15 Fresh Water Influx and Particle Flux Variability in the Bay of Bengal

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15.1 INTRODUCTION

In this chapter we review the results from an ongoing continuous sediment trap experiment at three locations in the Bay of Bengal, a marine region which comes under the influence of some of the largest rivers in the world - the Ganges/ Brahmaputra river system. The results from the study are expected to provide information on the response of marine biogeochemical cycles to this fresh water influx. Such information is critical to understanding the past, and possibly also future, changes in the marine carbon cycle and those induced by the injection of fresh water into the oceans from melting ice sheets, in particular.

In the following we discuss the major processes controlling particle fluxes to the deep Bay of Bengal based on information obtained from deep-moored traps (1727 m – 3010 m, compare Table 15.1) covering four years of study from October 1987 to November 1991. For detailed illustration of these processes, especially the influence of fresh water and sediment inputs, we have included a description of the fluxes and of the geochemical ratios measured at shallow and deep traps in the northern, central and southern areas of the Bay of Bengal during the period of 1987–88.

15.2 STUDY AREA

The Bay of Bengal is the catch basin for fresh water and sediment input from some of the world’s largest rivers (Figure 15.1). It is estimated that annually about 2 x 10^9 tons of sediments enters the Bay of Bengal with the major input coming from the rivers such as Ganges and Brahmaputra draining the Himalayas (Milliman and Meade, 1983). The inputs from these rivers exhibit high seasonal variabilities with the bulk occurring during the SW monsoon (Figure 15.2a). The other major contributors of terrigenous material to the Bay of Bengal are the

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Table 15.1 Sampling data of the sediment trap experiment in the Bay of Bengal

	Position N	Position E	Trap depth (m)	Trap depth (m)	Water depth (m)	Sampling start	Sampling end	Sampling interval (d)
NBBT$_{\text{N}}$ - Northern Bay of Bengal Trap - North								
01	17°27’	89°36’	809	1727	2263	10/28/87	02/28/88	13 x 9.5
02	17°27’	89°36’	754	1790	2267	04/01/88	10/06/88	13 x 14.5
03	17°27’	89°36’	967	2029	2265	11/02/88	10/19/89	13 x 27
NBBT$_{\text{S}}$ - Northern Bay of Bengal Trap - South								
04	15°14’	89°10’	1131	1717	2738	01/02/90	10/28/90	13 x 23
05	15°31’	89°13’	1131	2120	2706	12/05/90	10/26/91	13 x 25
CBBT - Central Bay of Bengal Trap								
01	13°09’	84°22’	906	2282	3259	10/28/87	02/28/88	13 x 9.5
02	13°09’	84°22’	950	2227	3263	04/01/88	10/06/88	13 x 14.5
03	13°09’	84°21’	950	2286	3263	11/02/88	10/19/89	13 x 27
04	13°08’	84°17’	988	2327	3312	04/06/90	11/21/90	1x21, 8x23, 4x6
05	13°09’	84°20’	893	2282	3267	12/05/90	10/26/91	13 x 25
SBBT - Southern Bay of Bengal Trap								
01	04°28’	87°19’	1040	3006	4017	10/28/87	02/28/88	13 x 9.5
02	04°28’	87°18’	1017	2983	4045	04/01/88	10/06/88	13 x 14.5
05	05°01’	87°09’	1071	3010	3996	12/05/90	10/26/91	13 x 25

Errors in rotation:
CBBT-01, 2282 m = deep: 11/06/87 to 03/22/88, 12 x 9.5, 1 x 23
CBBT-03, 2286 m = deep: Cup 11 sampled 2 intervals (07/30/89 to 09/22/89)
CBBT-03, 2286 m = deep: Cup 12 = interval 13

peninsular Indian rivers such as the Mahanadi, Godavari, Krishna and Cauvery which have their peak discharges during the later phase of the SW monsoon. The enormous fresh water discharges cause changes in the surface salinity of the Bay of Bengal over a wide range of values both seasonally and geographically (LaViolette, 1967). The greatest change (by more than 7‰) occurs towards the end of the SW monsoon when the water discharge from the Ganges and Brahmaputra and from the peninsular Indian rivers is at a maximum.

The drainage basins of the rivers are drastically affected by human activities such as deforestation which has an effect also on nutrient transport of the rivers. It has been found that nitrogen transport in these rivers has, in addition to the dissolved nitrogen load, a major component associated with the particulate fraction and which is derived from eroding soils (Ittekkot and Zhang, 1989). This nutrient loading is enhanced by the use of nitrogen fertilizers for agriculture and by the direct introduction of nutrients from highly populated areas.

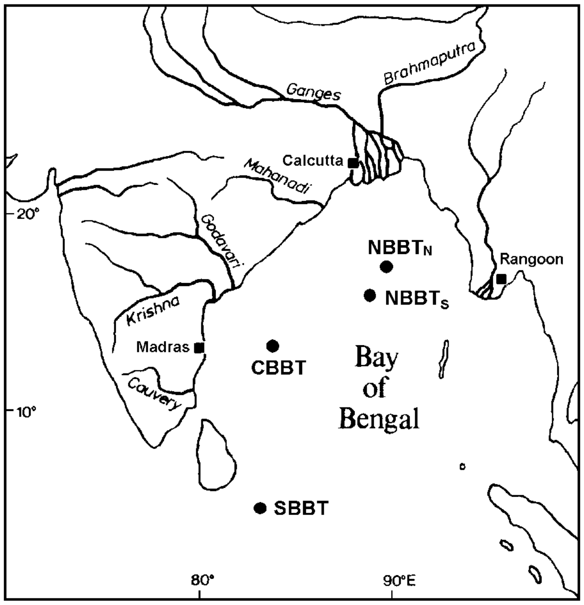

Figure 15.1 Locations of the sediment trap moorings in the northern ($NBBT_N$, $NBBT_S$), central (CBBT) and southern (SBBT) Bay of Bengal (for details see Table 15.1).

15.3 METHODS

15.3.1 SAMPLING

Samples were collected during an ongoing sediment trap experiment in the Bay of Bengal since October 1987. Briefly, three moorings, each consisting of two time-series sediment traps (Mark VI, Honjo and Doherty, 1988) were deployed at three locations in the northern, central and southern Bay of Bengal (Figure 15.1). The traps are programmed to collect settling particles at intervals of approximately one to four weeks (Table 15.1).

Prior to deployment the collection cups were filled with deep-sea water to which 35 g NaCl l^{-1} and 3.33 g $HgCl_2$ l^{-1} were added in order to minimize loss by diffusion and biological alteration during underwater storage (Knauer et al., 1984; Lee et al., 1992). On recovery of the traps the samples were wet-sieved and split using a precision rotary splitter. The < 1 mm fraction was filtered through preweighed polycarbonate filters (0.45 µm, Nuclepore) and dried at 40°C for 24 hours. This fraction was used for flux calculations.

15.3.2 ANALYSES

Carbonate was determined by heating the sample with phosphoric acid and subsequent quantification of the evolved CO_2 in a NaOH solution by conductivity (WÖSTHOFF Carmhograph). Biogenic opal was determined photometrically after extraction of silica into a Na_2CO_3 solution (modified after Mortlock and Froelich, 1989). Nitrogen and total carbon content were determined using a CN analyzer (NA-1500 Nitrogen Analyzer, Carlo Erba). Organic carbon was calculated as the difference between total carbon and carbonate carbon. The content of lithogenic material was calculated as the difference between 100 and the sum of carbonate, opal and organic matter (organic matter = C_{org} x 1.8, Müller et al., 1986) content. For further details see Haake et al., (1993). C/N, Carbonate/opal and $C_{org}/C_{Carbonate}$ ratios were calculated by weight percent.

15.3.3 WIND SPEED AND SEA SURFACE TEMPERATURE

Wind speed data are from ship observations within a radius of 2° around the study sites (Indian Daily Weather Report).

The sea surface temperature (SST) data used in this study were provided by the Distributed Active Archive Center (DAAC) of the Jet Propulsion Laboratory (JPL). The data base is a weekly composite, Multichannel Sea Surface Temperature (MCSST) estimate based on the AVHRR (Advanced Very High Resolution Radiometer) measurements. The MCSST data are interpolated for 18 km resolution. We present time series of MCSST for the pixel location closest to the three sediment trap locations.

15.4 TOTAL AND COMPONENT FLUXES

Total fluxes in the Bay of Bengal vary between 52–340 mg m^{-2} d^{-1} during the period of investigation. The associated component fluxes are in the range of 11–140 mg m^{-2} d^{-1} for carbonate, 6–137 mg m^{-2} d^{-1} for opal, 9–199 mg m^{-2} d^{-1} for lithogenic matter, and 2.4–14.6 mg m^{-2} d^{-1} for organic carbon. The variability of these fluxes at the individual stations is discussed below.

15.4.1 NORTHERN BAY OF BENGAL

The highest fluxes were recorded in 1988 during the SW monsoon (Figures 15.2b and 15.3). The Indian summer monsoon was the strongest in the year 1988. The year also saw severe floods in Bangladesh which caused large scale losses in property and human lives (Das et al., 1989b). Enormous amounts of fresh water and sediments were discharged into the Bay of Bengal during that year. These inputs and the associated nutrients led to high primary productivity in coastal

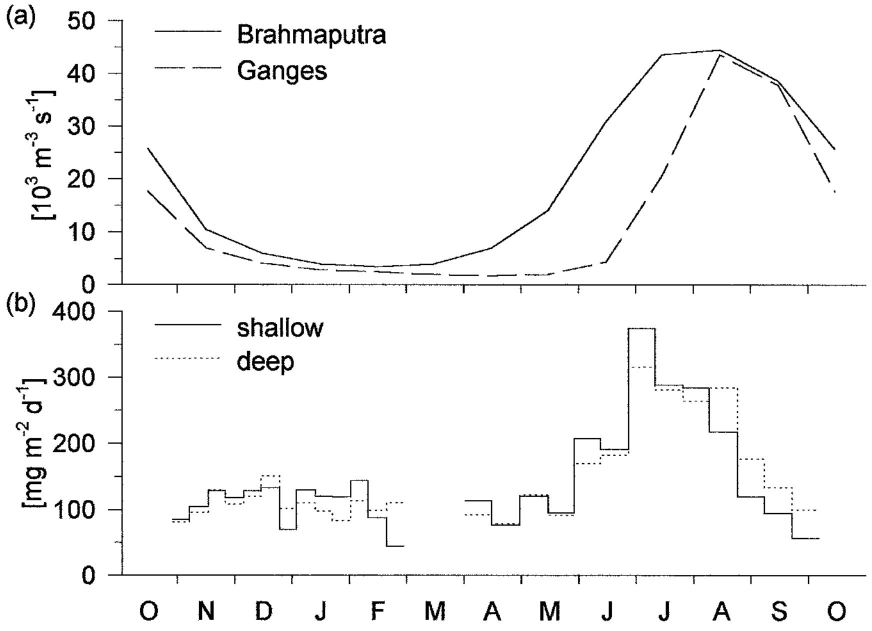

Figure 15.2 (a) Water discharge (from Unesco, 1979) and (b) total fluxes in the northern Bay of Bengal from October 1987 to October 1988.

areas and river plumes with the effect of enhancing the particle flux to the deep ocean. In the Bay of Bengal, the effects of these processes were felt at the northern station ($NBBT_N$) which is located approximately 480 km off the mouth of the Ganges/Brahmaputra river system (Figure 15.1).

The seasonal pattern of particle flux in 1989 at the same station differs from 1988 (Figure 15.3). The particle flux maximum which was observed in 1988 was absent. The 1989 SW monsoon was also weaker than 1988 (Parthasarathy et al., 1992) and this had the effect of reducing river inputs to the Bay of Bengal. On the other hand wind speeds were much stronger in 1989 which resulted in a rapid cooling of the surface layers in March. This also indicated nutrient input from deeper water layers and subsequently elevated biological production of particles. Therefore particle fluxes at this station in 1989 showed a prolonged period of high fluxes between March and October instead of recording peak fluxes for a short time period as in 1988 (Figure 15.3). Thus, although there was a difference in the seasonal flux pattern, the total annual fluxes recorded for the two years were almost identical (52 g m^{-2}, Table 15.2a).

An interesting feature of particle flux in the northern parts of the Bay of Bengal was the spatial variability observed. The fluxes measured at a station about 200

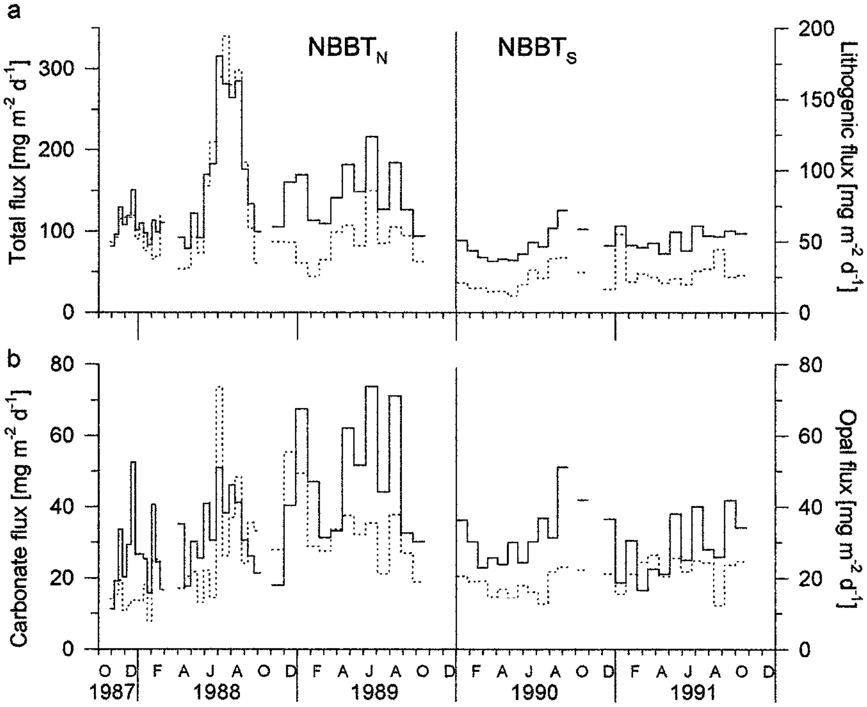

Figure 15.3 (a) Total fluxes (—) and lithogenic fluxes (·····), and (b) carbonate fluxes (—) and opal fluxes (·····) in the northern Bay of Bengal.

km south of the northern station (NBBT $_S$, Figure 15.1) in 1990 and 1991 were characterized by low fluxes and an absence of any pronounced seasonal signals (Figure 15.3). This may be due, on the one hand, to the weaker SW monsoon in the years 1990 and 1991 in comparison to the two previous years (Parthasarathy et al., 1992) and, on the other, to the diversion of the river plume away from the trap location by the prevailing surface circulation pattern in the northern Bay of Bengal (Madhusudana Rao, 1985). The difference in flux patterns observed at these two stations located about 200 km away from each other may result from the varying influence of the inputs from the Ganges/Brahmaputra river system. If river-derived mineral particles are incorporated into large organic aggregates derived from primary production within river plumes, then this also may accelerate particle sedimentation in the sea (Ittekkot, 1991; 1993; Figure 15.4). Primary production in river plumes effectively acts as a biological barrier preventing the dispersal of river-derived suspended material towards the open ocean.

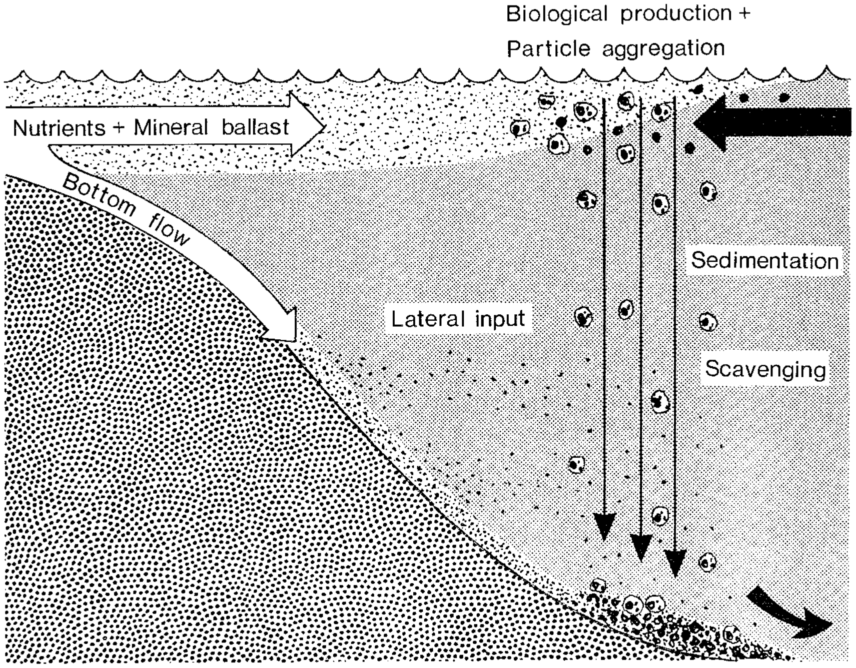

Figure 15.4 The supply of nutrients by the rivers leads to high primary productivity in river plumes advected far into the open ocean. The biogenic particles incorporate suspended lithogenic particles which are also supplied by the river and can thus be transported faster into the deep sea where they scavenge fine lithogenic particles advected from the continental slope (from Ittekkot, 1991).

During the monsoons, carbonate fluxes in the northern Bay of Bengal were more than twice those recorded during the intermonsoon periods. The flux pattern correlated well with the wind speed pattern which suggests that biological carbonate production was mainly controlled by nutrient input to the surface layers by wind-induced mixed layer deepening. Foraminiferal populations less tolerant to salinity changes (e.g., *Globigerinoides sacculifer*) had lower flux rates in the northern Bay of Bengal than in the central Bay of Bengal (Guptha et al., 1996). The temporal and spatial pattern of their appearance and abundance was indicative of strong surface salinity fluctuations even within the SW monsoon periods. Such changes were consistent with particle fluxes associated with an advancing and retreating river plume postulated by Reemtsma et al. (1993) and are reminiscent of particle flux changes to the deep sea encountered in polar regions in association with seasonal changes in ice cover (this volume, Chapters 7 and 13).

The fluxes of opal and lithogenic material at the northern station (Figure 15.3) appeared to be directly related to discharge from the rivers and there was no clear-cut correlation between wind speeds and fluxes as was observed for carbonate fluxes (Bartsch, 1993). Biogenic opal and lithogenic fluxes were highest during the 1988 SW monsoon, which was also characterized by high rainfall and high river inputs. Lithogenic matter made up to 59% and opal up to 32% of the total flux in 1987/88 at the northern station (Bartsch, 1993) and both were much higher than those measured in most of the other oceanic regions (this volume, Chapter 7). The river inputs contributed directly to the fluxes by introducing lithogenic material, and indirectly by bringing in nutrients including large quantities of dissolved silicate to the surface layers stimulating biological productivity, especially of diatoms. This increase in diatom production in the upper ocean due to fresh water influx was reflected in the flux pattern at this station. Similar to the pattern observed in total fluxes, biogenic opal and lithogenic fluxes were less variable in 1990 and 1991 at NBBT_S, where the traps were located 200 km south of NBBT_N (Figure 15.3). Also the fluxes of both components were lower than those measured at the northern station indicating the absence of fluvial influence.

15.4.2 CENTRAL BAY OF BENGAL

At the central Bay of Bengal station (CBBT) marked seasonality was observed in each of the investigated years with high fluxes during both SW and NE monsoon periods (Figure 15.5, Table 15.2b).

Carbonate fluxes in the central Bay of Bengal were higher than those measured at the northern stations. Higher fluxes (more than twice) occurred during the monsoons than during the intermonsoon periods. The opal fluxes were generally higher during both monsoons whereas high lithogenic fluxes occurred mainly during the SW monsoon. The particle flux maximum observed between October 1990 and January 1991 represents an exception to this general trend. During this period of four months, opal fluxes of 8.2 g m^{-2} and fluxes of lithogenic material of 19.4 g m^{-2} were recorded. Lithogenic material contributed 54% of the total flux indicating a strong influence of land-derived material introduced from the rivers during this period. The terrigenous nature of the settling particles was further confirmed by their comparatively low $\delta^{15}N$ values (Schäfer and Ittekkot, 1995). The central trap location was about 480 km off the mouths of the Indian peninsular rivers, Godavari and Krishna (Figure 15.1), the drainage basins of which received more than double the annual average rainfall during August 1990 (Gupta et al., 1991b). Also, the recorded rainfall between October and December 1990 was more than thrice that of the average, resulting in high water levels in the rivers and floods in the drainage area (Gupta et al., 1991c).

The Bay of Bengal is also affected by storms and the track of one such storm crossed the location on November 1, 1990 (Gupta et al., 1991a). The resulting turbulent mixing of the upper ocean entraining nutrients from the deeper layers to the euphotic zone enhances biological productivity in the surface layers. This, and the increased terrigenous influx from rivers and from shelf sediments, could have contributed to the high fluxes and to the pattern of component fluxes observed during this period. A peak flux in January 1988 consisting mainly of opal in the central Bay of Bengal also appeared to be related to enhanced cyclonic activity in the region between November and December 1987 (Das et al., 1989a; Figure 15.5).

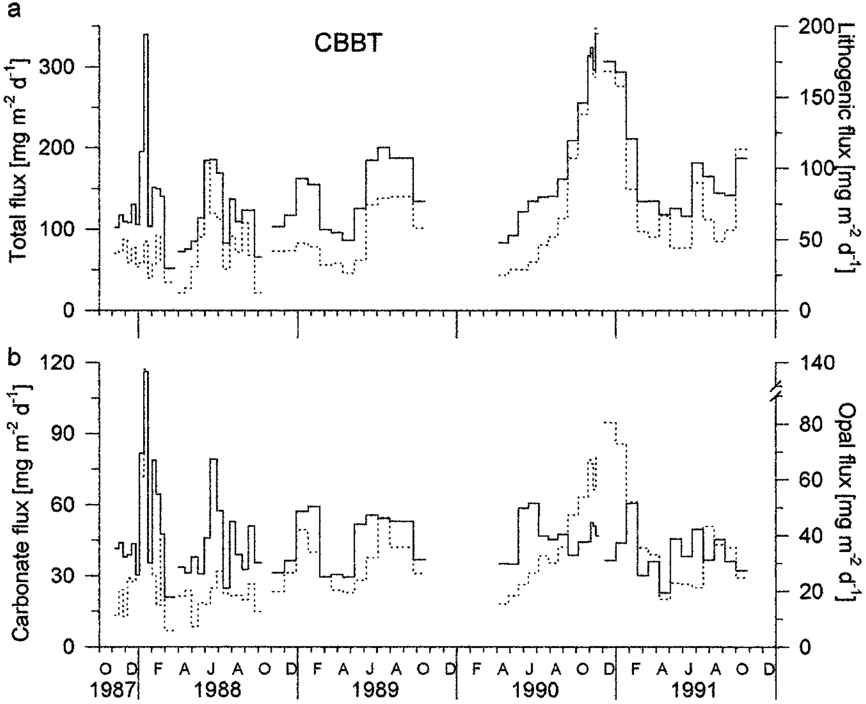

Figure 15.5 (a) Total fluxes (—) and lithogenic fluxes (·····), and (b) carbonate fluxes (—) and opal fluxes (·····) in the central Bay of Bengal.

15.4.3 SOUTHERN BAY OF BENGAL

In contrast to the northern and central stations, seasonality in wind speeds was much stronger in the southern Bay of Bengal (Figure 15.6). The increase in wind speeds caused a decrease in sea surface temperature of about 3°C during the SW monsoon, and of 1–2°C during the NE monsoon (Figure 15.6). High particle fluxes were recorded in the deep sea within about 3 to 4 weeks after the decrease