

# **Atmospheric deposition and surface stratification as controls of contrasting chlorophyll abundance in the North Indian Ocean**

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**Abstract.** Intense upwelling during summer and convection in winter are believed to drive higher biological productivity in the Arabian Sea than in the Bay of Bengal. Although the Arabian Sea receives substantial atmospheric deposition of dust aerosols, its role in biological activity is unknown. We have analyzed chlorophyll-a (SeaWiFS), absorbing aerosol index (TOMS), surface winds (NCEP), and modeled dust deposition and SST (OI) data during two distinct seasons June–August (JJA, summer months) and October–December (OND, winter months) for the period 1997–2004. Climatologies of physicochemical properties have been developed from World Ocean Atlas 2001 (WOA01). Our results suggest that despite the strong vertical supply of nutrients in the western and central Arabian Sea regions, maximal chlorophyll-a was limited to the former region in both JJA and OND periods, suggesting the importance of atmospherically transported substances in determining chlorophyll abundance in the North Indian Ocean. Time-averages (1997-2004) revealed chlorophyll abundances in northwestern regions are larger than in other regions of the respective basins. The NW regions of the Arabian Sea and the Bay of Bengal have exhibited contrasting chlorophyll distribution patterns during El Niño years (1997-98 and 2002-03; positive SST anomalies); decreased and increased chlorophyll contents in respective regions. Following the passage of tropical cyclones, SeaWiFS records depicted large areas in the Arabian Sea to experience intensified chlorophyll production with strong wind speeds of 55-65 knots whereas its enhanced production occurred only in small patches even under the influence of Orissa Super Cyclone of October 1999 (wind speed up to 140 knots) due to strong stratification.

## 1. Introduction

The Arabian Sea and the Bay of Bengal are similar in their location (tropical), physical geography (semi-enclosed, closed in the north by Asia) and in experiencing solar insolation and changing monsoon winds. The southwest monsoon winds produce major differences between the two basins: the Arabian Sea experiences stronger upwelling when rapid surface cooling occurs due to entrainment forced by strong winds [Findlater, 1969] whereas excess precipitation over evaporation in the Bay of Bengal, together with large river runoff [Subrahmanian, 1993], leads to strong surface stratification. These differences are believed to be responsible for contrasting chemical and biological conditions in the Arabian Sea and Bay of Bengal [Kumar et al., 1995]. Weaker winds over the Bay facilitate shallow mixed layer depths (MLD) due to poor vertical mixing [Shenoi et al., 2002] and therefore, this basin is biologically less productive compared to the Arabian Sea [Prasanna Kumar et al., 2002]. The shallower MLD results in lower supply of nutrients from deep waters to the surface mixed layer, where most of the biological activity occurs due to the available Photosynthetically Active Radiation (PAR). The amount of PAR decreases exponentially with depth wherein the exponent is determined by the transparency of water [Behrenfeld and Falkowski, 1997]. The physical and biological processes control the biogeochemical properties of seawater. The North Indian Ocean, particularly the Arabian Sea, is one of the most oxygen-depleted regions among the world oceans and acts as a source of climatologically important gases, such as nitrous oxide (N<sub>2</sub>O) [Naqvi et al., 2006, and references therein]. On the other hand, the Bay of Bengal is a weaker emitter of N<sub>2</sub>O and carbon dioxide (CO<sub>2</sub>) [Kumar et al., 1995 for a review].

The biological productivity or photosynthesis is controlled, apart from PAR and nutrients (nitrate, phosphate, silicate etc.), by the availability of other essential micro-constituent nutrients such as iron. Most studies on the North Indian Ocean productivity and chlorophyll have focused on nutrient inputs to the mixed layer from deep [*Prasanna Kumar et al.*, 2002; *Goes et al.*, 2005]. Nitrate deposition over the eastern Arabian Sea has been noted to be far lower than supplied by vertical mixing [*Sarin et al.*, 1999]. Only recently the significance of atmospheric inputs of nutrients and micro-nutrients to the surface ocean is increasingly being emphasized [e.g. *Jickells et al.*, 2005]. *Patra et al.* [2005] have ascribed the northern Africa and the Gulf as the source regions of aerosols found over the Arabian Sea during the southwest monsoon. This observation is consistent with higher sinking fluxes of lithogenic and dolomite materials, in the Arabian Sea, derived from Arabia region and transported by northwesterlies during the southwest monsoon [*Nair*, 2006]. These mineral dust aerosols deposited on the Arabian Sea surface are found to be rich in nutrients and micro-nutrients [*Tindale and Peaseb*, 1999; *Measures and Vink*, 1999; *Rengarajan and Sarin*, 2004]. *Measures and Vink* [1999] have shown that the supply of Fe through aeolian dust is a requirement for biological production in the nutrient-rich upwelled water in the western Arabian Sea coast, and more prominently in the water that advects offshore. Thus the relative significance of atmospheric deposition over the upward supply of nutrients to the surface layers across the pycnocline to surface chlorophyll in the North Indian Ocean needs to be evaluated.

Southwest monsoon winds induce strong upwelling in the Arabian Sea than in the Bay of Bengal [*Prasanna Kumar et al.*, 2002], while intense convection is facilitated by cold dry winds in winter in the Arabian Sea [*Madhupratap et al.*, 1996]. Large freshwater influx into the Bay of Bengal not only causes temperature inversions [*Thadathil et al.*, 2002] but also forms a strong barrier layer

through surface stratification [Vinayachandran et al., 2002]. The low biological productivity in the Bay compared to that in the Arabian Sea is attributed to poor vertical mixing in the former, which in turn is due to weak winds and stratification [Prasanna Kumar et al., 2002; Shenoi et al., 2002]. Here is an issue to resolve between the roles of surface stratification and wind strength: Does the Bay become more biologically productive than its western counterpart when the wind speeds over the former are equal or greater than over the latter region? Which is relatively more important for biological production in the two basins: wind speed or stratification? During tropical cyclones, the mixed layer depth (MLD) can deepen by about 30 m over a large area at wind speeds of  $\sim 135 \text{ km h}^{-1}$  [Dickey et al., 1998], which is expected to break the pycnocline and pump nutrients in to the surface layer. Some results suggested significant impact of hurricanes and cyclones on the recently increased emissions of  $\text{CO}_2$  and  $\text{N}_2\text{O}$  at the local and global scales [Bates et al. 1998; Patra et al., 2004]. A significant surface cooling of about  $6^\circ\text{C}$  was found, from satellite measurements, in the Bay of Bengal following the passage of Orissa super cyclone in 1999 [Sadhuram, 2004]. Such sudden cooling can only occur through strong entrainment that facilitates upward pumping of cold and nutrient rich waters creating conditions conducive for higher biological production. The effects of tropical cyclones within the Bay of Bengal and the Arabian Sea on increased chlorophyll abundances have been studied [Kundu et al., 2001; Subrahmanyam et al., 2002; Rao et al., 2006] but no comparative study is made on the biological response between the Arabian Sea and the Bay of Bengal under identical or different wind speed scenarios.

The main aim of the present study, therefore, is to evaluate (a) the relative significance of atmospheric nutrient (including trace metal) supplies over that by vertical mixing to the surface ocean and (b) importance of surface stratification over wind speeds (turbulence) in facilitating

upward supplies of nutrients to stimulate biological activity in the North Indian Ocean. For this purpose we used surface chlorophyll-a abundance to represent biological productivity. A combination of TOMS Aerosol Index and modeled dust deposition were used as proxies for atmospheric nutrient input to the sea surface. To resolve the relative importance of stratification and wind speeds on vertical mixing and upward supply of nutrients we studied changes in chlorophyll-a concentrations following tropical cyclones. This is based on an inherent assumption that the biological activity in the tropical latitudes is limited by availability of nutrients and not light [Moore *et al.*, 2002] since we are using satellite-measured information obtained under clear sky conditions only [McClain *et al.*, 2004]. Even if some cloud cover prevails during the observation, our assumption will still be valid, as the reduced light would have probably led to low chlorophyll abundance than potentially expected from cyclone induced vertical mixing.

## 2. Material and Methods

Our study period is from 1997 to 2004, chosen due to data availability to test the questions discussed above. The climatological data used for characterizing surface features of the Arabian Sea and the Bay of Bengal are the one-degree objectively analyzed fields from the World Ocean Atlas 2001 (WOA01), generated using the World Ocean Database 2001 [see Conkright *et al.*, 2002; online resource: [www.nodc.noaa.gov](http://www.nodc.noaa.gov)]. Chlorophyll-a is constructed from the 9×9 km monthly and weekly means fields produced by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) team (Level-3 binned data; source: <ftp://oceans.gsfc.nasa.gov>) [McClain *et al.*, 2004]. The SeaWiFS derived chlorophyll concentrations are representative of phytoplankton standing stock throughout

the photic zone [Bailey and Werdell, 2006]. Under most conditions surface chlorophyll-a can be treated as a quantitative indicator of the primary productivity for the Arabian Sea [e.g., Savidge and Gilpin, 1999; Sarma, 2006]. The NCEP/NCAR reanalysis winds [Kistler et al., 2001], and optimally interpolated sea-surface temperature [Reynolds et al., 2002] are used for understanding physical mechanisms for chlorophyll variations.

The absorbing aerosol index (AAI) [Herman et al., 1997], representing the column abundance of dust, smoke etc., is obtained from the Earth Probe/Total Ozone Mapping Spectrometer (EP/TOMS) as monthly means (source: <http://toms.gsfc.nasa.gov>, version 8, positive values only) at a  $1.25 \times 1.0^\circ$  resolution. As it is difficult to separate between the aerosols of land (soil dust, biomass burning aerosols etc.) and oceanic origins (e.g., sea-salts) using the conventional aerosol optical depths (AODs), we used TOMS AAI as the proxy for land-originated aerosols to ocean surface. This approach has limitations, since TOMS AAI response to scattering aerosols (e.g. sulfate or sea salts) will be negative, and thus may hide absorbing aerosols [e.g. Torres et al., 2002]. Satellite optical depth data are also not very good at capturing spatial variability in deposition [Mahowald et al., 2003]. In the regions considered here, model estimates suggest that it is likely both that the mineral aerosols have an optical depth that is above the detection limit for the TOMS AAI instrument and that mineral aerosols represent a significant fraction of the absorbing aerosol fraction, thus allowing us to use TOMS AAI to examine dust column variability (not shown). This is not the case for most regions of the ocean. A comparison of aerosol optical depth (AOD) time series observed at Solar Village, Saudi Arabia ( $46.4^\circ\text{E}$ ,  $24.9^\circ\text{N}$ , 650 MSL) AERONET site [Dubovik et al., 2002] with an area averaged TOMS AAI ( $44\text{-}50^\circ\text{N}$ ,  $23\text{-}27^\circ\text{N}$ ) show statistically significant correlations for monthly observations for the period 1999-2000 ( $r=0.75$ ,  $P<0.0001$ ) or 1999-2004 ( $r=0.80$ ,

$P < 0.0001$ ). Similar correlation coefficients are also obtained between AODs at Solar Village and AAI over north-west Arabian Sea. This suggests a common source of dust in both regions and also gives us confidence on TOMS AAI dataset for the present application. We also have used the dust deposition values based on a modeling study [Luo *et al.*, 2003; Mahowald *et al.*, 2003]. The sources of dust are simulated using Dust Entrainment and Deposition (DEAD) model [Zender *et al.*, 2003], and the transport, dry and wet depositions are modeled using the MATCH transport model driven by the NCEP reanalysis [Rasch *et al.*, 1997; Mahowald *et al.*, 1997]. Although these dust deposition estimates are based on models using meteorology representing the best information we have for the state of the atmosphere (NCEP/NCAR reanalysis winds), they are however model results. We believe that a combination of TOMS AAI and modeled deposition will provide insight into real atmospheric processes. Model and data analysis suggest relatively constant values of iron in different mineral aerosols [Hand *et al.*, 2004; Mahowald *et al.*, 2005]. More important are fluctuations in the bioavailability of the iron (e.g. Jickells and Spokes, 2001; Luo *et al.*, 2005). It is not known what fraction of iron is bioavailable, but most studies assume that the soluble iron fraction is a proxy for the bioavailable fraction [e.g. Jickells and Spokes, 2001; Mahowald *et al.*, 2005]. Although there are fluctuations in the solubility of the iron in observations and model studies, largely the deposition patterns for soluble iron are thought to follow total iron deposition patterns, because of the larger spatial gradients in the iron deposition than solubility [Luo *et al.*, 2005]. So here we will use dust deposition patterns as a proxy for bioavailable iron patterns.

The information on track analysis and intensity (in terms of wind speeds and categories) of tropical cyclones over the Arabian Sea and the Bay of Bengal are obtained from <https://metoc.npmoc.navy.mil/jtwc> [see also Chu *et al.*, 2002]. We examined approximately 25



cyclone events based on information available for the period 1997-2005 and selected 6 cases for our analysis based on data availability in the chlorophyll (Table 1). For example, if the chlorophyll (SeaWiFS) data along a cyclone path are not available for two consecutive weeks during and after the event that particular case is rejected. In the first case the wind speeds were similar but in the second and third the winds were nearly twice stronger in the Bay of Bengal than in the Arabian Sea (Table 1). In fact, cases 2 and 3 over the Bay belong to cyclones of category 4 and 5. As the selection is mainly based on SeaWiFS data availability (often SeaWiFS have data voids due to clouds abstraction), cyclones listed in Table 1 are in October-December period during which surface stratification prevails in both the basins, especially in October. Hence, the seasons of primary focus in this study are summer (June to August, JJA) and fall-intermonsoon to winter (October to December, OND); both the periods are important for testing the significance of atmospheric deposition but the second for wind forcing versus stratification. It should also be noted that the period 1997-2004 also nearly covers two El Niño periods (1997-98 and 2002-03).

### 3. Results and Discussions

Figure 1 shows the climatology of physical (temperature and salinity) and chemical (oxygen, nitrate, phosphate, and silicate) properties at the surface of the North Indian Ocean. During JJA period the southwesterly wind systems favour strong upwelling while in December northeasterlies facilitate winter convection as discussed above. Consequently biological productivity is higher during these seasons, particularly in the Arabian Sea [*Madhupratap et al.*, 1996; *Barber et al.*, 2001; *Prasanna Kumar et al.*, 2002]. Examining the significance of atmospheric deposition to chlorophyll

abundance during JJA and OND periods is appropriate and reliable since the nutrient supply through vertical mixing is also maximal at these times. The upwelling enhances surface nutrients concentrations to a maximal of 16  $\mu\text{M}$  of nitrate, 1.5  $\mu\text{M}$  of phosphate and 6  $\mu\text{M}$  of silicate [Morrison *et al.*, 1998] in the western Arabian Sea according to measurements. On the other hand, high nitrate of  $\sim 4 \mu\text{M}$  occurred as a result of convection in winter 1995 [de Sousa *et al.*, 1996] at the surface of the eastern Arabian Sea. Strong entrainment is reflected by lower sea-surface temperatures (SST) in the western Arabian Sea in JJA (due to upwelling) than even during the convection period (OND) and that in other parts of the region (Fig. 1). Higher surface salinity is caused by the evaporation in excess of precipitation in the central longitudinal belt of the Arabian Sea. The minimal salinities hugging the coastal regions of the Bay of Bengal exhibit the strong influence of river discharges on the surface ocean dynamics. A conspicuous surface salinity gradient could be seen from the northeast Bay to the north-central Arabian Sea. These features are typical of the study region and discussed in detail elsewhere [Shenoi *et al.*, 2002; and references therein]. The chemical properties of the Arabian Sea and the Bay of Bengal are also different in several respects and between the two seasons. Higher oxygen in OND compared to JJA period in the Bay of Bengal is caused by freshwater influx (solubility effect) and higher chlorophyll (oxygen release during photosynthesis) at the surface. Large amounts of nitrate and phosphate (as mentioned above) are supplied from the deeper water to the surface layer during the JJA months, thus greater chlorophyll can be sustained off the western boundary of the Arabian Sea (Fig. 1). Further, the nutrient laden upwelled water is advected offshore, by the prevailing winds, that supports plankton growth in the following months in the central parts of the Arabian Sea (Manghnani *et al.*, 1998; Prasanna Kumar *et al.*, 2001). However, the chlorophyll concentrations have not increased on the return of clear sky, after the retreat of monsoonal clouds during JJA, due to weaker winds and

relatively low vertical mixing [Morrison *et al.*, 1998; Barber *et al.*, 2001]. The Bay of Bengal receives enormous discharges of materials among the world oceans from the rivers (mainly Ganges, Brahmaputra, Irrawaddy; Subrahmanian, 1993) that results in high silicate concentrations, particularly during the summer monsoon period [see Syvitski *et al.*, 2005; Gauns *et al.*, 2005].

### 3.1 Significance of atmospheric deposition over vertical mixing

Detailed analysis of measurements, made over the past few decades, has established an increase in chlorophyll in the coastal waters around the world [Gregg *et al.*, 2005] and in oceanic heat content [Levitus *et al.*, 2005]. Warming of the ocean may have reduced the upwelling intensity in recent years. If true, supply of nutrients through atmosphere assumes more importance for the observed increase in chlorophyll abundance. The distributions of chlorophyll-a, aerosol index and modeled dust depositions during the summer and winter monsoons are shown in Fig. 2 for the study region. The chlorophyll, in general, is much more abundant in the Arabian Sea than in the Bay of Bengal. The fine structure such as the high chlorophyll patch on the eastern side of Sri Lanka is associated with nutrient enrichment due to upwelling along the southwest coast of India and its subsequent transport eastward by the southwest monsoon current [Vinayachandran *et al.*, 2004]. The other feature, which is important in the present context, is the higher chlorophyll abundance around the coastline, particularly in the western Arabian Sea, primarily supported by nutrients and micronutrients through upwelling and to a lesser extent by the deposition of land aerosols. The Arabian Sea chlorophyll distribution contradicts the SST pattern but broadly correlate with the nitrate and phosphate distributions in both the seasons. There is a good similarity in spatial patterns of the modeled dust deposition or TOMS AAI (for JJA only) and chlorophyll abundance (Fig. 2).

During JJA months the area of the highest chlorophyll (off Oman and Yemen coast) does not coincide with the region of highest nutrients abundance (off Somalia coast; see Fig. 1), but has a good correlation with aerosol index (Fig. 2). The same conditions hold good for both JJA and OND months if the modeled dust depositions are considered for the western Arabian Sea. Since surface water in this part of the Arabian Sea is usually not depleted in nutrients, probably the micronutrients such as iron, might limit the biological activity, and hence its supply through dust deposition relaxes this limitation [Measures and Vink, 1999]. Though dissolved Fe brought from the subsurface waters by upwelling might support biological activity to some extent, the aeolian Fe supply supplements the requirement; the importance of which actually increases from coast to offshore regions [Measures and Vink, 1999]. On the other hand, despite higher nutrient concentrations during OND than JJA in the eastern Arabian Sea, higher chlorophyll-a abundance occurred during JJA compared to the OND season (Fig. 2). This suggests that the efficient nutrients utilization during the JJA season in the eastern Arabian Sea might be fueled by the aeolian Fe inputs, which are higher during JJA than OND (Fig. 2). Alternatively, low chl-a during October is due to the disappearance of nutrients that upwelled during JJA. Though nutrients are supplied by convective mixing during November and December, the biological growth is constrained since photic zone is shallower than mixed layer depth and resulting in low production and chlorophyll. Prevalence of salps (filter feeders) during winter monsoon also reduces chl-a levels (see Naqvi et al., 2002).

A biogeochemical model simulation suggests that diazotrophs growth in the northern Indian Ocean is limited by iron and phosphate, while the diatoms and small phytoplankton's growth is limited by nitrogen [Moore et al., 2002; Patra et al., 2006]. Typically the Arabian Sea and the Bay of Bengal

receive up to 20 and 10 g m<sup>-2</sup> yr<sup>-1</sup> mineral dust from the adjacent land regions, respectively, with a peak deposition during JJA period (Fig. 2). The dust bearing northwesterly winds occur close to sea-surface around 45°E but rise to 3 km around 70°E [Clemens, 1998] with a gradient of about 0.1 km degree<sup>-1</sup> longitude. From the AAI distribution and tracer transport modeling, Patra et al. [2005] concluded that during JJA months a large amount of aerosols is transported to the AS from northern Africa and the Gulf region and that a major fraction of these aerosols are deposited on the Arabian Sea surface. This is confirmed by the dust deposition model results (Fig. 2), and source apportionment studies (Luo et al., 2003). Further, Siefert et al. [1999] found that aerosols over 65°E have originated in the south during the southwest monsoon. This suggests that southwesterlies limit the transportation of dust bearing northwesterlies, originated in the Middle East, into central regions of the Arabian Sea. Higher chlorophyll (1997-2004) confined to the western Arabian Sea during the summer monsoon (Fig. 2) confirms that atmospherically deposited materials are important to sustain intense plankton blooms. The nature of dust being deposited over the Arabian Sea is also a function of the source region. For instance, southern branch of northwesterlies carries lithogenic matter (clay minerals) whereas its northern branch transports dolomite rich material (Nair, 2006). The aerosols collected in this area are rich in nutrients, non-sea salt sulfate, nitrate, and iron, and <sup>7</sup>Be and <sup>210</sup>Pb data clearly indicated their source as the land [Sarin et al., 1999; Rengarajan and Sarin, 2004]. On the other hand, the Bay of Bengal receives less aerosols from the Middle East as from the soils of the Indian subcontinent due to its immediate wet deposition by the summer monsoon rain. Gauns et al. (2005) observed low rates of primary production during summer monsoon compared to the other seasons. Therefore, chlorophyll abundance in the North Indian Ocean may be determined not just by nutrient supplies through upwelling or convection processes but also by the availability of micronutrients such as iron or other critical elements being

supplemented by atmospheric dust deposition. During the OND months both the oceanic basins receive low inputs of land-originated aerosols as seen from the aerosol index.

We employed a statistical analyses among chlorophyll, AAI and dust depositions (Table 2), assuming that dust deposition is a proxy for bioavailable iron deposition (discussed in more detail above). The Arabian Sea and the Bay of Bengal has been divided into four regions each [northwest (NW), northeast (NE), southwest (SW) and southeast (SE)]; geographical boundaries have been defined in Table 2 and Fig. 3 to understand the geographical variability and relationships in properties. The correlation coefficients for the time series of the important variables confirm that chlorophyll is significantly related to AAI and dust deposition in the western parts of the Arabian Sea and the Bay of Bengal. It also appears that AAI and dust deposition are significantly correlated in these regions, showing the consistency of these two independently derived proxies for iron deposition. The time lead/lag between AAI and dust deposition arise from the time difference in maximum aerosol abundance in the atmosphere (AAI) and most intense deposition following onset of Indian summer monsoon in June. Even though the supply of aerosols to Arabian Sea region is not reduced, the residence time of aerosols is shortened by efficient wet scavenging. The relations between chlorophyll and dust are much stronger for the northwestern Arabian Sea and for southwestern Bay of Bengal in the respective basins. However, correlations between anomalies do not exhibit such strong correlations for most regions, except for the north-west Arabian Sea. As it can be seen from Fig. 3 that north-west Arabian Sea experiences maximum interannual variations in chlorophyll concentrations and for the other regions interannual variability is much weaker. This explains weaker correlations in anomalies. Correlations cannot prove causation, but rather show the consistency between the hypothesis that iron deposition may enhance ocean productivity. The

fact that dust deposition proxies lead the chlorophyll deposition by 1-3 months in the correlations is consistent with the iron fertilization hypothesis. However, the lack of correlation in the anomalies is not consistent with the iron fertilization hypothesis, suggesting that on interannual time scales, other processes may be important. For example, strong correlations between monthly mean values of chlorophyll and wind speed in Table 2 suggest the physical mechanisms are also needed to act in harmony to explain the satellite-derived chlorophyll variations [see also *Goes et al.*, 2005].

### 3.2 Trends and causes of interannual variability in Chlorophyll during 1997-2004.

Figure 3 shows the area-weighted average time series of SeaWiFS chlorophyll-a, TOMS aerosol index, NCEP/NCAR horizontal wind speed and optimally interpolated (OI) SST anomaly for the period 1997-2004. The SST anomalies reached maximal values in both the basins coinciding with 1997-98 and 2002-03 El Niño periods. There was a decrease in SST anomaly from 1997-98 to 1999 after which it increased to reach maximal values during 2002-03 followed by a decrease again. The wind speeds did not exhibit significant variations over the 1997-2004 period but there are obvious differences not only between the two basins but also within each basin. Maximal wind speed during the southwest monsoon in the NW Arabian Sea was  $\sim 14 \text{ m s}^{-1}$  but less in the NE Bay of Bengal ( $\sim 9 \text{ m s}^{-1}$ ). The speeds were in the order NW>NE~SW>SE in the Arabian Sea and NE>SW>NW>SE in the Bay. Moreover, the wind speeds were distinctly and systematically different between SW (high) and NE (low) monsoons in the Arabian Sea but not so different in the Bay of Bengal (Fig. 3).

The seasonal cycles of TOMS-AAI in the Arabian Sea sub-regions typically have two peaks. The first one occurred in the eastern parts during the spring/pre-monsoon season (MAM: March-April-

May). Origin of these aerosols (green lines; Fig. 3) is presumably the Indian subcontinent and swept to sea by prevailing northeasterly winds [Ramachandran and Jayaraman, 2002]. A second peak is found during JJA months and is a result of the transport of land-originated aerosols from the northern Africa and Gulf regions [Patra et al., 2005]. The seasonal cycle peaks in both AAI and Chlorophyll showed a gradual increase from 1998 to 2000 and then a decrease. We see this to a lesser extent in the modeled dust deposition. As an independent confirmation, AERONET optical depths at Solar Village (available from 1999 to 2005) show a minimum in 2002 and an increase afterwards (not shown), also consistent with the TOMS AAI fluctuations in this region. In the Bay of Bengal only one peak is observed during the spring season primarily due to the transport of aerosols from the Indian subcontinent [Moorthy et al., 2003] that also increased from 1998 to 2000. Note here that the aerosols from these two continents are quite different in composition; the aerosols from the North Africa and the Gulf are predominantly naturally produced soil or desert dusts, but those from the Indian subcontinents are rich in anthropogenic components [Prospero et al., 2002]. Therefore, the ocean fertilization capacity of the aerosols transported from west to the Arabian Sea could be higher compared to that carried over to the Bay of Bengal. Iron concentration in aerosols collected over the Arabian Sea ( $\sim 600 \text{ ng m}^{-3}$ ) is about twice higher than in those found over the Bay of Bengal ( $\sim 300 \text{ ng m}^{-3}$ ). The nitrate concentrations are also comparatively higher in aerosols over the Arabian Sea. These results of differences in aerosol compositions are obtained during the February-April period [Rangarajan and Sarin, 2004], and thus we could expect even greater contrast in their composition during the JJA period when dust aerosols from the northern Africa and the Gulf are transported to the Arabian Sea.



In the Arabian Sea the chlorophyll abundance was in the order NW>NE>SW>SE regions (Fig. 3) that agrees well with wind strengths. The eastern regions have not shown any systematic change over the study period. The western regions behaved differently: chlorophyll showed a gradual increase from 1997 to 2004 in the SW region but it increased up to 2000, showed a minimum in 2002 before increasing again in the NW region. The minimal chlorophyll abundances during 1998 and 2002-03 coincide with the two El Niño years. Low chlorophyll in 1998 in Fig. 3 is also in agreement with the 30% decrease in photic zone primary production in the Arabian Sea following the 1997-98 Indian Ocean Dipole [Sarma, 2006]. The interannual chlorophyll variability in the present study (Fig. 3) appears to be at variance with its gradual increase in the western Arabian Sea from 1997 to 2004 reported by Goes *et al.* [2005]. Although chlorophyll in the SW region exhibited a gradual increase from 1997 to 2004 (Fig. 3), in concurrence with Goes *et al.* [2005] observation, the chlorophyll content in the NW region (chlorophyll content here is about 3-4 times more than in the SW region and largely determines the total chlorophyll content in the whole of western Arabian Sea) decreased during El Niño years (1997-98 and 2002-03) due to reduced upwelling as revealed by higher SST anomalies (Fig. 3). In contrast to that in the Arabian Sea, the NW Bay of Bengal contained high chlorophyll in 1998 and 2002-03, and exhibited a gradual decrease from 1998 to 2001. Whether the decreased Indian monsoon rainfall from 1998 to 2001 [Rajeevan *et al.*, 2004] is related to the decrease in chlorophyll or not is unknown. Therefore, chlorophyll abundance in the NW regions of the Arabian Sea and the Bay of Bengal behaves contrastingly to the El Niño forcings because of reduced upwelling (lower SST anomalies) and perhaps more nutrient pumping (facilitated by decreased rainfall) into surface layers, respectively. The two El Niño events covered in this study are different in intensity: 1997 event is the strongest event in the last century [Srinivasan and Nanjundiah, 2002] whereas that of 2002 is marked by prolonged summer monsoon

breaks [Fasullo, 2005]. Higher chlorophyll abundance in the Bay of Bengal may have been driven by unusually intense rainfall in 1997, in comparison to other El Nino years [Srinivasan and Nanjundiah, 2002], that facilitated higher nutrients discharges from rivers. Availability of silicate promotes diatoms production in near coastal ecosystems but weaker sinking fluxes in El Nino years [Rixen and Ittekkot, 2006]. Chlorophyll in the SW Bay of Bengal, again in contrast to that in the SW Arabian Sea, decreased gradually from 1998 to 2003. The difference in chlorophyll - is very large between summer and winter monsoons in the NW region compared to that in the NE parts of both the Arabian Sea and the Bay of Bengal. Chlorophyll in the northern Arabian Sea exhibits greater interannual variability with the highest value of  $3.0 \text{ mg m}^{-3}$  in August 2000. In general, chlorophyll values are greater in the northern Arabian Sea (varying typically between  $0.3\text{-}0.6 \text{ mg m}^{-3}$ ) compared to those in the southern Arabian Sea, southern Bay of Bengal (average  $\sim 0.2 \text{ mg m}^{-3}$ ) and the northern Bay of Bengal (values  $\sim 0.2\text{-}0.5 \text{ mg m}^{-3}$ ). The SE regions of both the seas exhibit the weakest seasonal cycle in chlorophyll compared to other three sub-regions. The anomalously high chlorophyll concentration around December 1997 – January 1998 over the southeastern Bay of Bengal is probably a result of iron fertilization by the Indonesian forest fires [e.g., Abram et al., 2003] and nutrients supply by Sumatra upwelling system [Saji et al., 1999].

### 3.3 Significance of surface stratification over wind strength

Deep water mixing with the surface water across the pycnocline/nutricline is primarily responsible to sustain observed chlorophyll levels in the mixed layer. Pycnocline/nutricline is defined as the layer in which the density/nutrients concentrations increase sharply and is generally located near

the mixed layer depth (MLD). Lower biological productivity in the Bay of Bengal compared to that in the Arabian Sea [Qasim, 1977] is caused by poor vertical mixing due to the presence of strong stratification and weak winds [Shenoi et al., 2002; Prasanna Kumar et al., 2002]. To determine the relative importance of wind and stratification in controlling the vertical mixing, we used tropical cyclones as a tool in the natural laboratory of the North Indian Ocean. Under short spells of strong wind forcing, lasting about a week, it is possible to study the extent of vertical mixing and hence nutrient supplies from the deep through mapping the increase in satellite-measured chlorophyll as a proxy. On average, the Bay of Bengal experiences greater numbers of cyclones compared to the Arabian Sea because SST in the former region is mostly in excess of 28.0°C required for the development of low pressure systems [Gadgil et al., 1984; Emanuel, 2005]. The most number of cyclones in this part of the world occur during the post-monsoon months through December.

Figures 4 and 5 show the 8-day anomalous chlorophyll distributions along with its 40-day averages (bottom row) for three cyclones each in the Arabian Sea and Bay of Bengal (Table 1). The maps in the left, middle and right columns in Figures 4 and 5 represent cyclone cases 1, 2 and 3, respectively described in Table 1. Anomalies are calculated by subtracting the average chlorophyll concentrations of five 8-day maps of each cyclone from that of 8-day map corresponding to the same event. The analysis period of each cyclone includes genesis, maturity and decay of plankton blooms, in terms of chlorophyll abundance, caused by the passage of cyclone. The cyclone tracks and strength (winds speed) are shown in the bottom panels. Fortuitously the cyclones considered have very different trajectories and landfall regions in both the Arabian Sea and the Bay of Bengal.

The cyclones over the Arabian Sea formed on the eastern side where the surface water is warmer and moved in west or northwest direction. On two occasions the cyclones dissipated before landfall and the other passed the Oman coast. In all three cases chlorophyll anomalies reached up to 0.5-1.0  $\text{mg m}^{-3}$  following the dissipation of cyclones over a large area ( $5 \times 5$  degrees; see Fig. 4) in the central region. When smaller grids of  $9 \times 9$  km are considered the chlorophyll anomalies are found to reach 6.0  $\text{mg m}^{-3}$  (not shown). In general, high chlorophyll values appear to have been mostly sustained for about two weeks before the surface water returned to original average chlorophyll values of 0.2-0.8  $\text{mg m}^{-3}$ . Note that the chlorophyll enhancement is recorded all along the path of cyclones including open ocean and coastal regions.

Two cases of cyclones over the Bay of Bengal were very powerful with maximal wind speeds more than twice (up to 140 knots) compared to those in the AS (55-65 knots). The case 3 cyclone (Fig. 5; right column) is referred to as the 'Orissa Super Cyclone' as it belonged to category 5 and devastating nature. According to the UN Office for the Coordination of Humanitarian Affairs (OCHA) this cyclone is reported to have killed over 10,000 people and livestock of 406,000 while dislodging millions of residents of Orissa, an eastern state of India. Despite the strong cyclonic winds of cases 2 and 3 only marginal increases in weekly chlorophyll, anomalies of about 0.1  $\text{mg m}^{-3}$  in the open ocean region are found following their passage over the Bay of Bengal. The enhancements near the landfall regions are greater ( $\sim 0.5$ -1.0  $\text{mg m}^{-3}$ ) compared to the open ocean region. This maximum chlorophyll increase in the central Bay is about an order of magnitude small compared to its enhancement in the central Arabian Sea. More over, areas experiencing enhanced chlorophyll production were large in the Arabian Sea than in the Bay (Figs. 4 and 5) where vertical mixing seems to have occurred only in small patches. These differences in the cyclone triggered

‘biological pump’ over the Arabian Sea and the Bay of Bengal clearly reveal that surface stratification plays the major role in controlling extent of nutrient supply from the deep. Strength of stratification in upper layers of the Bay of Bengal, as could be seen through sharp gradients in temperature and salinity, is more than in the Arabian Sea (Fig. 6). Comparatively weak gradients in salinity both in vertical and horizontal scales in the Arabian Sea facilitate easy churning of upper layers even by weak winds, as reflected by enhanced chlorophyll production in large areas at wind speeds of 55-65 knots (Fig. 4). On the other hand, chlorophyll increase occurred only in small patches (Fig. 5) indicating that surface stratification could not be fully broken down in the Bay even by very strong winds of 120-140 knots. Therefore, surface stratification in the bay formed by freshwater discharge is the major reason than weak winds for poor vertical mixing and low biological production.

#### **4. Conclusions**

Upwelling and convection processes are less favoured in the Bay of Bengal compared to that in the Arabian Sea presumably due to weak prevailing winds and stronger surface stratification. In this attempt we studied the relative significance of atmospheric deposition and surface stratification over vertical mixing and wind strengths, respectively, in maintaining chlorophyll abundances. We have used SeaWiFS chlorophyll, TOMS aerosol index, NCEP/NCAR wind speed, MATCH/NCEP/DEAD modeled dust depositions and OI sea-surface temperature for understanding competing roles of nutrients supplied atmospherically from land and from the deeper ocean to sustain biological productivity in the surface waters of the North Indian Ocean. The period of this study was 1997-2004 covering two El Nino events. Our results suggest that the higher

chlorophyll abundance in the Arabian Sea compared to the Bay of Bengal is not merely controlled by vertical mixing supplied nutrients but also depend on some critical atmospheric inputs. Tropical cyclone events are utilized as the experimental test beds for illustrating contrasting behaviour of the Arabian Sea and Bay of Bengal in response to the surface forcing such as winds. The surface stratification (barrier layer) in the Bay of Bengal is only weakly perturbed (in small patches) by strong cyclonic events (maximal wind speed ~140 knot) to allow mixing across the thermocline. On the other hand, much weaker tropical cyclones (wind speed ~60 knots) can invigorate mixing and bring nutrients to the surface through entrainment. These results are based on correlations and inference from available data, and thus cannot be considered conclusive. Long time series measurement at a few sites would help us better quantify the role of atmospheric and oceanic material inputs in controlling the surface ocean productivity and chlorophyll abundance in the North Indian Ocean.

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**Table 1:** List of tropical cyclone cases used in this study. The period of occurrence and maximum wind speeds are given (in knot; 1 knot is roughly equivalent to  $0.51 \text{ m s}^{-1}$ ) as an indicator of the intensity. This table Figures 4 and 5 clearly show that even at great speeds wind is not able to churn up the bay as it can easily do in the Arabian Sea even at low speeds.

Cyclone case	Arabian Sea	Wind Speed	Bay of Bengal	Wind Speed
1	28 Nov.-06 Dec. 2000	65	28 Nov.-06 Dec. 2000	65
2	02-14 Nov. 1997	55	15-18 Oct. 1999	120
3	11-17 Dec. 1998	65	25 Oct-03 Nov. 1999	140

**Table 2:** Correlations of chlorophyll (Chla), TOMS AAI, dust depositions (dust), sea-surface temperature (SST) and wind using monthly mean values and monthly mean anomalies are given. The anomalies are estimated by subtracting an average seasonal cycle over each data period from the monthly values. Higher correlations between the (1) monthly values are obtained due to similarity in seasonality and (2) monthly anomalies indicate similarity in interannual variabilities of two parameters. The maximum correlations with lead-lag within parenthesis are shown (positive and negative values for lead and lag, respectively). For example, Chla lags by 3 months to AAI for the region  $52\text{-}64^{\circ}\text{E}$ ,  $10^{\circ}\text{N}$ . Note the highest correlations between TOMS AAI and dust depositions with chlorophyll for the western Arabian Sea regions at 2.5 and 1 months average lags, respectively. Similar high correlations are found for the north-western part of the Bay of Bengal.

P.T.O.

Region	Correlations using monthly mean values (lags in parenthesis)			Correlations in monthly mean anomalies (lags in parenthesis)		
	Chlorophyll and Biogeochemical parameters					
	Chla-AAI (9/97- 12/00; N≈36)	Chla-Dust (9/97- 12/04; N≈84)	AAI-Dust (9/97-12/00; N≈36)	Chla-AAI (9/97- 12/00; N≈36)	Chla-Dust (9/97-12/04; N≈84)	AAI-Dust (9/97-12/00; N≈36)
<b>52-64°E,Eq-10°N</b>	0.55(-3)	0.59(-1)	0.61(3)	0.21(-2)	0.00( 0)	0.28(-2)
<b>64-76°E,Eq-10°N</b>	0.28(-3)	0.52(-2)	0.49(3)	0.13(-2)	0.29(-3)	0.34( 1)
<b>52-64°E,10-20°N</b>	0.72(-2)	0.86(-1)	0.73(0)	0.73(-2)	0.24(-1)	0.28(-3)
<b>64-76°E,10-20°N</b>	0.24(-3)	0.56(-2)	0.80(3)	0.36(-2)	0.16( 0)	0.40( 1)
<b>80-89°E,Eq-10°N</b>	0.52(-3)	0.74(-1)	0.48(2)	0.00( 0)	0.21(-1)	0.29(-3)
<b>89-98°E,Eq-10°N</b>	0.00( 0)	0.00( 0)	0.22(3)	0.00( 0)	0.14( 0)	0.24(-2)
<b>80-85°E,10-20°N</b>	0.30(-3)	0.27(-1)	0.66(3)	0.17(-3)	0.01(-1)	0.34( 2)
<b>85-90°E,10-20°N</b>	0.14(-3)	0.45(-2)	0.77(3)	0.18(-3)	0.14( 3)	0.26( 2)
	Chlorophyll and Physical parameters					
	Chla-SST	Chla-Wind		Chla-SST	Chla-Wind	
<b>52-64°E,Eq-10°N</b>	0.12( 3)	0.70(-1)		0.09( 3)	0.16( 0)	
<b>64-76°E,Eq-10°N</b>	0.00( 0)	0.37(-2)		0.02(-3)	0.34( 0)	
<b>52-64°E,10-20°N</b>	0.23( 3)	0.84(-1)		0.00( 0)	0.25(-3)	
<b>64-76°E,10-20°N</b>	0.23( 2)	0.61(-1)		0.07( 2)	0.19(-3)	
<b>80-89°E,Eq-10°N</b>	0.03( 3)	0.75( 0)		0.05(-1)	0.41( 0)	
<b>89-98°E,Eq-10°N</b>	0.40( 2)	0.00( 0)		0.42( 2)	0.08( 0)	
<b>80-85°E,10-20°N</b>	0.15( 1)	0.25(-3)		0.18( 3)	0.12( 0)	
<b>85-90°E,10-20°N</b>	0.06(-2)	0.41( 0)		0.00( 0)	0.37( 0)	

**Figure Captions:**

**Figure 1:** Physical and chemical characteristics of surface seawater of the Arabian Sea and Bay of Bengal during periods of the south-west monsoon (JJA: June-July-August) and inter to winter monsoon (OND: October-November-December). The climatological distributions are prepared using the WOCE-2001 dataset.

**Figure 2:** Spatial patterns in observed chlorophyll-a and aerosol index, and modelled dust depositions in the Arabian Sea and Bay of Bengal are shown for JJA and OND seasons. The climatology in seasonal averages for chlorophyll, aerosol index, and dust depositions are calculated over a period 1998-2004, 1997-2000, and 1997-2004, respectively.

**Figure 3:** Area-averaged time-series of SeaWiFS chlorophyll-a (top/1st row), TOMS aerosol index (2nd row), NCEP surface winds speed (3rd row), and OI sea-surface temperature (bottom/4th row) for the period 1997-2004 are shown. Because AAI values after the year 2000 are a suspect we have discarded them.

**Figure 4:** Changes in 8-day distributions of SeaWiFS chlorophyll-a during three cyclone cases in the Arabian Sea (top five rows). The columns correspond to each cyclone. Column 1: 28 Nov.-06 Dec. 2000 (a; Day of year: 333-341), Column 2: 02-14 Nov. 1997 (b; Day of year: 306-318), and Column 3: 11-17 Dec. 1998 (c; Day of year: 345-351). Average values in five weeks around each cyclone and the trajectories of cyclone eye (marked numbers are winds speed) are shown in the



bottom panels. The days of year for 8-day periods are given at top of the panels. See text for selection criteria for the cyclone cases.

**Figure 5:** Same as Fig. 4, but during three cyclone cases in the Bay of Bengal. Column 1: 28 Nov. - 06 Dec, 2000 (a; Day of year: 333-341), Column 2: 15-18 Oct. 1999 (b; Day of year: 288-291), and Column 3: 25 Oct. - 03 Nov. 1999 (c; Day of year: 298-307).

**Figure 6:** Climatological latitudinal variations in vertical profiles of physical and chemical properties in the central Arabian Sea (top two rows; along 64°E longitude) and Bay of Bengal (bottom two rows; along 88°E longitude). Only the OND season is shown since all the selected cyclone events occurred in this season.

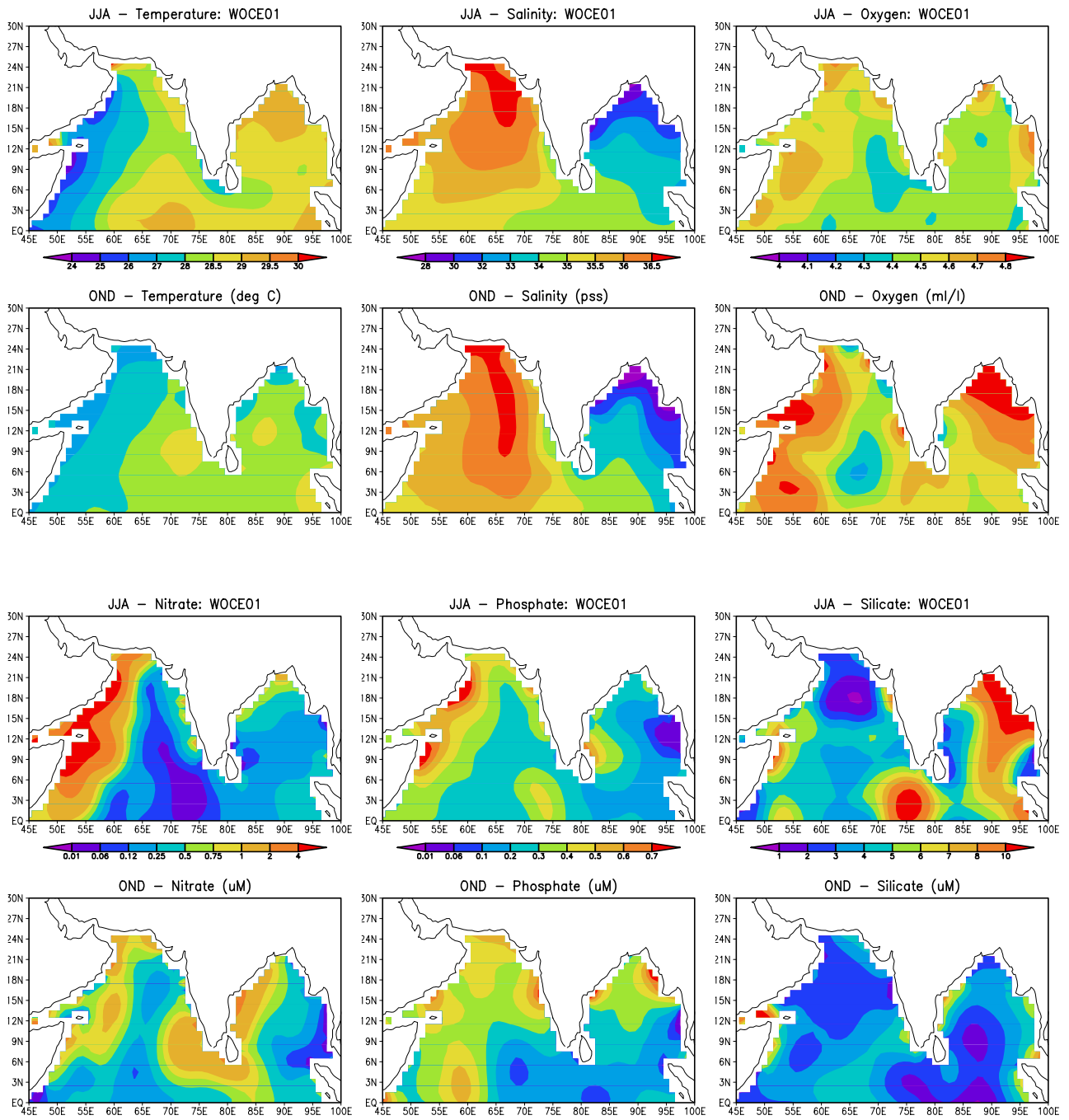


Figure 1

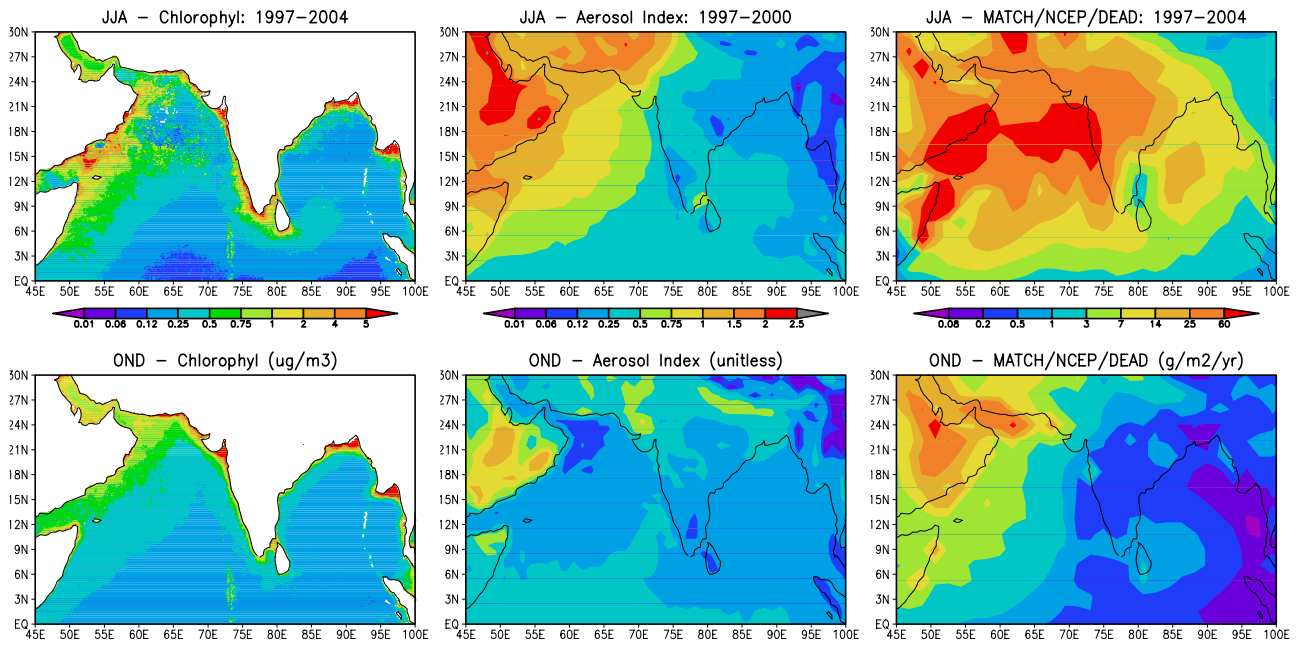


Figure 2

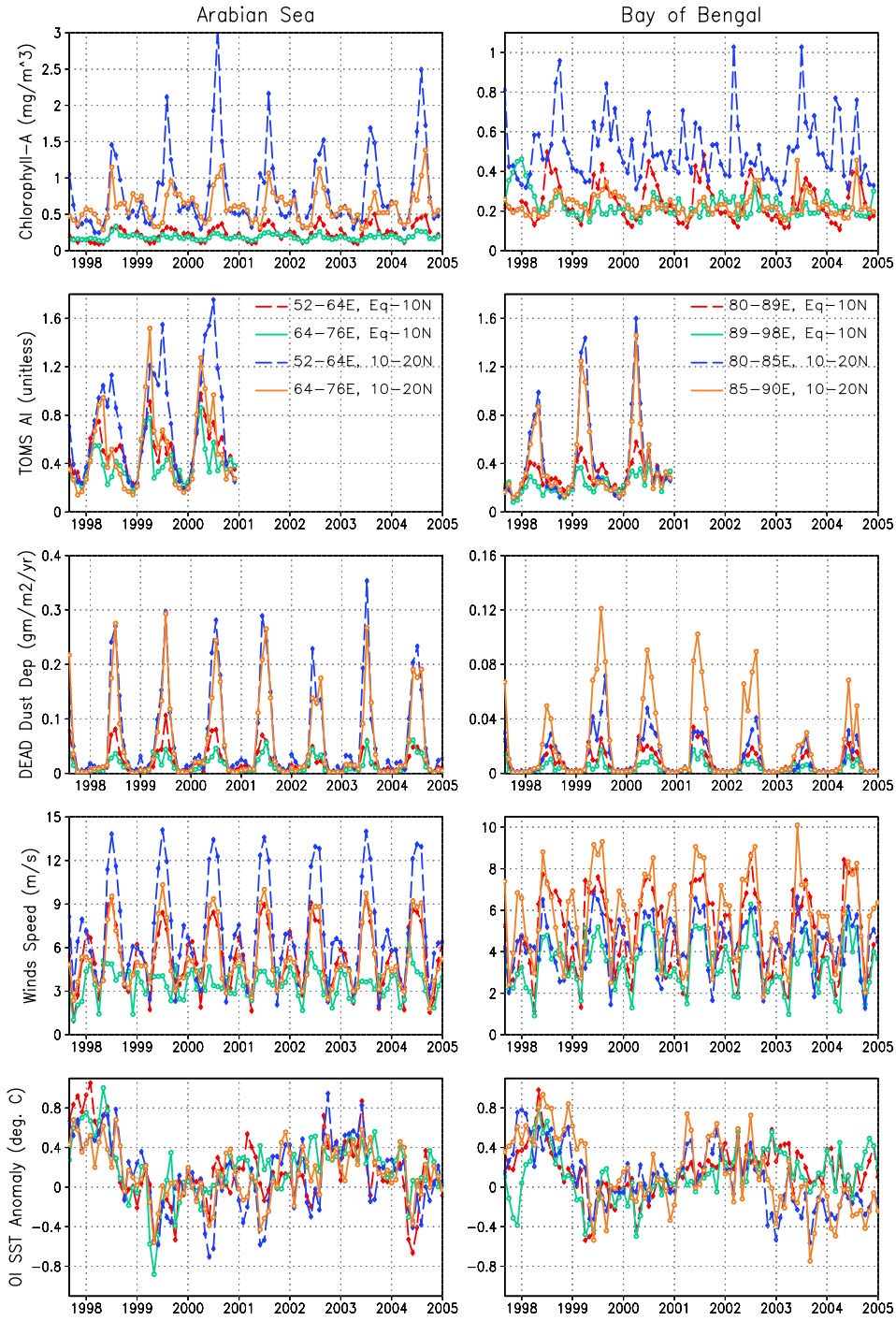


Figure 3

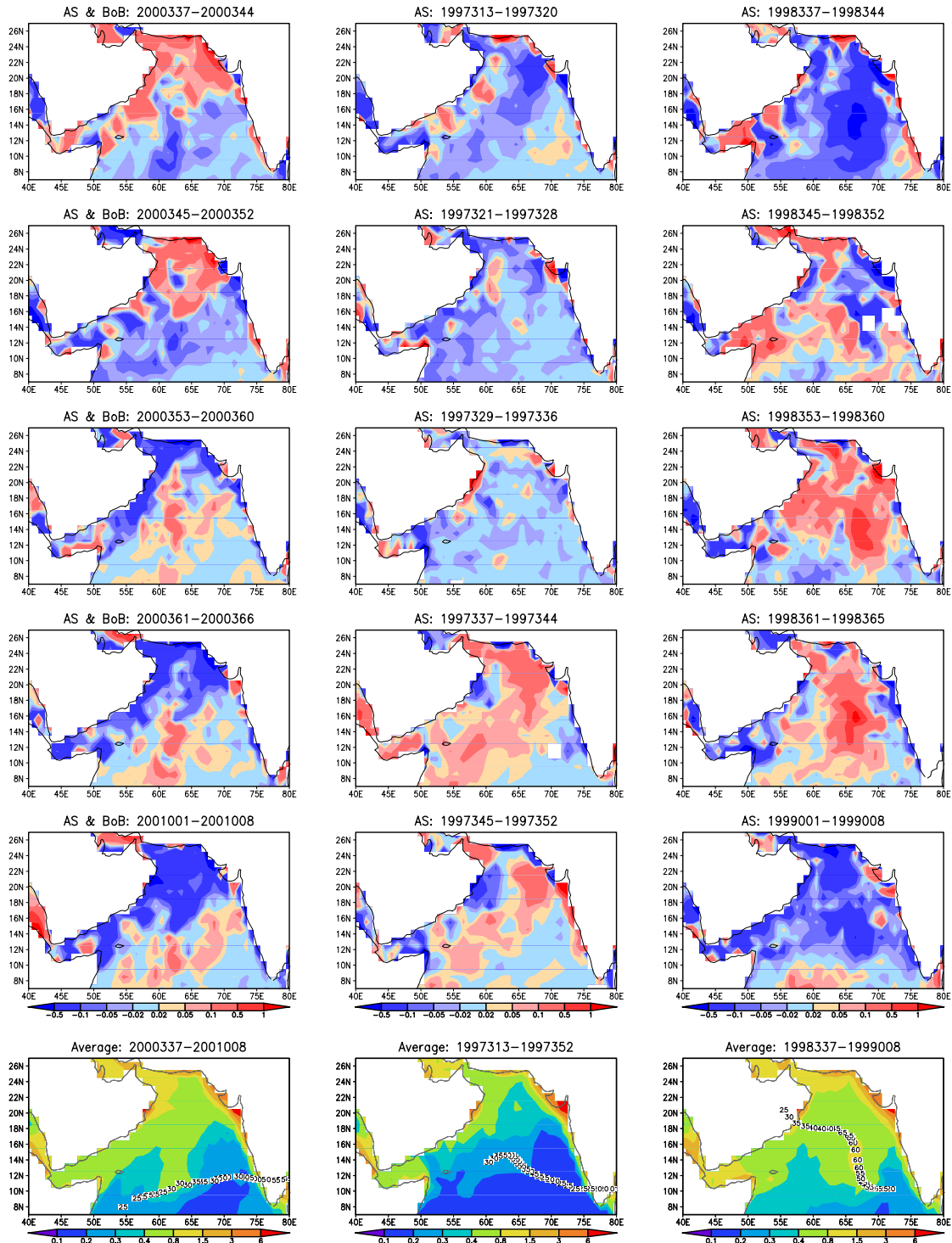


Figure 4

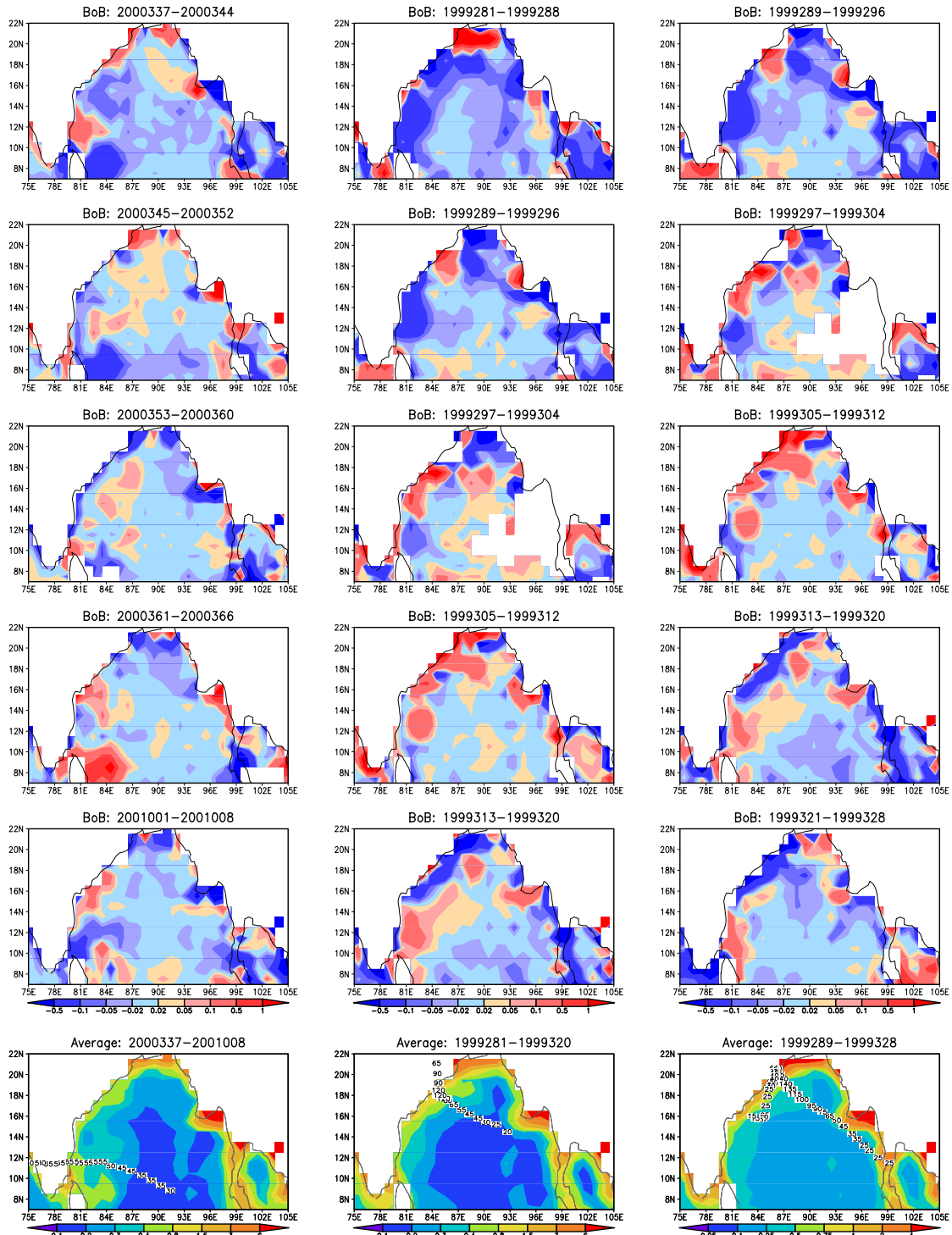


Figure 5

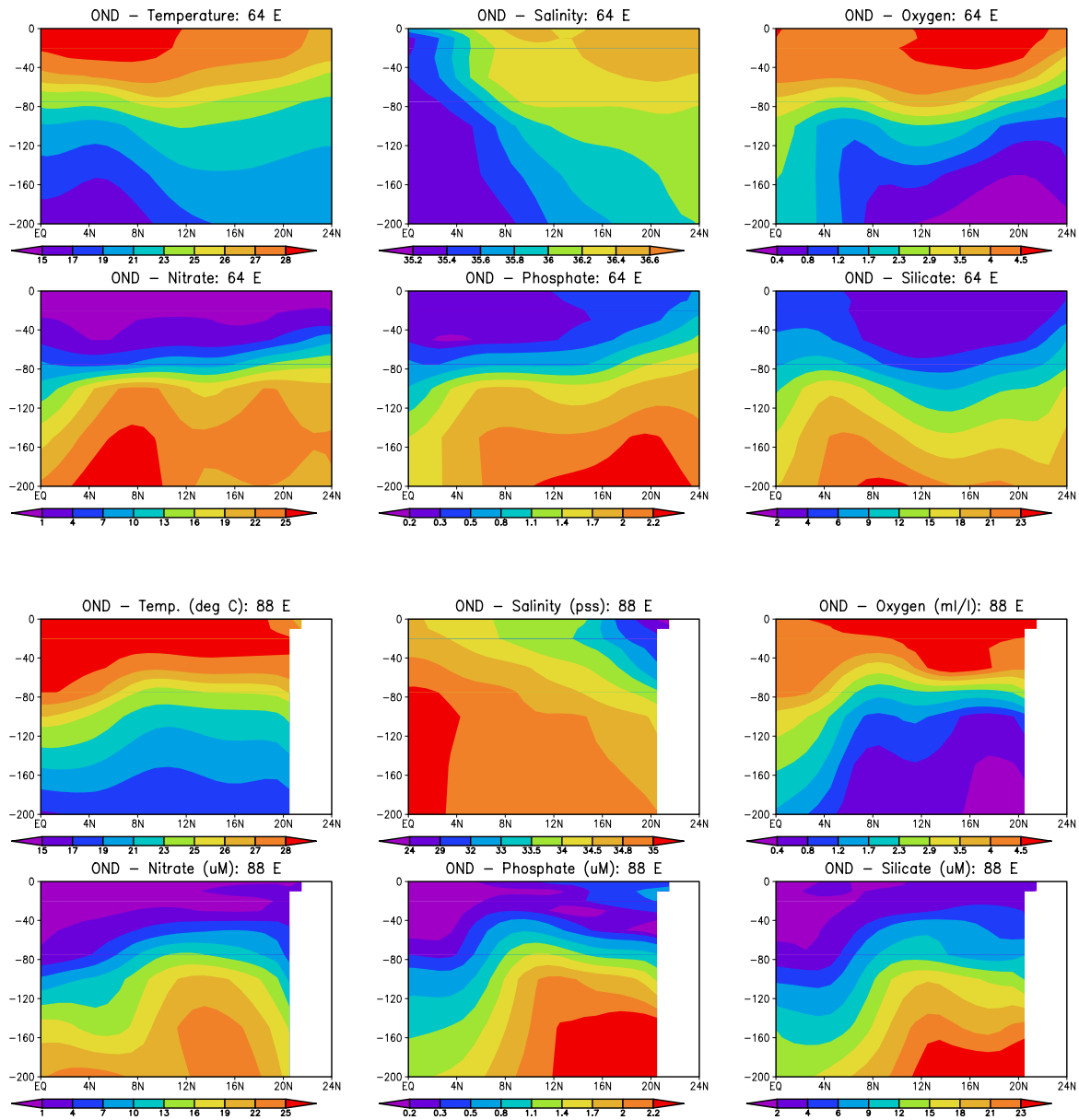


Figure 6