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The seasonal 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. BLT presents a significant seasonal variation in the TIO, mainly attributed to the variations of the sea surface salinity (SSS) and the thermocline. In particular, BLT anomalies are negatively correlated to SSS anomalies in the western TIO, except in summer. In the eastern TIO, the thermocline anomalies positively impact BLT anomalies in all seasons. However, the dependency of BLT anomalies on thermocline in the western TIO is only observed in winter.

Furthermore, it is found that BLT could feedback on SSS, as BLT of the spring-time can negatively affect the SSS of the summer-time in the western TIO. In terms of the interannual BLT variation, we found that both the Indian Ocean Dipole (IOD) and El Niño South Oscillation (ENSO) events could impact the variation of BLT by affecting the thermocline, especially in the eastern TIO. In addition, BLT in the western TIO presents remarkable seasonal phase locking feature during the El Niño years. During the developing and mature phases of El Niño, thicker BLT is due to the change of thermocline, while during the decaying phase of El Niño, BLT anomalies opposing to the weakened thermocline change, become more significant because of the change of SSS.

1 Introduction

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 tropic 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 where the temperature within the layer is 0.2°C lower than that of the surface (de Boyer Montégut et al., 2004). However, the definition of the mixed layer has recently been changed by using the oceanic density with assuming the density within the layer is 0.03 kg/m^3 smaller than the surface (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 the oceanic dynamic 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 South Oscillation

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(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 cyclone in the pre-monsoon season (Masson et al., 2005; Neetu et al., 2012).

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 Inter Tropical Cyclone 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 thicken the BLT (Seo et al., 2009).

In the TIO, the features of BLT variation have been found very similar to the variation 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 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 isothermal layer. Furthermore, the tight relationship between BLT and zonal SSS gradient was also reported in the TIO at the sub-seasonal time scale (Bosc et al., 2009).

However, existing studies on the interannual variability of BLT were mainly for specific years and lack of the long-term verification and the co-varying between the BLT and SSS variation is not always hold 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 with observations 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

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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 of TTD_{DTm02} and $MLD_{DReqDT02}$. TTD_{DTm02} is the top of thermocline depth defined as the depth at which the surface temperature cooled by 0.2 °C and $MLD_{DReqDT02}$ is the mixed layer depth defined in density with a variable threshold criterion (de Boyer Montégut et al., 2007; Mignot et al., 2007).

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, which has reduced systematic errors to a level in the upper ocean and improved the accuracy of poleward variability in the tropic (Carton et al., 2018). It has 26 vertical levels with 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 density and temperature.

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 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 validation purpose and to calculate the Nino3.4 index (5°N-5°S,170°W-120°W).

In all the datasets, we removed the annual cycle before proceeding with correlation. The simultaneous and lead-lag correlations are used in this study with the t-student significance test. The composition analysis is employed in studying the interannual variability of BLT with Monte-Carlo significance test. 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). In our study period, there are seven positive IOD years, including 1982, 1983, 1994, 1997, 2006, 2012 and 2015, and seven negative IOD years, including 1981, 1989, 1992, 1996, 1998, 2010 and 2014, while four El Niño and five La Nina years are 1982, 1987,1991,1997 and 1988, 1998, 1999, 2007, 2010, respectively.

3 BLT in the Indian Ocean

BLT calculated by SODA version 3 reanalysis data is briefly assessed against Argo float observation from 2005 to 2010. Figure 1 shows the distributions of the climatological mean of BLT in the TIO. A clear east-west contrasting distribution of the climatological mean BLT can be observed in both Argo and SODA in the TIO, with thick BLT in the east and thin BLT in the west. BLT calculated by SODA in the Bay of Bengal is underestimated compared to that by Argo. This weakened BLT may be because of lacking the runoff data in the Bay of Bengal (Carton et al., 2018; Carton and Giese, 2008, 2006). With this in mind, we focus on using SODA version 3 data for analyzing the seasonal and interannual variability of BLT in the TIO from 1980 to 2015.

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4 Seasonal Variation

To understand the seasonal variability of BLT in the TIO, Figure 2 presents the distributions of SSS and BLT during winter (December-January-February), spring (March-April-May, MAM), summer (June-July-August, JJA) and autumn (September-October-November, SON). 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, salt water in the western TIO (40°E-90°E, 5°N -12°S) elongates to the east during winter and spring and retreats during summer and autumn, while the corresponding thin BLT does not vary accordingly. In contrast, there is significant seasonal variability of BLT in the eastern TIO (90°E-100°E, 5°N -12°S), with its maxima occurred in 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 spring and strongest during autumn. Thus, the seasonal variability of BLT in the TIO is not always co-varying with SSS.

To do more detailed correlation analysis, we choose the area of (12°S –5°N, 40°E-100°E) as the TIO. This area is selected because it 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 3 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. Instead, a short-term (less than two months) negative relationship between BLT and SST anomalies can be observed in the eastern TIO during winter, with colder water connecting to thicker BLT and vice versa (Fig. 3a). 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 winter and spring with saltier (fresher) water corresponding to thinner (thicker) BLT (Fig. 3b), 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 (Fig.4), as their in-phase relationship shows (Fig.3b). SSS anomalies in winter and autumn not only have a certain in-phase relationship with BLT anomalies but could also lead to the change of the corresponding BLT anomalies at least two months earlier (Fig.4a,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 (Fig. 4b). In July, it is only

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found the BLT feedback in the western TIO, implying that the spring-time BLT anomalies can give a negative impact on the summer-time SSS anomalies (Fig. 4c).

Figure 5 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.

In summary, during autumn, BLT anomalies in the eastern TIO is 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 winter, due to strong wind convergence induced by both the winter monsoon wind and the southeasterlies (Yokoi et al., 2012), BLT anomalies is 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 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 summer is affected by the spring-time BLT in the western TIO without the BLT-thermocline relationship.

5 Interannual Variation

In regard to the different mechanisms of BLT variation between the western TIO and the eastern TIO, we have since investigated the interannual variability of BLT by averaging the western TIO (12°S –5°N, 50°E-75°E) and the eastern TIO (12°S –5°N, 90°E-100°E) separately. Figure 6 presents the compositing seasonal variations of SSS, BLT, and thermocline based on the positive and negative IOD events during the period of 1980-2015. In the eastern TIO (Fig.6a,c,e), there is no significant signal of SSS during the IOD events while thermocline accompanying with 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 deeper thermocline. In the western TIO (Fig.6b,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 circumstance to sustain warmer water.

The compositing seasonal variations of SSS, BLT, and thermocline are also shown in Figure 7 but based on the ENSO events. In the eastern TIO (Fig.7a,c,e), the thinner BLT mainly connects to the shallower thermocline during the developing and mature phases of El Niño (Fig.7c, 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 (Fig.7b,d,f), the deepening thermocline, due to the westward downwelling Rossby wave and the

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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 are 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 of the positive IOD or El Niño events. Then, it is affected by SSS during the decaying phase of the positive IOD or El Niño events.

Next, we calculate the lead-lag correlations of BLT, thermocline and SSS anomalies with the Nino3.4 index from 1980 to 2015. The BLT-El Niño relationship experiences two phases (Fig.8a) 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 (Fig.8b), 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 Fig.8a. 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 Fig.7d. This enlarged pattern accompanies with the appearance of a negative correlation between SSS and ENSO (Fig.8c). 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.

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. 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. Then, 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 variability of BLT in the TIO was investigated mainly by using SODA version 3 reanalysis dataset from 1980 to 2015 in this study. The distribution of BLT has a difference between the eastern and the western TIO, with thick BLT in the east and thin BLT in the west. Also, the contributors to the seasonal variability of BLT is different between the eastern and western TIO. In the eastern TIO, BLT is mainly affected by thermocline change, shown as the deeper thermocline leading to the thicker BLT. This positive correlation between BLT and thermocline is more prominent in autumn. In the western Indian Ocean, the factors affecting the BLT change with the season. During autumn, SSS overwhelming SST has a remarkably negative impact on the BLT. The saltier water is, the thinner BLT is. Both SSS and thermocline anomalies make contributions to the BLT during winter. The positive SSS anomalies shoal BLT while the positive thermocline anomalies thicken

BLT. During spring, BLT anomalies are mainly driven by SSS. Meanwhile, there is a weak BLT feedback on SSS anomalies, which is intensified in 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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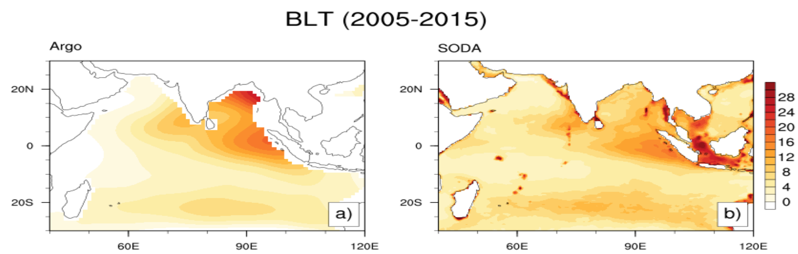

Figure 1. The distributions of the climatological mean of BLT obtained from Argo (a) and SODA (b) from 2005 to 2015 in the Indian Ocean (Unit: m).

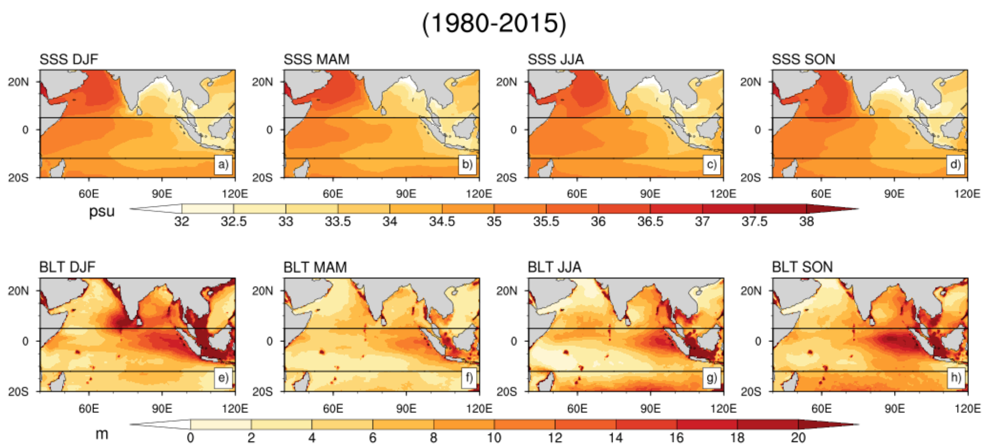

Figure 2. The seasonal distributions of SSS (unit: psu; a-d) and BLT (unit: m; e-h) in the Indian Ocean from 1980 to 2015 (The two black lines represent the latitudes of 12°S and 5°N respectively).

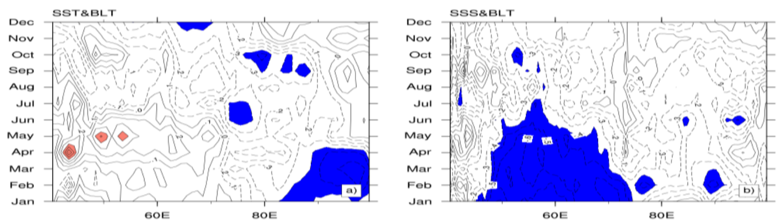

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Figure 3. Simultaneous correlations along the area of (12°S-5°N) for (a) SST and (b) SSS anomalies in respect to BLT anomalies [Shaded areas exceed the 95% significance level; red (blue) shaded areas represent the areas with the positive (negative) correlation coefficients].

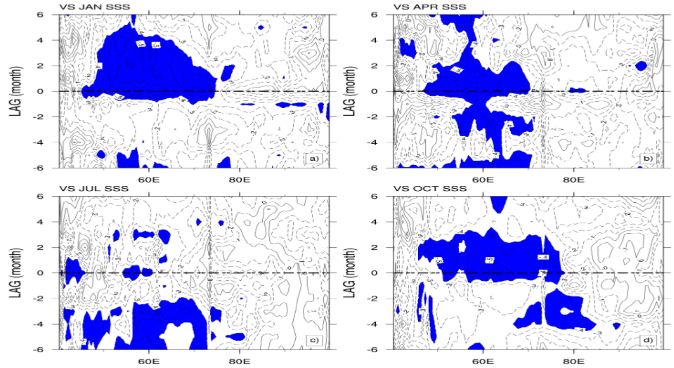

Figure 4. Lead – leg crossing correlations between BLT and SSS anomalies for (a) January, (b) April, (c) July, and (f) October along the area of (12°S-5°N) from 1980 to 2015 (Shaded areas exceed 95% significance level; Positive lag means SSS leads BLT; blue shaded areas represent the negative correlation; the thick black dashed line represents the in-phase correlation).

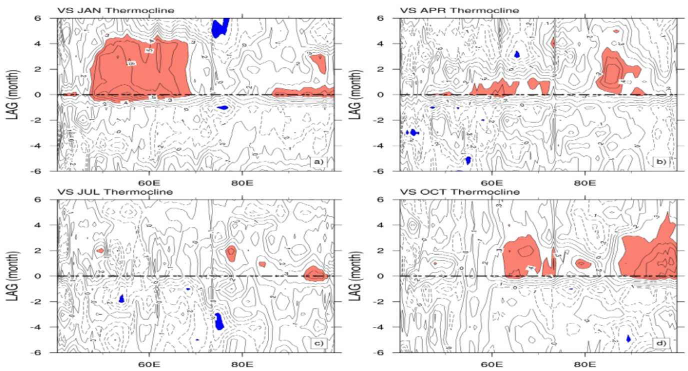

Figure 5. Same as Fig. 4 but for thermocline and BLT anomalies [red (blue) shaded areas represent the positive (negative) correlation; the thick black dashed line represents the in-phase correlation].

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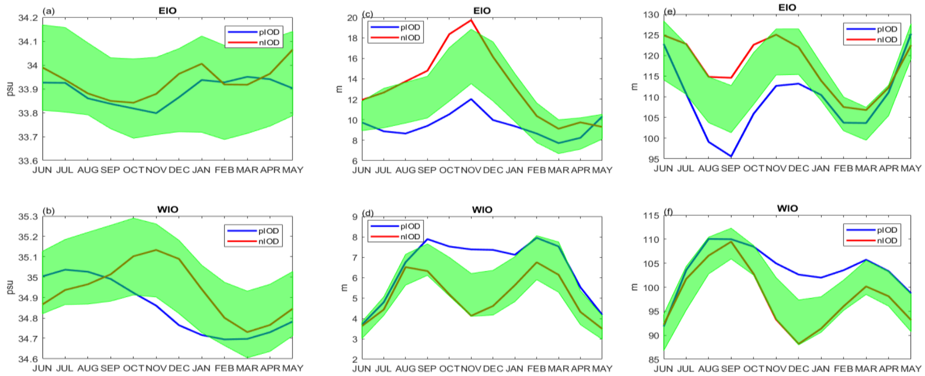

Figure 6. The composting seasonal variations of SSS (a, b; unit: psu), BLT (c, d; unit: m) and thermocline (e, f; unit: m) in the IOD events during the period of 1980-2015 averaged by the areas of the eastern TIO (90°E-100°E, 12°S-5°N) and the western TIO (50°E-75°E,12°S-5°N) separately (The blue line represents compositing in the positive IOD events; the red one represents that in the negative IOD events and the green shaded area represents the 95% Monte-Carlo significance level).

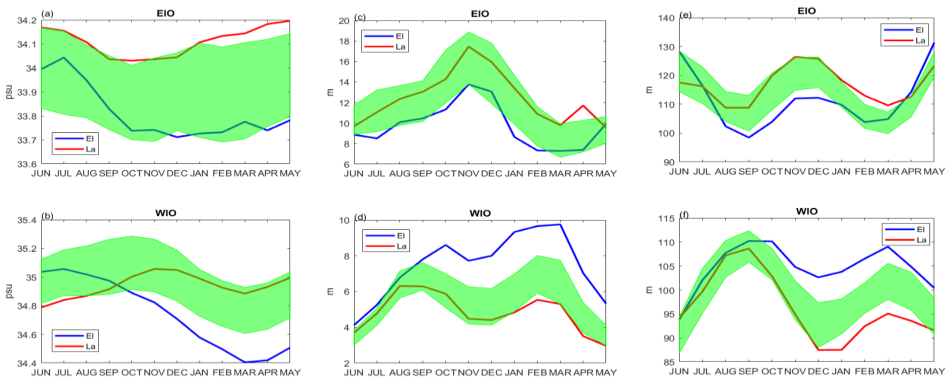

Figure 7. Same as Fig.6 but compositing on the El Niño and La Nina years

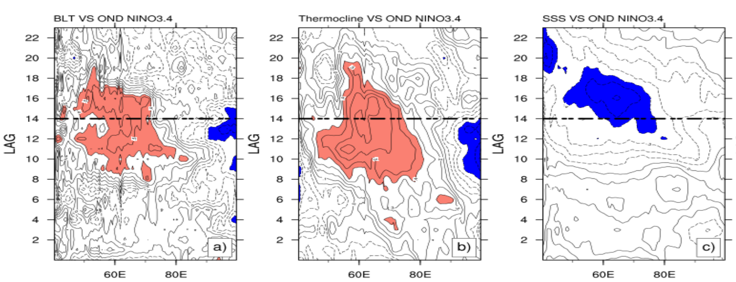

Figure 8. Lagged correlations of (a) BLT, (b) thermocline, and (c) SSS anomalies, averaged in (12°S-5°N), with the Nino3.4 index as a function of longitude and calendar month (Shaded areas exceed 95% significance level; positive lagging correlations are shaded in red and negative ones are in blue; the thick black dashed line represents the start of the decaying phase of El Niño).