

Significantly dominant warm-core eddies: an ecological indicator of the basin-scale low biological production in the Bay of Bengal

*¹Jyothibabu, R., ¹Karnan, C., ¹Arunpandi, N., ¹Santhi Krishnan, S., ¹Balachandran, K.K.,
²Sahu, K.C

¹CSIR- National Institute of Oceanography, Regional Centre, Kochi, India

²Berhampur University, Odisha, India

Telephone: +91 484 2390814; Fax: +91 484 2390618

* Corresponding author, E-mail: rjyothibabu@nio.org

Abstract

This paper introduces the cumulative impact of cyclonic (cold-core) and anticyclonic (warm-core) eddies on the distribution of phytoplankton biomass in the Bay of Bengal (BoB). Estimations of the ocean surface eddy features in the BoB using satellite-derived monthly, seasonal, and multi-year (2012-2016) datasets showed significant dominance of warm-core features over the cold-core ones. Multi-year monthly data of the BoB evidenced strikingly higher geographical area (%) for warm cores (av. 16.5 ± 5.5) compared to the cold-core features (av. 2 ± 1.2). The highest warm-core extent (%) was in May (av. 25.8 ± 1.4), followed by April (av. 22.6 ± 1.4), February (av. 19.5 ± 0.3) and March (av. 18.3 ± 0.9). Contrastingly, a relatively higher extent (%) of cold cores occurred in November (av. 3.9 ± 2.2), October (av. 3.78 ± 2.0), and December (av. 3.5 ± 2.1). The analysis also showed that the extreme oligotrophy of the study domain during the Pre-Monsoon (March-May) was caused by a robust, warm gyre. Upwelling and winter convection, which enhances phytoplankton biomass in the Arabian Sea, are either very weak or absent in the BoB. Similarly, nutrient inputs through river influx into the BoB are insufficient to enhance phytoplankton stock beyond the shelfwaters. In this scenario, we showed here that the significantly larger spread of warm-core over the cold-core eddies is a simple ecological indication of the basin-scale low phytoplankton stock in the BoB.

Keywords: Phytoplankton, chlorophylla, eddy, gyre, oligotrophic, Bay of Bengal

1. Introduction

Bay of Bengal (BoB) is a large oceanic basin in the north-eastern section of the Indian Ocean and has low phytoplankton biomass and production compared to the adjacent Arabian Sea (Prasannakumar et al., 2002; Gauns et al., 2005). Eddies are very common in the BoB, an outcome of peculiar coastal geometry, circulation, and remote forcing (Cheng et al., 2018). They can play an essential role in plankton distribution as they modify the vertical distribution of physicochemical parameters (McGillicuddy et al., 1998; 2003; Flierl and McGillicuddy, 2002; Batten and Crawford, 2005; Mackas and Coyle, 2005; Strzelecki et al., 2007; Feng et al., 2007). Both cyclonic and anticyclonic eddies exist in the BoB, in which the former increases the phytoplankton biomass through divergence and associated nitrate restoration in the surface waters. In contrast, anticyclonic eddies decrease the phytoplankton biomass through surface water convergence and nutrient impoverishment (Prasannakumar et al., 2004, 2007; Jyothibabu et al., 2008; 2015).

The topic of eddies in the BoB, concerning the phytoplankton biomass distribution, has caught the attention of researchers fairly recently, emerging as a prominent area of interest within the last two decades (Prasannakumar et al., 2004, 2007; Vinayachandran and Simi Mathew, 2008; Vidya and Prasannakumar, 2013; Jyothibabu et al., 2015). However, standard *in-situ* studies on the distribution of phytoplankton biomass were in place since the 1960s (Bhattathiri et al., 1980; Gomes et al., 2000; Prasannakumar et al., 2002; Gauns et al., 2005; Madhu et al., 2006). The standard message in these *in-situ* studies is that the BoB basin has low phytoplankton production except in the regions adjacent to its western and northern boundaries. There are some studies on cyclonic (cold-core) eddies from the BoB showing that such eddies cause enhanced phytoplankton stock in the BoB, and proposed further that such eddies are the natural mechanism to enhance biological production (Prasannakumar et al., 2004, 2007; Vidya and Prasannakumar, 2013). Remarkably, no previous studies have accounted for the contribution of the numerous anticyclonic (warm-core) eddies existing in the BoB throughout the year. Further, the collective effect of cold-core and warm-core eddies on the phytoplankton biomass production and distribution in the region is still lacking.

Studies in the past showed that the seasonal ocean processes that make the Arabian Sea productive (coastal upwelling during the Southwest Monsoon and winter convection during the Northeast Monsoon) are either absent or very weak in the BoB (Table 1; Gomes et al., 2000; Jyothibabu et al., 2002 & 2008; Gauns et al., 2005). Also, river inputs are not sufficient to enrich nutrient levels beyond the narrow shelf waters in the BoB (Sarin et al., 1989; Prasannakumar et al., 2002; Jyothibabu et al., 2008; Krishna et al., 2015; Sarma et al., 2016). The ocean surface layers in the BoB have low-nutrient throughout the year. In such situations, eddies could govern the distribution of

nutrients and, thereby, the overall plankton production. Therefore, we propose the idea that the cumulative effect of the two kinds of eddies governs the basin-scale distribution of phytoplankton biomass in the BoB. To investigate this idea, we assessed the relative geographical extent of cyclonic and anticyclonic eddies in the BoB over different time scales (monthly, inter-seasonal, and inter-annual). It also proposed the cumulative impact of these two kinds of eddies on the phytoplankton biomass distribution in the BoB imprinted in the past in-situ studies.

2. Methods

The sampling domain in the BoB was selected 1° far from the coastline to avoid any possible interaction from coastal inputs over the eddy-infested regions (Figure 1). Relevant satellite datasets from online sources presented the oceanographic setting in the sampling domain (7.99°N - 20.96°N; 80.8°E - 92°E). Weekly datasets of Mean Sea Level Anomaly (MSLA) and geostrophic currents were retrieved for five years (2012 - 2016) from Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) live access server (aviso.altimetry.fr). The spatial plots of MSLA were overlaid with geostrophic currents to identify eddies/gyres following the criteria of ± 10 cm of MSLA along with the circular pattern of geostrophic currents and closed contour lines (Chaigneau et al., 2008; Vinayachandran, 2009). The identified eddy features were additionally verified through manual validation to ensure the accuracy of the information generated. The area of eddy/gyre infestation was calculated from the number of pixels covering the selected sampling domain. The weekly datasets were processed to obtain monthly, seasonal, and annual scale variation of the respective parameters. Phytoplankton biomass (chlorophyll *a*) data were retrieved from MODIS-AQUA through NASA's Giovanni web server (giovanni.gsfc.nasa.gov). Open-source applications such as Pyferret (ferret.pmel.noaa.gov), R (rstudio.com), QGIS (qgis.org), and ODView (odv.awi.de) were used in this study for data extraction, analysis and presentation purposes. Statistical analyses such as normality tests and Wilcoxon pairwise comparison of the data differences was conducted in R-Studio (version 1.2.5001)

3. Results and Discussion

An estimate based on satellite data shows that numerous eddies exist in the western and central BoB (Figures 2 & 3). Eddy formation along the Indian coastline in the BoB is the result of baroclinic instability of the East India Coastal Current (Kurien et al., 2010; Cheng et al., 2013, 2018; Chen et al., 2018). Conversely, remote forcing by equatorial winds through the generation of Kelvin wave is the primary cause behind the eddy generation in the central BoB (Cheng et al., 2013; Chatterjee et al., 2017). From March to September [Pre-Monsoon (March-May) and Southwest Monsoon (June -

September)], a sizeable warm gyre occupies a significant part of the western BoB. In contrast, a cold gyre of relatively less geographical extent fills the South-western BoB during November-December (Northeast Monsoon) (Figure 2&3). It appears that the large warm gyre in the study domain is the main reason for the extreme oligotrophy of the western BoB during the Pre-Monsoon (Gomes et al., 2000; Madhu et al., 2006) and noticeably low productivity during the Southwest Monsoon (Prasannakumar et al., 2002; Madhu et al., 2006).

Although cyclonic (cold-core) eddies typically increase the phytoplankton biomass production in the surface waters through upwelling of nutrients from the subsurface, the same is not always right for BoB, especially in regions where strong low-saline surface water stratification prevails. In such areas, cold-core eddies were unable to break the low salinity stratification of the top 20m surface layer, thereby curtailing their effects only to the subsurface waters (Prasannakumar et al., 2007; Jyothibabu et al., 2008). This peculiar oceanographic feature in the BoB is the reason for the cyclonic eddy-induced enhanced chlorophyll biomass misses out in satellite imageries (Jyothibabu et al., 2015). The cold-core eddies in the BoB can certainly increase phytoplankton biomass, but prominently in the subsurface waters. However, this enhancement in phytoplankton biomass, which is relative to the severe oligotrophic conditions in the adjacent regions, is rather moderate in quantitative terms when compared to the coastal upwelling or winter convection regions of the Arabian Sea (Jyothibabu et al., 2015). Importantly, this situation may change in the southern BoB during the Northeast/ Winter Monsoon, where surface salinity stratification is the weak and moderate enhancement in phytoplankton biomass occurs in the surface waters under the influence of a giant cold gyre (Vinayachandran and Simi Mathew, 2008). However, this enhanced phytoplankton biomass concentration, even in the south-western BoB during the Northeast monsoon associated with the cold gyre, is moderate. It is much lower than the winter bloom situation in the northern Arabian Sea (north of 16°N) due to winter convection or upwelling situation along the Southwest coast of India during the Southwest Monsoon (Figure 4). In essence, cold-core eddies are the mechanism enhancing phytoplankton biomass production in the BoB, making the otherwise oligotrophic region moderately productive (Jyothibabu et al., 2008; Prasannakumar et al., 2004, 2007). Due to the presence of several warm-core and core-eddies in the Bay of Bengal, the vertical distribution of nutrients shows some general spatial variations i.e., a deepening of isolines of nutrients in warm-core and a shallowing in the cold-cores (Jyothibabu et al., 2017). A recent study by Sarma et al., (2018) presented the vertical distribution pattern of macronutrients (nitrate, phosphate and silicate) in the western Bay of Bengal infested by warm-core and cold-core eddies. The warm-core eddies very clearly decreased the concentration of all

macronutrients in the upper euphotic column compared to the non-eddy regions. For eg, the isoline of 0.5 μM of nitrate, which was situated at 30m depth in the non-eddy region was found at much deeper depths (50 to 60m) in warm-core eddy regions. This essentially shows the surface water convergence in the warm-core eddy regions, which cause extremely nutrient-depleted surface waters occupying the upper euphotic column leading to low phytoplankton biomass production.

The spatial distribution of cold and warm-core features in the BoB evidenced the occurrence of a very prominent warm gyre, which is attributable to the extreme oligotrophy of the western BoB during the Pre-Monsoon (Gomes et al., 2000; Madhu et al., 2006) and noticeably low production during the Southwest Monsoon (Prasannakumar et al., 2002; Madhu et al., 2006). Considering the numerous cold-core and warm-core eddies in the BoB and their role in altering the spatial distribution of phytoplankton biomass, their cumulative impact could be rather useful to explain the overall biological production. The month-wise analysis of the relative dominance of warm cores and cold cores in the study domain showed a more significant percentage of the geographical extent for warm-cores (av. 16.5 ± 5.5) compared to the cold-cores (av. 2 ± 1.2). The highest percentage of the warm-core area was in May (av. 25.8 ± 1.4), followed by April (av. 22.6 ± 1.4), February (av. 19.5 ± 0.3) and March (av. 18.3 ± 0.9). On the other hand, though the cold-core geographical extent was significantly lower, their relatively high percentage extent was found during November (av. 3.9 ± 2.2), October (av. 3.78 ± 2.0), and December (av. 3.5 ± 2.1). The pairwise comparison (Wilcoxon test) showed that the area of the warm-core eddy was significantly higher than the area of cold-core eddy ($p < 0.001$) throughout the sampling period.

Season-wise analysis of the percentage contribution of warm-core and cold-core features in the study domain showed significant domination of the former. The percentage contribution of warm-core was the highest during the Premonsoon (av. 22.2 ± 1.3), followed by the Southwest Monsoon (av. 6.9 ± 1.2). On the other hand, the percentage of cold-core was relatively high during the Southwest Monsoon (av. 6.9 ± 1.2), followed by the Northeast Monsoon (av. 2.2 ± 2.1). The percentage contribution of cold-core and warm-core features in the study domain showed some inter-annual variability when considered the 5 years (2012-2016). But the warm core significantly dominated over cold-core features in all the five years considered here. The percentage contribution of the warm-core region was the highest in 2016 (23.4) compared to the rest of the years (Figure 5). The dominance of warm-cores in the context of a changing ocean warming poses the possibility of nutrient impoverishment in the ocean surface waters in the future. Given such a future scenario, the dominant warm-core features in the BoB may have negative implications such as a significant

decrease in the basin-scale phytoplankton biomass and thereby, an increase in the severity of oligotrophy.

Eddies persistent for days to months are common in the BoB, and they are mostly mobile features drifting several 10s to 100s of kilometres during their life span between formation and dissipation (Jyothibabu et al., 2015; Jagadeesan et al., 2019). There are many eddies in the BoB that remain rather stable in an area and persist for several months; clearly, these eddies are genuinely influential in altering the plankton production in such regions. The age of eddies is another essential aspect to be looked at in a biological context as a time lag always exists between the ocean physical processes and its manifestations on the biological production in different trophic levels (Jagadeesan et al., 2019). Prolonged (mature) eddies that are consistent for several months can undoubtedly alter the biological and biogeochemical features in isolated regions of the BoB (Vidya and Prasannakumar, 2013; Jyothibabu et al., 2015; Jagadeesan et al., 2019). The persistent cold-core eddy situated for several months in the central-western BoB is the main reason for the higher than expected level of vertical biogenic flux observed there in the sediment traps (Vidya and Prasannakumar, 2013). Similarly, the prolonged cold gyre in the South-western BoB during the Northeast Monsoon period could enhance phytoplankton biomass production (Vinayachandran and Simi Mathew, 2008). Likewise, protracted warm-cores in the BoB have an inducing impact on the formation of *Trichodesmium* blooms, and such blooms channel large amounts of molecular nitrogen into the ocean (Jyothibabu et al., 2017)

It is assessed here whether the past *insitu* studies have genuinely represented the basin-scale scenario of phytoplankton biomass distribution in the BoB. These studies necessarily present BoB with relatively low phytoplankton biomass production (Figure 6). The only critical difference between these studies is in finding out the crucial causative factor responsible for observing the low plankton production in the BoB. Before Gomes et al. (2000), the general belief was that the low underwater solar radiation due to the massive sediment influx and heavy cloud cover is the most important causative factor for the low phytoplankton production in the BoB. Gomes et al., (2000) and later studies have shown that it is the nitrate limitation in the surface waters due to the stable low-salinity stratification as the main causative factors for the observed low phytoplankton biomass production in the BoB. It was observed in this study that nitracline (1 μ m concentration of nitrate) was situated very deep (~60m) in the water column during the Pre-Monsoon period, which is characterised by extensive warm gyre in the entire western Bay of Bengal.

Nonetheless, the general message in all these studies is the low phytoplankton biomass production in BoB (Table 2), and here, the most valid question is that how such a consistent signature reflects in all those past studies and how realistic they are? A close observation of the sampling points in the historical studies would suffice to answer the above query (Figure 6). Even though the ocean mesoscale processes and their implications were unknown during those periods, the widespread, somewhat random distribution of sampling points in the historical studies would have allowed them to account the impact of both the warm-core and cold-core features existing during that period. In essence, it seems that the earlier *in-situ* studies have reasonably accounted for the biological impacts of randomly distributed cyclonic and anticyclonic features. Hence, the general idea of the phytoplankton biomass production in the BoB presented in them seems to be realistic and consistent from an oceanographic standpoint.

4. Conclusion

This study corroborates the view that the basin-scale nitrogen limitation in the surface waters arising from the strong low-saline stratification, lack of upwelling, and absence of winter convection are the primary causes behind the low phytoplankton biomass production in the BoB. The proposition in a few more recent studies that ocean surface eddies are the mechanism that enhances phytoplankton production in the BoB looks to be incomplete and unrealistic. Mostly, this proposition is misleading, as both cyclonic (cold core) and anticyclonic (warm core) features are numerous and co-occur in the region. Considering only the cold-core features and highlighting them to draw general conclusions on plankton production pattern in the BoB have an inherent scientific flaw. Therefore, estimations were carried out here about the extent of ocean surface eddy features in the BoB on a monthly scale over a multi-year (2012-2016) period, using satellite datasets. This study evidenced strikingly higher geographical area (%) for warm cores (av. 16.5 ± 5.5) compared to the cold cores (av. 2 ± 1.2). And concludes that cold-core eddies could certainly enhance the phytoplankton biomass production in some secluded regions in the BoB. But, the cumulative impact of warm-core and cold-core eddies in the BoB is negative on the basin-scale phytoplankton biomass production due to the significant dominance of the former regardless of the seasons. Therefore, we propose that the predominance of warm-cores can be considered as an environmental indication of the basin-scale oligotrophy of the BoB.

References

- Batten, S.D. and Crawford, W.R., 2005. The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 52, 991-1009.
- Bhattathiri, P. M. A., Devassy, V. P., Radhakrishna, K., 1980. Primary production in the Bay of Bengal during the southwest monsoon of 1978. *Mahasagar*, 13(4), 315-323.
- Chaigneau, A., Gizolme, A., & Grados, C. (2008). Mesoscale eddies off Peru in altimeter records: Identification algorithms and eddy spatio-temporal patterns. *Progress in Oceanography*, 79(2-4), 106-119.
- Chatterjee, A., Shankar, D., McCreary, J. P., Vinayachandran, P. N., & Mukherjee, A. (2017). Dynamics of Andaman Sea circulation and its Role in connecting the equatorial Indian Ocean to the Bay of Bengal. *Journal of Geophysical Research: Oceans*, 122, 3200–3218. <https://doi.org/10.1002/2016JC012300>.
- Chen, G., Li, Y., Xie, Q., & Wang, D. 2018. Origins of eddy kinetic energy in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, 123, 2097–2115. <https://doi.org/10.1002/2017JC013455>.
- Cheng, X., Xie, S.-P., McCreary, J. P., Qi, Y., & Du, Y. (2013). Intraseasonal variability of sea surface height in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, 118, 816–830. <https://doi.org/10.1002/JGRC.20075>.
- Cheng, X., McCreary, J. P., Qiu, B., Qi, Y., Du, Y., & Chen, X. (2018). Dynamics of eddy generation in the central Bay of Bengal. *Journal of Geophysical Research: Oceans*, 123, 6861–6875. <https://doi.org/10.1029/2018JC014100>.
- Davis, C.S., McGillicuddy Jr. D.J., 2006. Transatlantic Abundance of the N₂ - Fixing Colonial Cyanobacterium *Trichodesmium*. *Science* 312, 1517.
- Feng, M., Majewski, L.J., Fandry, C.B. and Waite, A.M., 2007. Characteristics of two counter-rotating eddies in the Leeuwin Current system off the Western Australian coast. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 54, 961-980.
- Flierl, G. and McGillicuddy, D.J., 2002. Mesoscale and submesoscale physical-biological interactions. *The sea*, 12, 113-185.
- Gauns, M., Madhupratap, M., Ramaiah, N., Jyothibabu, R., Fernandes, F., Paul, J., Prasannakumar, S., 2005. Comparative accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and Bay of Bengal. *Deep-Sea Research II* 52, 2003 - 2017. Gomes et al., 2000.

Gomes, H. R., Goes, J. I., Saino, T., 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research*, 20(3), 313-330.

Jagadeesan, L., Sampath Kumar, G., Rao, D. N., Surendrababu, N., Srinivas, T.N.R., 2019, Role of eddies in structuring the mesozooplankton composition in coastal waters of the western Bay of Bengal. *Ecological indicators* 105, 137-155. <https://doi.org/10.1016/j.ecolind.2019.05.068>.

Jyothibabu, R., Maheswaran, P. A., Madhu, N. V., Mohammed Ashraf, T. T., Vijay John Gerson, Haridas, P.C., Venugopal, P., Revichandran, C., Nair K. K. C., Gopalakrishnan, T. C. 2002. Differential response of winter cooling on biological production in the north-eastern Arabian Sea and the north-western Bay of Bengal, *Current Science* 87, 783-791.

Jyothibabu, R., Madhu, N.V., Maheswaran, P.A., Jayalakshmy, K.V., Nair, K.K.C., Achuthankutty, C.T., 2008. Seasonal variation of microzooplankton (20-200 μm) and its possible implications on the vertical carbon flux in the western Bay of Bengal. *Continental Shelf Research* 28, 737-755.

Jyothibabu, R., Madhu, N.V., Habeebrehman, H., Jayalakshmy, K.V., Nair, K.K.C., & Achuthankutty, C.T. (2010) Re-evaluation of 'paradox of mesozooplankton' in the eastern Arabian Sea based on ship and satellite observations. *Journal of Marine Systems*, 81, 235-251.

Jyothibabu, R., Vinayachandran, P.N., Madhu, N.V., Robin, R.S., Karnan, C., Jagadeesan, L., Anjusha, A., (2015). Phytoplankton size structure in the southern Bay of Bengal modified by the Summer Monsoon Current and associated eddies: Implications on the vertical biogenic flux *Journal of Marine Systems* 143:98-119.

Jyothibabu, R., Karnan, C., Jagadeesan, L., Arunpandi, N., Pandiarajan, R.S., Muraleedharan, K.R., & Balachandran, K.K. (2017). *Trichodesmium* blooms and warm-core ocean surface features in the Arabian Sea and the Bay of Bengal. *Marine pollution bulletin*, 121, 201-215.

Krishna, M.S., M.H.K. Prasad, D.B. Rao, S. Viswanadham, V.V.S.S. Sarma, and N.P.C. Reddy. 2015. Export of dissolved inorganic nutrients to the northern Indian Ocean from the Indian monsoonal rivers during discharge period. *Geochemica et Cosmochemica Acta* 172:430-443,

Kumar, S., Ramesh, R., Sardesai, S., Sheshshayee, M. S., 2004. High new production in the Bay of Bengal: Possible causes and implications. *Geophysical Research Letters*, 31, L18304.

Kurien, P., Ikeda, M., & Valsala, V. K. (2010). Mesoscale variability along the east coast of India in spring as revealed from satellite data and O.G.C.M. simulations. *Journal of Oceanography*, 66(2), 273-289. <https://doi.org/10.1007/s10872-010-0024-x>.

Mackas, D.L. and Coyle, K.O., 2005. Shelf-offshore exchange processes, and their effects on mesozooplankton biomass and community composition patterns in the northeast Pacific. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 52, 707-725.

Madhu, N. V., Jyothibabu, R., Maheswaran, P. A., Gerson, V. J., Gopalakrishnan, T. C., Nair, K. K. C., 2006. Lack of seasonality in phytoplankton standing stock (chlorophyll a) and production in the western Bay of Bengal. *Continental Shelf Research*, 26, 1868-1883.

Madhupratap, M., Gauns, M., Ramaiah, N., Kumar, S.P., Muraleedharan, P.M., De Sousa, S.N., Sardesai, S., Muraleedharan, U., 2003. Biogeochemistry of the Bay of Bengal: physical, chemical and primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 50, 881-896.

McGillicuddy, D.J., Robinson, A.R., Siegel, D.A., Jannasch, H.W., Johnson, R., Dickey, T.D., McNeil, J., Michaels, A.F. and Knap, A.H., 1998. Influence of mesoscale eddies on new production in the Sargasso Sea. *Nature*, 394, 263-266.

McGillicuddy, D.J., Anderson, L.A., Doney, S.C. and Maltrud, M.E., 2003. Eddy-driven sources and sinks of nutrients in the upper ocean: Results from a 0.1 resolution model of the North Atlantic. *Global Biogeochemical Cycles*, 17(2).

Prasanna Kumar, S., Muraleedharan, P.M., Prasad, T.G., Gauns, M., Ramaiah, N., de Souza, S. N., Sardesai, S., Madhupratap, M., 2002. Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea? *Geophysical Research Letters* 29, 88-1-88-4 <https://doi.org/10.1029/2002GL016013>

Prasannakumar, S., Nuncio, M., Narvekar, J., Kumar, A., Sardesai, S., de Souza, S.N., Gauns, M., Ramaiah, N., Madhupratap, M., 2004. Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal. *Geophysical Research Letters* 31, L07309.

Prasannakumar, S., Nuncio, M., Ramaiah, N., Sardesai, S., Narvekar, J., Fernandes, V., Paul, J. T. 2007. Eddy-mediated biological productivity in the Bay of Bengal during fall and spring inter-monsoons. *Deep-Sea Research I* 54, 1619 - 1640. Prasannakumar et al., 2008.

Sarin, M.M., S. Krishnaswami, K. Dilli, B.L.K. Somayajulu, and W.S. Moore. 1989. Major ion chemistry of the Ganga-Brahmaputra river system: Weathering processes and fluxes to the Bay of Bengal. *Geochimica et Cosmochimica Acta* 53:997–1,009, [http://dx.doi.org/10.1016/0016-7037\(89\)90205-6](http://dx.doi.org/10.1016/0016-7037(89)90205-6).

Sarma, V.V.S.S., G.D. Rao, R. Viswanadham, C.K. Sherin, J. Salisbury, M.M. Omand, A. Mahadevan, V.S.N. Murty, E.L. Shroyer, M. Baumgartner, and K.M. Stafford. 2016. Effects of freshwater stratification on nutrients, dissolved oxygen, and phytoplankton in the Bay of Bengal. *Oceanography* 29(2):222–231, <http://dx.doi.org/10.5670/oceanog.2016.54>.

Sarma, V.V.S.S., Jagadeesan, L., Dalabehera, H.B., Rao D.N., Kumar, G.S., Durgadevi, D.S., Yadav, K., Behera, S., Priya, M.M.R. 2018. Role of eddies on the intensity of the oxygen minimum zone in the Bay of Bengal 168, 48-53.

Strzelecki, J., Koslow, J.A. and Waite, A., 2007. Comparison of mesozooplankton communities from a pair of warm-and cold-core eddies off the coast of Western Australia. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 54, 1103-1112.

Vidya, P. J., Prasannakumar, S., 2013. Role of mesoscale eddies on the variability of biogenic flux in the northern and central Bay of Bengal. *Journal of Geophysical Research: Oceans*, 118, 5760–5771, doi:10.1002/jgrc.20423.

Vinayachandran, P.N., 2009. Impact of physical processes on chlorophyll distribution in the Bay of Bengal, Indian Ocean biogeochemical processes and ecological variability, Wiggert et al. (Eds). *Geophysical Monograph Series*, American Geophysical Union, 71 - 86.

Vinayachandran, P.N., Simi Mathew, 2008. Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones. *Geophysical Research Letters* 30, 1572, doi:10.1029/2002gl016717, 2003.

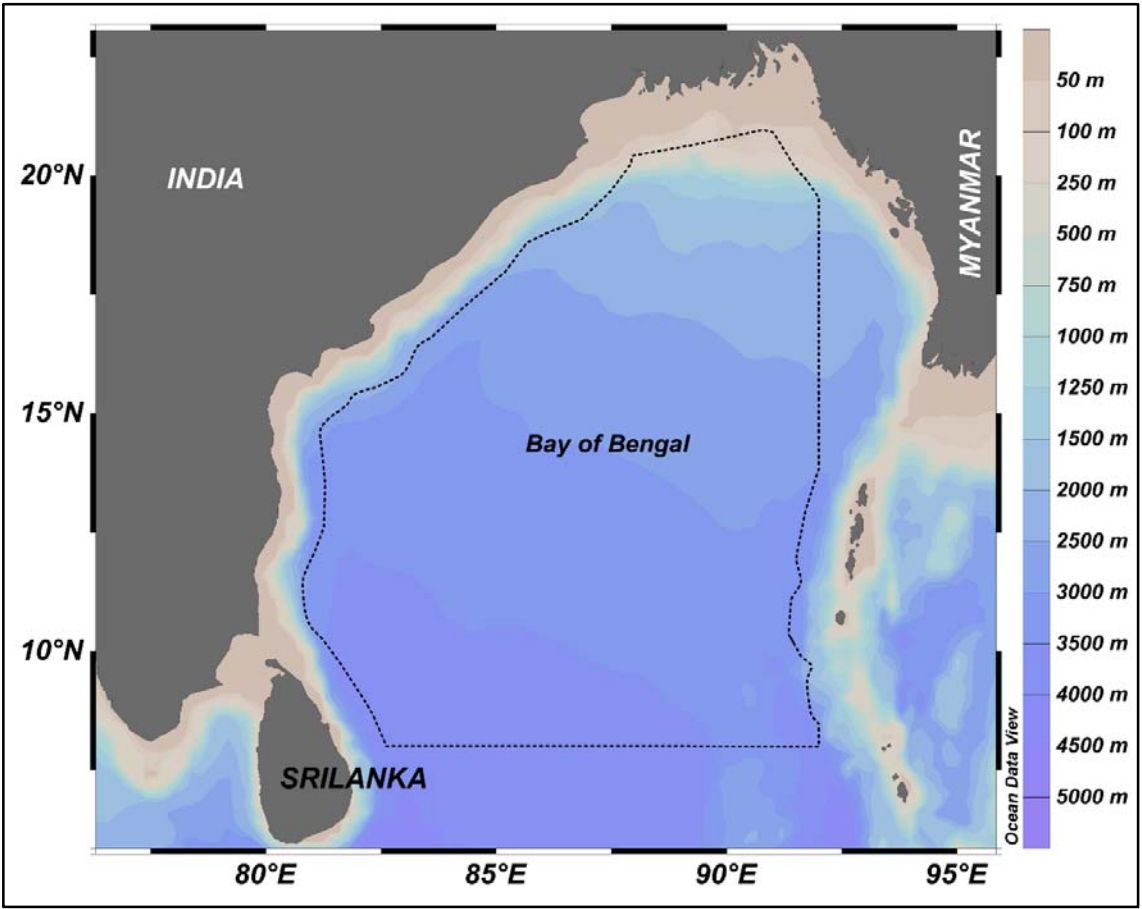


Figure 1 - The study domain in the Bay of Bengal is described in a dotted line shape. Regions $<1^\circ$ close to the coastline are not considered as the coastal inputs may alter the typical biological characteristics of eddies considered in this study.

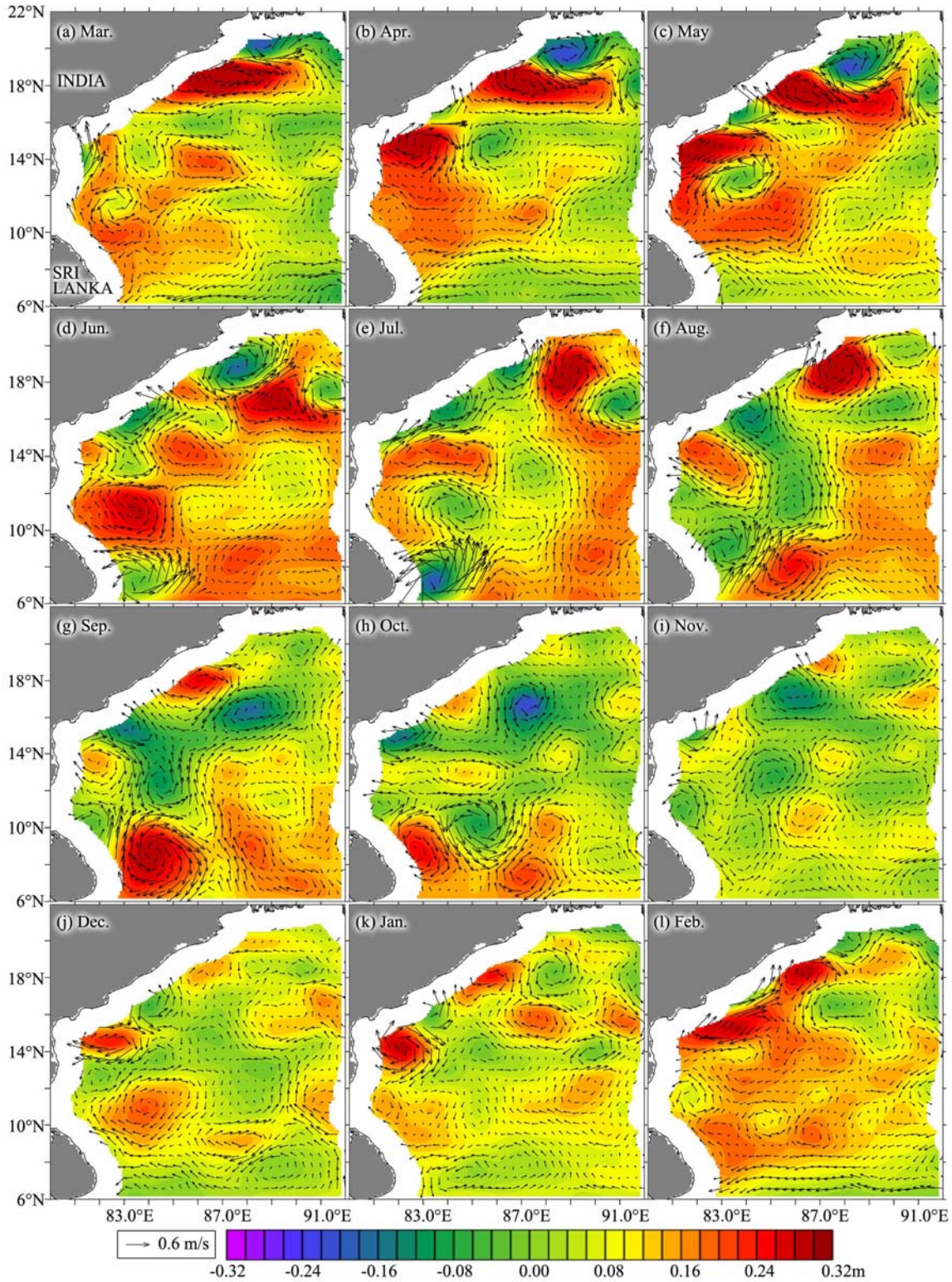


Figure 2 - Eddies in the Bay of Bengal resolved every month for 2015. Red shade with clockwise surface currents represents warm-core features, whereas, blue shade with anticlockwise currents represent cold-core features. Regions $<1^\circ$ close to the coastline are blanked to show that this region is not considered in the present study to avoid any possible land/river inputs.

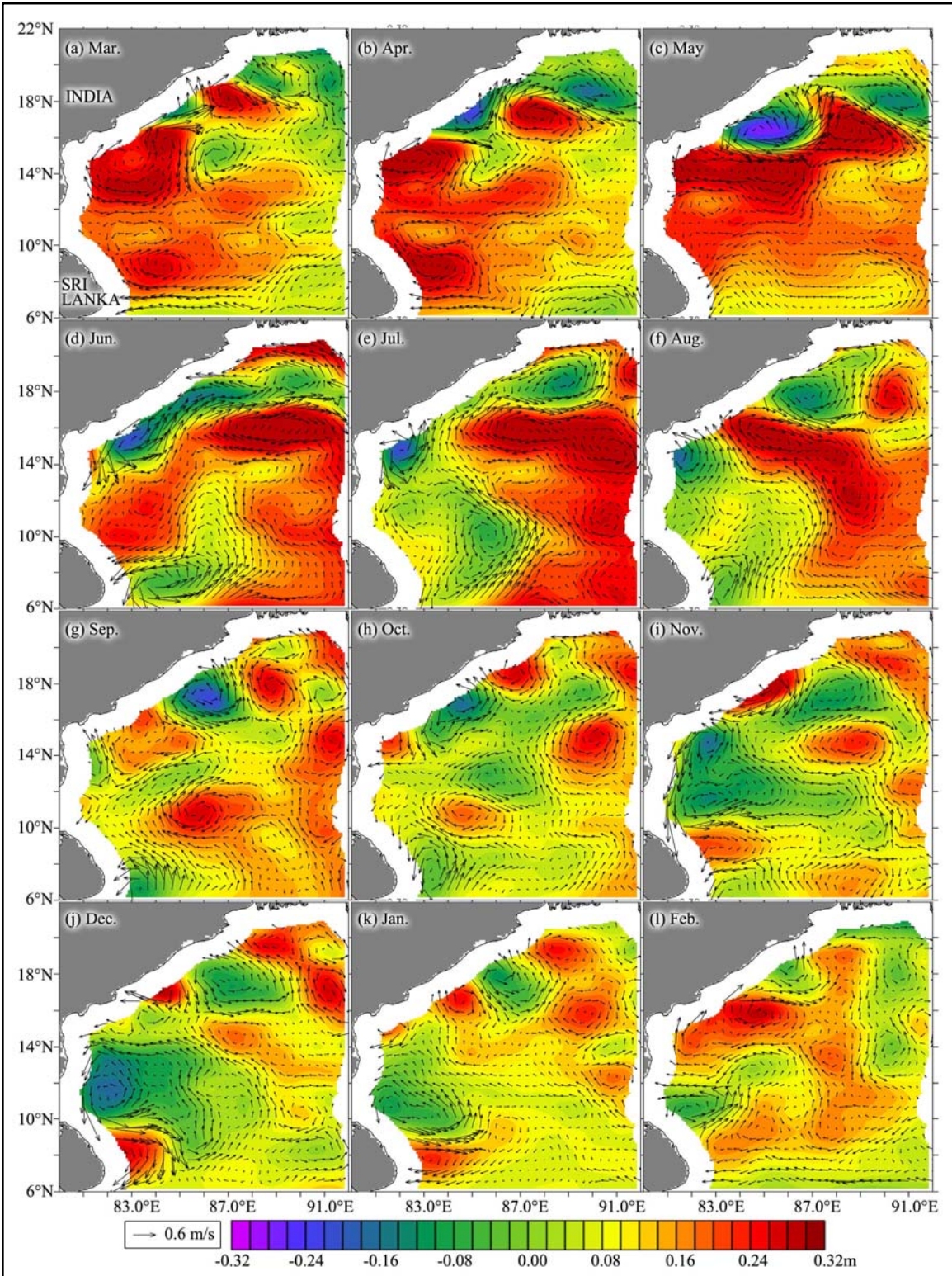


Figure 3- Eddies in the Bay of Bengal resolved every month for 2016. Red shade with clockwise surface currents represents warm-core features, whereas, blue shade with anticlockwise currents represent cold-core features. Regions $<1^\circ$ close to the coastline are blanked to show that this region is not considered in the present study to avoid any possible land/river inputs.

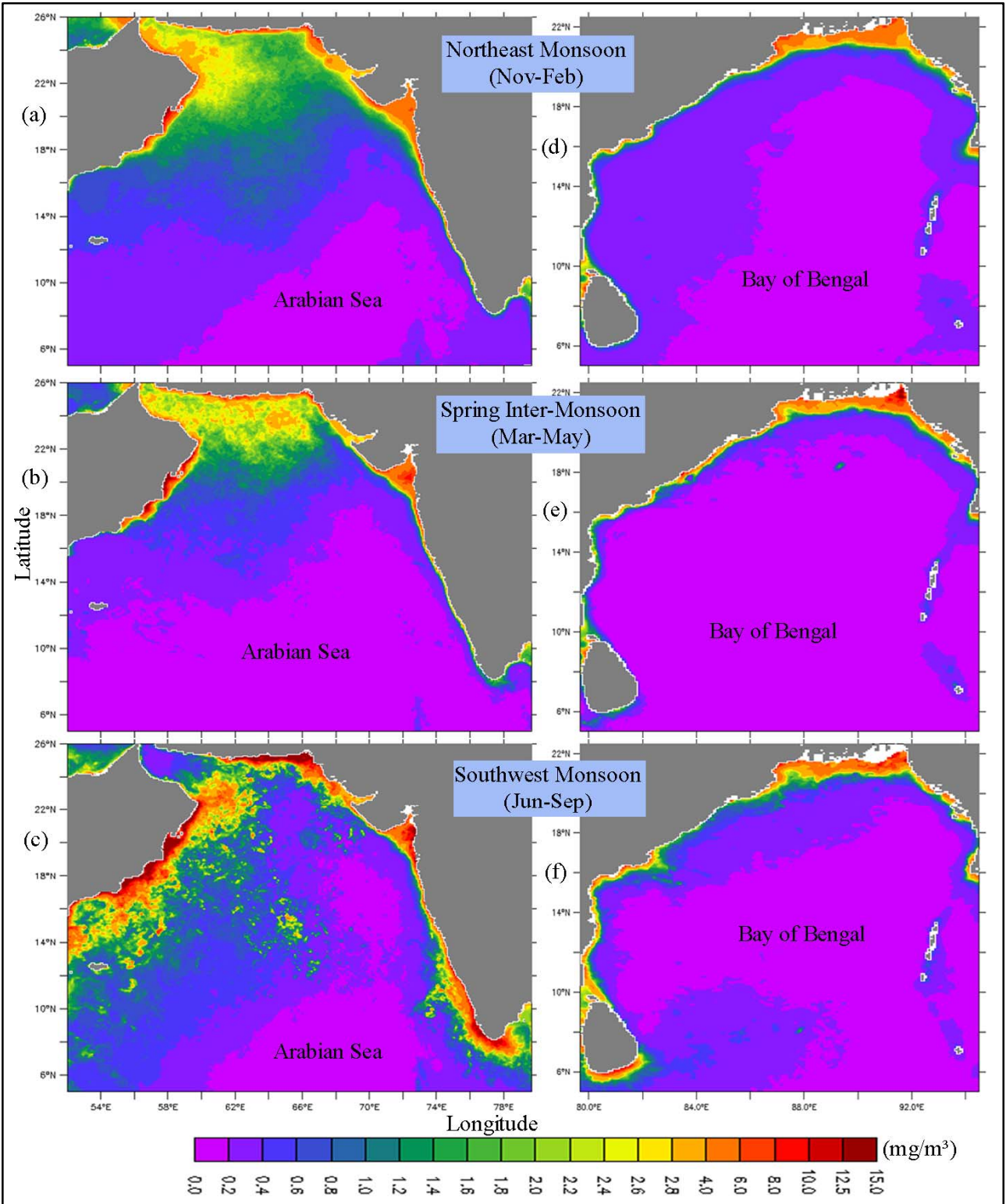


Figure 4 - Spatial distribution of phytoplankton biomass (chlorophyll *a*) in the Arabian Sea and the Bay of Bengal during different seasons.

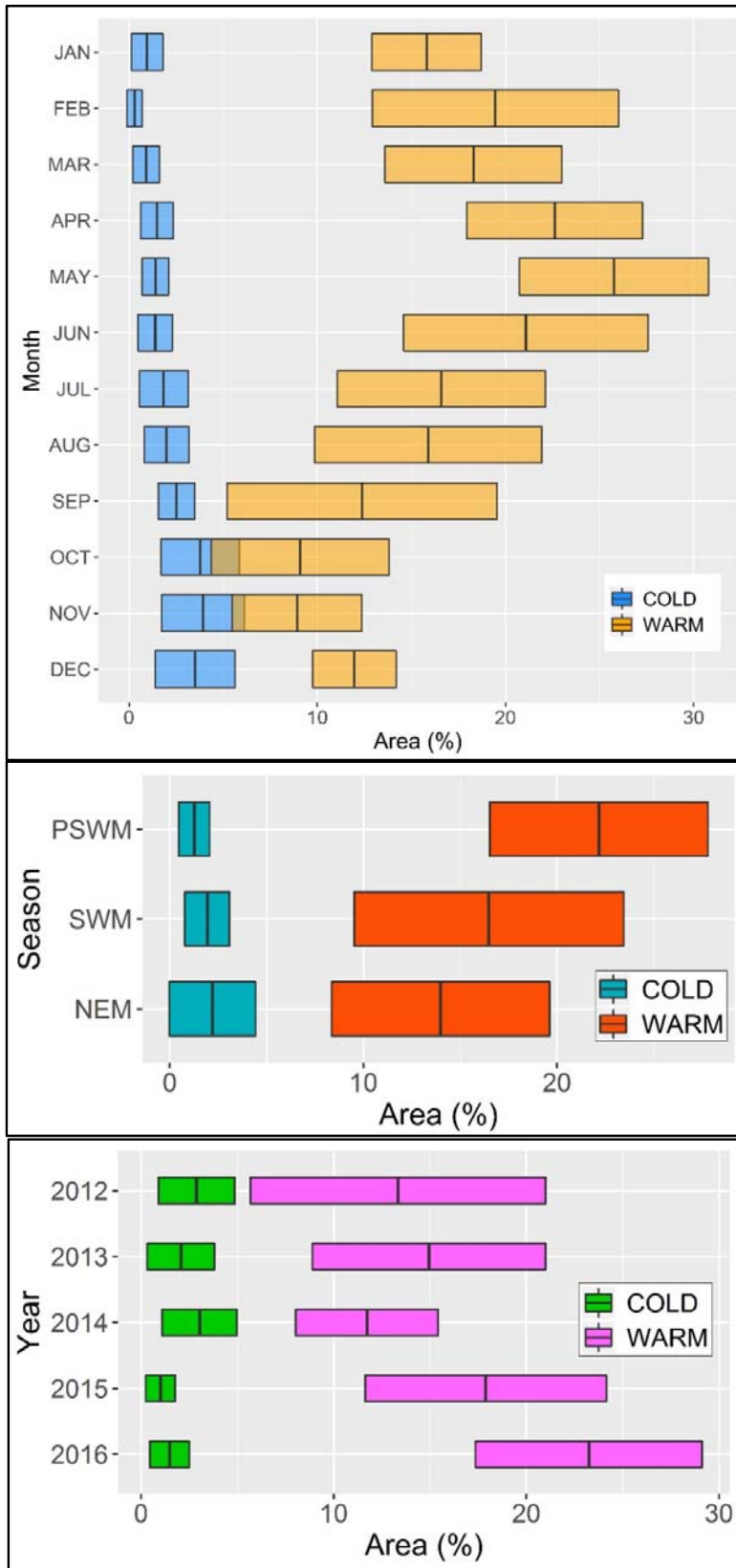


Figure 5 - Percentage dominance of warm-core and cold-core surface features in the Bay of Bengal. Mean and standard deviations are represented as blocks.

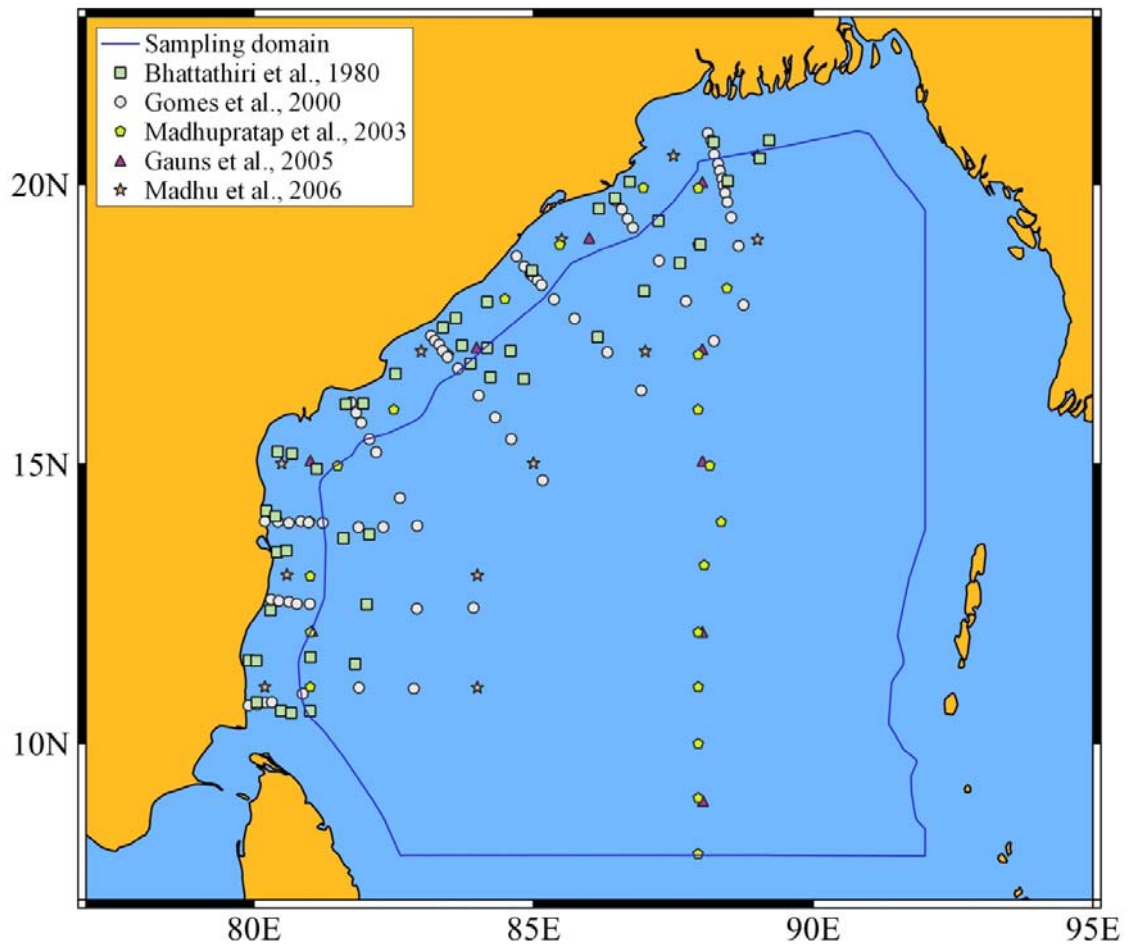


Figure 6 - A composite image of locations sampled in various past studies in the Bay of Bengal. The extensive spatial coverage of the sampling is evident in most of the earlier studies. The study domain considered in this study is represented in the blue line.

Arabian Sea (AS)	Bay of Bengal (BoB)
<p>Southwest/Summer Monsoon (June to September): High phytoplankton production due to coastal upwelling and lateral advection & enhanced wind mixing. The water column is characterized by colder SST, strong winds, deep oceanic MLD and nutrient-rich upper layers. Biological variables show several folds higher values in AS than in BoB. (Surface chl_a 4-5 times, Integrated chl_a 3-5 times and Integrated PP 8 times greater than the BoB)</p>	<p>Low biological production is driven by strong stratification arising from warm and low saline waters. Weaker winds are unable to break the stratification, which inhibits wind mixing and introduction of nutrients from the subsurface. Nutrients in River influx are not strong enough to enhance phytoplankton production beyond the shelf waters. Coastal upwelling found to be very weak due to the ‘cap’ effect of freshwater influx from rivers</p>
<p>Spring Intermonsoon/PreMonsoon (March to May): Very low chlorophyll (10-15mg m⁻²) and primary production (< 300 mg C m⁻² d⁻¹). Characterized by warm SST, weak winds, shallow MLD and nutrient-depleted upper layer. But still, noticeably higher phytoplankton biomass is evident in the northwestern Arabian Sea as an aftermath of the protracted winter convection effect. <i>Trichodesmium</i> blooms are quite common during this period as an indication of prolonged nitrogen depletion in the surface waters</p>	<p>Very low phytoplankton production throughout the BoB, except for regions very close to the coastline. This is effected by strong stratification arising from increased solar radiation and weak winds. Highly transparent water column. <i>Trichodesmium</i> blooms are widespread during this period. Very deep chlorophyll maxima layers, even more, profound than in the AS during the same period, a clear indication of nutrient impoverished ocean surface layers</p>
<p>Northeast/Winter Monsoon (November to January): Coldest and saltiest waters, weak winds, deep MLD, decreased solar radiation increased evaporation and plenty of nutrients. Winter cooling and convection injects nutrients to surface layers. Winter phytoplankton blooms are driven by cooling and convective mixing</p>	<p>Cloudy sky, low solar radiation and increased evaporation prevail in the BoB. Cold but low saline waters in the surface layers of the northern BoB. Winter cooling but no convection and injection of nutrients to surface layers caused by the low saline surface waters</p>
<p>Annual scale: High biological production during the summer and winter monsoons in the AS happens through wind mixing, upwelling and lateral advection, winter convection etc. These cause extensive phytoplankton blooms during the Southwest and Northeast Monsoon periods</p>	<p>Annual scale: Low saline water remains in the upper ocean creating strong stratification. The seasonal environmental forcing mechanisms in the BoB are incapable of breaking the strong stratification and bring nutrients to the upper euphotic column. As a result, the BoB remains low productive throughout the year as compared to the AS</p>

Table 1 - Summary of environmental characteristics/mechanisms in the Arabian Sea and Bay of Bengal, making these basins with different plankton production levels.

Literature	Year (season)	Chlorophyll <i>a</i>	Primary production
Bhattathiri et al., 1980	1978 (SWM)	0.15 mg m ⁻³	2-143.1 mg C m ⁻³ d ⁻¹
Gomes et al., 2000	1991 (PM)	18.8 ± 9 mg m ⁻²	160 ± 80 mg C m ⁻² d ⁻¹
	1989 (SWM)	97 ± 48 mg m ⁻²	300 ± 200 mg C m ⁻² d ⁻¹
	1991 (NEM)	27.6 ± 7 mg m ⁻²	300 ± 100 mg C m ⁻² d ⁻¹
Madhupratap et al., 2003	2001 (SWM)	0.1 - 0.3 mg m ⁻³	90 - 220 mg C m ⁻² d ⁻¹
	2002 (FIM)	14 - 23 mg m ⁻²	184 - 512 mg C m ⁻² d ⁻¹
Gauns et al., 2005	2001 (NEM)	8.4 - 17.4 mg m ⁻²	99 - 423 mg C m ⁻² d ⁻¹
	2001 (SWM)	10.2 - 11.5 mg m ⁻²	89 - 221 mg C m ⁻² d ⁻¹
	2002 (SWM)	0.2 ± 0.1 mg m ⁻³	7.5 ± 7.1 mg C m ⁻³ d ⁻¹
Madhu et al., 2006	2000 (NEM)	0.1 ± 0.1 mg m ⁻³	4 ± 2.6 mg C m ⁻³ d ⁻¹
	2000 (SIM)	<0.3 mg m ⁻³	<6 mg C m ⁻³ d ⁻¹

Table 2 - Earlier *in-situ* studies describe the BoB with low phytoplankton production. The nitrate, chlorophyll-*a* and primary production values from the present study domain have been collated. Average depth at which 1 μM of nitrate (nitracline) was found in in the above data have been represented. Chlorophyll-*a* presented in ‘mg m⁻³’ represent surface values, and in ‘mg m⁻²’ are integrated euphotic column values. Similarly, primary production values in mg ‘C m⁻³’ are surface values, and in mg ‘C m⁻²’ are integrated euphotic column values.

