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Spatial and Seasonal Variability of Mixed Layer Depth in the Tropical Atlantic at 10 °W using 40 Years of Observation Data

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Abstract

The spatial and seasonal variability of the mixed layer depth (MLD) was studied using hydrological data from several databases collected over the period October 1973 to March 2017 at 10 °W between latitudes 2 °N and 10 °S in the Gulf of Guinea. The density threshold method with 0.03 kg m-3 criterion was used to calculate the MLD. In the equatorial band, the seasonal average MLD is 20 m whatever the season. At 6 °S and 10 °S, the MLD is relatively higher during the cold season. The MLD varies between 21 and 37 m at 6 °S, and the seasonal averages MLD are 21 and 40 m respectively during the hot and cold seasons. At 10 °S, during the hot season, the MLD varies between 28 and 52 m and the seasonal average is 39.5 m. During the cold season, the MLD varies between 45 and 55 m with a seasonal average of 49 m.

Keywords: Atlantic Ocean, Gulf of Guinea, Mixed Layer, Spatial Variability, Seasonal Variability

1. Introduction

Oceanographers define the mixed layer as the surface layer of the ocean with almost uniform hydrographic properties (temperature, salinity and density). The mixed layer is the buffer zone between the atmosphere and the deep ocean in which different flows occur, such as, transfer of heat, mass and momentum (Schneider and Müller, 1990; Brainerd and Gregg, 1995; Dong et al., 2008). This layer is essential in the study of the climate system since it affects changes in sea surface temperature (de Boyer Montégut et al., 2007; Donlon et al., 2009; Rugg et al., 2016).

The depth of the mixed layer (MLD) is generally determined using temperature, salinity or density profiles (Rath et al., 2016) as well as different definition criteria (Kara et al., 2003). In the tropical Atlantic, the mixed layer has been the subject of various scientific studies. Wade et al. (2011) determined the MLD using a temperature threshold criterion as in the climatology of de Boyer Montegut et al. (2004) ($\Delta T = 0.2$ °C). In contrast, Peter et al. (2006) determined the MLD from a density threshold ($\Delta\sigma\theta = 0.05$ kg m^{-3}). Recently, N'Guessan et al. (2019) have shown that the method of Holte and Talley (2009) using the density threshold (0.03 kg m^{-3}) is best suited to determine the MLD at 4 °W in the Eastern Tropical Atlantic. These studies are made possible thanks to the improvement of oceanographic data acquisition techniques which make it possible to increase the number of temperature and salinity profiles. This is the case in Tropical Atlantic at 10 °W, where data from recent programs such as PIRATA (Prediction and Research moored Array in the Tropical Atlantic) and EGEE give the opportunity, in addition to historical surveys data, to study the MLD.

The MLD can undergo diurnal (Brainerd and Gregg, 1995), seasonal and intraseasonal variabilities (Kara et al., 2003; Holte and Talley, 2009) due to turbulence generated in the ocean by the wind, convective cooling, breaking waves, current shear, and other physical processes. Some scientific studies have also depicted a spatial variability of the MLD in several oceans (Brainerd and Gregg, 1995; Holte and Talley, 2009; Keerthi et al., 2013; 2016; Zeng and Wang, 2017; Holte et al., 2017).

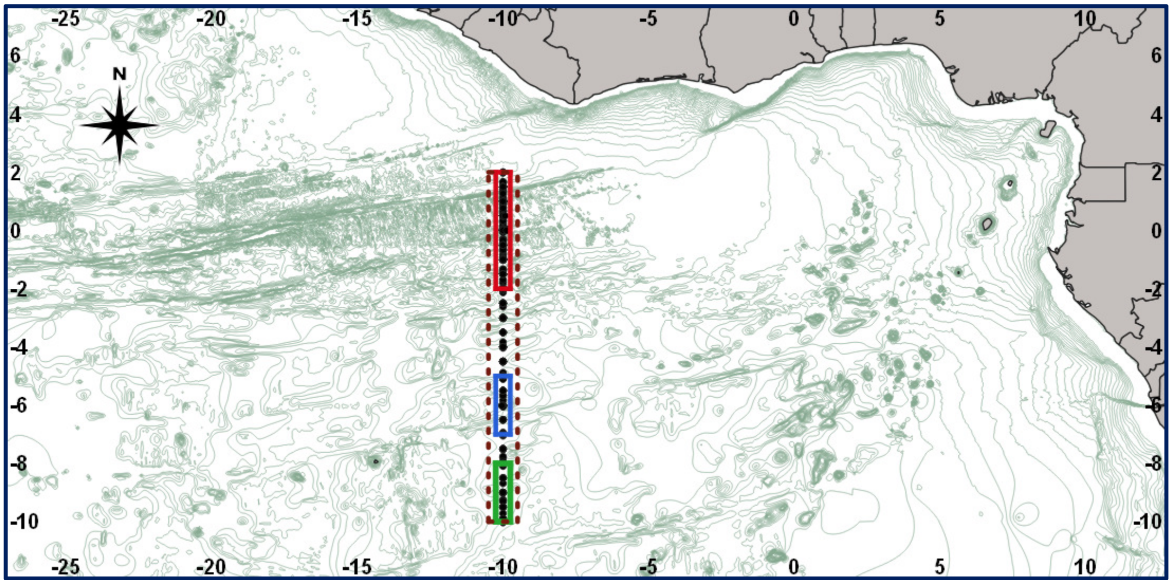
In the tropical Atlantic, studies in relation to MLD variability are scarce. Peter (2007) studied the variability of the mixed layer temperature in the equatorial Atlantic using numerical simulations. Wade (2010) calculated mixed layer heat budgets from Argo profiles to identify both the role of surface heat fluxes and the vertical mixing in the Gulf of Guinea. Da-Allada et al. (2013) investigated the causes of the seasonal cycle of the near-surface salinity using a mixed layer salinity model and a combination of satellite products, atmospheric reanalyzes, and in situ observations over the period 2000-2008.

This paper aims to study the spatial and seasonal variability of the mixed layer depth in the Gulf of Guinea at 10 °W.

2. Study Area, Data Collection and Processing

The study was carried out in the Gulf of Guinea (GG) (Figure 1) defined as the region extending from 15 °S to 5 °N and from 15 °W to 15 °E (Kolodziejczyk et al., 2014).

Figure 1: Study area located in tropical Atlantic. CTD stations are indicated by black dots. The three boxes indicate from top to bottom, the equatorial zone in red (2 °N -2 °S), the 6 °S zone (5 °S -7 °S) in blue and the 10 °S zone (8 °S-10 °S) in green



The hydrological data used were extracted from a box centered on 10 °W ± 0.25 between latitudes 2 °N and 10 °S. These data consisted of a combination of historical and recent CTD data with different vertical, spatial and temporal distribution and resolutions, collected between October 1973 and March 2017 during several survey programs, including PIRATA (Servain et al., 1998; Bourlès et al., 2008), EQUALANT (Bourlès et al., 2002), and EGEE. These data were acquired from two databases: CORIOLIS (http://www.CORIOLIS.eu.org/) and the Scientific Information System for the Sea (SISMER) of IFREMER. All of these cruises are summarized in the table below. Data processing have been performed as in N'Guessan et al. (2019).

Table: Summary of cruises used along 10 °W

Cruises	Months	Years	Latitude	Days
RECIF CAP 7314 NANSEN	October	1973	1 °N-10 °S	18-26
GATE PHASE 2	July-August	1974	2 °N-2 °S	25-12
SUPREA	July	1978	2 °N-6 °S	4-9
FOCAL-2-4	February-April-July	1983	2 °N-2 °S	5-6; 31
FOCAL-6-7-8	February-April-July	1984	2 °N-2 °S	09; 28-29; 25-26
Cither-1	January	1993	4,5 °S	13
PIRATA-FR1	September	1997	2 °N-10 °S	9-15
PICOLO	July	1998	1,5 °N	24
PIRATA-FR2	April	1998	10 °S	11
PIRATA-FR3	January	1999	2 °N-6 °S	26-29
EQUALENT 1999/PIRATA-FR4	August	1999	2 °N-10 °S	12-18
PIRATA-FR5	October-November	1999	2 °N-10 °S	30-31 et 1-3
PIRATA-FR6	March	2000	2 °N-6 °S	10-14
EQUALENT2000/PIRATA-FR7	July-August	2000	2 °N-6 °S	29 et 03
PIRATA-FR8	November	2000	2 °N-10 °S	21-27
PIRATA-FR9	November	2001	2 °N-10 °S	22-27
PIRATA-FR10	October	2001	0 °N	12
PIRATA-FR11	December	2002	1,5 °N-10 °S	26-30
PIRATA-FR12	February	2004	1,5 °N-10 °S	3-9
PIRATA-FR14/EGEE 1	Jun	2005	2 °N-10 °S	14-19

EGEE 2	September	2005	2 °N-10 °S	9-14
PIRATA-FR15/EGEE 3	Jun	2006	2 °N-10 °S	1-10
EGEE 4	November	2006	2 °N-6 °S	20-23
PIRATA-FR17/EGEE 5	Jun-July	2007	2 °N-10 °S	27 et 01
EGGE 6	September	2007	2 °N-3 °S	21-24
PIRATA-FR16	May	2007	0 °N	30
PIRTA-FR18	September	2008	1 °N-1,5 °N	19
PIRTA-FR19	Jun-July	2009	0 °N-1,5 °N	22 et 13-14
PIRTA-FR20	September-October	2010	0 °N-1,5 °N	27-28 et 10
FVNM	September	2010	9 °S-10 °S	28
DBBT	May-July	2011	1 °N-2 °S	22-26; 06-09
PIRATA-FR21	May-Jun	2011	0 °N-1,5 °N	7 et 5
WTEC	August	2011	10 °S	13
PIRATA-FR22lge1	March	2012	0 °N	29
PIRATA-FR22leg2	April	2012	1,5 °N-10 °S	7-13
PIRATA-FR23leg1	May	2013	1,5 °N-10 °S	20-27
PIRATA-FR24leg2	April-May	2014	1,5 °N-10 °S	19-27 et 3
PIRATA-FR25	March-April	2015	0 °N-10 °S	24 et 5-6
PIRATA-FR26	March	2016	1,5 °N-10 °S	18-23
PIRATA-FR27	March	2017	1,5 °N-10 °S	8-27

3. Methods

3.1. Determination of the Mixed Layers Depth (MLD)

The MLD was determined using Holte and Talley density threshold method with a criterion of 0.03 kg m^{-3} as in N'Guessan et al. (2019).

3.2. MLD Spatial and Seasonal Variability Study

The climatological mean MLDs were calculated on a one-degree resolution grid computed between 2 °N and 10 °S. The spatial variability is analyzed using a plotted 2-dimensional diagram (climatological mean MLD as a function of latitude).

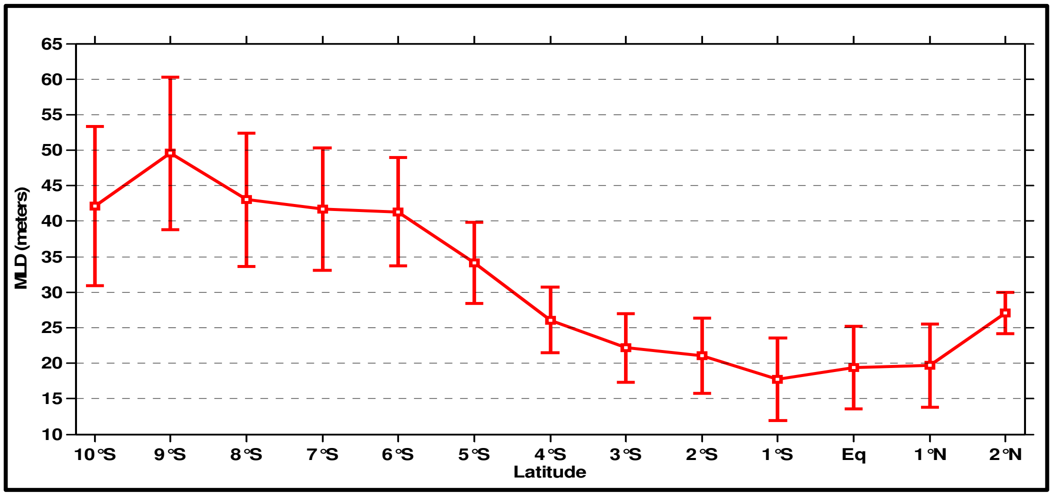
For each season, and for the different zones, the climatological monthly mean MLDs were calculated and plotted on the same graph. The evolution of the monthly and thus seasonal variability were analyzed for the hot (November to April) and the cold seasons (May to October) in the three different areas: the equatorial zone (2 °N-2 °S), the 6°S zone (5 °S-7 °S) and the 10 °S zone (8 °S-10 °S).

4. Results

4.1. Latitudinal Variability of MLD

Figure 2 shows the spatial evolution of the climatological mean MLD over the period 1973 to 2017 between 2 °N and 10 °S at 10 °W. The MLD varies between 18 and 50 m. From 2 °N up to 4.5 °S, the MLDs are less than 30 m. The MLD decreases from 27 m at 2 °N, to a minimum of 18 m at 1 °S before increasing to about 30 m at 4.5 °S. Between 4.5 °S and 9 °S the MLD increases greatly from 30 to 50 m and then decreases to 42.5 m at 10 °S.

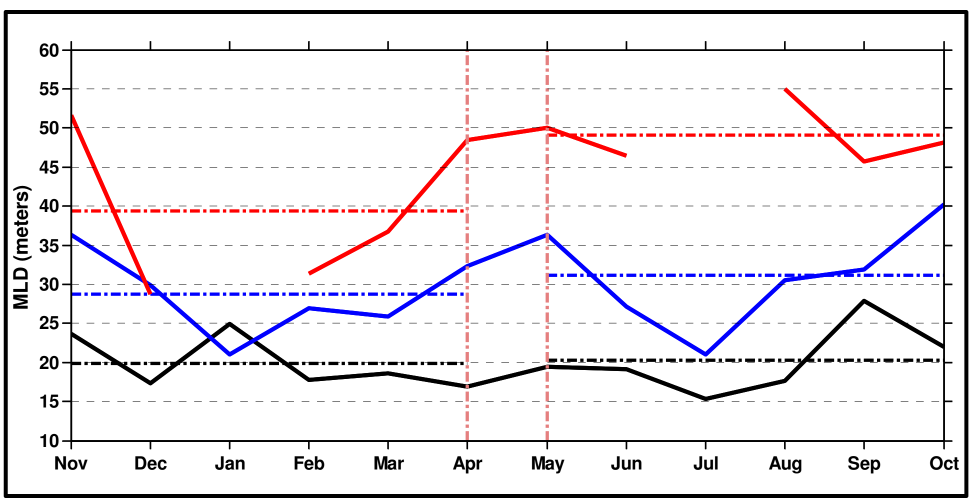
Figure 2: MLD spatial variability between 2 °N and 10 °S along the 10 °W radial from October 1973 to March 2017. The error bars on the graph represent the standard deviation values



4.2. Seasonal Variability of MLD

Figure 3 shows the evolution of the climatological monthly mean MLD in the equatorial zone, the 6 °S and the 10 °S zone during both hot and cold seasons.

Figure 3: MLD seasonal evolution at the equator (black curve), 6 °S (blue curve) and 10 °S (red curve) over the radial 10 ° W from October 1973 to March 2017. The black, blue and red dashed lines represent the seasonal averages at the equator, at 6 °S and 10 °S respectively. Left: hot season, right: cold season



4.2.1. Equatorial Zone

During the hot season (November to April), the MLDs vary between 17 and 25 m. The maximum MLDs are observed in November and January and the low values in December and between February and April. During the cold season (May to October), the MLDs range between 15 and 28 m. Decreasing MLD are observed from May (19.5 m) to a minimum in July (15 m). Then, the MLD increases from July to October (22 m) with a maximum of 28 m in September. The seasonal average MLD in the equatorial band is of 20 m whatever the season.

4.2.2. 6 °S Zone
At 6 °S, in the hot season, the MLD varies between 21 and 37 m. The MLDs values decrease from a maximum of 37 m in November to a minimum of 21 m in January and then deepen to about 33 m in April. Seasonal average in hot season is 28 m. During the cold season, from May to October, MLDs vary between 21 and 40 m. The minimum values are observed in July (21 m) and the maximum values of 40 m in October. The seasonal average of MLD is about 32 m.

4.2.3. 10 °S Zone
At 10 °S, in the hot season, the MLD varies between 28 and 52 m. The MLD is 52 m in November and 28 m in December. It deepens regularly after December, reaching 48 m in April. The seasonal average during hot season is about 40 m. During the cold season, the MLD varies between 45 and 55 m. MLD slightly decreases from 50 m in May, to a minimum of 44 m in June. It then reaches the maximum depth of 55 m in August. The MLDs then move to a minimum of 45 m in September before deepening again to 48 m in October. The seasonal average during cold season is approximately 50 m.

5. Discussion
5.1. Spatial Variability

The MLD values increase from the equatorial band to the 10 °S zone. In the equatorial band our results reveal that MLDs are overall less than 30 m. These results are consistent with those of Planton et al. (2018) and Peter (2007), who both obtained MLDs ranging between 10 to 30 m by using numerical models. According to Foltz et al. (2013), these MLD are shallower than those in the western equatorial basin of tropical Atlantic Ocean. South of the equator, deeper MLDs values were observed at 10 °S compared to those of 6 °S. These higher MLD values were also found by Wade et al. (2011) in this same area. Using the de Boyer Montégut et al. (2004) 0.2 °C temperature threshold criterion, to study the mixed-layer heat budget in the Eastern Equatorial Atlantic from 2005 to 2007, these authors show that MLD values range between 20 to 40 m in the 6 °S zone while they vary from 21 à 65 m in 10 °S zone. South of the equatorial band, this sharp increase of the MLD could be explained by a negative buoyancy flow leading to an increase in the density of the ocean surface layer (Gill, 1982).

5.2. Seasonal Variability

5.2.1. Equatorial Zone
This work shows that the seasonal average MLD in the equatorial band is of 20 m whatever the season. Similar result was also observed by Foltz et al. (2003) who found MLDs values ranging from 17 m in July to 34 m in October along the equator at 10 °W. Camara et al. (2015) using a density criterion with a threshold 0.01 kg m^{-3} to estimate the MLD when studying the mixed layer salt budget in the equatorial zone of the tropical Atlantic ocean also concluded that the seasonal variations of the MLD are relatively weak during each of these seasons.

The relatively high MLD values obtained between September - November and January have also been observed by Planton et al. (2018) between October and November in the equatorial basin from 15 °W to 0 °E between 1 °N and 4 °S. Jouanno et al. (2011), using a regional model of the seasonal thermal balance in the Equatorial Atlantic confirmed the deepening of the mixed layer from July to October. The increase in MLD observed between September and November could indeed be explained by the reduction in incident solar radiation, but also by an increase in the latent heat flux which is superimposed on the heat loss of the mixed layer due to the diapycnal mixing (Hummels et al., 2013). These heat losses from the MLD lead to cooling of the water and lead to a reduction in buoyancy which causes a deepening of the mixed layer. Although it is true that our results indicate weak MLD in the equatorial zone, the months of September to January however show a slight deepening while Camara et al. (2015) found low values over the same period. He attributed these shallow depths to the result of the seasonal upper layer stratification due to summer heating.

The slight decreases of the MLD in December are also observed by Jouanno et al. (2011) at the East Equatorial Atlantic at 10 °W. According to Jouanno et al. (2011), this decrease in MLD could be caused by the relaxation of the winds in December which leads to a strengthening of the stratification of the surface layers and a decrease in MLD. Weingartner and Weisberg (1991a; b) also noted a weak MLD from mid-December to early May at 28 °W during the Equatorial Atlantic program (SEQUAL). They attributed the decrease in MLD to the low wind speeds between December and April.

From February to April, the mixed layer depth also slightly decreases. Foltz et al. (2003) and Hummels et al. (2013; 2014) have indeed shown that during the hot season, the variation in MLD is mainly governed by incident heat flows, short wavelengths and latent heat flows. Heat flows due to long wavelengths remain constant throughout the year (Foltz et al., 2003; Weingartner and Weisberg, 1991a; b). Indeed, from January to April, Foltz et al. (2003) observed a slight increase in short wavelength radiation and a decrease in latent heat at the equator at 10 °W. These two factors lead to an increase in buoyancy by decreasing the density of the waters and a reinforcement of the stratification which cause a decrease in the MLD. Skielka et al. (2010) similarly explained from the results of a general model of oceanic turbulence (Burchard et al., 1999) that the drop in MLD to 0 °N-23 °W between February and April could be attributed to the low intensity of the surface winds driving low turbulent mechanical production (TKE) coupled with high stratification of the upper layers. According to these authors, these two factors help prevent the deepening of the mixed layer.

Between April and June, our results indicate an increase in MLD which could be explained by a strengthening of the winds. This increase in turbulence has also been observed by Giordani et al. (2013), as well as Brandt et al. (2014). In fact, the strengthening of the winds leads to an increase in turbulence (Renault, 2008), increases vertical mixing (Casado Lopez, 2011) and prevents stratification. In addition, strong winds cause a loss of heat in the mixed layer (Josey, 2003; Herrmann and Somot, 2008) which leads to a reduction in the buoyancy flow of the surface layers. The superimposition of these two factors causes the increase in MLD. The increase in MLD observed over this period can also be due to the upwelling and the effect of cold water transported by zonal advection in the equatorial band from the East (Skielka et al., 2010).

Between July and August, the increase in observed MLD could be due to the increase in vertical mixing resulting from the strong shear between the South Equatorial Current (SEC) and the Equatorial Undercurrent (EUC) in the equatorial band. Planton et al. (2018) in their study of the oceanic processes controlling the interannual variability of the cold water tongue from the "intense" events of the cold water tongue had also observed an intensification of the winds between April to August as well as an increase in the vertical current shear between the EUC and the SEC. Foltz et al. (2003) also mentioned the strengthening in the equatorial band of the SEC in the boreal summer (July-September). Vertical mixing under the mixed layer caused by the shearing of these two currents prevents stratification and causes the MLD to increase.

However Camara et al. (2015) observed a weak MLD from April to October. According to these authors, the shallowing MLD is simply a result of the seasonal upper layer stratification due to summer heating.

5.2.2. Zone 6°S and Zone 10°S

The results of seasonal variations obtained at 6 °S and 10 °S show that the evolution of the MLD in the two zones is almost similar despite the fact that the weather conditions are different from one to another (Wade, 2010). The variability of the MLD would be governed by the same factors or forcing. The 6 °S and 10 °S zones will therefore be considered as a single zone which we will note (6 °S-10 °S). Hummels et al. (2014) in their study at 10 °S on the study of diapycnal heat fluxes and heat balance of the mixed layer in the Atlantic cold tongue did not reveal any particular difference in the 6

°S zone. Furthermore, Foltz et al. (2003), although having studied the heat flows at 6 °S and 10 °S, in their interpretation considered the 2 zones as a single zone.

The MLD obtained at 6 °S and 10 °S are deeper than those at the equator. Peter (2007) and Wade (2010) found MLD of about 40 m in this area band. Seasonal variations show that MLDs are higher during the cold season in both areas. However, the deepest MLDs are observed at 10 °S as confirmed by the spatial distributions. Hummels et al. (Hummels et al., 2014) also observed that the MLDs (determined with a temperature criterion of 0.5 °C) are deeper in the cold season compared to those in the hot season with seasonal averages of 80 m and 40 m respectively. MLDs between 40 and 50 m were observed by Planton (2015) during EGEE campaigns at 6 °S in the cold season and he also found MLDs over 60 m in the hot season (November).

From October to January, the decrease of the MLD is the result of an increasing of the net heat flux. Indeed, the modeling results of Carton and Zhou (1997) shown that solar heating and absorbed solar radiation are two of the important MLD driving factors south of 5 °S in the Atlantic ocean. This increasing net heat flux has also been observed by Wade et al. (2011) in the southern equator region. During August to the end of the year, which includes the period from October to January, the net surface heat flux increases and gradually warms the mixed layer due to increasing incoming solar radiation and reducing latent heat flux due to decreasing winds. The increase of net heat leads to an increase of buoyancy flux, while the decrease of winds reinforces the stratification. The effects of these two factors result in the decreasing of the MLD. From January to May, the MLD increases due to the decrease of the net heat flux in the 6 °S-10 °S area as observed by Wade et al. (2011).

From May to October, the MLD is cooled due to the increase of latent heat flux (Hummels et al., 2014). Wade et al. (2011) also shown that the net surface heat fluxes contribute to cool the mixed layer from April to August because of the increase of latent heat flux. During the May-October period, net surface heat fluxes significantly cool the ML by up to 90 W m^{-2} due to the increase of the latent heat flux associated with increased winds as well as a reduction in the incoming solar radiation.

From May to July in the 6 °S-10 °S area our results show decreasing MLD. However, during this period, increasing winds and latent heat flux as well as a reduction in the incoming solar radiation are observed (Wade et al., 2011; Hummels et al., 2014). These factors should normally cool mixed layer and hence lead to an increase of the MLD. But, during the same period, Hummels et al. (2014) found from numerical results that meridional advection from the north and zonal heat advection by the SECC contribute to warm the mixed layer. Should the combining effects of these two factors play to decrease the MLD from May to July in the 6 °S-10 °S?

From July to October, the incident heat flux increases while remaining weaker than the latent heat flux. The increase of the MLD can then be explained by the decrease of the buoyancy flux due to the increase of the density of surface waters. According to Hummels et al. (2014), increasing winds peaking in August occur south of the equator which increases the latent heat flux and contribute to cool the mixed layer and increase the MLD.

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Compliance with Ethical Standards

Conflict of Interest statement On behalf of all authors, we state that there is no conflict of interest.

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