

**A comparative estimate of carbon flux in the  
Arabian Sea and the Bay of Bengal**

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The Arabian Sea and Bay of Bengal are tropical basins experiencing monsoonal wind forcing which reverses semi-annually. This brings changes in physics, chemistry and biology of the upper water column on a seasonal scale and ultimately regulates the sinking fluxes of the region. An attempt is made here to focus on factors responsible for fluxes of carbon from the upper layers to the deep. Higher fluxes are observed during southwest and northeast season in both the regions. In contrast to Arabian Sea, an immense quantity of freshwater runoff together with warmer SST (~30°C) makes the northern Bay strongly stratified. The runoff also brings in billions of tonnes of fluvial matter as well. Stratification constrains subsurface nutrient input into the surface waters thereby reducing the primary production in the Bay of Bengal. The total living carbon content in the Bay of Bengal is much lower than in the Arabian Sea. Higher downward fluxes associated with deep mixed layer and high production in the Arabian Sea during summer and winter pinpoint importance of strong winds causing mixing and upwelling during summer and evaporative cooling and convection during winter. Inability of the low speed winds to break the stratification in the Bay of Bengal keeps the region low productive throughout the year. Therefore, river water associated with the terrigenous material due to ballast effect appears to swipe off surface producers to deep thereby increasing the downward fluxes of total particulates, which are sometimes even higher than that of the more productive Arabian Sea.

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## 1. Introduction

The Indian Ocean in the north comprises of the Arabian Sea (AS) and the Bay of Bengal (BOB), encompassing the Laccadive and the Andaman Seas. Although the geographical settings of these two basins are somewhat similar, the hydrographic and hydrochemical characteristics differ widely. This happens despite both seas coming under the influence of the seasonally changing monsoonal gyre (Wyrski, 1973) and have significant effects on global carbon and nitrogen cycles. The AS receives lower volumes of river runoff ( $0.3 \times 10^{12} \text{ m}^{-3} \text{ yr}^{-1}$ ) compared to BOB ( $1.6 \times 10^{12} \text{ m}^{-3} \text{ yr}^{-1}$ ). Rivers Tapi and Narmada are two of the very few major rivers draining into AS. On the other hand, a large number of rivers such as Irrawady, Brahmaputra, Ganges, Godavari, Krishna and Cauvery discharge into the BOB (Subramanian, 1993). As a result, BOB surface waters are 3-7psu less saline than the AS (Prasanna Kumar et al. 2002). Contrastingly, excessive evaporation over precipitation leads to the formation of higher surface salinities in the AS -Arabian Sea High Salinity Water (ASHSW; ca. 36 psu) which sink and renew deep-waters (Dietrich, 1973). Strong south-westerly winds during southwest monsoon result in coastal and open ocean upwelling in the AS. Both seas experience atmospheric forcing over seasons leading to regular intra-annual oscillations in biological productivity. These result in seasonal as well as yearly variations in fluxes from the upper ocean to the deep (Haake et al., 1993; Lee et al., 1998; Unger et al., 2003). However, the relationships between primary producers, consumers and flux rates of AS and BOB are not completely understood. The purpose of this paper is to find out 1) the pathways of transport of organic carbon in the two seas and 2) the reasons why the observed productivity in the two basins and particle fluxes to the deep do not often match. To address these questions, data sets collected from 1994 onwards under the programmes -Joint Global Ocean Flux Study (JGOFS-India), Bay of Bengal Process Studies (BOBPS) and Marine Research on Living Resources (MRLR) were used. Data collected under the Indo-German sediment trap programme (AS - May 1986 to May 1987 and BOB - October 1987 to October 1988, Ittekkot et al., 1991; Nair et al., 1989; Ramaswamy and Nair, 1994) were also used for substantiating the fluxes. Though these data sets have come from various years, an attempt is made to rationalize the observations with the prime idea of realizing the fluxes in these basins with quite contrasting productivity patterns.

## 2. Materials and Methods

Based on the regional monsoonal cycles, the AS and BOB were sampled seasonally under the JGOFS and BOBPS. In the AS, collections were made during northeast monsoon (NEM, February 1995), southwest monsoon (SWM, July-August 1995 and August 1996) and spring inter-monsoon (SPIM, April-May 1994) under JGOFS. Bay of Bengal measurements under BOBPS were limited to southwest monsoon (SWM, July-August 2001) and fall intermonsoon (FIM, September- October 2002). We used the data set from BOB collected under the MRLR project for NEM.

Locations of sampling from the coastal and open ocean areas in the Arabian Sea and Bay of Bengal are shown in Figure 1. Essentially JGOFS protocol (UNESCO, 1994) were followed for collection and analyses of the samples. Many details regarding the collection and processing of samples of parameters measured are given in Krishnaswamy and Nair (1996). Cruise details are shown in Table 1. Procedures for certain biological parameters are mentioned in brief. Water samples were collected by CTD (Sea-Bird electronics) rosette sampler fitted with 12 litre GO Flo (General Oceanics, Miami FL, USA) bottles. Samples from upper 120 m depth (0, 10, 20,40,60,80,100 and 120 m) were used for the analysis of biological and chemical parameters. Meteorological data was obtained using the shipboard automatic weather station. Temperature and salinity data profiles were taken from pre-calibrated CTD. Samples were analysed for nutrients (nitrite, nitrate and silicate) with a SKALAR auto-analyser. However, only nitrate values are discussed in this paper.

Primary production was measured by  $^{14}\text{C}$ -technique at all the stations. Four 300 ml capacity Polycarbonate (Nalgene, USA) bottles (3 light, 1 dark) at each depth were used for this study. After adding  $^{14}\text{C}$ , these bottles were incubated *in-situ* at respective depths from sunrise to sunset (~12 hrs). Incorporation of  $\text{NaH}^{14}\text{CO}_3$  by phytoplankton was determined by filtering incubated samples through 25 mm GF/F filters, exposed them to fumes of HCl and the radioactivity was measured with a Packard 2500 TR scintillation counter. Care was taken not to expose PP samples to light prior to filtration.

Phytoplankton cell counts were noted from samples fixed with 2% Lugol's iodine and 3% formaldehyde (final concentration v/v). A settling and siphoning procedure was followed to concentrate samples. Two replicates of 1ml concentrate were examined microscopically in a Sedgwick-Rafter plankton counting chamber at 200X magnification.

For chlorophyll estimation, samples were filtered through 47mm GF/F filters (0.7µm pore size) and extracted in 10 ml 90% acetone in dark for 24 hrs in a refrigerator. A Turner Designs fluorometer was used for measuring fluorescence. Chl *a* (mg m<sup>-3</sup>) values were converted to carbon using 50 as a conversion factor (Banse, 1988).

Bacterial production rates were calculated using the <sup>3</sup>H-tritiated thymidine incorporation rates, wherein an aliquot of 100µl working solution (59 nmole) <sup>3</sup>H-tritiated thymidine (BARC, Mumbai) was added to 20ml triplicate samples from each depth. These samples were then incubated in the dark for 1 hr. The uptake was stopped by adding 37% formaldehyde to yield a final concentration of 3%. Samples were filtered through 0.22µm cellulose acetate filter and cold TCA precipitation and ethanol extraction carried out. Liquid scintillation cocktail was added to each vial with the filters and the later assayed for radioactivity using Packard 2500TR liquid scintillation counter. A factor of 11 fg C per bacterial cell was used for calculating bacterial carbon (Garrison et al., 2000).

A known volume of water sample (10L) initially screened gently through 200µm mesh size for microzooplankton studies. This was then siphoned through a PVC tubing with its cod end fitted with a 20µm Nitex screen to concentrate to 100ml. Lugol's iodine was added to a final concentration of 1% to fix them and formaldehyde (3% final concentration v/v) as a preservative. Identification, counting and sizing of microzooplankton was carried out using an inverted microscope at 100 to 400X magnification.

The length and breadth from 50 individuals of each group were measured and used to calculate biovolume using appropriate geometric formula (Edler, 1979). Carbon was estimated from biovolumes by using biovolume to carbon conversion factors provided by Putt and Stoecker (1989) for ciliates; by Lessard (1991) for heterotrophic dinoflagellates and by Michaels et al. (1995) for sarcodines. Naupliar carbon was estimated according to Berggreen et al. (1988). 30% of the total estimated volume was added to compensate for shrinkage due to Lugol's iodine fixation (Muller and Geller, 1993).

Mesozooplankton samples were collected with a Multiple Plankton Net of 0.25 m<sup>2</sup> mouth area. Although, five depths (1000-500m; 500-300m; 300-base of thermocline; base of thermocline to top of thermocline and top of thermocline to surface) were sampled, data set of only latter two strata (0-200m) are used in the present study. The biomass of mesozooplankton was estimated before preservation by the conventional

displacement volume method, wherein concentrated samples were blotted on absorbent paper and then displaced volume was measured in a graduated cylinder. The displacement volume was converted to dry weight using a factor of 0.075 g dry wt ml<sup>-1</sup> and then to carbon as 34% of the dry weight (Madhupratap et al. 1981).

At times *Pyrosomes* occurred in mat form in the Bay of Bengal and it was difficult to measure their total biomass by displacement method. Normally they were filled-up into 1 or 2 L polythene bottles and an estimation of their volume was noted. Five replicates of known wet weight of the *Pyrosomes* were dried and their dry weights were  $18 \pm 2\%$  of the wet weight. Assuming, 30% of this dry weight to be carbon, their carbon biomass was calculated and included into total biomass.

Energy required by an organism to sustain their biomass was calculated based on gross growth efficiencies, which were 0.3 in mesozooplankton (Ikeda and Matoda, 1978); 0.4 in microzooplankton (Fenchel, 1987), and 0.5 in bacteria (Cole et al., 1988).

Particulate organic carbon suspended in the water column (without excluding phytoplankton/or zooplankton) was analyzed by CHN analyser by filtering known volume (3 litre) of whole water sample onto a pre-combusted 47mm diameter GF/F filter (0.7µm pore size). Individual sample filter was wrapped in precombusted aluminium foil and stored frozen at low temperature (-20°C) until analysis. In the laboratory, these filters were dried overnight at 60°C and exposed to fuming HCL to remove inorganic carbonate. All filters were dried at 60°C before cutting into 4 equal parts for POC analysis on a Perkin Elmer 2400 CHN analyzer. Minimum of two quarters of the filter papers were used for analyzing the carbon contents. Total living particulate carbon (TLPC) was calculated as the sum total of chlorophyll *a*, bacteria, microzooplankton, and mesozooplankton standing stock. This TLPC was subtracted from POC to obtain non-living particulate carbon (NLPC).

Bacterial, phytoplankton and microzooplankton data were first integrated and converted to carbon biomass. These were then log-transformed ( $\log_{10} X+1$ ) to normalize and correlation was determined using the excel package.

Data from different depths from a sampling location were integrated vertically to obtain column values, the data from different sampling stations (spatial) were compared for realizing a trend, if there were any.

Arabian Sea data on wind speed, sea surface temperature (SST) and mixed layer depth (MLD) reported earlier by Prasanna Kumar et al. (2002) were used to understand the changes in the top layer of the ocean over seasons in the open ocean along 64° E.

### 3. Results

#### 3.1 Arabian Sea

During SWM, winds were strong (up to  $17 \text{ m s}^{-1}$ ) and southerly with the highest speeds occurring near the axis of Findlater Jet (16-17° N). During NEM, winds were generally weak ( $2\text{-}7 \text{ m s}^{-1}$ ) and northerly/north-easterly. SPIM (March to May), which is a transitional period between NEM and SWM, had light winds ( $< 5 \text{ m s}^{-1}$ ).

SST did not show any significant north-south variation during SWM season. Temperature was around  $26.5^\circ\text{C}$ . During NEM, SST decreased from  $28^\circ\text{C}$  in the southern latitudes to about  $24^\circ\text{C}$  in the north, whereas, in SPIM the SST was high ( $\sim 29^\circ\text{C}$ ) throughout the AS.

However, MLD during SWM shoaled from 100m depth in the south to about 45m near the axis of the Findlater Jet and remained shallow north of the Jet.

An intense low-altitude wind jet that flows across the Arabian Sea from East Africa to the Indian Subcontinent during southwest monsoon is known as the Findlater jet (Findlater, 1969). The MLD during NEM was deep in the north (deepest was 120 m at  $17^\circ\text{N}$ ) and shoaled steadily to 65m (south of  $17^\circ\text{N}$ ). In SPIM, the MLD was shallow and varied between 30 and 35 m, but at  $19\text{-}20^\circ\text{N}$  it further shallowed to 10 m.

Along  $64^\circ\text{E}$  nitrate was at very low levels in the upper 50m in the south during SWM (Fig. 2a). During SPIM, surface nitrates were at undetectable levels in upper layers throughout the AS (Fig. 2b). About  $2\mu\text{M}$  of nitrate concentration in the surface waters in the northern latitudes was recorded during NEM (Fig. 2c).

The column values of chlorophyll *a* reflected these seasonal trends with higher average concentrations during SWM ( $41 \text{ mg m}^{-2}$ ) followed by NEM ( $20 \text{ mg m}^{-2}$ ) and SPIM ( $11 \text{ mg m}^{-2}$ ). Primary production (PP,  $\text{mg C m}^{-2} \text{ d}^{-1}$ ) also showed seasonal variations similar to that of Chl *a*. PP was the highest during SWM ( $950 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) and intermediate during NEM ( $510 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) and lowest during SPIM ( $210 \text{ mg C m}^{-2} \text{ d}^{-1}$ ). Moderate ( $643 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) to high ( $985 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) PP was observed in the northern region ( $21^\circ\text{N } 64^\circ\text{E}$ ) in NEM.

Numerical abundance of phytoplankton (cells  $\times 10^8 \text{ m}^{-2}$ ) during the three seasons varied from 0.3 to 10 (SWM), 1.7 to 170 (NEM) and 0.4 to 1.2 (SPIM). Diatoms formed the major group with contributions up to 86% of the total phytoplankton populations. Unlike phytoplankton, bacterial densities were the highest during SPIM, ranging from 0.24 to  $0.96 \times 10^9 \text{ cells l}^{-1}$ . In contrast to SPIM, bacterial abundance was about an order of magnitude lower during NEM ( $0.05$  to  $0.09 \times 10^9 \text{ cells l}^{-1}$ ) and SWM ( $0.011$  to  $0.64 \times 10^9 \text{ cells l}^{-1}$ ). Bacterial production (BP) was very high during SPIM ( $25$  to  $50 \text{ p mol l}^{-1} \text{ h}^{-1}$ ) compared to SWM ( $0.062$  to  $3 \text{ p mol l}^{-1} \text{ h}^{-1}$ ) or NEM ( $1.36$  and  $4.66 \text{ p mole l}^{-1} \text{ h}^{-1}$ ).

Microzooplankton (20-200 $\mu\text{m}$  in size) population also showed variations similar to that of bacteria seasonally with higher numbers during SPIM ( $700 \text{ l}^{-1}$ ) than in SWM ( $300 \text{ l}^{-1}$ ) or NEM ( $130 \text{ l}^{-1}$ ). Ciliates and heterotrophic dinoflagellates dominated the community (ca. 85-90%). Tintinnid ciliates, *Tintinnopsis*, *Eutintinnus*, *Favella*, *Amphorides*, *Codonellopsis*, *Parundella*, *Rhabdonellopsis*, *Dyctyocysta*, *Codonella*, *Tintinnus*, and *Xystonellopsis* were dominant. *Strobilidium* and *Strombidium spp.* were common among the naked ciliates. Nauplii and copepodite stages of micrometazoans and radiolarians, acantharians, and foraminiferans were also frequently found. Heterotrophic dinoflagellates mostly comprised of *Protoperidinium spp.*, *Gymnodinium spp.*, *Gyrodinium spp.*, *Dynophysis*, and *Noctiluca*. Average mezooplankton biomass was almost invariable irrespective of seasons (SPIM,  $0.6 \text{ ml m}^{-3}$ ; SWM and NEM,  $0.5 \text{ ml m}^{-3}$ ). Particulate organic carbon was high during NEM ( $140$ - $290 \text{ mg m}^{-3}$ ) followed by SWM ( $80$ - $195$ ) and least during SPIM ( $73$ - $150$ ).

Statistically, MZP relationship was significant with phytoplankton both during NEM ( $r=0.3$ ,  $p<0.02$ ,  $n=48$ ) and SWM ( $r=0.6$ ,  $p<0.001$ ,  $n=56$ ) and with bacteria in SPIM ( $r=0.76$ ;  $p<0.001$ ,  $n=30$ ). But, BP and PP were decoupled particularly during SPIM ( $r=-0.6$ ;  $p<0.001$ ,  $n=41$ ).

### 3.2 Bay of Bengal

Winds varied from southwest to northwest during SWM (July-August 2001) and had a speed of about  $4 \text{ m s}^{-1}$  (south of  $15^\circ\text{N}$  along  $88^\circ\text{E}$ ) to  $10.5 \text{ m s}^{-1}$  (north of  $15^\circ\text{N}$ ). During FIM (September-October 2002), winds were more intense in the southern region (avg.  $7 \text{ m s}^{-1}$ , south of  $15^\circ\text{N}$ ) than in the north (ca.  $4 \text{ m s}^{-1}$ ). SSTs varied between  $28.4^\circ\text{C}$  and  $29.5^\circ\text{C}$  during SWM and were higher compared to AS with temperature around  $30^\circ\text{C}$ , sea surface was warmer during FIM. During SWM, MLD shoaled towards the north from  $25\text{m}$  (at  $9^\circ\text{N}$ ) to  $\leq 5\text{m}$  (at  $20^\circ\text{N}$ ). In the surface layer, salinity increased southwards from

ca. 27.6 psu at 17°N to about 33.5 psu south of 15°N. Similar to SMW, shallow MLD was also recorded during FIM, which shoaled from ~30m in the south to  $\leq 5$ m towards the north (Fig. 2d). Surface salinity also decreased from south (~34.0 psu at 7°N) to north (~27 psu at 20°N).

Nitrate was low to undetectable levels in the upper waters (Fig. 2e) during both the seasons. Coastal waters during SWM had slightly higher phytoplankton biomass (chl *a*) in the upper 120m (chl *a*; 12-19 mg m<sup>-2</sup>) than the oceanic (9-11 mg m<sup>-2</sup>). These ranges are more or less comparable to FIM (coastal: 9-18 mg m<sup>-2</sup>; oceanic: 10-24 mg m<sup>-2</sup>). SCM coinciding with the nutricline depth (ca. 40m) was observed below mixed layer at most of the stations during SWM. The observed PP rate during FIM varied from 180 to 512 mg C m<sup>-2</sup> d<sup>-1</sup> and from 90-520 mg C m<sup>-2</sup> d<sup>-1</sup> during SWM. Corresponding to chl *a* estimates, the phytoplankton cell counts in upper 60m depth ranged from 0.41 x 10<sup>8</sup> to 7.1 x 10<sup>8</sup> m<sup>-2</sup> during SWM. This range is slightly higher than that of the FIM (0.19 x 10<sup>8</sup> to 2.9 x 10<sup>8</sup> m<sup>-2</sup>). Northern most stations were richer in phytoplankton cell counts during both the seasons. Diatoms dominated the phytoplankton population forming ca. 85% during both the seasons.

Bacterial abundance in SWM was somewhat higher (0.02 to 59.7 x 10<sup>9</sup> l<sup>-1</sup>) than that of FIM (0.04-2.6 x 10<sup>9</sup> cells l<sup>-1</sup>). Clear subsurface maxima were also evident at most of the stations. Mesozooplankton biomass in the upper 1000m was similar during both the seasons (ca. 0.05 to 0.10 ml.m<sup>-3</sup>). At some stations (south of 15°N) huge swarms/colonies of *Pyrosoma* were observed even in deeper waters. They were sparse and occurred at surface during SWM. Variations in day-night biomass were imminent suggesting vertical migration (particularly during FIM) (Fig. 3a). Microzooplankton were dominated by ciliates and heterotrophic dinoflagellates like in the AS. Tintinnid ciliates, *Amphorella*, *Dictyocysta*, *Epiplocyclus*, *Eutintinnus*, *Rhabdonella*, *Salpingacantha*, *Salpingella* and *Undella* were predominant forms. Unidentified species of *Strobilidium* and *Strombidium* spp. dominated the naked ciliates. Heterotrophic dinoflagellates mostly comprised of *Gymnodinium* spp., *Gyrodinium* spp., and *Dynophysis*. Average cell concentrations of MZP were comparable during SWM (avg. 45 org. l<sup>-1</sup>) and FIM (avg. 50 org. l<sup>-1</sup>, upper 200m) but they were several fold lower than that observed from the AS (SPIM and SWM; Fig. 3b). Contribution by heterotrophic dinoflagellates to the total MZP community (ca. 50%) was not very different from that of AS. Abundance of ciliates contribution was relatively higher in AS (47%) than in Bay of Bengal (30%). Overall,



bacterial population showed an increase in BOB compared to the AS while MZP showed a decrease.

POC measurements made under MRLR showed relatively higher values during SWM (69-398 mg m<sup>-3</sup>) than NEM (56-264 mg m<sup>-3</sup>) and SPIM (103-213 mg m<sup>-3</sup>).

#### 4. Discussion

But for the common feature of monsoonal wind reversals, it is obvious that there are stark differences in physical and chemical fields between the AS and BOB over seasons. SSTs are lower during SWM and NEM in the AS because of upwelling and winter cooling respectively aiding pumping in of nutrients to upper layers thus increasing productivity. In the northern AS, nutrients during SWM were supplied by open ocean upwelling induced by positive wind stress curl. In southern areas also nutrients seem to be advected to open waters from the upwelling areas of western AS (Prasanna Kumar et al., 2001). High nutrient concentrations below the mixed layer (~50m) resulted in development of subsurface chlorophyll maximum (SCM) during SPIM, which fluctuated between 60 and 80m. Aeolian dust input as much as 100 million tones brought in by monsoon winds (Sirocko and Sarnthein, 1989) would aid higher production through availability of trace metals such as iron in this period. The AS thus remains productive for nearly 8-9 months (except SPIM, mid-march to June beginning). In the BOB this doesn't happen as SSTs are always higher. This warm SST plus the low salinity that lead to strong stratification prevents the entrainment of nutrients in the surface all through the year resulting in low primary productivity. The wind speeds thus not able to erode the thermocline. Several biological features (chl *a*, PP, phytoplankton abundance, MZP and mesozooplankton) therefore were several fold lower in the BOB compared to AS (Fig. 4). Data set of PP, chl *a*, abundance of bacteria, phytoplankton and microzooplankton at selected stations in the Arabian Sea and the Bay of Bengal are given in table 2. There are some records of higher chl *a* and PP from the BOB (see Madhupratap et al., 2003). Along inshore waters of the east coast of India during SPIM (Gomes et al., 2000) reported that in small pockets where eddy like structure was located, the PP ranged from 100-400 mg C m<sup>-3</sup> d<sup>-1</sup>, but the surrounding areas had maximum values of only 10-40 mg C m<sup>-3</sup> d<sup>-1</sup>. Antoine et al. (1996) calculated PP as high as 2000 mg C m<sup>-2</sup> d<sup>-1</sup> based on satellite chl *a* from the northern coastal region of BOB. However, from our observations and data it is clear that the total living carbon content in the AS and BOB are very different

In the AS, higher contribution to the total carbon pool is apparently from the non-living particulate organic carbon (NLPC). Total living particulate organic carbon [TLPC, zooplankton (micro- and meso) + phytoplankton + bacteria] biomass observed during SPIM ( $52 \text{ mg C m}^{-3}$ ) was comparable to SWM ( $52 \text{ mg C m}^{-3}$ ) and more than NEM ( $39 \text{ mg C m}^{-3}$ ) even though phytoplankton biomass was the lowest during SPIM (Fig. 5). These TLPC values contributed ca. 34-71%, 13-27% and 6.5-27% to the total POC during SPIM, NEM and SWM respectively. Amount of NLPC available during SPIM was comparable to that of productive seasons (NEM & SWM). MZP contributed up to 47, 37 and 26% of TLPC during SPIM, SWM and NEM, respectively. This points out the importance of MZP in the carbon transfer in the AS. As Landry et al. (1998) suggested, during SWM and NEM microzooplankton consume about 75-80% of the daily primary production in the western AS. It could be more during SPIM as their population is higher and phytoplankton production is the lowest. Our calculation carried out based on gross growth efficiency implies that bacterial and phytoplankton biomass are unable to cater to energy requirement of micro- and mesozooplankton (Gauns, 2000) except during SWM. With assumptions that (i) the requirements of MZP calculated based on the available factors is true, and (ii) their major source of energy is particulate form, then MZP, may alternatively switch over to NPLC for meeting their energy requirements. Different modes of nutrition (heterotrophic and mixotrophic) in dinoflagellates, a dominant group of MZP, is well known. Non-living particulate carbon was quite high in AS to meet up the energy required during SPIM (Fig. 5). Heterotrophic and mixotrophic modes are well represented in the marine plankton including mesozooplankton (Hanson, et al., 1991; Lessard, 1991) and are known to consume a variety of food items such as detrital material including carcasses and faeces. Previous studies (Berggreen et al. 1988, Ohman and Runge 1994) indicate that herbivorous zooplankton also consume other available particles apart from consuming phytoplankton, indicating switchover in feeding behavior. In the AS MZP and mesozooplankton are major players in conversion and remineralisation (Sarma et al., 2003). Because of their low preponderance in the BOB, the pathways of carbon may be taking different course (may be ballast effect, see later). Lower salinity, stratification and low phytoplankton availability appear to govern the biology of MZP in the BOB. We need to elucidate the ways of carbon transfer in the BOB as it has sizable bacterial abundance and POC.

Data obtained from drifting sediment traps deployed just below the euphotic zone during the present study in the AS have been used to delineate export fluxes from surface

waters. POC fluxes showed a gradient similar to PP patterns with enhanced export in the northern part of the Arabian Sea. During SWM, POC fluxes were higher (224-284, avg. 250 mg C m<sup>-2</sup> d<sup>-1</sup>) than NEM (135-260, avg. 192 mg C m<sup>-2</sup> d<sup>-1</sup>) and SPIM (161-202, avg. 182 mg C m<sup>-2</sup> d<sup>-1</sup>). Ramaswamy and Nair (1994) reported strong seasonality with generally lower particle fluxes in the northern Indian Ocean during the intermonsoon compared to the monsoon periods. Results of particulate organic carbon flux from the 1995 US JGOFS (Lee et al., 1998) Arabian Sea process study indicates that on an average only 4.3 – 8.2% of the carbon fixed by primary producers is exported to 100 m, which is similar to those found in the US JGOFS study in the equatorial Pacific. Our study points towards net heterotrophic conditions in the AS. Ratios between autotrophic to heterotrophic biomass was also quite low during SPIM (0.1) than that of SWM (0.7) or NEM (0.3). This is an important indication to suggest that heterotrophs dominate the living particulate carbon biomass especially during SPIM. Further, the amount of carbon reaching at 1000m [calculated from primary production using equation given by Suess (1980)] suggests seasonal differences i.e 0.09, 0.24 and 0.37 mg C m<sup>-3</sup> d<sup>-1</sup> during SPIM, NEM and SWM respectively.

With an estimated >100 million metric tones, the stocks of mesopelagic fish-mycetophids (Myctophidae) are very sizable in the Arabian Sea (Gjosaeter, 1984). They are strong diel migrators, coming to the surface layers at night for feeding and migrating down to 200-400m during day. Thus, migratory animals (eg. including mesozooplankton) feeding near the surface and then metabolizing and excreting at depth can also act as major vehicles transporting more organic matter to the deep. Mesozooplankton were observed to be mostly dominated by calanoid copepods forming as much as 61% during SWM and 25% during SPIM. Poecilostomatoida was the dominant (28.5%) during SPIM, Madhupratap et al., 1996b). In the western AS, copepods (*Calanoides carinatus* and *Eucalanus subtenuis*) are known to graze about 50-100% of diatom population from an upwelling region though the impact of MZP is equally important (Landry et al., 1998; Smith et al., 2001). Apparently, a high population of mesozooplankton could prevent an early diatom bloom by exerting grazing pressure. Once, they [copepodid (CV) stages] attain enough lipid reserves, they migrate to deeper depths and diapause easing the pressure and allow blooms. Early stages (copepodid) of *C. Carinatus* occur at mid depths in the central and eastern AS as well (Madhupratap et al., this volume). Thus, when the grazing pressure slackens a large quantify of unutilized biogenic siliceous material sink (see Honjo et al., 1999). We suspect, these fluxes would have been much more if MZP did not exert pressure on already lowly populated diatoms during SPIM.

Unlike the AS, the BOB receives considerable amount of fluvial inputs via some of the world's largest rivers (Miliman and Meade, 1983) particularly during southwest monsoon. Contribution of terrigenous material due to the rivers from the Indian subcontinent amounts to  $1387 \times 10^6$  tons  $y^{-1}$  in the BOB as against  $195 \times 10^6$  in the AS (Subramaniam, 1993). Strong stratification (aided by low salinity and higher SSTs) makes the BOB less productive and the riverine inflow does not bring in quantifiable nutrients into the open sea (Sen Gupta and Naqvi, 1984; Rao et al., 1994; Madhupratap et al., 2003).

Puzzlingly enough, considering the differences in productivity patterns between the two seas, the annual average flux ( $g\ m^{-2}\ y^{-1}$ ) obtained from deep sediment traps (Fig. 6a) do not vary much between the AS (36) and BOB (42) (Ramaswamy and Nair, 1994). If data on particle fluxes from both WAST and SBBT are excluded from calculation here, the annual average fluxes are still about  $28\ g\ m^{-2}\ y^{-1}$  in AS and  $46\ g\ m^{-2}\ y^{-1}$  in BOB. Higher lithogenic flux (Fig. 6b) in the BOB is not surprising because of the riverine input but the average rates of opal flux are comparable to that of the AS (Fig. 6c). Maximum fluxes from the Bay are reported during southwest monsoon (Ittekkot et al., 1991) when discharge from the rivers is maximal. Sinking fluxes of biogenic matter (carbonate, opal and organic matter) are several fold higher in the BOB (Ittekkot et al., 1991). This is an uncharacteristic event that needs to be elucidated.

Additional mode of transportation of organic matter into the deep is through the secretion/exudation of mucous material by phytoplankton or mesozooplankton (Anderson and Zeitzschel, 1970; Jumars et al., 1989). The organic transport could be in the form of transparent exopolymer particles (TEP) or respiration rates. These TEP are formed as a result of aggregation of organic particles or exudates (Alldredge et al., 1993; Passow et al., 1994). Study on TEP carried out by Kumar et al. (1998) from open waters of the BOB (along  $88^{\circ}E$ ) and AS (along  $64^{\circ}E$ ) had more number of smaller sized TEP in Bay ( $4400-7790\ ml^{-1}$ ) than in AS ( $130-350\ ml^{-1}$ ). However, TEP concentrations were higher in the AS (ca.  $25-102\ mg$  equivalent of alginic acid  $l^{-1}$ ) than those in the BOB (ca.  $7-13\ mg$  equivalent of alginic acid  $l^{-1}$ ). Percentages of TEP harboring mineral grains were more in BOB (75-86%) in contrast to AS (33-46%) thus facilitating faster sedimentation in the Bay as a result of ballast effect (Ittekkot et al., 1991). Nevertheless, respiratory electron transports (ETS) in subsurface waters (200-500m) of the BOB ( $5.62\ meq\ m^{-2}\ h^{-1}$ ) are significantly lesser than those measured in the AS ( $13.27\ meq\ m^{-2}\ h^{-1}$ ; Naqvi et al., 1996).

## **5. Conclusions**

Surface production and other biological features of the AS are more pronounced quantitatively than in the BOB although both the basins experience similar atmospheric forcings. Nevertheless, the particle fluxes to the deep between these two seas are almost comparable presumably as a result of ballast effect caused by mineral particles in the riverine input in the Bay. The many uncertainties notwithstanding, it is inferred from the available information that the mechanisms of material fluxes in the Bay remove a large fraction of surface production rather quickly and thus making the Bay an important sink for biogenic materials.

## **Acknowledgements**

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## References

- Allredge, A.L., Passow, U., Logan, B.E., 1993. The abundance and significance of a class of large transparent organic particles in the ocean. *Deep-Sea Research*, 40, 1131-1140.
- Anderson, G.G., Zeitzschel, R. P. 1970. Release of dissolved organic matter by marine phytoplankton in coastal offshore areas of the northeast Pacific Ocean. *Limnology and Oceanography* 15, 402-407.
- Antoine, D., Andre, J.M., Morel, A., 1996. Oceanic primary production 2. Estimation at global scale from satellite (coastal zone color scanner) chlorophyll. *Global Biogeochemical Cycles* 10, 57-69.
- Banse, K., 1988. Estimates of average phytoplankton division rates in the open ocean Arabian Sea. *Indian Journal of Marine Science* 17, 31-36.
- Bauer, J.G., Hitchcock, G.L., Olson, D.B., 1991. Influence of monsoonally-forced Ekman dynamics upon surface layer depth and plankton biomass distribution in the Arabian Sea. *Deep-Sea Research* 38, 531-553.
- Berggreen, U., Hansen, B., Kiorboe, T., 1988. Food size spectra, ingestion and growth of the *Acartia tonsa* during development: implication for determination of copepod production. *Marine Biology* 99, 341-352.
- Cole, J.J., Finlay, S., Pace, M.L., 1988. Bacterial production in salt and fresh water ecosystems: A cross system overview. *Marine Ecology Progress Series* 43, 1-10.
- de Sousa, S.N., Kumar, M.D., Sardesai, S., Sarma, V.V.S.S., Shirodkar, P., 1996. Seasonal variability in oxygen and nutrients in the central and eastern Arabian Sea. *Current Science* 71, 847-851.
- Dietrich, G. 1973. The unique situation in the environment of the Indian Ocean. In: Zeitzschel, B. (Eds.) *The Biology of the Indian Ocean*. Springer, Berlin, pp. 1-6.
- Fenchel, T. 1987. *Ecology of Protozoa - The Biology of Free-Living Phagotrophic Protists*. Springer-Verlag, Berlin.
- Gaines, G., Elbrachter, M., 1987. Heterotrophic nutrition. In: Taylor, F.J.R. (Ed.), *The Biology of Dinoflagellates*. Blackwell Scientific Publications, pp. 224-268.
- Garrison, D.L., Gowing, M.M., Huges, M.P., Campbell, L., Caron, D.A., Dennett, M.R., Shalapyonok, A., Olson, R.J., Landry, M.R., Brown, S.L., Liu Hong-Bin, Azam, F., Steward, G.F., Ducklow, H. W., Smith, D.C., 2000. Microbial food web structure in the Arabian Sea: a US JGOFS study. *Deep-Sea Research II* 47, 1387-1422
- Gauns, M. 2000. Role of microzooplankton in the food chain dynamics of some tropical marine environments. Ph D thesis, University of Goa, India. p 210

- Gomes, H.R., Goes, J.I., Saino, T., 2000. Influence of physical process and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research* 20, 313-330.
- Hansen, B, Hansen,PJ., Nielsen,T.G., 1991. Effects of large nongrazable particles on clearance and swimming behaviour of zooplankton. *J. Experimental Marine Biology Ecology*, 153, 257-269.
- Haake, B., Bartsch, M., Rixen, T., Ramaswamy, V., Nair, R.R., Curry, W.B., 1993. Seasonality and interannual variability of particle fluxes to the Arabian Sea. *Deep Sea Research* 40, 1323-1344.
- Honjo, S., Dymond, J., Prell, W., Ittekkot, V., 1999. Monsoon-controlled export fluxes to the interior of the Arabian Sea. *Deep-Sea Research II* 46, 1859-1902.
- Ikeda, T., Motoda, S. 1978. Estimated zooplankton production and their ammonia excretion in the Kuroshio and adjacent seas. *Fish Bulletin* 75, 357-357
- Ittekkot, V., Nair, R.R., Honjo, S., Ramaswamy, V., Bartsch, M., Manganini, S., Desai, B.N., 1991. Enhanced particle fluxes in the Bay of Bengal induced by injection of fresh water. *Nature* 351, 385-387.
- Jumars, P.A., Penry, D.C., Baross, J.A., Perry, M.J., Frost, B.W., 1989. Closing the Microbial loop: dissolved carbon pathway to heterotrophic bacteria from incomplete ingestion, digestion and absorption in animal. *Deep-Sea Research* 36, 483-495.
- Krishnaswamy, K., Nair R.R. (Eds.), 1996. Joint Global Ocean Flux Studies (JGOFS-India). *Current Science* 71, 831-900.
- Kumar, M.D., Sarma, V.V.S.S., Ramaiah, N., Gauns, M., de Souza, S.N. 1998. Biogeochemical significance of transparent exopolymer particles in the Indian Ocean. *Geophysical Research Letters*, 25, 81-84.
- Landry, M.R., Brown, S.L., Campbell, L., Constantinou, J., Liu, H. 1998. Spatial patterns in phytoplankton growth and microzooplankton grazing in the Arabian Sea during monsoon forcing. *Deep-Sea Research II*, 45, 2353-2368.
- Lee, C., Murray, D.W., Barber, R.T., Buesseler, K.O., Dymond, J., Hedges, J.I., Honjo, S., Manganini, S.J., Marra, J., Moser, C., Peterson, M.L., Prell, W.L., Wakeham, S.G., 1998. Particulate organic carbon fluxes: compilation of results from the 1995 US JGOFS Arabian Sea Process Study. *Deep-Sea Research II*, 45, 2489-2501.
- Lessard, E.J. 1991. The trophic role of heterotrophic dinoflagellates in diverse marine environments. *Marine Microbial Food Webs* 5, 49-58.
- Madhupratap, M., Achuthankutty, C.T., Nair, S.R.S., Nair, V.R., 1981. Zooplankton abundance in the Andaman Sea. *Indian Journal Of Marine Science* 107, 258-261.

- Madhupratap, M., Prasanna Kumar, S., Bhattathiri, P.M.A., Kumar, M. D., Raghukumar, S., Nair, K.K.C., Ramaiah, N., 1996a. Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature*, 384, 549-552.
- Madhupratap, M., Gopalakrishnan, T.C., Haridas, P., Nair, K.K.C., Aravindakshan, P.N., Padmavati, G., Paul, S. 1996b. Lack of seasonal and geographical variation in mesozooplankton biomass in the Arabian Sea and its structure in the mixed layer. *Current Science* 71, 863-868.
- Madhupratap, M., Gauns, Mangesh, Ramaiah, N., Prasanna Kumar, S., Muraleedharan, P.M., de Souza, S. N., Sardesai, S., Muraleedharan, Usha 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 II* 50, 881-896.
- Madhupratap, M., Padmavati, G., Haridas, P., Stephen. Vertical structure of mesozooplankton and calanoid copepods in the upper 1000 m of the eastern Andaman Sea (Bay of Bengal). *Deep Sea Research II*, (this issue).
- Michaels, A.F., Caron, D.A., Swanberg, N.R., Howse, F.A., Michaels, C.M., 1995. Planktonic sarcodines (Acantharia, Radiolaria, Foraminifera) in surface waters near Bermuda: Abundance, biomass and vertical flux. *Journal of Plankton Research* 17, 131-163
- Miliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. *The Journal of Geology* 9, 1-9.
- Nair, R.R., Ittekkot, V., Manganini, S.J., Ramaswamy, V., Haake, B., Degens, E. T., Dessai, B.N., Honjo, S., 1989. Monsoon related particle fluxes to the deep Arabian Sea. *Nature* 338, 747-751.
- Naqvi S. W. A., Shailaja, M.S., Kumar D.M., Sen Gupta, R., 1996. Respiration rates in subsurface waters of the northern Indian Ocean: evidence for low decomposition rates of organic matter within the water column in the Bay of Bengal. *Deep Sea Research II* 43, 73-81.
- Ohman, M. D., Runge, J. A., 1994. Sustained fecundity when phytoplankton resources are in short supply: Omnivory by *Calanus finmarchicus* in the Gulf of St. Lawrence *Limnology Oceanography*, 39, 21-36.
- Passow, U., Alldredge, A.L., 1994. Distribution, size and bacterial colonization of transparent exopolymer particles (TEP) in the ocean. *Marine Ecology Progress Series*, 113, 185-198.
- Prasanna Kumar, S., Madhupratap, M., Kumar, M.D., Gauns, M., Muraleedharan, P.M., Sarma, V.V.S.S., De Souza, S.N., 2000. Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea. *Proceedings Indian Academy of Sciences (Earth Planetary Sciences)* 109,433-441.



- Prasanna Kumar, S., Ramaiah, N., Gauns Mangesh, Sarma, V.V.S.S., Muraleedharan, P.M., Raghukumar, S., Kumar, M. D., Madhupratap, M., 2001. Physical forcing of biological productivity in the northern Arabian Sea during the northeast monsoon. *Deep-Sea Research II* 48, 1115-1126.
- Prasanna Kumar, S., Muraleedharan, P. M., Prasad, T.G., Gauns, M., Ramaiah, N., de Souza, S.N., Sardesai S., Madhupratap M., 2002. Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea?. *Geophysical Research Letters* 29, 2235. doi:10.1029/2002GL016013.
- Putt, M., Stoecker, D.K., 1989. An experimentally determined carbon volume ratio for marine oligotrichous ciliates from estuarine and coastal waters. *Limnology and Oceanography* 34, 1097-1103.
- Ramaiah, N., Raghukumar, S., Gauns Mangesh, Madhupratap, M. Seasonal variations in carbon biomass of bacteria, thraustochytrids and microzooplankton in the Northern Arabian Sea. *Deep Sea Research II*, (This issue).
- Ramaswamy, V., Nair, R.R. 1994. Fluxes of material in the Arabian Sea and Bay of Bengal – sediment trap studies. *Proceedings Indian Academy of Sciences (Earth Planetary Sciences)* 103, 189-210.
- Rao, C.K., Naqvi, S.W.A., Kumar, M.D., Varaprasad, S.J.D., Jayakumar, A., George, M.D., Singbal, S.Y.S., 1994. Hydrochemistry of the Bay of Bengal: possible reasons for a different water-column cycling of carbon and nitrogen from the Arabian Sea. *Marine Chemistry* 47, 279-290.
- Sawant, S, Madhupratap M, 1996. Seasonality and composition of phytoplankton in the Arabian Sea. *Current Science* 71, 869-873.
- Sarine M.M., Rangarajan, R., Ramaswamy, V., 1996. <sup>234</sup>Th scavenging and particle export fluxes from the upper 100m of the Arabian Sea. *Current Science* 71, 888-893.
- Sarma, V.V.S.S., Swathi, P.S., Kumar, M.D., Prasanna Kumar, S., Bhattathiri, P. M. A., Madhupratap, M., Ramaswamy, V., Sarin, M.M., Gauns, M., Ramaiah, N., Sardesai, S., de Sousa S. N., (2003). Carbon budget in the eastern and central Arabian Sea: An Indian JGOFS Synthesis. *Global Biogeochemical Cycle*, 17,1102 doi:10.1029/1002GB001978
- Sen Gupta, R., Naqvi, S.W.A., 1984. Chemical oceanography of the Indian Ocean, north of the equator. *Deep-Sea Research II* 31, 671-706.
- Sirocko, F., Sarnthein, M., 1989. Wind-borne deposits in the northwestern Indian Ocean: record of Holocene sediments versus modern satellite data. In: Leinen, M., Samthein, M. (Eds.), *Paleoclimatology and Paleometereology, modern and past patterns of global atmospheric tranport*, pp. 401-433.
- Smith, S.L., Codispoti, L.A., Morrison, Barber, R.T., 1998. The 1994-1996 Arabian Sea Expedition: an integrated, interdisciplinary investigation of the response of the northwestern Indian Ocean to monsoonal forcing *Deep-Sea Research* 45, 1905-1915.

- Smith, S.L., 2001. Understanding the Arabian Sea: reflection on the 1994-1996 Arabian Sea expedition. *Deep Sea Research II* 48, 1385-1402.
- Smith, S.L., Madhupratap, M. (in press). Mesozooplankton of the Arabian Sea: Patterns influenced by seasons, upwelling and oxygen concentrations. In: *Biogeochemical Oceanography of the Arabian Sea*, Springer-Verlag, Berlin.
- Subramanian, V. (1993). Sediment load of Indian rivers. *Current Science* 64, 928-930.
- Suess, E., 1980. Particulate organic carbon flux in the oceans-surface productivity and oxygen utilization. *Nature* 288, 260-263.
- UNESCO, 1994. Protocols for the Joint Global Ocean Flux Study (JGOFS). Manual and Guides 29, pp. 170.
- Unger, D., Ittekkot, V., Schafer, P., Tiemann, J., Reschke, S., 2003. Seasonality and interannual variability of particle input and oceanographic processes. *Deep-Sea Research II*, 50, 897-923.
- Wyrтки, K., 1973. Physical oceanography of the Indian Ocean. In: Zeitschel, B. (Ed.), *The biology of the Indian ocean*, Springer-Verlag, Berlin, pp. 18-36.

## Legends to figures

**Figure 1.** Sampling locations. Filled circles indicate stations covered under Joint Global Ocean Flux studies in the Arabian Sea and Bay of Bengal Process Studies programme in the Bay of Bengal. Open circle denote sediment trap mooring locations. Since limited data set was available from MRLR project, stations covered under this project (11°N along 80.1°E 84°E; 13°N along 80.4°E & 84°E; 15°N along 80.2° & 85°E; 17°N along 83° & 87°E; 19°N along 86° & 89°E and 20.5°E along 87.3° & 89°E) are not included here.

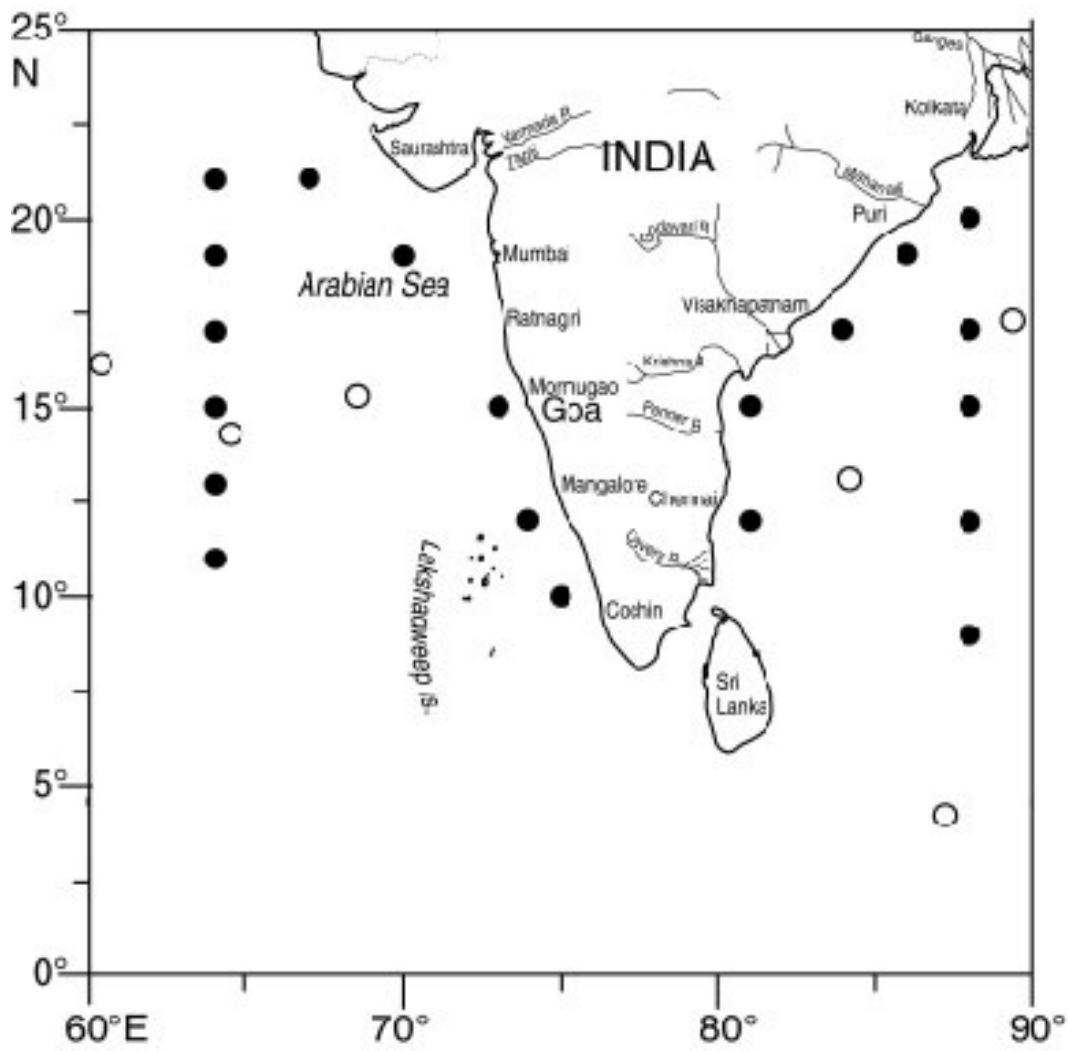
**Figure 2.** Vertical sections of nitrate ( $\mu\text{M}$ ) along the open ocean track of Arabian Sea (a, b, c; along 64°E) and Bay of Bengal (d & e; along 88°E) during different seasons. Dotted line indicate 1  $\mu\text{M}$  contour. Note the change in contour interval in (d) and (e).

**Figure 3.** (a) Mesozooplankton biomass ( $\text{ml m}^{-3}$ ) at different depth strata of the northern most station (Night –shaded) and, (b) microzooplankton (average organisms  $\times 10^6 \text{ m}^{-2}$ ) in the Arabian Sea and Bay of Bengal during different seasons. ND denotes no data.

**Figure 4.** Living carbon biomass ( $\text{mg C m}^{-2}$ ) of phytoplankton (chl *a*), bacteria, microzooplankton and mesozooplankton in the Arabian Sea and Bay of Bengal during different seasons. ND denotes no data.

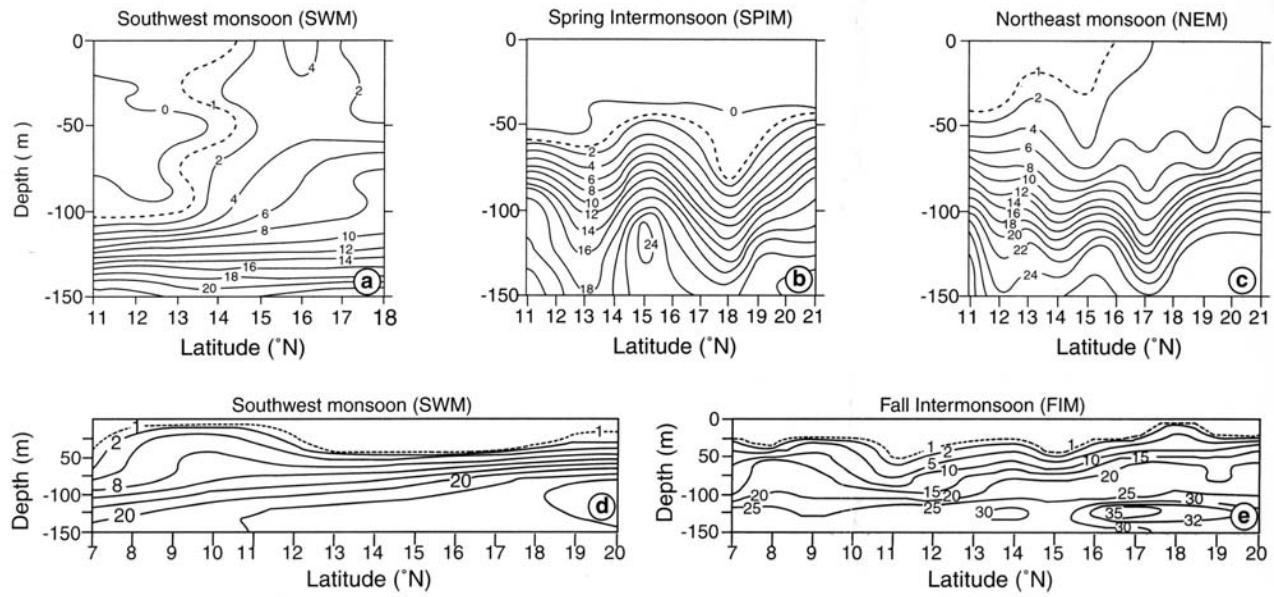
**Figure 5.** Seasonal variations in the living carbon biomass in the Arabian Sea (phytoplankton–P, bacteria-B, microzooplankton-MZ and mesozooplankton-MS), particulate organic carbon (POC), and downward fluxes out of the photic zone (100m) are shown. NLPC and LPC denote nonliving particulate organic carbon and living particulate carbon respectively.

**Figure 6.** Average annual particle fluxes of (a) total, (b) lithogenic and (c) opal at various locations of sediment trap moorings in the western (WAST), central (CAST) and eastern (EAST) Arabian Sea and northern (NBBT), central (CBBT) and southern (SBBT) Bay of Bengal (adapted from Ramaswamy and Nair, 1994)



**Fig. 1.** Mangesh Gauns et al.





**Fig. 2.** Mangesh Gauns et al.

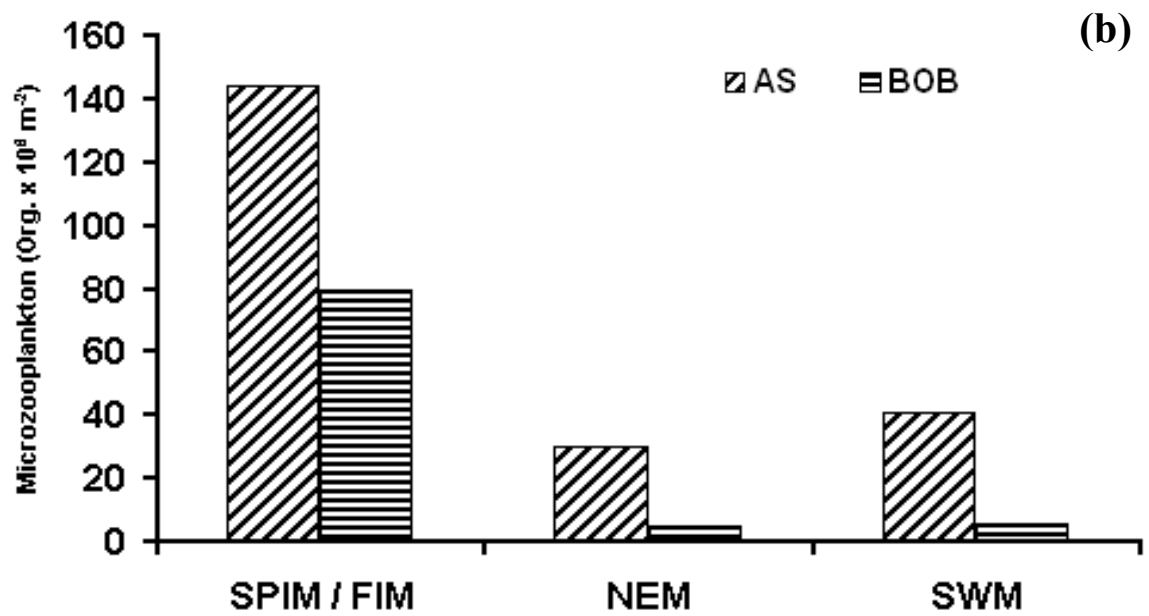
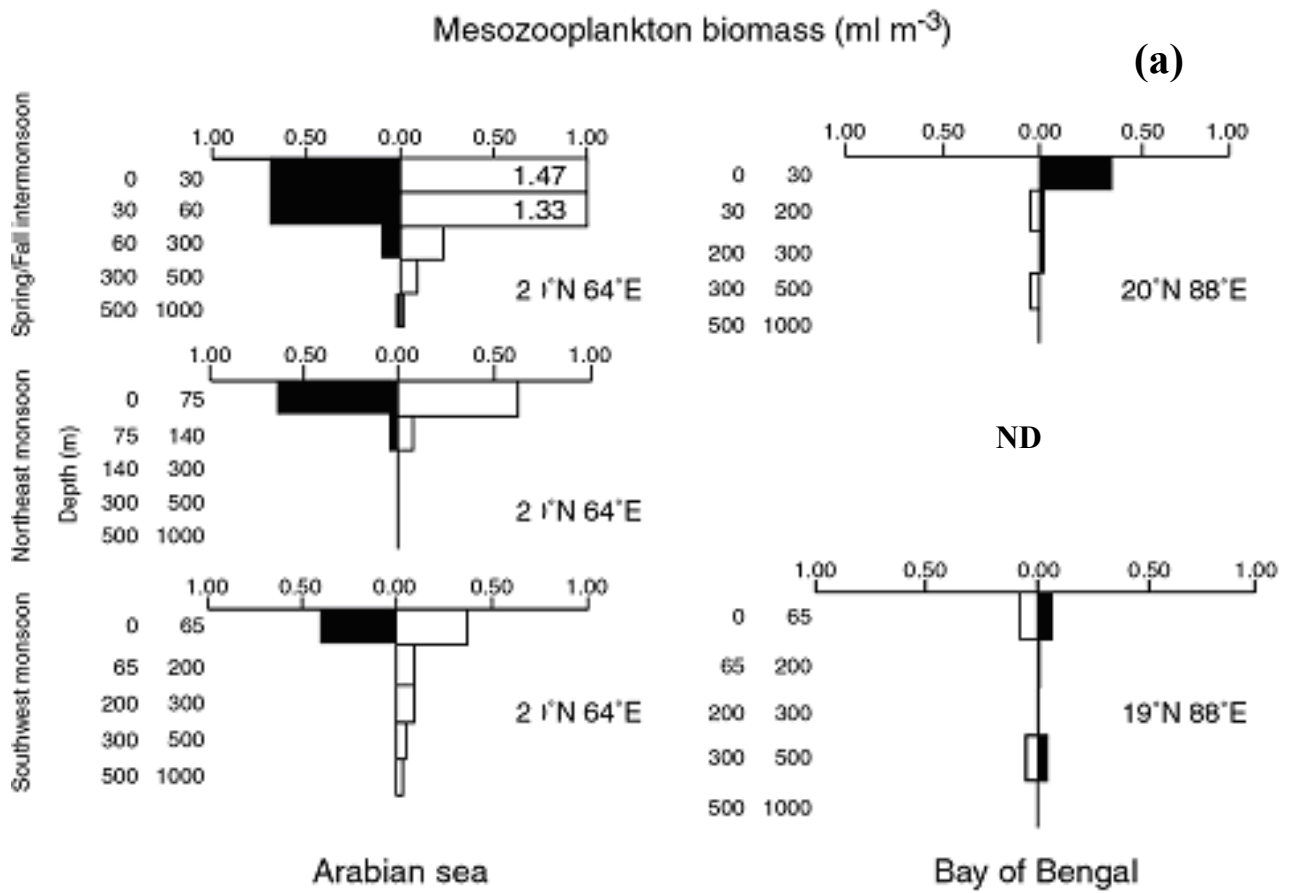


Fig. 3. Mangesh Gauns et al.

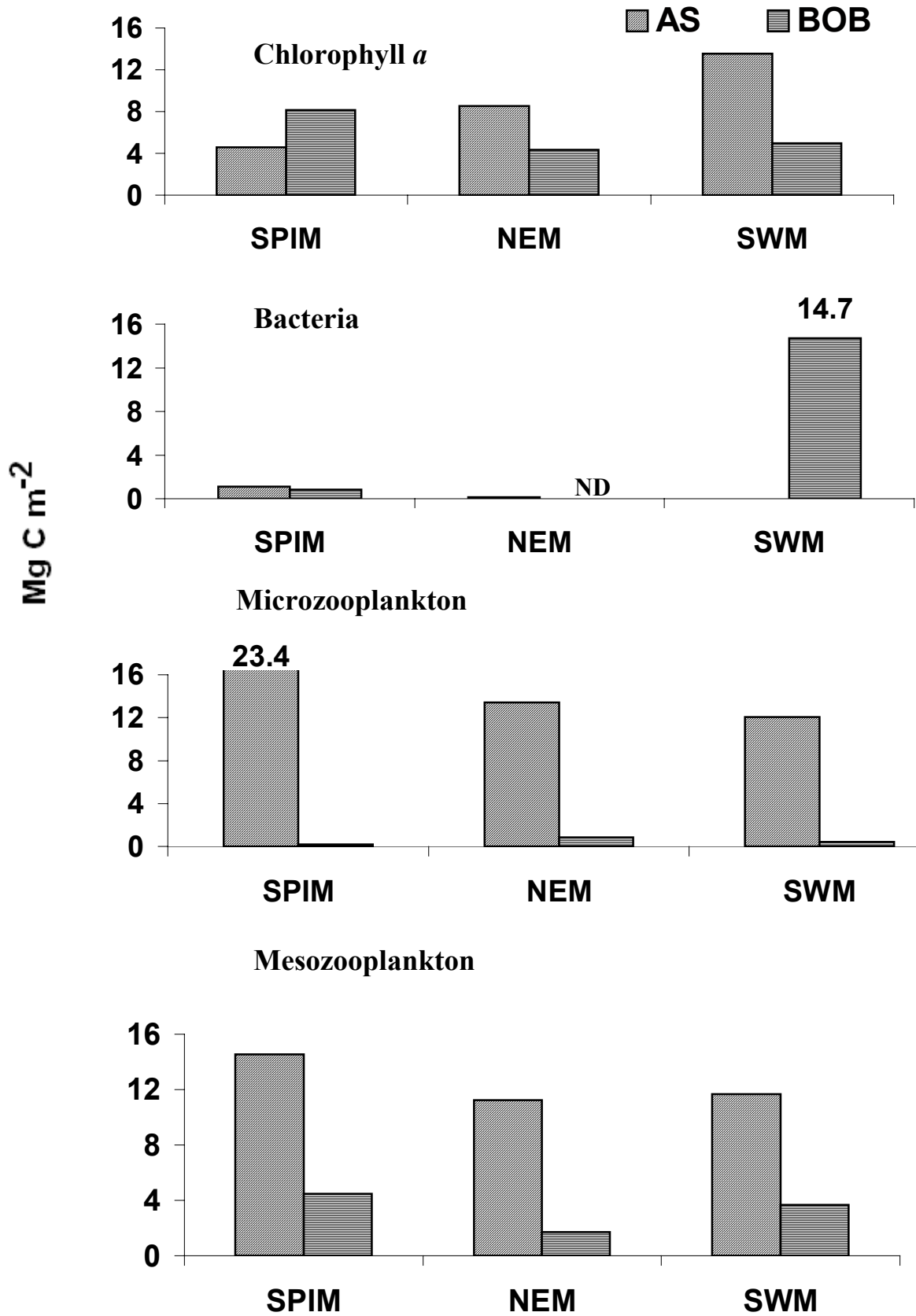


Fig. 4. Mangesh Gauns et al.



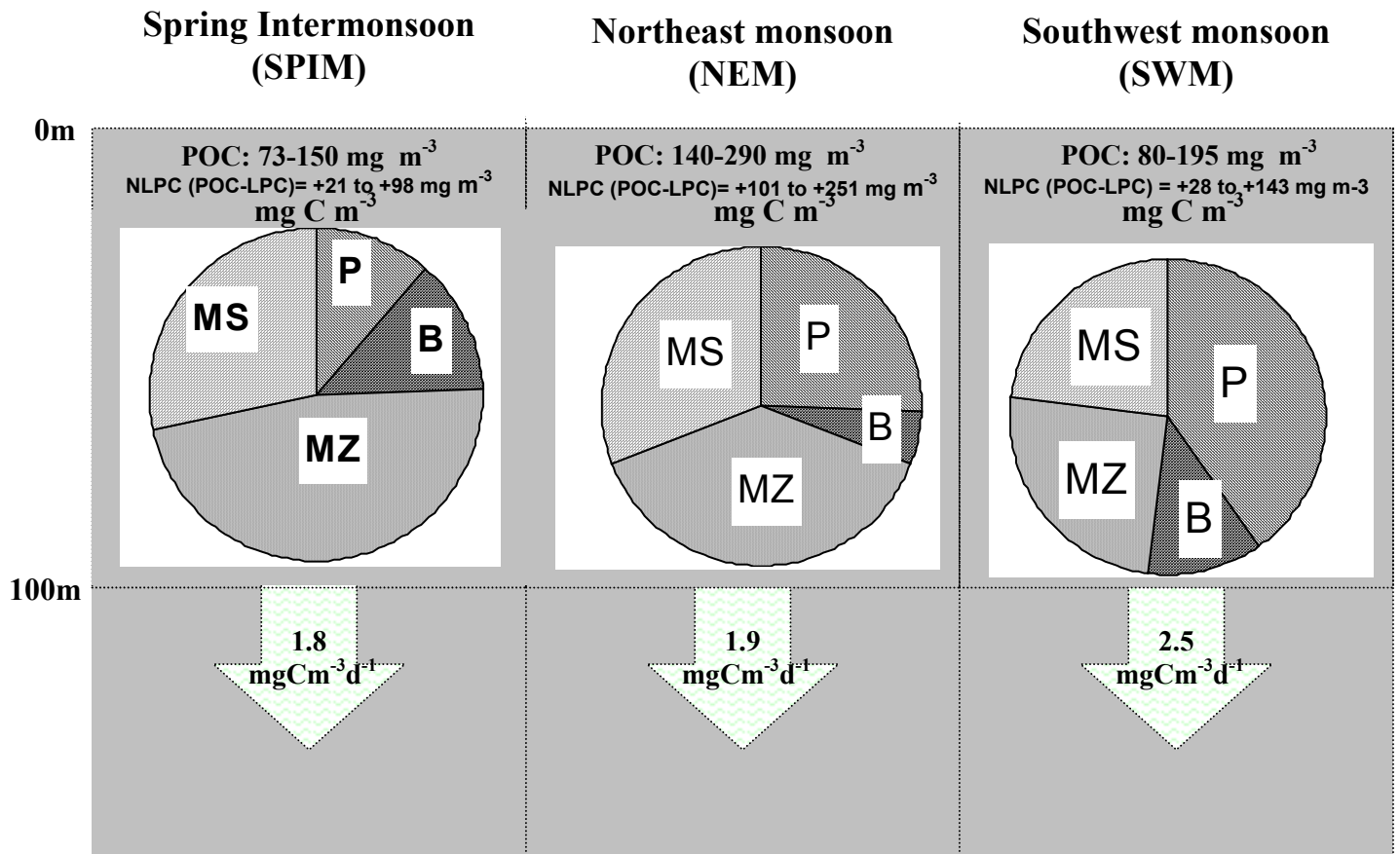


Fig. 5. Mangesh Gauns et al.

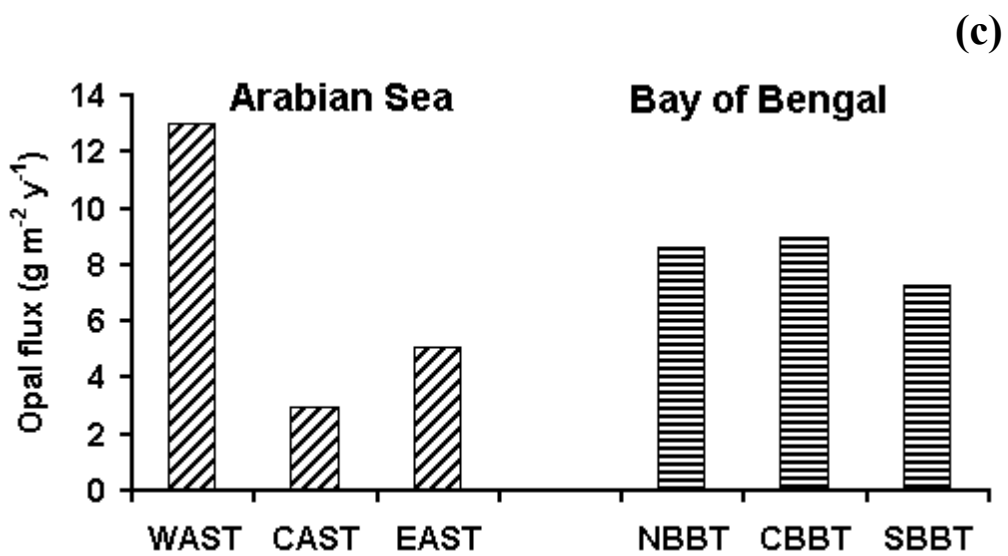
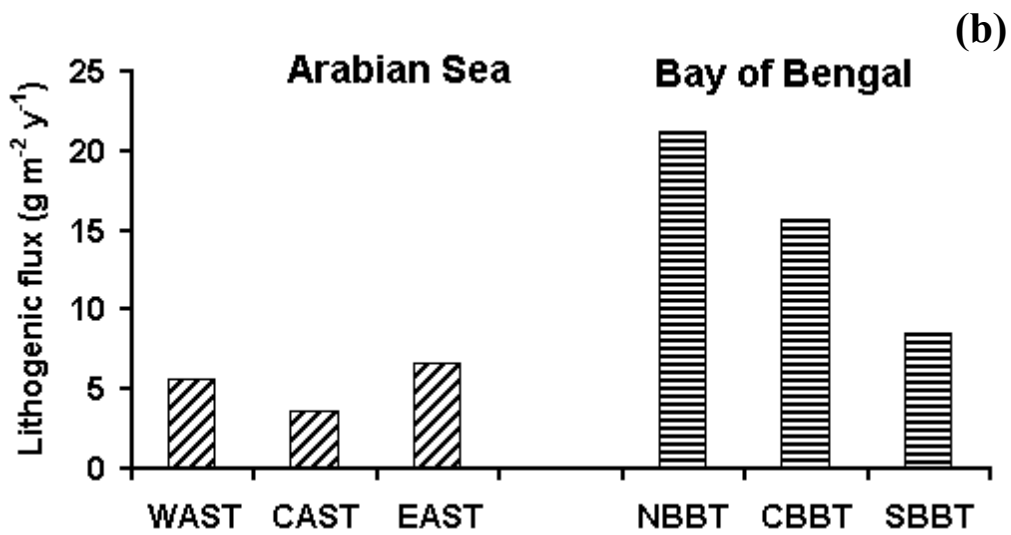
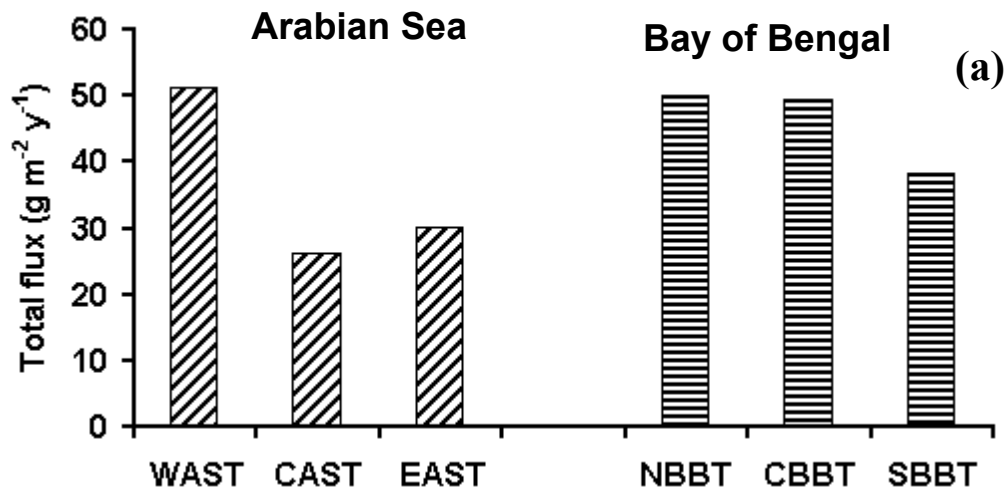


Fig. 6. Mangesh Gauns et al.

**Table 1:** Various details pertaining to the cruises conducted in the Arabian Sea and Bay of Bengal

Study region	Research Vessel	Cruise No	Sampling period	Season of the year	Region of Sampling
Arabian Sea	Sagar Kanya	SK-91	12 April -12 May 1994	Spring Intermonsoon (SPIM)	11°N-21°N along 64°E& 10°N - 21°N along the western Indian coast
		SK-99	2 February - 5 March 1995	Northeast Monsoon (winter, NEM)	
		SK-104	20 July- 2 August 1995	Southwest monsoon (summer, SWM)	
		SK-105	3-25 August 1996		
Bay of Bengal	Sagar Kanya	SK-166	6 July-2 August 2001	Summer monsoon	9°N-20°N along 88°E & 10°N - 19°N along the eastern Indian coast
		SK-182	14 September - 2 October 2002	Fall Intermonsoon	
	Sagar Sampada	MRLR	20 November - 18 December 2001	Northeast Monsoon (winter, NEM)	11°N 84°E; 15°N 85°E; 20.5°N 89°E; 11°N 80.1°E; 15°N 80.2°E and, 19°N 86°E.

**Table 2:** Data set (at selected stations) used for understanding the organic fluxes to the deep in Arabian Sea and Bay of Bengal

Arabian Sea		Primary Productivity			Chlorophyll a			Bacteria			Phytoplankton			Microzooplankton		
		(mg C m <sup>-2</sup> d <sup>-1</sup> )			(mg m <sup>-2</sup> )			(Cell Nos. x 10 <sup>12</sup> m <sup>-2</sup> )			(Cell Nos. x 10 <sup>8</sup> m <sup>-2</sup> )			(Nos. x 10 <sup>3</sup> m <sup>-2</sup> )		
		SPIM	NEM	SWM	SPIM	NEM	SWM	SPIM	NEM	SWM	SPIM	NEM	SWM	SPIM	NEM	SWM
Open ocean track	11°N 64°E	163	337		9	13		80	ND	32	0.5	1.7	10	166500	56250	33433
	15°N 64°E	168	606	1782	17	27	47	50	7	20	1.2	47	4.7	156500	37259	34550
	19°N 64°E	ND	477	830	9	21	28	29	5	12	0.8	6.1	2.3	161500	34153	31875
Coastal track	10°N 75°E	199	200	660	ND	10	16	67	ND	51	1.4	3.4	0.7	ND	26250	132588
	12°N 75°E	ND	ND	1760	11	ND	88	67	ND	ND	ND	ND	2.3	122000	ND	46151
	19°N 70°E	ND	ND	440	ND	17	21	ND	22	32	ND	91	0.4	69500	8888	22345

Bay of Bengal		Primary Productivity			Chlorophyll a			Bacteria			Phytoplankton			Microzooplankton		
		(mg C m <sup>-2</sup> d <sup>-1</sup> )			(mg m <sup>-2</sup> )			(Cell Nos. x 10 <sup>12</sup> m <sup>-2</sup> )			(Cell Nos. x 10 <sup>8</sup> m <sup>-2</sup> )			(Nos. x 10 <sup>3</sup> m <sup>-2</sup> )		
		SPIM	NEM	SWM	SPIM	NEM	SWM	SPIM	NEM	SWM	SPIM	NEM	SWM	FIM	NEM	SWM
Open ocean track	9°N 88°E	204	326 <sup>a</sup>	221	13	11.6 <sup>a</sup>	11.45	12	ND	2908	0.18	1.9 <sup>a</sup>	1.3	6688	3910 <sup>a</sup>	4530
	15°N 88°E	202	423 <sup>b</sup>	136	16	17.4 <sup>b</sup>	10.2	4	ND	33	0.11	1.3 <sup>b</sup>	0.8	5233	3430 <sup>b</sup>	4950
	20°N 88°E	427	99 <sup>c</sup>	89	14	8.4 <sup>c</sup>	11.15	13	ND	558	0.18	1.2 <sup>c</sup>	3.8	4105	2940 <sup>c</sup>	7950
Coastal track	12°N 82°E	305	566 <sup>d</sup>	502	19	21.5 <sup>d</sup>	12.7	9	ND	19	0.13	1.4 <sup>d</sup>	3.6	11330	5060 <sup>d</sup>	5600
	15°N 81°E	250	433 <sup>e</sup>	40	13	22.9 <sup>e</sup>	11.65	78	ND	112	0.07	2.3 <sup>e</sup>	0.5	3178	5150 <sup>e</sup>	7050
	19°N 85°E	469	253 <sup>f</sup>	434	11	7.1 <sup>f</sup>	18.7	113	ND	34	0.57	2.2 <sup>f</sup>	8.2	4283	3160 <sup>f</sup>	ND

ND: denotes no data a: 11°N 84°E; b: 15°N 85°E; c: 20.5°N 89°E; d: 11°N 80.1°E; e: 15°N 80.2°E and, f: 19°N 86°E.