

# Reviews and syntheses: Trends in primary production in the Bay of Bengal – is it at a tipping point?

Carolin R. Löscher<sup>1</sup>

<sup>1</sup> Nordcee, DIAS, Department of Biology, University of Southern Denmark, Campusvej 55, 5230 Odense M- DK

5 *Correspondence to:* Carolin R. Löscher ([cloescher@biology.sdu.dk](mailto:cloescher@biology.sdu.dk))

**Abstract.** Ocean primary production is the basis of the marine food web, sustaining life in the ocean via photosynthesis, and  
10 removing carbon dioxide from the atmosphere. Recently, a small but significant decrease of global marine primary  
production has been reported based on ocean color data, which was mostly ascribed to decreases in primary production in the  
northern Indian Ocean, particularly in the Bay of Bengal.

Available reports on primary production from the Bay of Bengal (BoB) are limited, and due to their spatial and temporal  
variability difficult to interpret. Primary production in the BoB has historically been described to be driven by diatom and  
15 chlorophyte clades, while only more recent datasets also show an abundance of smaller, visually difficult to detect  
cyanobacterial primary producers. The different character of the available datasets, i.e. direct counts, metagenomic and  
biogeochemical data, and satellite-based ocean color observations, make it difficult to derive a consistent pattern. However,  
making use of the most highly resolved dataset based on satellite imaging a shift in community composition of primary  
producers is visible in the BoB over the last two decades. This shift is driven by a decrease in chlorophyte abundance, and a  
20 coinciding increase in cyanobacterial abundance, despite stable concentrations of total chlorophyll. A similar but somewhat  
weaker trend is visible in the Arabian Sea, where satellite imaging points towards decreasing abundances of chlorophytes in  
the North and increasing abundances of cyanobacteria in the eastern parts. Statistical analysis indicated a correlation of this  
community change in the BoB to decreasing nitrate concentrations, which may provide an explanation for both, the decrease  
of eukaryotic nitrate-dependent primary producers and the increase of small unicellular cyanobacteria related to  
25 *Prochlorococcus*, which have a comparably higher affinity to nitrate. Changes in community composition of primary  
producers and an overall decrease of system productivity would strongly impact oxygen concentrations of the BoB's low  
oxygen intermediate waters. Assuming decreasing nitrate concentrations and concurrent decreasing biomass production,  
export and respiration, oxygen concentrations within the oxygen minimum zone would not be expected to further decrease.  
This effect could be enhanced by stronger stratification as a result of future warming, and thus possibly counteract oxygen  
30 decrease as a direct effect of stratification. Therefore, given a decrease in primary production, the BoB may not be at a  
tipping point for becoming anoxic, unless external nutrient inputs increase.

## 1 The role of the Bay of Bengal for primary production in the global Ocean – a historical perspective

Marine primary producers contribute around 50% to global net primary production (Behrenfeld et al. 2001), leading to a carbon flux from the atmosphere into the ocean of 45- 50 Pg C and up to 90 Pg C per year (Longhurst et al. 1995; Sabine et al. 2004; Sarmiento and Gruber 2002). Changes in ocean primary production exert an important control on atmospheric carbon dioxide (CO<sub>2</sub>) concentrations, and thus on global climate (Falkowski, Barber, and Smetacek 1998). The BoB has often been described as an area of low primary production compared to the Arabian Sea. This low productivity has classically been ascribed to a strongly stratified water column as a result of increased surface water temperatures (Kumar et al. 2004) in combination with lowered surface water salinity due to monsoon-governed episodes of massive rainfall and river discharge with maximum freshwater inputs in September (e.g., Mahadevan (2016)). The stratification extends through large parts of the BoB basin (Subramanian 1993), restricting nutrient fluxes to the surface and eventually limiting primary production. In coastal areas, nutrient inputs from the major rivers have been described to stimulate primary production, however, rapid consumption as well as a ballasting effect with lithogenic particles and subsequent sedimentation of organic matter prevent offshore transport (Singh, Gandhi, and Ramesh 2012; Singh and Ramesh 2011; Krishna et al. 2016; Kumar et al. 2004; Ittekkot 1993). Open waters therefore appear low in macronutrients, exhibiting at least temporarily a slight nitrogen undersaturation (Bristow et al. 2017; Löscher et al. 2020). However, nitrogen fixation has been described low to non-existent (Saxena et al. 2020; Löscher et al. 2020), therefore not compensating the nitrogen deficit. The available geological record suggests that nitrogen fixation is generally absent since the last glacial maximum where isotope records showed and enrichment in <sup>15</sup>N indicative for nitrogen fixation (Contreras-Rosales et al. 2016; Shetye et al. 2014; Dähnke and Thamdrup 2013). Corresponding to this absence of N<sub>2</sub> fixation, low primary production is suggested from deep time records of total organic carbon (TOC, Fig. 1A) on a time scale of 18kyr before present (BP).

While a decrease in primary production has been derived in models for the last decades (Fig. 1B; (Gregg and Rousseaux 2019; Roxy et al. 2016)) in the Indian Ocean, shorter historical records of primary production in the BoB are not too abundant. However, records of direct rate measurements go back to the RV Galathea and RV Anton Bruun expeditions in the early 1950ies, followed by the International Indian Ocean Expedition (IIOE) from 1959 to 1965 (Snider 1961). Those earliest records report primary production of 0.1 – 2.16 mg C m<sup>-2</sup> d<sup>-1</sup> for the shelf regions and 0.1 - 0.3 mg C m<sup>-2</sup> d<sup>-1</sup> for open ocean waters of the BoB. Comparably higher rates were reported from an expedition with the Russian RV Vityaz from 1956 to 1960, with rates between 70 to 3600 mg C m<sup>-2</sup> d<sup>-1</sup>, from a record from 1970 with a rate of 190 mg C m<sup>-2</sup> d<sup>-1</sup> (Nair et al. 1973), and from a summer monsoon situation in Aug./Sept. 1976 with rates between 130 and 330 mg C m<sup>-2</sup> d<sup>-1</sup> (Radhakrishna et al. 1978). Some of those earlier measurements were suggested to be biased as a result of trace metal contamination before trace metal clean techniques were available, a problem identified by calculating primary production to chlorophyll ratios, which turned out to be extremely high (250- 2500 compared to an average of 23 ± 13 in later data presented in Table 1; Madhupratap et al. (2003)). Later reports show a high variability of primary production ranging between 0.3 and 936 mg C m<sup>-2</sup> d<sup>-1</sup> (Gomes, Goes, and Saino 2000; Murty et al. 2000; Balachandran et al. 2008; Madhupratap

65 et al. 2003; Gauns et al. 2005; Kumar et al. 2010; Mohanty, Pramanik, and Dash 2014; Subha Anand et al. 2017; Löscher et al. 2020; Jyothibabu et al. 2004; Kumar et al. 2004; Madhu et al. 2006; Muraleedharan et al. 2007; Prasanna Kumar et al. 2002; Sarma et al. 2020; Saxena et al. 2020; Singh et al. 2015), and extremes of  $2200 \text{ mg C m}^{-2} \text{ d}^{-1}$  (Bhattathiri, Devassy, and Radhakrishna 1980), with generally higher rates in shelf regions as compared to the open ocean, which were combined into average rates of 500 and  $300 \text{ mg C m}^{-2} \text{ d}^{-1}$  for shelf and open ocean, respectively, to obtain a carbon flux budget (Naqvi et al. 70 2010). These average rates are quantitatively comparable to the studies presented in Table 1, however, for instance mesoscale water mass dynamics have been observed to promote primary production in the BoB beyond those ranges up to  $920 \text{ mg C m}^{-2} \text{ d}^{-1}$ , likely because of eddy-related decreases in stratification and pumping of nutrients into otherwise nutrient-exhausted photic surface waters (Sarma and Udaya Bhaskar 2018). Direct assessments of primary production in eddies of the BoB showed an increase in primary production and surface chlorophyll concentrations due to eddy-related nutrient pumping 75 (Singh et al. 2015; Sarma et al. 2020), with increased primary production being associated with diatom blooms (Vidya and Prasanna Kumar 2013). Eddies and other mesoscale and sub-mesoscale dynamics are frequent in the BoB (Cui, Yang, and Ma 2016; Greaser et al. 2020; Dandapat and Chakraborty 2016; Vimal Kumar et al. 2016), and therefore may cause significant variation in primary production patterns. Additional variation results from the strong influence of the two monsoon governed seasons on primary production ((Gomes, Goes, and Saino 2000; Jyothibabu et al. 2018; Madhu et al. 80 2002; Gauns et al. 2005); Table 1). Based on the presented data, a current estimate of primary production would be in the range of  $361 \pm 145$  and  $236 \pm 121 \text{ mg C m}^{-2} \text{ d}^{-1}$  for coastal and open ocean regions, respectively, which is one order of magnitude below the Arabian Sea, depending on the region and time of the year (Naqvi et al. 2010).

## 2 Key primary producers in BoB waters

Compared to records of primary production, even less data on the primary producer community are available, and 85 chlorophyll concentrations are often the only parameter presented (Table 1). Typically, coastal chlorophyll concentrations are about an order of magnitude higher compared to those in the central BoB (e.g. (Radhakrishna et al. 1978; Ramaiah et al. 2010; Balachandran et al. 2008; Gauns et al. 2005; Kumar et al. 2010). A detailed glider-based survey in the southern open ocean waters of the BoB recorded chlorophyll distributions with maxima of  $0.3\text{--}1.2 \text{ mg m}^{-3}$  located at the base of the mixed layer at about 50 - 60 m water depth (Thushara et al. 2019). Records of discrete measurements show a comparable 90 distribution for the open waters of the BoB and in addition an extension of chlorophyll concentrations of up to  $0.3 \text{ mg m}^{-3}$  north of  $15^\circ\text{N}$  possibly connected to riverine nutrient imports (Bhushan et al. 2018; Löscher et al. 2020; Li et al. 2012). Exemplaric vertical profiles of open ocean chlorophyll distributions and a diversity of typically observable primary producers are depicted in Figure 2.

Historically available phytoplankton diversity records have methodological limitations relying mostly on direct or 95 microscopic phytoplankton counts; therefore, small sized phytoplankton and cyanobacteria are likely underrepresented. There is, however, a general consensus in earlier and newer studies that diatoms dominate the pool of primary producers

(Gauns et al. 2005; Madhupratap et al. 2003; Devassy, Bhattathiri, and Radhakrishna 1983), with some historical records being astonishingly detailed, presenting phytoplankton distribution down to the genus and species levels (Nair and Gopinathan 1983) and their results are comparable to more recent studies (Ramaiah et al. 2010) showing a diversity of diatoms including *Thalassiothrix*, *Nitzschia*, *Thalassionema*, *Skeletonema*, *Chaetoceros* and *Coscinodiscus* clades being abundant (Devassy, Bhattathiri, and Radhakrishna 1983; Ramaiah et al. 2010). Diversity analysis based on bulk DNA and amplicon sequencing complemented those previously available datasets by adding a higher diversity of eukaryotic phytoplankton, including *Pelagophyceae*, *Haptophyceae*, *Chrysophyceae*, *Eustigmatophyceae*, *Xanthophyceae*, *Cryptophyceae*, *Dictyochophyceae*, and *Pinguiphyceae* and importantly by adding small cyanobacteria, which are difficult to count microscopically and were therefore not included into previous records (Löscher et al. 2020; Yuqiu et al. 2020; Bernal, Anil, and Amol 2019; Larkin et al. 2020; Pujari et al. 2019). Those cyanobacteria accounted for up to 60% of the primary producer abundance in sequence datasets in the central BoB (Li et al. 2012), and include *Synechococcus* and *Prochlorococcus*, the former has been detected from the surface down to the chlorophyll maximum, while the latter has been found abundant in the lower margin of the chlorophyll maximum at around 50 – 80 m water depth, slightly deeper than the maximum of eukaryotic primary producers (Löscher et al. 2020; Yuqiu et al. 2020). The *Prochlorococcus* population has been described to consist of several different ecotypes of the HLII clade with their respective abundances being governed by macro- and micronutrient distribution and by temperature (Larkin et al. 2020; Pujari et al. 2019). Similar distributions of *Prochlorococcus* and *Synechococcus* have been found in other OMZ areas (Beman and Carolan 2013; Franz et al. 2012; Meyer et al. 2015), following similar vertical and coast to open ocean patterns. The deeper maximum of *Prochlorococcus* as a result of its pigment composition adapted to lower light levels (Moore, Rocap, and Chisholm 1998; Rocap et al. 2003) possibly allows for utilization of nutrients from sinking organics matter at the lower boundary of the mixed layer. Metagenomes from the Atlantic have previously demonstrated the genetic potential of *Prochlorococcus* HLII clades to grow on nitrate (Rusch et al. 2007) supporting earlier suggestion that some *Prochlorococcus* ecotypes thrive at the base of the euphotic zone to acquire nitrate from underlying waters (Vaulot and Partensky 1992; Olson et al. 1990). While there is a body of literature describing distribution patterns of *Prochlorococcus* ecotype (e.g. (Johnson et al. 2006; Martiny, Kathuria, and Berube 2009; Moore, Rocap, and Chisholm 1998)), the relative contribution of different *Prochlorococcus* ecotypes to primary production in the ocean is not well resolved. In addition, information on the specific contribution of *Prochlorococcus* ecotypes detected in the BoB to bulk primary production is not available. Thus, it is unclear if a change in *Prochlorococcus* ecotype composition as suggested by Larkin et al., 2019, in response to changing temperatures, nutrient concentration, or iron stress would correspond to changes in overall *Prochlorococcus* primary production. A community shift in small cyanobacteria may be somewhat speculative and with unknown impacts on bulk primary production. However, an overall increase in abundance of small cyanobacteria in concert with a decrease of eukaryotic primary producers would be expected to impact BoB biogeochemistry, especially with regard to the spatial expansion and the intensity of the OMZ through modified export production and respiration in low oxygen intermediate waters.

130 Besides those small cyanobacteria, there are reports on nitrogen fixing cyanobacteria of the *Trichodesmium* clade (Devassy, Bhattathiri, and Radhakrishna 1983; Jyothibabu et al. 2017; Sahu et al. 2017; Hegde et al. 2008; Shetye et al. 2013; Wu et al. 2019); other reports included diatom-diazotroph associations playing a role for BoB nitrogen fixation (Bhaskar et al. 2007). However, for both types of nitrogen fixing primary producers, datasets are not conclusive and indicate high spatial and temporal variability. Nitrogen fixing microbes have been proposed to be limited by iron, other micronutrients or organic  
135 matter in the BoB (Löscher et al. 2020; Saxena et al. 2020; Shetye et al. 2013; Benavides et al. 2018). While micronutrients would have the potential to also directly limit primary production, a limitation of nitrogen fixers by organic matter would result in a feedback regulation of low primary production limiting nitrogen fixation and resulting low nitrogen availability limiting primary production.

### 140 **3 Trends in primary production in the BoB**

Satellite data from 1998 to 2015 suggest a decrease in primary production in the global ocean (Gregg et al. 2003; Behrenfeld et al. 2006), and recent studies deducted a decrease in ocean primary production of 2.1% per decade associated largely to a decrease of chlorophytes in the marine photic realm (Gregg, Rousseaux, and Franz 2017; Gregg and Rousseaux 2019). However, a recent study, derived a nonlinear trend in primary production from a similar time episode, between 1998 and  
145 2018 (Kulk et al. 2020). Decreasing rates of primary production have been associated with high latitude regions (Gregg et al. 2003), but also with the Northern and Equatorial Indian Ocean with a decrease of 9.7 and 17.2 % per decade, respectively (Gregg and Rousseaux 2019). These estimates, based on satellite imaging, were explained by a decrease in diatom and chlorophyte primary production of 15.4 and 24.8 % per decade, respectively, for both the BoB and its sister basin, the Arabian Sea (Fig. 3). This decrease has been connected to decreasing nitrate and silicate concentrations of 32.4% and 22.8%  
150 per decade in those waters limiting those larger, fast-growing primary producer groups (Gregg and Rousseaux 2019), with nitrate rather than silicate being limiting primary production if assuming Redfield stoichiometry (Kumar et al. 2010; Radhakrishna et al. 1978). At the same time, an increase in small cyanobacterial primary producers, *Prochlorococcus* and *Synechococcus*, was described in this region, with an increase in cyanobacterial primary production of 16.7 % per decade (Gregg and Rousseaux 2019). Satellite-based imaging indeed showed a southward expansion and increase in abundance of  
155 cyanobacteria in the Bay of Bengal and through the Southern Arabian Sea (Fig. 3). Molecular genetic data showed, however, that not only *Prochlorococcus* is expanding but that mostly certain ecotypes of high light *Prochlorococcus* increased in abundance and extended their habitat (Larkin et al. 2020). Given the decrease in both nitrate and silicate, a decrease in the silicate correlated ecotypes currently dominant in the northern BoB would be expected and those may be replaced by an open ocean ecotype sensitive to increasing iron concentrations in those waters. The overall increase in cyanobacteria derived  
160 from satellite monitoring is, however, not provable by direct measurements due to the lack of counts in the earlier reports, and further doesn't seem to impact the overall prediction on primary production decrease.

Qualitatively consistent with the short term trend of decreasing primary production between 1998 and 2015, a pronounced decrease of up to 20% in phytoplankton in the Western Indian Ocean over the past six decades has been ascribed to increasing ocean stratification as a consequence of rapid warming in the Indian Ocean, which suppresses nutrient mixing from subsurface layers (Roxy et al. 2016). This result is indeed consistent with a long term trend with decreasing productivity since the last glacial maximum (Contreras-Rosales et al. 2016; Shetye et al. 2014). With primary production leading to respiration and a concurrent oxygen loss in intermediate waters, this may provide an explanation for why the BoB is the only oxygen minimum zone region with traces of oxygen left in its core waters. It has often been suggested that the BoB is at a tipping point to developing severe anoxia (Bristow et al. 2017; Canfield et al. 2019; Rixen et al. 2020), which is a threshold with only minor changes in biogeochemistry leading to a consumption of oxygen traces in the oxygen minimum zone. This scenario is, however, challenged by decreasing primary production on long-term, as well as decadal time scales.

#### **4 Possible scenarios in response to changes in primary production on the BoB OMZ**

Reports of decreasing primary production in the BoB available from geological records, Earth system modelling, and satellite imaging are consistent over different time scales. But explanations on why primary production and chlorophyll concentrations decrease differ. Proposed important parameters include iron stress with iron concentrations having decreased in the geological record over the last 5000 years (Shetye et al. 2014), a decrease in nitrate and silicate availability directly impacting primary producer growth (Gregg and Rousseaux 2019), a rapid temperature increase of 0.6°C over the last six decades, or a combination of those factors, which may directly or indirectly via increased stratification decrease primary production (Roxy et al. 2016). These considerations cannot clearly be compared and evaluated using the few direct measurements available, as those expose a high temporal and spatial variability. They allow, however, for exploring theoretically what would happen to the BoB biogeochemistry if nutrient concentrations would decrease further, with the exception of coastal regions, where nitrogen inputs may increase and enter the ocean via rivers but would also at the same time be removed quickly and close to the coast as currently happening in the BoB (Naqvi et al. 2010), and temperatures would increase.

Assuming a limitation of primary production by nitrogen availability, we would expect a niche for nitrogen fixation developing in the BoB. Until now, nitrogen fixation rates have shown to be low (Löscher et al. 2020; Saxena et al. 2020) and while there were reports on local blooms of the efficient nitrogen fixer *Trichodesmium* (Shetye et al. 2013), the nitrogen fixer community is dominated by typically less active heterotrophic bacteria (Wu et al. 2019; Turk-Kubo et al. 2014). However, our understanding of the diazotroph community composition and N<sub>2</sub> fixation rates is hampered by the low number of available datasets and their spatial and seasonal bias. Nitrogen fixers in general have a high requirement for iron, therefore an iron limitation could ultimately limit nitrogen fixation and indirectly primary production, as discussed earlier (Löscher et al. 2020). A further decrease in iron would intensify this limitation and progressively decrease the productivity in the BoB. In

195 addition, a decrease in silicate would limit diatom growth which need silica to form their frustules. Therefore, a combined decrease of iron, nitrate and silicate concentrations will lower primary production of various groups of primary producers at the same time, which may not only explain the trend visible from satellite imaging (Gregg and Rousseaux 2019) but may allow to predict a future trend for the BoB biogeochemistry.

Our earlier studies presented possible feedback cycles that are able to explain the persistent nanomolar levels of oxygen in the BoB OMZ (Canfield et al. 2019; Löscher et al. 2020). One approach included low mixing levels, or permanent stratification limiting euphotic zone nutrient concentrations to an extent that new production is persistently low and organic matter recycling will not support the organic carbon requirement of the detected heterotrophic nitrogen fixer community. This we suggested to lead the system to being locked in a low productivity and increasingly nitrogen limited scenario with the OMZ increasingly weakening. Applying lower concentrations of nitrate and iron (Fig. 4; silicate is not parametrized in our model but would lead to a similar effect if it would be limiting primary production), we observe that the OMZ respiration will lower, low oxygen concentrations will be maintained, and denitrification will only occur if nutrients are imported into the OMZ from land, via rivers, from the atmosphere, or by increased upwelling (Fig. 4). This would mean the BoB may not be at a tipping point towards anoxia but is a system with a weakening OMZ in its open waters, with progressive warming stabilizing this trend by increasing stratification in the photic zone and cutting this part of the water column off any nutrient supply.

Comparing scenarios of primary production and its impact on the BoB OMZ, the last glacial maximum signifies an episode of high productivity in the geological record (Contreras-Rosales et al. (2016), Fig. 5A). Higher land runoff and riverine inputs led to both higher nutrient imports, but also increased loads of terrigenous material leading facilitating organic carbon export from the productive zone to the sediments through ballasting. This effect is currently also seen, with nutrients being imported and consumed close to the shelf and organic material exported out of the photic zone (Fig. 5B), leading to a carbon pump with similar export rates like in the Arabian Sea (Singh and Ramesh 2015). A scenario with production being enhanced would strongly depend on external nutrient inputs, those could come from land and riverine inflow, and could for example result from deforestation, enhanced monsoon events, increasing atmospheric input, or enhanced upwelling, which has been described to enhance primary production in (sub-) mesoscale features (Sarma and Udaya Bhaskar (2018), Fig. 5B). Because global warming will result in increased stratification, enhanced nutrient pumping from deeper waters may be limited to mesoscale eddies, the BoB may be a rather stable system in itself and the observed and predicted changes in primary producers are not suggestive of a development of anoxia in the BoB OMZ.

225

Acknowledgement

230 I thank C. F. Reeder, P. Xu and J. Rønning, J. Lincy, and D. E. Canfield for helpful discussions on BoB productivity patterns and the BoB OMZ, I also thank the Villum foundation for funding my research (Grant no. 29411). I thank M. Benavides and A. Singh for their helpful and constructive reviews.



## References

- 235 Balachandran, K. K., Laluraj C M, Jyothibabu Retnamma, N. V. Madhu, K. R. Muralledharan, J. G. Vijay, P. A. Maheswaran, T. T. M. Ashraff, K. K. C. Nair, and C. T. Achuthankutty. 2008. 'Hydrography and biogeochemistry of the north western Bay of Bengal and the north eastern Arabian Sea during winter monsoon', *Journal of Marine Systems*, 73: 76-86.
- Behrenfeld, Michael J., Robert T. O'Malley, David A. Siegel, Charles R. McClain, Jorge L. Sarmiento, Gene C. Feldman, Allen J. Milligan, Paul G. Falkowski, Ricardo M. Letelier, and Emmanuel S. Boss. 2006. 'Climate-driven trends in contemporary ocean productivity', *Nature*, 444: 752-55.
- 240 Behrenfeld, Michael J., James T. Randerson, Charles R. McClain, Gene C. Feldman, Sietse O. Los, Compton J. Tucker, Paul G. Falkowski, Christopher B. Field, Robert Frouin, Wayne E. Esaias, Dorota D. Kolber, and Nathan H. Pollack. 2001. 'Biospheric Primary Production During an ENSO Transition', 291: 2594-97.
- Bemal, Suchandan, Arga Chandrashekar Anil, and P. Amol. 2019. 'Picophytoplankton variability: Influence of Rossby wave propagation in the southeastern Arabian Sea', *Journal of Marine Systems*, 199: 103221.
- 245 Beman, J. Michael, and Molly T. Carolan. 2013. 'Deoxygenation alters bacterial diversity and community composition in the oceans largest oxygen minimum zone', *Nat Commun*, 4.
- Benavides, Mar, Chloé Martias, Hila Elifantz, Ilana Berman-Frank, Cécile Dupouy, and Sophie Bonnet. 2018. 'Dissolved Organic Matter Influences N2 Fixation in the New Caledonian Lagoon (Western Tropical South Pacific)', *Frontiers in Marine Science*, 5.
- 250 Bhaskar, Jane T, Nagappa Ramaiah, Mangesh Gauns, and Veronica Fernandes. 2007. 'Preponderance of a few diatom species among the highly diverse microphytoplankton assemblages in the Bay of Bengal', *J Marine Biology*, 152: 63-75.
- Bhattachiri, P.M.A., V.P. Devassy, and K. Radhakrishna. 1980. 'Primary production in the Bay of Bengal during southwest monsoon of 1978', *Mahasagar-Bulletin of the National Institute of Oceanography*, 13: 315-23.
- Bhushan, Ravi, Srinivas Bikkina, Jayati Chatterjee, Satinder Singh, Vineet Goswami, C. L, and A. K. Sudheer. 2018. 'Evidence for enhanced chlorophyll-a levels in the Bay of Bengal during early north-east monsoon', *Journal of Oceanography and Marine Science*, 9: 15-23.
- 255 Boyle, R. A., J. R. Clark, S. W. Poulton, G. Shields-Zhou, D. E. Canfield, and T. M. Lenton. 2013. 'Nitrogen cycle feedbacks as a control on euxinia in the mid-Proterozoic ocean', *Nature Communications*, 4: 1533.
- Bristow, L. A., C. M. Callbeck, M. Larsen, M. A. Altabet, J. Dekaezemacker, M. Forth, M. Gauns, R. N. Glud, M. M. M. Kuypers, G. Lavik, J. Milucka, S. W. A. Naqvi, A. Pratihary, N. P. Revsbech, B. Thamdrup, A. H. Treusch, and D. E. Canfield. 2017. 'N2 production rates limited by nitrite availability in the Bay of Bengal oxygen minimum zone', *Nature Geosci*, 10: 24-29.
- 260 Canfield, Don E., Beate Kraft, Carolin R. Löscher, Richard A. Boyle, Bo Thamdrup, and Frank J. Stewart. 2019. 'The regulation of oxygen to low concentrations in marine oxygen-minimum zones', *Journal of Marine Research*, 77: 297-324.
- Contreras-Rosales, L. A., E. Schefuß, V. Meyer, L. Palamenghi, A. Lückge, and T. C. Jennerjahn. 2016. 'Origin and fate of sedimentary organic matter in the northern Bay of Bengal during the last 18ka', *Global and Planetary Change*, 146: 53-66.
- 265 Cui, Wei, Jengang Yang, and Yi Ma. 2016. 'A statistical analysis of mesoscale eddies in the Bay of Bengal from 22-year altimetry data', *Acta Oceanologica Sinica*, 35: 16.
- Dandapat, S., and A. Chakraborty. 2016. 'Mesoscale Eddies in the Western Bay of Bengal as Observed From Satellite Altimetry in 1993–2014: Statistical Characteristics, Variability and Three-Dimensional Properties', *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9: 5044-54.
- 270 Devassy, V.P. , P.M.A. Bhattachiri, and K. Radhakrishna. 1983. 'Primary production in the Bay of Bengal during August, 1977', *Mahasagar-Bulletin of National Institute of Oceanography*, 16: 443-47.
- Dähnke, K., and B. Thamdrup. 2013. 'Nitrogen isotope dynamics and fractionation during sedimentary denitrification in Boknis Eck, Baltic Sea', *Biogeochemistry*, 10: 3079-88.
- Falkowski, P. G., R. T. Barber, and V. V. Smetacek. 1998. 'Biogeochemical Controls and Feedbacks on Ocean Primary Production', *Science*, 281: 200-7.
- 275 Franz, Jasmin, Gerd Krahmhann, Gaute Lavik, Patricia Grasse, Thorsten Dittmar, and Ulf Riebesell. 2012. 'Dynamics and stoichiometry of nutrients and phytoplankton in waters influenced by the oxygen minimum zone in the eastern tropical Pacific', *Deep-Sea Research Part I: Oceanographic Research Papers*, 62: 20-31.
- 280 Gauns, Mangesh, M. Madhuratap, Ramaiah Nagappa, Jyothibabu Retnamma, V. Fernandes, Jane Bhaskar, and S. PrasannaKumar. 2005. 'Comparative accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and the Bay of Bengal', *Deep Sea Research Part II Topical Studies in Oceanography*, 52.
- Gomes, H. R., J. I. Goes, and T. Saino. 2000. 'Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal', *Cont. Shelf Res.*, 20: 313–30.
- 285 Greaser, Samantha R., Bulusu Subrahmanyam, Corinne B. Trott, and Heather L. Roman-Stork. 2020. 'Interactions Between Mesoscale Eddies and Synoptic Oscillations in the Bay of Bengal During the Strong Monsoon of 2019', *Journal of Geophysical Research: Oceans*, 125: e2020JC016772.

- Gregg, W. W., C. S. Rousseaux, and B. A. Franz. 2017. 'Global trends in ocean phytoplankton: a new assessment using revised ocean colour data', *Remote Sens Lett*, 8: 1102-11.
- 290 Gregg, Watson W., and Nancy W Casey. 2007. 'Modeling coccolithophores in the global oceans', *Deep Sea Research Part II: Topical Studies in Oceanography*, 54: 447-77.
- Gregg, Watson W., Margarita E. Conkright, Paul Ginoux, John E. O'Reilly, and Nancy W. Casey. 2003. 'Ocean primary production and climate: Global decadal changes', 30.
- Gregg, Watson W., and Cecile S. Rousseaux. 2019. 'Global ocean primary production trends in the modern ocean color satellite record (1998–2015)', *Environmental Research Letters*, 14: 124011.
- 295 Hegde, S., Arga Anil, Jagadish Patil, Smita Mitbavkar, Venkat Krishnamurthy, and Vissa Gopalakrishna. 2008. 'Influence of environmental settings on the prevalence of *Trichodesmium* spp. in the Bay of Bengal', *Marine Ecology Progress Series*, 356.
- Ittekkot, Venugopalan. 1993. 'The abiotically driven biological pump in the ocean and short-term fluctuations in atmospheric CO<sub>2</sub> contents', *Global and Planetary Change*, 8: 17-25.
- Johnson, Z. I., E. R. Zinser, A. Coe, N. P. McNulty, E. M. Woodward, and S. W. Chisholm. 2006. 'Niche partitioning among *Prochlorococcus* ecotypes along ocean-scale environmental gradients', *Science*, 311: 1737-40.
- 300 Jyothibabu, R., N. Arunpandi, L. Jagadeesan, C. Karnan, K. R. Lallu, and P. N. Vinayachandran. 2018. 'Response of phytoplankton to heavy cloud cover and turbidity in the northern Bay of Bengal', *Scientific Reports*, 8: 11282-82.
- Jyothibabu, R., C. Karnan, L. Jagadeesan, N. Arunpandi, R. S. Pandiarajan, K. R. Muraleedharan, and K. K. Balachandran. 2017. 'Trichodesmium blooms and warm-core ocean surface features in the Arabian Sea and the Bay of Bengal', *Marine Pollution Bulletin*, 121: 201-15.
- 305 Jyothibabu, R., P. A. Maheswaran, N. V. Madhu, T. T. M. Asharaf, V. J. Gerson, Haridas C, Padmaja Venugopal, C. Revichandran, K. K. C. Nair, and T. C. Gopalakrishnan. 2004. 'Differential response of winter cooling on biological production in the northeastern Arabian Sea and northwestern Bay of Bengal', *Curr. Sci.*, 87.
- Krishna, M. S., M. H. K. Prasad, D. B. Rao, R. Viswanadham, V. V. S. S. Sarma, and N. P. C. Reddy. 2016. 'Export of dissolved inorganic nutrients to the northern Indian Ocean from the Indian monsoonal rivers during discharge period', *Geochimica et Cosmochimica Acta*, 172: 430-43.
- 310 Kulk, Gemma, Trevor Platt, James Dingle, Thomas Jackson, Bror F. Jönsson, Heather A. Bouman, Marcel Babin, Robert J. W. Brewin, Martina Doblin, Marta Estrada, Francisco G. Figueiras, Ken Furuya, Natalia González-Benítez, Hafsteinn G. Gudfinnsson, Kristinn Gudmundsson, Bangqin Huang, Tomonori Isada, Žarko Kovač, Vivian A. Lutz, Emilio Marañón, Mini Raman, Katherine Richardson, Patrick D. Rozema, Willem H. van de Poll, Valeria Segura, Gavin H. Tilstone, Julia Uitz, Virginie van Dongen-Vogels, Takashi Yoshikawa, and Shubha Sathyendranath. 2020. 'Primary Production, an Index of Climate Change in the Ocean: Satellite-Based Estimates over Two Decades', *Remote Sensing*, 12: 826.
- 315 Kumar, S. Prasanna, Jayu Narvekar, Nuncio Murukesh, Ramaiah Nagappa, S. Sardesai, Mangesh Gauns, V. Fernandes, and Jane Bhaskar. 2010. 'Is the biological productivity in the Bay of Bengal light limited?', *Current Science*, 98: 1331-39.
- 320 Kumar, Sanjeev, R. Ramesh, S. Sardesai, and M. S. Sheshshayee. 2004. 'High new production in the Bay of Bengal: Possible causes and implications', *Geophysical Research Letters*, 31.
- Larkin, Alyse A., Catherine A. Garcia, Kimberly A. Ingoglia, Nathan S. Garcia, Steven E. Baer, Benjamin S. Twining, Michael W. Lomas, and Adam C. Martiny. 2020. 'Subtle biogeochemical regimes in the Indian Ocean revealed by spatial and diel frequency of *Prochlorococcus* haplotypes', 65: S220-S32.
- 325 Li, Gang, Qiang Lin, Guangyan Ni, Pingping Shen, Yanzhi Fan, Liangmin Huang, and Yehui Tan. 2012. 'Vertical Patterns of Early Summer Chlorophyll a Concentration in the Indian Ocean with Special Reference to the Variation of Deep Chlorophyll Maximum', *Journal of Marine Biology*, 2012: 801248.
- Longhurst, A. R., S. Sathyendrenath, T. Platt, C. Caverhill, and J. Plankton Res. 1995. 'An estimation of global primary production in the ocean from satellite radiometer data', *J. Plankton Res.*, 17: 1245–71.
- 330 Löscher, C. R., W. Mohr, H. W. Bange, and D. E. Canfield. 2020. 'No nitrogen fixation in the Bay of Bengal?', *Biogeosciences* 17: 851–64.
- Madhu, N., R. Jyothibabu, P. Maheswaran, V. J. Gerson, T. Gopalakrishnan, and K. Nair. 2006. 'Lack of seasonality in phytoplankton standing stock (chlorophyll a) and production in the western Bay of Bengal', *Continental Shelf Research*, 26: 1868–83.
- 335 Madhu, N. V., P. A. Maheswaran, Jyothibabu Retnamma, V. Sunil, C. Revichandran, Balasubramanian Thangavel, T. C. Gopalakrishnan, and K. K. C. Nair. 2002. 'Enhanced biological production off Chennai triggered by October 1999 super cyclone (Orissa)', *Current Science*, 82.
- Madhupratap, M., Mangesh Gauns, Ramaiah Nagappa, S. PrasannaKumar, P. M. Muraleedharan, S. N. DeSousa, Sandip Sardesai, and Dr Usha Muraleedharan. 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.
- 340 Mahadevan, Amala. 2016. 'The Impact of Submesoscale Physics on Primary Productivity of Plankton', *Annual Review of Marine Science*, 8: 161-84.

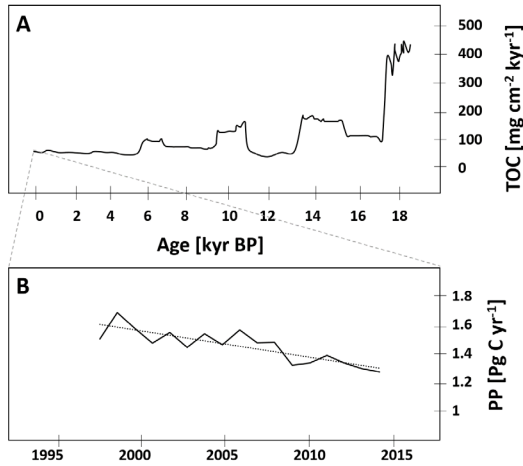
- Martiny, A. C., S. Kathuria, and P. M. Berube. 2009. 'Widespread metabolic potential for nitrite and nitrate assimilation among Prochlorococcus ecotypes', *Proc Natl Acad Sci U S A*, 106: 10787-92.
- 345 Meyer, J., C. R. Löscher, S. C. Neulinger, A. F. Reichel, A. Loginova, C. Borchard, R. A. Schmitz, H. Hauss, R. Kiko, and U. Riebesell. 2015. 'Changing nutrient stoichiometry affects phytoplankton production, DOP build up and dinitrogen fixation – a mesocosm experiment in the eastern tropical North Atlantic', *Biogeosciences Discuss.*, 12: 9991-10029.
- Mohanty, Swati Sucharita, D.S. Pramanik, and B.P. Dash. 2014. 'Primary Productivity of Bay of Bengal at Chandipur in Odisha,India', *International Journal of Scientific and Research Publications*, 4.
- 350 Moore, Lisa R., Gabrielle Rocop, and Sallie W. Chisholm. 1998. 'Physiology and molecular phylogeny of coexisting Prochlorococcus ecotypes', *Nature*, 393: 464-67.
- Muraleedharan, K. , P. Jasmine, C. T. Achuthankutty, C. Revichandran, P. D. Kumar, P. Anand, and G. Rejomon. 2007. 'Influence of basin-scale and mesoscale physical processes on biological productivity in the Bay of Bengal during the summer monsoon', *Progress in Oceanography*, 72: 364–83.
- 355 Murty, V.S.N. , G.V.M. Gupta, V.V. Sarma, B.P. Rao, D. Jyothi, P.N.M. Shastri, and Y. Supraveena. 2000. 'Effect of vertical stability and circulation on the depth of the chlorophyll maximum in the Bay of Bengal during May-June, 1996', *Deep-Sea Research I*, 47: 859-73.
- Nair, P.V. Ramachandran, and C.P. Gopinathan. 1983. 'Primary production in coastal waters', *CMFRI Bulletin*, 34: 29-32.
- Nair, P.V.R. , S. Samuel, K.J. Joseph, and V.K. Balachandran. 1973. 'Primary production and potential fishery resources in the seas around India.' in, *Proceedings of the symposium on 'Living resources of the seas around India'* (Cochin: Central Marine Fisheries Research Institute.).
- 360 Naqvi, S. W. A., H. Naik, W. D'Souza, P. V. Narvekar, A. L. Paropkari, and H. W. Bange. 2010. 'Carbon and nitrogen fluxes in the North Indian Ocean.' in K.-K. Liu, L. Atkinson, R. Quiñones and L. Talaue-McManus (eds.), *Carbon and nutrient fluxes in continental margins: A global synthesis* (Springer-Verlag: New York).
- 365 Olson, Robert J, Sallie W Chisholm, Erik R Zettler, Mark A Altabet, and Jeffrey A %J Deep Sea Research Part A. Oceanographic Research Papers Dusenberry. 1990. 'Spatial and temporal distributions of prochlorophyte picoplankton in the North Atlantic Ocean', 37: 1033-51.
- Prasanna Kumar, S. , P. M. Muraleedharan, Prasad Thoppil, Mangesh Gauns, Ramaiah Nagappa, S. N. De Souza, Smeeta Sardesai, and M. Madhupratap. 2002. 'Why Bay of Bengal is less productive during summer monsoon compared to the Arabian Sea?', *Geophysical Research Letters*, 29: 881-84.
- 370 Pujari, Laxman, Chao Wu, Jinjun Kan, Nan Li, Xingzhou Wang, Guicheng Zhang, Xiaomei Shang, Min Wang, Chun Zhou, and Jun Sun. 2019. 'Diversity and Spatial Distribution of Chromophytic Phytoplankton in the Bay of Bengal Revealed by RuBisCO Genes (rbcL)', 10.
- Radhakrishna, K., V.P. Devassay, R.M.S. Bhargava, and P.M.A. Bhattathiri. 1978. 'Primary production in the Northern Arabian Sea', *Indian Journal of Marine Sciences*, 7: 271-75.
- 375 Ramaiah, N., V. Fernandes, Jane Bhaskar, Jyothibabu Retnamma, Mangesh Gauns, and E. A. Jayraj. 2010. 'Seasonal variability in biological carbon biomass standing stocks and production in the surface layers of the Bay of Bengal', *Indian Journal of Marine Sciences*, 39.
- Rixen, T., G. Cowie, B. Gaye, J. Goes, H. do Rosário Gomes, R. R. Hood, Z. Lachkar, H. Schmidt, J. Segschneider, and A. Singh. 2020. 'Reviews and syntheses: Present, past, and future of the oxygen minimum zone in the northern Indian Ocean', *Biogeosciences*, 17: 6051-80.
- 380 Rocop, G., F. W. Larimer, J. Lamerdin, S. Malfatti, P. Chain, N. A. Ahlgren, A. Arellano, M. Coleman, L. Hauser, W. R. Hess, Z. I. Johnson, M. Land, D. Lindell, A. F. Post, W. Regala, M. Shah, S. L. Shaw, C. Steglich, M. B. Sullivan, C. S. Ting, A. Tolonen, E. A. Webb, E. R. Zinser, and S. W. Chisholm. 2003. 'Genome divergence in two Prochlorococcus ecotypes reflects oceanic niche differentiation', *Nature*, 424: 1042-7.
- 385 Roxy, Mathew Koll, Aditi Modi, Raghu Murtugudde, Vinu Valsala, Swapna Panickal, S. Prasanna Kumar, M. Ravichandran, Marcello Vichi, and Marina Lévy. 2016. 'A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean', 43: 826-33.
- Rusch, Douglas B., Aaron L. Halpern, Granger Sutton, Karla B. Heidelberg, Shannon Williamson, Shibu Yooseph, Dongying Wu, Jonathan A. Eisen, Jeff M. Hoffman, Karin Remington, Karen Beeson, Bao Tran, Hamilton Smith, Holly Baden-Tillson, Clare Stewart, Joyce Thorpe, Jason Freeman, Cynthia Andrews-Pfannkoch, Joseph E. Venter, Kelvin Li, Saul Kravitz, John F. Heidelberg, Terry Utterback, Yu-Hui Rogers, Luisa I. Falcón, Valeria Souza, Germán Bonilla-Rosso, Luis E. Eguiarte, David M. Karl, Shubha Sathyendranath, Trevor Platt, Eldredge Bermingham, Victor Gallardo, Giselle Tamayo-Castillo, Michael R. Ferrari, Robert L. Strausberg, Kenneth Nealson, Robert Friedman, Marvin Frazier, and J. Craig Venter. 2007. 'The Sorcerer II Global Ocean Sampling Expedition: Northwest Atlantic through Eastern Tropical Pacific', *PLOS Biology*, 5: e77.
- 390 Sabine, Christopher L., Richard A. Feely, Nicolas Gruber, Robert M. Key, Kitack Lee, John L. Bullister, Rik Wanninkhof, C. S. Wong, Douglas W. R. Wallace, Bronte Tilbrook, Frank J. Millero, Tsung-Hung Peng, Alexander Kozyr, Tsueno Ono, and Aida F. Rios. 2004. 'The Oceanic Sink for Anthropogenic CO<sub>2</sub>', 305: 367-71.
- 395

- 400 Sahu, Biraja Kumar, Sanjiba Kumar Baliarsingh, Aneesh A. Lotliker, Chandanlal Parida, Suchismita Srichandan, and Kali Charan Sahu. 2017. 'Winter thermal inversion and Trichodesmium dominance in north-western Bay of Bengal', *Ocean Science Journal*, 52: 301-06.
- Sarma, V., M. Chopra, D. Rao, M. Priya, G. Rajula, D. Lakshmi, and V. Rao. 2020. 'Role of eddies on controlling total and size-fractionated primary production in the Bay of Bengal', *Continental Shelf Research*, 204.
- 405 Sarma, V. V. S. S., and T. V. S. Udaya Bhaskar. 2018. 'Ventilation of Oxygen to Oxygen Minimum Zone Due to Anticyclonic Eddies in the Bay of Bengal', 123: 2145-53.
- Sarmiento, Jorge, and Nicolas Gruber. 2002. 'Sinks for Anthropogenic Carbon', *Physics Today*, 55: 30-36.
- Saxena, Himanshu, Deepika Sahoo, Mohammad Atif Khan, Sanjeev Kumar, A. K. Sudheer, and Arvind Singh. 2020. 'Dinitrogen fixation rates in the Bay of Bengal during summer monsoon', *Environmental Research Communications*, 2: 051007.
- 410 Shetye, Suhas S., Maruthadu Sudhakar, Rahul Mohan, and Babula Jena. 2014. 'Contrasting productivity and redox potential in Arabian Sea and Bay of Bengal', *Journal of Earth Science*, 25: 366-70.
- Shetye, Suhas, Maruthadu Sudhakar, Babula Jena, and Rahul Mohan. 2013. 'Occurrence of Nitrogen Fixing Cyanobacterium Trichodesmium under Elevated CO<sub>2</sub> Conditions in the Western Bay of Bengal', *International Journal of Oceanography*, 2013: 350465.
- 415 Singh, A., N. Gandhi, and R. Ramesh. 2012. 'Contribution of atmospheric nitrogen deposition to new production in the nitrogen limited photic zone of the northern Indian Ocean', *Journal Geophysical Research*, 117.
- Singh, A., and R. Ramesh. 2011. 'Contribution of riverine dissolved inorganic nitrogen flux to new production in the coastal northern Indian Ocean: An assessment', *Int. J. Oceanogr.*, 2011: 7p.
- Singh, Arvind, Naveen Gandhi, R. Ramesh, and S. Prakash. 2015. 'Role of cyclonic eddy in enhancing primary and new production in the Bay of Bengal', *Journal of Sea Research*, 97: 5-13.
- 420 Singh, Arvind, and R. Ramesh. 2015. 'Environmental controls on new and primary production in the northern Indian Ocean', *Progress in Oceanography*, 131: 138-45.
- Snider, R. G. 1961. 'The Indian Ocean expedition—An international venture', 42: 289-94.
- Subha Anand, S., R. Rengarajan, V. V. S. S. Sarma, A. K. Sudheer, R. Bhushan, and S. K. Singh. 2017. 'Spatial variability of upper ocean POC export in the Bay of Bengal and the Indian Ocean determined using particle-reactive 234Th', 122: 3753-70.
- 425 Subramanian, V. 1993. 'Sediment load of Indian rivers', *Curr. Sci.*, 64: 928–30.
- Thushara, V., P. N. M. Vinayachandran, A. J. Matthews, B. G. M. Webber, and B. Y. Queste. 2019. 'Vertical distribution of chlorophyll in dynamically distinct regions of the southern Bay of Bengal', *Biogeosciences*, 16: 1447-68.
- Turk-Kubo, K. A., M. Karamchandani, D. G. Capone, and J. P. Zehr. 2014. 'The paradox of marine heterotrophic nitrogen fixation: abundances of heterotrophic diazotrophs do not account for nitrogen fixation rates in the Eastern Tropical South Pacific',
- 430 *Environ Microbiol*, 16: 3095–114.
- Vaulot, Daniel, and Frédéric J. Deep Sea Research Part A. Oceanographic Research Papers Partensky. 1992. 'Cell cycle distributions of prochlorophytes in the north western Mediterranean Sea', 39: 727-42.
- Vidya, P. J., and S. Prasanna Kumar. 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: 5760-71.
- 435 Vimal Kumar, KG, KJ Jayalakshmi, R. Sajeev, and GVM Gupta. 2016. 'Role of Mesoscale Eddies in the Distribution Pattern of Zooplankton Standing Stock of Western Bay of Bengal During Spring Transition', *J Mar Biol Oceanogr*, 5.
- Wu, Chao, Jinjun Kan, Haijiao Liu, Laxman Pujari, Congcong Guo, Xingzhou Wang, and Jun Sun. 2019. 'Heterotrophic Bacteria Dominate the Diazotrophic Community in the Eastern Indian Ocean (EIO) during Pre-Southwest Monsoon', *Microbial Ecology*, 78: 804–19.
- 440 Yuqiu, Wei, Zhao Xiangwei, Yuying Zhao, danyue huang, and Jun Sun. 2020. 'Biogeographic variations of picophytoplankton in three contrasting seas: the Bay of Bengal, South China Sea and Western Pacific Ocean', *Aquatic Microbial Ecology*, 84.

**Table 1: Historical record of water column integrated chlorophyll a concentration, surface chlorophyll a concentration, and primary production**

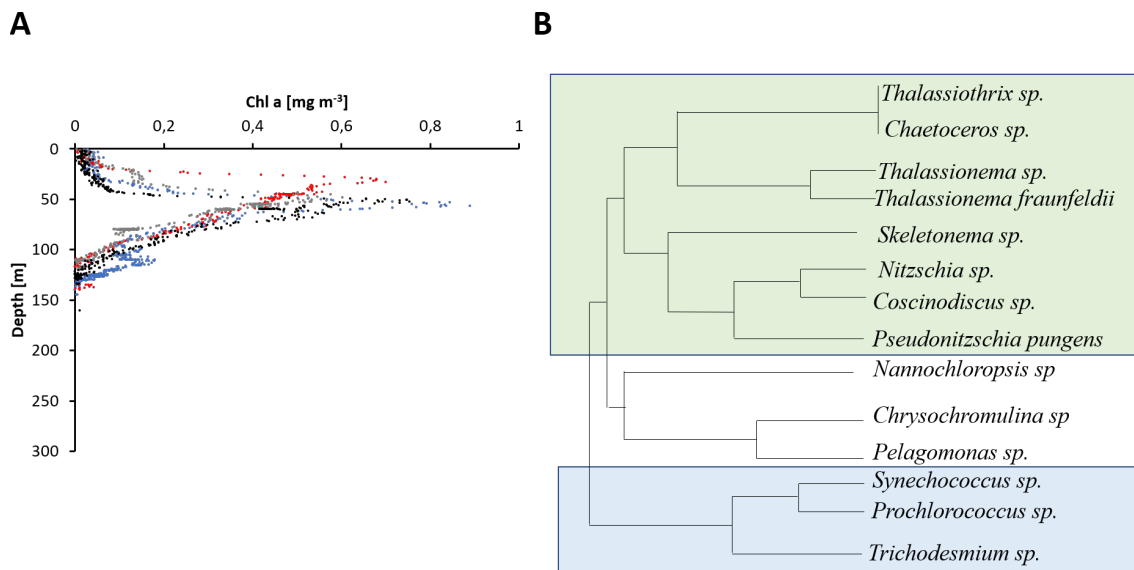
Year	Month	Season	water column integrated Chl a [ $\text{mg m}^{-2}$ ]	Surface Chl a [ $\text{mg m}^{-3}$ ]	Primary production [ $\text{mg C m}^{-2} \text{d}^{-1}$ ]	Reference
1951					0.1 - 2.16	Galathea and Anton Brunn expedition, Steemann Nielsen and Jensen, 1957
1956					70 to 3600	R.V. Vityaz in 1956-60
1961					190	Nair 1970
1976		summer monsoon	8.63 - 28.45	0.084 - 1.67	129.99 - 329.49	Rhadakrishna et al 1978
1977		summer monsoon	2.11 - 33.72	0.03 - 1.04		Devassy et al 1983
1978	Aug	summer monsoon	1.28 - 33.72 (up to 50)	0.01 - 1.01	180 - 2200	Bhattahiri et al. 1980
1996	May/ June	summer monsoon		0.01 - 0.2		Murty et al 2000
1996	April/ May	spring intermonsoon	up to 53		4.5	Gomes et al 2000
1996		summer monsoon	up to 92		0.3	Gomes et al 2000
2000	July / Aug	summer monsoon			coastal: 350 $\pm$ 225 oceanic: 251 $\pm$ 177	Madhu et al., 2006
2000	Nov/ Dec	winter monsoon		9.0 - 15	87 - 187	Balachandran et al 2008
2000	Dec	winter monsoon			coastal: 252 $\pm$ 210 oceanic: 231 $\pm$ 150	Madhu et al., 2006
2001	Nov/ Dec	winter monsoon	coastal: 7 - 23 oceanic: 8 - 18	coastal: 0.06 - 0.16 oceanic: 0.06 - 0.28	coastal: 253 - 566 oceanic: 99- 423	Gauns et al., 2005 Madhupratap et al. 2003
2001	July/ Aug	summer monsoon	coastal: 12-19 oceanic: 10 - 11		coastal: 40 - 502 oceanic: 89 - 221	Gauns et al. 2005
2002	April	spring intermonsoon			coastal: 308 $\pm$ 120 oceanic: 303 $\pm$ 95	Madhu et al., 2006
2002	April/ May	spring intermonsoon		0.25 - 0.4		Prasanna Kumar et al., 2010
2002	Sept/ Oct	intermonsoon	coastal: 11 - 19 oceanic: 13 - 16		coastal: 250 - 469 oceanic: 202 - 427	Gauns et al., 2005
2002	Nov/ Dec	winter monsoon	coastal: 9 - 15 oceanic: 9-13		coastal: 115 - 187 oceanic: 87 - 164	Jyothibabu et al., 2004
2003	April/ May	pre-monsoon			154-975 (average coastal: 552, average oceanic: 284)	Kumar et al., 2004
2003	July / Aug	summer monsoon	anticyclonic warm gyre: 1.84 cyclonic eddy: 5.01 upwelling zone: 5.2		anticyclonic warm gyre: negligible cyclonic eddy: 163 upwelling zone: 271	Muraleedharan et al., 2006
2003	Sept	summer monsoon		0.2 - 0.35	89.4 - 220.6	Prasanna Kumar et al., 2010
2003		fall intermonsoon		0.3 - 0.4	184.14 - 512.85	Prasanna Kumar et al., 2010
2003	Sept/Oct	post-monsoon			coastal: 281 oceanic: 364	Kumar et al., 2004
2007	Nov/Dec	pre-/ early winter monsoon			cyclonic eddy: 203-430	Singh et al., 2015
2010		summer			221.41 $\pm$ 4.97	Swati Sucharita Mohanty et al. 2014
2010		winter			186.69 $\pm$ 9.87	Swati Sucharita Mohanty et al. 2014
2010		monsoon			151.25 $\pm$ 2.16	Swati Sucharita Mohanty et al. 2014
2010		post-monsoon			167.87 $\pm$ 3.02	Swati Sucharita Mohanty et al. 2014
2014	Jan	NE monsoon		0.08 - 0.035	1.4 - 9.3	Löscher et al., 2020
2014	March April	intermonsoon			182 - 1261 (average 936 $\pm$ 350)	Anand et al., 2017
2018	March/ April	intermonsoon	34.6 $\pm$ 4	cyclonic eddy 0.35 $\pm$ 0.08 outside eddy 0.22 $\pm$ 0.06	411-920	Sarma, et al., 2019
2018	March/ April	intermonsoon	26.4 $\pm$ 4			Sarma, et al., 2019
2018	March/ April	intermonsoon	23.6 $\pm$ 3	anticyclonic eddy northern region 0.11 $\pm$ 0.06		Sarma, et al., 2019
2018	March/ April	intermonsoon	22.2 $\pm$ 3	anticyclonic eddy southern region 0.10 $\pm$ 0.03		Sarma, et al., 2019
2018	July/Aug	summer monsoon			288-1044	Saxena et al., 2020

## Figures

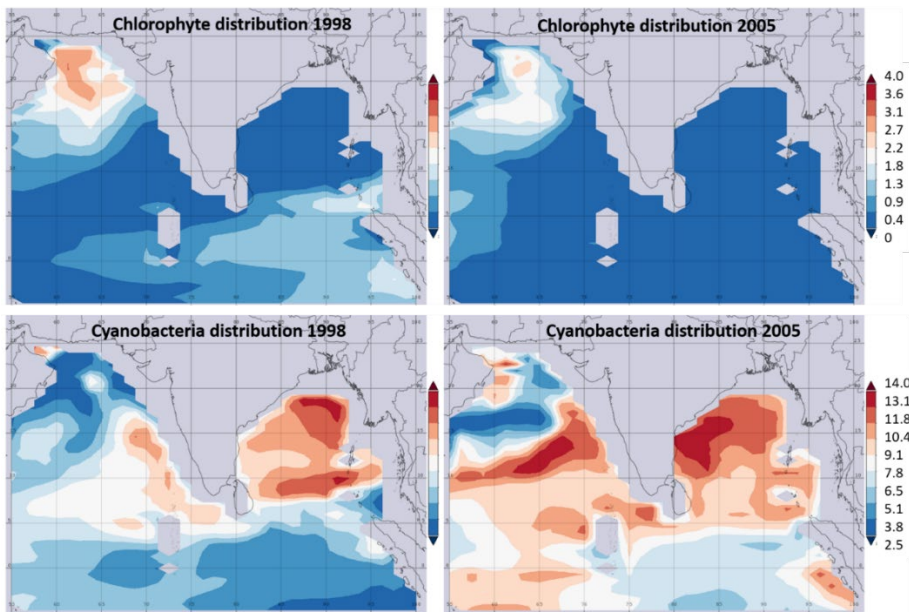


460

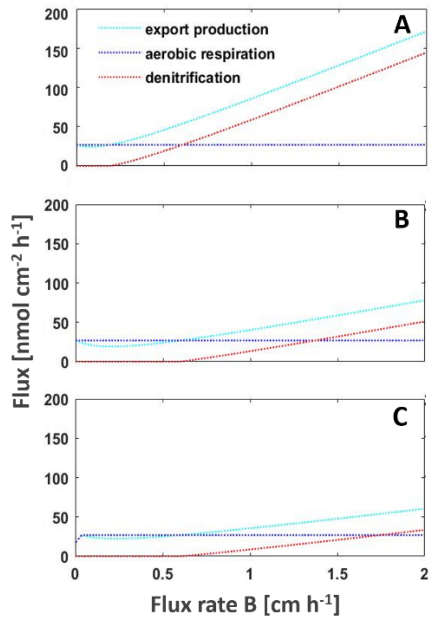
**Figure 1: (A) Trends of total organic carbon (TOC) in the sediment record over the last 18 kyr before present adapted from Contreras-Rosales et al. (2016), and (B) modelled decrease in primary production between 1998 and 2014 modified from Gregg and Rousseaux (2019)**



**465 Figure 2: (A) Vertical profiles of chlorophyll a from four stations in the open ocean region of the BoB taken from Löscher et al. (2020). (B) Schematic depiction of the phylogenetic diversity of primary producers identified in the BoB, green box: diatoms, blue box: cyanobacteria.**

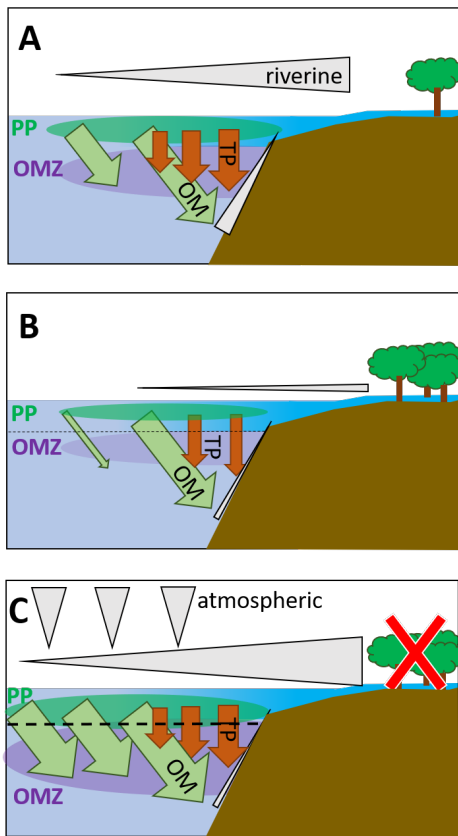


**Figure 3: Satellite imaging- based comparison of chlorophytes (top) and cyanobacteria from 1998 and 2015 in  $\text{mg m}^{-3}$**   
 470 <sup>3</sup> Data obtained from a combination of the Sea-viewing Wide Field of view Sensor (SeaWiFS), the Moderate  
 Resolution Imaging Spectroradiometer (MODIS-Aqua), and the Visible Infrared Imaging Radiometer Suite  
 (VIIRS) satellite product as available from <https://giovanni.gsfc.nasa.gov> have been averaged from Jan to 15Dec  
 1998 and 2005, respectively. The combination of those sensors allows for covering a range of different  
 wavelengths useful to identify different phytoplankton clades. The maps have been generated using the NASA  
 475 Ocean Biogeochemical Model (NOBM, (Gregg and Casey 2007)) using the most recent version of NASA ocean  
 colour data product (R2014). NOBM is designed to represent open ocean areas (water depths > 200 m).



480 **Figure 4: Model of the main processes export production, aerobic respiration and denitrification shaping the intensity of the BoB OMZ to changing nutrient fluxes from either riverine, land, atmospheric inputs or upwelling to increased upwelling, with (A) current nutrient loads (B) decreased nitrate concentrations by 32% as predicted by Gregg et al. (2019) and (C) with both, decreased nitrate concentrations and decreased nutrient fluxes from deeper waters as a result of warming-dependent increased stratification. The model is adapted from Boyle et al. (2013).**





485 **Figure 5: Schematic depiction of fluxes impacting primary production and the oxygen minimum zone in the BoB (A) during the last glacial maximum (modified from Contreras-Rosales et al. (2016)), (B) currently, (C) and in a scenario leading to an anoxic OMZ.** The latter would require higher nutrient fluxes from either the atmosphere, from upwelling or from rivers and land. Fluxes from land may increase e.g. from deforestation, or enhanced rainfalls, however, higher terrigenous particle load would likely accompany increased nutrient loads and therefore, even if coastal primary production

490 would increase, export production would increase via ballasting, too. The effect on the OMZ would then be rather small. Upwelling-dependent nutrient pumping is unlikely to increase due to warming and enhanced stratification but may occur especially in eddy systems, i.e. as eddy pumping. Grey triangles depict nutrient fluxes from land and rivers, from upwelling along the shelf and from the atmosphere, brown arrows depict terrigenous particle fluxes as imported from rivers and leading to ballasting and enhanced organic carbon export, green arrows depict organic material exported from the photic zone primary production (green bubble, PP) into the OMZ (purple bubble). Sizes of triangles, arrows, and bubbles qualitatively

495 indicate proportions.