# Response to RC2 (12th October 2017)

## Title: Importance of vertical mixing and barrier layer variation on seasonal mixed layer heat balance in the Bay of Bengal

We would like to thank the referee for the time and effort used to review our manuscript. Your helpful and constructive comments are highly appreciated. This reply addresses all the points highlighted by you.

### Specific comments

There are few already published works (Girishkumar et al., 2011; Girishkumar et al., 2013) used the RAMA data at the same locations as this study and discussed about the mixed layer heat budget, mechanism of BLT variation, importance of BLT, temperature inversions and vertical processes on the ML heat budget. So, the authors need to be very specific what is new in this study that was not known from the previous studies.

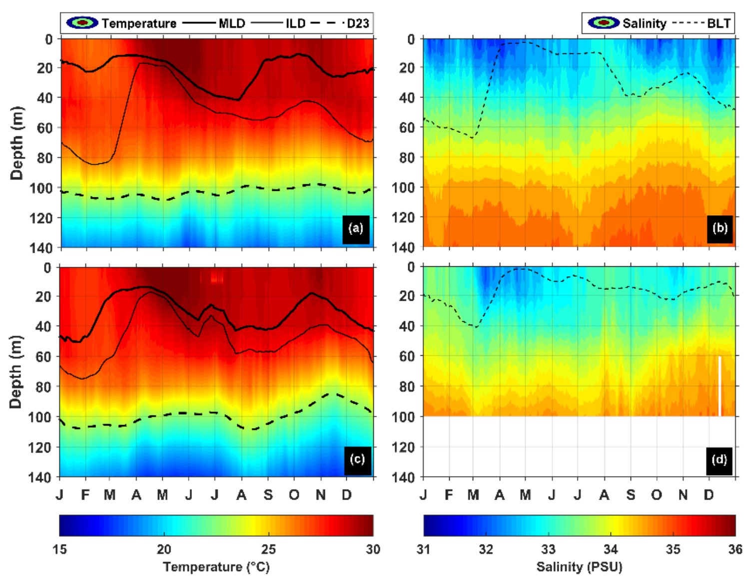
01. Girishkumar et al., 2011 use data from RAMA mooring at 8°N, 90°E with remote sensing data to discuss the intra-seasonal variability of BLT in the south central BoB from November 2006 to April 2009. They points out that the observed intra-seasonal variability during the study period is mainly due to the movement of ILD in the presence of shallow mixed-layer. Further they suggests that both ILD and BLT are modulated by the westward propagating intra-seasonal Rossby waves.
02. Girishkumar et al., 2013 use data from RAMA mooring at 8°N, 90°E for two winters (2006-07, 2007-08) to pointed out the importance of temperature inversions during the winter season. They discuss the influence of temperature inversions and BLT on mixed-layer heat budget. Further they suggests temperature inversions are associated with thicker BL and heating by penetrative solar radiation below the mixed-layer is greater than the heating of the mixed-layer by net surface heat flux and horizontal advection.
03. In this study we use observation data from six RAMA moorings located along 90°E from January 2008 to December 2016 with CTD, satellite and model data to study the importance of vertical mixing and BL variation on seasonal mixed-layer heat budget in the BoB. We points out that the seasonal cycle of BLT, vertical mixing and mixed-layer heat storage are prominent at 15°N, 90°E and weakens towards the equator. Further we points out the positive correlation between BLT and vertical mixing at all mooring locations. Then we discuss about the seasonal stability at the mooring locations and points out the importance of monsoon transition periods. The BoB is more stable during monsoon transition periods due to thermal and salinity stratification and the vertical mixing remains relatively small during this period. Then we points out that the vertical mixing plays the secondary role in the mixed-layer heat balance. Further we suggests that the entrainment is more important in the vertical mixing process in the BoB based on our results. Strong salinity stratification and moderate BLT thickness reduce the vertical mixing during post-summer monsoon and helps to maintain warmer SSTs in the BoB. We use NCOM and CTD profile data to provide evidences for the conditions estimated at RAMA mooring locations. Further based on the strongest seasonal cycles observed and data availability, we select mooring at 15°N, 90°E to explain the conditions in the central BoB in detail.

    The results of this study thus discuss the importance of BLT and vertical mixing on the seasonal mixed-layer heat balance in the BoB. Further it brings the importance of variability of these conditions during post-summer monsoon, a crucial period for active air-sea interaction in this region.

In my opinion, “vertical mixing” is not the right representation of q{-h} in the title and abstract. The term q{-h} in the MLD heat budget equation represents the heat flux through the base of the ML. This represent the vertical mixing at the base of the mixed layer. The way “vertical mixing” used in the title and abstract, it points towards vertical mixing processes in the water column. That’s why, when q{-h} is defined as vertical mixing, the statement in line 38 is misleading as the BLT always suppresses vertical mixing. Re-wording “vertical mixing” in the title and the abstract would be useful.

- We have replaced the word “vertical mixing” with “vertical heat flux”

The study used data from the RAMA moorings at location 15, 12, 8, 4, 1.5 and 0 N. Then why the figures 3-7 and 9 do not show fields at all the RAMA locations? It is very hard to follow the results comparing the central and southern BoB.




- We have edited the figure 3 as it explain the conditions at all the mooring locations selected in this study. New figure illustrates the variations of subsurface temperature, salinity, MLD, ILD, BLT and 23°C isothermal layer at the mooring locations. Then we selected the mooring at 15°N, 90°E to indicate the seasonal variability in detail due to its data availability and strong seasonal cycles. The figures 4-7 explains the seasonal conditions at central BoB.
- Figure 8 clearly illustrates the variability of vertical process and BLT from central BoB to equator. As we are discussing about the importance of vertical process and BLT on the mixed-layer heat balance, we use figure 8 to comparatively explain the changes in vertical process and BLT at all the mooring locations.
- Finally we select the mooring location with the highest variability observed in BLT and vertical process to explain the conditions in detail. So figure 9 illustrates the importance of entrainment in mixed layer heat balance at 15°N, 90°E.

**The following changes were made to the manuscript;**

Line 180 to 183,

Next, we examine the stratification in the upper 140 m at the RAMA locations in the BoB. The moorings are located from the central BoB to the equator, which are in a region of strong seasonal variability of BLT (Figure 1). We have selected the mooring at 15°N, 90°E (Figures 3a, 3b), which has the longest

Next, we examine the stratification in the upper 120 m at the RAMA locations in the BoB. The moorings are located from the central BoB to the equator, which are in a region of strong seasonal variability of BLT (Figure 1). Figure 4 shows the variability of MLD, ILD, BLT and 23°C isotherm (D23) with subsurface temperature and salinity at each RAMA mooring location. We have selected the mooring at 15°N, 90°E (Figures 4a, 4b), which has the longest

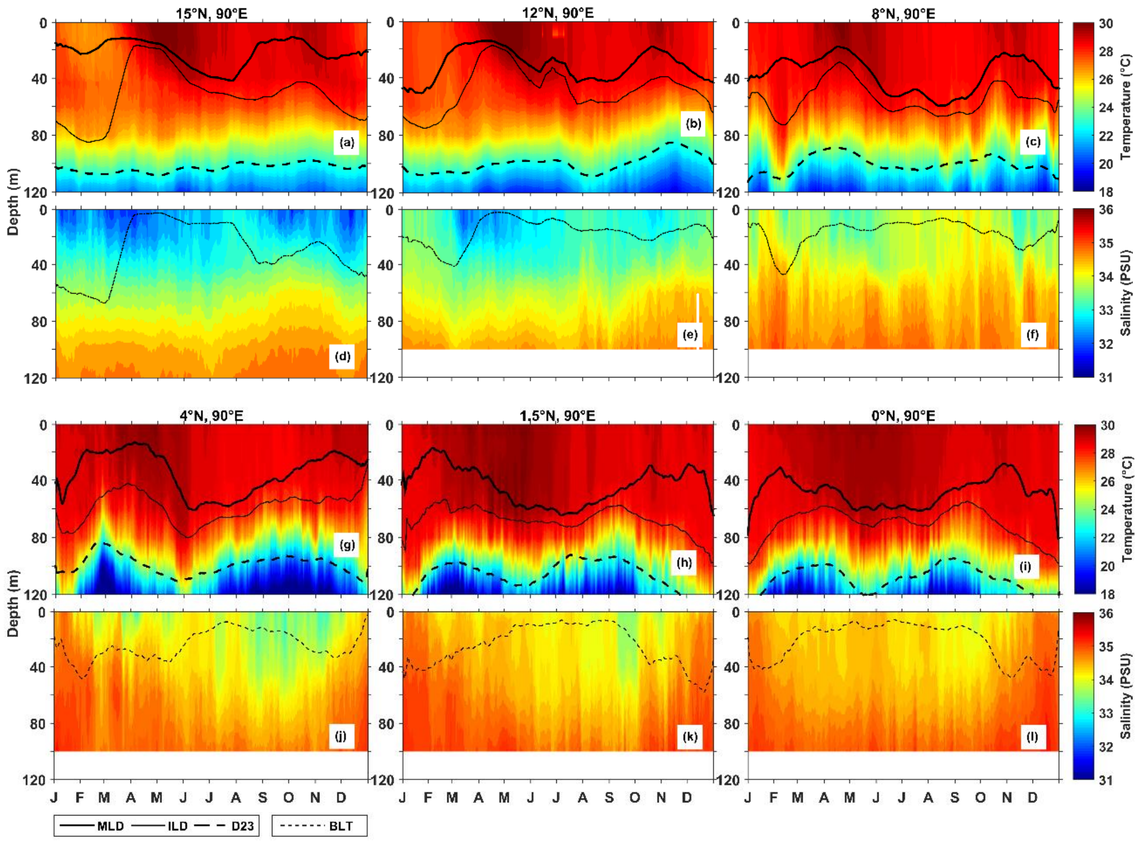



**Figure 4.** Time series of daily averaged RAMA data from January 2008 – December 2016 at 15°N, 12°N, 8°N, 4°N, 1.5°N, and 0°N, 90°E. (a, b, c, g, h, i) subsurface temperature measured by RAMA moorings, (d, e, f, j, k, l) subsurface salinity measured by RAMA buoy moorings. In the figure: thick line (MLD), thin line (ILD), thick-dashed line (D23) and thin-dashed line (BLT).

A figure or table for the RAMA data coverage will be useful.

**The following changes were made to the manuscript;**

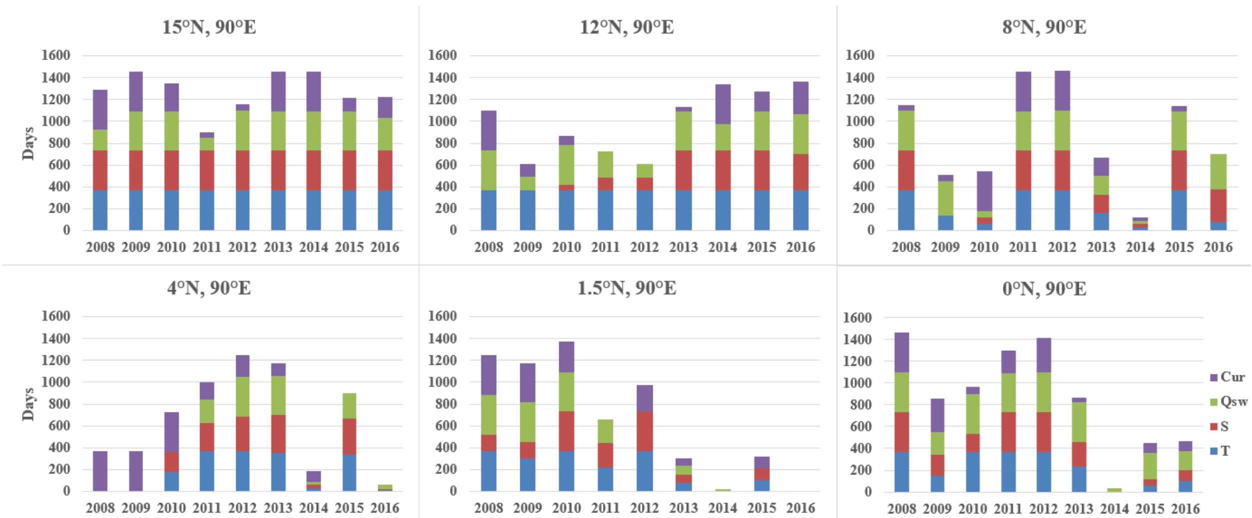



**Figure 3.** Availability of daily measurements from January 2008 to December 2016 at RAMA moorings in the BoB. Blue color represents temperature (T), red color represents salinity (S), green color represents shortwave radiation ($Q_{sw}$) and purple represents currents (u, v) measured at 10 m depth (Cur).

- Figure explains the availability of temperature (T) and salinity (S) up to 120m, shortwave radiation (Qsw) and currents at 10m depth (Cur) at all the mooring locations from January 2008 to December 2016.

What is the justification for selecting the averaging months for summer monsoon? In general May is considered as the pre-monsoon because the summer monsoon sets in around the beginning of June.

- When selecting the averaging months for summer monsoon authors have used either May or June as the onset month. For example: May to September (Shankar et al., 2002). June to September (Rao et al., 2012). Some have been very specific, $6^{th}$ May to $24^{th}$ September (Warner et al., 2016).
- In this study, based on average wind observations by RAMA moorings at 15°N, 12°N and 8°N 90°E for the 9 years we consider the mid-May as the onset of the summer monsoon. Then we select mid-May to September as the months for summer monsoon.

**The following changes were made to the manuscript;**

BL almost disappears during pre-summer monsoon (March-April) associated with low precipitation (Figure 1b), low surface freshening and warmer SST (Figure 2b). During summer monsoon (May-September), BLT is relatively thicker in the eastern boundary of the BoB, associated with higher precipitation (Figure 1c) and surface freshening (Figure 2c).

BL almost disappears during pre-summer monsoon (March – mid-May) associated with low precipitation (Figure 1b), low surface freshening and warmer SST (Figure 2b). During summer monsoon (mid-May –September), BLT is relatively thicker in the eastern boundary of the BoB, associated with higher precipitation (Figure 1c) and surface freshening (Figure 2c).

## Figure 4: At which RAMA location?

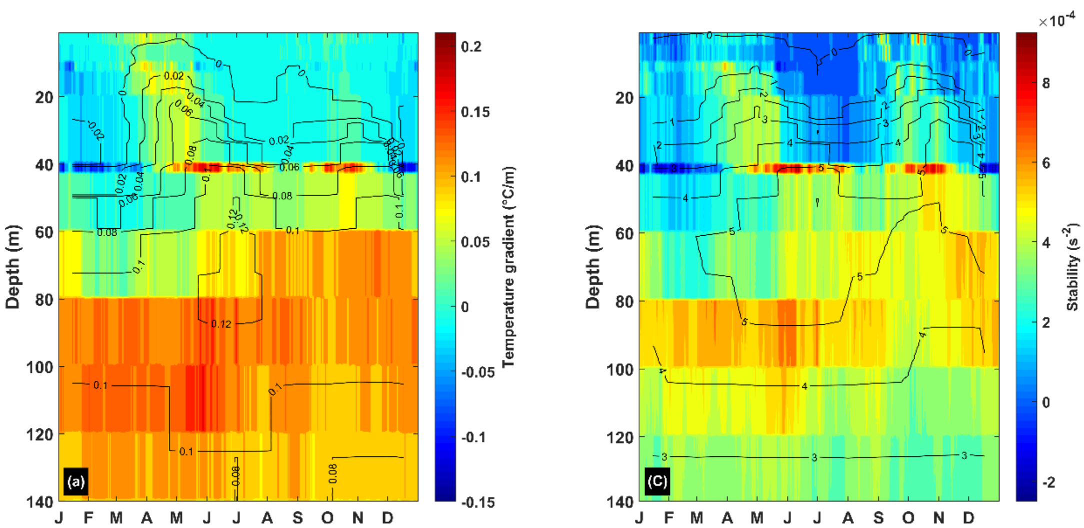
**Figure 4.** Comparison of NCOM (red) and RAMA (blue) estimated monthly climatologies of (a) MLD, (b) ILD, and (c) BLT.

**The following changes were made to the manuscript;**

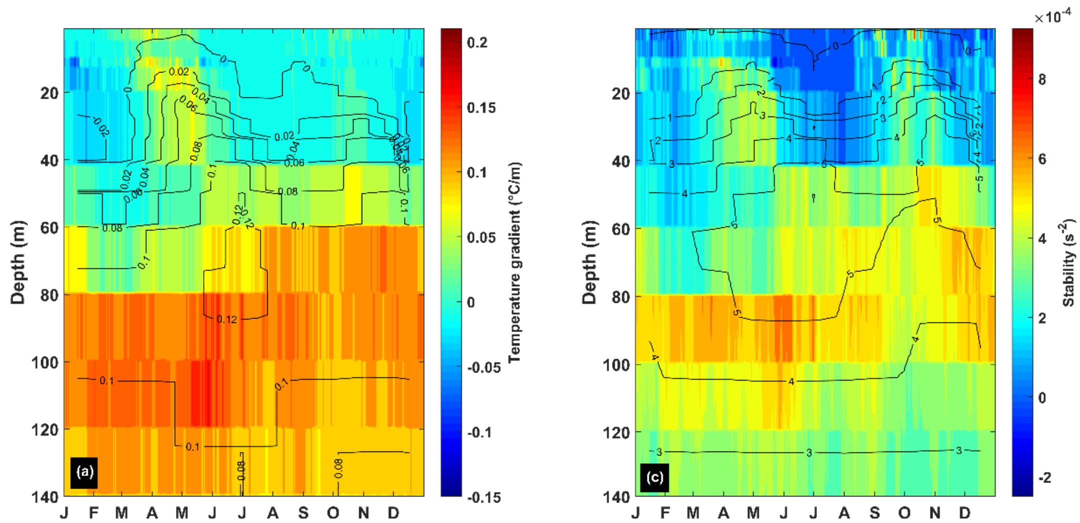
**Figure 4.** Comparison of NCOM (red) and RAMA (blue) estimated monthly climatologies of (a) MLD, (b) ILD, and (c) BLT at 15°N, 90°E.

## Figure 5: Why there is a patch of the higher amplitude of temperature gradient and stability at 40m depth?

- The patch of the higher amplitude of temperature gradient and stability at 40m depth is due to an error in the calculation of temperature gradient. The error associated with data at 40m depth was resolved.



**The following changes were made to the manuscript;**




The poor vertical resolution of the data raises concern about how well the stratification has been resolved from this data. The authors can check the stability profiles computed from nearby other observation data with higher vertical resolution.

To address this issue we have used CTD data from National Oceanographic Data Center (NODC) from January 2000 to December 2016 (www.nodc.noaa.gov). We have selected the region covering the RAMA mooring at 15°N, 90°E and there were 68 CTD profiles in the region (14-18°N, 88-92°E) from April 2007 to April 2016. CTD profiles were not available during May and December. The calculated stability from CTD follows a similar pattern with the results from RAMA and NCOM data.

**The following changes were made to the manuscript;**

Line 153 to 155,

Further we use the Navy Coastal Ocean Model (NCOM) monthly climatological data (from 1990 to 2011) (Ke Huang et al., 2015) to compare with the observed seasonal variability in upper layer stratification, subsurface temperature and salinity gradients, and the stability at 15°N, 90°E by the RAMA mooring.

Further we use the Navy Coastal Ocean Model (NCOM) monthly climatological data (from 1990 to 2011) (Ke Huang et al., 2015) and CTD data from National Oceanographic Data Center (NODC) to compare with the observed seasonal variability in upper layer stratification, subsurface temperature and salinity gradients, and the stability at 15°N, 90°E by the RAMA mooring. We have selected the region covering the RAMA mooring at 15°N, 90°E and there were 68 CTD profiles in the region (14-18°N, 88-92°E) from April 2007 to April 2016. CTD profiles were not available during May and December.

Line 205 to 210,

The estimated upper ocean stability illustrates that the upper ocean layers at 15°N, 90°E are more stable during monsoon transition periods compared to that of winter and summer (Figure 5c). Thus the results pointed out that winter and summer favors the vertical mixing (Thangaprakash et al., 2016) with the presence of more unstable layers in the central BoB, and pre and post-summer monsoon tends to inhibit the vertical mixing due to the presence of more stable water layers.

The estimated upper ocean stability illustrates that the upper ocean layers at 15°N, 90°E are more stable during monsoon transition periods compared to that of winter and summer (Figure 6c). It is evident from the estimated mean stability in the region (14-18°N, 88-92°E) using 68 CTD profiles (Figure 6d). Thus the results pointed out that winter and summer favors the vertical mixing (Thangaprakash et al., 2016) with the presence of more unstable layers in the central BoB, and pre and post-summer monsoon tends to inhibit the vertical mixing due to the presence of more stable water layers.

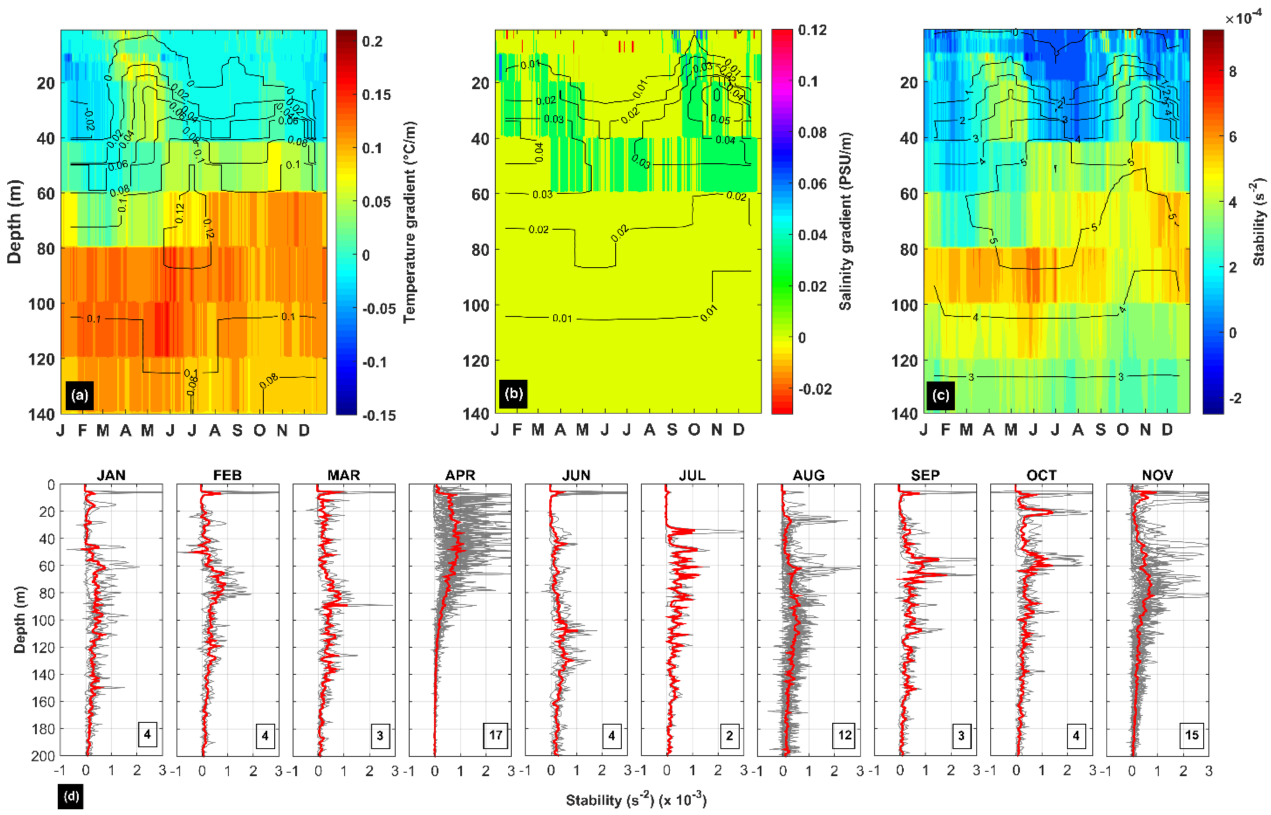



**Figure 6.** Comparison of upper ocean stability estimated from NCOM (contour) and RAMA (color shaded) at 15°N, 90°E. (a) Temperature gradient (positive when temperature decreases downward), (b) salinity gradient (positive when salinity increases downward), (c) stability (in terms of buoyancy frequency), and (d) stability estimated for individual months using 68 CTD profiles (NODC) from April 2007 – April 2016 for the region 14-18°N, 88-92°E. In figure d, gray color (individual profiles), red color (mean), and the numbers in boxes represent number of profiles available for each month.

It is not clear why NCOM fields were used. How accurate are the NCOM fields in this region?

We use NCOM fields to compare with the vertical structure observed at RAMA locations. Also, compared to other model data NCOM has a good vertical resolution. The stability estimated from CTD profiles also provide similar pattern to the results computed using NCOM and RAMA data.

NCOM field have been used in Ke Huang et al., 2015 for the Indian Ocean including BoB.

Line 118: The MLD criterion is not clear. Is it density change by 0.125kg/mˆ3 or density change equivalent to 0.8C temperature change?

- In this study we have considered the density change equivalent to 0.8°C temperature change from the surface to estimate the MLD.

**The following changes were made to the manuscript;**

MLD is defined as the depth where the density has changed by 0.125 kg $m^{-3}$ ($\Delta T = 0.8\ °C$) from the surface value at 1 m (Rao and Sivakumar, 2000; Kara et al., 2003).

MLD is defined as the depth where the density changed is equivalent to 0.8 $°C$ temperature change from the surface value at 1 m (Rao and Sivakumar, 2000; Kara et al., 2003).

Line 165: Section 3.1 discusses about ILD, MLD, BLT, stratification which are not the surface conditions. Then why “surface conditions” in the section title?

- In this study section 3.1 discusses about climatological conditions in the Bay of Bengal.

**The following changes were made to the manuscript;**

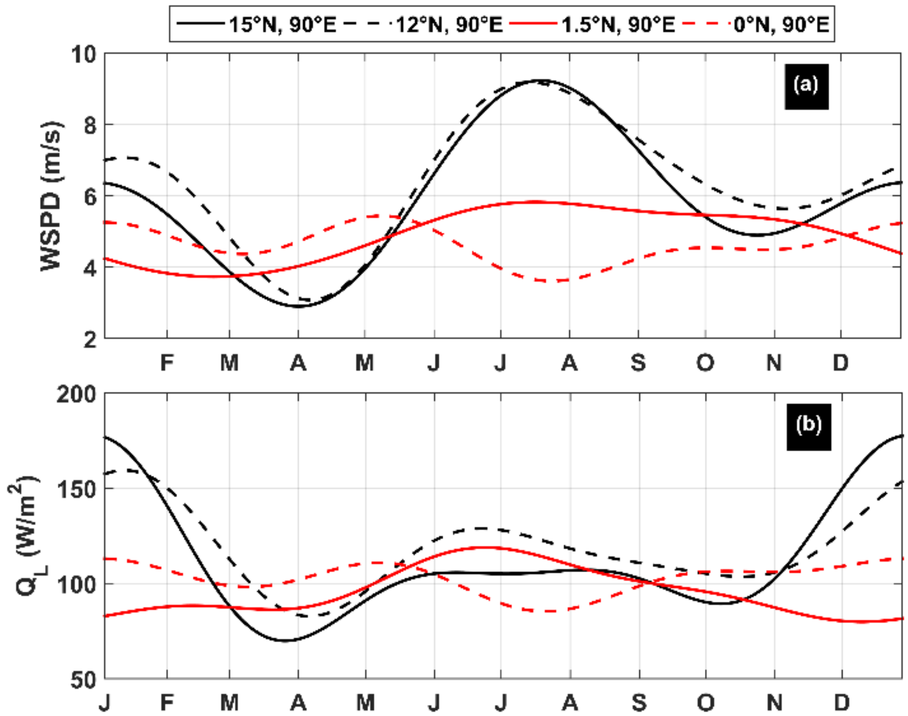
3.1 Variability of climatological surface conditions in the BoB

3.1 Variability of climatological conditions in the BoB

Line 221-223: Where is the evidence? Any figure or reference?

Wind speed undergoes a more pronounced seasonal cycle at 15°N and 12°N compared to that at 8°N, 4°N, 1.5°N and 0°N, tending to enhance the seasonal cycle of $Q_L$ in the central BoB.

- We have concluded this from the observation at RAMA moorings. Generally latent heat loss is affected by the wind. We did not include the figure in the manuscript.
- The figure below clearly illustrates the conditions stated in line 221-223.




Separating the importance of q{-h} and BLT into two subsections might be useful.

**The following changes were made to the manuscript;**

- We have seperated  the importance of vertical process and BLT. The results are explained in **Section 3.3**.

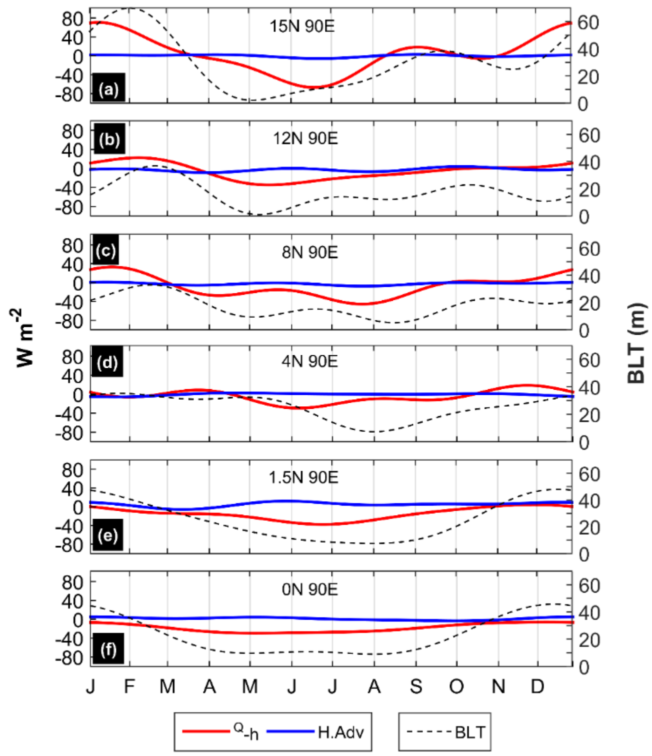
Line 325: What is the “missing source”?

We have found a missing source of warming during August–September in the central BoB up to ~25 Wm$^{-2}$. The uncertinities are mainly associated with measurement errors, calculation errors and parameterization of the vertical process.

**The following changes were made to the manuscript;**

We have found a missing source of warming in $Q_{-h}$ (when estimated as the residual term) during August–September in the central BoB up to ~25 Wm$^{-2}$. Estimated entrainment and vertical diffusion remains relatively small and indicates a cooling tendency during that period. The uncertinities may be associated with measurement errors, calculation errors and parameterization of the vertical process.

Table 1: Why correlation is smallest at 4N and higher towards north and south?




According to the figure (figure 8 in the text) the BLT remains relatively constant from mid-December to mid-June at 4°N, 90°E. During the same time period the contribution of $Q_{-h}$ also remains relatively constant. That is the reason for the observed correlation between BLT and $Q_{-h}$ at this location. Similar to observations at other mooring locations the correlation is positive at 4°N, 90°E, but it is not strong due to the almost constant BLT.

## The following changes were made to the manuscript;

Line 313 to 316,

The horizontal mixed-layer heat advection also weaker compared to that of vertical mixing. The vertical mixing at the base of the mixed layer ($Q_{-h}$), estimated as the residual in the heat balance following Foltz and McPhaden (2009), also follows a pronounced seasonal cycle in the central BoB, and is correlated positively with the seasonal cycle of BLT at each mooring location. We find that

The horizontal mixed-layer heat advection also weaker compared to that of vertical mixing. The vertical mixing at the base of the mixed layer ($Q_{-h}$), estimated as the residual in the heat balance following Foltz and McPhaden (2009), also follows a pronounced seasonal cycle in the central BoB, and is correlated positively with the seasonal cycle of BLT at each mooring location (Table 1). At 4°N, 90°E RAMA mooring the estimated BLT and $Q_{-h}$ remains relatively constant from mid-December to mid-June (Figure 9) and because of that the computed correlation is smallest compared to other locations. We find that