Response to RC1 (25th September 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 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

It is useful to state clearly what is new in the study and what has been concluded from the previous in both the Abstract and Summary.

Time series measurements from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) moorings at 15° N, 90° E; 12° N, 90° E; 8° N, 90° E; 4° N, 90° E; 1.5° N, 90° E; 0° N, 90° E are used to investigate the seasonal mixed-layer heat balance and the importance of barrier layer thickness (BLT) and vertical mixing (Q_{-h}) in the Bay of Bengal (BoB). It is found that the BLT, Q_{-h} and mixed-layer heat balance all have a strong seasonality in the central BoB. Sea surface temperature (SST), salinity and wind are important for the observed strongest seasonal cycle of BLT in the central BoB, and wind is more important than the SST in the southern BoB. The heat storage rate (HSR) is primarily driven by latent heat flux and shortwave radiation ($Q_{SW}\ and\ Q_L$). Seasonal variations and the magnitudes of longwave radiation (Q_{LW}), sensible heat flux (Q_S), and horizontal mixed-layer heat advection are much weaker compared to those of $Q_{SW}\ and\ Q_L$. Q_{-h} follows a pronounced seasonal cycle in the central BoB and is significantly positively correlated with the seasonal cycle of BLT at each mooring location. The seasonal variability of the stability favors the Q_{-h} during winter and summer monsoon and suppress Q_{-h} during monsoon transition periods. We found that Q_{-h} plays the secondary role in the seasonal mixed-layer heat balance in the BoB. It is evident from the analysis that Q_{-h} associated with temperature inversion (ΔT) warms the mixed layer during winter and cools the mixed layer during summer. The warming tendency during winter is strong in the central BoB and weakens towards the equator, indicating a cooling tendency around the year. Our analysis further indicates the weakening of Q_{-h} during monsoon transition periods favors the existence of warmer SST in the BoB, associated with thermal and salinity stratification in the central BoB.

The following changes were made to the manuscript;

Time series measurements from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) moorings at 15° N, 90° E; 12° N, 90° E; 8° N, 90° E; 4° N, 90° E; 1.5° N, 90° E; 0° N, 90° E are used to investigate the seasonal mixed-layer heat balance and the importance of barrier layer thickness (BLT) and vertical mixing (Q_{-h}) in the Bay of Bengal (BoB). It is found that the BLT, Q_{-h} and mixed-layer heat balance all have a strong seasonality in the central BoB. Sea surface temperature, salinity and wind are important for the observed strongest seasonal cycle of BLT in the central BoB. Consistent with earlier studies, the seasonal mixed-layer heat balance is primarily controls by latent heat flux and shortwave radiation ($Q_{SW}\ and\ Q_L$) and we found that Q_{-h} plays the secondary role compared to the weaker horizontal mixed-layer heat advection in the BoB. It is noted that Q_{-h} is significantly positively correlated with the seasonal cycle of BLT at each mooring location. The seasonal variability of the stability favors the Q_{-h} during winter (high BLT) and summer (relatively low BLT) monsoon and suppress Q_{-h} during monsoon transition periods (Moderate BLT). It is evident from the analysis that Q_{-h} associated with temperature inversion (ΔT) warms the mixed layer during winter. Thermal and salinity stratification is obvious during monsoon transition periods and favors the existence of warmer SST in the BoB due to weakening of Q_{-h}. Our analysis further indicates entrainment (E) is more important in Q_{-h} and pointed out the weakening of E associated with BLT tends to weaken the SST-cooling during post-summer monsoon.

I would suggest separating the “Summary and conclusion” section into “Summary” and “Discussion”, which will make the reader easy to follow the new findings.

Summary and Conclusions: In this study, we examine the seasonal mixed-layer heat balance and the importance of the vertical process and BLT in the BoB, using time series measurements recorded at 15°N, 90°E; 12°N, 90°E; 8°N, 90°E; 4°N, 90°E; 1.5°N, 90°E; 0°N, 90°E by the RAMA moorings. At all the mooring locations, it is found that the seasonal changes in mixed-layer HSR is primarily driven by shortwave radiation (Q_{SW}) and latent heat flux (Q_L). The seasonality of HSR is more pronounced in the central BoB. Seasonal variations and magnitudes of longwave radiation (Q_{LW}), sensible heat flux (Q_S) are smaller compared to those of $Q_{SW}\ and\ Q_L$. 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 Q_{-h} plays the secondary role in mixed-layer heat balance in the BoB. It is evident from the analysis that the vertical mixing associated with temperature inversion (ΔT) warms the mixed layer during winter and cools the mixed layer during summer. The warming tendency during winter is strong in the central BoB and weakens towards the equator, indicating a cooling tendency around the year. The impact of BLT on Q_{-h} is the strongest at 15°N, 90°E where the seasonal cycle of BLT is the strongest, which is consistent with the results of Foltz and McPhaden (2009) in the central tropical Atlanctic.

To examine the importance of entrainment and vertical diffusion in the vertical process, we estimated vertical mixing following Girishkumar et al. (2013), and found that entrainment is more important in the vertical process. 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. Our results further indicate that entrainment is weaker during post-summer monsoon period, which tends to weaken the SST cooling by vertical mixing and helps to maintain warmer surface temperature at all the locations. The seasonal variability of the upper ocean stability favors the Q_{-h} during winter and summer monsoon and suppress Q_{-h} during monsoon transition periods in the BoB. The surface heat fluxes alone do not account for the changes observed in seasonal mixed-layer heat balance. Thus, it brings the importance of vertical mixing, which influences the seasonal variability of mixed-layer heat balance in the BoB.

This study further indicates that MLD, ILD and BLT undergo a strong seasonal cycle in the central BoB. It is evident from our results the change in ILD with SST is important for the change in BLT during winter and pre-summer monsoons, while the change in MLD with wind and surface freshning is important during summer and post-summer monsoons in the central BoB. The significant positive correlation between BLT and Q_{-h} means that vertical mixing is the weakest when the BL is the thickest. We have found that, time periods with the thicker and thinner barrier layers are associated with significant vertical mixing where the moderate BLT supresses the vertical mixing in the central BoB during the periods with strong upper ocean stability. The warming and cooling tendencies by vertical mixing associated with the variability of BLT in the central BoB are consistent with the results of Vialard and Delecluse (1998b) in the western equatorial Pacific and Foltz and McPhaden (2009) in the central tropical Atlantic. Thus, it illustrates the imporatnce of the seasonal cycle of BLT on the mixed-layer heat balnce in the central BoB.

The results of this study thus indicate the importance of BLT and vertical mixing on the seasonal mixed-layer heat balance in the BoB. Late phase of summer monsoon and post-summer monsoon are a period of active air-sea interaction in the BoB, and it is possible that weakening of vertical mixing and strong stratification (higher stability) during this period influence the intensity and frequency of BoB cyclones. Moreover, studies with systematic measurements are needed to understand the upper-ocean dynamics, the process of vertical mixing and its influence on mixed-layer temperature in the BoB, which can influence the weather and climate in the region and beyond.

The following changes were made to the manuscript;

Discussion: In this study, we examine the seasonal mixed-layer heat balance and the importance of the vertical process and BLT in the BoB, using time series measurements recorded at 15°N, 90°E; 12°N, 90°E; 8°N, 90°E; 4°N, 90°E; 1.5°N, 90°E; 0°N, 90°E by the RAMA moorings. At all the mooring locations, it is found that the seasonal changes in mixed-layer HSR is primarily driven by shortwave radiation (Q_{SW}) and latent heat flux (Q_L). The seasonality of HSR is more pronounced in the central BoB. Seasonal variations and magnitudes of longwave radiation (Q_{LW}), sensible heat flux (Q_S) are smaller compared to those of $Q_{SW}\ and\ Q_L$. 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 Q_{-h} plays the secondary role in mixed-layer heat balance in the BoB. It is evident from the analysis that the vertical mixing associated with temperature inversion (ΔT) warms the mixed layer during winter and cools the mixed layer during summer. The warming tendency during winter is strong in the central BoB and weakens towards the equator, indicating a cooling tendency around the year. The impact of BLT on Q_{-h} is the strongest at 15°N, 90°E where the seasonal cycle of BLT is the strongest, which is consistent with the results of Foltz and McPhaden (2009) in the central tropical Atlanctic.

To examine the importance of entrainment and vertical diffusion in the vertical process, we estimated vertical mixing following Girishkumar et al. (2013), and found that entrainment is more important in the vertical process. 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. Our results further indicate that entrainment is weaker during post-summer monsoon period, which tends to weaken the SST cooling by vertical mixing and helps to maintain warmer surface temperature at all the locations. The seasonal variability of the upper ocean stability favors the Q_{-h} during winter and summer monsoon and suppress Q_{-h} during monsoon transition periods in the BoB. The surface heat fluxes alone do not account for the changes observed in seasonal mixed-layer heat balance. Thus, it brings the importance of vertical mixing, which influences the seasonal variability of mixed-layer heat balance in the BoB.

This study further indicates that MLD, ILD and BLT undergo a strong seasonal cycle in the central BoB. It is evident from our results the change in ILD with SST is important for the change in BLT during winter and pre-summer monsoons, while the change in MLD with wind and surface freshning is important during summer and post-summer monsoons in the central BoB. The significant positive correlation between BLT and Q_{-h} means that vertical mixing is the weakest when the BL is the thickest. We have found that, time periods with the thicker and thinner barrier layers are associated with significant vertical mixing where the moderate BLT supresses the vertical mixing in the central BoB during the periods with strong upper ocean stability. The warming and cooling tendencies by vertical mixing associated with the variability of BLT in the central BoB are consistent with the results of Vialard and Delecluse (1998b) in the western equatorial Pacific and Foltz and McPhaden (2009) in the central tropical Atlantic. Thus, it illustrates the imporatnce of the seasonal cycle of BLT on the mixed-layer heat balnce in the central BoB.

Summary: Consistent with earlier studies, our results reveals that the seasonal mixed-layer heat balance is primarily controls by Q_{SW} and Q_L. Q_{-h} plays the seconadary role in mixed-layer heat balance in the BoB. Seasonal variability of BLT influences the Q_{-h} and brings the relative importance to the mixed-layer heat balance in the BoB. Entrainment is more important in Q_{-h} compared to that of vertical diffusion. Sengupta et al. (2008) pointed out that SST-cooling along the track of pre-summer monsoon tropical cyclones (TCs) is about 3 °C, whereas cooling due to post-summer monsoon TCs is ~1 °C. It is evident from our results that BoB is more stable during monsoon transition periods and variability observed in Q_{-h} points out that upper-ocean is more stable during post-summer monsoon. Further it suggests salinity stratification provides more stability compared to thermal stratification in the BoB. The results of this study thus indicate the importance of BLT and vertical mixing on the seasonal mixed-layer heat balance in the BoB. Late phase of summer monsoon and post-summer monsoon are a period of active air-sea interaction, and it is possible that weakening of vertical mixing and strong stratification (higher stability) during this period influence the intensity and frequency of BoB cyclones. Moreover, studies with systematic measurements are needed to understand the upper-ocean dynamics, the process of vertical mixing and its influence on mixed-layer temperature in the BoB, which can influence the weather and climate in the region and beyond.

Figure 3: it is useful to show the monthly wind speed in Figure 3 at the selected sites in order to make the statement that the wind speed is the main driver of the barrier layer thickness variation in line 192, or make the statement to the discussion.

Thus, it indicates that SST, salinity and wind are important for the observed strongest seasonal cycle of BLT in the central BoB, and that wind is more important than SST for the variability of BLT in the southern BoB (Girishkumar et al., 2011; Felton et al., 2014).

The following changes were made to the manuscript;

Thus, it indicates that SST, salinity and wind are important for the observed strongest seasonal cycle of BLT in the central BoB (Girishkumar et al., 2011; Felton et al., 2014).

- The statement is moved to the discussion.

The paragraph starting from line 180: it is not clear how the error bars are calculated.

The estimated mean errors in MLD and ILD are typically ±2 m and ±3 m with a standard deviation of ±8 m and ±18 m, giving errors in BLT of around ±5 m with a standard deviation of ±19 m. MLD in the central BoB exhibits a prominent seasonal variation (Figure 6d) with surface freshening and wind forcing, reaching a maximum in July (42±8 m) when the wind is at its maximum (Babu et al., 2004). ILD varies out of phase with SST, reaching its maximum (87±18 m) in February when SST is minimum and reaching its minimum (16±18 m) in April when SST is at its maximum (Figure 6). The seasonal cycle of BLT varies with ILD, reaching its maximum (69±19 m) in February (highest ILD) and its minimum (2±19 m) in April (lowest ILD) (Figure 3b) then with MLD during summer.

The following changes were made to the manuscript;

The estimated standard errors ($SE = standard\ deviation/\sqrt{n}$) in MLD and ILD are typically ±2 m and ±3 m with a standard deviation of ±8 m and ±18 m, giving errors in BLT of around ±5 m with a standard deviation of ±19 m. MLD in the central BoB exhibits a prominent seasonal variation (Figure 6d) with surface freshening and wind forcing, reaching a maximum in July (42±8 m) when the wind is at its maximum (Babu et al., 2004). ILD varies out of phase with SST, reaching its maximum (87±18 m) in February when SST is minimum and reaching its minimum (16±18 m) in April when SST is at its maximum (Figure 6). The seasonal cycle of BLT varies with ILD, reaching its maximum

(69±19 m) in February (highest ILD) and its minimum (2±19 m) in April (lowest ILD) (Figure 3b) then with MLD during summer.

Figure 6 is cited in line 189 before figures 4 and 5 appear in the text.

ILD varies out of phase with SST, reaching its maximum (87±18 m) in February when SST is minimum and reaching its minimum (16±18 m) in April when SST is at its maximum (Figure 6).

The following changes were made to the manuscript;

ILD varies out of phase with SST, reaching its maximum (87±18 m) in February when SST is minimum and reaching its minimum (16±18 m) in April when SST is at its maximum.

- Figure 6 is clearly described in section 3.2 mixed-layer heat balance.

Lines 239-241 need rewording.

Though HSR is primarily driven by Q_{SW} and Q_L, the difference observed during summer and winter monsoons brings the importance played by other terms in mixed-layer heat balance as secondary.

The following changes were made to the manuscript;

Though HSR is primarily driven by Q_{SW} and Q_L, the variations observed during summer and winter monsoons in HSR pointed out the importance of the secondary role played by other terms in the mixed-layer heat balance compared to that of Q_{SW} and Q_L.

Section 3.3 is more like a discussion.

- In section 3.3 we compare our new results observed during post-summer monsoon period with previous findings to highlight the role of vertical mixing during that period.

Our results illustrate the shallowest MLD (Figure 6d), associated with a moderate BL (Figure 8), forms during this season in the central BoB. Thus, stratification helps to maintain a warm surface layer, inhibiting SST cooling, and contribution from vertical mixing remains minimum during this period (Figures 8a, 9b). Chacko et al. (2012) suggested the significance of vertical mixing over surface forcing in inducing mixed-layer temperature variability in the BoB and Sengupta et al. (2008) pointed out that during post-summer monsoon the northern BoB responds quite differently to cyclones than during pre-summer monsoon. Stability during post-summer monsoon due to salinity stratification is stronger compared to that of pre-summer monsoon due to thermal stratification and that may be the reason for the observed differences during cyclone events. Observations from moored RAMA buoys revealed that the importance of seasonal vertical process in SST cooling/warming associated with BLT in the BoB.

The following changes were made to the manuscript;

Our results illustrate the shallowest MLD (Figure 6d) associated with a moderate BL (Figure 8) forms during this season in the central BoB. The stratification (relatively higher stability) helps to maintain a warm surface layer, inhibiting SST cooling. Contribution from vertical mixing remains minimum during this period (Figures 8a, 9b). Chacko et al. (2012) suggested the significance of vertical mixing over surface forcing in inducing mixed-layer temperature variability in the BoB and Sengupta et al. (2008) pointed out that during post-summer monsoon the northern BoB responds quite differently to cyclones compared to pre-summer monsoon. Stability during post-summer monsoon because of salinity stratification is stronger compared to that of pre-summer monsoon due to thermal stratification (Figure 5). Thus observations from moored RAMA buoys revealed that the relatively strong stratification and weaker mixing favors the existence of warmer surface layer during post-summer monsoon, and suggests the importance of seasonal vertical mixing in SST cooling/warming associated with BLT in the BoB.