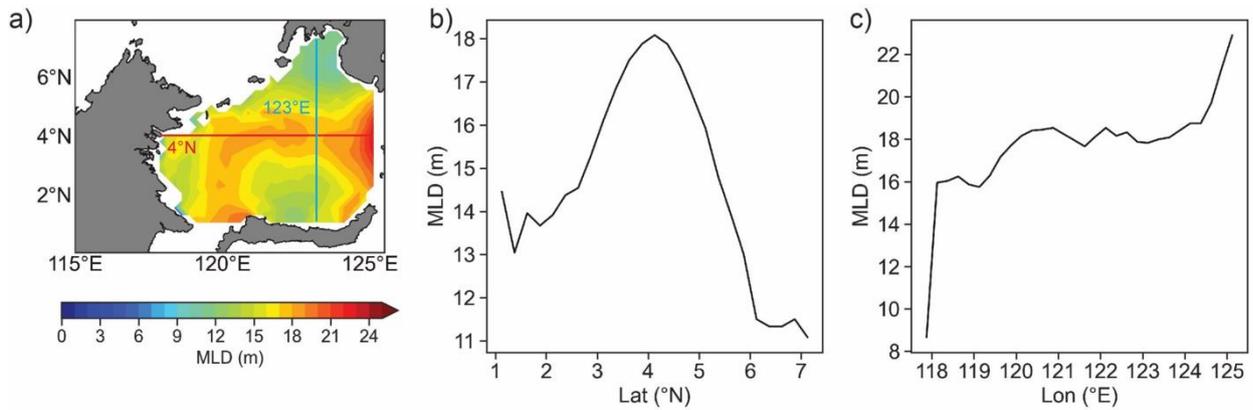
Figure 3. a) annual mean of mixed layer depth (m) in Sulawesi Sea, b) its latitudinal variation along 123°E, and c) its longitudinal variation along 4°N.

Gambar 3. a) Rata-rata tahunan kedalaman lapisan tercampur (m) di Laut Sulawesi, b) variasi garis lintang di sepanjang 123°BT, dan c) variasi longitudinal di sepanjang 4°LU.
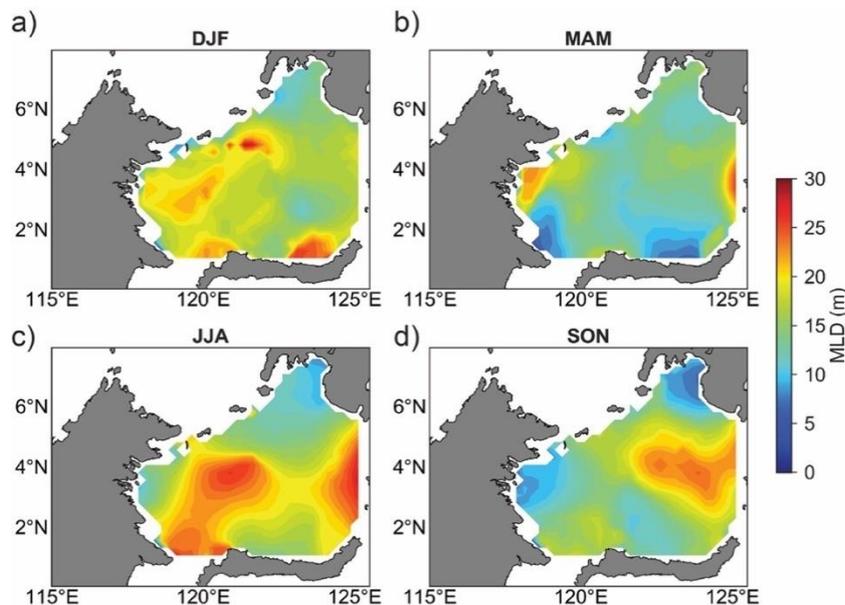

Figure 4. Mixed layer depth (m) in Sulawesi Sea at a) northeast monsoon (DJF), b) first transition monsoon (MAM), c) southwest monsoon (JJA) and d) second transition monsoon (SON).

Gambar 4. Kedalaman lapisan tercampur (m) di Laut Sulawesi pada a) monsun timur laut (DJF), b) monsun transisi pertama (MAM), c) monsun barat daya (JJA) dan d) monsun transisi kedua (SON).

To examine the MLD on each season, we construct the seasonal MLD in the Sulawesi Sea as shown in Figure 4. This figure shows that the MLD in the Sulawesi Sea varies both spatially and temporally, the MLD in the northeast monsoon (DJF) is in the range of 10-25m with the deepest spatial distribution located in the western part of the Sulawesi Sea, while the MLD tends to be relatively shallower in the east to the north of Sulawesi Sea. In the first transition monsoon (MAM), there is a shallower range of MLD than the previous season with the MLD ranges from 3-20 m. In the southwest monsoon (JJA), the MLD in the Sulawesi Sea is much deeper than MLD during the northeast

168

monsoon. The deepest MLD is distributed spatially is in the west, south, to the center of Sulawesi Sea, MLD in this season ranges from 15-30 m. In the second transition monsoon (SON), there is a shallow MLD relatively similar to the MLD during the first transition monsoon. Nonetheless, a fairly deep MLD of about 18-25 m is found on the west side of Sulawesi Sea. In general, the MLD in the southwest monsoon is the deepest compared to another season, the MLD in the northeast monsoon shows as the second deepest, and MLD in both transition monsoon is relatively shallow.
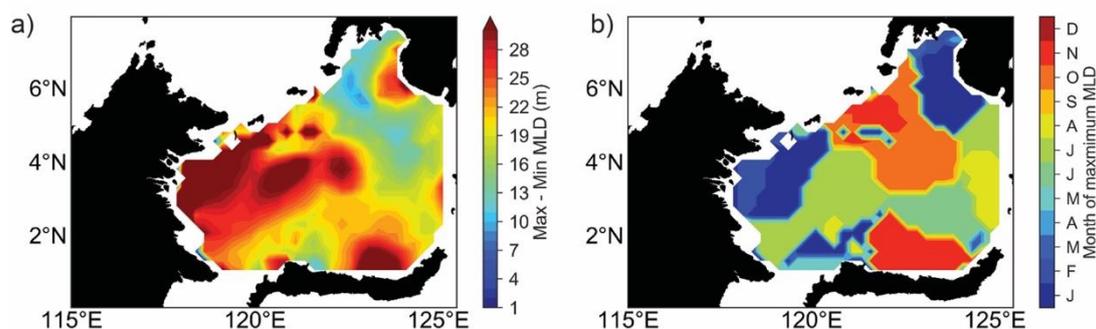
Figure 5. Maps of (a) the MLD difference (maximum - minimum), and (b) the month when the MLD reaches the maximum.

Gambar 5. Peta (a) selisih kedalaman lapisan tercampur (maksimum - minimum), dan (b) pada bulan saat kedalaman lapisan tercampur mencapai maksimum.

Figure 5 shows the seasonal variability of MLD constructed from MLD difference (maximum-minimum), and the month when the MLD reaches the maximum. This difference is basically reflected the diversity of spatial patterns of the monthly MLD between maximum and minimum MLD on each grid location. The value of the difference between the maximum and minimum MLD indicates monthly spatial variability of MLD each grid locations, whereas the high values reflect that the MLD can be deeper in particular month and change drastically into shallower at several month after, meanwhile low value reflects that the MLD does not not changes much every month. Seasonal variability of the MLD difference is larger (>27 m) over the region between 118°–123°E and 0°–6°N and near the Kalimantan coast, and near the north of Sulawesi Island, while smaller (~7 m) in the near of Mindanao Island (Figure 5a). Months at which the maximum MLD appears in the climatological mean also have spatial diversity, ranging from January to December (Figure 5b). The month of maximum MLD is varied on each side of the Sulawesi Sea. The dominant months are May, June, July, August, occupying more than 50% of the entire domain, while some local areas show in October to December. Near the Mindanao and Kalimantan coasts, maximum MLDs typically appear in January and February. On the east coast of Kalimantan Island where the MLD difference is largest (Figure 5a) reaches its maximum mostly in January. In the north of the Sulawesi coast, the maximum MLD occurs one or two months earlier (in December or November). This is interesting since the annual mean MLD in this region is quite shallow (Figure 3), but the MLD differences are large (Figure 5a), this indicates that the MLD quite fluctuates in this location.

To provide an overview of seasonal variation of MLD in the Sulawesi Sea, a relative frequency histogram is calculated for each season (Figure 6). The histogram reveals that the MLD distribution is changed clearly in all seasons, with both mean and median are also change, with nearly the same value both in mean and median. In the northeast monsoon, the distribution of MLD has a peak at around 16 m, with the mean MLD for the entire Sulawesi Sea in this season at 18 m. In the first transition monsoon, the histogram peak becomes shallower (14 m), and the mean (15 m) is also shallower than the previous season. The mean of MLD in southwest monsoon is the largest (18 m) among all seasons, with the large distribution of deeper MLD (> 20m) compare to the peak at 18 m, and almost (40% of the total) MLDs are 18-25 m. In the second transition monsoon, the mean of MLD becomes shallower than the previous season (16m). In general, the MLD in the southwest monsoon is the largest, while both first and second transition monsoons have moderate values. The first transition monsoon has the smallest spread and almost all (60% of the total) MLDs are 10–14 m, indicating small spatial variation of the MLD.
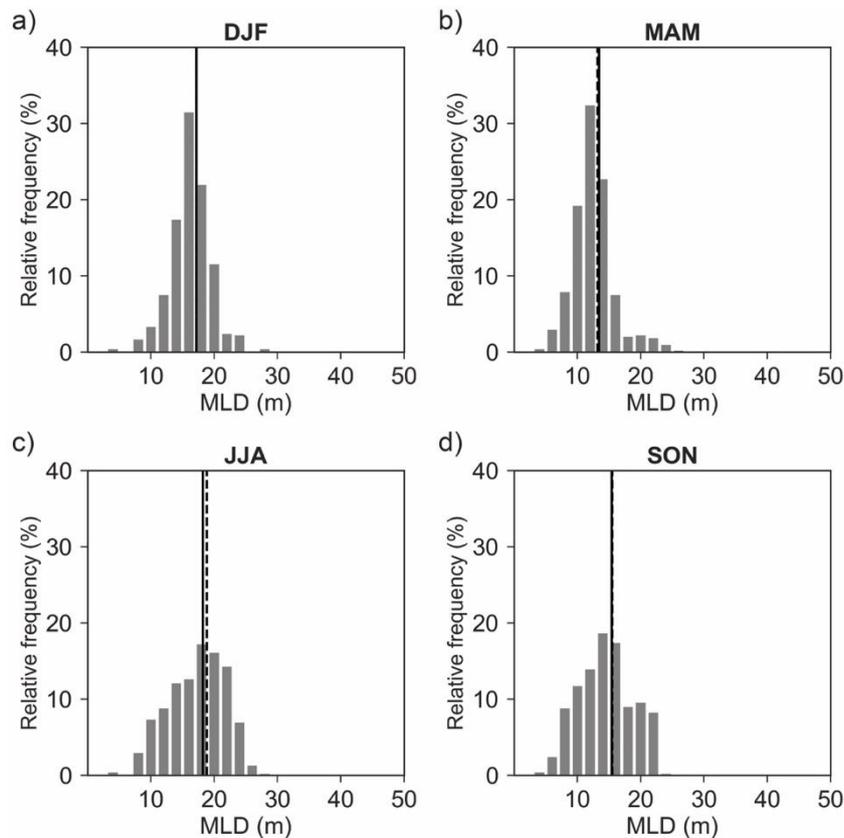
Figure 6. Frequency histogram of MLD in each season: a) northeast monsoon (December–January–February), b) first transition monsoon (March–April–May), c) southwest monsoon (June–July–August) and d) second transition monsoon (September–October–November). Median (thick lines) and mean (dotted lines) for each season are also plotted.

Gambar 6. Frekuensi histogram kedalaman lapisan tercampur di setiap musim: a) monsun timur laut (Desember–Januari–Februari), b) monsun transisi pertama (Maret–April–Mei), c) monsun barat daya (Juni–Juli–Agustus) dan d) musim transisi kedua (September–Oktober–November). Median (garis tebal) dan mean (garis putus-putus) untuk setiap musim juga ditampilkan.

B. Atmospheric forcing

To understand the influence of the mechanical forcing over the seasonal variability of MLD, the seasonal MLD are correspond with different atmospheric forcing including mechanical forcing from wind and buoyancy forcing from surface heat flux as well as *P-E* balance representing the freshwater flux. Wind stress is a mechanical forcing that affects MLD. The wind stress in Figure 7 shows spatial and temporal variations from various sides of the Sulawesi Sea. In the northeast monsoon (DJF), the strongest wind stress (> 0.8 N m^{-2}) is in the west of Sulawesi Sea, which is adjacent to the western Tropical Pacific Ocean, besides this area, the average of wind stress is weak in the range of 0.01-0.10 N m^{-2}. In the first transition monsoon (MAM), the similar pattern of wind stress (with previous season) in the Sulawesi Sea appears but tends to be weaker ranging from 0.02-0.06 N m^{-2} in all areas except in the west side of the sea that close the western Pacific Ocean is stronger of about 0.14 N m^{-2}. In the southwest monsoon (JJA), wind stress is relatively stronger, and it spreads over almost all parts of the Sulawesi Sea with values ranging from 0.01 to 0.16 N m^{-2}. In the second transition monsoon (SON), there is weak wind stress ranging from 0.02 to 0.04 N m^{-2} distributed in all areas of the Sulawesi Sea. In general, wind stress in the southwest monsoon (JJA) is the strongest, while both in the two-transition monsoon, wind stress is relatively weak with the weakest wind stress being in the second transition monsoon (SON).
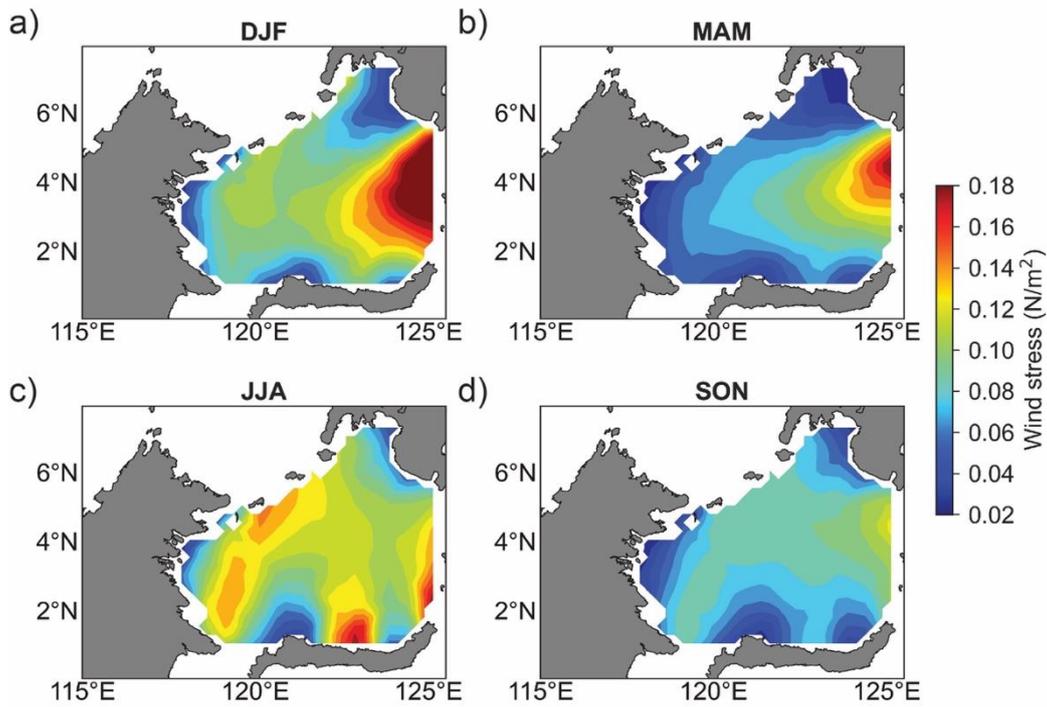
Figure 7. Wind stress (N m^{-2}) in Sulawesi Sea at a) northeast monsoon (DJF), b) first transition monsoon (MAM), c) southwest monsoon (JJA) and d) second transition monsoon (SON).
Gambar 7. Gaya tekan angin (N m^{-2}) di Laut Sulawesi pada a) monsun timur laut (DJF), b) monsun transisi pertama (MAM), c) monsun barat daya boreal (JJA) dan d) monsun transisi kedua (SON).

Figure 8. Buoyancy flux (kg m^{-2} s^{-1}) in Sulawesi Sea at a) northeast monsoon (DJF), b) first transition monsoon (MAM), c) southwest monsoon (JJA) and d) second transition monsoon (SON).
Gambar 8. Fluks daya apung (kg m^{-2} s^{-1}) di Laut Sulawesi pada a) monsun timur laut (DJF), b) monsun transisi pertama (MAM), c) monsun barat daya boreal (JJA) dan d) monsun transisi kedua (SON).
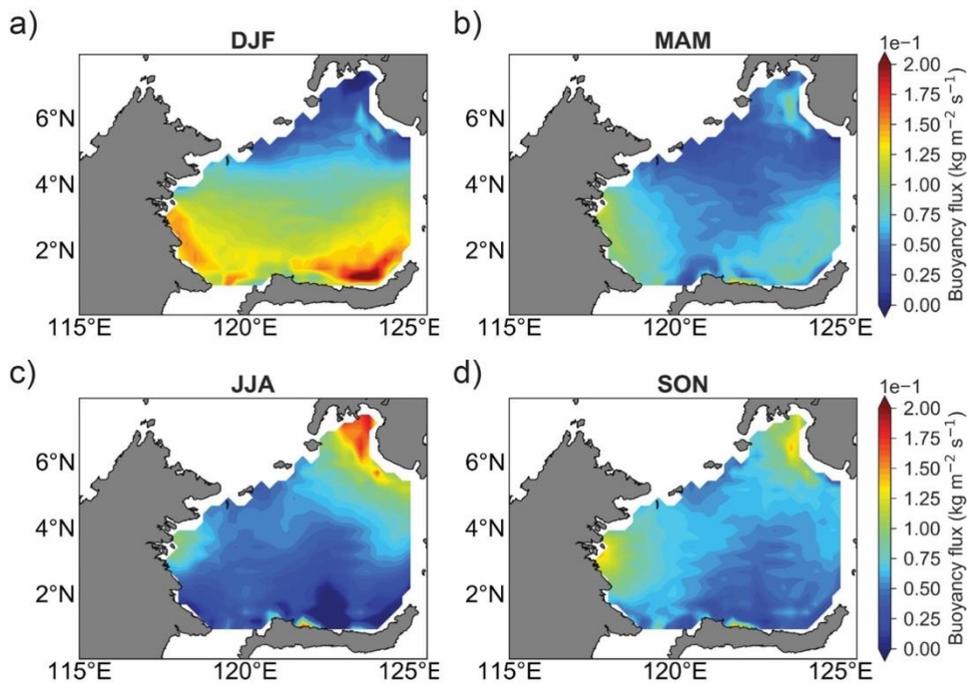
Figure 8 shows the distribution of surface buoyancy flux in the Sulawesi Sea. Like MLD, the surface buoyancy flux also exhibits spatial and temporal variations. In the northeast monsoon (DJF), the surface buoyancy flux in the Sulawesi Sea is varied spatially with the large

value at a range of 60-90 W.m^{-2} distributed in almost entire of Sulawesi Sea except for the north part near the Mindanao coast, with the highest distribution located in the north coast of Sulawesi Island. This largest buoyancy flux in this region seems to be associated with the high variability of MLD spatially as shown in Figure 5.

In the first transition monsoon (MAM), the surface buoyancy flux is low at a range of 0.25-1.25 kg m^{-2} s^{-1} and fairly low distributed in all

areas. In the southwest monsoon (JJA), the surface buoyancy flux is also distributed relatively low ranging from 0.25-1.25 kg m^{-2} s^{-1} except in the near Mindanao coast. In the second transition monsoon (SON), the surface buoyancy flux is also low with the highest distribution located in the near coastlines. In general, the distribution of low surface buoyancy flux occurs in the first transition monsoon (MAM), while the high distribution occurs in the northeast monsoon (DJF).
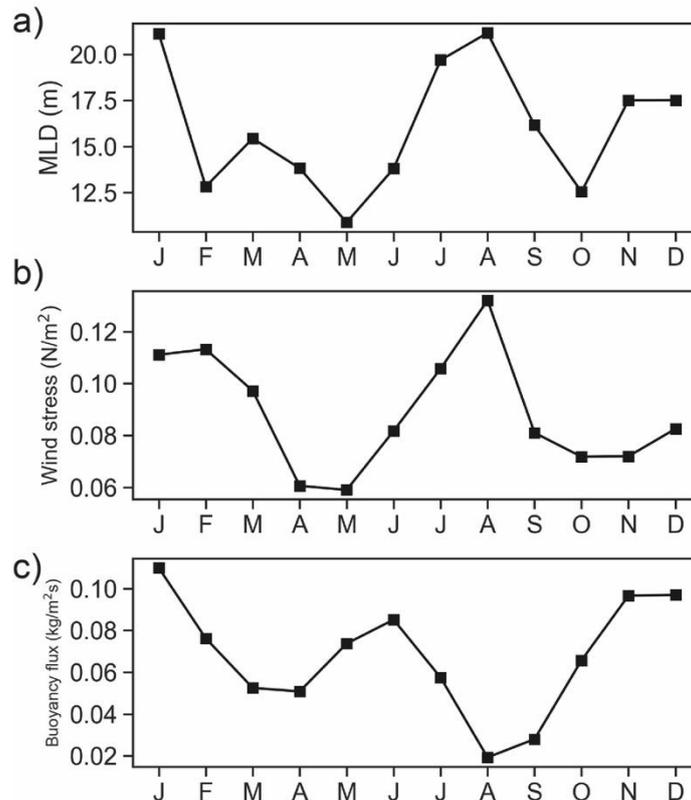

Figure 9. Monthly climatology of a) mixed layer depth (m), b) wind stress (N m^{-2}), and c) buoyancy flux (kg m^{-2} s^{-1}) in Sulawesi Sea. The averaging area in the entire of Sulawesi Sea.
Gambar 9. Klimatologi bulanan a) kedalaman lapisan tercampur (m), b) gaya tekan angin (N m^{-2}), dan c) fluks daya apung (kg m^{-2} s^{-1}) di Laut Sulawesi. Wilayah rerata di seluruh Laut Sulawesi.

To see the overall monthly changes of MLD, we estimated basin-averaged MLD. Figure 9 shows the mean of monthly climatology of MLD (and atmospheric forcing) over the entire Sulawesi Sea. Figure 9 shows the basin-averaged MLD are deep during JJA with reaches the maximum in August, while both in the transition monsoon (MAM and SON), the MLD is much shallower with the minimum MLD occurs in March. This deepest MLD (Figure 9a) coincides with the low surface buoyancy flux (Figure 9b) and strongest wind stress in August (Figure 9c), while shallowest MLD coincides with weakest wind stress and

relatively high surface buoyancy flux in May. In the seasonal view, wind stress is relatively strong during JJA compared to the MAM and SON (Figure 9b), and low surface buoyancy flux appears in JJA (Figure 9c).

Discussion

From the previous results, it shows that, generally, the deepening of MLD during southwest monsoon coincides with the strengthening of wind stress and decreasing surface buoyancy flux. In contrast, the shallowing of MLD during transition monsoon

coincides with the weakening of wind stress and increasing surface buoyancy flux. Nonetheless, in northeast monsoon, even though MLD is also relatively deeper compare with monsoon transition, it coincides with relatively high wind stress, and the surface buoyancy flux that quite large, it appears as the largest in January among all months.

Lead–lag correlation analysis as shown in Figure 10 further reveal the monthly correlation of the wind stress and buoyancy flux to the MLD. Wind stress and MLD have a strong positive correlation (0.7) at zero-time lag (Figure 10a), this indicates that the stronger wind, the deeper MLD, and the weaker wind the shallower MLD. While the buoyancy flux has a negative correlation (0.5) to the MLD with approximately 4 months lags before the peak of the event (Figure 10b). This indicates that the higher the buoyancy flux, the shallower MLD, and the lower the buoyancy flux, the deeper MLD. The buoyancy flux influences the density, and thus the thickness of the MLD. Nonetheless, the buoyancy flux has a lower correlation compared to the wind stress to the seasonal MLD, thus this implies that the wind stress plays the main role to regulates the deepening of MLD in the entire Sulawesi Sea.

The mechanisms explaining the seasonal MLD variations to the dependency between wind stress and buoyancy flux spatially by using partial regression can be qualitatively assessed from Figure 11. The mechanisms largely vary from one season to another. During the northeast monsoon, the large coefficients of MLD and wind stress varied in the Sulawesi Sea (Figure 11a in DJF), with low correlation is found in the central of Sulawesi Sea, while the large coefficients of MLD and buoyancy flux are found mostly in the entire of Sulawesi Sea (Figure 11bin DJF). This may indicate that the surface buoyancy flux appears to dominate the MLD variability in northeast monsoon. Comparing to another season (MAM, JJA, and SON), the correlation between wind stress (Figure 11a) and buoyancy flux (Figure 11b) have a similar distribution, which indicates both wind stress and buoyancy flux play an almost equivalent role to dominate the MLD variability.

Considering the spatial scale, this study shows that a relatively small and semi-enclosed sea such as the Sulawesi Sea may show various properties related to MLD variability. The thickness of the MLD depends on both mechanical and buoyancy forcing. The MLDs rapidly shoals through the transition monsoon time (March to May, and September to November) over the whole basin due to strong buoyancy flux and weak wind. As the southwest monsoon strengthens, the MLD develops over the entire Sulawesi Sea accompanied by significant local deepening due to weak buoyancy flux and strong wind. The relatively deep MLD during northeast monsoon seems to be accompanied by the strong wind, but the strong buoyancy flux seems to be balanced the effects of the wind to thin the MLD. Although the MLD in this study used different criteria than (Radjawane et al., 2015), the tendency where maximum and minimum MLD occurs in each month is similar, with MLD being deeper during JJA.
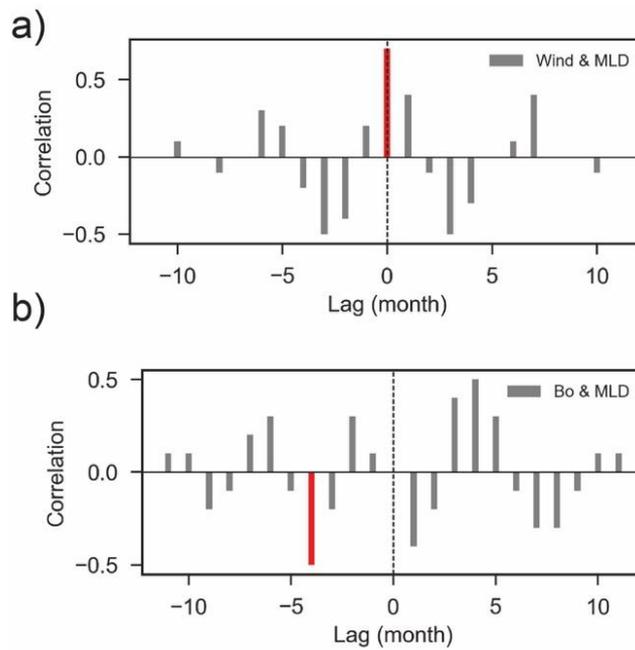
Figure 10. Correlation analysis at monthly lag intervals between a) wind stress and MLD, and b) buoyancy flux and MLD. Red bars denote the largest correlation.
Gambar 10. Analisis korelasi pada interval lag bulanan antara a) gaya tekan angin dan kedalaman lapisan tercampur, dan b) fluks daya apung dan kedalaman lapisan tercampur. Bar merah menunjukkan korelasi tertinggi.
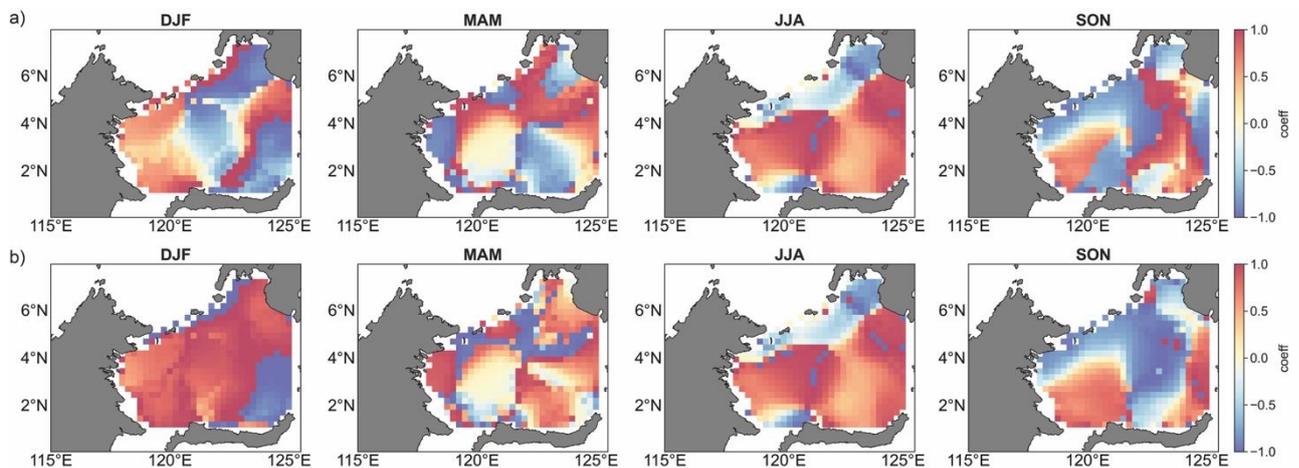

Figure 11. Partial regression coefficient of a) wind stress, and b) buoyancy flux onto MLD at northeast monsoon (DJF), first transition monsoon (MAM), southwest monsoon (JJA), and second transition monsoon (SON). The sign of the buoyancy flux is reverted to ease comparison with MLD variations.
Gambar 11. Koefisien regresi parsial dari a) gaya tekan angin, dan b) fluks daya apung terhadap kedalaman lapisan tercampur pada monsun timur laut (DJF), monsun transisi pertama (MAM), monsun barat daya (JJA), dan monsun transisi kedua (SON). Tanda fluks daya apung dibalikan untuk memudahkan perbandingan dengan variasi kedalaman lapisan tercampur.

Conclusion

The present study analyzes seasonal MLD in the Sulawesi Sea using WOA13 over the period 1955–2012. MLD is calculated in the potential density criterion. The interpretation of MLD is analyzed in terms of mechanical and buoyancy forcing. Mechanical forcing tends to parallel with the deepening of MLD. Therefore, the momentum flux from the atmosphere by the

winds is the dominant parameter regulating the MLD Sulawesi Sea. Nonetheless, the combination of mechanical and buoyancy forcings also shows its role seasonally. During southwest monsoon (JJA), the Sulawesi Sea experiences strong wind that tends to deepen MLD, and it also combines with the low surface buoyancy flux which also deepens the MLD. Where the mixed layer is deep, the temperature change is associated with small surface heat flux. The precipitation in the Indonesia region during this season is low. This low precipitation induces decrease surface buoyancy that increases in density forming a relatively deep MLD. This phenomenon is vice versa during transition monsoon. It also is remarked that the deep MLD during the winter monsoon is affected by the strong wind. However, the high surface buoyancy flux seems to induce the rising of density, thus shallowing the MLD. Generally, the deepening of MLD during summer monsoon occurs because of both mechanical and buoyancy forcing that are reinforcing each other, (it vice versa during the transition monsoon). However, in DJF, the buoyancy forcing plays an important role in counterbalanced the deepening of MLD from the mechanical forcing. Further analysis in this study should focus on the estimation of turbulence kinetic energy from winds and buoyancy forcing in the mixed layer depth seasonally through model analysis.

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