Response letter:

Xu YUAN, Xiaolong YU and Zhongbo SU

Dear Dr. A.J. George Nurser ,

We would like to thank you for the opportunity to revise our manuscript. Your valuable comments are greatly appreciated, which help us to improve the quality of this manuscript. In revising the paper, we have carefully considered all comments and suggestions. The language has been polished and mistakes in writing and gramma have been corrected to make the manuscript more readable. In this letter. Reviewers' comments are in gray shaded. Our responses are provided in blue color.

Major comments:

From the comments of Reviewer A and my own re-reading of the MS, I believe that the MS is still in a ragged state, and requires a careful read through and corrections.

We have carefully revised the manuscript. The language has been polished and the writing has been improved. We believe the manuscript is now readable and in an adequate state for consideration.

For instance, in the definition of BLT in line 76, $MLDDReqDT02$ is specified as the depth of the MLD; I take this to be the Kara et al. definition of MLD in terms of the density difference equivalent to a ΔT=0.2 °. However in the text on line 79 it states that the criterion is Δ\rho =0.03.

We have corrected the abbreviation of the mixed layer depth as "MLD" in the definition of BLT in Line 80 and in the definition of MLD in Lines 82-84.
"MLD is the mixed layer depth defined by oceanic density at which depth the density is 0.03 kg/m3 larger than that of the surface (de Boyer Montégut et al., 2007; Mignot et al., 2007)."

on p6, line 198-9 it is stated that "On the other hand, westerlies lead to Ekman pumping, which in turn, results in the thinner thermocline (green line)"
This looks wrong.

The statement has been corrected as following,
"In the meantime, westerlies lead to Ekman pumping in the western TIO, resulting in the thicker thermocline depth (green line) from December to April, which in turn, also makes the BL thicker."
See also Lines 184-186.

The last para lines 300-309 needs to make clearer which effects are in the western and eastern Indian Ocean.

We have re-written this paragraph as:
"The interannual variability of BLT exerts a seasonal phase locking pattern during the IOD and ENSO years. In the eastern TIO, thicker BL is led by the deeper thermocline due to wind-induced downwelling during the mature phase of the negative IOD events. In contrast, thinner BL is dominated

by the shallower thermocline due to wind-induced upwelling during the developing and mature phases of the positive IOD events. In the western TIO, the thicker BL is only observed during the mature and decaying phases of the positive IOD events, along with deeper thermocline and fresher surface water. The prominent patterns of BLT in the western TIO can only be detected during the El Niño events. According to the theory of Xie et al. (2002), there is warmer water developing in the eastern tropical Pacific Ocean (El Niño), resulting in the anomalous easterlies and invoking the downwelling Rossby wave along the equatorial TIO. Thereby, the thermocline depth has been deepened in the western TIO, resulting in the thicker BL. This thickening BL hampers the upwelling process and helps to sustain warmer SST. During the decaying phase of El Niño events, there is an anomalous ascending branch of the adjusted Walker circulation in the western TIO. As a result, SSS in the western TIO is decreasing due to abundant precipitation. Consequently, fresher surface water contributes to thickening BL, which in turn, sustains the warmer SST in the western TIO."
See also Lines 264-277 of the revised text.

Please take account of referee 1's comments, and look at the whole MS carefully; It's important that the MS is in an adequate state for the referee to review.

The manuscript has been carefully revised according to referee's comments. We believe it is now in an adequate state for consideration.

Dear Referee #1,

We would like to thank you for the opportunity to revise the manuscript. Your valuable comments are greatly appreciated, which help us improve the quality of this manuscript. In revising the paper, we have carefully considered all comments and suggestions. The language has been polished and mistakes in writing and gramma have been corrected to make the manuscript more readable. In this letter, reviewers' comments are in gray shaded, while our responses to the critics of the referees are provided in blue color.

Minor comments:

In the Abstract(Line9), it is mentioned that 'the western TIO (55°E-75°E, 5°N -12°S)', but in the text, '(55°E-80°E, 5°N -12°S)' is mostly used to represent the western TIO. In Line166, 'western TIO (55°E-75°E, 12°S-5°S)' also appears. Please unify the definition of western TIO.

The definition of the western TIO is now unified in the abstract and the text, where the range of longitude is set between 55°E and 75°E.
See Lines 121-122 in the revised manuscript.

Line10, 'SSS' => 'sea surface salinity (SSS)'

Corrected.

Line24, 'Tropic' => 'tropical'

Corrected.

Line44, 'Sea' => 'sea'

Corrected.

Line53, 'Yuhong et al., 2013' => 'Zhang et al., 2013'

The reference is now properly cited. See Line 64.

Line54-57, For positive IOD, how does the upwelling and less rainfall in the southeastern TIO induce a decrease in salinity? Both isothermal layer and mixed layer become shallower, it doesn't mean BLT will be thinner.

The statement has been revised to be logically robust.
"During the positive IOD year (e.g., 2006), thinner BL in the southeastern TIO is mainly led by the shallower thermocline induced by the upwelling Kelvin wave in the presence of weakly shoaling MLD."
See also Lines 56-57 in the revised text.

Line59, The abbreviation 'MLD' should be appeared in Line28.

Corrected.

Line78,' Isothermal Layer Depth (ILD) ' => 'isothermal layer depth (ILD)'

Corrected.

Line79, ‘smaller’ or ‘larger’ ?

We have corrected it to “larger”.

Line82, ‘Asia-pacific data-research center’ =>‘Asia-Pacific Data-Research Center’

Corrected.

Line86, ‘mixed layer depth’ => ‘MLD’

Corrected.

Line88, ‘SST’ is used before its definition in Line90

Corrected.

I decide to stop here, because I cann’t stand a revised version that involves so many mistakes. It is a waste of time to go on the review of the present version. I believe that the authors didn’t take the work seriously and suggest them make a self-examination first.

We have carefully revised the manuscript. The language has been polished and the writing has been improved. We believe the manuscript is now more readable and in an adequate state for consideration.

S~~The s~~easonal and interannual variabilities of the barrier layer thickness in the tropical Indian Ocean

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Abstract. ~~The seasonal and interannual variations of the barrier layer thickness (BLT) in the Tropical Indian Ocean (TIO) is investigated in this study using the Simple Ocean Data Assimilation (SODA) version 3 reanalysis dataset from 1980 to 2015. Seasonally, BLT anomalies in the western TIO (55°E-75°E, 5°N -12°S) are negatively correlated to SSS anomalies due to the change of the freshwater in boreal winter, spring, and autumn. In boreal winter, thermocline anomalies induced by the upwelling due to the local wind change positively correlates with BLT anomalies in the western TIO. In contrast, BLT anomalies are not well correlated with both SSS and thermocline anomalies in the eastern TIO (85°E-100°E, 5°N -12°S) in all four seasons. Prominent BLT and thermocline anomalies in the western TIO could be observed in both positive and negative Indian Ocean Dipole (IOD) years, while thicker BLT and deeper thermocline in the eastern TIO are prominent only in the positive IOD years. On the other hand, BLT in the western TIO presents a remarkable seasonal phase locking feature during the El Niño years. Thicker BLT in the western TIO is due to deepening thermocline induced by the westward Rossby wave during the developing and mature phases of El Niño, while thickening BLT opposing to the weakened thermocline change, becomes more significant due to the decreasing SSS induced by the freshwater during the decaying phase of El Niño~~ The seasonal and interannual variations of the barrier layer thickness (BLT) in the tropical Indian Ocean (TIO) is investigated in this study using the Simple Ocean Data Assimilation version 3 (SODA v3) ocean reanalysis dataset. Analysis of this study suggests energetic but divergent seasonal variabilities of BLT in the western TIO (55°E-75°E, 5°N -12°S) and the eastern TIO (85°E-100°E, 5°N -12°S). For instance, the thinner barrier layer (BL) is observed in the western TIO during boreal winter as a result of decreasing sea surface salinity (SSS) and shallower thermocline, which are associated with the intrusion of freshwater flux and the wind-induced downwelling, respectively. On the contrary, the variation of BLT in the eastern TIO mainly corresponds to the thermocline in all seasons. The interannual variability of BLT is explored with Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO). During the mature phase of the positive IOD events, thinner BL in the eastern TIO is attributed to the shallower thermocline, while thicker BL appears in the western TIO due to deeper thermocline and fresher surface water.

During the negative IOD events, thicker BL only occurs in the eastern TIO corresponding to the deeper thermocline. During the ENSO events, prominent BLT patterns are observed in the western TIO corresponding to two different physical processes during the developing and decaying phase of the El Niño events. During the developing phase of El Niño events, thicker BL in the western TIO is associated with deepening thermocline induced by the westward Rossby wave. During the decaying phase of El Niño events, the thermocline is weakly deepening while the BLT reaches its maxima induced by the decreasing SSS.~~.~~

1 Introduction

The upper-ocean traditionally included only the mixed layer and the thermocline. The terminology barrier layer (BL), was recently raised as the mixed layer depth (MLD) was redefined from using the temperature (de Boyer Montégut et al., 2004) to using the oceanic density (Kara et al., 2000; Mignot et al., 2007). The barrier layer thickness (BLT) is simply the depth between the bottom of the mixed layer defined by density, and the top of the thermocline (Lukas and Lindstrom, 1991; Masson et al., 2002; Sprintall and Tomczak, 1992). Although BL is much thinner than the other two layers, it plays a key role in oceanic dynamics and air-sea interaction. For example, BL helps to sustain the heat in the mixed layer by isolating the temperature in the upper ocean from the cooling entrainment. Accordingly, BL is crucial in the formation of the El Niño Southern Oscillation (ENSO) and contributes to the formation of the different ENSO types (conventional ENSO and ENSO Modoki) (Singh et al., 2011; Maes, 2002; Maes et al., 2006; Maes et al., 2005). Also, the spatial structure of BLT led by different Ekman drift is crucial for the formation of monsoon cyclones in the pre-monsoon season (Thadathil et al., 2007; Vinayachandran et al., 2002; Masson et al., 2005; Neetu et al., 2012). ~~The upper-ocean variability, particularly the formation and variability of the mixed layer, can provide a broad perspective to better understand the air-sea interaction and the impacts of climate events on the marine ecosystem. The Tropic Indian Ocean (TIO) with a shallower thermocline in the west (Yokoi et al., 2012, 2008; Yu et al., 2005) and stronger interannual variation in the east (Li et al., 2003; Saji et al., 1999) comparing to the tropical Pacific and the Atlantic Ocean, provides a unique study region to investigate the variability of upper ocean.~~

~~Traditionally, the mixed layer depth was defined by the temperature (de Boyer Montégut et al., 2004). However, the mixed layer has recently been redefined by using the oceanic density (Kara et al., 2000; Mignot et al., 2007). The new definition results in novel terminology, the barrier layer. The barrier layer thickness (BLT) is defined as the depth from the mixed layer bottom to the top of the thermocline (Lukas and Lindstrom, 1991; Masson et al., 2002; Sprintall and Tomczak, 1992). BLT plays a key role in oceanic dynamics and air-sea interaction. For example, BLT isolates the density of the mixed layer from the cooling entrainment, helping to sustain the heat for the formation of the El Niño Southern Oscillation (ENSO) (Maes, 2002; Maes et al., 2006; Maes et al., 2005), as well as contributing to the formation of the different ENSO types (conventional ENSO and ENSO Modoki) (Singh et al., 2011). The spatial structure of BLT led by different Ekman drift (Thadathil et al., 2007; Vinayachandran et al., 2002) is crucial for the formation of monsoon cyclones in the pre-monsoon season (Masson et al., 2005; Neetu et al., 2012).~~

The variability of BLT is mainly affected by the change of MLD and thermocline due to various mechanisms, such as heavy precipitation, oceanic currents, wind stress, and oceanic waves (Bosc et al., 2009; Mignot et al., 2007; Masson et al., 2002; Qu and Meyers, 2005). For instance, thicker BL mainly presents in the areas beneath

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Formatted: Font: (Asian) Times New Roman the Intertropical Convergence Zone (ITCZ) with decreasing SSS due to abundant rainfall (Vialard and Delecluse, 1998) or large river discharge (Pailler et al., 1999). The strong wind stress anomalies could also contribute to thickening the BL via deepening the thermocline (Seo et al., 2009).

~~The variability of BLT is attributed to various mechanisms, such as heavy precipitation, oceanic currents, wind stress, and oceanic waves (Bosc et al., 2009; Mignot et al., 2007). For instance, thicker BLT mainly locates in the areas beneath the Intertropical Convergence Zone (ITCZ) due to abundant rainfall (Vialard and Delecluse, 1998) or regions with large river runoff (Pailler et al., 1999). The strong wind stress anomalies could also contribute to thickening the BLT (Seo et al., 2009).~~

Comparedto the tropical Pacific and the Atlantic Ocean, the tropical Indian Ocean (TIO) is characterized with a shallower thermocline in the west (Yokoi et al., 2012, 2008; Yu et al., 2005) and stronger interannual variation of upper-ocean temperature in the east (Li et al., 2003; Saji et al., 1999), which provides a unique region to evaluate the seasonal and interannual variabilities of BLT.

The strong seasonality of BLT has been observed in some subregions of the TIO, such as the southeastern Arabian Sea, the Bay of Bengal, and the southeastern TIO (Schott et al., 2009). These regions are also characterized by the strong seasonality of SSS due to different hydrological processes (Rao, 2003; Subrahmanyam et al., 2011; Zhang et al., 2016; Zhang and Du, 2012). Overall, the seasonality of BLT in the TIO is partly consistent with the change of SSS due to the impact of freshwater (Masson et al., 2002; Qu and Meyers, 2005).

The interannual variability of BLT in the southeastern TIO could be partly explained by IOD events (Qiu et al., 2012). During the positive IOD year (*e.g.*, 2006), thinner BL in the southeastern TIO is mainly led by the shallower thermocline induced by the upwelling Kelvin wave in the presence of weakly shoaling MLD. In the negative IOD year (*e.g.*, 2010), a thicker BL is expected due to the extending of the thermocline. Furthermore, at the sub-seasonal scale, the zonal SSS gradient driven by the freshwater advection results in a thicker BL to sustain a fresh and stable MLD (Drushka et al., 2014).

Existing studies on the interannual variability of BLT were mainly focused on specific years and lacking long-term evaluation. More importantly, the interannual variability of both thermocline and SSS are supposed to be associated with the ENSO events (Grunseich et al., 2011; Rao and Sivakumar, 2003; Subrahmanyam et al., 2011; Zhang et al., 2013), but relationships between BLT and ENSO are scarcely reported in the TIO. Also, the relative impact of SSS and thermocline depth on the variability of BLT and SSS variation is still unclear and is not systematically investigated in the TIO. Thus, the evolution of the seasonal and interannual variabilities of BLT and its relationship with SSS and thermocline anomalies are still highly desired. The Simple Ocean Data Assimilation (SODA) version 3 ocean reanalysis dataset covers time-series data from 1980 to 2015, which could be adequate for such purpose.

The remainder of this paper is arranged as follows. In Section 2, we briefly describe the datasets and methods. Comparisons of the BLT variability interpreted from both observed and reanalysis datasets in the TIO is presented in Section 3. Section 4 presents the seasonal variability of the BLT in the TIO, while its interannual variability is shown in Section 5. At last, summary and discussions are given in Section 6. ~~In the TIO, the~~

~~features of BLT seasonal and interannual variation have been found very similar to that of Sea surface salinity (SSS). Firstly, the southeastern Arabian Sea, the Bay of Bengal, and the southeastern TIO, characterized by significant seasonal variability of SSS due to different hydrological processes, are also observed with the strong BLT seasonal variations (Schott et al., 2009). Secondly, it is reported that the seasonal variability of SSS in the TIO is mainly attributed to the freshwater (precipitation and runoff) and the horizontal advection (Rao, 2003; Subrahmanyam et al., 2011; Zhang et al., 2016; Zhang and Du, 2012), whereas the BLT annual variation could also be affected by the freshwater (Masson et al., 2002; Qu and Meyers, 2005). Moreover, the Indian Ocean Dipole (IOD) and ENSO have been intensively reported to have impacts on the interannual variability of SSS in the TIO (Grunseich et al., 2011; Rao and Sivakumar, 2003; Subrahmanyam et al., 2011; Yuhong et al., 2013), while the IOD events can also partly explain the interannual variability of BLT in the southeastern TIO (Qiu et al., 2012). In general, in the positive IOD year (*e.g.*, 2006), the isothermal layer is lifted by the upwelling Kelvin wave, and the mixed layer becomes shallower due to salinity decrease, which results in a thinner barrier. In the negative IOD year (*e.g.*, 2010), a thicker BLT is expected due to the extending of the isothermal layer. Furthermore, the tight relationship between BLT and zonal SSS gradient was also reported in the TIO at the sub-seasonal time scale. The zonal SSS gradient, led by the advection-driven freshwater, produces a thicker BLT, which in turn, sustains a fresh and stable mixed layer depth (MLD) (Drushka et al., 2014).~~

~~However, existing studies on the interannual variability of BLT were mainly for specific years and lack of long-term verification and the co-varying between the BLT and SSS variation is not always held in the TIO (Qiu et al., 2012). Also, the relationship between BLT and the thermocline anomaly is less documented in the TIO. As a result, further investigations of BLT seasonal and interannual variabilities and its relationship with SSS and thermocline anomalies are still highly desired. The Simple Ocean Data Assimilation (SODA) version 3 reanalysis dataset from 1980 to 2015 could be adequate for such purpose.~~

~~The remainder of this paper is arranged as follows. After a description of the datasets and methods in section 2, we compare the variability features of BLT obtained from observed and reanalysis datasets in the Indian Ocean in section 3. Section 4 presents the seasonal variation of the BLT anomalies in the TIO. Its interannual variability is shown in section 5. A summary and discussion are given in section 6.~~

2 Data and Methods

A series of monthly global gridded observation and reanalysis products were used to assess the variability of BLT in the Indian Ocean. At 1° horizontal resolution, this includes the Argo profiles products provided by the French Research Institute for Exploration of the Sea (Ifremer: http://www.ifremer.fr/cerweb/deboyer/mld/Subsurface_Barrier_Layer_Thickness.php) from 2005 to 2015. BLT is calculated as the difference between TTD_{DTm02} and $MLD\cancel{MLD_{DReqDT02}}$.

$$BLT = TTD_{DTm02} - MLD\cancel{MLD_{DReqDT02}}$$

where TTD_{DTm02} is ta depth at the top of thermocline, which is defined as the depth as the depth at which the surface temperature is cooled by 0.2 °C than sea surface temperature and hereafter referred to as the isothermal layer depth (ILD). MLD is the mixed layer depth defined by oceanic density at which depth the density is 0.03 kg/m^3 larger than that of the surface (de Boyer Montégut et al., 2007; Mignot et al., 2007).

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~~where TTD_{DTm02} is the top of thermocline depth defined as the depth at which the surface temperature cooled by 0.2 °C, which is also referred to as the Isothermal Layer Depth (ILD) henceforth. $MLD_{DReqDT02}$ is the mixed layer depth defined in oceanic density by assuming the density within the layer is 0.03 kg/m^3 smaller than that of the surface (de Boyer Montégut et al., 2007; Mignot et al., 2007).~~

Another dataset is the latest released SODA version 3 reanalysis data (1980-2015) with a horizontal resolution of 0.5°, which is hereafter denoted as SODA v3 data and can be accessed from the Asia-Pacific Data-Research Center (APDRC: http://apdrc.soest.hawaii.edu/datadoc/soda_3.3.1.php). SODA v3 has reduced systematic errors in the upper ocean and has improved the accuracy of the poleward variability in the tropic (Carton et al., 2018). It has 26 vertical levels with a 15 m resolution near the sea surface. We adopted the same Ifremer equation to calculate SODA BLT as the difference between density and temperature defined MLD.

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~~At 0.5° horizontal resolution, The latest released version 3 SODA ocean reanalysis data (1980-2015) provided by the Asia-pacific data-research center (APDRC: http://apdrc.soest.hawaii.edu/datadoc/soda_3.3.1.php) is employed in this study. SODA version 3 has reduced systematic errors to the level that are adequate for the no-model statistical objective analysis in the upper ocean and also has improved the accuracy of poleward variability in the tropic (Carton et al., 2018). It has 26 vertical levels with a 15-m resolution near the sea surface. We adopted the same Ifremer equation to calculate SODA BLT by using the mixed layer depth defined by both the density and temperature.~~

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Salinity and temperature in the first level (5m) are adopted as the SODA SSS and sea surface temperature (SST), respectively. The thermocline depth is defined as the depth of the 20 ℃ isotherms.

~~We take the salinity and temperature in the first level (5m) as the SODA SSS and SST, respectively. The thermocline depth is defined as the depth of 20 °C isotherm.~~

Monthly SST between 1980 and 2015 on a grid of 1°x1° is acquired from Hadley Center Global Sea Ice and Sea Surface Temperature (HadISST: https://climatedataguide.ucar.edu/climate-data/sst-data-hadisst-v11) to calculate the Nino3.4 index. The Nino3.4 index is the average SST anomaly in the area of (5°N -5°S, 170°W -120°W).

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The simultaneous and lead-lag correlations are evaluated in this study with the *t*-student significance test. In all the datasets, we removed the annual cycle of each parameter before the interannual correlation analysis. The composition analysis is also employed to evaluate the interannual variability of BLT using the Monte-Carlo significance test. The process of Monte-Carlo is that the IOD/El Niño/La Nina years are randomly shuffled (10 000 times) for each month, and a mean *t*-student significance test is used to calculate the *t* statistic for the selected areas. The mean of the *t* statistic generated by the random simulations exceeding that of the actual *t* value is determined and assessed at the 5% significance level. The positive and negative IOD years are provided by the Bureau of Meteorology (http://www.bom.gov.au/climate/iod/), and the El Niño and La Nina years are obtained from Golden weather gate service (https://ggweather.com/enso/oni.htm). Monthly mean values are averaged over a three-sequential month for different seasons, *e.g.*, December-January-February (DJF) for boreal winter, March-April-May (MAM) for boreal spring, June-July-August (JJA) for boreal summer and September-October-November (SON) for boreal autumn. All the area-averaged parameters shown in this study are weighted by the cosine of the latitude.

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~~Monthly sea surface temperature (SST) obtained from Hadley Center Global Sea Ice and Sea Surface Temperature (HadISST: https://climatedataguide.ucar.edu/climate-data/sst-data-hadisst-v11) for 1980-2015 on a grid of 1°x1° is also used for the validation purpose and to calculate the Nino3.4 index (5°N-5°S,170°W-120°W).~~

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~~In all the datasets, we removed the annual cycle before proceeding with correlation. The simultaneous and lead-lag correlations are evaluated in this study with the *t*-student significance test. The composition analysis is employed in studying the interannual variability of BLT with the Monte-Carlo significance test. For each month, the IOD/El Niño/La Nina years are randomly shuffled (10 000 times) and a mean *t*-student significance test t statistic for the selected areas is calculated. The mean of the t statistic generated by the random simulations exceeding that of the actual t value is determined and assessed at the 5% significance level. The positive and negative IOD years are provided by the Bureau of Meteorology (http://www.bom.gov.au/climate/iod/) and the El Niño and La Nina years are obtained from Golden weather gate service (https://ggweather.com/enso/oni.htm). Monthly mean fields are averaged over a three-sequential month for different seasons, *e.g.*, December-January-February (DJF) for boreal winter, March-April-May (MAM) for boreal spring, June-July-August (JJA) for boreal summer and September-October-November (SON) for boreal autumn. All the area-averaged parameters shown in this study are weighted by the cosine of the latitude.~~

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3 BLT in the Indian Ocean

BLT in the TIO calculated from SODA v3 is first validated against Argo float observation from 2005 to 2015. As shown in Figure 1, the seasonal BLT climatology obtained from SODA v3 is biased thinner in the Bay of Bengal in all seasons compared to that derived from Argo. This thinner BL in SODA v3 is probably because it lascks the runoff data from the Bay of Bengal as input in its reanalysis (Carton et al., 2018; Carton and Giese, 2008, 2006). Additionally, SODA BLT fails to capture the BLT feature on the west coast of Africa and the northwestern Arabian Sea (see the white areas right to green line), where no BLT is expected due to the salinity inversion. However, for the area of interest in the TIO (55°E-100°E, 5°N -12°S), the BLT in SODA v3 shows a coherent spatial pattern with the Argo BLT, where BL is, in general, thicker in the east and thinner in the west. The seasonal evolution of BLT in the east obtained from SODA is consistent with that from Argo, shown as a decreasing trend from boreal winter to spring and an increasing trend from boreal summer to autumn.

~~BLT calculated by SODA version 3 reanalysis data is assessed against Argo float observation from 2005 to 2015. Figure 1 shows the distributions of the climatological BLT in the TIO for different seasons. BLT climatology obtained from SODA presents a thinner bias in the Bay of Bengal in all four seasons comparing to Argo BLT. This weakened BLT is probably because of lacking the runoff data in the Bay of Bengal (Carton et al., 2018; Carton and Giese, 2008, 2006). SODA BLT fails to capture the BLT feature in the western TIO and northwestern Arabian Sea where no BLT is expected (white areas with green line). However, for the area of interest, the BLT in SODA shows a coherent spatial pattern with the Argo BLT in the TIO (55°E-100°E, 5°N-12°S). For instance, thicker BLT locates in the eastern TIO while thinner BLT locates in the western TIO. The seasonal evolution of BLT in the eastern TIO obtained from SODA is consistent with that from Argo as well. The area and intensity of BLT in the eastern TIO experience decreasing from boreal winter to spring and increasing in both boreal summer and autumn.~~

Two sub-regions are highlighted to evaluate the seasonal and interannual variabilities of SODA BLT, namely western TIO (55°E-75°E, 5°N -12°S) and eastern TIO (85°E-100°E, 5°N -12°S). Because these two sub-regions not only represent the zonal difference of the BLT in the TIO but also include the well-known areas of Seychelles Chicago Thermocline Ridge [SCTR, (60°E-75°E, 12°S-5°S)] and the eastern IOD area [IODE, (90°E-100°E,10°S-EQ)] (Manola et al., 2015; Yokoi et al., 2012, 2008). As shown in Figure 2, region-averaged BLT obtained from SODA v3 in the western TIO is greater than that of Argo, especially during boreal summer and autumn. In the eastern TIO, SODA v3 BLT is quite comparable with that of Argo, except for slight discrepancies in June and July. The trend of BLT seasonality obtained from SODA v3 and Argo are, however, overall consistent, suggesting the robustness of using SODA v3 data in interpreting the BLT variabilities in the TIO.

Due to the insufficient temperature-salinity observations, we only compare the interannual variability of the SODA v3 BLT with the Argo between 2005 and 2010. As shown in Figure 3, the interannual variability of BLT from SODA v3 and Argo is very consistent in both the western and eastern TIO. The correlation coefficients between SODA v3 and Argo for the western and eastern TIO are 0.75 and 0.90, respectively. Results in Figure 3 confirm that SODA v3 is adequate to evaluate the long-term seasonal and interannual variabilities of the BLT in the TIO.

The seasonal and interannual variations of MLD and ILD averaged over the western and eastern TIO are also presented in Figure 4 to investigate the dominant driver for the BLT variability. Overall, the seasonal variabilities of MLD and ILD present a consistent annual cycle in both subregions. The seasonality of BLT, however, exerts discrepancies between these two regions (Figures 4a and 4b). Specifically, a semi-annual cycle of BLT is observed in the western TIO, compared to an annual cycle of BLT observed in the eastern TIO. The interannual variabilities of BLT are also different in the western and eastern TIO (Figure 4c and 4d). In the western TIO, the interannual variability of BLT is more related to the ILD variation. For example, the years with thicker BL in the western are associated with deeper ILD, such as 1982, 1983, 1991, and 1996. On the contrary, in the eastern TIO, the relative impact of MLD and ILD on the interannual variability of BLT cannot be discriminated. For instance, deeper BLT occurs in 1981, 1985, and 1996 corresponding to relatively shallower MLD, while the other years of deeper BLT, such as 1994, 1999, and 2001, are associated with deeper ILD. Additionally, the interannual correlation coefficients between BLT and MLD are -0.07 and -0.25 for the western and eastern TIO, respectively, and the correlations coefficients between BLT and ILD are 0.47 and 0.38 in those two sub-regions. The low correlation coefficients suggest that neither MLD nor ILD can fully explain the BLT variabilities in the TIO. Therefore, the difference of BLT variabilities in the western and eastern TIO needs to be further explained. In the subsequent analysis, the variables in MLD, including SST and SSS, and the thermocline are selected to explain the BLT variabilities in the TIO.

~~To evaluate the seasonal and interannual variabilities of SODA BLT, the region-averaged BLT over two separated boxes (from 55 °E -80°E and from 85°E to 100°E, respectively) along with the band between 5°N and 12°S is shown in Figure 2 and Figure 3. In Figure 2, both SODA reanalysis and Argo capture the seasonality of BLT, although the details are somewhat different. In the west sector (55°E -80°E), the thickest BLT is in boreal winter while relatively thin BLT is in boreal spring. In contrast, in the eastern sector (85°E-100°E), the relatively thick BLT occurs in boreal autumn while the thin BLT occurs in boreal spring and summer.~~

~~Due to the insufficient temperature-salinity observations, we only compare the interannual variability of the SODA BLT with the Argo during 2005-2010. Two curves show good consistency in both west of 80°E and east of 80°E (Figure 3). Respective correlations between SODA and observation for the west of 80°E and east of 80°E are 0.75 and 0.90, which are statistically significant at the 99.9 % confidence level.~~

~~Thus, comparisons between SODA and Argo BLT show the SODA capability in representing the seasonal and interannual variability of the BLT in the TIO. In the next section, we will only use SODA reanalysis data to investigate the seasonal and interannual variability of BLT in the TIO (55°E-100°E, 5°N -12°S) from 1980 to 2015.~~

~~The seasonal and interannual variations of MLD and ILD averaged over the west sector (55°E-80°E, 5°N -12°S) and the east sector (85°E-100°E, 5°N -12°S) have also been calculated and presented in Figure 4 to investigate the dominant driver for the BLT variability. However, it is hard to conclude either MLD or ILD as the main dominator. In particular, both MLD and ILD display an annual cycle while BLT presents a semi-annual cycle in the western sector. In the eastern sector, both MLD and ILD increase from March to August and decrease from September to February, while BLT increases from March to November and decreases from December to February. Thus, the impacts of MLD and ILD on the BLT is dependent on the seasons. On the other hand, from their interannual time series, there is no BLT (negative) in the years with deeper MLD, while prominent BLT exists in the years with deeper ILD. We also calculated the correlation coefficients between BLT and MLD and ILD, which are -0.07 and 0.47 in the west sector and -0.25 and 0.38 in the east sector. The interannual variation of BLT is mainly related to the ILD variation in the TIO. To further study the seasonal and interannual variations of BLT, we choose the variables in MLD, such as SST and SSS, and thermocline (prominent variations in the deeper ocean).~~

4 Seasonal variation

It is well known that the area with the thickest BL in the TIO corresponds to freshest surface water, while the areas of the thinnest BL corresponds to saltiest surface water (Agarwal et al., 2012; Felton et al., 2014; Han and McCreary, 2001; Vinayachandran and Nanjundiah, 2009). The spatial feature between BLT and SSS in different seasons are presented in Figure 5, where the seasonality of SSS and BLT does not co-vary, especially near the equator. For example, surface saltier water in the western TIO elongates eastward during boreal winter and spring and retreats during boreal summer and autumn, while BLT does not vary accordingly. In the eastern TIO, BLT presents a more prominent seasonality than that of SSS, with a maximum in boreal autumn.

Figure 6 shows the in-phase correlations of SST and SSS anomalies with BLT anomalies. Here, the SSS, SST and BLT anomalies have been averaged as the functions of longitude vs. time in the western and eastern TIO, respectively. The seasonal BLT-SST relationship in the western TIO is not robust as only a few areas exceed the 95% significance level (see Figure 6a). A short-term (less than two months) negative correlation between BLT and SST anomalies can be observed in the eastern TIO during boreal winter. This negative BLT-SST correlation also exists when the HadISST data is employed (figure not shown). Compared with the seasonal BLT-SST relationship, the seasonal BLT-SSS relationship is more prominent in the TIO, especially in the western TIO (Figure 6b). This negative correlation between BLT and SSS starts from January and extends to June.

To further understand the seasonal relationship of BLT with SSS and thermocline, we adopt the lead-lag crossing correlation analysis for BLT anomalies with respect to SSS and the thermocline depth anomalies in January (JAN), April (APR), July (JUL) and October (OCT). The significant area of the lead-lag negative correlation between SSS and BLT mainly locates in the western TIO (Figures 7a-d), which is consistent with that of their in-phase correlation (Figure 6b). During boreal winter, spring, and autumn, the variation of SSS could affect BLT variability in the next two months (Figures 7a and 7d). For example, fresher (saltier) water in October in the western TIO could lead to thicker (thinner) BL in November and December. The positive correlation between BLT and the thermocline depth is much prominent in the western TIO, particularly in January. The variation of the thermocline in January has an impact on BLT variations up to the next four months (Figure 7e). During boreal autumn, a strong BLT-thermocline correlation mainly occurs in the eastern TIO. The variation of the thermocline in October could have an impact on BLT variations in the three successive months (Figure 7h).

We also examined the corresponding atmospheric forcing in the western and eastern TIO. Figure 8 shows the seasonal evolution of the upper-ocean salinity, MLD, ILD, the thermocline depth, the freshwater flux (Precipitation minus Evaporation, P-E), and the zonal component of the wind stress. In the western TIO, freshening of the upper-ocean water from October to April is observed due to freshwater flux, which in turn, thickens the BL, consistent with the analysis in Figure 6b. In the meantime, westerlies lead to Ekman pumping in the western TIO, resulting in the thicker thermocline depth (green line) from December to April, which in turn, also makes the BL thicker. Driving factors of the BLT seasonality in the eastern TIO are more complex than that in the western TIO. Firstly, the seasonal evolution of SSS has a semi-annual feature, while THE freshwater flux does not. This can be explained by the Indonesian throughflow, which brings freshwater from the Pacific Ocean into the eastern TIO (Shinoda et al., 2012). Secondly, the thermocline presents the opposite seasonal cycle compared with that in the western TIO. However, the zonal wind stress displays a similar seasonal variation in both the western and eastern TIO. Last but not least, the salinity in the deeper ocean varies similarly to the thermocline in the eastern TIO, which is not observed in the western TIO. Thus, the freshwater flux and the wind-driven upwelling cannot fully explain the BLT seasonality in the eastern TIO. Felton et al. (2014) have suggested that the seasonal BLT variation in the eastern TIO may be related to the sea level and ILD oscillation.

~~To understand the seasonal variability of BLT in the TIO, Figure 5 presents the distributions of SSS and BLT during boreal winter, spring, summer, and autumn. The BLT distribution pattern is inversely correlated to the SSS distribution, where thick BLT is observed with fresh water in the eastern TIO, and vice versa in the western TIO. This is consistent with previous studies (Agarwal et al., 2012; Felton et al., 2014; Han and McCreary, 2001; Vinayachandran and Nanjundiah, 2009). Although both SSS and BLT have a similar distribution in the TIO, their seasonal variabilities do not co-vary with each other, especially near the equator. For example, saltwater in the western sector (55°E-80°E, 5°N -12°S) elongates to the east during boreal winter and spring and retreats during boreal summer and autumn, while the corresponding thin BLT does not vary accordingly. In contrast, there is significant seasonal variability of BLT in the eastern sector (85°E-100°E, 5°N -12°S), with its maxima occurred in boreal autumn. Besides, there is a weak seasonal variability of the east-west SSS gradient along the equator (5°N -12°S) while the zonal BLT gradient becomes more significant in boreal spring and strongest during boreal autumn. Thus, the seasonal variability of BLT in the TIO is not always co-varying with SSS.~~

~~To do a more detailed correlation analysis, we averaged data along the TIO. This area is adequate to demonstrate the difference in the seasonal variability between SSS and BLT. In addition, the well-known area of Seychelles Chicago Thermocline Ridge [SCTR, (60°E-80°E, 12°S-5°S)] (Manola et al., 2015; Yokoi et al., 2012, 2008) and the eastern IOD area [IODE, (90°E-110°E,10°S-EQ)] are also within the selected regions.~~

~~BLT anomalies were obtained from SODA version 3 reanalysis data averaged along the TIO (12°S – 5°N) as a function of longitude vs. time. Figure 6 displays the in-phase correlations of SST and SSS anomalies with BLT anomalies respectively. At the seasonal time scale, although it has been proven that SST has a tight relationship with thermocline (Yokoi et al., 2012), there is no significant relationship between SST and BLT anomalies in the western TIO (55°E-75°E, 12°S-5°S). Instead, a short-term (less than two months) negative relationship between BLT and SST anomalies can be observed in the eastern TIO (85°E-100°E, 12°S-5°S) during boreal winter, with colder water connecting to thicker BLT and vice versa (Figure 6a). This SST-BLT relationship can also be found by correlating with SST anomalies obtained from the HadISST (Figure not shown), except their negative correlated area is smaller. On the contrary, a remarkable negative in-phase SSS-BLT (blue shaded) relationship, shows in the western TIO during boreal winter and spring with saltier (fresher) water corresponding to thinner (thicker) BLT (Figure 6b), while there is no significant relationship between SSS and BLT anomalies in the east.~~

~~To further understand the seasonal variability of BLT anomalies, we use the lead-lag crossing correlation for BLT anomalies in respect to SSS anomalies in January (JAN), April (APR), July (JUL) and October (OCT). The significant lead-lag relationship between SSS and BLT anomalies mainly locates in the western TIO (Figure 7), where is consistent with their in-phase relationship (Figure 6). SSS anomalies in boreal winter and autumn not only have a certain in-phase relationship with BLT anomalies but could also result in the change of the corresponding BLT anomalies at least two months earlier (Figure 7a,d). For example, in the western TIO, saltier water in October is presented with thinner BLT and can result in thinner BLT in November and December; saltier water in January associated with thinner BLT could lead to thinner BLT until May. This leading relationship of SSS anomalies on BLT anomalies is also found in April, but with a weaker negative BLT feedback from January and February (Figure 7b). In July, it is only found the BLT feedback in the western TIO, implying that the spring-time BLT anomalies can have a negative impact on the summer-time SSS anomalies (Figure 7c).~~

~~Figure 8 shows the lead-lag crossing correlation between BLT and the thermocline anomalies. Thermocline anomalies have a positive correlation coefficient with BLT anomalies. Particularly, deeper thermocline in October is along with thicker BLT in the central and the eastern TIO and has a positive leading effect on the BLT anomalies in November and December. Although deeper thermocline in January is associated with thicker BLT in the eastern TIO, there is no leading impact of thermocline anomalies on the BLT anomalies in the following months. In contrast, the remarkable in-phase and leading relationships between thermocline and BLT anomalies in January can be seen in the western TIO, which has since weakened in April. A weaker leading effect of thermocline anomalies on BLT anomalies in April appears in the eastern TIO. In July, there is little correlation between thermocline and BLT anomalies in the TIO.~~

~~According to the above analysis, we examined the corresponding atmospheric forcing in the western TIO and eastern TIO, respectively. Figure 9 shows the seasonal evolution of the upper-ocean salinity, MLD, ILD, thermocline, freshwater flux (Precipitation minus Evaporation, P-E), and the zonal component of the wind stress.~~

~~In the western TIO, freshwater flux freshens the upper-ocean water from October to April, which in turn, thickens the BLT, consistent with the analysis in Figure 7. On the other hand, westerlies lead to Ekman pumping, which in turn, results in the thinner thermocline (green line) to affect the BLT. In the eastern TIO, the seasonal variation of BLT is more complex than that in the western TIO. Firstly, the seasonal evolution of SSS has a semi-annual feature, while freshwater flux does not. This may link to the Indonesian throughflow which brings freshwater from the Pacific Ocean into the eastern TIO (Shinoda et al., 2012). Secondly, the thermocline presents the opposite seasonal cycle comparing with that in the western TIO, although the zonal wind stress displays a similar seasonal variation in both the western and eastern TIO. Last but not least, we also noticed that the salinity in the deeper ocean varies similar to the thermocline in the eastern TIO, which is different in the western TIO. Thus, the seasonal variation of BLT in the eastern TIO is not mainly driven by freshwater flux and wind-driven upwelling. Felton et al. (2014) have suggested that the seasonal BLT variation in the eastern TIO may be related to the sea level and ILD oscillation.~~

~~In summary, during boreal autumn, BLT anomalies in the eastern TIO are determined by the subsurface oceanic process while SSS anomalies drive BLT anomalies in the western TIO with the negative in-phase and leading impacts. During boreal winter, due to strong wind convergence induced by both the winter monsoon wind and the southeasterlies (Yokoi et al., 2012), BLT anomalies are affected by both SSS and thermocline anomalies in the western TIO. SSS anomalies have a negative influence on BLT anomalies while thermocline anomalies have a positive impact. This negative SSS-BLT relationship sustains until boreal spring with weaker negative feedback of the BLT anomalies on the surface. A relatively weaker thermocline-BLT relationship is observed in the eastern TIO. SSS in boreal summer is affected by the spring-time BLT in the western TIO without the BLT-thermocline relationship.~~

5 Interannual Variation

IOD, as the zonal SST gradients along the equatorial TIO, is a crucial climate mode on the interannual scale (Schott et al., 2009). IOD events mostly develop and mature within boreal autumn and decay in boreal winter (Saji et al., 1999). It corresponds well with local precipitation and wind change and has an impact on the SSS (Saji and Yamagata, 2003a). The intensity of IOD could be defined by the Dipole Mode Index (DMI), which is the difference between SST anomalies in the region of (10°S –10°N, 50°E-70°E) and (10°S –EQ, 90°E-110°E) (Saji et al., 1999). Based on the DMI, we composited the monthly SSS, BLT, and the thermocline depth anomalies for positive IOD (pIOD) and negative IOD (nIOD) events, respectively. The corresponding years are listed in Table 1. Figure 9 presents the composited seasonal variations for our current dataset during the period of 1980-2015. The Monte-Carlo procedure has been used to evaluate the significance of the composite variations (green shaded areas). If the value of the variables exceeds the green shaded areas, it is assessed significant at the 95% significance level. In the eastern TIO (Figures 9a, 9c, and 9e), there are no prominent patterns of SSS during the negative (positive) IOD events. This is because the eastward (westward) saltier (fresher) water advection can compensate for the reduced (increased) precipitation due to the presence of the strong Wyrtki jet (Thompson et al., 2006). In contrast, the thermocline and BLT display a prominent seasonal phase locking feature in the eastern TIO. Specifically, during the mature and decaying phases of the positive IOD events, shallower thermocline depth due to strong upwelling leads to thinner BL. This thinner BL provides favorable circumstances for the cold water intrusion into the ocean surface, which contributes to the intensification of the positive IOD events (Deshpande et al., 2014). During the mature phase of the negative IOD events, deeper thermocline along with a thicker BL could be observed in the eastern TIO due to the strong downwelling. In the western TIO (Figures 9b, 9d, and 9f), the thicker BL prominently occurs only during the mature phase of the positive IOD events that are associated with deeper thermocline and fresher surface water, which are attributed due to the wind-induced downwelling and the westward freshwater advection, respectively.

In previous studies, a significant seasonal phase-locking impact of ENSO on the TIO has been addressed (Schott et al., 2009; Zhang and Yang, 2007). This seasonal phase-locking impact mainly exists during the developing phase of ENSO (boreal autumn), the mature phase of ENSO (boreal winter), and the decaying phase of ENSO (boreal spring) in different areas of the TIO. We composited our variables based on the ENSO events from Table 2. Figure 10 presents the composited results of the seasonal variation of BLT, SSS, and thermocline. The thinner BL is mainly associated with shallower thermocline during the developing and mature phases of El Niño (Figures 10c and 10e), which can be explained by the anomalous easterlies along the equator invoked by the adjusted Walker Circulation (Alexander et al., 2002; Kug and Kang, 2006). In the western TIO, thicker BL presents two peaks during the developing and decaying phase of El Niño events (Figure 10d). The first peak of thicker BLT corresponds to a peak of deepening thermocline depth due to the westward downwelling Rossby wave and the anomalous wind stress induced by El Niño (Kug and Kang, 2006; Xie et al., 2002). The second peak of thicker BL is more significant, which connects to the peak of the deepening thermocline and decreasing SSS (Figures 10b and 10f).

The pattern of BLT in the western TIO during the El Niño events is the most prominent, and its two peaks can be explained by two physical mechanisms. Thus, we calculate the lead-lag correlations between BLT, thermocline and SSS anomalies and the Nino3.4 index from 1980 to 2015 to investigate the BLT-El Niño relationship. The correlation coefficients between the thermocline depth anomalies and the Nino3.4 index reach the significant values during the mature period of El Niño (Figure 11b). Also, the correlation between thermocline and Nino3.4 index shows a time delay that is longitude dependent, which is consistent with the result of Xie et al., (2002). This deeper thermocline due to the westward downwelling Rossby wave induced by El Niño affects the corresponding BL. As shown in Figure 11a, a remarkably positive correlation between BLT and the Nino3.4 index is one month apart. Then, the correlation between the thermocline depth anomalies and El Niño becomes weaker during the decaying period of El Niño (Figure 11b). However, there is an enlarged correlation between BLT and ENSO. This enlarged pattern accompanies with the appearance of a negative correlation between SSS and ENSO (Figure 11c). The negative SSS anomalies due to precipitation induced by El Niño via the adjusting Walker circulation and the westward Rossby wave in the western TIO thicken the BLT anomalies (Figures 11d and 11e).

To further verify the impact of IOD and ENSO events on the interannual variation of BLT, the time series of BLT, SSS, and thermocline anomalies averaged over the western TIO during boreal winter and spring from 1980 to 2015 are shown in Figure 12. During boreal winter (Figure 12a), thicker BL and deeper thermocline could be found in 1983, 1992, 1998, corresponding to the mature phase of El Niño events (Table 2). During boreal spring (Figure 12b), thicker BL and deeper thermocline could also be observed in the decaying phase of El Niño events, accompanied with fresher surface water. On the other hand, the effect of IOD on the interannual variability of BLT could be observed in specific years as well, such as 1983,1998, and 2006 (Table 1).

~~IOD, as the zonal SST gradients along the equatorial TIO, is a crucial climate mode on the interannual time scale (Schott et al., 2009). It corresponds well with local precipitation and wind change and has impacts on the SSS (Saji and Yamagata, 2003a). IOD events mostly develop and mature within the boreal autumn and decay in boreal winter (Saji et al., 1999). The intensity of IOD could be defined by the Dipole Mode Index (DMI), which is the difference between SST anomalies in the region of (10°S–10°N, 50°E-70°E) and (10°S–EQ, 90°E-110°E) (Saji et al., 1999). Accordingly, we composited the monthly SSS, BLT and thermocline anomalies for positive IOD (pIOD) events and negative IOD (nIOD) evens based on DMI. The corresponding years are listed in Table 1. Figure 10 presents the composited seasonal variations for our current dataset during the period of 1980-2015. The Monte-Carlo procedure has been used to evaluate the significance of the composite variations (green shaded areas). If a signal exceed the green shaded areas, it is assessed significant at the 95% significance level. In the eastern TIO (Figure 10a,c,e), there is no significant signal of SSS during the IOD events while thermocline accompanying BLT displays the prominent seasonal phase locking feature. Both thin BLT and shallow thermocline appear during the mature and decaying phases of the positive IOD events due to the reduced precipitation and the strong upwelling (Thompson et al., 2006), which in turn, contributes to intensifying the positive IOD events coupled with SST (Deshpande et al., 2014). Thicker BLT can be found in the mature phase of the negative IOD events along with a deeper thermocline. In the western TIO (Figure 10b,d,f), SSS, BLT, and thermocline only respond well to the positive IOD events. BLT has been thickened due to deeper thermocline and fresher water, providing favorable circumstances to sustain warmer water.~~

~~The interannual variability of the TIO is remotely affected by ENSO. A significant seasonal phase-locking impact of ENSO on the TIO has been addressed in previous studies (Schott et al., 2009; Zhang and Yang, 2007). Normally, there are three phases of ENSO, namely the developing phase of ENSO (boreal autumn), the mature phase of ENSO (boreal winter) and the decaying phase of ENSO (boreal spring). We composited our variables based on the ENSO events from Table 2. Figure 11 presents the composited results of the seasonal variation. In the eastern TIO (Figure 11a,c,e), the thinner BLT mainly connects to the shallower thermocline during the developing and mature phases of El Niño (Figure 11c, e), due to the anomalous easterlies along the equator invoked by the adjusted Walker Circulation (Alexander et al., 2002; Kug and Kang, 2006). In the western TIO (Figure 11b,d,f), the deepening thermocline, due to the westward downwelling Rossby wave and the anomalous wind stress induced by El Niño (Kug and Kang, 2006; Xie et al., 2002), peaks in the El Niño developing phase. A following weak peak of thermocline anomalies appears during the decaying phase of El Niño events. The corresponding BLT has a similar semi-annual variation in the El Niño years, but with the intensified second peak after the mature phase of El Niño attributed to the fresher surface water.~~

~~The seasonal phase locking of BLT is prominent in the eastern TIO mainly induced by the corresponding thermocline in both the IOD and the ENSO years. In the western TIO, the variation of BLT is influenced by thermocline during the developing and mature phases and affected by SSS during the decaying phase of the positive IOD or El Niño events.~~

~~The relationship between BLT and El Niño could also be detected in the time series of BLT, SSS and thermocline anomalies averaged over the western TIO during boreal winter and spring from 1980 to 2015 (Figure 12). During boreal winter (Figure 12a), deeper BLT and thermocline could be found in 1983, 1992, 1998, corresponding to the mature phase of El Niño. During spring (Figure 12b), deeper BLT and thermocline~~

~~could also be observed in the decaying phase of El Niño years, accompanying with fresher water. On the other hand, the effect of IOD on the interannual variability of BLT could be observed in specific years as well, such as 1983,1998 and 2006.~~

~~Next, we calculate the lead-lag correlations of BLT, thermocline and SSS anomalies with the Nino3.4 index (averaged SST anomalies in the area of (5°N–5°S, 170°W–120°W)) from 1980 to 2015. The BLT-El Niño relationship experiences two phases (Figure 13a) linking to the subsurface and surface effects. In particular, the correlation coefficients between the thermocline anomalies and the Nino3.4 index reach the noticeable values during the mature period of El Niño (Figure 13b), and their correlation has a longitude-dependent time-delay, which is consistent with the result of Xie et al., (2002). This deeper thermocline resulted by El Niño via the westward downwelling Rossby wave affects the corresponding BLT anomalies, shown as one month later of the remarkably positive correlation between BLT anomalies and the Nino3.4 index in Figure 13a. Then, the correlation between the thermocline anomalies and El Niño becomes weaker during the decaying period of El Niño. However, there is an enlarged correlation between BLT and ENSO, corresponding to the intensifying second peak of BLT shown in Figure 10d. This enlarged pattern accompanies with the appearance of a negative correlation between SSS and ENSO (Figure 13c). The negative SSS anomalies induced by El Niño via the adjusting Walker circulation and the westward Rossby wave in the western TIO thicken the BLT anomalies (Figure 13d,e).~~

~~In conclusion, according to the theory of Xie et al. (2002), there is warmer water developing in the eastern tropical Pacific Ocean (El Niño), resulting in the anomalous easterlies and invoking the downwelling Rossby wave along the equatorial TIO (Figure 13e). Thereby, thermocline has been deepened in the western TIO associated with the thicker BLT. This thickening BLT hampers the upwelling process and benefits to sustain warmer SST. On the other hand, there is an anomalous ascending branch of the Walker circulation adjusted during the mature phase of El Niño. As a result, abundant precipitation forms over the TIO, impacting on SSS. Consequently, fresher surface water helps to thicken BLT, which in turn, prolongs the warmer SST in the western TIO.~~

6 Summary

The seasonal and interannual variabilities of BLT in the TIO are investigated by using the SODA v3 ocean reanalysis dataset. SODA v3 reasonably well reproduces the observed mean and variabilities of BLT in the TIO when compared to Argo.

The dominant contributors to the BLT seasonality are different in the western and eastern TIO. BLT in the eastern TIO is positively correlated to the thermocline depth during boreal autumn, winter and spring, and the positive impact could last for the next three to four months. On the contrary, BLT in the western TIO is negatively correlated to SSS during boreal winter, spring, and autumn. The change of SSS can further control BLT variation in up to two subsequent months. Additionally, the change of BLT in the western TIO during boreal winter could also be affected by the variation of the thermocline depth. For instance, during boreal winter, fresher surface water and shallower thermocline depth result in thinner BL in the western TIO, which is due to freshwater flux and strong wind convergence induced by both the winter monsoon wind and the south-easterlies (Yokoi et al., 2012).

The interannual variability of BLT exerts a seasonal phase locking pattern during the IOD and ENSO years. In the eastern TIO, thicker BL is led by the deeper thermocline due to wind-induced downwelling during the mature phase of the negative IOD events. In contrast, thinner BL is dominated by the shallower thermocline due to wind-induced upwelling during the developing and mature phases of the positive IOD events. In the western TIO, the thicker BL is only observed during the mature and decaying phases of the positive IOD events, along with deeper thermocline and fresher surface water.

The prominent patterns of BLT in the western TIO can only be detected during the El Niño events. According to the theory of Xie et al. (2002), there is warmer water developing in the eastern tropical Pacific Ocean (El Niño), resulting in the anomalous easterlies and invoking the downwelling Rossby wave along the equatorial TIO. Thereby, the thermocline depth has been deepened in the western TIO, resulting in the thicker BL. This thickening BL hampers the upwelling process and helps to sustain warmer SST. During the decaying phase of El Niño events, there is an anomalous ascending branch of the adjusted Walker circulation in the western TIO. As a result, SSS in the western TIO is decreasing due to abundant precipitation. Consequently, fresher surface water contributes to thickening BL, which in turn, sustains the warmer SST in the western TIO.

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Field Code Changed

~~The seasonal and interannual variability of BLT in the TIO was investigated mainly by using the SODA version 3 reanalysis dataset from 1980 to 2015. Although SODA differs in representing the no BLT status near the land mass in the western TIO as shown in Argo, the SODA BLT displays the spatial feature in a good agreement with the Argo BLT. Also, the seasonal and interannual variations of BLT in SODA is consistent with that in Argo. Despite the biases in the spatial feature and variabilities of BLT, SODA is deemed to reproduce overall reasonably well the main characteristics of the BLT in the TIO, and thus it has merits for further exploration of the long-term seasonal and interannual variability of the BLT in the TIO.~~

~~The contributors to the seasonal variability of BLT is different between the eastern and western TIO. In the eastern TIO, BLT is weakly affected by thermocline change, shown as the deeper thermocline leading to the thicker BLT. This positive correlation between BLT and thermocline is prominent in boreal autumn. In the western Indian Ocean, the factors affecting the BLT change with the season. During boreal autumn, SSS has a remarkably negative correlation with the BLT. The saltier the water is, the thinner the BLT is. Both SSS and thermocline anomalies have contributions to the BLT during boreal winter through the freshwater flux and the winter monsoon wind-driven upwelling. The positive SSS anomalies shoal BLT while the positive thermocline anomalies thicken BLT. During boreal spring, BLT anomalies are mainly driven by SSS. Meanwhile, there is a weak BLT feedback on SSS anomalies, which is intensified in boreal summer.~~

~~In terms of the interannual variation, thicker BLT is distinct in the negative IOD and the La Nina years while thinner BLT occurs in the positive IOD and the El Niño years. On the other hand, the prominent BLT shows~~

~~clear seasonal phase locking during the IOD and El Niño years. Particularly, in the eastern TIO BLT co-varies with thermocline during the mature phase of both the IOD and El Niño events. Both SSS and thermocline contribute to the change of BLT in the western TIO after the mature phase of the positive IOD events, and their impacts on the BLT variation are enhanced in the El Niño years. In general, the warmer water in the tropical Pacific Ocean deepens thermocline in the western TIO, resulting in thicker BLT. The correlation between thermocline and El Niño becomes weaker during the decaying phase of El Niño, but the pattern of the correlation between BLT and El Niño is enlarged attributed to the variation of SSS. Fresher water induced by the abundant precipitation due to El Niño thickens the BLT after the mature phase of El Niño.~~

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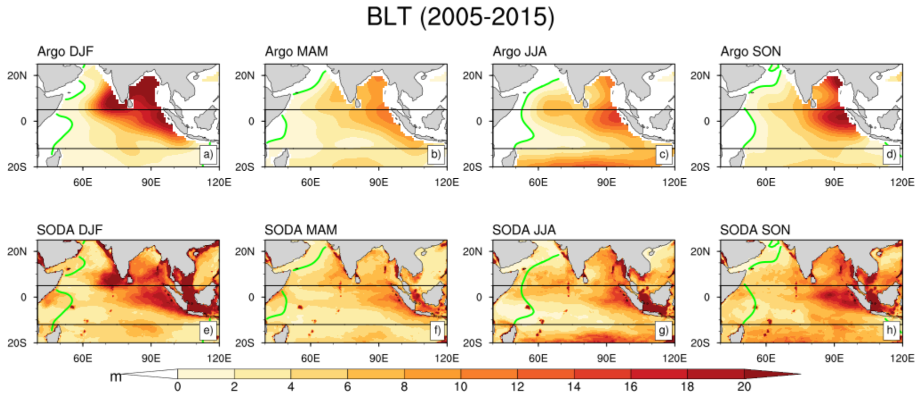


Figure 1. Seasonal distributions of the BLT climatology obtained from Argo (a) and SODA (b) from 2005 to 2015 in the Indian Ocean. Units: m. The thicker green line is the zero BLT line from Argo.

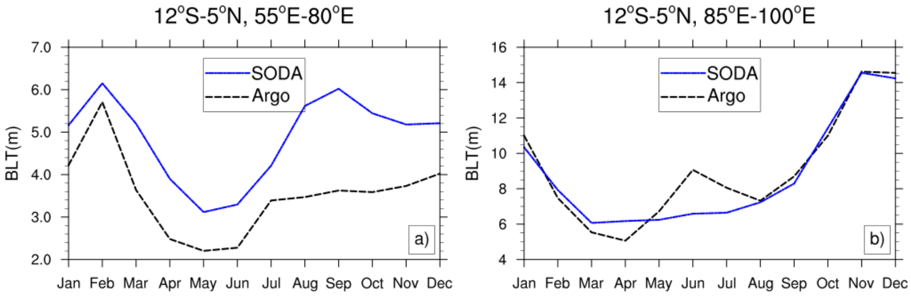


Figure 2. Seasonal cycle of the region-averaged BLT for SODA and Argo: a) from 55°E to 80 °E and 12°S and 5°N, and b) from 85°E to 100 °E and 12°S and 5°N.

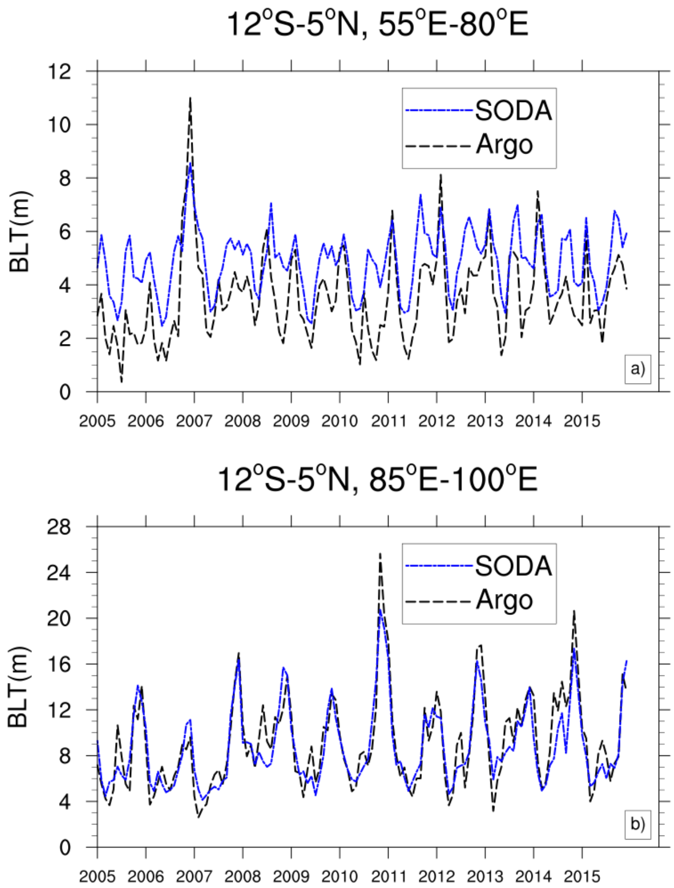


Figure 3. Interannual time series of the region-averaged BLT for SODA and Argo: a) from 55°E to 80 °E and 12°S and 5°N, and b) from 85°E to 100 °E and 12°S and 5°N.

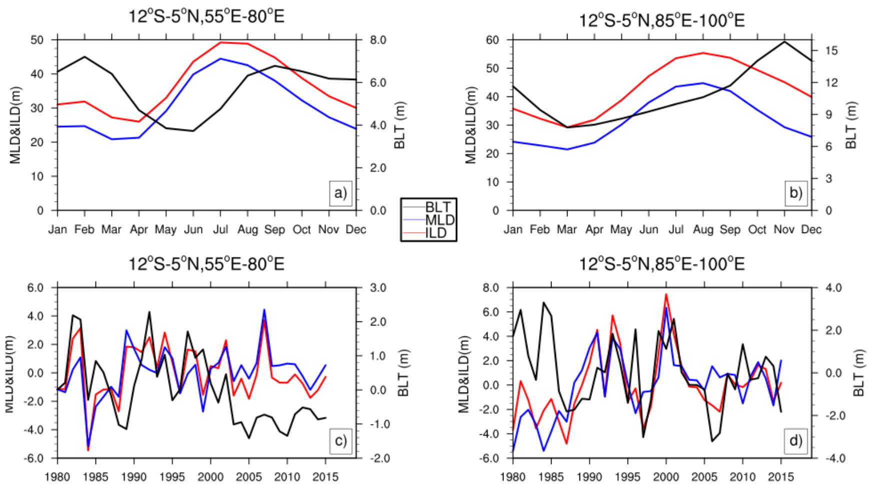


Figure 4. The seasonal and interannual variations of BLT, MLD and ILD : a,c) from 55°E to 80 °E and 12°S and 5°N, and b,d) from 85°E to 100 °E and 12°S and 5°N.

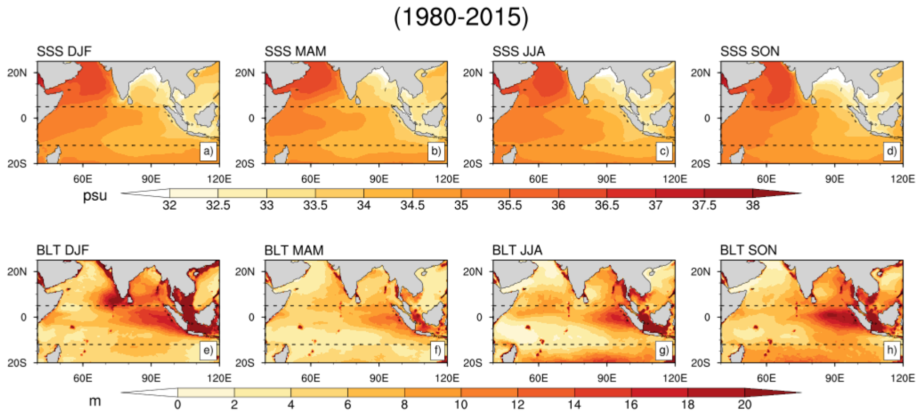


Figure 5. The seasonal distributions of SSS (unit: psu; a-d) and BLT (unit: m; e-h) in the Indian Ocean from 1980 to 2015. The two dashed black lines represent the latitudes of 12°S and 5°N, respectively.

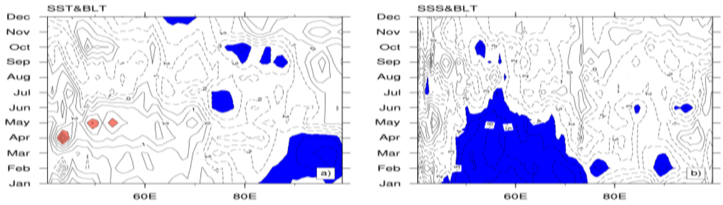
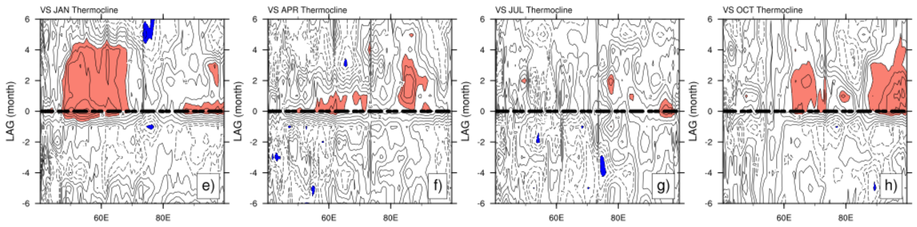
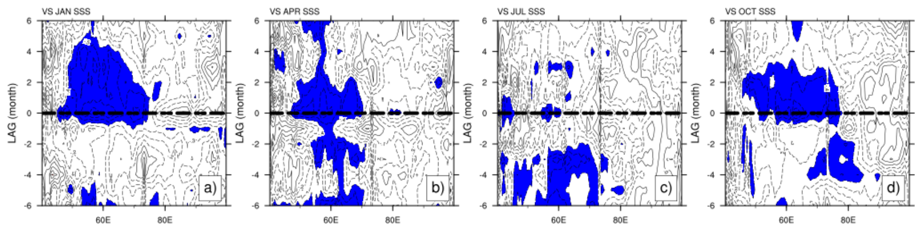


Figure 6. Simultaneous correlations along the area of (12°S-5°N) for (a) SST and (b) SSS anomalies with respect to BLT anomalies. Shaded areas exceed the 95% significance level, while the red and blue shaded areas represent the areas with the positive and negative correlation coefficients, respectively.





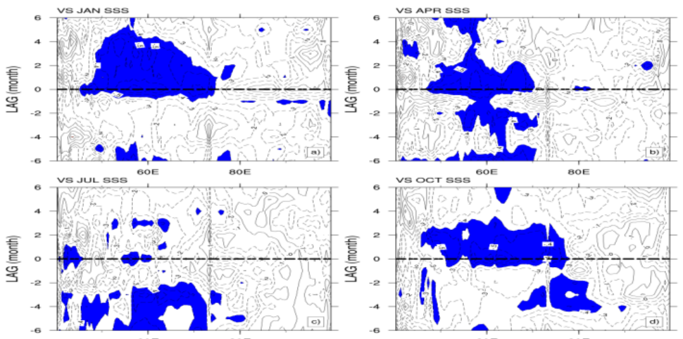
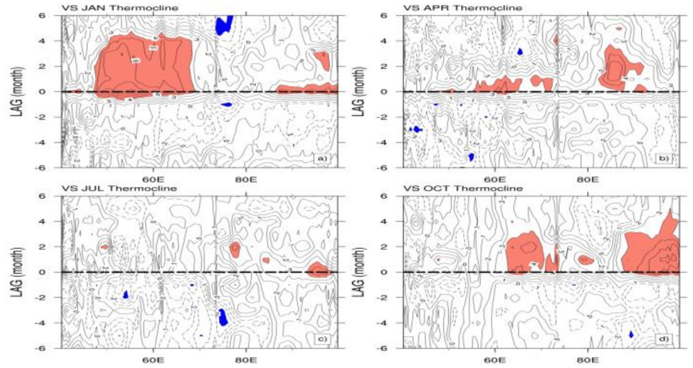


Figure 7. Lead – lag crossing correlations of BLT with SSS (a-d) and thermocline(e-h) anomalies for January (JAN), April (APR), July (JUL), and October (OCT) along the area of (12°S-5°N) from 1980 to 2015. Shaded areas exceed the 95% significance level. Positive lag means SSS (thermocline) leads BLT, and vice versa. Blue (red) shaded areas represent the negative (positive) correlation. The thick black dashed line represents the in-phase correlation.

~~**Figure 7. Lead – lag crossing correlations between BLT and SSS anomalies for (a) January, (b) April, (c) July, and (f) October along the area of (12°S-5°N) from 1980 to 2015. Shaded areas exceed the 95% significance level. Positive lag means SSS leads BLT. Blue shaded areas represent the negative correlation. The thick black dashed line represents the in-phase correlation.**~~



~~Figure 8. Same as Figure 6 but for thermocline and BLT anomalies. Red (blue) shaded areas represent the positive (negative) correlation. The thick black dashed line represents the in-phase correlation.~~

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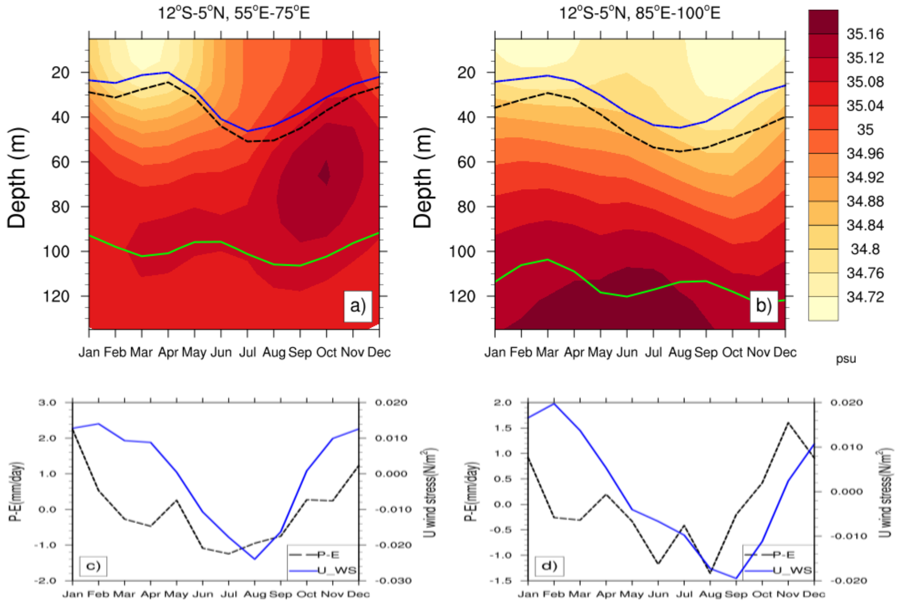
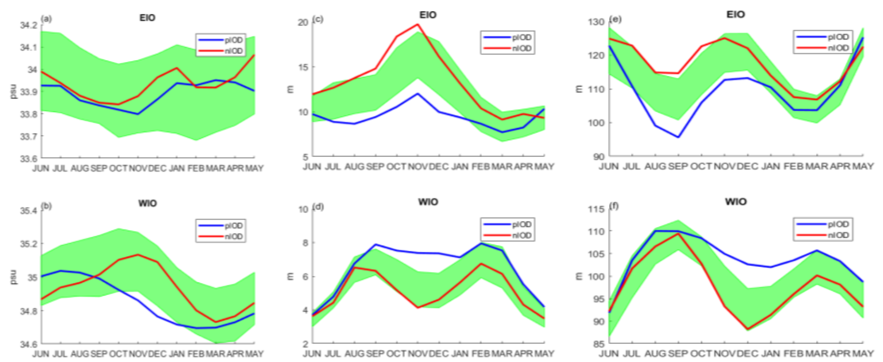


Figure 8~~9~~. Seasonal variation in the (a,c)western TIO (12°S-5°N, 55°E-75°E) and (b,d) eastern TIO (12°S-5°N, 85°E-100°E). The top figures show the depth-time plots of the upper-ocean salinity (shaded), thermocline (green line), isothermal layer (black dashed line) and mixed layer (blue line). The bottom figures show the freshwater flux (P-E) and zonal component of the wind stress (U_WS) anomalies.

~~**Table 1**~~

~~**List of positive IOD events and negative IOD events in our study period.**~~

~~pIOD years~~	~~1982~~	~~1983~~	~~1994~~	~~1997~~	~~2006~~	~~2012~~	~~2015~~
~~nIOD years~~	~~1981~~	~~1989~~	~~1992~~	~~1996~~	~~1998~~	~~2010~~	~~2014~~



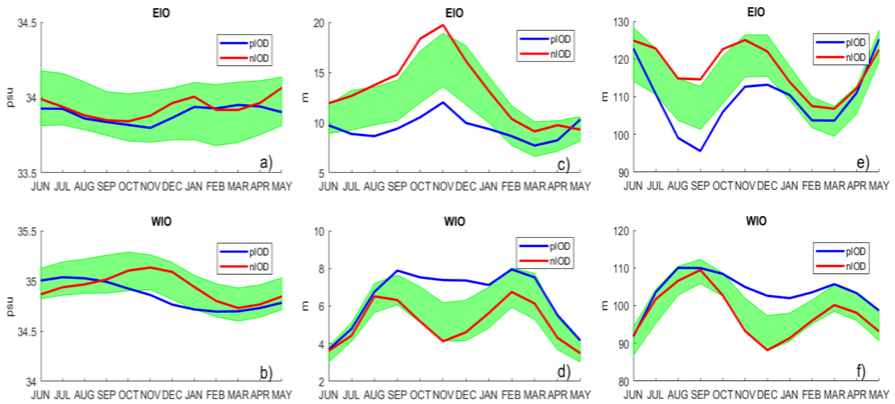
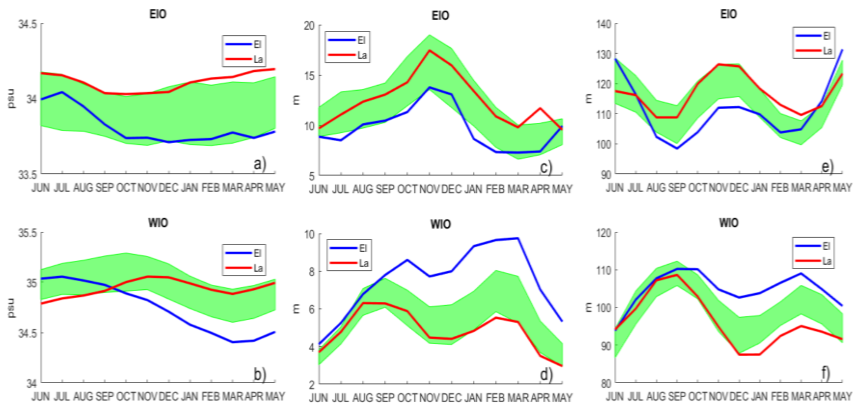


Figure 9~~10~~. The compositing seasonal variations of SSS (a, b; unit: psu), BLT (c, d; unit: m) and thermocline (e, f; unit: m) in the IOD events during the period of 1980-2015 averaged by the areas of the eastern TIO (85°E-100°E, 12°S-5°N) and the western TIO (55°E-75°E,12°S-5°N), separately.The blue line represents compositing in the positive IOD events and the red one represents that in the negative IOD events and the green shaded area represents the 95% Monte-Carlo significance level.

~~**Table 2**~~

~~**List of El Niño events and La Nina events in our study period.**~~

~~El Niño years~~	~~1982~~	~~1987~~	~~1991~~	~~1997~~	
~~La Nina years~~	~~1988~~	~~1998~~	~~1999~~	~~2007~~	~~2010~~



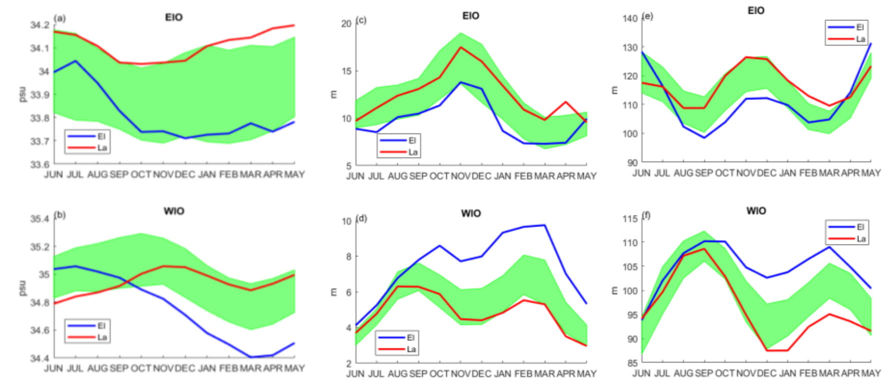
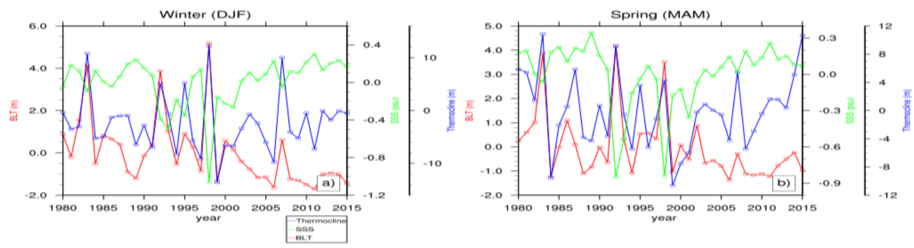


Figure 10~~1~~. Same as Figure 9~~10~~ but compositing on the El Niño and La Nina years.



~~**Figure 12. Time series of BLT, SSS and thermocline anomalies averaged over the western TIO (12°S-5°N, 55°E-75°E) during boreal winter (a) and spring (b) from 1980 to 2015. Red, green, and blue lines represent BLT, SSS and thermocline, respectively.**~~

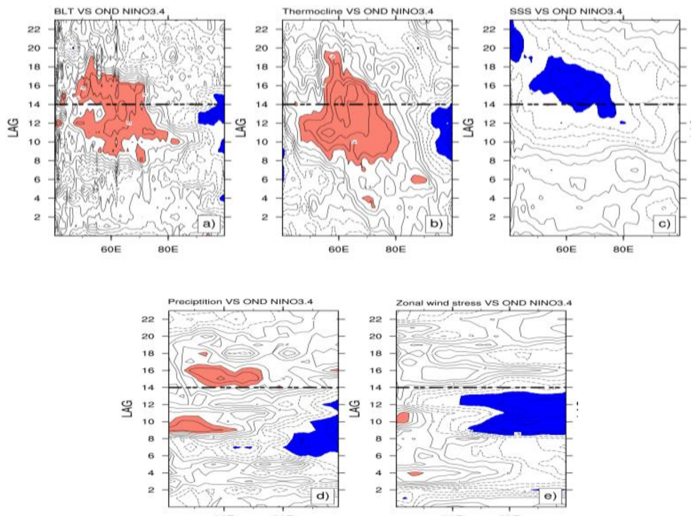


Figure 11~~3~~. Lagged correlations of (a) BLT, (b) thermocline, (c) SSS anomalies, (d) precipitation anomalies, and (e) zonal wind stress anomalies averaged in (12°S-5°N), with the Nino3.4 index as a function of longitude and calendar month (Shaded areas exceed 95% significance level; positive lagging correlations are shaded in red and negative ones are in blue; the thick black dashed line represents the start of the decaying phase of El Niño).

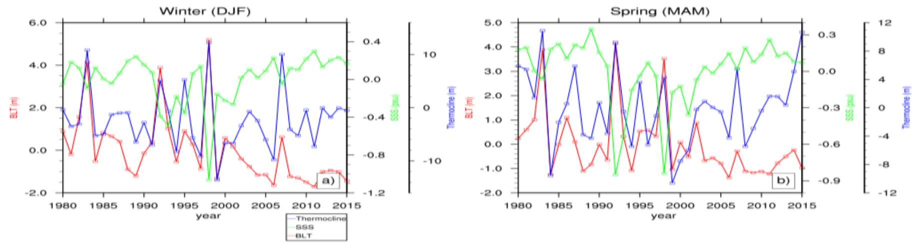


Figure 12. Time series of BLT, SSS and thermocline anomalies averaged over the western TIO (12°S-5°N, 55°E-75°E) during boreal winter (a) and spring (b) from 1980 to 2015. Red, green, and blue lines represent BLT, SSS and thermocline, respectively.

Table 1

List of positive IOD events and negative IOD events in our study period.

pIOD years	1982	1983	1994	1997	2006	2012	2015
nIOD years	1981	1989	1992	1996	1998	2010	2014

Table 2

List of El Niño events and La Nina events in our study period.

El Niño years	1982	1987	1991	1997	
La Nina years	1988	1998	1999	2007	2010