

## Fluxes of material in the Arabian Sea and Bay of Bengal – Sediment trap studies

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**Abstract.** In order to investigate how monsoons influence biogeochemical fluxes in the ocean, twelve time-series sediment traps were deployed at six locations in the northern Indian Ocean. In this paper we present particle flux data collected during May 1986 to November 1991 and November 1987 to November 1992 in the Arabian Sea and Bay of Bengal respectively. Particle fluxes were high during both the SW and NE monsoons in the Arabian Sea as well as in the Bay of Bengal. The mechanisms of particle production and transport, however, differ in both the regions.

In the Arabian Sea, average annual fluxes are over  $50 \text{ g m}^{-2} \text{ y}^{-1}$  in the western Arabian Sea and less than  $27 \text{ g m}^{-2} \text{ y}^{-1}$  in the central part. Biogenic matter is dominant at sites located near upwelling centers, and is less degraded during peak flux periods. High particle fluxes in the offshore areas of the Arabian Sea are caused by injection of nutrients into the euphotic zone due to wind-induced mixed layer deepening.

In the Bay of Bengal, average annual fluxes are highest in the central Bay of Bengal (over  $50 \text{ g m}^{-2} \text{ y}^{-1}$ ) and are least in the southern part of the Bay ( $37 \text{ g m}^{-2} \text{ y}^{-1}$ ). Particle flux patterns coincide with freshwater discharge patterns of the Ganges-Brahmaputra river system. Opal/carbonate and organic carbon/carbonate carbon ratios increase during the SW monsoon due to variations in salinity and productivity patterns in the surface waters as a result of increased freshwater and nutrient input from rivers.

Comparison of 5 years data show that fluxes of biogenic and lithogenic particulate matter are higher in the Bay of Bengal even though the Arabian Sea is considered to be more productive. Our results indicate that in the northern Indian Ocean interannual variability in organic carbon flux is directly related to the strength and intensity of the SW monsoon while its transfer from the upper layers to the deep sea is partly controlled by input of lithogenic matter from adjacent continents.

**Keywords.** Particle fluxes; interannual variability; Arabian Sea; Bay of Bengal; monsoons; carbonates; opal; organic carbon; lithogenics; sedimentation rate.

### 1. Introduction

The entire northern Indian Ocean comes under the influence of the seasonally changing monsoon gyre of the upper ocean (Wyrki 1973). This area experiences extremes in atmospheric forcing leading to regular oscillations in biological productivity, from extremely high primary production during the monsoons to oligotrophic conditions during the intermonsoon periods. Strong SW monsoon winds blow over the region from June to September while NE winds blow between December and February (Cadet and Diehl 1984). During the SW monsoon period clockwise surface circulation leads to coastal upwelling along the western margins of the Arabian Sea and Bay of Bengal (Currie *et al* 1973) and along the western margin of India (Sharma 1978). Enormous, pulsed, freshwater discharge mainly during the SW monsoon period (Rao 1979; Ittekkot and Arain 1986; Ittekkot *et al* 1985) results in

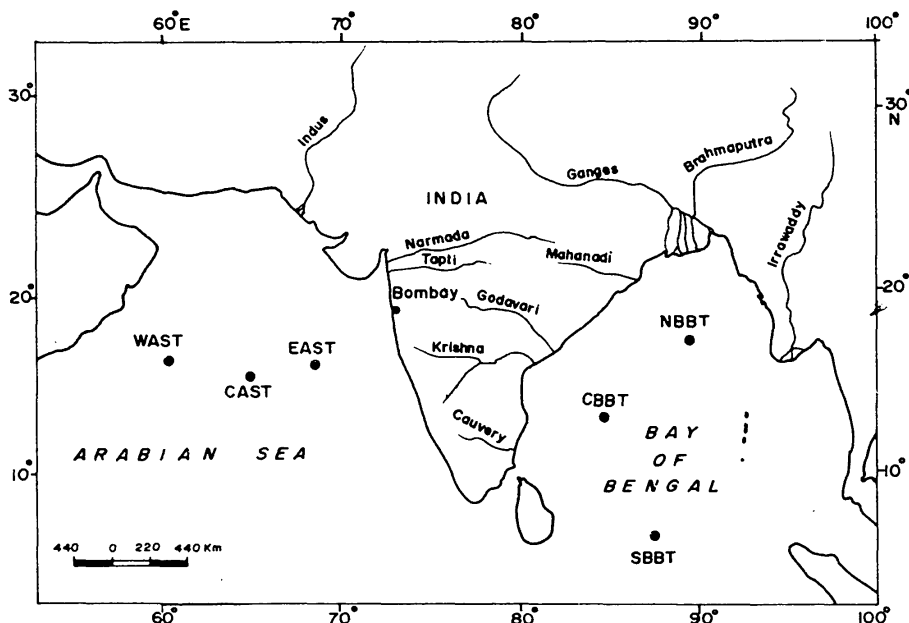


Figure 1. Location of sediment trap moorings used in this study.

large changes in the surface salinity over the entire Bay of Bengal (Wyrski 1973; Murthy *et al* 1990). The regular alternate forcing of the northern Indian Ocean makes it an important site for studying carbon transfer processes in the oceans.

Vertical flux of biogenic particles play a major role in sequestering carbon from the atmosphere into the deep ocean. To study the influence of monsoons on these processes, time-series sediment traps (Honjo and Doherty 1988) were deployed at six locations in the Arabian Sea and Bay of Bengal (figure 1). In this paper we review factors controlling particle fluxes and their interannual variability in the northern Indian Ocean.

## 2. Methods

PARFLUX MARK VI time-series sediment traps (Honjo and Doherty 1988) with a collecting area of 0.5 m<sup>2</sup> and 13 collecting cups have been deployed at three locations in the western (16° 20'N; 60° 30'E) central (14° 30'N; 65° 46'E) and eastern (15° 30'N; 68° 45'E) Arabian Sea and at three sites in the northern (17° 26'N; 89° 35'E), central (13° 09'N; 84° 21'E) and southern (04° 26'N; 87° 19'E) Bay of Bengal. In this paper we present data from the deep traps positioned approximately 1000 meters above the sea floor. Mooring locations and trap depths are given in table 1. Data is presented for the years 1986–91 and 1987–92 for the Arabian Sea and Bay of Bengal respectively. Data on component fluxes are available for 1986–90 and 1987–1989 for the Arabian Sea and Bay of Bengal respectively. Gaps in data are due to malfunctioning of the traps and/or considerable disturbance due to swimmer activity. During the first year of the study, sampling interval was between 9.5 to 13 days; in subsequent years they were between 21 to 29 days.

**Table 1.** Location, water depth and trap depth of sediment trap deployments used in this study.

Station	Lat.	Long.	Water depth m	Trap depth m
WAST	16° 20'N	60° 30'E	4020	3024
CAST	14° 30'N	64° 45'E	3900	2914
EAST	15° 30'N	68° 45'E	3770	2787
NBBT	17° 26'N	89° 35'E	2263	1727
CBBT	13° 09'N	84° 21'E	3259	2282
SBBT	04° 26'N	87° 19'E	4017	3006

Prior to deployment the sampling cups were filled with sea water from the trap location. Mercuric chloride ( $3.3 \text{ g l}^{-1}$ ) was added as a preservative. The samples were sieved through a 1 mm nylon sieve to exclude swimmers and split with a precision rotary splitter. The samples were filtered onto Nuclepore polycarbonate membrane filters, dried at  $45^\circ\text{C}$  and weighed to estimate total fluxes.

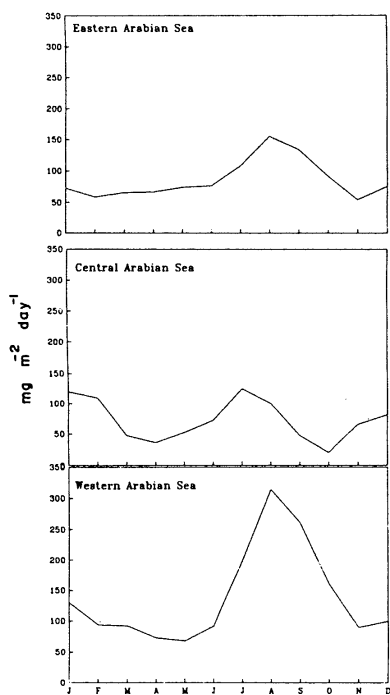
Brief description of methods used to determine first order components like carbonate, opal, organic matter and lithogenic fluxes are given below. Carbonate was determined by weight loss after treatment with dilute acetic acid. The method used for determination of biogenic silica is a modification of the one used by Eggimann (1980). The sample was transferred to clean polyethylene containers and treated with 10 ml of sodium carbonate (2 M) and kept in a water-bath at  $90^\circ\text{C}$  for 2 hours. Silicon in the leachate was measured using atomic absorption spectrophotometry after diluting to the required level. Assuming an average water content of 10% for opal, Si concentrations were multiplied with 2.4 to calculate biogenic opal content. Total carbon was measured with a Carlo Erba elemental analyzer and organic carbon calculated by subtracting carbonate carbon from total carbon. Organic matter was estimated by multiplying organic carbon by 1.8. Lithogenic fluxes were calculated by subtracting carbonate, organic matter and opal fluxes from the total flux.

Due to malfunction of the traps or logistic reasons, there was sometimes a gap of one or more months between the end of sampling period and subsequent redeployment of the traps. Calculated annual fluxes for these data sets can vary depending on the method of calculation used. In an earlier paper (Haake *et al* 1993) we had calculated the average daily flux for the sampling period and multiplied by 365 to obtain the annual flux. Using this method we had overestimated the annual flux for some of the years as the sampling gaps were mostly during low flux periods. In this paper we have taken the average flux for 5 years to fill in the gaps.

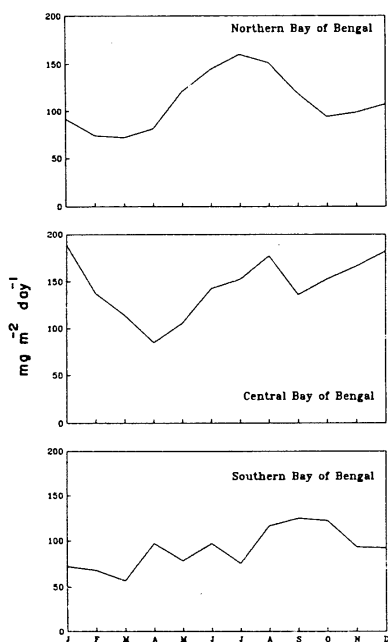
### 3. Results

#### 3.1 Particle fluxes

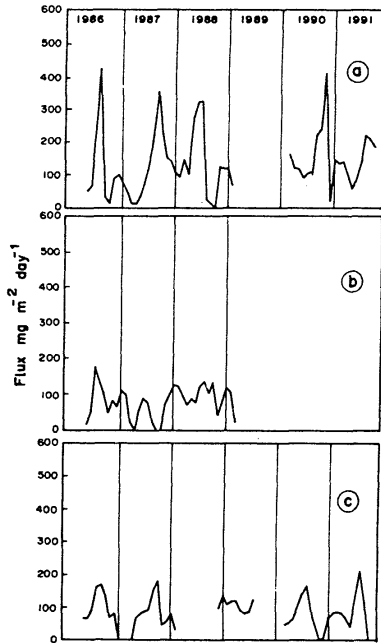
All sites in the northern Indian Ocean showed strong seasonality with generally higher fluxes during the monsoons compared to the intermonsoon period (figures 2 and 3). Variation in total particle fluxes during the entire sampling period is shown in figures 4 and 5 and average annual rain rates of total particulates and first order components are given in table 5.



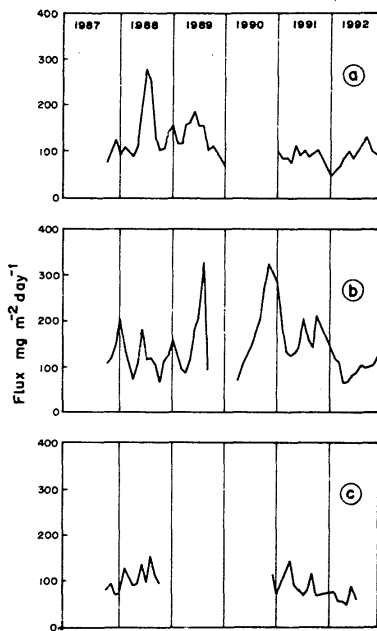
**Figure 2.** Total flux for the deep traps in the eastern, central and western Arabian Sea averaged for the period May 1986 to November 1991. Trap depths are given in table 1.



**Figure 3.** Total flux for the northern, central and southern Bay of Bengal averaged for the period November 1987 to November 1992. Trap depths are given in table 1.



**Figure 4.** Time-series data on particle fluxes ( $\text{mg m}^{-2} \text{ day}^{-1}$ ) in the deep traps of the (a) western, (b) central and (c) eastern Arabian Sea for the period May 1986 to November 1991. Since sampling intervals were not uniform for all the deployments the average flux for each month is shown in the figure.



**Figure 5.** Time-series data on particle fluxes ( $\text{mg m}^{-2} \text{ day}^{-1}$ ) in the deep traps of the (a) northern, (b) central and (c) southern Bay of Bengal for the period November 1987 to November 1992. Since sampling intervals were not uniform for all the deployments the average flux for each month is shown in the figure.

3.1a *Western Arabian Sea*: High particle fluxes were observed between June and September and a secondary maxima between December and February (figure 4). Peak fluxes were during July–August in 1986, 1988 and 1991 and in August–September in 1987 and 1990. Data for 1989 is not available. Carbonates are the major component of particulate matter at this site contributing 35 to 70 per cent of the total fluxes. Very high carbonate fluxes, over  $300 \text{ mg m}^{-2} \text{ day}^{-1}$ , are seen during the SW period in the western Arabian Sea (Nair *et al* 1989). Here carbonates are mainly contributed by foraminifers and coccolithophorids with minor contributions by pteropods. During the southwest monsoon up to 15,000 planktonic foraminifers per square meter per day were captured by the sediment traps (Curry *et al* 1992).

Opal fluxes are normally about  $40 \text{ mg m}^{-2} \text{ day}^{-1}$  but increase to over  $100 \text{ mg m}^{-2} \text{ day}^{-1}$  during August–September. The main contributor of opal are diatoms, radiolarians and silicoflagellates. Microscope observations show that *rhizosolenia sp.* is the dominant diatom in the traps (Nair *et al* 1989). Opal percentage increase during peak flux periods especially during the late SW monsoon period due to a diatom bloom. In 1990 their percentage exceeded 50 per cent. However, during the SW monsoon period of 1988 opal fluxes did not exceed 20 per cent even though total fluxes were very high. Organic carbon fluxes were also low during this year.

Lithogenic fluxes are also high during the SW monsoon period with peak fluxes generally between 30 to  $40 \text{ mg m}^{-2} \text{ day}^{-1}$ . In 1988, during July–August their fluxes exceeded  $100 \text{ mg m}^{-2} \text{ day}^{-1}$ . Organic carbon percentages were between 4 and 9% with lower percentages during high flux periods.

3.1b *Central Arabian Sea*: Total fluxes ranged between 0.1 to  $180 \text{ mg m}^{-2} \text{ day}^{-1}$ , with high fluxes occurring during both the monsoons from June to September and November to February (figure 4). Highest fluxes were measured during the SW monsoon period of 1986 and 1988. Fluxes during the SW monsoon of 1987 were less than even those measured during the NE monsoon period. Fluxes during this year were around  $90 \text{ mg m}^{-2} \text{ day}^{-1}$  in June but dropped to less than  $50 \text{ mg m}^{-2} \text{ day}^{-1}$  between July and September.

Carbonates are the main component at this site contributing 53 to 73% of the total fluxes. Lithogenic fluxes are high only during the SW monsoon period and contributed between 5 and 24% of the total fluxes. Biogenic opal fluxes are lower than the western Arabian Sea contributing around 10% of the total fluxes. Organic carbon fluxes were moderate to high during both the monsoon period and ranged between 4.3 and 8.7%.

3.1c *Eastern Arabian Sea*: Total fluxes measured at this site ranged between 0.1 and  $210 \text{ mg m}^{-2} \text{ day}^{-1}$  (figure 4). Fluxes during the SW monsoon exceeded  $150 \text{ mg m}^{-2} \text{ day}^{-1}$  for the years 1986, 1987, 1990 and 1991. In 1989 fluxes during the SW monsoon period was low but high between January and April. Compared to the other two areas the eastern Arabian Sea showed more interannual variability especially during the NE monsoon and pre-SW monsoon period. Fluxes during the NE monsoon period were less than  $1 \text{ mg m}^{-2} \text{ day}^{-1}$  during 1986–87, 1987–88 and 1989–90 but exceeded  $100 \text{ mg m}^{-2} \text{ day}^{-1}$  during 1988–89 and were between 50 to  $100 \text{ mg m}^{-2} \text{ day}^{-1}$  during 1990–91.

Carbonates percentages are between 35 and 65% and biogenic opal between 10 and 30% with higher opal and lower carbonates during high flux periods. Lithogenic percentages were distinctly higher than at the other two sites contributing between 10 and 33% of the total fluxes. Organic carbon percentages are between 3.8 and 10%.

3.1d *Northern Bay of Bengal*: In 1988 and 1989 total annual particulate fluxes in the northern Bay of Bengal were 52.5 and 47  $\text{g m}^{-2} \text{y}^{-1}$  respectively. In subsequent years annual fluxes did not exceed 34  $\text{g m}^{-2} \text{y}^{-1}$ . High fluxes exceeding 100  $\text{mg m}^{-2} \text{day}^{-1}$  were observed between May and October but in 1991 and 1992 high fluxes continued till end of November (figure 5).

Component flux data available up to 1989 show that lithogenic matter and carbonates are the main constituents of the sediment trap samples. During 1988 lithogenics contributed over 50% of the particulate matter but in 1989 their contribution was around 30%. Carbonates contributed about 20% to the total fluxes in 1988 but in 1989 they were the main constituent, contributing over 30% of the total fluxes. Opal fluxes ranged between 15 and 20% with higher contribution during peak flux periods. Organic carbon percentages (6 to 8%) were higher compared to the central and southern Bay of Bengal.

3.1e *Central Bay of Bengal*: Total particle fluxes at this site exceed 100  $\text{mg m}^{-2} \text{day}^{-1}$  throughout almost the entire year. In 1988, 1991 and 1992 peak fluxes during the SW monsoon were around 200  $\text{mg m}^{-2} \text{day}^{-1}$  but exceeded 300  $\text{mg m}^{-2} \text{day}^{-1}$  during 1989 and 1990. In 1990 high fluxes started in April and continued till February 1991. During 1988 total annual fluxes were less than the northern Bay of Bengal but in subsequent years were much higher (table 2). Fluxes during the NE monsoon showed a lot of variability and in some years were comparable with those during the SW monsoon (figures 3 and 5).

Component fluxes in the central Bay of Bengal are more uniform with carbonates contribution being between 30 to 40% of the total fluxes. Opal constitute 16 to 20% while lithogenics contributed 30 to 35% of total fluxes. Organic carbon percentages ranged between 5 and 7%.

3.1f *Southern Bay of Bengal*: Only limited particle flux data are available for this site due to malfunction of the traps. Total annual fluxes were 37.6 and 35.1  $\text{g m}^{-2}$  for the years 1988 and 1991 respectively. Fluxes at this site did not show any regular pattern (figure 3). Highest fluxes were 140  $\text{mg m}^{-2} \text{day}^{-1}$  during February 1991. Component fluxes show that carbonates are the dominant component and contributing nearly 50% of the total flux. Opal contribution is around 19% while lithogenics

**Table 2.** Table showing average annual flux at six sites in the northern Indian Ocean. Also shown are the Monsoon Index (MI) and number of monsoon days at 15°N Latitude. All fluxes are in  $\text{g m}^{-2} \text{y}^{-1}$ .

Year	Monsoon index	No. of monsoon days	WAST	CAST	Annual flux $\text{g m}^{-2} \text{y}^{-1}$ EAST	NBBT	CBBT	SBBT
1986	-12	125	43.1	26.7	34.0			
1987	-19	128	44.1	20.3	23.9			
1988	16	124	51.4	32.0		52.5	44.1	37.6
1989	1	125			37.2	47.0	49.0	
1990	8	148	67.8		24.2		60.9	
1991	-9	125	50.9		32.1	33.2	60.7	35.1
1992	-3	124				32.5	36.6	
<b>Average annual flux</b>			<b>51.4</b>	<b>26.3</b>	<b>30.3</b>	<b>41.3</b>	<b>50.3</b>	<b>36.4</b>

constitute 22% of the total flux. Organic carbon formed less than 5.4% of the total fluxes.

#### 4. Discussion

##### 4.1 Total particle fluxes

A 5-year average of annual fluxes in the northern Indian Ocean range between 26 and  $51 \text{ g m}^{-2} \text{ y}^{-1}$  (table 2). Average annual fluxes exceeded  $50 \text{ g m}^{-2} \text{ y}^{-1}$  in the central Bay of Bengal and in the western Arabian Sea. Comparison of the two regions show that total particle and biogenic components are consistently higher in the Bay of Bengal even though the Arabian Sea is considered to be more productive (Babenerd and Krey 1974; Krey and Babenerd 1976; Qasim 1977). In 1990 an annual flux value of  $68 \text{ g m}^{-2} \text{ y}^{-1}$  was recorded in the western Arabian Sea which is amongst the highest recorded in tropical open ocean areas exceeded only in the Panama Bight where fluxes were over  $100 \text{ g m}^{-2} \text{ y}^{-1}$  due to a coccolithophorid bloom. Annual particle flux in tropical open ocean areas normally range between 11 to  $45 \text{ g m}^{-2} \text{ y}^{-1}$  (table 3; Wefer 1989). High fluxes up to  $67 \text{ g m}^{-2} \text{ y}^{-1}$  are reported from upwelling areas. At higher latitudes annual fluxes cover a wide range from less than  $1 \text{ g m}^{-2} \text{ y}^{-1}$  to over  $110 \text{ g m}^{-2} \text{ y}^{-1}$  (Wefer 1989; table 3). Annual fluxes for the central and eastern Arabian Sea and southern Bay of Bengal fall within the range for tropical open ocean areas, but values from the western Arabian Sea and central Bay of Bengal resemble those reported from upwelling areas or high latitude high productive areas (table 3). The reason for the extremely high total fluxes in the central Bay of Bengal and high organic carbon fluxes in the northern Indian Ocean is not very clear and can be understood by detailed studies on upper ocean processes.

##### 4.2 Seasonality

A prominent feature here is the seasonal flux pattern of particles which follows the monsoon cycle. This seasonality is more pronounced in the Arabian Sea where between 53 and 70% of the total particle fluxes are during the southwest monsoon period. The bimodal pattern in particle fluxes (figure 2) show that the Arabian Sea alternates between oligotrophic conditions during the intermonsoon periods to highly eutrophic conditions during the monsoons. Chlorophyll concentrations and primary productivity in the surface waters also show a similar pattern (Banse 1987; Yoder *et al* 1991). This similarity in flux pattern at all three sites indicates that a common factor govern particle fluxes in the entire Arabian Sea.

The monsoon winds intensify as a low-level jet in the western Arabian Sea and causes open ocean upwelling near the Oman coast. Upwelling has also been reported from the west coast of India (Sharma 1976). Nutrient rich upwelled waters from nearby upwelling area can be carried offshore by vigorous surface currents and advected over the traps (Elliot and Savidge 1990; Swallow 1984) to contribute part of the observed high particle fluxes in the western and eastern Arabian Sea. It is also possible that particles produced in the nearby upwelling centers are horizontally advected at depth.

A different process operates in the central parts of the Arabian Sea. Here, there is a close similarity between wind speeds and particle fluxes (figure 6). During high wind



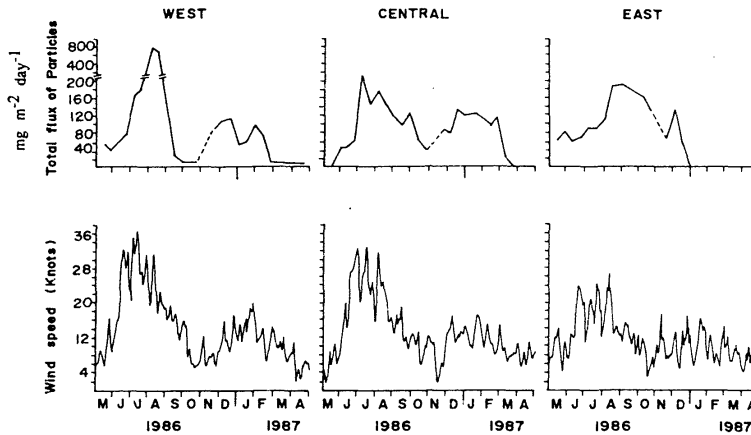
Table 3. Annual flux rates ( $\text{g m}^{-2} \text{y}^{-1}$ ) at intermediate depths (600 to 3800 m) in the world oceans.

Site	Period	Lat.	Long.	Trap depth m	Annual flux $\text{g m}^{-2} \text{y}^{-1}$	Reference
<b>Tropical oceans</b>						
Eastern Arabian Sea	86-91	16° 20'N	60° 30'E	2500	30.3	This paper
Central Arabian Sea	86-91	14° 30'N	64° 45'E	2500	26.3	This paper
Western Arabian Sea	86-91	15° 30'N	58° 45'E	2500	51.4	This paper
Northern Bay of Bengal	87-92	17° 26'N	89° 35'E	2500	41.3	This paper
Central Bay of Bengal	87-92	13° 09'N	84° 21'E	2500	50.3	This paper
Southern Bay of Bengal	87-92	4° 26'N	87° 19'E	2500	36.4	This paper
Sargasso Sea	78-80	32° 05'N	64° 15'N	3200	13.2	Deuser <i>et al</i> 1981
North Atlantic 34 N		34° 00'N	21° 00'W	2000	26.9	Honjo and Mangani 1993
North Atlantic 48 N		48° 00'N	21° 00'W	2000	22.4	Honjo and Mangani 1993
Hatteras Abyssal Plain	82-83	32° 73'N	70° 82'W		20.0	Dymond and Lyle 1994
Nares Abyssal Plain	83-84	23° 20'N	63° 98'W		11.9	Dymond and Lyle 1994
Guinea Basin Upper	89-90	01° 47'N	11° 07'W	853	28.1	Wefer and Fischer 1993
Guinea Basin Lower	89-90	01° 47'N	11° 07'W	3921	37.3	Wefer and Fischer 1993
Equatorial Atlantic GBI	89-90	02° 10'S	09° 54'W	696	09.4	Wefer and Fischer 1993
Panama Basin	79-80	5° 21'N	81° 53'W	3560	124.7	Honjo <i>et al</i> 1982
North Pacific	340 days	47° 58'N	129° 55'W	1950	12.6	Dymond and Lyle 1994
				2100	24.4	
Tropical Pacific	82-84	1° 0'N	139° 00'W	3495	21.8	Dymond and Lyle 1994
				2908	41.7	
Tropical Pacific	82-84	11° 0'N	140° 00'W		13.2	Dymond and Lyle 1994
MFZ	83-84	39° 49'N	127° 69'W	3400	39.7	Dymond and Lyle 1994
JDF	84-85	47° 97'N	128° 10'W		25.0	Dymond and Lyle 1994
G	87-88	41° 55'N	132° 00'W		10.3	Dymond and Lyle 1994
H	80-81	6° 57'N	92° 77'W		25.5	Dymond and Lyle 1994
M	80-81	8° 83'N	103° 98'W		19.8	Dymond and Lyle 1994
South China Sea	1 year	14° 36'N	115° 06'E		15.0	Wiesner <i>et al</i> 1993

(Continued)

Table 3. (Continued)

Site	Period	Lat.	Long.	Trap depth m	Annual flux $\text{g m}^{-2} \text{y}^{-1}$	Reference
<b>Upwelling areas</b>						
Cap Blanc 1	88-89	20° 55'N	19° 44'W	2195	66.8	Wefer and Fischer 1993
Cap Blanc 2	89-90	21° 08'N	20° 41'W	3502	55.5	Wefer and Fischer 1993
Walvis Ridge WR1	88-89	20° 04'S	09° 10'E	1640	59.1	Wefer and Fischer 1993
Walvis Ridge WR2 Upper	89-90	20° 02'S	09° 09'E	599	48.8	Wefer and Fischer 1993
Walvis Ridge WR2 Lower	89-90	20° 02'S	90° 09'E	1654	37.4	Wefer and Fischer 1993
<b>High latitudes</b>						
Station Papa	85-86	50° 0'N	145° 00'W	3800	45.0	Honjo <i>et al</i> 1984
Norway Abyssal Plain	85-86	65° 31'N	00° 64'E	2630	17.4	Honjo <i>et al</i> 1987
West Norwegian Sea	85-86	70° 00'N	01° 58'W	2749	16.8	Honjo <i>et al</i> 1987
Lofoten Basin	83-84	69° 30'N	10° 00'E	2761	22.8	Honjo <i>et al</i> 1987
Greelan Basin GB21	85-86	74° 35'N	06° 43'W	1966	08.8	Honjo <i>et al</i> 1987
Greelan Basin GB23	85-86	74° 35'N	06° 43'W	2823	10.2	Honjo <i>et al</i> 1988
Bear Island	84-85	75° 51'N	11° 28'E	1700	28.3	Honjo <i>et al</i> 1987
Fram Straits	84-85	78° 51'N	01° 22'E	2442	07.2	Wefer <i>et al</i> 1989
Bransfield straits	85-86	62° 15'S	57° 31'W	1588	107.7	Wefer 1989
Bransfield straits	83-84	62° 15'S	57° 31'W	1588	110.0	Wefer 1989
Weddell Sea	85-86	62° 26'S	34° 45'W	863	0.4	Fischer <i>et al</i> 1988



**Figure 6.** Particle flux and wind speed patterns in the eastern, central and western Arabian Sea. Data from the deep traps is presented for the period May 1986 to May 1987. Both particle fluxes and wind speeds are higher during the monsoons (from Nair *et al* 1989).

speed periods, the sea surface temperature is reduced and the mixed layer deepens from about 30 to 40 m during the premonsoon months to over 100 m during the southwest monsoon period (Hastenrath and Lamb 1979; Bauer *et al* 1991). The surface waters are enriched in nutrients primarily due to mixing with nutrient rich sub-surface waters as well as turbulent entrainment from the nutracline (Nair *et al* 1989). A deep chlorophyll maximum around 80 to 100 m depth is formed due to a combination of Ekman pumping and advection of dense fluids from the north (Bauer *et al* 1991). Shallow mixed layers are found throughout the Arabian Sea between September and November which again deepen by December (Bauer *et al* 1991). During the NE monsoon, winter blooms of phytoplankton are found in the northern and central parts of the Arabian Sea (Banse and McClain 1986). High primary production during both the SW and NE monsoons is reflected in high particle fluxes to the deep sea. Wind induced nutrient pumping into the euphotic zone is especially effective in the Arabian Sea as the sub-surface waters here have high nutrient concentrations (Ryther and Menzel 1965).

The monsoon winds bring in more than 100 million tonnes of eolian dust into the Arabian Sea every year (Sirocko and Sarnthein 1989) which increases the availability of iron in the photic zone. The simultaneous introduction of nutrients and soluble trace metals into the surface waters of the Arabian Sea may produce a more intense bloom than would otherwise occur. The response of the biological pump to increased wind speeds is extremely fast as the increase in primary productivity and particle fluxes begins almost simultaneously with the onset of the monsoons.

Particle fluxes in the Bay of Bengal also show a seasonality, though not so strong as the Arabian Sea with 36 to 52 per cent of the fluxes occurring during the southwest monsoon period. During the rest of the year particle fluxes are relatively low or moderate. Particle flux patterns in the northern and central Bay of Bengal coincided with freshwater discharge patterns of the Ganges-Brahmaputra rivers (figure 7). The maximum in particle fluxes are related to meltwater discharge from the Himalayan snows during summer and input of freshwater and suspended matter due to monsoon rains (Ittekkot *et al* 1991).

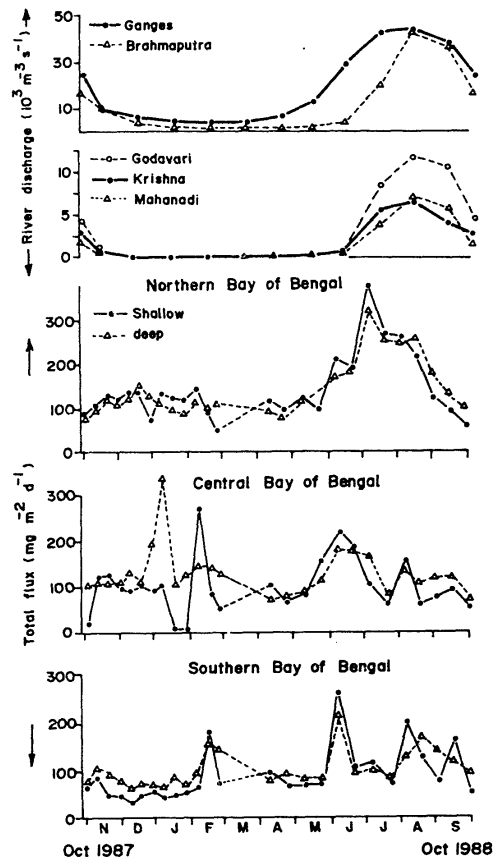


Figure 7. Particle fluxes in the deep traps in the northern, central and southern Bay of Bengal from November 1987 to November 1988 and freshwater river discharge pattern of major rivers in the region (from Ittekkot *et al* 1991).

River plumes enriched in nutrients together with turbulent mixing at the base of the halocline can significantly increase primary production in the offshore areas of the Bay of Bengal. Similar high productivity and high particle fluxes have been reported for river plumes of the Amazon (Deuser *et al* 1988; Muller-Krager *et al* 1988). Further, mineral particles delivered by rivers can get incorporated in biogenic aggregates making them denser and thus accelerating their settling rate (Ittekkot and Haake 1990; Ramaswamy *et al* 1991; Haake and Ittekkot 1990; Ittekkot *et al* 1992). In the central Bay of Bengal, particle fluxes are high during both the SW and NE monsoons (figure 3). While fluxes during the SW monsoons are similar to those in the northern Bay of Bengal, fluxes were much higher during the NE monsoons. The reasons for higher fluxes in the central Bay of Bengal during the NE monsoons is not very clear. A number of tropical cyclones cross the central Bay of Bengal during November and December. These cyclones may be mixing up the surface waters with nutrient-rich deeper waters thereby stimulating primary productivity.

### 4.3 Interannual variability

Interannual variability of particle fluxes in the northern Indian Ocean range between 3.4 to 21% of total annual fluxes. Maximum variability was in the Central Bay of Bengal (21%) while the northern Bay of Bengal and Arabian Sea showed a variability between 17.2 and 18.8%.

In the western and central Arabian Sea, interannual variability of particle fluxes resulted mostly due to variations during the SW monsoon period. At these sites, variations in monsoon intensity can be correlated with particle fluxes (table 2). 1986, 1987 and 1991 were years of weak monsoons with a monsoon index of -12, -19 and -4 respectively (Parthasarathy *et al* 1992) while the years 1988 and 1989 and 1990 had above average rainfall with monsoon index values of +16, +1 and +8 respectively (table 2). Total annual fluxes measured in the western and central Arabian Sea during 1986 and 1987 were much lower compared to those measured during 1988 and 1990. However, fluxes measured in the western Arabian Sea during 1991, a weak monsoon year, were only slightly less than those measured during 1988, a strong monsoon year. This may be partly due to the fact that there is a northward shift in the area of maximum windstress during a strong monsoon year (Anderson and Prell 1992).

Another factor affecting annual particle fluxes is the duration of the SW monsoon. Normal onset and retreat dates for the SW monsoons over 15°N Latitude in the Arabian Sea are 5th June and 1st October respectively (Anon 1992). The highest annual flux recorded during the study period in the western Arabian Sea is during 1990 (table 2). In this year the monsoon set in by 20th May and lasted till 15th October, a total of 148 days compared to a normal of 119 days (Anon 1992). Fluxes recorded in the eastern Arabian Sea during the SW monsoon of 1990 were also comparatively higher (table 4).

In the eastern Arabian Sea, interannual variability is mostly due to particle flux variations during the post SW monsoon period and during the NE monsoon. Fluxes during the NE monsoon of 1986-87, 1987-88 and 1989-90 were low while they were high during NE monsoon of 1988-89 and 1990-91. It is observed that during the years the NE monsoon particle fluxes were high, SST during the corresponding period were lower than 26°C (Haake *et al* 1993). Warm, nutrient-poor surface waters from the equatorial Indian Ocean cover the eastern Arabian Sea during the winter months.

**Table 4.** Table showing total flux in the eastern Arabian Sea during the SW monsoon period and total rainfall between 1st June and 31 September over India and over Konkan and Goa. Average rainfall over India is 850 mm while it is 2382 mm over Konkan and Goa. Rainfall data is from Parthasarathy *et al* 1992.

Year	Total particle flux during SW monsoon  g m <sup>-2</sup>	Total rainfall during SW monsoon	
		Konkan and Goa mm	All India mm
1986	15.2	1867	746.5
1987	13.0	2695	687.9
1988		2955	990.6
1989	12.6	2619	862.3
1990	15.8	2953	917.1
1991	15.9	2805	814.5

This leads to reduced productivity and lower fluxes during the NE monsoons (Banse and McClain 1986). Presumably, the northward flow of the equatorial Indian Ocean waters to the eastern Arabian Sea was reduced during the winter of 1988–89 and 1990–91.

Fluxes in the eastern Arabian Sea during the SW monsoon period are better correlated with the rainfall pattern over the adjacent subdivisions of Konkan and Goa in the western part of Peninsular India (table 4). In some years, like for example 1987, the progress of the monsoon was normal up to Bombay (17°N Lat.) but further northward progress was very sluggish. Consequently, during the SW monsoon of this year, Konkan and Goa received more than the normal rainfall but the Indian Subcontinent experienced one of the worst droughts of the century (table 4; Parthasarathy *et al* 1992). Both rainfall in this subdivision as well as particle fluxes in the eastern Arabian Sea during the SW monsoon of 1987 and 1989 were low compared to similar periods in 1990 and 1991. However, in 1986 rainfall over both Konkan and Goa as well as India were extremely low but fluxes are relatively high and has been provisionally attributed to lateral advection of particles from a plankton bloom on the continental margin of western India (Ramaswamy *et al* 1991; Madhupratap *et al* 1990).

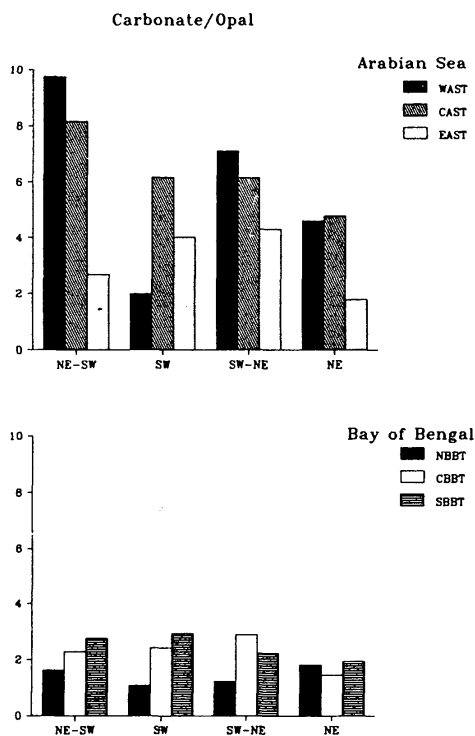
Since seasonality of particle fluxes in the Bay of Bengal are related to river discharge it is reasonable to expect that interannual variability will also be related to the intensity of the monsoon. In the northern Bay of Bengal annual flux data is available for the years 1988, 1989, 1991 and 1992. Monsoon Index during 1988 and 1989 were positive and negative during 1991 and 1992 (table 2). Annual fluxes also showed a similar pattern, being high during 1988 and 1989 and comparatively low during 1991 and 1992 (table 2).

In the central Bay of Bengal there seems to be no direct relation between annual fluxes and monsoon strength. Fluxes during 1990 and 1991 are similar inspite of 1990 being a good monsoon year and 1991 being a poor monsoon (table 2). Most of the variability is between August and November. In 1988 fluxes during October and November accounted for 13.3 percent of the annual fluxes while in 1990 they accounted for 34.4 percent of the annual fluxes. Factors controlling interannual variability of particle fluxes here is not very clear but may be dependent among other factors on circulation pattern and western boundary current, direction of southerly flow of the freshwater plume and lateral advection of material from coastal upwelling areas and number of tropical cyclones during the late SW monsoon and post SW monsoon period.

In the southern Bay of Bengal data available for two years show similar fluxes although monsoon intensity varied considerably during these years. According to Haake *et al* (1993b) particle fluxes here may be related to northward movement of the Inter Tropical Convergence Zone, which migrates from 5°S Latitude in February to 15°N Latitude in July (Gadgil *et al* 1984).

#### 4.4 Carbonate fluxes and carbonate/opal ratios

Carbonate/opal ratios (figure 8) indicate the prevalent planktonic community structure which in turn is dependent on nutrient availability. In the Arabian Sea carbonate/opal ratios are high during the NE monsoon and intermonsoon period but low during the SW monsoon period. It is interesting to note that during the earlier part of the SW monsoon period when total particle fluxes are moderately high (between 50 and



**Figure 8.** Seasonal variation in the ratio of carbonate to opal in the deep traps of the eastern (EAST), central (CAST) and western (WAST) Arabian Sea and northern (NBBT), central (CBBT) and southern (SBBT) Bay of Bengal. Data is presented for the SW monsoon (June 1st to 30th September), SW-NE intermonsoon period (1st October to 30th November), NE monsoon (1st December to 28th February) and NE-SW intermonsoon period (1st March to 31st May). Trap location and depth are given in table 1.

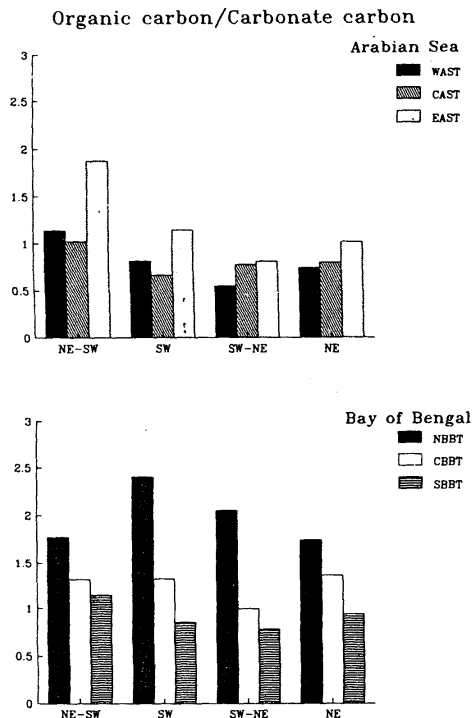
$200 \text{ mg m}^{-2} \text{ day}^{-1}$ ) carbonate/opal ratios increase, (figure 5) but during the later part of the monsoon when particle fluxes exceed  $200 \text{ mg m}^{-2} \text{ day}^{-1}$  there is a fall in the ratios. Probably, the coccolith production is high during the early SW monsoon period and is replaced by diatoms during the later part of monsoon (Haake *et al* 1993).

Carbonate percentages as well as carbonate/opal ratios in the Bay of Bengal (figure 8) are much less compared to the Arabian Sea. In the Bay of Bengal, salinity changes are sharp especially during August and September when values drop to less than 27 parts per thousand in the northern part of the Bay (Murthy *et al* 1990). Coccolithophorids can tolerate large variations in salinity between 16 to 45 parts per thousand (Haq 1978) and a new population may be established within a few days. Foraminifers on the other hand have limited tolerance to salinity changes and show change in species, size, ornamentation and chamber size for even small changes in salinity, as low as 1 to 2 per thousand (Boltovskoy and Wright 1976). Lower salinity is also thought to inhibit foraminiferal calcification (Hemleben *et al* 1987) and this is seen in the diminished productivity of foraminifers in the northern Bay of Bengal (Guptha *et al* 1994). Pteropods also have thinner tests during this period. In the central and southern Bay of Bengal, salinity changes are not so sharp with the result that carbonate variations are not pronounced.

#### 4.5 Organic carbon fluxes

Organic carbon fluxes in the Arabian Sea range from less than  $1 \text{ mg m}^{-2} \text{ day}^{-1}$  during both the intermonsoon period to over  $30 \text{ mg m}^{-2} \text{ day}^{-1}$  during the SW monsoon period (Haake *et al* 1992). Highest fluxes of organic carbon are in the western Arabian Sea and decrease towards the east. Low organic matter percentage as well as minima in contribution of amino acid carbon to total carbon were observed during particle flux maxima of the southwest monsoon (Haake *et al* 1992). Fluxes of organic carbon in the Bay of Bengal is comparable to those in the Arabian Sea in spite of having a lower primary productivity and lower zooplankton concentration (Qasim 1977; Rao 1973). This may partly be due to higher lithogenic fluxes in the Bay of Bengal as transfer of organic aggregates to the deep sea is aided by incorporation of lithogenic matter into organic aggregates which increases their stability and density and settling rates (Ramaswamy *et al* 1991; Ittekkot *et al* 1992).

Berger and Kier (1984) have suggested that rain ratio of organic carbon/carbonate carbon increases with increasing export production. They have shown that this shift in the rain ratio has great implication for the  $\text{CO}_2$  budget of the surface and deep ocean. Increase in organic carbon/carbonate carbon ratios (figure 9) during high flux periods is seen in both the regions of the northern Indian Ocean. These ratios are



**Figure 9.** Seasonal variation in the ratio of organic carbon to carbonate carbon in the deep traps of the eastern (EAST), central (CAST) and western (WAST) Arabian Sea and northern (NBBT), central (CBBT) and southern (SBBT) Bay of Bengal. Data is presented for the SW monsoon (June 1st to 30th September) SW-NE intermonsoon period (1st October to 30th November) NE monsoon (1st December to 28th February) and NE-SW intermonsoon period (1st March to 31st May). Trap location and depth are given in table 1.



considerably higher in the Bay of Bengal than in the Arabian Sea. Whether this means that the Bay of Bengal is a bigger sink for atmospheric CO<sub>2</sub> remains to be seen. High organic carbon/carbonate carbon ratios in the Bay of Bengal is also due to, as discussed before, more efficient transfer of organic matter to the deep sea because of greater availability of lithogenic matter.

#### 4.6 Lithogenic fluxes

The main source of lithogenic material to the Arabian Sea are the Indus, Narmada and Tapti rivers and eolian input from the Somali-Arab deserts (Goldberg and Griffin 1970; Weser 1974; Kolla *et al* 1981; Sirocko 1989). Clay mineral studies of sediment trap material show that eolian material derived from Arab-Somali regions cover the entire Arabian Sea (Ramaswamy *et al* 1991). Even the eastern Arabian Sea traps received palygorskite, a mineral found in the deserts of Arabia and transported to this site by monsoon winds (Ramaswamy *et al* 1991). Fluvial material is mostly derived from the Indus and other rivers draining the Indian Peninsula and is restricted to the eastern part of the Arabian Sea due to clockwise surface circulation during peak discharge periods of the rivers (Ramaswamy *et al* 1991).

Based on lithogenic/organic carbon ratios, Ramaswamy *et al* (1991) have demonstrated a strong biological control on lithogenic particle sedimentation in the Arabian Sea. Lithogenic particles settle only during periods of high productivity. High Lith/C.org ratios during June show that lithogenic particles accumulating in the surface layers during the premonsoon periods are removed at the beginning of the SW monsoon due to increase in fluxes of organic aggregates.

Lithogenic fluxes are well correlated with particulate organic carbon fluxes at all sites in the northern Indian Ocean. It is known that fine lithogenic particles in the ocean cannot settle independently as their sinking velocity is very low (Honjo *et al* 1982). Also, organic matter is remineralized very efficiently in the upper ocean and only a small fraction escapes the photic zone. It is observed that when lithogenic input from land coincides with high primary production periods in the oceans, there is an increase in the fluxes of both lithogenic and biogenic particles. Similar relation can be seen in the fluxes of eolian dust from the Sahara deserts and upwelling in the equatorial Atlantic (Wefer and Fischer 1993).

Higher lithogenic fluxes in the Bay of Bengal are to be expected as the suspended sediments input here is higher than the Arabian Sea by an order of magnitude. What is surprising is that the southern Bay of Bengal traps, which is more than 1500 km away from the major rivers, has a higher lithogenic flux (table 5) than even the eastern or western Arabian Sea traps located about 400 km away from continents and in areas known to have very high eolian and fluvial input (Kolla *et al* 1981; Kolla and Kidd 1982; Sirocko 1989).

From the sediment trap fluxes it is estimated that out of more than 2500 million tonnes of lithogenic matter discharged into the northern Indian Ocean, only 30 to 40 million tonnes of the lithogenic matter is being deposited in the deeper part of the northern Indian Ocean as hemi-pelagic sediments. In the Arabian Sea, cross shelf transport is negligible (Ramaswamy and Nair 1989) whereas in the Bay of Bengal there is considerable cross shelf transport of fluvial sediments. Hemipelagic sedimentation accounts for less than 5% of the total lithogenic matter discharged into the northern Indian Ocean. Most of the sediment transport is probably by near

**Table 5.** Table showing average annual rain rates of particulate matter and first order components in the northern Indian Ocean and their accumulation rates in sediments. Rain rates are average fluxes for the period 1986–91 and 1987–89 in the Arabian Sea and Bay of Bengal respectively. Rain rates for the Bay of Bengal reported in this table are different from that of table 2 because component flux data is available for only two years. All fluxes are in  $\text{g m}^{-2} \text{y}^{-1}$ .

Station	Total	Carbonate	Opal	Lithogenics	C.org
<b>Western Arabian Sea</b>					
WAST	51.4	28.0	13.0	5.6	2.9
KL-71*	33.8	18.3	2.1	12.8	0.37
<b>Central Arabian Sea</b>					
CAST	26.3	16.4	3.0	3.6	1.6
KL-15*	23.3	15.3	0.15	6.6	0.08
<b>Eastern Arabian Sea</b>					
EAST	30.3	15.5	5.1	6.7	1.9
KL-36*	18.5	13.0	0.1	5.5	0.19
<b>Northern Bay of Bengal</b>					
NBBT	50.2	14.3	8.6	21.2	3.1
30P#	30.0	1.5	0.2	27.9	0.02
<b>Central Bay of Bengal</b>					
CBBT	49.3	18.5	9.0	15.7	3.1
22PG#	5.6	1.6	0.03	3.9	0.01
<b>Southern Bay of Bengal</b>					
SBBT	38.2	18.5	7.3	8.6	2.0
44G#	5.1	3.1	0.04	0.04	0.01

\* Holocene accumulation rates calculated from Sirockko 1989.

# Holocene accumulation rates calculated from Sarin *et al* 1979.

bottom processes like high density lutite flows, turbidity currents, transport through submarine channels etc. However, very little information exists on these processes.

#### 4.7 Particle sedimentation and remineralization

Table 5 shows that rain rates of particles compared with accumulation rates in sediments. It must be kept in mind that trap fluxes reported here are an average of 4 or 5 years while accumulation rates in sediments are an average of the last 8000 years. Also sediment trap techniques are far from perfect and can lead to serious over or underestimation of the actual flux. Still, if used with care we can get important information about biogeochemical cycling of elements in the oceans. Of particular interest are the sites and rates of remineralization of particles (Walsh *et al* 1988).

Organic carbon fluxes decrease with depth and between 30 and 40 per cent of the organic matter is decomposed between the shallow and deep traps (Haake *et al* 1992). Less than 15 per cent of the material reaching the 3000 m water depth is preserved in sediments (table 5) indicating that the benthic boundary layer is the major site of organic matter degradation (Honjo *et al* 1982; Cole *et al* 1987).

Similarly, more than 84% of opal is remineralized at the sediment-water interface. Opal concentrations in the sediments of the Arabian Sea are much higher than the Bay of Bengal (Kolla and Kidd 1982). Contrary to expectations, annual opal fluxes

are high in the Bay of Bengal and fluxes here are comparable to those in the western Arabian Sea (table 5). Higher opal preservation in the sediments of the Arabian Sea may be due to a combination of factors like higher bulk accumulation rate, flux pattern and quality of opal particles. A major difference in opal flux pattern between the two regions is that in the Arabian Sea opal fluxes are episodic with 84 per cent of the opal flux during the SW monsoon period whereas in the Bay of Bengal moderate fluxes are maintained throughout the year. The number of colonial radiolarians, which have thicker tests compared to diatoms, are also more in the Arabian Sea (unpublished cruise reports of RV Sagar Kanya and RV Sonne).

In the Arabian Sea bulk accumulation rates from sediment traps are comparable to sedimentation rates and the offset between the two is less than a factor of two (Sirocko *et al* 1991; table 2). Lithogenic fluxes in the traps are consistently less than sedimentation rates showing that additional material is transported and deposited through near bottom processes like, for example, nepheloid layer flows.

In the Bay of Bengal, not much data is available on sedimentation rates. Based on  $^{230}\text{Th}$  and  $^{210}\text{Pb}$  isotopes, Sarin *et al* (1979) have reported sedimentation rates between 2 and 40 mm per thousand years during the Holocene. Trap fluxes are comparable to sediment accumulation rates only in the northern Bay of Bengal (table 2). In the central and southern Bay of Bengal, sedimentation rates are less by a factor of 5. The reasons for this is not very clear. Dissolution of carbonates can account for only a fraction of the difference as the sea floor lies well above the calcium compensation depth (Kolla and Kidd 1982). Furthermore, even the flux rates of lithogenic material alone is more than the total Holocene sedimentation rates. Another possibility is that sediments are getting resuspended and eroded. Though there are indications of strong bottom current activity in the Bay of Bengal (Kolla *et al* 1976) these currents are restricted only to the western part of the Bay. Sediment traps can overestimate fluxes, but a fairly good relation is seen between rain rates and accumulation rates in the Arabian Sea and northern Bay of Bengal. A more likely explanation is that the sedimentation rates reported by Sarin *et al* (1979) are underestimates. Sedimentation rates as low as 2 mm per thousand years are generally reported only in areas of extremely low productivity such as central Oceanic Gyres (Lisitzin 1975).

## 5. Summary

Particle fluxes in the Arabian Sea and northern Bay of Bengal seem to be related to the strength and intensity of the monsoons though the correlation is not always very good. Interannual variability in particle fluxes in the central and southern Bay of Bengal is still not adequately explained. We have only just begun to understand the processes controlling biogeochemical fluxes in the northern Indian Ocean and a lot more needs to be done. It is still not clear if the northern Indian Ocean is a major source or sink for  $\text{CO}_2$ . We do not as yet have reliable time series data on primary productivity using clean techniques for this region. The contribution of organic matter from highly productive continental shelves to the deep sea has not been quantified. The role of organic matter produced in the photic zone and those resuspended from the continental margins in maintaining suboxic conditions in the Arabian Sea is not yet fully understood. Remote sensing of the ocean surface coupled with multi-disciplinary cruises and particle flux studies with moored sediment traps at strategic

locations on continental margins should help in a better understanding of carbon cycling in the oceans.

### Acknowledgements

Many of the ideas expressed in this paper have evolved out of discussions with Dr. V Ittekkot and his group from the Institute of Biogeochemistry and Marine Chemistry, Hamburg University, Germany, and we thank them for their cooperation. Dr. B N Desai, Director, NIO is thanked for his continuous support for the project. Financial support was provided by Council of Scientific and Industrial Research, New Delhi and Federal German Ministry of Research and Technology, Bonn. Ship time on ORV Sagar Kanya was provided by Department of Ocean Development, New Delhi.

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