

## Response to the Reviewer #2

We wish to thank the referee for the constructive criticism that helped us to improve the manuscript. In the light of the comments, we modified the manuscript and point-wise modification is detailed below.

### General Comments:

#### Abstract:

*Reviewer's comment:* I find the abstract a little too long. Perhaps the authors could emphasize on the major results like the seasonal contrasts and/or the north/south contrasts, without describing all the processes. The material is there, this is just a matter of synthesizing it.

**Response:** As suggested we have completely rewritten the abstract and only highlighted the results which is reproduced below:

Mixed layer is the most variable and dynamically active part of the marine environment that couples the underlying ocean to the atmosphere and plays an important role in determining the chlorophyll concentration. We examined the processes controlling the seasonal variability of the mixed layer depth in the Bay of Bengal and its association with the chlorophyll using a suite of in situ as well as remote sensing data. A strong coupling between mixed layer depth and chlorophyll biomass was seen during spring intermonsoon and summer monsoon, but for different reasons. In spring intermonsoon the thermal-dominated stratification and associated shallow mixed layer makes the upper waters of the Bay of Bengal nutrient depleted and oligotrophic. In summer, the haline-dominated stratification in the northern Bay though shallows the mixed layer, the riverine input of nutrients enhances the surface chlorophyll. This enhancement is confined only to the surface layer and with increasing depth the chlorophyll biomass decreases rapidly due to the rapid reduction in sunlight by the suspended sediment. In the south advection of high salinity waters from the Arabian Sea and westward propagating Rossby wave led to the formation of deep mixed layer, except in the Indo-Sri Lanka region where the shallow mixed layer was associated with nutrient enrichment and enhanced chlorophyll. Though a general association between nitrate and chlorophyll distribution was not discernible during winter monsoon, the southern part of the western boundary showed enhancement in chlorophyll. The mismatch between the low nitrate and comparatively higher chlorophyll biomass indicated the efficacy of the limited data to adequately resolve the coupling between the mixed layer processes and the chlorophyll biomass.

### Results and discussion:

*Reviewer's comment:* I strongly recommend the authors to discuss their results in a SEPARATE section:

1) *The paper is entitled "Mixed layer variability and chlorophyll a biomass in the Bay of Bengal" and basically that is exactly what we have in the results and summary: a paragraph on MLD and then a paragraph on chlorophyll a and nitrate. The separation between the two is ok in the result section but the discussion about the coupling appears poor mostly because you don't couple them in the text. I recommend you really highlight the coupling in the discussion by describing the seasonal cycle of MLD, nitrates and chlorophyll a at the same time, instead of going through the complete seasonal cycle for MLD and then talk about the biogeochemical variables. This comment apply to the abstract too.*

**Response:** As suggested we have separated Results from Discussion by adding a separate Discussion section in which the coupling between the chlorophyll and mixed layer was brought out explicitly by bringing together the seasonal cycle of MLD, nitrate and chlorophyll at the same time. This part is reproduced below:

The most notable feature of the present study is that it collates available in situ temperature and salinity data in the Bay of Bengal from a variety of sources such as hydrocast, CTD and Argo to examine the basin-wide variability of mixed layer on a seasonal time scale. It further examined the less explored coupling between mixed layer variability and changes in the chlorophyll biomass in the Bay of Bengal by assembling all the available in situ chlorophyll and nutrient data. Most of the earlier studies attempted to understand mixed layer variability in the tropical Indian Ocean, of which the Bay of Bengal forms a part, either using monthly mean climatology (for e.g., Rao et al, 1989; Monterey and Levitus, 1997) or using individual cruise-based data of limited spatial and temporal coverage (for e.g., Gopalakrishna et al., 1988; Prasad, 2004; Narvekar and Prasanna Kumar; 2006). Major conclusion of these studies was that wind-driven mixing and net heat flux largely controlled the seasonal cycle of mixed layer depth in the open Bay of Bengal (see Kirthi et al. 2012 and the references therein), while fresh water flux driven stratification was important in the northern Bay during summer monsoon (Han et al., 2001; Shenoi et al., 2002; Anitha et al., 2008; Seo et al., 2009). The present study explored the role of Rossby wave propagation and advection of high salinity Arabian Sea waters in regulating the mixed layer depth, in addition to the fluxes of heat and fresh water.

The characteristic feature of the variability of basin-wide mixed layer depth in the Bay of Bengal was (1) a distinct seasonality and (2) a striking north-south variability in any given season. This indicated the role of temporally varying ocean-atmospheric process in regulating the mixed layer depth and also the impact of spatially different processes controlling mixed layer in any given season. These spatially and temporally varying processes controlling mixed layer, in turn, could potentially influence the availability of nutrients in the upper ocean (euphotic zone) there by modulating the chlorophyll biomass through photosynthetic processes. During spring intermonsoon peak solar heating and associated net heat flux maxima strongly stratify the upper ocean waters. The prevailing weak and variable winds are unable to initiate deep mixing due to the strong stratification, leading to the formation of shallow mixed layer. The presence of comparatively shallower MLD in the northern Bay of Bengal compared to south indicates the role of low salinity waters in augmenting the stratification in the north. Thus, a combination of processes such as strong thermal stratification and weak winds could explain the presence of basin-wide shallow MLD during spring intermonsoon, while the latitudinal gradient in upper ocean salinity offers an explanation for the spatial variation of MLD through haline stratification. Consistent with this, basin-wide nitrate concentration as well as chlorophyll

biomass in the upper water column, away from coastal boundary, was very low. The satellite-derived chlorophyll pigment concentration also showed a similar pattern with low values. Caution must be exercised in drawing inferences on the small scale features seen in both nitrate and chlorophyll contours which are not spatially collocated. This could be due to the artifact of contouring in regions which are under sampled. Thus, the basin-scale nitrate concentration and chlorophyll biomass indicated the prevalence of oligotrophic conditions during spring intermonsoon associated with shallow mixed layer arising from a combination of strong thermal stratification and weak winds.

In summer, when basin-wide winds were the strongest, a corresponding deep mixed layer was not seen in the entire basin. Instead a strong spatial gradient with very shallow mixed layer in the north and deep mixed layer towards south was observed, except in the region off southern part of peninsular India and eastern part off Sri Lanka. Though this pattern of spatial distribution was similar to that of spring intermonsoon except the region off peninsular India and Sri Lanka, the latitudinal gradient was much stronger, especially towards the north. The shallow mixed layer in the northern Bay of Bengal was the combined effect of excess precipitation over evaporation and the freshwater influx from the adjoining rivers, both of which results in producing strong haline stratification. Thus the winds, though strong in the northern Bay, were unable to break the stratification and initiate deep wind-mixing as inferred from static stability parameter. A similar result was arrived at by Shenoi et al. (2002) based on kinetic energy and by Vinayachandran et al. (2002) in the context of barrier layer formation (see also Thadathil et al., 2007). Using modeling Han et al. (2001) also obtained a thin mixed layer in the region where precipitation exceeded evaporation.

The deep mixed layer in the south was driven by two processes, the advection of high salinity waters from Arabian Sea into the Bay of Bengal and the westward propagation of Rossby waves from the eastern boundary. Narvekar and Prasanna Kumar (2006) obtained a similar conclusion while examining the MLD variability in the central Bay of Bengal during summer monsoon. In the present study the band of deep MLD extending from southwestern Bay into the central Bay was associated with the advection of Arabian Sea high salinity waters, while the deep MLD in the central and eastern part of the Bay was associated with propagation of Rossby wave of annual periodicity. The shallow mixed layer seen off southern part of the peninsular India was due to the monsoon driven upwelling, while that east of Sri Lanka was due to the upward Ekman pumping and associated Sri Lanka dome (Vinayachandran and Yamagata, 1998). The basin-wide nitrate distribution showed two distinct regions of elevated concentrations, one in the northern Bay and the other a region encompassing the southern part of the peninsular India and the region east of Sri Lanka. The chlorophyll *a* biomass though showed a weak increase in the surface, it did not show a commensurate increase in accordance with the nutrient availability in the upper 50m. Based on in situ measurements of chlorophyll and nutrients and satellite derived diffuse attenuation coefficient and photosynthetically active radiation (PAR) Prasanna Kumar et al. (2010) showed that though the river influx enhanced the nutrient availability in the euphotic zone during summer, the associated sediment load severely curtailed the downward penetration of PAR in the northern Bay. In the south the chlorophyll *a* biomass showed a strong enhancement in accordance with the nitrate concentration in the Indo-Sri Lanka region which was driven by the upwelling along the southern part of the peninsular India and upward Ekman pumping east of Sri Lanka (Vinayachandran 2013).

During fall intermonsoon spatial distribution of mixed layer depth was similar to that of summer monsoon except that the shallow MLD regions in the Indo-Sri Lanka regions wakens and

disappears with the weakening of summer monsoon winds. Though the in situ nutrient and chlorophyll data were not available for fall intermonsoon, the satellite-derived chlorophyll pigment concentrations showed a pattern similar to that of summer monsoon, except that its intensity was reduced considerably.

In winter the radiate heat loss and evaporative cooling leads to the net heat loss from the upper ocean. The positive fresh water flux (E-P) results in the increase of the surface salinity in winter. The combined effect of net cooling and increase in salinity of the upper water column leads to a rapid basin-wide decrease in water column stratification. This coupled with the strong winds leads to greater wind-mixing and finally the deep mixed layer. The basin-wide nitrate distribution somehow did not manifest the impact of deep mixing by way of nutrient enhancement. Similarly, the distribution of chlorophyll *a* biomass also did not show any prominent enhancement, except along the southern part of the western boundary. Levy et al. (2007) also identified the western and northeastern Bay of Bengal as the regions of winter bloom based on a novel method using two parameters such as timing of the bloom onset and cumulative increase in chlorophyll. A similar increase was also noticed by Vinayachandran and Mathew (2003) and Vinayachandran (2013) using chlorophyll *a* climatology from SeaWiFS during 1999 to 2006. Currie et al. (2013) reported not only an increase in surface chlorophyll but also net primary production in the southern Bay of Bengal during winter. We believe that the reason why the present study could not capture the winter chlorophyll enhancement may be due to the sparse distribution of the available in situ chlorophyll and nitrate data.

*We have also added a “Concluding remark” para which is reproduced below:*

The most notable limitation of the study is lack of adequate spatial and temporal coverage of the in situ chlorophyll and nutrient data, unlike the temperature and salinity data. This inhibited us from making a detailed inference on seasonal cycle of these parameters from monthly mean climatology, instead we have to depend on seasonal climatology to infer the seasonal cycle. We were also unable to resolve the variability associated with meso-scale eddy which is a dominant mode of intra-seasonal variability. The general lack of correspondence between nitrate distribution and chlorophyll biomass points to the efficacy of the sparse data and under sampling in the Bay of Bengal. Though Argo could enrich the temperature and salinity data base in the Bay of Bengal chlorophyll and nutrients data is still have to largely depend on in situ measurements. Hence to circumvent the biogeochemical data inadequacy major observational programme needs to be launched in the Bay of Bengal.

*2) To me a strong limitation to this paper is that there is not one reference to the work of others in the discussion/result section, not even one! There are several points that could be discussed (I cite a few papers but there are others): - what is the main driver controlling MLD? - How do your findings compare to the work of other on Chlorophyll and physical drivers on seasonal time scales (Lévy et al., JGR 2007, Vinayachandran et al., 2013)? - how do your climatological study fit in the context of the several papers that were published on extreme events (cyclones etc. Prasanna Kumar et al., DSR 2004, 2007) and interannual variability (Currie et al., Biogeosciences 2013) and their*

*impact on chlorophyll in the Bay of Bengal - the role of Rossby waves in controlling the MLD and chlorophyll?*

Currie J.C., Lengaigne M., Vialard J. Kaplan D M, Aumont O, Naqvi SWA and Maury O: *Indian Ocean Dipole and El Niño/Southern Oscillation impacts on regional chlorophyll anomalies in the Indian Ocean, Biogeosciences, 10, 6677-6698, doi:10.5194/bg-10-6677-2013, 2013.*

Lévy, M., D. Shankar, J.-M. André, S. S. C. Shenoi, F. Durand, and C. de Boyer Montégut (2007). *Basin-wide seasonal evolution of the Indian Ocean's phytoplankton blooms*, *J. Geophys. Res.* 112, C12014, doi:10.1029/2007JC004090

Vinayachandran, P. N. (2013) *Impact of Physical Processes on Chlorophyll Distribution in the Bay of Bengal*, in *Indian Ocean Biogeochemical Processes and Ecological Variability* (eds J. D. Wiggert, R. R. Hood, S.Wajih. A. Naqvi, K. H. Brink and S. L. Smith), American Geophysical Union, Washington, D. C.. doi:10.1029/2008GM000705

**Response:** As suggested we have completely modified the discussion by introducing appropriate references of earlier work and compared our results against the earlier work. Included all the suggested references (kindly note the modifications in the accompanying modified manuscript in RED).

#### **Minor comments:**

**Reviewer's comment:** In the introduction, the authors went through the effort of referencing most of the studies on ML in the BoB chronologically. Although it is well written, I found it difficult to get a clear message of what the results were and what the opened questions are.

For example, *the two following sentences state that some work has been done but do not really help the reader in understanding what the findings were: " Influence of salinity on the seasonal evolution of mixed layer in the Bay of Bengal was studied by Rao and Sivakumar (2003) using climatological data. Narvekar and Prasanna Kumar (2006) examined the seasonal cycle of mixed layer in the central Bay of Bengal and its association to chlorophyll using more comprehensive data set including Argo data."*

**Response:** We have modified this part of the manuscript in Page 4 as follows:

Rao and Sivakumar (2003), using climatological data, showed that incorporation of salinity reduces the thickness of the mixed layer and horizontal advection dominates over the local fresh water flux in producing the large variability in surface salinity in winter while fresh water flux overwhelms advection during summer. Narvekar and Prasanna Kumar (2006) examined the seasonal cycle of mixed layer in the central Bay of Bengal using more comprehensive data set including Argo data and argued that advection Arabian Sea high salinity water mass and Rossby wave propagation are important in altering the mixed layer depth. Further, they showed a strong coupling between chlorophyll distribution and mixed layer depth during spring intermonsoon.

**Reviewer's comment:** P16420 L1: I wouldn't refer to "eddy-like structures", which could be confusing for the reader as most of them are more likely to emerge from the interpolation technique than from eddies. Climatologies you are looking at smooth out the signature of mesoscale structures. In particularly stable features, you might indeed catch structures such as the Sri Lanka Dome.

**Response:** We have removed the "eddy-like structure" from the text from pages 16 & 17 and replaced as following:

At 50 and 100 m, ~~however, the eddy-like mesoscale~~ the closed contour patterns which were prominently seen should be taken with caution as this could arise due to the efficacy of interpolation of less adequate data (Fig.11c, d).

As in summer monsoon, the closed-contour ~~The eddy-like mesoscale~~ feature was discernible at these depths.

We have also included the feature of "Sri Lana dome" in the Discussion while dealing with enhanced nutrient and chlorophyll in summer east of Sri Lanka (kindly note the modifications in the accompanying modified manuscript in RED).

.