

Chapter 6 – Role of eddies in the distribution of nutrients and Chlorophyll

6.1. Introduction

It has been found that from the previous chapters that eddy displaced the isopycnals, which were uplifted/depressed at the center of cyclonic/anticyclonic eddies. The up-sloping of the isopycnals due to eddy-pumping are known to enrich the oligotrophic surface layers [Falkowski *et al.*, 1991, Olaisala *et al.*, 1993, Mc Gillicuddy and Robinson, 1997, Mc Gillicuddy *et al.*, 1998, Seki *et al.*, 2001]. In the presence of adequate sunlight this will lead to enhanced rates of biological productivity. In the case of anticyclonic eddies, the nutrient poor surface waters are pushed down to deeper layers and do not result in any ecosystem response [Siegel *et al.*, 1999].

In the north Indian Ocean, which lies in the tropics, light is usually not a limiting factor that determines biological productivity. Hence, any mechanism that brings or take away the nutrients from the euphotic zone would determine the biological productivity of the region. In the Arabian Sea, biological productivity is tightly coupled to the atmospheric forcing. In winter, it is the convective mixing that result in high productivity [Madhupratap *et al.*, 1996, Prasanna Kumar *et al.*, 2001], while in summer it is through the coastal upwelling along the western margin as well as cyclonic wind-stress curl-driven open ocean upwelling in the north of the Findlater Jet [Prasanna Kumar *et al.*, 2000]. The two transition seasons, fall and spring intermonsoons, represents the least productive regime. The BOB, however, is traditionally considered to be a low productive basin. The recent measurements showed that it is 8 times less productive compared to the Arabian Sea [Prasanna Kumar *et al.*, 2002] and marked with feeble seasonality. This

primarily stems from the fact that processes operating in the Arabian Sea such as convective mixing and upwelling are not known to operate here. Upwelling along the western margins of the BOB was reported earlier, but confined very close to the coast [Shetye *et al.*, 1991]. Heavy sediment load brought in by the rivers would suppress whatsoever little effect of upwelling by inhibiting the penetration of light to deeper layers. Notwithstanding this, comparable rates of annual export of organic carbon by the BOB to the deep with that of Arabian sea [Ramaswamy and Nair, 1994] seems to be a puzzle. In this chapter the role of eddies is explored, which is expected to shed some light on this paradox.

6.2. Summer monsoon 2001

Nutrient structure along the central BOB showed that the concentrations were below detectable levels in the upper 40 m of the water column (Figure 6.2.1). However, centered at 9°N a doming in the isopleths was noticed. This doming was consistent with the thermohaline structure and the satellite derived sea-level anomaly, which showed the presence of a cyclonic eddy (CES1) at this location. Under the influence of CES1 the 1 μ mol nitrate isopleth was uplifted by about 45 meters (from 80 to 35 m). Similar doming can be seen for phosphate as well as silicate. However, two other eddies CES2 (16°N) and CES3 (19°N) that were prominently present in the thermohaline structure did not show its signature distinctly by way of upward displacement of isopleths at these location. In addition to the doming of isopleths, the nutrient distribution showed a general northward shoaling.

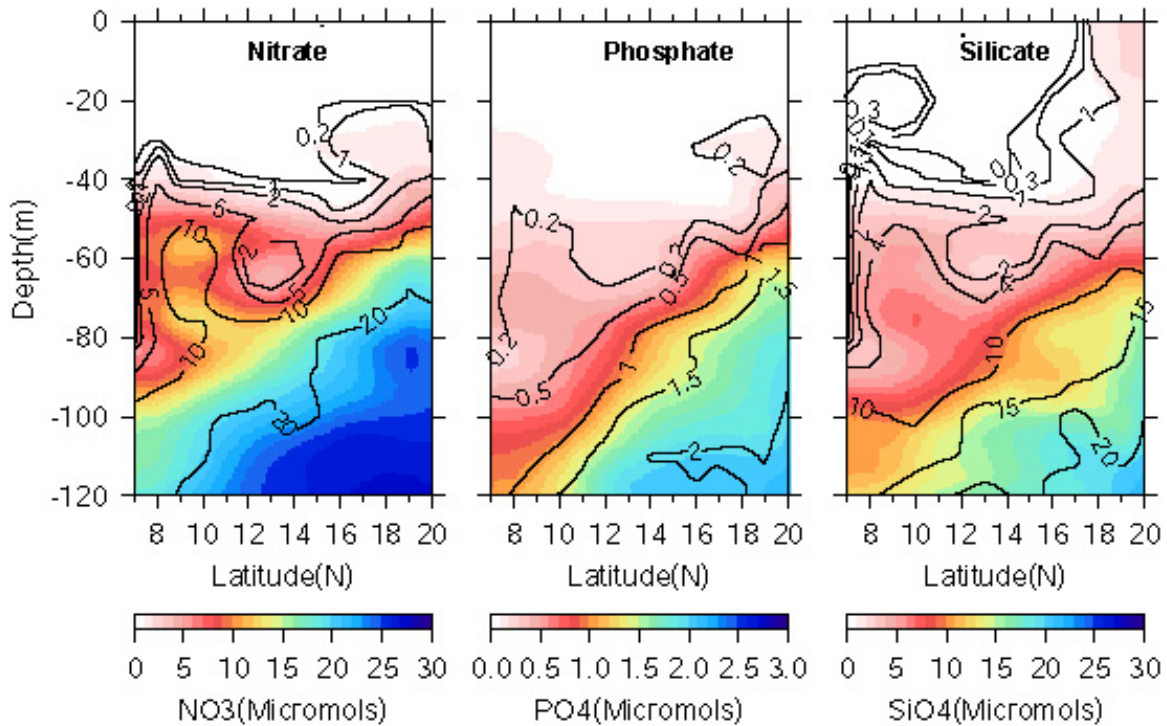


Figure 6.2.1. Vertical structure of nutrients in the central BOB (88°E) during summer monsoon (July-August, 2001). Shoaling of isopleths can be seen centered about 9°N coinciding with the location of the cyclonic eddy CES1. Also a surface enhancement of nutrients can be seen in the northern part of the transect. Note that only selected contours are drawn.

Chlorophyll *a* distribution showed a subsurface chlorophyll maxima (SCM) located at about 40 m depth in the south with a concentration of 0.3 mg/m^3 which showed a gradual shoaling towards north (Figure 6.2.2a), consistent with the thermohaline and the nutrient structure. Enhanced level of chlorophyll was noticed at three locations between 9 and 12°N, between 16 and 18°N, and between 18 and 20 °N. The first one was linked to the cyclonic eddy CES1 which pumped nutrient-rich subsurface waters into the euphotic zone and the second one with the CES2, whereas the third region of high chlorophyll was found to be at the surface ($> 0.2 \text{ mg/m}^3$), coinciding with the location of CES3. But CES3 was mainly confined below 50 m (see Figure 4.2.1.1). In such case one would expect an enhanced level of nutrient and chlorophyll *a* some where in that depth region. Though nutrient was higher at the location of CES3, enhanced levels of chlorophyll was noticed at the surface. Surface enrichment of the nutrients was also noted in this location,

which indicates a riverine source, since this last sampling location along the central BOB falls close to the Ganges-Bhramaputra discharge region. Thus, the enhanced level of chlorophyll resulted from a combination of riverine input, eddy pumping and by the northward shoaling of the nutrient isopleths.

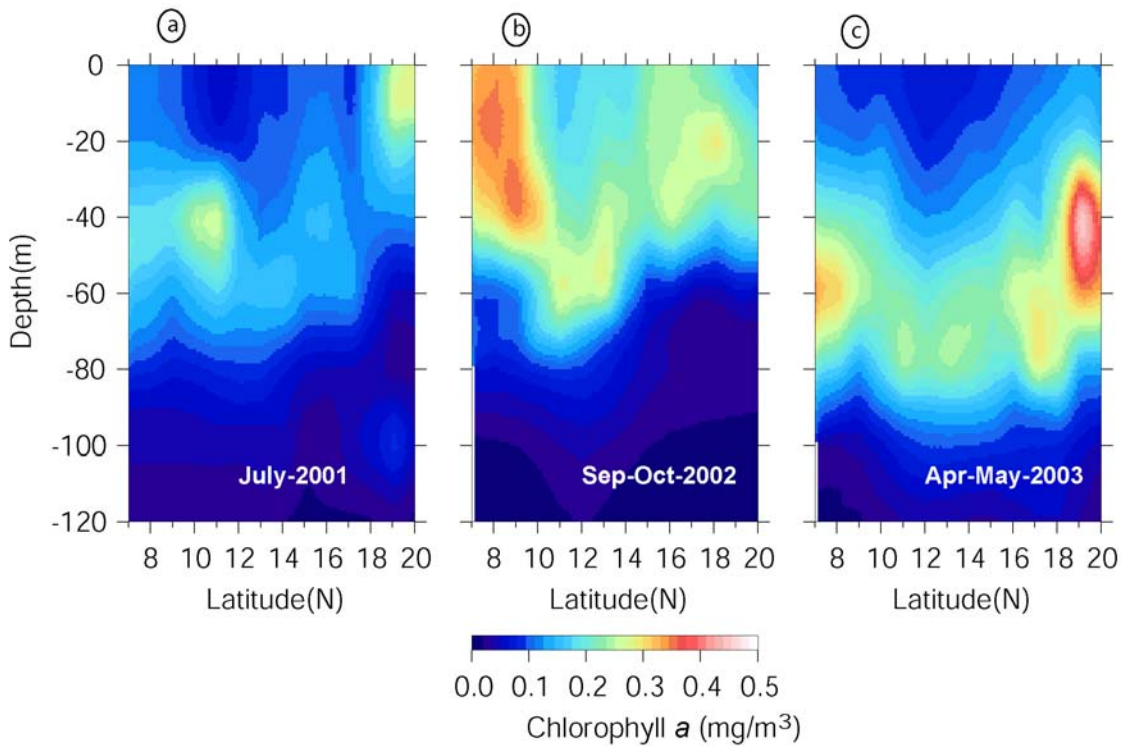


Figure.6.2.2. Chlorophyll *a* concentration during the three seasons a) summer monsoon b) fall inter monsoon and c) spring intermonsoon along the central BOB (88°E). Enhancement of chlorophyll *a* concentration can be seen coinciding with the location of cyclonic eddies. CES1(9°N) during summer monsoon, CEF1(9°N), CEF3(14°N) during fall inter-monsoon, and CESP1 (11°N), CESP3 (16°N) and CESP4 (19°N) during spring intermonsoon. Subsurface chlorophyll maxima centered at 12°N was depressed during fall intermonsoon (Sept-Oct, 2002) under the influence of anticyclonic eddy ACF2 (12°N).

However, the lack of a subsurface chlorophyll maximum in the north where CES3 was located indicated the possibility of limitation of light due to the enormous quantity of sediment load brought-in by the river discharge.

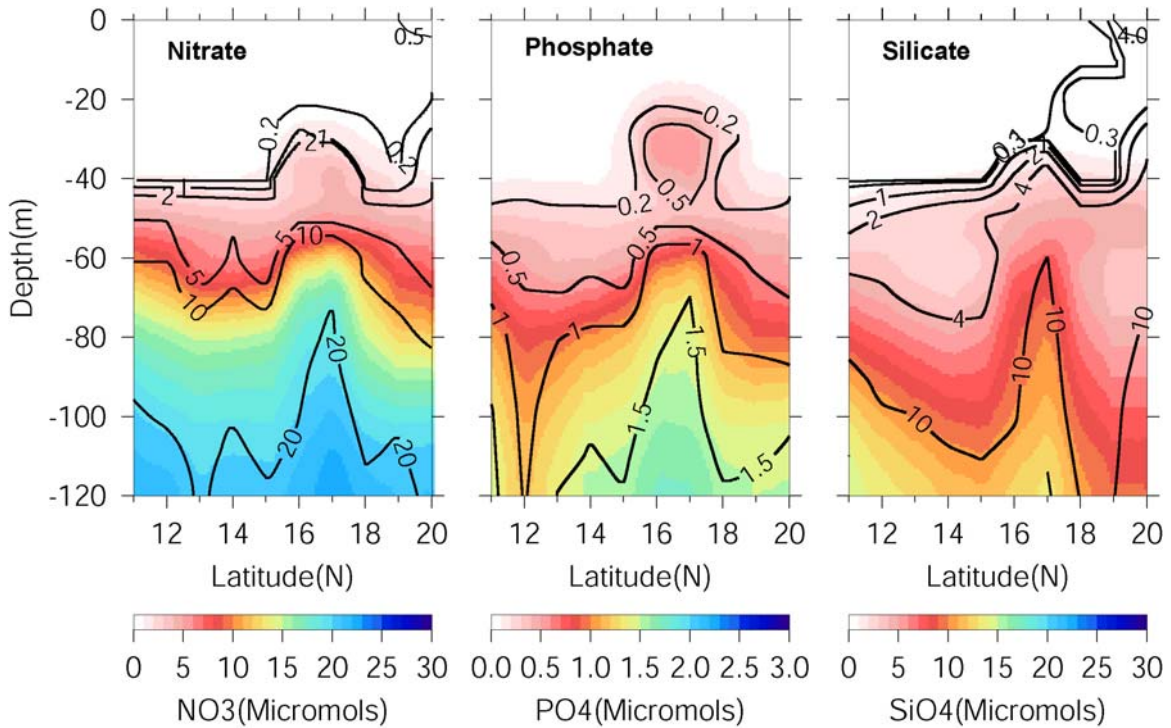


Figure.6.2.3. Nutrients along the western boundary of the BOB during summer monsoon (July-August, 2001). The region between 16 and 18°N is enriched with nutrients because of the upward eddy pumping associated with NCE-2001. Note that only selected contours are drawn.

Surface nutrient concentration, in general, was found to be below detection limits along the western boundary too [Figure 6.2.3]. However, in the north the nitrate as well as silicate showed a surface enhancement up to 0.5 and 4 μ mol. The most prominent feature was the doming of nutrient isopleths centered about 17°N, which forms the center of NCE during 2001. Under the influence of the NCE, 1 μ mol contour for nitrate shoaled to about 30 m. Similar enhancements were also seen in the phosphate as well as silicate distribution. Concurrent with this nutrient enrichment, chlorophyll *a* concentrations also showed enhancement from 0.25 mg/m^3 within the SCM in the south to 0.35 mg/m^3 in the location of NCE. Apart from the enhancement of chlorophyll within the SCM, the SCM itself shoaled under the influence of NCE (Figure 6.2.4).

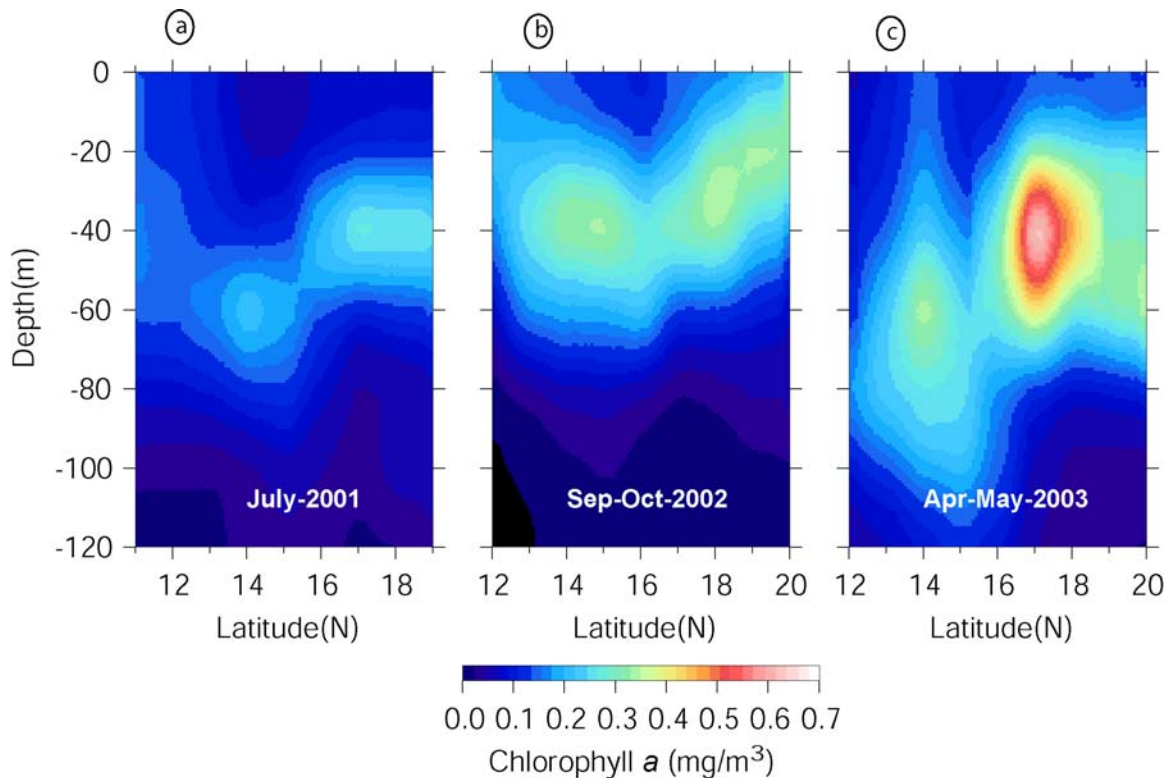


Figure.6.2.4 Chlorophyll a concentration during the three seasons a) summer monsoon b) fall inter monsoon c) spring intermonsoon along the western boundary of BOB. Enhancement of chlorophyll a concentration can be seen between 16 and 19°N coinciding with the location of NCE.

6.3. Fall intermonsoon 2002

Prominent features in the nutrient structure during fall intermonsoon were the undulations in the isopleths (Figure 6.3.1). Doming of isopleths was noticed centered at 9 (CEF1) and 14°N (CEF3) and a depression can be found centered at 11°N (ACF2). The upper 20 meters along the central BOB was oligotrophic, however, the undulations enhanced the level of nutrients along the track. For example, 1 μ mol contour reached 20 m depth under the influence of cyclonic eddy CEF1, corresponding enrichment was found for CEF3 also. However, the anticyclonic eddy ACF2 has pushed down the nutrient

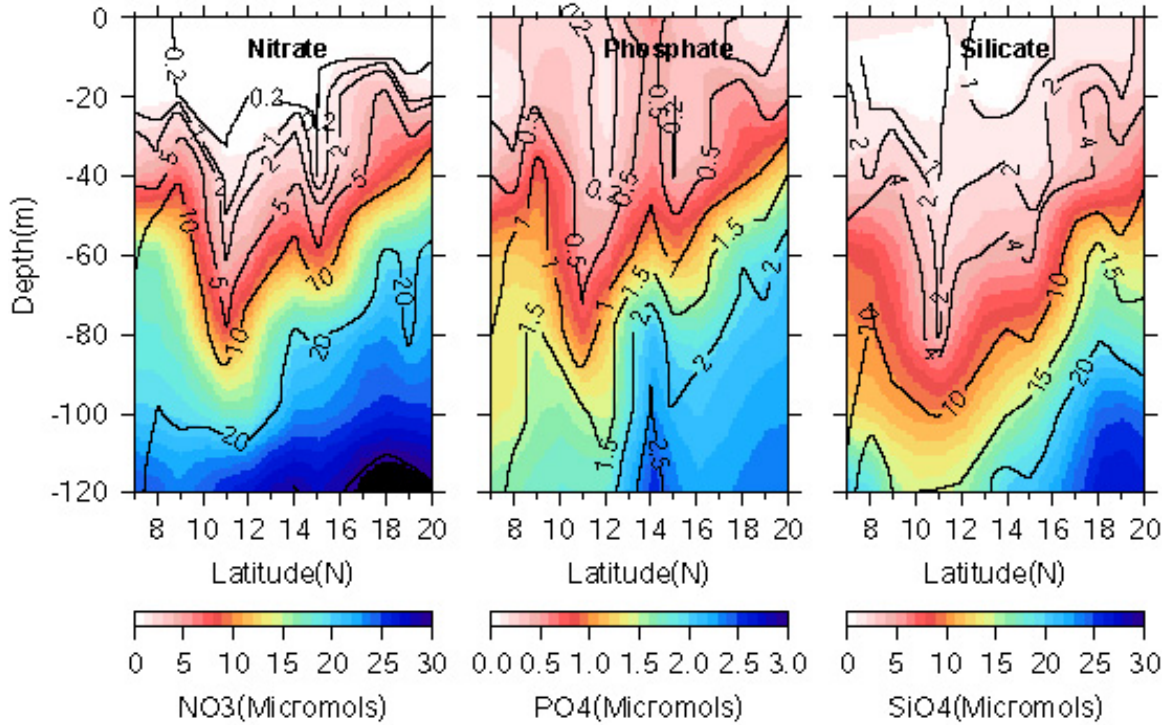


Figure 6.3.1. Vertical structure of nutrients in the central BOB (88°E) during fall inter monsoon (Sep-Oct, 2002). under the influence of the cyclonic eddies CEF1 and CEF3 centered at 9 and 14°N the nutrient isopleths domed while that under the influence of anticyclonic eddy ACF2 near 12°N isopleths are depressed. Note that only selected contours are drawn.

isopleths resulting in the depletion of nutrients in the euphotic zone. The general south-north shoaling noted during summer monsoon along in the central BOB was present during this season also. Along the western boundary also enhanced nutrient concentration was found at the location of NCE (18°N), whereas an anticyclonic eddy, which is a remnant of spring time circulation pushed the isopleths down resulting in nutrient depletion (Figure 6.3.2).

Variability in the chlorophyll *a* concentration followed the variability in the nutrient structure. Enhanced levels of chlorophyll *a* were noticed between 7-10°N, 13-15°N and 16-18°N. The first zone corresponds to the location of CEF1, second one with CEF3 and the third one with a large cyclonic circulation in which CEF3 was a part (Figure 6.2.2b).

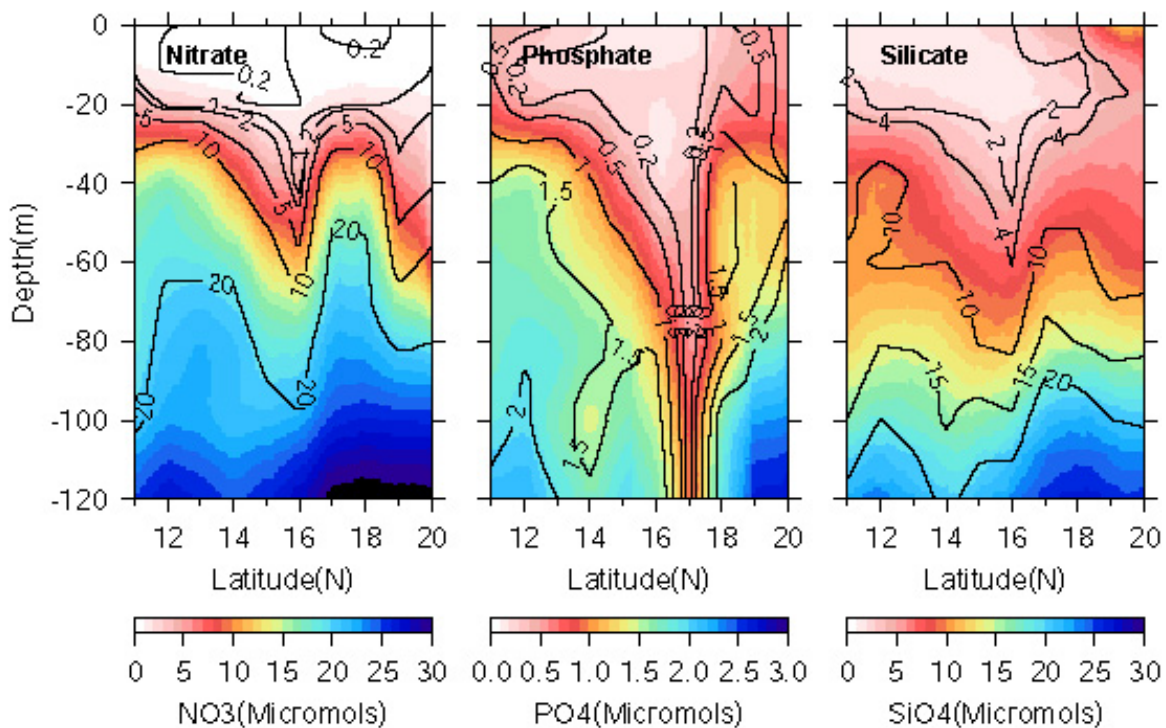


Figure.6.3.2. Nutrients along the western boundary of the BOB during fall inter monsoon (Sep-Oct, 2002). The region between 16 and 18°N is enriched with nutrients because of the upward eddy-pumping associated with NCE-2002. Depression in nutrient isopleth seen between 14-16°N can be linked to the anticyclonic circulation. Note that only selected contours are drawn.

Along the western boundary, enhanced levels of chlorophyll *a* were noticed at 14° and at 18°N. Both corresponds to the location of cyclonic eddies SCE and NCE (Figure 6.2.4b). No significant decrease in the chlorophyll *a* concentration was noticed at 16°N where a remnant anticyclonic circulation was found.

6.4. Spring intermonsoon 2003

One large scale feature in the distribution of nutrients along the central BOB was a depression in the vertical structure. This depression rendered the top 30 m of the water column oligotrophic during this season. However, the vertical nutrient structure was characterized by several undulations that domed and depressed at several locations where

eddies were present (Figure 6.4.1). Noticeable domings were found between 11-12°N (CESP1), 14-16°N(CESP3) and 18-20°N(CESP4) and depressions at 12-14°N(ACSP2) and 16-18°N. These locations were close to the cyclonic and anticyclonic eddies described in chapter 4. Vertical structure showed that the doming resulted in enhancing the levels of nutrients in the upper 50 m of the water column. For example 2 μ mol nitrate contour has shoaled to about 35 m for CESP4. Corresponding enrichment in phosphate can also be seen, however concentration of silicate does not vary much because of the high ambient concentration. Another noteworthy feature was the high surface concentration of silicate, 2 μ mol, situated near 13°N (Figure 6.4.1), which indicated the advection of surface waters from source region such as Ganges-Brahmaputra or Irawaddy river out flows.

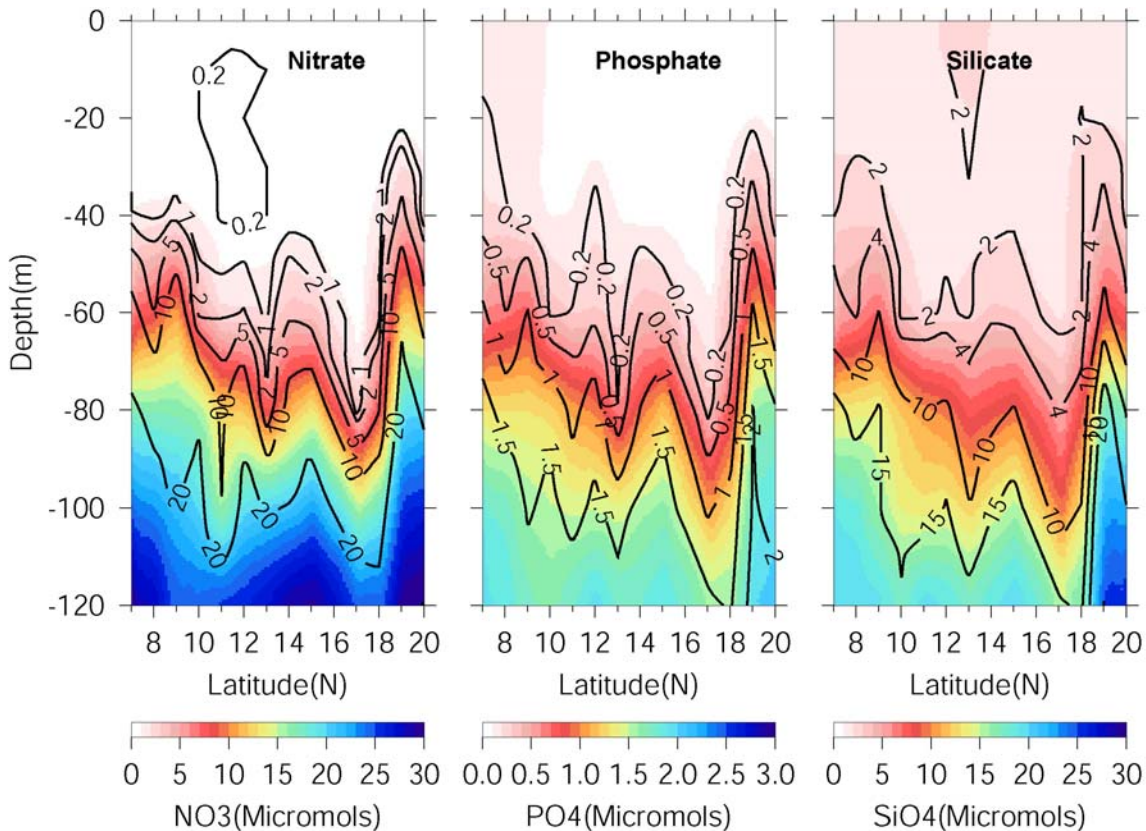


Figure 6.4.1. Vertical structure of nutrients in the central BOB (88°E) during Spring inter monsoon (Apr-May, 2003). Note that only selected contours are drawn.

Chlorophyll structure also showed elevated a level coinciding with the location of eddies. A major enhancement (0.6 mg/m^3) along the track occurred at 19°N corresponding with the location of CESP4. Elevated values in SCM could be seen centered about 16°N , 11°N and 9°N which corresponds to the location of CESP3, CESP1 and a large cyclonic circulation which had not been sampled as it fell outside the track (Figure 6.2.2c).

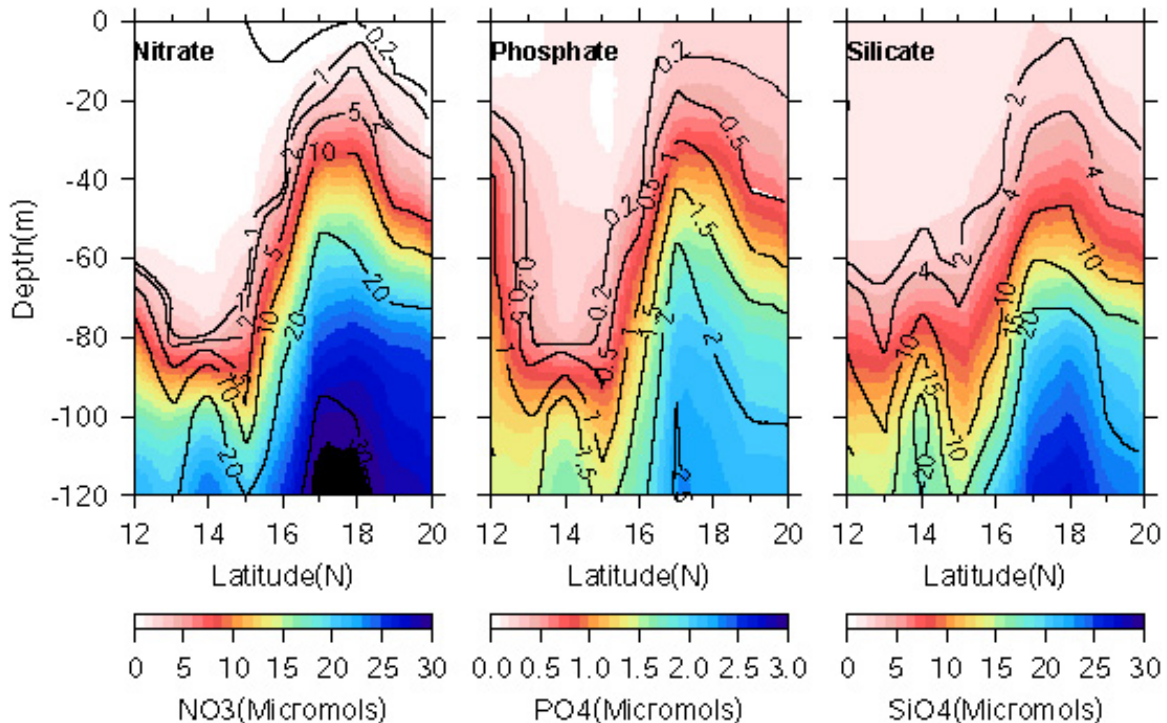


Figure.6.4.2. Nutrients along the western boundary of the BOB during spring inter monsoon (Apr-May, 2003). The region between 16 and 18°N was enriched with nutrients because of the upward eddy-pumping associated with NCE-2003. Depression in nutrient isopleth seen between 14 - 16°N can be linked to the anticyclonic circulation. Note that only selected contours are drawn.

Along the western boundary also the undulation in the nutrient structure coincided with the location of eddies (Figure 6.4.2). Maximum upwelling of nutrient isopleths occurred between 17 - 20°N coinciding with the location of NCE. Another upwelling was noticed at 14° , again corresponding with the location of a cyclonic circulation. In the case of NCE, the $2 \mu \text{ mol}$ contour reached 20 m depth which was located at a depth of 60 m outside the eddy. Similar doming coinciding with the location of eddies could be seen for phosphate and silicate.

Chlorophyll profile also showed enhanced concentrations coinciding with the locations of eddies along the western boundary (Figure 6.2.4c). Two such regions were between 16-18°N and 13-15°N, the first one was the location of NCE and the second one was the location of a transient cyclonic eddy SCE discussed in chapter 3.

6.5. Summary

Variability in the nutrient and the chlorophyll concentrations have been discussed in this chapter in the context of cyclonic and anticyclonic eddies. Under normal situation, the upper 20 m of the water column in all the 3 seasons were devoid of nutrients, except in the north. Accordingly, the chlorophyll distribution showed the surface chlorophyll was, in general, about 0.1 mg/m^3 and subsurface chlorophyll maximum (SCM) existed in all the seasons. During summer and fall intermonsoon, surface enrichment of nutrients occurred in the north due to the riverine input from Ganges-Brahmaputra river system. Hence the surface chlorophyll concentration also showed an increase in this region. In all the 3 seasons studied, large enhancement of nutrient was noticed in the locations of eddies both along the central as well as the western boundary of the BOB. This was mediated by the upward eddy-pumping which resulted in enhanced chlorophyll concentration. The upward eddy-pumping not only enhanced the chlorophyll content in the SCM, but moved it towards the surface. During summer the highest chlorophyll concentration was associated with cyclonic eddy NCE at 17°N along the western boundary and CES1 at 9°N with values in excess of 0.3 mg/m^3 . The highest eddy-induced chlorophyll concentration during fall intermonsoon was 0.4 mg/m^3 which was associated with cyclonic eddy CEF1. The highest eddy-induced chlorophyll concentration

among all the 3 seasons occurred during spring intermonsoon at 18°N along the western boundary associated with NCE and in the central BOB at 19°N associated with CESP4. In both cases the chlorophyll a concentrations were in excess of 0.6 mg/m³.

In summary, eddies enhanced the chlorophyll by 2 to 6 times by eddy-pumping of subsurface nutrient to upper water column. In addition to these eddy-mediated changes, perceptible enhancement of chlorophyll due to seasonally changing atmospheric forcing was not discernible. Thus, eddy-induced chlorophyll enhancement offers an alternate /additional mechanism to ballast theory and could at least partially resolve the issue of comparable rates of annual organic flux to deep in the high productive Arabian Sea and the low productive BOB.