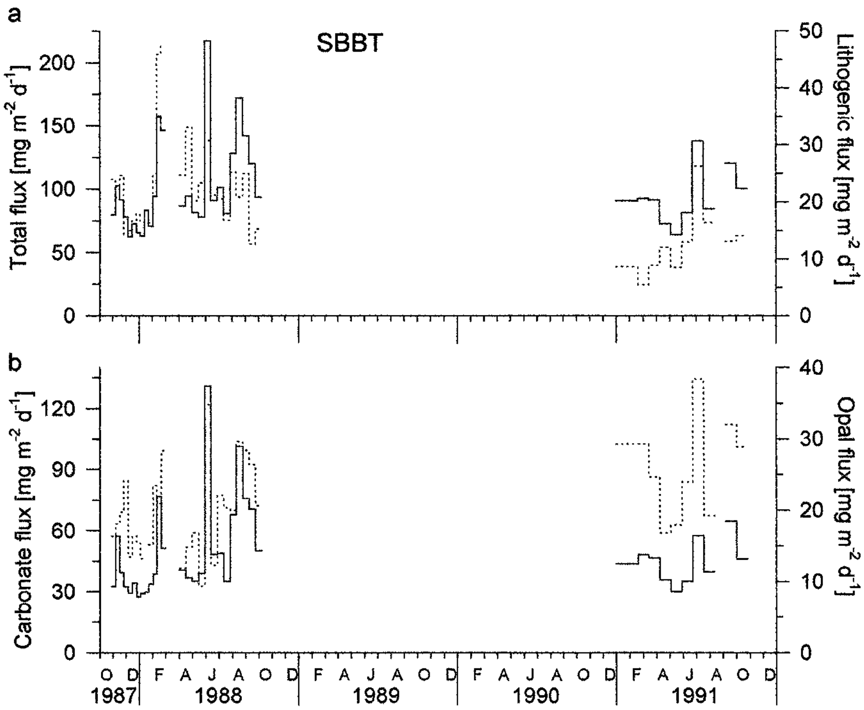

Figure 15.7 (a) Total fluxes (—) and lithogenic fluxes (·····), and (b) carbonate fluxes (—) and opal fluxes (·····) in the southern Bay of Bengal.

in surface temperature (Figure 15.6). Wind-induced mixed layer deepening brings nutrient-rich subsurface waters to the euphotic zone and enhances primary productivity and as a consequence particle flux to the deep ocean (Nair et al., 1989). Because of technical problems data for only two years are presented here (i.e., 1987–88 and 1991) during which period the particle flux patterns were similar (Figure 15.7).

The southern Bay of Bengal is characterized by higher carbonate fluxes and lower opal and lithogenic fluxes in comparison with the northernmost and the central stations. The total flux pattern was mainly determined by carbonate fluxes. Here again, the close association of total fluxes and wind speeds suggests that wind-induced mixed layer deepening had the general effect of increasing carbonate production in the Bay of Bengal.

15.5 INTERANNUAL VARIABILITY

15.5.1 SEASONAL SIGNALS

In the northern Bay of Bengal ($NBBT_N$) the seasonal pattern of particle fluxes was highly variable from year to year (Figure 15.3, Table 15.2a). The particle flux maximum between June and September 1988 correlated with periods of high river inputs and was a result of a strong monsoon during that year. The recorded rainfall was one of the highest in this century (Parthasarathy et al., 1992). A weak SW monsoon in 1989 resulted in less marked flux peaks during that year. Particle flux was influenced more by wind speeds than by river inputs in 1989 (Bartsch, 1993). At $NBBT_S$ the fluxes were lower in both years, with slightly elevated SW monsoon fluxes (Table 15.2a).

In the central Bay of Bengal the investigated years were marked by a distinct seasonality in the flux pattern with maxima during both the monsoons (Figure 15.5, Table 15.2b). The exceptional particle flux maximum of 36 g m^{-2} measured between October 1990 and January 1991 was due to an extreme flood event which led to a lateral injection of particulate matter to the deep sea. This event contributed about 60% to the total annual flux at this station.

Seasonality of particle fluxes with slightly higher fluxes during the SW monsoon was seen in both the investigated years in the southern Bay of Bengal (Figure 15.7, Table 15.2c).

15.5.2 TOTAL AND COMPONENT FLUXES

The total annual particle fluxes in the Bay of Bengal did not show any significant interannual variability except for the central station where it resulted mainly from the effect of extreme events such as floods and cyclonic activities in 1989/90 and 1990/91 (Table 15.2b). The observed higher fluxes during these extreme events were caused by higher lithogenic matter and opal fluxes.

In the northern Bay of Bengal ($NBBT_N$), the total annual fluxes were very similar in both the investigated years. The component fluxes varied however considerably from year to year as a result of the varying intensities of fluvial influence. The fluxes of lithogenic matter decreased from 1987/88 to 1988/89 whereas the carbonate and opal fluxes increased (Table 15.2a). At $NBBT_S$ the component fluxes were comparatively similar within the two years studied. No significant interannual variability was observed in carbonate fluxes. The data of two years sampling at the southern Bay of Bengal station suggested very low interannual variabilities in the total and the component fluxes (Table 15.2c).

15.6 COMPARISON WITH OTHER MARINE REGIONS

The total annual flux rates in the Bay of Bengal varied between 31 and 64 g m^{-2}, a range which is found in other marine regions such as the Arabian Sea (Haake et al., 1993; this volume, Chapter 14), eastern Atlantic (Wefer and Fischer, 1993; thsi volume, Chapter 10), polar regions and in the Gulf of Alaska (Honjo, 1990). Higher fluxes have been reported from the Bransfield and Fram Straits, where laterally derived lithogenic material influences the flux pattern (Wefer et al., 1988; Hebbeln and Wefer, 1991) and in the Panama Basin where an unusual coccolithophorid bloom contributed to the observed high flux in 1980 (Honjo, 1982). The total annual fluxes determined in the Bay of Bengal are higher than those recorded in the western tropical Pacific (this volume, Chapter 17), the northeast Pacific (Dymond and Roth, 1988), the South China Sea (this volume, Chapter 16) and within the subtropical and north Atlantic (Deuser, 1986; this volume, Chapter 9; Honjo and Manganini, 1993; this volume Chapter 6; Von Bodungen et al., 1991).

Another important feature of the Bay of Bengal flux pattern is the low carbonate flux in the northern and central Bay of Bengal compared to other marine regions. The average lithogenic matter content in the Bay of Bengal (25–54%) is higher than in other tropical marine regions (1–25%; Dymond and Collier, 1988; Haake et al., 1993). Similar lithogenic matter contributions to total fluxes (up to 60%) are seen however in polar regions, where particle flux pattern is influenced by the extent of the seasonal ice cover and/or by processes occurring at the ice edge (Wefer et al., 1990; Von Bodungen et al., 1991).

Fluxes of nitrogen and organic carbon in the northern Bay of Bengal (Table 15.2a) are among the highest values ever reported for marine regions and are similar to those from regions influenced by upwelling processes such as the western Arabian Sea (Haake et al., 1993; this volume, Chapter 14) and along the coast of West Africa (Wefer and Fischer, 1993; this volume, Chapter 10).

15.7 GENERAL DISCUSSION

Marine ecosystems under the influence of fresh water discharges have been found to have specific characteristics with respect to the prevailing upper ocean biology and sedimentary geochemistry. For example, the fresh water plume of the Amazon has a decisive influence on the chemistry and sediment distribution in the tropical Atlantic (Milliman et al., 1975; Gibbs, 1976). The inputs from the Amazon also increase the biological production in shelf areas. The major components of suspended matter in brackish water lenses along the Amazon river mouth are frustules of diatoms (Kidd and Sander, 1979). The high diatom production resulting from high silicate content of river water is, however, not reflected in the sediments because of the lateral transport of the freshly produced material and/or a result of high dissolution rates within the water column. The influence of the Amazon River is also observed in the hydrochemistry and the biological productivity of the western tropical Atlantic and of the eastern Caribbean Sea during spring and summer, which is the period of high rainfall in South America. During these periods fresh water lenses of up to 600 km in diameter have been observed several hundred kilometers north and east of the Amazon estuary. Data on particle flux to the deep western tropical Atlantic show a variability which appeared to be related to the northwestern movement of the plumes of the rivers Amazon and Orinoco (Deuser et al., 1988).

In order to illustrate the importance of river discharge for such processes we present the detailed information collected during the first year of the experiment in the Bay of Bengal. These data were chosen since they most strikingly demonstrate the effect of fresh water inputs on marine sedimentation, and the effects of other factors are less significant. Periods immediately following high river discharge are characterized by high total fluxes caused by enhanced inputs of lithogenic material from the rivers in the northern Bay of Bengal (Figure 15.2).

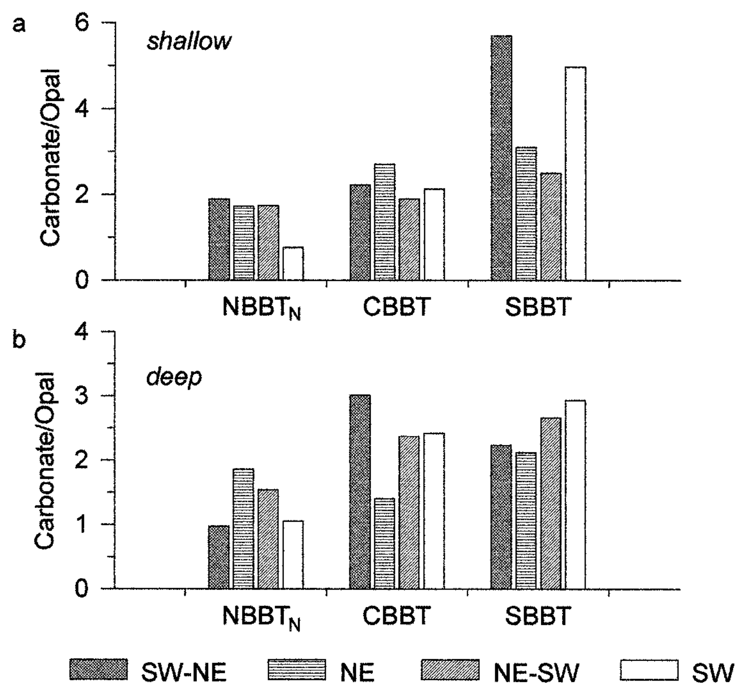

Figure 15.8 Carbonate/opal ratios of settling particles in the Bay of Bengal 1987/88.

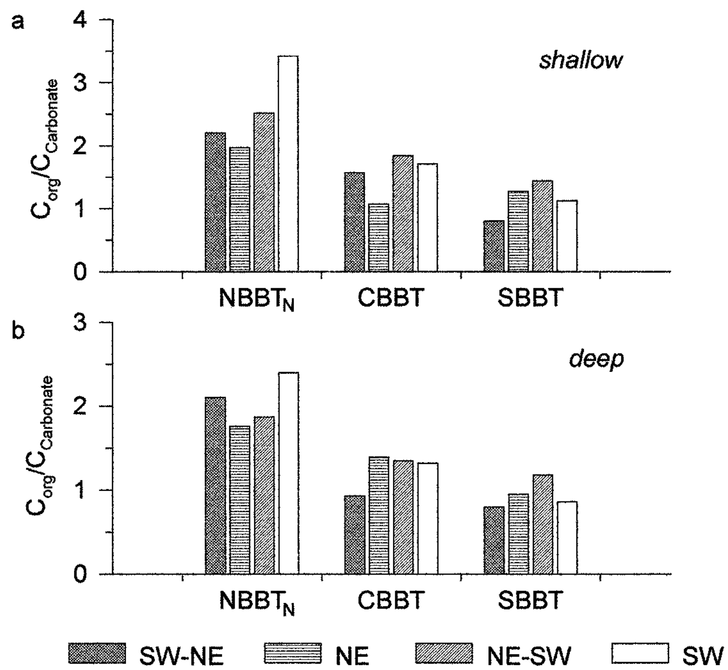

Figure 15.9 $C_{org}/C_{Carbonate}$ ratios of settling particles in the Bay of Bengal 1987/88.

Furthermore, biogenic matter associated with these high fluxes exhibit low carbonate to opal ratios which in turn increase the rain ratios of $C_{org}/C_{Carbonate}$ especially during the SW monsoon period (Figures 15.8 and 15.9). Carbonate/ opal ratios increase and the $C_{org}/C_{Carbonate}$ ratios decrease towards the central and southern stations.

The changes in the ratios of individual communities contributing to biological productivity in marine regions are of significance within the context of the marine carbon cycling and, in particular, the uptake of CO_2 by the oceans. Carbon cycling in the ocean is determined in part by the composition of primary producers. It determines the rain ratio of $C_{org}/C_{Carbonate}$ with higher ratios resulting in a more efficient biological carbon dioxide pump (Heinze et al., 1991). The settling of particulate organic carbon decreases the total carbon and partial pressure of CO_2 in the surface layers, whereas the removal of carbonate from surface waters aids in increasing atmospheric CO_2 by shifting the carbonate equilibria (Berger and Keir, 1984; Dymond and Lyle, 1985). Thus the differences in initial production ratio of calcium carbonate to organic carbon can effect significant short term variations in atmospheric CO_2. The changes in upper ocean plankton community structure favoring, for example, diatoms over coccolithophorids will increase the rain ratio of $C_{org}/C_{Carbonate}$ and hence the efficiency of the marine organic carbon pump (Ittekkot et al., 1991).

The results from the Bay of Bengal thus have implications for research on the recent history of the earth's climate, specifically that relating to short-term CO_2 fluctuations in the atmosphere during glacial-interglacial transitions. For example, the retreat of the ice sheets during the last deglaciation proceeded stepwise, with at least two large influxes of fresh water into the oceans accompanied by changes in the pattern of ocean circulation (Fairbanks, 1989). In analogy to our above-mentioned results for a marine region, such recorded inputs might have caused short-term changes in marine removal processes of climatic significance.

Yet another aspect of the results from the Bay of Bengal is the effect of extreme events such as floods and cyclonic activity in the region. Two major sedimentation events were recorded at the central Bay of Bengal station during January 1988 in the aftermath of a cyclone and from October to December 1990 during floods affecting the peninsular Indian rivers. The impact of these events in marine carbon cycling is yet to be ascertained. The projected climate changes due to an increase in CO_2 concentrations in the atmosphere are expected to have an impact on the frequency and intensity of extreme events of the type encountered in the Bay of Bengal. One of the messages from our results is that these changes could have significant feedbacks to global carbon cycle and to the global climate system.

15.8 CONCLUSIONS

Particle flux patterns in the Bay of Bengal are influenced to a large extent by fresh water and sediment inputs from the rivers and from wind-induced mixed layer deepening. The effect of river inputs decreases in an offshore direction. The quantity of fluxes is largely determined by lithogenic matter. Interannual variability of total fluxes is a result of variations in the lithogenic matter fluxes at the northern and central locations. Fresh water and nutrient inputs associated with the river discharges also induce seasonal changes in the relative contributions of opal and carbonate to the biogenic components which are characterized by low carbonate/opal ratios and, as a result, high organic carbon/carbonate-carbon ratios. These results are reminiscent of particle sedimentation in the polar regions where the extent of ice cover and ice edge production are major controlling factors. At locations away from the influence of rivers wind-driven biological processes determine the nature and quantity of fluxes. In general, these processes lead to a dominance of carbonate sedimentation in the Bay of Bengal especially in its southern parts. Superimposed on these processes are those of sedimentation induced by extreme events such as floods and cyclonic activity.

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