Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea?

S. Prasanna Kumar, P.M. Muraleedharan, T.G. Prasad[1], M. Gauns, N. Ramaiah, S.N. de Souza, S. Sardesai and M. Madhupratap

National Institute of Oceanography, Dona Paula, Goa-403 004, India
[1]Naval Postgraduate School, Monterey, CA 93943, U.S.A.

Abstract. The Bay of Bengal is traditionally considered to be a less productive basin compared to the Arabian Sea. We explore the reasons for this in the central Bay during summer when both are subjected to strong monsoon forcing. Copious rainfall and river water freshen the upper layers of the Bay by 3-7 psu during summer, and SST was warmer by 1.5-2°C than in the central Arabian Sea. This leads to a strongly stratified surface layer. The weaker winds over the Bay are unable to erode the strongly stratified surface layer, thereby restricting the turbulent wind-driven vertical mixing to a shallow depth of < 20m. This inhibits any possible introduction of nutrients from below, situated close to the mixed layer bottom, into the upper layers. While advection of nutrients rich water into the euphotic zone makes the Arabian Sea highly productive, this process is unlikely in the Bay of Bengal.

1. Introduction

The Bay of Bengal in the eastern part of the north Indian Ocean is a tropical basin. Like its western counterpart, the Arabian Sea, it is land locked in the north and forced by seasonally reversing monsoon winds. Accordingly, the surface circulation of both the basins undergoes seasonal reversal. Despite these striking similarities, the basins show large contrast in its biological productivity (see the chlorophyll data in Figure 1). Arabian Sea is one of the world's most productive regions of the ocean and during summer (June-September) monsoon this is brought about through a range of physical processes. For example, the coastal upwelling along Somalia, Arabia and southern part of the west coast of India turns the coastal waters into a region of high biological productivity. The open ocean upwelling [*Bauer et al*., 1991; *Brock et al.,* 1991], wind-driven mixing [*McCreary et al.,* 1996; *Lee et al*., 2000] and lateral advection [*Young and Kindle, 1994*; *Prasanna Kumar et al*., 2001] makes the open ocean waters of the central Arabian Sea more productive. In contrast, the Bay of Bengal is traditionally considered to be a region of lesser biological productivity and recent measurements using clean techniques for phytoplankton ^{14}C uptake also corroborate this fact (for a review see *Madhupratap et al.*, in press). Although, this has been variedly attributed to the light inhibition due to turbidity and/or cloud cover, narrow shelf etc, the exact physical process is unclear. In this paper we examine the physical processes that makes the Bay of Bengal a less productive region in comparison to the Arabian Sea.

2. Observation and Analysis

In a recent set of measurements in 2001 onboard ORV Sagar Kanya in the central Bay of Bengal, 14 CTD (Conductivity-Temperature-Depth) stations were occupied at 1-degree interval along 88°E from 7°N to 20°N during summer (6 July to 2 August, Figure 1). A Sea-Bird CTD was employed to obtain profiles of temperature and salinity in the upper 1000m. CTD salinity was calibrated against water samples collected simultaneously by a rosette sampler fitted with 30-L Go-Flo bottles and analyzed with a Guildline 8400 Autosal. Water samples from various depths were analyzed for nitrate and silicate with a SKALAR auto-analyzer. Apart from the high-resolution physical and chemical measurements, five biological stations were also occupied (Figure 1), each for over 24-h for measuring chlorophyll *a* and primary production (for measurement details see *Madhupratap et al*., in press). We compare these measurements with similar data collected in the central Arabian Sea along 64^oE from 13^o to 19^oN (Figure 1) during summer (3-25 August) 1996, under a Indian Joint Global Ocean Flux Study (JGOFS) cruise (see *Prasanna Kumar et al*., [2001] for details). Surface meteorological parameters were also collected along both tracks and all the above measurements followed the JGOFS protocol [*UNESCO*, 1994]. The rationale behind comparing summer data of two different ~~years,~~ years is based on the fact that though semi-annual switching of the winds may have inter-annual variability, on the whole, the summer monsoon is a highly regular phenomenon [*Fieux and Stommel*, 1977].

3. Results and Discussion

The surface chlorophyll *a* in the central Bay of Bengal weakly increased from 0.06 mg/m^3 in the south to 0.28 mg/m^3 in the north (Figure 2a). In the Arabian Sea, the variation was from 0.32 to 1.12 mg/m^3 indicating that it was 4-5 times higher compared to the Bay of Bengal. Integrated chlorophyll *a* (up to 120m) apart from being low varied only nominally form 9 to 11 mg/m^2 in the Bay of Bengal, but showed large variations, 26 to 60 mg/m^2, in the Arabian Sea (Figure 2b). This again was 3-5 times higher in the Arabian Sea in comparison to the Bay of Bengal. Integrated primary productivity (up to 120m) varied from 89 to 221 mg C m^{-2} d^{-1} in the Bay of Bengal, while that in the Arabian Sea varied from 770 to 1782 mg C m^{-2} d^{-1} (Figure 2c), an 8 fold increase in comparison to the Bay of Bengal. An interesting observation was the presence of a subsurface chlorophyll maximum (SCM) in the Bay of Bengal between 20 and 60m, which was not discernible in the Arabian Sea during the same season (vertical profile not presented). The chlorophyll *a* in the SCM varied from 0.14 mg/m^3 to 0.28 mg/m^3. Thus, the overall low chlorophyll *a* concentration and PP in the Bay of Bengal is intriguing considering the fact that both the basins come under the southwest monsoon regime. We begin by examining the factors that regulate the biological production in the tropical oceans. In particular, we identify the contrasting physical conditions between these two basins that are responsible for the low productivity in the Bay of Bengal.

Primary production, in general, is regulated by the availability of sunlight and nutrients. In tropical basins where sunlight is not usually a limiting factor, except during overcast conditions, the biological production is limited by the availability of nutrients and hence it is important to analyze the nutrient fields. In the Bay of Bengal, the upper 30m of the water column was depleted of nitrate (Figure 3a). The nitracline, in general, was situated between 50 and 100m depth. Silicate distributions were similar to that of nitrate, except for a high concentration of more than 2 μM in the upper waters in the north (Figure 3b). The higher silicate in the surface indicates that it must have originated from a source in the north. The vertical salinity distribution showed a strong gradient in the upper 30m, ~1.5 psu in the south and ~7 psu north of 17^oN, with considerable freshening towards the north (Figure 3c). It is to be noted that the salt balance in these upper layers is maintained through estuarine entrainment mechanism. Between 30 and 100m, the salinity changes with depth were gradual, and below 100m waters were homogeneous in salinity. Contrary to this, the temperature distribution showed thermally homogeneous waters in the upper

30m except where a cold core eddy (inferred from the upward sloping isopleths in both temperature and nutrients) introduced temperature gradients (Figure 3d). The thermocline, situated between 50 to 200m, extended well below the nitracline. The inferences from these are (1) the upper 30m layer, though remain isothermal, is highly stratified due to excessive freshening, and (2) is devoid of nutrients, except in the north. The freshening is in part due to oceanic precipitation (~ 2 m per year, *Prasad*, [1997]) as well as by the run off from peninsular rivers such as Brahmaputra, Ganges, Irrawady, Godavari, Mahanadi, Krishna, and Kaveri (1.625 x 10^{-12} m^3 yr^{-1}, *Subramanian*, [1993]).

It is important to examine various mechanisms by which nutrients could be supplied to the upper waters of the open ocean. River run off could transport nutrients into the open ocean. The high silicate content in the surface waters in the north lends support to this. However, the nitrate depleted upper layers, even in the northern region, coupled with low chlorophyll and PP suggests that there is no significant river input of nitrate to the open ocean which could support an enhanced biological production. It shows that the nitrate transported by the rivers is biologically consumed within the estuarine and coastal region. Upwelling could be another mechanism by which nutrients from the nitracline could be made available to the upper layers and advected laterally out of the upwelling region. This appears to be one of the important process by which nutrients-rich upwelled water from the coasts of Somalia and Arabia is being transported to the central Arabian Sea and contributes to the biological productivity [*Prasanna Kumar et al.*, 2001]. In the Bay of Bengal, upwelling reported so far, is confined very close to the coast (mostly within 40 km) along the southwestern boundary during summer and seems to be episodic [*Murty and Varadachari*, 1968; *Shetye et al.*, 1991]. One of the reasons for the lack of intense upwelling along the western boundary of the Bay of Bengal during summer, in spite of the upwelling-favorable southwesterly winds, is the equator-ward flow of the freshwater plume which could overwhelm the offshore Ekman transport [*Gopalakrishna and Sastry*, 1985]. Wind-stirring may be yet another mechanism by which nutrients from the upper thermocline could be transported vertically upward into the euphotic zone by convective entrainment, as it happens in the Arabian Sea [*Lee et al.,* 2000]. The fact that the upper 30m layer of the water column is nutrient-depleted and very low in PP suggests that wind-driven mixing may not be a dominant mechanism. The reason appears to be the upper ocean stratification.

The question then is how strong is the stratification and can the strong monsoon winds erode the stratification? To address this, we analyzed the upper ocean temperature, salinity and wind data along with the thickness of the mixed layer of both the basins. The sea surface temperature (SST) in the Bay of Bengal was higher than that in the Arabian Sea (at least 1.5-2^{o}C, Figure 4a) and is consistent with Levitus climatology [*Conkright et al*., 1994], indicating a possibility of stronger stratification in the Bay of Bengal. The sea surface salinity (SSS) in the Bay was about 3 psu fresher than the average Arabian Sea value of 36.2 psu (Figure 4b). In fact north of 17^{o}N, the SSS showed a drastic drop in the Bay of Bengal by an additional 5.5 psu. In terms of density (sigma-t), the Bay of Bengal water was on an average 4 kg m^{-3} lighter than its western counter part and north of 17^{o}N, it become~~s~~ further lighter by an additional 2 kg m^{-3} providing necessary condition for stronger stratification in the upper Bay of Bengal. A comparison of the measured wind speeds showed that they were almost of the same magnitudes in both the basins (Figure 4c). The mixed layer depth (MLD), defined as the depth at which *in situ* sigma-t exceeds the surface value by 0.2, however, showed large difference between the two basins (Figure 4d). Though the trend were similar, with northward shoaling of MLD in both the basins, in the Bay of Bengal MLD was on an average 60m shallower than that of the Arabian Sea. The northward shoaling of MLD in both the basins, however, were driven by different mechanisms – in the Arabian Sea, the cyclonic wind-stress curl and in the Bay of Bengal, the freshening from oceanic precipitation and river run-off.

In order to determine the degree of stratification, we calculated the static stability parameter (*E*, *Pond and Pickard*, [1983]) for both basins. Profiles of *E* showed large stability values in the upper 30m in the Bay of Bengal in the north (Figure 5), which was about 3-4 orders of magnitude higher than that in the Arabian Sea. Profiles of *E* were similar with the stability maxima situated in the upper 60m (not presented), but their magnitude showed a decrease towards south (for example, 50-100 x 10^{-5} m^{-1} at 13^{o}N). The surface buoyancy in the Bay of Bengal must be further strengthened because of the stronger influence of heat flux, suggested by *Prasad* [1997], in addition to fresh water flux mentioned above. Thus, the increased surface buoyancy flux due to warmer and fresher waters in the upper layers of the Bay of Bengal inhibits any possible introduction of nutrients situated close to the mixed layer bottom. Though the summer monsoon winds remain similar, these winds in the Arabian Sea could introduce nutrients to the euphotic zone, by a variety of processes such as wind-driven mixing, upward Ekman pumping and lateral advection of upwelled waters from the coastal regions. However, similar winds were insufficient to break the strong stratification through wind-driven mixing in the Bay of Bengal. Coupled to this, the nonexistence of strong coastal upwelling, which could otherwise supply nutrients laterally from the coastal region to the open ocean, further eliminates any possibility of nutrient input to the upper ocean. The observed SCM is the manifestation of oligotrophic upper layers overlying a nutrient rich subsurface congenial for biological fertilization in presence of adequate sunlight. A similar situation is encountered in the Arabian Sea during spring intermonsoon (March-April) when the upper waters are warm, stratified and oligotrophic and chlorophyll profiles show the presence of SCM [*Bhattathiri et al.*, 1996].

The physical processes that control the primary production in the Bay of Bengal is also investigated in a level 2 one-dimensional turbulent closure model. The model equations and forcing fields are discussed in a recent paper by *Prasad and Ikeda* [2002]. Briefly, the model is forced with 12-hourly winds from the European Center for Medium Weather Forecast (ECMWF) and surface fluxes from the Southampton Oceanography Climatology (SOC). The model vertical resolution is 1m with 200 levels. Model integration is started during April (using Levitus temperature and salinity) and integrated forward in time for a period of 14 months. In Figure 6, we show the time-latitude plots of MLD and SST along two meridional sections (64.5^{o}E and 88.5^{o}E). MLD is computed following the same method described above. Clearly, the bi-modal variability of the MLD and SST on both basins are simulated reasonably well and comparable with the observations. During summer, the wind-driven turbulent mixing is considerably strong in the Arabian Sea, leading to deep MLD (80m) and cool SST (28^{o}C). In the Bay of Bengal, however, the MLD remains shallow (~30m) and SST (30^{o}C) is high. The shallow MLD in the Bay of Bengal indicates two possibility (a) weak winds and/or (b) stable strong stratification. An examination of the basin-wide wind revealed that in the Arabian Sea during June, July and August wind is about 3-4 m/s stronger than that in the Bay of

Bengal and is consistent with COADS climatology [*Woodruff et al.,* 1987]. The increased near surface stratification due to warm SST and large freshwater flux together with less stronger winds in comparison to the Arabian Sea inhibits the turbulent vertical mixing to a shallow depth in the Bay of Bengal. The northward decreasing trend in MLD on both the basins agree with that in the observations.

In summary, the *in situ* measurements clearly indicated that the upper layers of the open ocean waters were devoid of nitrate, though some quantities of silicate was brought in by the river run-off. The low biological production stems primarily from the lack of availability of nutrients in the upper layers arising from strong stratification and weaker winds in comparison to the Arabian Sea, which inhibits/curtails vertical mixing. This points to the fact that other factors such as cloud cover, turbidity etc. as speculated earlier could play only a secondary role in regulating the biological production in the Bay of Bengal, in the absence of adequate nutrients in the surface layers.

Acknowledgments. Authors thank Ajoy Kumar for the SeaWiFS data, Govindan Nampoothiri for help in CTD data collection, and Mahale and Shayam for preparing the diagrams. This work was supported by the Department of Ocean Development under the program Bay of Bengal Process Studies (BOBPS). This is NIO contribution no.3793.

References

Bauer, S., G. Hitchcock, and D. Olson, Influence of monsoonally-forced Ekman dynamics upon the surface layer depth and plankton biomass distribution in the Arabian Sea, *Deep-Sea Res., 38,* 531-553, 1991.

Bhattathiri, P.M.A., A. Pant, S. Sawant, M. Gauns, S.G.P. Matondkar, and R. Mohanraju, Phytoplankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994-1995, *Curr. Sci*., 71, 857-862, 1996.

Brock, J., McClain,C., Luther, M., and W. Hay, The phytoplankton bloom in the northwestern Arabian Sea during the southwest monsoon of 1979, *J. Geophys. Res., 96*, 20623-20642, 1991.

Conkright, M.E., S. Levitus, T.P. Boyer, D.M. Bartolacci and M.E. Luther, Atlas of the Northern Indian Ocean, University of South Florida, St. Petersburg, FL, 150pp., 1994.

Fieux, M. and H. Stommel, Onset of the southwest monsoon over the Arabian Sea from marine reports of surface winds: structure and variability, *Mon. Weather Rev., 105*, 2001-2025, 1977.

Lee, C., B. Jones, K. Brink, and A. Fischer, The upper-ocean response to monsoonal forcing in the Arabian Sea: seasonal and spatial variability, *Deep-Sea Res. II, 47*, 1177-1226, 2000.

Madhupratap, M., M. Gauns, N. Ramaiah, S. Prasanna Kumar, P.M. Muraleedharan, S.N. de Souza, S. Sardesai, and Usha Muraleedharan, Biogeochemistryof the Bay of Bengal: Physical, chemical and primary Productivity characteristics of the central and western Bay of Bengal during summer monsoon, *Deep-Sea Res. II*, in press.

McCreary, J.P., K.E. Kohler, R.R. Hood and D.B. Olson, A four-component ecosystem model of biological activity in the Arabian Sea. *Prog. Oceanogr., 37*, 193-240, 1996.

Murty, C.S., and V.V.R. Varadachari, Upwelling along the east coast of India, *Bull. Nat. Inst. Sci. India*, *36*, 80-86, 1968.

Pond, S., and G.L. Pickard, Introductory dynamical oceanography, Pergamon Press, New York, 241 pp.

Prasad, T.G., Annual and seasonal mean buoyancy fluxes for the tropical Indian Ocean, *Curr. Sci., 73*, 667-674, 1997.

Prasad, T. G., and M. Ikeda, The wintertime water mass formation in the northern Arabian Sea: A model study, *J. Phys. Oceanogr*., *32,* 1028-1040, 2002.

Prasanna Kumar, S., M. Madhupratap, M. Dileep Kumar, P.M. Muraleedharan, S. N. de Souza, M. Gauns and V.V.S.S. Sarma, High biological productivity in the central Arabian Sea during summer monsoon driven by Ekman pumping and lateral advection, *Curr. Sci., 81*, 1633-1638, 2001.

Shetye, S.R., S.S.C. Shenoi, A.D. Gouveia, G.S. Michael, D. Sundar and G. Nampoothiri, Wind-driven coastal upwelling along the western boundary of theBay of Bengal during the southwest monsoon, *Cont. Shelf Res*., *11*, 1397-1408, 1991.

Subramanian, V., Sediment load of Indian Rivers, *Curr. Sci., 64*, 928-930, 1993.

UNESCO, Protocols for the Joint Global Ocean Flux Study (JGOFS) Core Measurements, SCOR Manual and guides, Paris, 29, 170pp., 1994.

Woodruff, S.D., R.J. Slutz, R.L. Jenne, and P.M. Steurer, A comprehensive ocean-atmosphere data set, *Bull. Am. Meteorol. Soc., 68*, 1239-1250, 1987.

Figure Caption

Figure 1 Monthly mean distribution of chlorophyll obtained from SeaWiFS for July 2001. The filled circle represents the location of CTD stations along 64^{o}E in the Arabian Sea and along 88^{o}E in the Bay of Bengal respectively, while the open circle denotes the location of biological measurements. The Bay of Bengal measurements were taken during July-August 2001, while those in the Arabian Sea were during August 1996 (except at 11^{o}N which was in July 1995). The black patches indicate regions where data is contaminated by cloud.

Figure 2 Latitudinal variation of (a) surface chlorophyll *a*, integrated (b) chlorophyll *a* and (c) Primary productivity in the Bay of Bengal (solid line) during July-August 2001 and in the Arabian Sea (broken line) during August 1996 (except at 11^{o}N which was in July 1995).

Figure 3 Vertical distribution of (a) nitrate (μM) (b) silicate (μM) (c) salinity (psu) and (d) temperature (^{o}C) in the upper 200m along 88^{o}E in the Bay of Bengal during July-August 2001. The dark circles in (a) and (b) denote the location of the samples.

Figure 4 Latitudinal distribution of (a) sea surface temperature (SST, ^{o}C), (b) sea surface salinity (SSS, psu), (c) wind speed (m/s), and (d) mixed layer depth (MLD, m) in the Bay of Bengal (solid line) and the Arabian Sea (broken line).

Figure 5 Profiles of upper ocean static stability parameter (E, m^{-1}) at 19^{o}N in the Bay of Bengal (solid line) and the Arabian Sea (broken line).

Figure 6 Time-latitude plots of MLD (top panel) and SST (bottom panel) from the model along 64.5^{o}E and 88.5^{o}E. Contour interval for MLD (SST) is 10m (0.5^{o}C). Shading is provided for the MLD (SST) > 60m (<27.5^{o}C). Left panels are for the Arabian Sea while those in the right are for the Bay of Bengal.

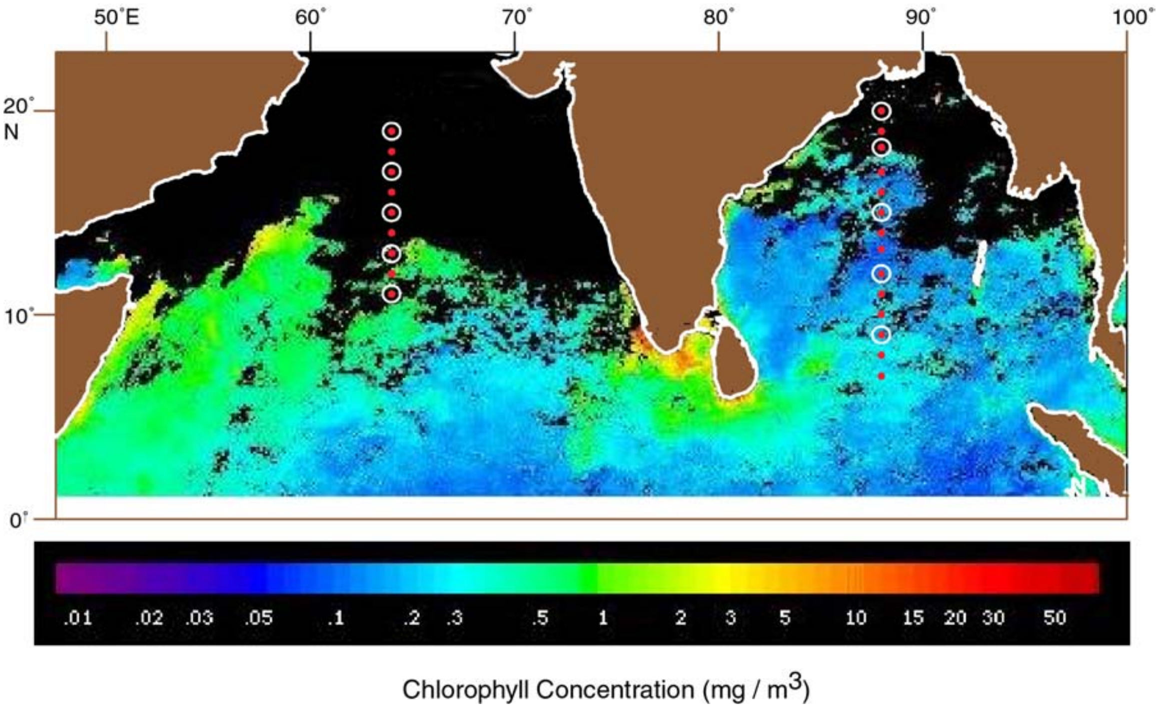

Figure 1 Monthly mean distribution of chlorophyll obtained from SeaWiFS for July 2001. The filled circle represents the location of CTD stations along 64^{o}E in the Arabian Sea and along 88^{o}E in the Bay of Bengal respectively, while the open circle denotes the location of biological measurements. The Bay of Bengal measurements were taken during July-August 2001, while those in the Arabian Sea were during August 1996 (except at 11^{o}N which was in July 1995). The black patches indicate regions where data is contaminated by cloud.

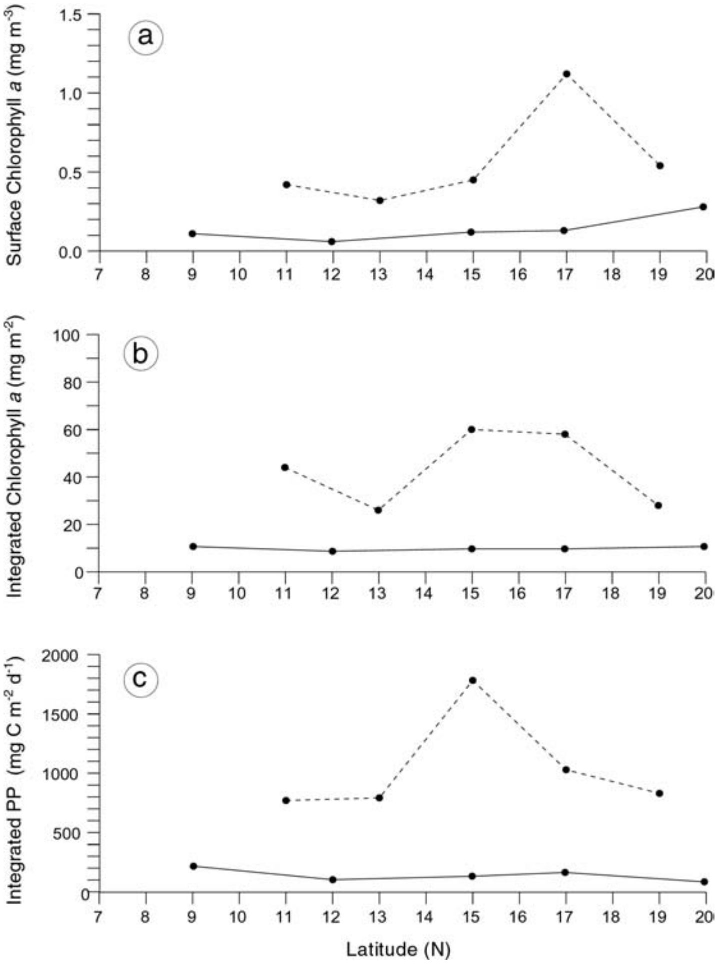

Figure 2 Latitudinal variation of (a) surface chlorophyll *a*, integrated (b) chlorophyll *a* and (c) Primary productivity in the Bay of Bengal (solid line) during July-August 2001 and in the Arabian Sea (broken line) during August 1996 (except at 11^{o}N which was in July 1995).

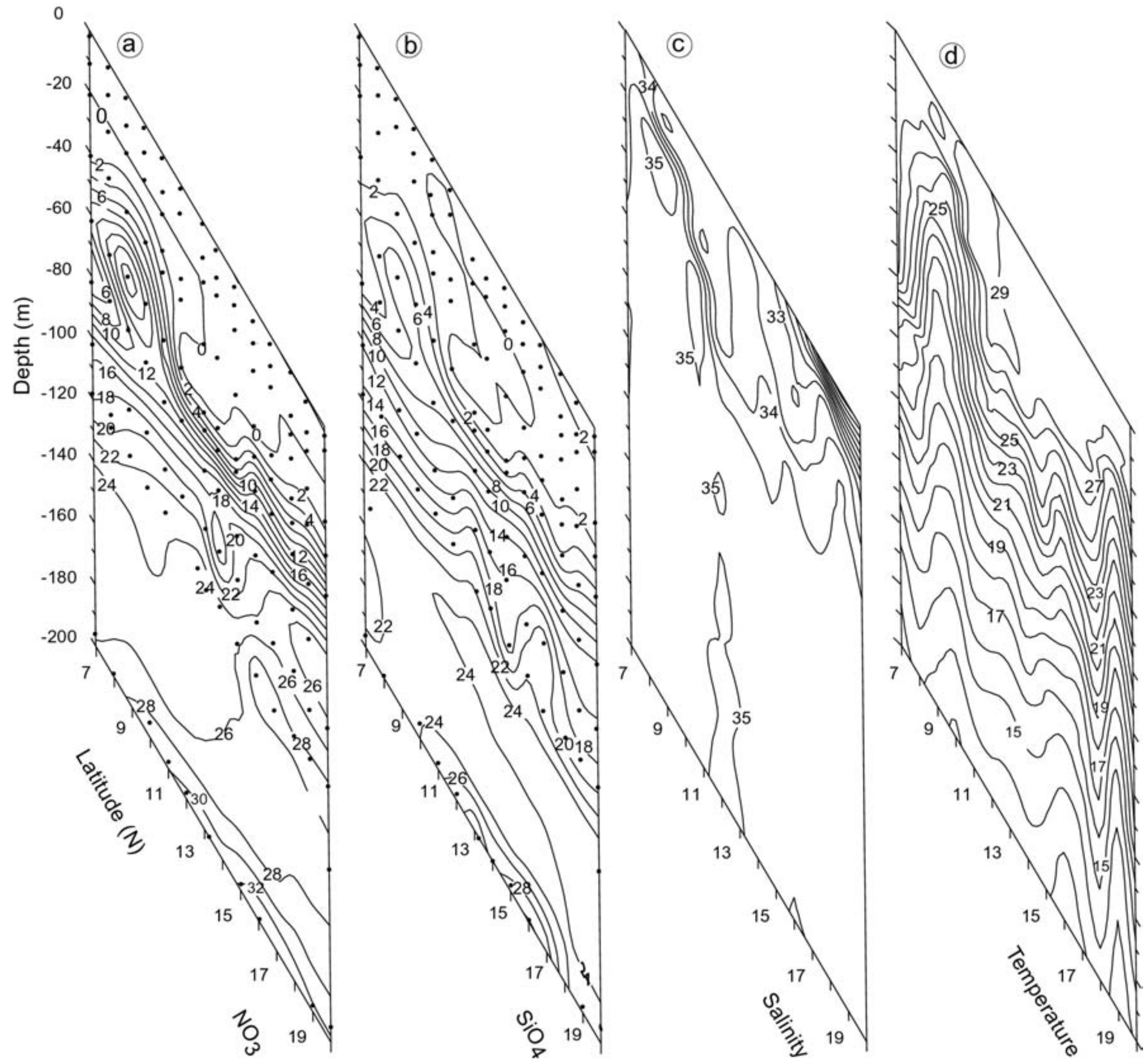

Fig. 3

Figure 3 Vertical distribution of (a) nitrate (µM) (b) silicate (µM) (c) salinity (psu) and (d) temperature (^oC) in the upper 200m along 88^oE in the Bay of Bengal during July-August 2001. The dark circles in (a) and (b) denote the location of the samples.

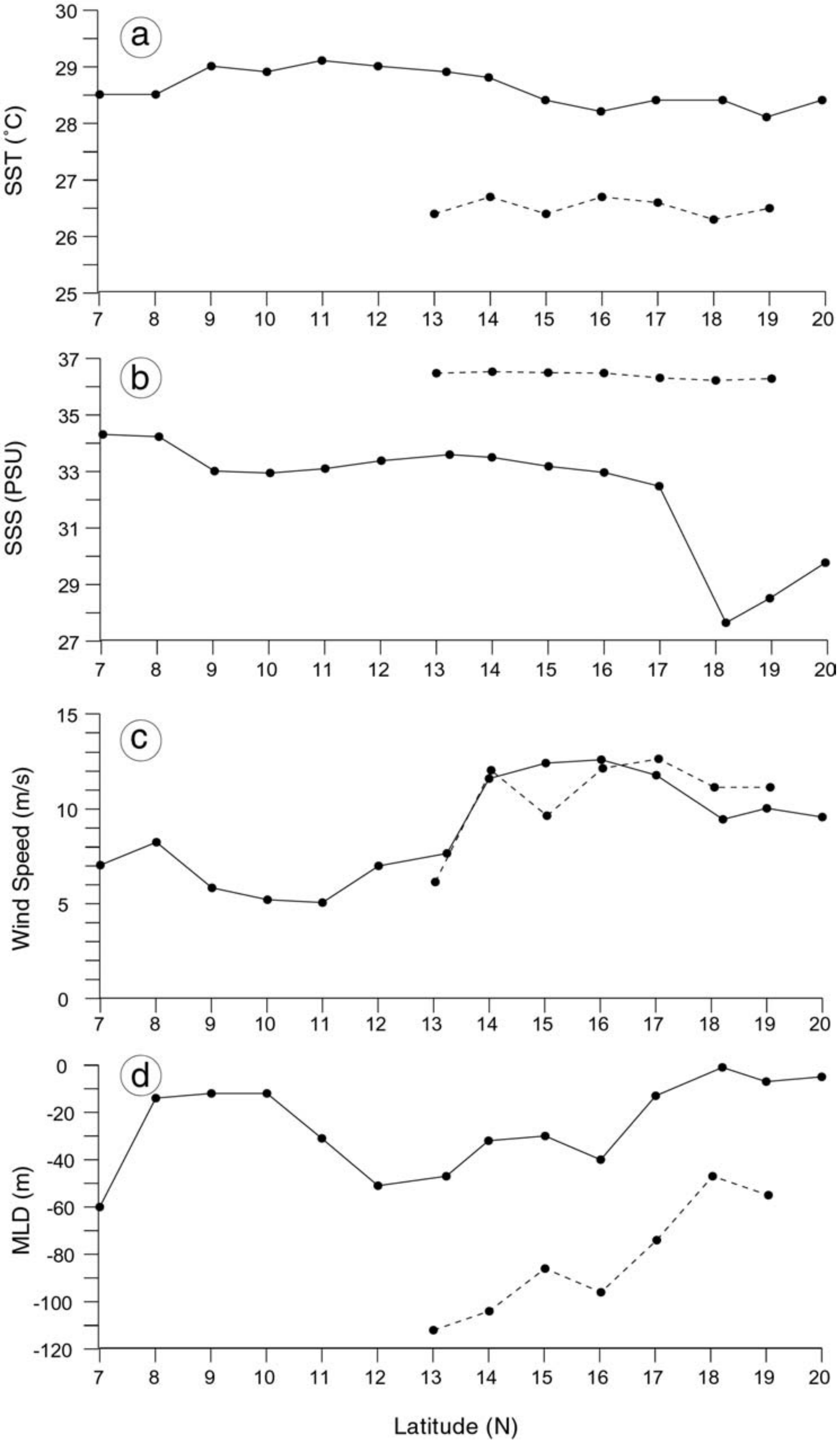

Figure 4 Latitudinal distribution of (a) sea surface temperature (SST, ^{o}C), (b) sea surface salinity (SSS, psu), (c) wind speed (m/s), and (d) mixed layer depth (MLD, m) in the Bay of Bengal (solid line) and the Arabian Sea (broken line).

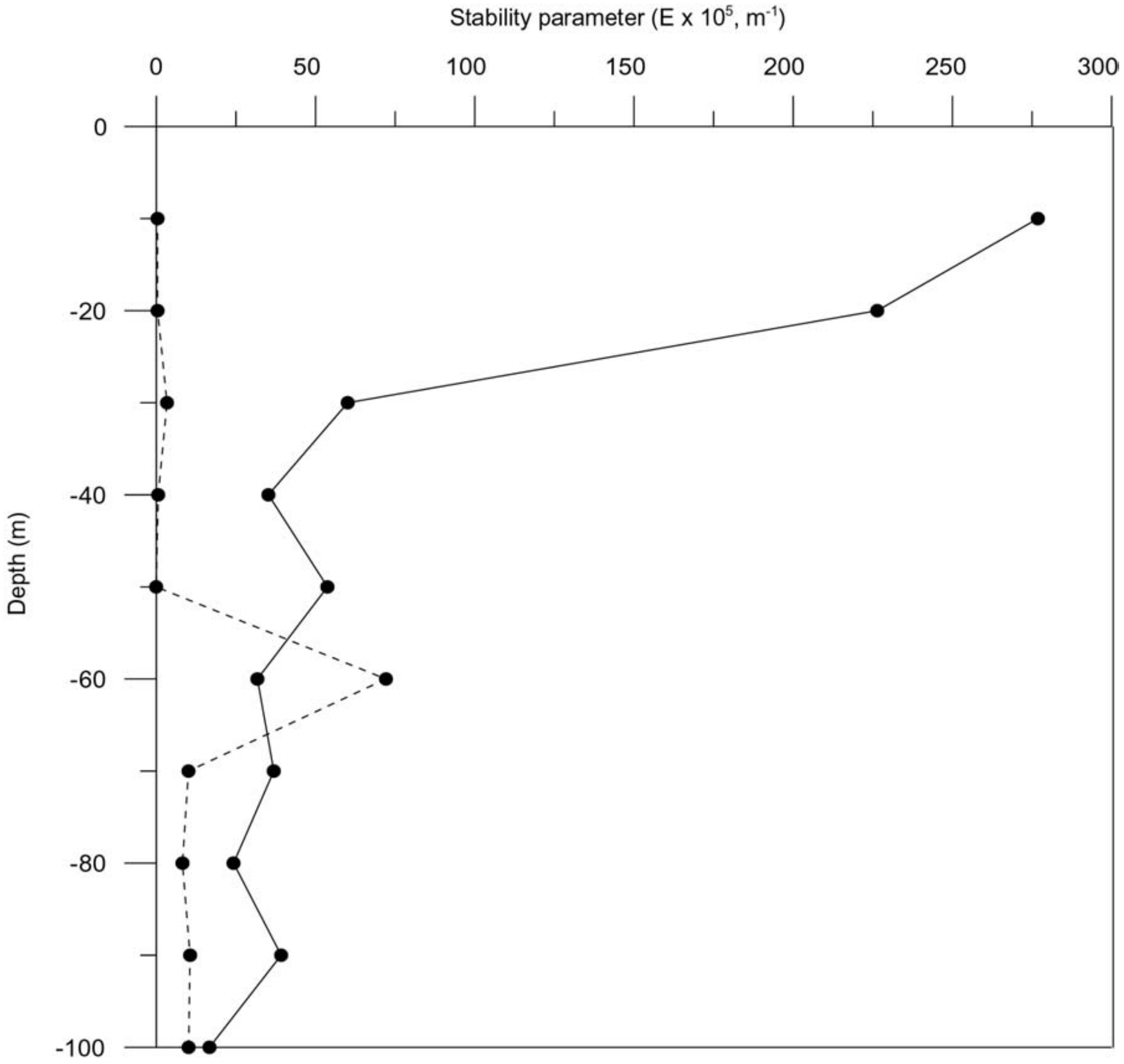

Figure 5 Profiles of upper ocean static stability parameter (E, m^{-1}) at 19^{o}N in the Bay of Bengal (solid line) and the Arabian Sea (broken line).

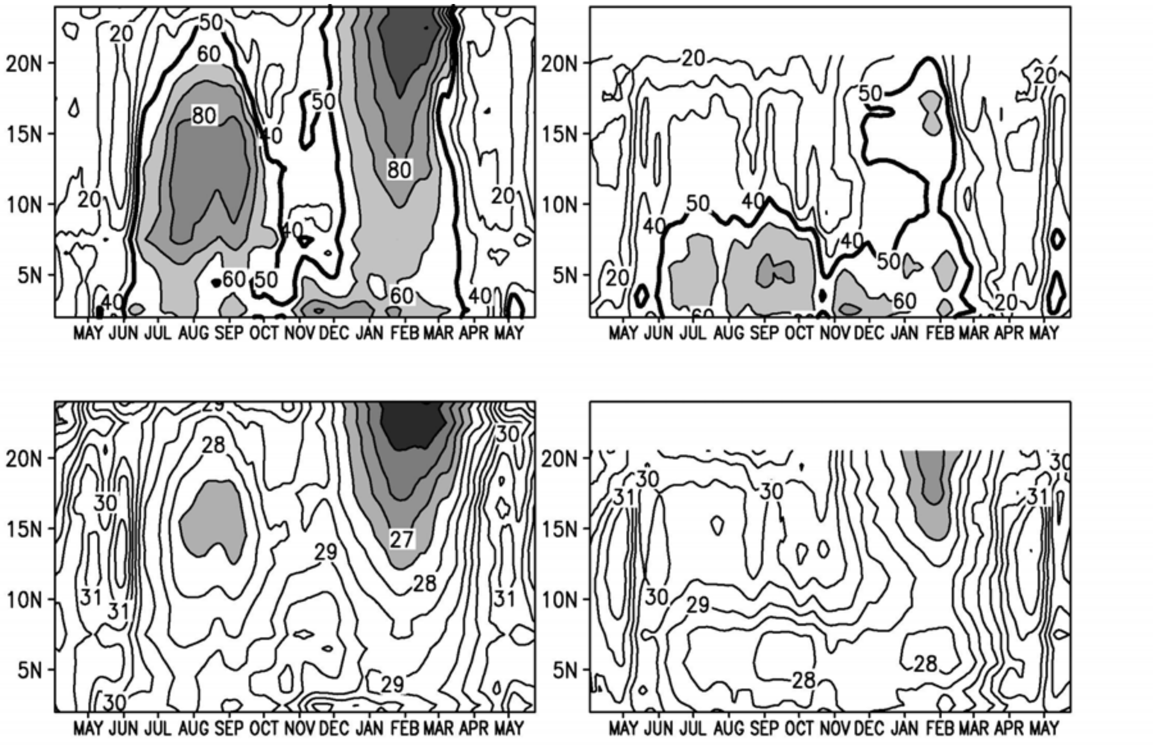

Fig. 6

Figure 6 Time-latitude plots of MLD (top panel) and SST (bottom panel) from the model along 64.5°E and 88.5°E. Contour interval for MLD (SST) is 10m (0.5°C). Shading is provided for the MLD (SST) > 60m (<27.5°C). Left panels are for the Arabian Sea while those in the right are for the Bay of Bengal.