

# **Sedimentation of Particulate Matter in the Dona Paula Bay, West Coast of India during November to May 1995-97.**

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**ABSTRACT** : Data on hydrography, nutrients, suspended and sedimented particles were collected at weekly interval from November to May during 1995 to 1997 at a station in the coastal waters of Dona Paula Bay. Suspended and sedimented particles were analysed for total suspended matter (SPM), total sedimented particulate matter (TPM), particulate organic carbon (POC), particulate organic nitrogen (PON), chlorophyll *a* (Chl *a*) and diatom abundance. Variations in hydrography and nutrients influenced the quantity and composition of sedimented particles. The TPM, POC, PON and Chl *a* fluxes showed small-scale seasonal variations and were higher in the summer (February to May) than in the winter (November to January). Resuspension of carbon accounted for ~25% of the gross POC and was highest (45%) in April 1997. The mean net POC flux was  $197 \pm 90 \text{ mg C m}^{-2} \text{ d}^{-1}$  and accounts for 4.6% of the TPM. The average C:N (w:w) ratio of the sedimented material was  $13.2 \pm 6.6$ . The POC/Chl *a* ratio was relatively higher in the sedimented material as compared to the suspended material. The particulate carbon reaching the bottom sediment was 39% of the primary production. The low organic carbon concentration (~0.1% of dry sediment) in the sediments imply that about 98% of the sedimented carbon was either consumed at the sediment-water interface or resuspended/advected before it was finally buried into the sediments.

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## **1. Introduction**

Coastal environments are well known for their high primary production (Romankevich 1984; Berner 1989). The amount of primary production exported out of the euphotic zone has been estimated with sediment traps. Particle sedimentation may follow a similar annual pattern as primary production, especially in deep-sea environments (Deuser and Ross 1980; Deuser et al. 1981; Honjo 1982, 1997). Particle flux attains its maximum within days to weeks after surface phytoplankton blooms, suggesting rapid transport of particles (Honjo and Weller, 1997). Large particles such as faecal pellets, faecal matter and amorphous aggregates of small particles including phytoplankton cells have been implicated as important vehicles for this rapid transport (Deuser and Ross 1980; Deuser et al. 1981; Asper 1987; Kiørboe et al 1994; Landry et al. 1994; Olesen and Lundsgaard 1995). The rapidly sinking particles form an important source of supply of organic matter to the benthos. Quality and quantity of organic matter reaching the sediments influence the growth and reproduction of shallow (Graf et al. 1982, 1983) and deep water benthic organisms (Billet et al. 1983).

Particle flux in open ocean is derived from living organisms, especially phytoplankton and aeolian particles. In coastal waters, terrestrial inputs and resuspension of bottom sediments may also influence the flux (Degens and Ittekkot 1985; Nelson et al. 1987; Sigleo and Schultz 1993; Heiskanen and Leppänen 1995; Lund-Hansen et al. 1999). Mass sedimentation has been reported for many coastal stations (Smetacek 1985; Skjoldal and Wassmann 1986; Harding et al. 1987; Lignell et al. 1993), especially when zooplankton biomass is low (Smetacek 1984; Riebesell et al. 1995; Wassmann 1991, 1998). Other factors, including nutrient depletion, light deficiency, life cycle events like sporulation/ cyst formation and deteriorating physiological condition of algae may also be responsible for mass sedimentation of phytoplankton blooms (Smetacek 1985; Skjoldal and Wassmann 1986; Wassmann 1991). Further, seasonal changes in temperature, salinity, winds and currents also influence the magnitude of mass flux and its composition in shallow marine environments (Wassman 1985; Harding et al. 1987; Bhosle et al. 1989; Heiskanen et al. 1998; Lund-Hansen et al. 1997, 1999).

Although sedimentation of organic matter is important to meet the benthic carbon demand, little is known about the sedimentation of particulate matter in shallow tropical environments. The present study was carried out primarily to assess the seasonal changes in the mass flux of particulate matter and its chemical composition in relation to hydrographical and biological parameters at a shallow water station in the Dona Paula Bay. Further, an attempt has been made to present a conservative estimate of the fate of particulate organic carbon at the study site.

## **2. Study Area**

The sampling station in the estuarine waters of the Dona Paula Bay (15°27'N, 73°48'E) along the west coast of India was about 8m deep (Fig. 1). Earlier works indicate that the surface water temperature ranges from 25 to 35°C at the station. Salinity fluctuated from a low of 10 psu during the south-west monsoon (June to September) to 35 psu during the summer months (February-May). Stratification of the water column is not observed during the sampling period (November to May) (see also Qasim and Sen Gupta 1981). The tidal range varied from neap tide of 0.25 m to spring tide of 2 m (Chandramohan et al. 1998). The currents varied from a low of  $\sim 1 \text{ cm s}^{-1}$  in November-December to a high of  $\sim 25 \text{ cm s}^{-1}$  in April-May (Jayakumar, personal communication). The mean significant wave height recorded in these waters was  $0.93 \pm 0.18 \text{ m}$  and the frequency of maximum height waves was  $\sim 10 \text{ s}$  (Vethamony and Ashok Kumar 1997). Nitrate concentrations during the study period are highest in November ( $3 \mu\text{M}$ ) and decline in April ( $\sim 1 \mu\text{M}$ ) (Devassy and Goes 1989). The site receives terrestrial organic inputs from the Zuari and Mandovi estuaries which are fringed with thick mangrove coverage (Wafar et al. 1997). The primary production has been reported to be higher in post-monsoon than in pre-monsoon months (Devassy and Goes 1988). The phytoplankton population in the study area is predominantly composed of diatoms with minor contributions from dinoflagellates and other algal forms. The area experiences periodic blooms of diatoms during December-January and April-May (Devassy and Goes 1988). The predominant diatom species are *Pleurosigma*, *Navicula*, *Nitzchia*, *Skeletonema*, *Chaetoceros*, *Rhizosolenia* and *Coscinodiscus*. The microzooplankton population is dominated by ciliates (76%) followed by flagellates (15%) and micrometazoans (9%) (M. Gauns, personal communication). The net zooplankton population is dominated by grazers like

copepods followed by chaetognaths, cladocerans and other carnivorous crustacean larvae (Padmavati and Goswami 1996). The herbivore and carnivore zooplankton are most abundant in November/December and in April/May, respectively (Padmavati and Goswami 1996). The bottom sediment at the station was a mixture of fine sand and silt.

### **3. Materials and Methods**

#### **3.1. Hydrography and nutrients**

Surface water samples were collected weekly using a clean PVC carboy from November to May during 1995-96 and 1996-97. Samples were analysed within half an hour of collection. Surface seawater temperature was recorded using a thermometer. Salinity, dissolved oxygen and dissolved nutrients - nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ) and phosphate ( $\text{PO}_4^{3-}$ ), were analysed following Parsons et al. (1984).

#### **3.2. Suspended particulate matter**

Known aliquots of surface sea water samples were filtered through pre-combusted ( $450^\circ\text{C}$ , 4 h) and pre-weighed GF/F glass fibre filters for the analysis of total suspended matter (SPM), particulate organic carbon (POC), particulate organic nitrogen (PON) and chlorophyll *a* (Chl *a*). All except Chl *a* samples were dried at  $40^\circ\text{C}$  and stored at room temperature ( $28 \pm 2^\circ\text{C}$ ) in clean plastic vials prior to analysis.

#### **3.3. Sedimentation of particulate matter**

The trap deployment began in November 1995 and continued until May 1997. As the study area could not be approached during the south-west monsoon (June to October), samples were not collected for these months. In order to collect sedimenting particles, duplicate PVC traps with an aspect ratio (height:width) of 5 were mounted on a stainless steel frame and deployed at a depth of 5 m (3 m above the bottom) using an anchor and floats. The mouth of the trap was 20 cm in diameter and had no baffles.

Before each deployment, the traps were first washed with dilute HCl and rinsed with distilled water. Mercuric chloride ( $180 \mu\text{M}$ ; Lee et al., 1993) was added as a preservative prior to each deployment. The traps were retrieved at weekly intervals. After retrieval, they were kept upright to allow the particles to settle. The excess water was siphoned off and the settled material was collected in clean PVC bottles. The

samples were passed through 300  $\mu\text{m}$  nylon mesh (Smetacek 1985) to remove large swimmers. Further the samples were observed under microscope to remove any visible zooplankton. The samples were then made up to a known volume. Aliquots were filtered onto GF/F filters for the analysis of total sedimented particulate material (TPM), POC, PON and Chl *a*.

#### ***3.4. Analyses of particulate material***

The SPM and TPM samples were washed with distilled water to remove salt, dried at 50°C and weighed on a micro-balance (Mettler M3 model). POC was analysed by the wet-oxidation method of Parsons et al. (1984). Samples were oxidized with dichromate oxidant in a boiling water bath and the excess of chromium ions was measured at 430 nm. Plain filters were treated similarly and were used as blanks. Glucose was used as a standard for calibration. PON was estimated following the method of Raimbault and Gerd (1991). Samples were treated with alkaline potassium peroxydisulphate ( $\text{K}_2\text{S}_2\text{O}_8$ ) in an autoclave for 90 min. The nitrate thus produced was then reduced to nitrite by passing through a cadmium column. The nitrite concentration was measured spectrophotometrically at 543nm following the technique of Parsons et al. (1984). Plain filter papers were treated in the same fashion and were used as blanks. EDTA was used as a standard for the calibration of the method. Chlorophyll *a* was extracted with 90% acetone and absorbance of the extract was measured before and after acidification using a Beckman spectrophotometer (DU-64 model). The Chl *a* and phaeopigment concentrations were estimated by using the equation given by Parsons et al. (1984). The coefficient of variation of the analytical methods used for TPM, POC, PON and Chl *a* based on 6 replicate analyses was 2.1, 2.4, 4.2 and 6.5%, respectively. Sediment organic carbon and nitrogen were estimated following the methods of El Wakeel and Riley (1956) and Raimbault and Gerd (1991), respectively.

#### ***3.5. Diatom flux***

An aliquot of the trap samples was fixed in Lugol's iodine and diluted to a known volume in a settling chamber. Enumeration of total cell numbers was carried out with a Nikon-diaphot inverted microscope and the diatoms were identified upto their generic level (Parsons et al. 1984).

### 3.6. *Estimation of resuspension*

Resuspension of bottom sediments influences the sedimentation rates of particulate matter measured by traps, especially in shallow water. To quantify the resuspended material in the traps, we adopted the ratio method (Gasith 1975; Taguchi 1982; Clavier et al. 1995), which employs the component in the sediment, and its concentration in suspended material using the equation:

$$C_t = XC_s + (1-X) C_r,$$

where  $C_t$ ,  $C_s$  and  $C_r$  are the concentration of organic carbon (as %) in trap, SPM and sediments, respectively and  $X$  is the proportion of sedimented material in the trap. This method however gives a biased estimate of resuspension if the study site is influenced by freshwater inflow (Taguchi 1982). During the period of sampling (November to May), the study site is not influenced by freshwater influx (Qasim and Sen Gupta 1981). Because of this our resuspension rates would not have been influenced to any great extent by the fresh water influx.

### 3.7. *Statistical analyses*

Simple linear regression was used to evaluate the relationships between various components of suspended and sedimented particulate material. Paired-sets ANOVA (Sokal and Rohlf 1981) was carried out to assess the weekly and monthly variations in suspended and sedimented particulate components.

## 4. Results

### 4.1. *Hydrography and nutrients*

Surface sea water temperature ranged from 27 to 37°C. It gradually decreased from November to March (1995-96) and increased in April-May. In the next year, it remained fairly constant from November to February (1996-97) and increased thereafter with the maximum in May (Fig. 2a). Surface salinity was also low (28 psu) in November, increased gradually and reached a highest value of 36.71 psu in May (Fig. 2b). The dissolved oxygen concentration was about 100  $\mu$ M in November and showed small scale variation from January onwards before it decreased again in April-May 1995-96, whereas the concentration of dissolved oxygen increased from December 1996 to April 1997 followed by a decrease in May (Fig. 2c).

The nitrate concentrations varied from 0.07 to 2.46  $\mu\text{M}$ . The concentrations were higher in November-December (2.50  $\mu\text{M}$ ) than in April- May (0.30  $\mu\text{M}$ ) (Fig. 2d). The mean nitrate concentration for the period 1995-96 was lower (0.88 $\pm$  0.92  $\mu\text{M}$ ) than in 1996-97 (1.05 $\pm$  1.00  $\mu\text{M}$ ). A similar trend was evident for nitrite (Fig. 2e). The phosphate concentration showed an increasing trend from November to April during both years (Fig. 2f). The mean concentrations were however, higher in 1995-96 (1.12 $\pm$  0.93  $\mu\text{M}$ ) than in 1996-97 (0.52 $\pm$  0.27  $\mu\text{M}$ ). The average phosphate concentration was 0.81 $\pm$  0.60  $\mu\text{M}$  for the entire sampling period.

#### **4.2. Suspended particulate matter**

The monthly means of suspended matter (SPM) concentrations varied from 12.9 $\pm$ 10.8 to 84.9 $\pm$  10.4  $\text{g m}^{-3}$  ( $\chi$ = 54.3 $\pm$  19  $\text{g m}^{-3}$ ) (Fig. 3a; Table 1). The SPM means increased from November 1995 to a maximum in May 1996, replaced by a decrease for the same point in 1996-97 (Fig. 3a). The POC showed two peaks- one in November (1241 $\pm$  590  $\text{mgC m}^{-3}$ ) and the other in February (1069  $\pm$  465  $\text{mgC m}^{-3}$ ) and the overall mean POC content was 744 $\pm$  251  $\text{mgC m}^{-3}$  (Fig. 3b; Table 1). The monthly mean PON concentrations ranged from 33.7 $\pm$  17.8  $\text{mg m}^{-3}$  to 163 $\pm$ 127  $\text{mg m}^{-3}$  and were generally higher in November-December (Fig. 3c). Chl *a* concentrations showed small scale fluctuations (1.1 $\pm$  0.5 to 14.4 $\pm$  4.7  $\text{mg m}^{-3}$ ;  $\chi$ = 4.0 $\pm$  3.4  $\text{mg m}^{-3}$ ) (Fig. 3d). In general, the surface water Chl *a* concentrations displayed small peaks in the months of November (1996), January-February and April-May.

POC content as a percentage of the SPM showed small scale variation with the exception of the November '95 value (0.5 to 6.7%;  $\chi$ =1.8 $\pm$  1.4% ) (Fig. 3b). High contribution of POC to the SPM was recorded for November 1995, thereafter the values decreased until May 1996. However, no trend was evident during 1996-97. The C:N ratio (w:w) of the SPM varied from 5.7 to 21.6 ( $\chi$ = 13.0 $\pm$  6.1) and was high in February (Fig. 3c). An irregular trend was also observed for the POC/Chl *a* ratio (Fig. 3d). The high mean C:N (w:w) ratio in February and a relatively low C:N (w:w) ratio in December and April (1996) were associated with high and low POC/Chl *a* ratio, respectively (Fig. 3c & d).

### 4.3. Sedimentation rates

Sedimentation rates of TPM ranged from 1.1 to 13.4 g m<sup>-2</sup> d<sup>-1</sup> ( $\chi = 5.4 \pm 2.6$  g m<sup>-2</sup> d<sup>-1</sup>) (Fig. 4a; Table 1). Peak fluxes were observed during February and May of both years (Fig. 4a). The high TPM fluxes in February were accompanied by high POC and PON fluxes (Fig. 4b & c). The mean sedimentation rates of POC and PON were 250 ± 120 and 28.1 ± 6.2 mg m<sup>-2</sup>d<sup>-1</sup>, respectively (Table 1). POC fluxes were high in January-February and decreased thereafter. A similar trend was recorded for PON (Fig. 4c). Sedimentation of Chl *a* ranged from 0.02 to 1 ± 0.4 mg m<sup>-2</sup>d<sup>-1</sup> and showed small variations during 1995-96 and greater variations in 1996-97 (Fig. 4d). The observed low Chl *a* flux may be due to the degradation of Chl *a* in the presence of the preservative. The Chl *a* fluxes tended to be higher in December (0.98 ± 0.9 mg m<sup>-2</sup>d<sup>-1</sup>) and February (1 ± 0.4 mg m<sup>-2</sup>d<sup>-1</sup>). In general, the fluxes of TPM, POC, PON and Chl *a* were higher in February to May (summer) than in November to January (winter) (Table 2).

### 4.4. Diatom flux

The diatom fluxes varied from 3.2 ± 3.9 to 64.8 ± 32.1 × 10<sup>4</sup> cells m<sup>-2</sup> d<sup>-1</sup> ( $\chi = 28.73 \pm 19$  × 10<sup>4</sup> cells m<sup>-2</sup> d<sup>-1</sup>) (Table 1; Fig. 5). The diatom flux showed consistent increase from November to April and then declined in May in the first year (1995-96). In the following year, the flux decreased from December to February, then started increasing until April followed by a decrease in May (Fig. 5). High diatom flux was accompanied by low nitrate concentrations of the surface sea water. *Navicula*, *Nitzschia*, *Coscinodiscus* and *Pleurosigma* were the most common diatom genera in the sedimented material. *Navicula* and *Nitzschia* were invariably found associated with the mass flux maxima observed in February, whereas *Navicula* and *Pleurosigma* were more abundant in the sedimented material in May. Benthic diatoms *Navicula*, *Nitzschia* and *Pleurosigma* were abundant in the water column (Devassy and Goes 1989).

### 4.5. Resuspension rates of carbon

Resuspension rates of the carbon ranged from 7% (January '97) to 44% (April 1997). The mean carbon resuspension rates for the entire sampling period was 25 ± 14.2% of the gross POC flux. The net sedimentation rates of carbon (Gross flux - (Mean



resuspension) ranged from 34 to 372 mgC m<sup>-2</sup>d<sup>-1</sup> and the mean net POC flux was 197 ± 91 mgC m<sup>-2</sup>d<sup>-1</sup> for the entire period.

#### 4.6. *Nature of the sedimented matter*

The relative contribution of the POC and PON as percentages of the TPM ranged from 2.3 ± 0.8% to 9.3 ± 9.7% (Fig. 4b) and 0.07 ± 0.01% to 0.94 ± 1.20 %, respectively. The POC content of the TPM (as %POC) showed large variations as compared to the suspended matter. The mean relative POC and PON content of the TPM were 5.4% ± 1.7% and 0.5% ± 0.3%, respectively (Table 1). The C:N ratio (w:w) ranged between 6.6 ± 2.7 and 30.3 ± 13.9 ( $\chi=13.2 \pm 6.60$ ) (Fig. 4c; Table 1). The POC:Chl *a* ratio (w:w) showed large seasonal variation (193.7 ± 45.20 to 4430 ± 24;  $\chi= 1193 \pm 1047$ ) ( Fig. 4d; Table 1). Particulate material sedimented in summer had relatively low C:N and POC:Chl *a* ratios (Table 2).

#### 4.7. *Relationship between various particulate parameters*

The SPM concentrations of the suspended matter showed a moderate relationship with Chl *a* ( $r=0.45$ ;  $p<0.01$ ). Poor relationships were also observed between POC and Chl *a* ( $r= 0.46$ ;  $p< 0.01$ ) as well as between POC and PON ( $r=0.41$ ;  $p< 0.01$ ) of the suspended matter. The observed poor relationship between POC and Chl *a* implies that only a small part of the suspended POC was derived from phytoplankton. However, there was a fairly good correlation between C:N (w:w) and POC/Chl *a* ratios ( $r= 0.63$ ;  $p<0.02$ ). In contrast, the sedimentation rates of the TPM showed significant relationships ( $p<0.001$ ;  $n= 54$ ) with the fluxes of POC ( $r=0.77$ ), PON ( $r=0.81$ ) and Chl *a* ( $r=0.64$ ). A significant relationship was also recorded between the fluxes of POC and PON ( $r=0.79$ ,  $p<0.001$ ). The Chl *a* flux also showed fairly good correlations with the flux of POC ( $r= 0.61$ ,  $p<0.001$ ) and PON ( $r= 0.71$ ;  $p<0.001$ ). The POC and Chl *a* relationship for the period November to January was poor ( $r= 0.45$ ,  $p< 0.01$ ) but showed significant correlation for the period February to May ( $r=0.72$ ,  $p< 0.001$ ) indicating a relatively higher phytoplankton contribution to the POC flux. Further, there was a significant linear relationship between the C:N (w:w) and POC/Chl *a* ratios ( $r= 0.91$ ;  $p<0.001$ ) of the sedimented matter.

A paired set two way ANOVA (Sokal and Rohlf, 1981) was carried out on the weekly and mean monthly data set for suspended and sedimented matter. No significant variation in the measured particulate parameters either on monthly or weekly basis was recorded except for Chl *a* ( $p < 0.05$ , for both the suspended and the sedimented matter) and PON flux ( $p < 0.05$ , monthly variations). This indicates that there was no clear seasonality for any other variable except for Chl *a* and PON samples.

#### 4.8. Sediment organic matter

The average carbon and nitrogen contents were  $981 \pm 371 \mu\text{gC g}^{-1}$  and  $86.6 \pm 18.5 \mu\text{g g}^{-1}$  of dry sediment, respectively. The sediment carbon content showed an increasing trend from November to May. The increase in sediment carbon content during the period February to May was associated with the increase in the carbon sedimentation rates. The C:N ratio (w:w) ranged from 6.9 to 19.07 ( $\chi = 11.40 \pm 3.84$ ). The mean sediment C:N ratio was relatively lower than that recorded for the trap (13.21).

## 5. Discussion

### 5.1. Sediment trap

Sediment trap data are influenced by several factors such as trap design, hydrodynamic conditions, wave action, wind speed and properties of sedimenting particles (Smetacek et al 1978; Gardner 1980a, b; Davies and Payne 1984; Taguchi et al. 1993; Bale 1998; Heiskanen et al. 1998; Lund-Hansen et al. 1999). We used cylindrical traps with a height to diameter ratio of 5:1. This ratio has been considered sufficient for minimising resuspension of trapped material by water turbulence entering the traps (Bloesch and Burns 1980; Gardner 1980b; Blomqvist and Kofoed 1981; Baker et al. 1988). Furthermore, the traps suspended at 5m might have been influenced by variable hydrodynamic conditions. For example, wind and wave-induced resuspension of bottom sediments and tidal currents may influence the sedimentation rates in shallow water environments (Butman 1986; Baker et al. 1988; Bale 1998; Lund-Hansen et al. 1997 and 1999). The traps being kept at 3 m above the sea floor might have overestimated the particle flux due to resuspension of the bottom sediments by strong bottom currents and high wave action. A few current measurements carried out at the study site suggest that the currents varied from 5 (November) to  $25 \text{ cm s}^{-1}$  (April-May) ( $\chi = 15 \text{ cm s}^{-1}$ ) (Jayakumar personal communication). The mean current speed ( $15 \text{ cm}$

s<sup>-1</sup>) during the study period was slightly lower than critical current speed (> 20 cm s<sup>-1</sup>) required for the resuspension of sandy sediments (Bloesch 1994). This suggests that our sedimentation rates may not have been influenced to any great extent by currents. The mean significant wave height (Hs) recorded at the study site was 0.93 ± 0.18 m and ranged from 0.83 to 1.12 m during 1996-97 (Vethamony and Ashok Kumar 1997). Thus it is possible that the observed changes in the significant wave height might have influenced our sedimentation rates. Further, the wind speed had a significant influence on the TPM flux (r= 0.643; p< 0.001). Due to these limitations, our results should be considered only indicative of quantities and composition of sinking particulate material.

It is rather difficult to assess the actual influence of hydrodynamic conditions on the efficiency of the sedimentation vessel (Bloesch and Burns 1980; Gardner 1980a & b; Butman 1986). Deployment of replicate traps at the same depth, however, provide useful information on the variability of the data. The TPM collected using duplicate traps indicated that the coefficient of variation was 22± 8.9%. This is well within the limits of 20 to 25% obtained with sediment traps of different designs (Pennington 1974; Kimmel et al. 1977; Prouse and Hargrave 1977; Davies and Payne 1984; Bodungen et al. 1986; Nelson et al. 1987).

## 5.2. Sedimentation rates

The gross sedimentation rate of TPM in the Dona Paula Bay averaged 5.4 g m<sup>-2</sup> d<sup>-1</sup> which was of the same level as that measured in other coastal marine localities, shallow bays and estuaries (Hargrave and Taguchi 1978; Taguchi 1982; Faganeli 1989; Sigleo and Schultz 1993; Clavier et al. 1995; Lund-Hansen et al. 1999). However a direct comparison may not be advisable due to differences in trap designs, exposure periods and differences in the hydrological aspects of different marine environments.

There was some relationship between the hydrography and phytoplankton development. The period 1995-96 was characterized by relatively higher nutrients and SPM, moderate temperature and salinity and low Chl *a*. It is possible that "shadow effect" caused by higher suspended load might have prevented the bloom formation thereby lowering the Chl *a* concentrations. The low Chl *a* concentrations and relatively higher POC concentration imply that the suspended material was not dominated by

phytoplankton. Conversely, during the period 1996-97, a decrease in nutrient concentrations accompanied by a concomitant increase in Chl *a* of surface waters suggest higher primary production. Thus, the periods with low and high surface water Chl *a* were characterised by low and high TPM and POC fluxes, respectively.

Despite the decrease observed in nutrient concentrations for the period November to May 1995-96, we did not observe any substantial increase in Chl *a* concentrations in the surface waters or in the trap material. Zooplankton biomass, especially herbivorous copepods, was high during this period (Padmavati and Goswami 1996). Thus, heavy grazing of phytoplankton by herbivorous copepods might have been responsible for the observed low Chl *a* content in both the suspended and sedimented material. However, a relatively lower herbivorous copepods recorded during 1996-97 might be responsible for a relatively higher amount of phytoplankton in the suspended and sedimented material (Goswami personal communication).

High sedimentation of diatoms in March-April probably indicate cessation of algal growth. The increase in cell sinking rate that accompanies cessation of algal growth (Smetacek 1984), however, results in mass sedimentation of cells when grazing is low. In our investigation, it is likely that the nutrient depletion caused the termination of diatom growth. Surface water nitrate and phosphate concentrations (especially 1996-97) consistently decreased over the period of observation and reached a minimal level (0.1  $\mu$ M nitrate; 0.36  $\mu$ M phosphate) in March/April that may have been associated with the termination of diatom growth. This was further substantiated by the significant ( $p < 0.001$ ) inverse relationships of diatom flux with both nitrate ( $r = -0.66$ ) and phosphate ( $r = -0.661$ ). Furthermore, zooplankton biomass, especially copepods, was also relatively low during this period (Goswami unpublished results). These factors could account for the high sedimentation rates of diatom observed in March/April.

The gross POC sedimentation and the percentage POC in the sedimented TPM were similar to that reported for other marine environments (see Bhosle et al. 1989 for a review). The relative percentage of POC in the TPM was higher than the organic carbon content of the bottom sediments as well as in the suspended matter of the study area. The observed differences in %POC in the SPM and TPM might be due to the fact that the sediment traps integrated the particulate material over a 4 m water column for a period of one week (Sigleo and Schultz, 1993). However, the suspended matter was

collected at a specific point of time and space during the study period. Higher percentage of POC in the TPM could also be due to contamination of trap samples by microzooplankton ( $< 300 \mu\text{m}$ ) leading to an over estimation of POC flux.

The POC sedimentation was corrected for the resuspension of the bottom sediments as suggested by the earlier workers (Gasith 1975; Taguchi 1982; Clavier et al. 1995). The net POC sedimentation (i.e. gross-resuspension) accounted for 75% of the gross POC sedimentation. The observed value of resuspension (25%) at our study site was relatively lower than that reported from other coastal environments. For example, 80 - 90% resuspension rate was recorded from the Gulf of Trieste (Faganeli 1989) and in the mangrove fringed lagoon waters (Clavier et al. 1995). The low resuspension estimates in this study could be due to under estimation of sediment organic carbon. It is possible that the use of Van-Ween grab for sediment sampling might have removed the fine organic rich particles thereby under-estimating the sediment organic carbon. The net POC sedimentation recorded in this investigation was lower than those reported in mangrove fringed lagoon of New Caledonia ( $756 \text{ mg m}^{-2} \text{ d}^{-1}$ ; Clavier et al. 1995), Tuamotu atoll lagoon, French Polynesia ( $350 \text{ mg m}^{-2} \text{ d}^{-1}$ ; Charpy and Charpy-Roubaud 1991) and Kanoeh Bay ( $490 \text{ mg m}^{-2} \text{ d}^{-1}$ ; Taguchi 1982). However, our net POC sedimentation was similar to that reported from Davies Reef (90 to  $141 \text{ mg m}^{-2} \text{ d}^{-1}$ ; Hansen et al. 1992) and other coastal environments (Bhosle et al. 1989).

### *5.3. Seasonal changes in the nature of particulate matter*

There were some differences in sedimentation in relation to the seasons. To illustrate this, we have divided the investigations into 2 periods: November to January as winter which showed high nutrient, low dissolved oxygen and relatively lower temperature, salinity and Chl *a* and February to May as summer which was characterized by low nutrient and relatively higher temperature, salinity, dissolved oxygen (especially 1996-97) and Chl *a* in the surface waters. The SPM of the surface waters did not exhibit very strong seasonal differences in its composition except for PON, Chl *a* and to some extent POC. In contrast, sedimented particulate material showed strong seasonality in their chemical composition.

The C:N and POC: Chl *a* ratios provide useful information on the composition of the sedimented material. Organic matter deposited during the winter period had

higher C:N (15.7) and POC:Chl *a* (1537) ratios indicating that the sinking fresh phytoplankton played a minor role in the vertical carbon flux during this period. Conversely, the summer period was characterized by relatively lower but still a high C:N (11.32) and POC:Chl *a* (779) ratio suggesting that relatively more fresh material sedimented during this period. Although these values of C:N and POC:Chl *a* were relatively higher than those observed for fresh phytoplankton, they provide enough evidence to suggest that there was an increased contribution from phytoplankton during summer. Moreover, the increased flux of algal material in the summer period was further confirmed by the higher Chl *a*: Phaeopigment ratio in the sedimented material (Table 2).

There were positive and significant ( $p < 0.001$ ) correlation between the fluxes of TPM and POC, PON and Chl *a* suggesting a common origin of these components of the sedimented material. It has been suggested that large particles such as faecal pellets, faecal matter and marine snow play an important role in rapid transport of material to the sea floor (Honjo 1982; Asper 1987; Honjo 1997). The vehicle for the transport of the organic matter to the sea floor in the present investigation appears to be sinking phytoplankton cells as indicated by a fairly good correlation between the fluxes of Chl *a* and POC.

#### *5.4. Fate of sedimented organic carbon*

Based on the data collected during this study, a conservative estimate of the fate of organic carbon (POC) at the study site was evaluated. The average primary production (PP) at the study site was  $510 \text{ mg m}^{-2} \text{ d}^{-1}$  (Wafar et al. 1997; Qasim and Wafar, 1990). The net sedimented carbon ( $197 \text{ mg m}^{-2} \text{ d}^{-1}$ ) accounted for 39% of the PP. Such higher percentage of PP may be due to the under estimation of resuspension rates and/or contamination of trap material by microzooplankton. The phytoplanktonic carbon contribution to the net POC flux was calculated assuming the POC/Chl *a* ratio of 40 (Banse 1977) and the mean total pigment flux ( $0.9 \text{ mg m}^{-2} \text{ d}^{-1}$ ). The estimated phytoplanktonic carbon in the trap was about  $37 \text{ mgC m}^{-2} \text{ d}^{-1}$  which accounted for 7.3% of the PP. The mean diatom carbon was  $582 \text{ } \mu\text{gC m}^{-2} \text{ d}^{-1}$  which contributed only 2% to the phytoplanktonic carbon flux. Such low contribution of the phytoplanktonic carbon has been recorded for other shallow sub-tropical marine environments (< 25m depth) (Charpy and Charpy-Roubaud, 1991; Clavier et al. 1995). In contrast, Suess (1980)

reported very high contribution (40 to 80%) of phytoplankton carbon to the carbon flux for coastal waters.

The net sedimented carbon ( $197 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) indicates that 61% ( $313 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) of the primary production was mineralised in the water column (Fig. 6). It is possible that the organic carbon lost from the water column might have been metabolised by bacteria, recycled through the microbial loop, grazed by zooplankton, got converted to dissolved organic carbon (DOC) or simply got transported to the off shore waters. The bacterial productivity at the study site was  $28 \text{ mgC m}^{-2} \text{ d}^{-1}$  (Gomes et al. 1991). If we assume bacterial efficiency as 50% (Gomes et al. 1991), then the carbon assimilated by the bacterial population was  $56 \text{ mgC m}^{-2} \text{ d}^{-1}$  which accounted for 18% of the total carbon lost in the water column. The mean production rates of ciliates and flagellates in the study area are 64 and  $10.4 \text{ mg C m}^{-2} \text{ d}^{-1}$  (M. Gauns, unpublished data). Assuming a conversion efficiency of 40% (Fenchel 1987), assimilation by ciliates and flagellates amounted to 160 (31.4% of PP) and  $26 \text{ mg C m}^{-2} \text{ d}^{-1}$  (5% of PP) respectively, for the period 1995-97. The estimated mesozooplankton production in the study area is  $22 \text{ mgC m}^{-2} \text{ d}^{-1}$  (Qasim and Wafar, 1990). Assuming an ecological efficiency of 19% (Dalal and Parulekar 1992), the zooplankton assimilation was  $116 \text{ mgC m}^{-2} \text{ d}^{-1}$  which accounted for 37% of the carbon lost in the water column. Thus combined assimilation of organic carbon by bacteria, ciliates, flagellates and mesozooplankton ( $358 \text{ mgC m}^{-2} \text{ d}^{-1}$ ) was more than the organic carbon lost during sedimentation. Moreover, there is no estimate of lateral advection to off-shore waters which may add to the organic carbon lost in the water column. The surface sediments were poor in organic matter ( $981 \mu\text{g g}^{-1}$  dry sediments,  $\sim 0.1\%$  w/w). Under these circumstances, the supply of organic matter ( $197 \text{ mgC m}^{-2} \text{ d}^{-1}$ ) due to the settling particles- which might be an overestimate, may have a stimulatory effect on the growth and reproduction of benthic organisms (Graf et al. 1982; Billet et al. 1983).

Macrobenthic production at the study site was estimated to be  $22 \text{ mgC m}^{-2} \text{ d}^{-1}$  (Qasim and Wafar 1990) which is equivalent to a carbon demand of  $220 \text{ mgC m}^{-2} \text{ d}^{-1}$ , assuming an ecological efficiency of 10% (Slobodkin 1962). Other carbon sources such as benthic primary production and organic matter input from the other parts of the Bay may perhaps account for the deficit carbon supply to the benthic organisms.

## 6. Conclusions

Weekly sediment trap data collected from a shallow water station in the Dona Paula Bay provided useful information on the sedimentation rates and its chemical composition. Physical and biological factors influenced the quality and quantity of the trap samples. The TPM sedimentation showed significant correlation with wind speed suggesting the importance of resuspension of bottom sediments during the study period.

High and low sedimentation rates of particulate matter were associated with high and low phytoplankton biomass (as Chl *a*) in the water column. During summer, TPM flux was high with relatively fresh organic material in the trap samples as evident from the low POC: Chl *a*, C:N and high Chl *a*: Phaeopigment ratios. Conversely, low TPM flux in winter was associated with high POC: Chl *a*, C:N and low Chl *a*: Phaeopigment ratios indicating export of detritus rich organic matter.

The inverse correlations of diatom sedimentation rates with both nitrate and phosphate indicate the importance of nutrients in controlling the sedimentation of diatoms. About 39% of the primary production was exported to the benthos, which appears to be higher for the tropical waters perhaps due to the under-estimation of sediment carbon and/or contamination of the trap samples by microzooplankton. The bottom sediments are poor in organic carbon (~0.1%). Thus, the increased flux of relatively fresh organic matter in summer may influence the benthic organisms.

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### Legends to the Figures:

Figure 1. Location of the sampling station (●).

Figure 2. Mean monthly variations of (a) temperature; (b) salinity; (c) dissolved oxygen; (d) nitrate; (e) nitrite and (f) phosphate in the surface waters of Dona Paula Bay from November 1995 to May 1997. Each point indicates the mean of 4 weekly observations. Bars indicate  $\pm$  standard deviations.

Figure 3. Mean monthly variations of (left axis, bars) (a) suspended particulate matter (SPM); (b) particulate organic carbon (POC); (c) particulate organic nitrogen (PON) and (d) chlorophyll *a* (Chl. *a*) and (right axis, lines) (b) POC:SPM (as %); (c) C:N (w:w) and (d) POC:Chl *a* (w:w) of suspended material from November 1995 to May 1997. Each value indicates the mean of 4 weekly observations. Bars indicate  $\pm$  standard deviations.

Figure 4. Mean monthly variations of (left axis, bars) (a) total sedimented particulate matter (TPM); (b) particulate organic carbon (POC); (c) particulate organic nitrogen (PON) and (d) chlorophyll *a* (Chl. *a*) and (right axis, lines) (b) POC:TPM (as %); (c) C:N (w:w) and (d) POC:Chl *a* (w:w) of the sedimented material from November 1995 to May 1997. Each value indicates the mean of 4 weekly observations. Bars indicate  $\pm$  standard deviations.

Figure 5. Mean monthly flux of total diatom abundance. Each point indicates the mean of 4 weekly observation. Bars indicate  $\pm$  standard deviations.

Figure 6. Schematic representation of the fate of organic carbon in the Dona Paula Bay.

TABLE 1. Mean concentration of suspended ( $\text{mg m}^{-3}$ ) and sedimented particulate matter ( $\text{mg m}^{-2} \text{d}^{-1}$ ) in the Dona-Paula Bay during the entire period (1995–1997) of sampling. \* =  $\text{g m}^{-3}$ ; \*\* =  $\text{g m}^{-2} \text{d}^{-1}$ ; SD = Standard Deviation; CV = Coefficient of Variation.

Parameters	Mean	SD	CV
Suspended material			
SPM*	54.30	19	36
POC	744.00	251	34
PON	69.00	40	59
chl <i>a</i>	4.00	3.40	87
Phaeopigment	17.0	1.70	—
POC:PON (w:w)	13.00	6.00	47
POC:chl <i>a</i> (w:w)	289	204	71
chl <i>a</i> : Phaeo. (w: w)	2.36	2	85
POC:SPM (as %)	1.80	1.40	94
PON:SPM (as %)	0.12	—	—
Sedimented material			
TPM**	5.44	2.60	47
POC	251	120	48
PON	28.0	6.70	24
chl <i>a</i>	0.39	0.30	78
Phaeopigment	0.54	0.32	60
POC:PON (w:w)	13.2	6.60	50
POC:chl <i>a</i> (w:w)	1.193	1.047	88
chl <i>a</i> : Phaeo. (w: w)	0.72	0.95	—
POC:TPM	5.4	1.70	38
PON:TPM	0.5	0.26	44
Diatom flux ( $10^4 \text{ cells m}^{-2} \text{d}^{-1}$ )	28.7	19.00	67



TABLE 2. Seasonal variations in the suspended ( $\text{mg m}^{-3}$ ) and sedimented particulate matter ( $\text{mg m}^{-2} \text{d}^{-1}$ ) for the winter (November-January) and the summer (February–May) period in the Dona-Paula Bay. \* =  $\text{g m}^{-3}$ ; \*\* =  $\text{g m}^{-2} \text{d}^{-1}$ ; Mean (SD).

Parameters	Winter	Summer
Suspended material		
SPM*	51.0 (18)	54.6 (17)
POC	762 (282)	730 (206)
PON	91.9 (48.1)	51 (13)
chl <i>a</i>	2.9 (1.7)	4.6 (4)
Phaeopigment	2.8 (3)	4.1 (2)
POC:PON (w:w)	9.9 (5.4)	15.3 (5)
POC:chl <i>a</i> (w:w)	338 (222)	252 (166)
chl <i>a</i> : Phaeo. (w :w)	1.04 (0.53)	1.12 (1.60)
POC:SPM (as %)	1.5 (1.50)	1.3 (1.20)
PON:SPM (as %)	0.18 (0.20)	0.09 (0.07)
Sedimented material		
TPM*	4.00 (1.8)	6.5 (2)
POC	194 (101)	291 (118)
PON	16.3 (9.4)	36.43 (12)
chl <i>a</i>	0.31 (0.31)	0.45 (0.3)
Phaeopigment	0.52 (0.63)	0.48 (0.42)
POC:PON (w:w)	15.7 (10)	11.32 (2.86)
POC:chl <i>a</i> (w:w)	1537 (1486)	779 (240)
chl <i>a</i> : Phaeo. (w :w)	0.59 (0.50)	0.95 (0.66)
POC:TPM	5.9 (2.0)	5 (2)
PON:TPM	0.5 (0.3)	0.6 (0.2)
Diatom flux ( $10^4 \text{ cells m}^{-2} \text{d}^{-1}$ )	17.46 (15)	35.78 (18.8)

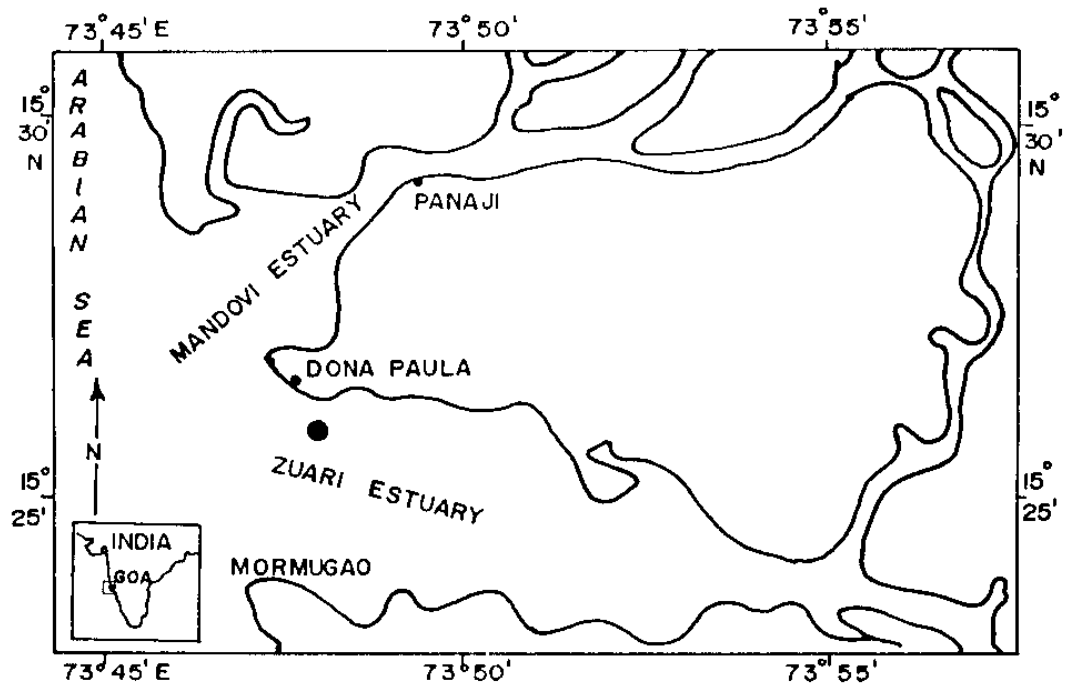


Fig. 1. Location of the sampling station (●) in Dona Paula Bay, India.

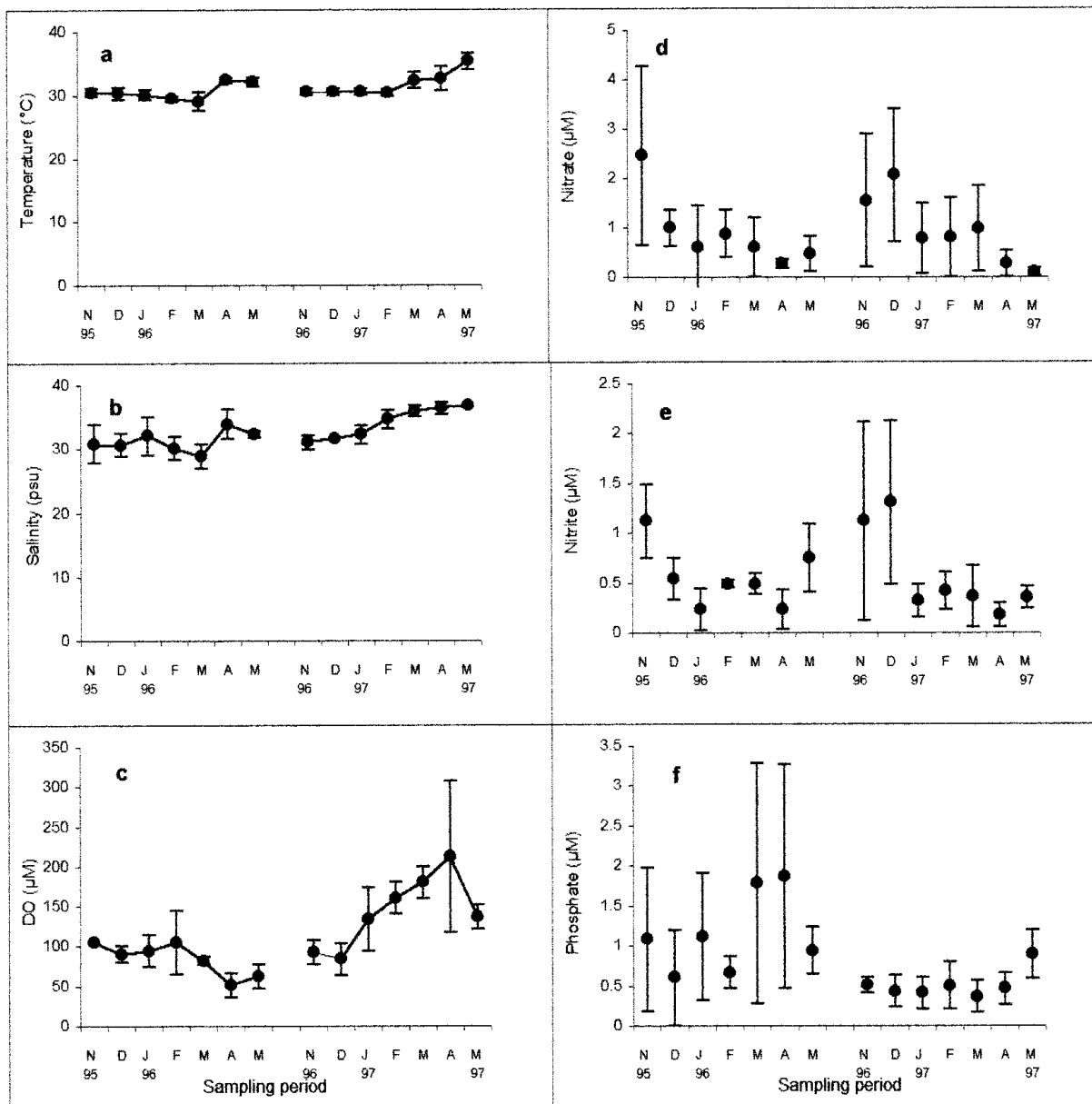


Fig. 2. Mean monthly variations of (a) temperature, (b) salinity, (c) dissolved oxygen, (d) nitrate, (e) nitrite, and (f) phosphate in the surface waters of Dona Paula Bay from November 1995 to May 1997. Each point indicates the mean of 4 weekly observations. Bars indicate  $\pm$  SD.

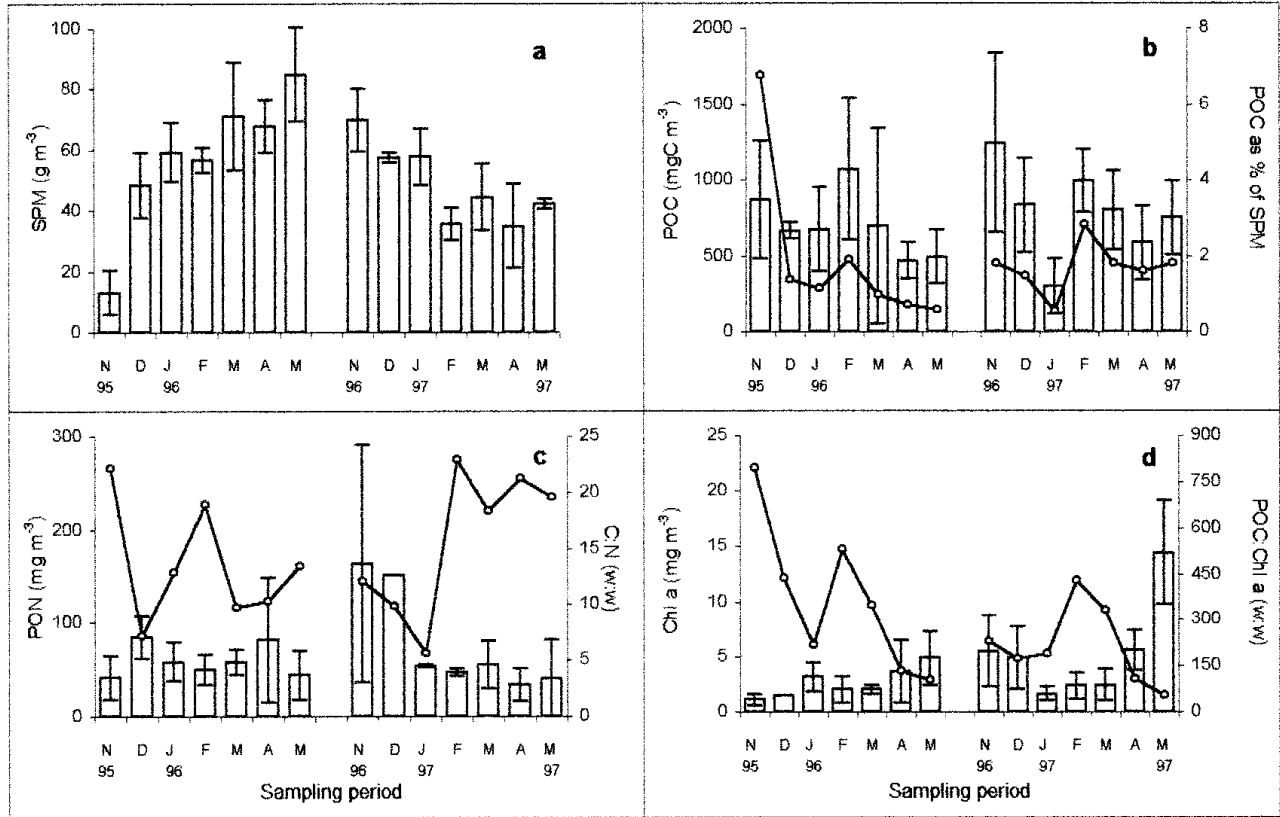


Fig. 3. Mean monthly variations of (a) suspended particulate matter (SPM), (b) particulate organic carbon (POC), (c) particulate organic nitrogen (PON), and (d) chlorophyll *a* (chl *a*) (left axis, bars), and (b) POC: SPM (as %), (c) C:N (w:w), and (d) POC: chl *a* (w:w) (right axis, lines) of suspended material from November 1995 to May 1997. Each value indicates the mean of 4 weekly observations. Bars indicate  $\pm$  SD.

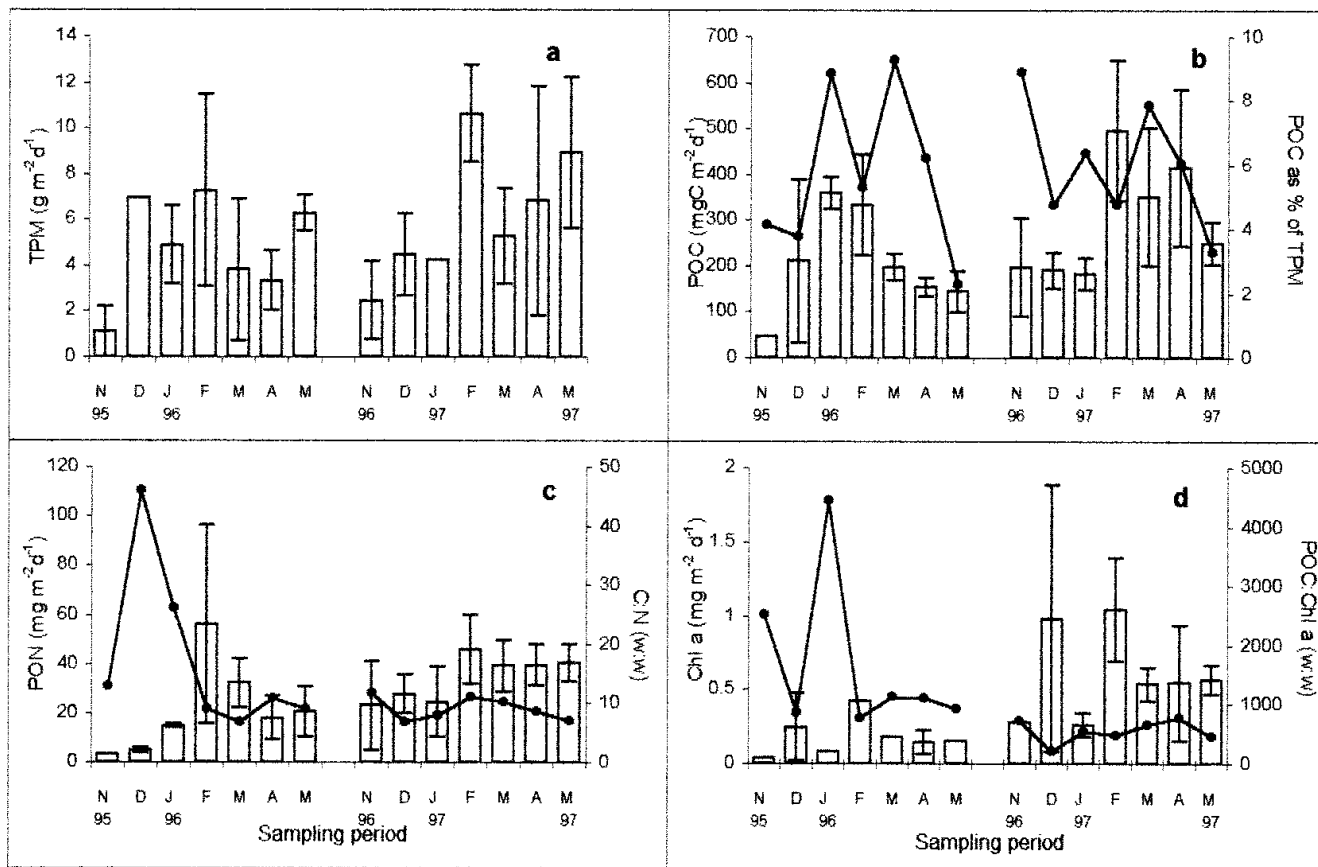


Fig. 4. Mean monthly variations of (a) total sedimented particulate matter (TPM), (b) particulate organic carbon (POC), (c) particulate organic nitrogen (PON), and (d) chlorophyll *a* (chl *a*) (left axis, bars), and (b) POC:TPM (as %), (c) C:N (w:w), and (d) POC: chl *a* (w:w) (right axis, lines) of the sedimented material from November 1995 to May 1997. Each value indicates the mean of 4 weekly observations. Bars indicate  $\pm$  SD.

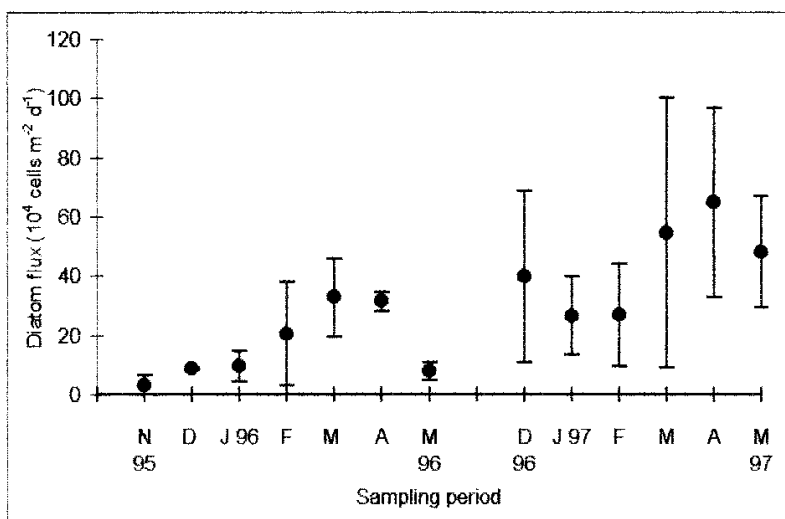


Fig. 5. Mean monthly flux of total diatom abundance. Each point indicates the mean of 4 weekly observations. Bars indicate  $\pm$  SD.

## Fate of organic carbon in the Dona-Paula Bay

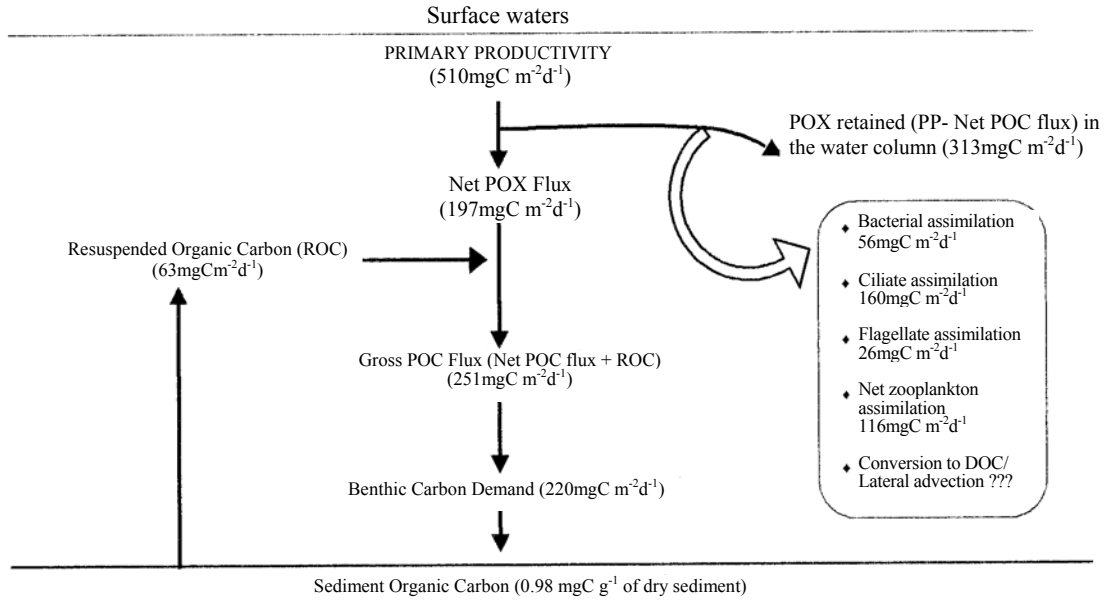


Fig. 6. Schematic representation of the fate of organic carbon in the Dona Paula Bay, India.