Sediment Dispersion in the Bay of Bengal

Chapter · January 2008

DOI: 10.1007/978-1-4020-6646-7_5

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1. INTRODUCTION

The Bay of Bengal is about 2090 km long and 1610 km wide, bordered on the west by Sri Lanka and India, on the north by Bangladesh, and on the east by Myanmar (earlier Burma) and Thailand. The Andaman and Nicobar Islands separate it from the Andaman Sea, its eastern arm. The Bay of Bengal and the Andaman Sea are together defined as the oceanic area north of 5°N, bordered by the Indian subcontinent, Myanmar, Thailand, Malay Peninsula and Sumatra (Fig. 1). This unique semi-enclosed basin experiences seasonally reversing monsoons and depressions, severe cyclonic storms (SCS), and consequently receives a large amount of rainfall and river run-off in the tropics. It also encounters the largest seasonal sea level fluctuations (-40 cm to +54 cm) anywhere on the earth. An interesting characteristic of this area is its low saline surface water caused by large river run off from the Indian subcontinent and Myanmar. The circulation and hydrography of the Bay of Bengal is complex due to the interplay of semi-annually reversing monsoonal winds and the associated heat and freshwater fluxes. Apart from this, the inflow of warm high saline waters of the Arabian Sea, the Persian Gulf and the Red Sea origin and a number of synoptic disturbances (cyclones) originating during both pre-monsoon (May) and post-monsoon (October) period also affects the dispersal pattern in the Bay of Bengal. The impacts of the enormous discharge of riverine fresh water and sediments are least understood. However, the consequences could be severe, like changes in coastal morphology and the ecosystem since these rivers carry disposed sewage, industrial effluents, agricultural residues, etc. into the Bay of Bengal which contains higher concentration of Biochemical Oxygen Demand (BOD)

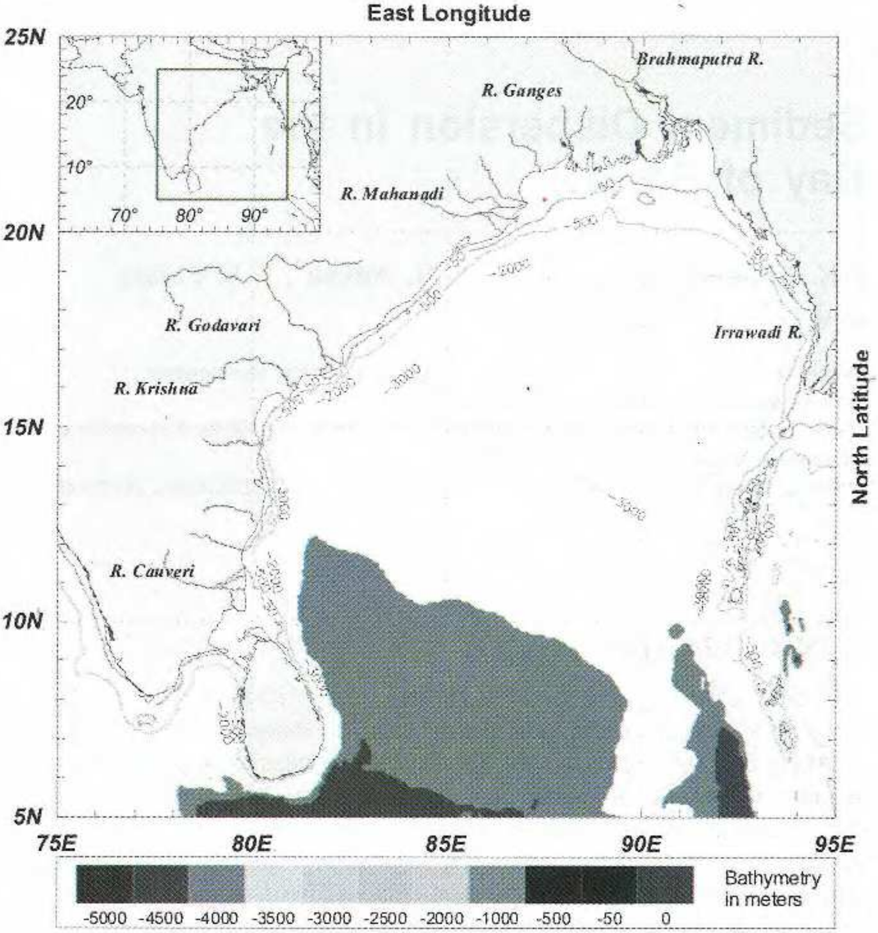

Figure 1: A glimpse of the northern Indian Ocean (inset) with the box showing the area of interest; major river systems, and bottom topography of the Bay of Bengal.

and faecal coliform. Due to the influence of water density and monsoon wind, the seasonal changes of the sea level in the Bay are remarkable and one of the highest in the world. It ranges from 166 cm at Khidirpur to 130 cm at Kolkata (Calcutta) and 118 cm at Chittagong. But towards the southwestern coast near Chennai (Madras) and Vishakhapatnam, the range is small compared to the northern and northeastern coasts of the Bay. The lowest variation of sea level at the southeastern coast of India is believed due to its geographical location at the edge of a comparatively deep sea. This is one of the probable reasons (accounting ~40%) for the differential sea levels between the Bay of Bengal and the Arabian Sea (Shankar and Shetye, 2001). Hence, it is very important to monitor and understand the fate of the freshwater discharge and the sediments. With the aid of satellite observation, it is now possible to revisit the source to sink pathways of this hefty fluvial discharge into the Bay. Remote sensing ocean colour data is a key parameter since it has the capability to estimate the suspended particulate matter empirically for light's interaction at selected wavelengths.

The Bay of Bengal is one of the largest fresh water and sediment input sites of the world ocean. The annual fresh water discharge into the Bay exceeds 1.5×10^{12} m^3 reducing the mean salinity by about 7‰ in the northernmost part. Fluxes of water are closely connected to the transport of sediment and dissolved constituents through river systems. The Bay receives about 2000 million tons of sediments annually contributed mainly through the Himalayan rivers—the Ganga and the Brahmaputra; Indian Peninsular rivers—the Mahanadi, the Godavari, the Krishna and the Kaveri, and the Irrawady and the Salween from the Myanmar.

2. CLIMATOLOGY OF RIVER DISCHARGE INTO THE BAY

The historical observations from the Global Runoff Data Centre (GRDC) database provide a unique opportunity to assess the volume discharges by the major river systems into the world ocean. The Global Monthly River Discharge Data Set contains monthly averaged discharge measurements for 1018 stations located throughout the world. The period of record varies widely from station to station with a mean of 21.5 years. The data are basically derived from the published UNESCO archives for river discharge, and checked against information obtained from the Global Runoff Centre in Koblenz, Germany through the U.S. National Geophysical Data Center in Boulder, Colorado.

Typically, river discharge is measured through the use of a rating curve that relates local water level height to discharge and generally river gauging is thought to have an accuracy of 5-10% (Vorosmarty et al., 1998).

Figures 2 and 3 show, respectively, the annual river discharge (from GRDC data) in different months and the GRDC stations corresponding to major rivers discharging into the Bay from the north and west. It is worth mentioning that measurement locations on the Ganges, the Brahmaputra and the Irrawady are about 300-400 km away from their mouths. These three rivers are perennial yet, the Ganges-Brahmaputra (hereafter G-B) system brings massive volumes during the summer monsoon. Fluxes form the Brahmaputra and the Irrawady remain almost flat during the entire summer monsoon whereas the Ganges, the Godavari and the Krishna show the peaks in August. Annual cycle of river discharge also gives a clear picture of negligible contribution by the Krishna-Godavari (hereafter, K-G) system during February through May, until the set of summer monsoon in June. The G-B system is still active and supplies more than 8000 m^3 s^{-1} during the winter monsoon.

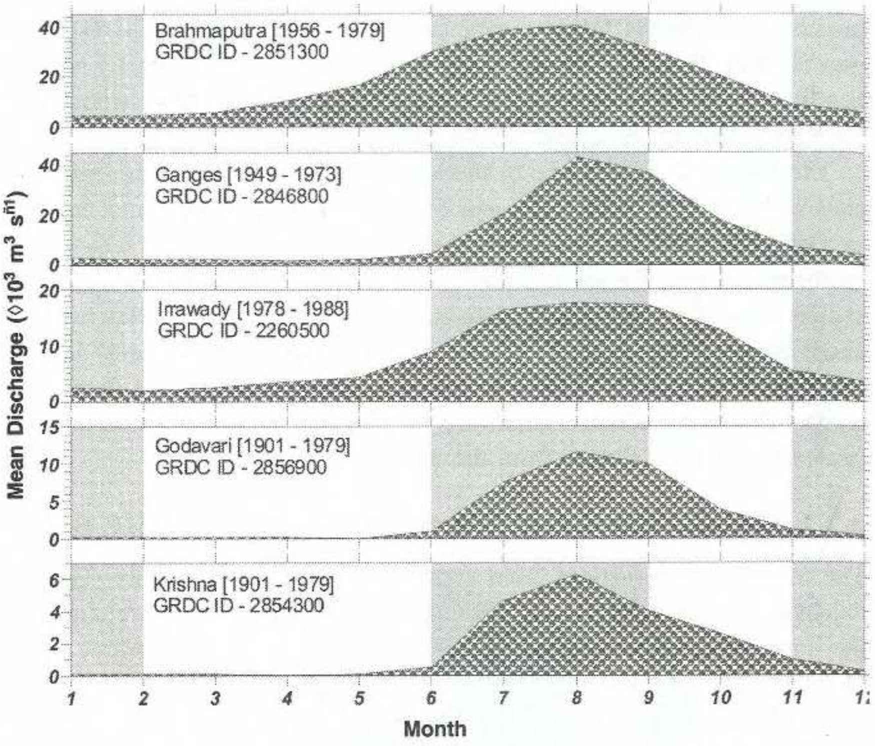

Figure 2: Monthly mean volume discharge into the Bay of Bengal at selected GRDC locations. Summer (SW) and winter (NE) monsoon months are highlighted with background grey shades.

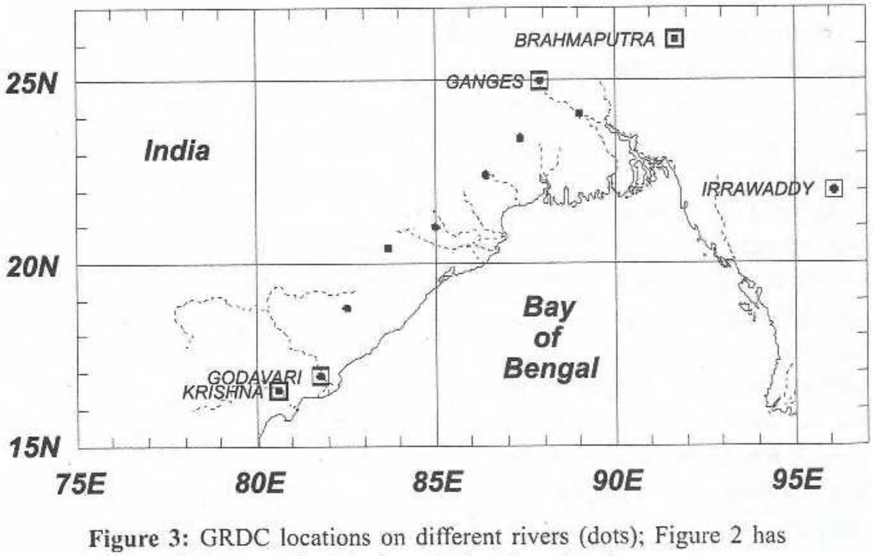

Figure 3: GRDC locations on different rivers (dots); Figure 2 has reference to the locations depicted as dots in squares.

The bounteous freshwater influx reduces the surface salinity considerably in the northern Bay. The hydrographic properties of the shelf region change drastically with seasons, especially in monsoons. Historically, it has been observed that surface salinities off Visakhapatnam of 29‰ and 34‰ in January and March, respectively, drop down to ~18‰ during the summer (SW) monsoon (Ganapathi and Murty, 1954). An SST gradient of ~1°C from north (26°C) to south (27°C) during winter is quite apparent in the Bay, which is basically instigated by the cold, dry north-easterlies aiding latent heat flux (evaporative cooling) and sensible heat flux (convection) from the sea surface in the northern Bay of Bengal. Another important aspect observed in the coastal Bay is the volume transfer, especially by the Himalayan rivers, in the northern sectors. The G-B system alone yields ~1000 × 10^6 tonnes/year of suspended sediment at a point around 200 km from the ocean in Bangladesh (Milliman and Meade, 1983), which is approximately 8% of the total sediment load reaching the global oceans (Milliman and Syvitski, 1992). This appears to be the highest suspended sediment load of any river system in the world and the large accumulation rate (665 × 10^6 t yr^{-1}) of sediments makes up the Bengal Delta and the 16.5 km thick Submarine Fan (Wasson, 2003), the largest deep sea fan in the world built up by turbidite deposits of the G-B origins (Kolla and Kidd, 1982; Emmel and Curray, 1984). Nath et al. (1989), from their geochemical analyses of deep-sea sediments in the Central Indian Basin, confirmed that the sediments from the G-B source are transported even south of the equator up to 8°S, covering a large distance of over 3000 km from the river mouth. Goodbred and Kuehl (1989) estimated the deposition as ~21% in the sub-aqueous delta and ~29% in the fan, of the combined (G-B) river transport (980 × 10^6 t yr^{-1}).

Table 1: Sediment yield and volume run-off by the major riverine systems to the Bay of Bengal

River System	*Basin area (× 10^3 km^2)*	*Run-off (× 10^6 m^3 yr^{-1})*	*Sediment load (× 10^6 tonnes yr^{-1})*
Ganga	750.0	493.0	329.0
Brahmaputra	580.0	510.0	597.0
Irrawady	430.0	422.0	265.0
Godavari	313.0	92.2	170.0
Krishna	251.4	32.4	4.0
Mahanadi	41.0	54.5	15.7
Brahmani	28.2	16.3	20.4
Cauvery	66.3	21.5	1.5

Source: Subramanian (1993)

Table 1 briefly summarises the sediment yield and volume run-off to the Bay by these rivers (River Brahmani, apart from the major seven rivers, is included in the list here since it has a significant contribution to the sediment load). The huge volume of freshwater influx (Table 1) together with monsoon winds strongly influences the circulation, stratification, productivity and sedimentation pattern in the Bay of Bengal. Vertical stratification, in the Bay, due to temperature variation holds for greater depths (>100 m); however, salinity dominates this phenomenon in shallow waters which is not very commonly observed elsewhere. The effect of freshwater discharge on particle fluxes and fate of terrigenous material discharge are demonstrated respectively by Ittekkot et al. (1991) and Ramaswamy et al. (1997). The dispersal of sediments within the province is affected primarily by surface oceanic circulation and by bottom and turbidity currents (Kolla et al., 1976). Even though the seasonally reversing East India Coastal Current (EICC), which is about 200 m deep and 100 km wide (Wyrtki, 1973), plays an important role in the sediment transport along the central and south-central part of the east coast of India, large freshwater influx from the G-B system during the SW monsoon overpowers other processes giving rise to equator-ward freshwater plumes against the prevailing local winds (Shetye et al., 1991).

Table 2: Seasonal runoff volumes of major rivers

River system	*Annual mean (m^3s^{-1})*	*NE (DJF) monsoon ratio*	*SW (JJA) monsoon ratio*	*Total Run-off volume ($\times 10^9$ m^3)*	
				NEM	*SWM*
Mahaweli	226	0.42997	0.16267	3.0645	1.1549
Godavari	3180	0.02198	0.55407	2.2043	55.5646
Krishna	1730	0.02089	0.61949	1.1397	33.7977
Mahanadi	1710	0.02109	0.59933	1.1373	32.3198
Pennar	95	0.20271	0.13814	0.6073	0.4193
Damodar	329	0.03059	0.56124	0.3174	5.8231
Ganga	11892	0.06532	0.49260	24.4967	184.7363
Brahmaputra	16186	0.05949	0.49552	30.3672	252.9340
Cauvery	664	0.20271	0.13814	4.2447	2.8926
Irrawady	13018	0.04863	0.52915	19.9660	217.2345
Salween[1]	5421	0.04863	0.52915	8.3143	90.4615
Meghna[2]	4215	0.05949	0.95520	7.9079	65.8666
([1]in Myanmar and [2]in Bangladesh)			Total	103.7673	943.2049

Source: Rao and Murty (1992)

The results of copious, pulsed freshwater and terrigenous discharge during the SW monsoon (Ittekkot et al., 1985; Ittekkot, 1993) are observed as a fair reduction in the surface salinity (more than 7‰ in the northern Bay) over the entire Bay (LaViolette, 1967; Wyrtki, 1973; Murty et al., 1990). Most of the freshwater influx to the Bay occurs during the southwest monsoon. As reported by Ittekkot et al. (1985), more than 80% of the annual water discharge in the Ganges occurs between July and November, during which more than 80% of the annual sediment discharge is accounted with suspended matter concentrations up to 1250 mg l^{-1}. Typical figures of volume runoff during the two monsoons are depicted in Table 2 (Rao and Murty, 1992). It is obvious that except for some southern peninsular rivers (Cauvery, Pennar and Mahaweli), all other rivers discharge maximum volume during the SW monsoon.

Figure 4 shows the inter-annual variability of volume discharge in a 20-year (1960-1980) time-series. The seasonal cycle is strongly reflected in all small seasonal and large perennial rivers. During the peak months, the volume discharge varies from as low as 3×10^4 m^3s^{-1} to as high as 6×10^4 m^3s^{-1} by both the Ganges and the Brahmaputra rivers. The amount of flux also decreases gradually towards the mouth as the total volume is distributed among the tributaries. The upper two panels (a and b) of Fig. 4 show the volume discharge at Panda and Bahadurabad in the Brahmaputra. Figures 4c and d show the volume discharge at Paksay and Farakka in the Ganges respectively. The volume discharges by four peninsular rivers are shown in Figs. 4e-h. The massive flux is contributed from the Himalayan source apart from the seasonal contribution by the peninsular rivers. The off season discharge by the G-B is almost equivalent to (sometimes greater than) the volume discharge by any single peninsular river (Fig. 4).

The summer monsoon rainfall index (Fig. 5) is an important parameter which controls the river discharge during the period. It is clear, however, from Figs 4 and 5 that the one-to-one correlation between monsoonal rainfall and volume discharge is predominant for the peninsular rivers. The Himalayan rivers often show discrepancies from the summer monsoon rainfall leaving a complicated trace to understand the complex seasonal dynamics at the mouth. Hence it is important to find out the fluvial pathways of the huge volume influx by the G-B system.

3. CIRCULATION IN THE BAY AND SEDIMENT DISPERSION

The circulation in the Bay is a complex phenomenon because of the seasonally reversing monsoon wind forcing coupled with the large volume of fresh water discharge from various rivers. Retrospective studies on the circulation

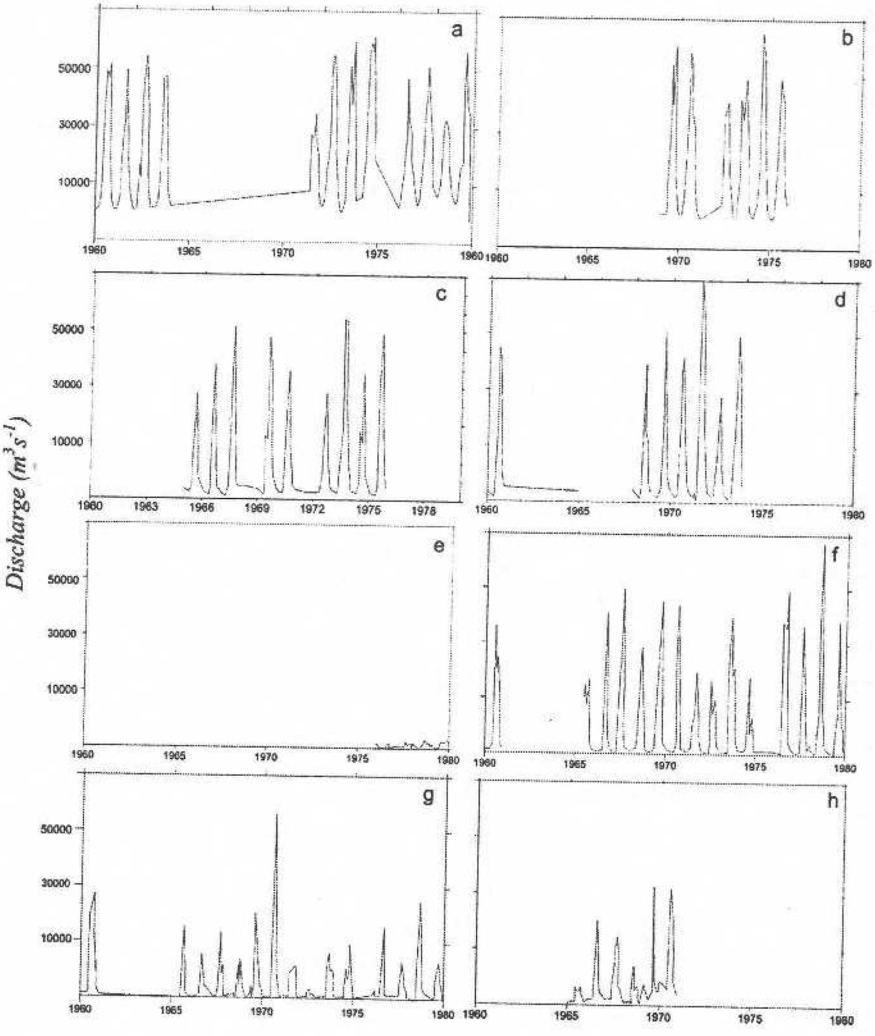

Figure 4: Time series of historical measurements (1960-1980) of net volume discharge by the Himalayan and Peninsular rivers. For River Bramhaputra at (a) Panda (91.70E/26.13N) and (b) Bahadurabad (86.66E/25.18N); for River Ganga at (c) Paksay (89.03E/24.08N) and (d) Farakka (87.92E/24.83N); (e) for River Cavery (78.83E/10.83N); (f) for River Godavari (81.78E/16.92N); (g) for River Krishna (80.62E/16.52N) and (h) for River Mahanadi (83.67E/20.42N).

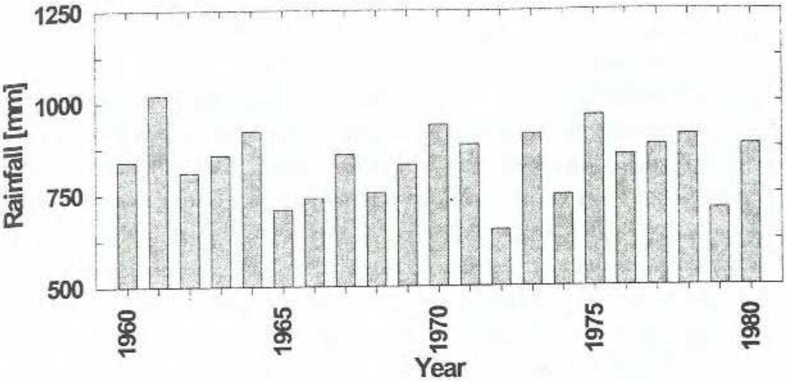

Figure 5: Summer monsoon rainfall (June-September) indices over India for the period 1960-1980. (Data source: IRI/LDEO Climate data library, downloadable from http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.india).

of the Bay of Bengal (La Fond and La Fond, 1968; Varadachari et al., 1968; Duing, 1970; Wrytki, 1971; Rao, 1977; Rao and Sastry, 1981) are based on the hydrographic data, limited both in space and time, who suggested the circulation to be predominantly anti-cyclonic during pre-monsoon (March-May) and cyclonic during post-monsoon (October-November) (La Fond and La Fond, 1968). Based on the *International Indian Ocean Expedition* (IIOE) data, Duing (1970) suggested that the circulation in the bay is anti-cyclonic throughout the year. In an experiment on the circulation and geostrophic transport in the Bay of Bengal, Rao and Murty (1992) observed the circulation in the Bay as primarily cyclonic surrounded by cyclonic and anti-cyclonic gyres during the beginning of both the monsoons. They also mentioned that the circulation during NE monsoon consists multiple-cellular cyclonic and anti-cyclonic gyres extending to deeper depths. During the northern hemisphere winter (boreal winter), the main features of the ocean currents include large-scale anticyclonic flow in the Bay of Bengal surface waters (Potemra, 1991). This gyre decays into eddies in spring and then transition into a weaker, cyclonic gyre by late summer.

In modern oceanography, the general circulation in the Bay of Bengal is characterised by anti-cyclonic flow during most months and strong cyclonic flow during November. Currents are weak and variable in January. In the west, the *East Indian Current* (EIC) strengthens as the NE Monsoon becomes stronger, exceeding 0.5 ms^{-1} in March (Fig. 6) and remaining strong (0.7-1.0 ms^{-1}) until May/June (Tomczak and Godfrey, 2001). Throughout this time the current runs into the wind, apparently as an extension of the *North Equatorial Current* (NEC). During the SW monsoon season, currents in the entire Bay are weak and variable again. The highest velocities (around 0.5 ms^{-1}) are found in the *East Indian Current* and the flow along the eastern coast rarely exceeds 0.2 ms^{-1} but is often directed into the wind. An indication of a current reversal in the west is seen in September (Fig. 6). Currents are consistently southwestward and strong (0.5 ms^{-1} and more) north of 15°N and close to the shelf southwestward flow prevails.

Complete reversal of the *East Indian Current* into the *East Indian Winter Jet* (EIWJ) is not achieved until late October, when water from the Equatorial Jet enters the Bay in the east and a cyclonic circulation is established. The *East Indian Winter Jet* (EIWJ) is a powerful western boundary current with velocities consistently above 1.0 ms^{-1}. It follows the topography south of Sri Lanka and feeds its water into the Arabian Sea. Very little exchange occurs with the *Equatorial Jet* (EJ) south of Sri Lanka; currents in the separation zone between the two jets (near 3°N) are weak and variable. The *East Indian Winter Jet* (EIWJ) fades away from the north in late December, its southern part merging with the developing *North Equatorial Current* (NEC).

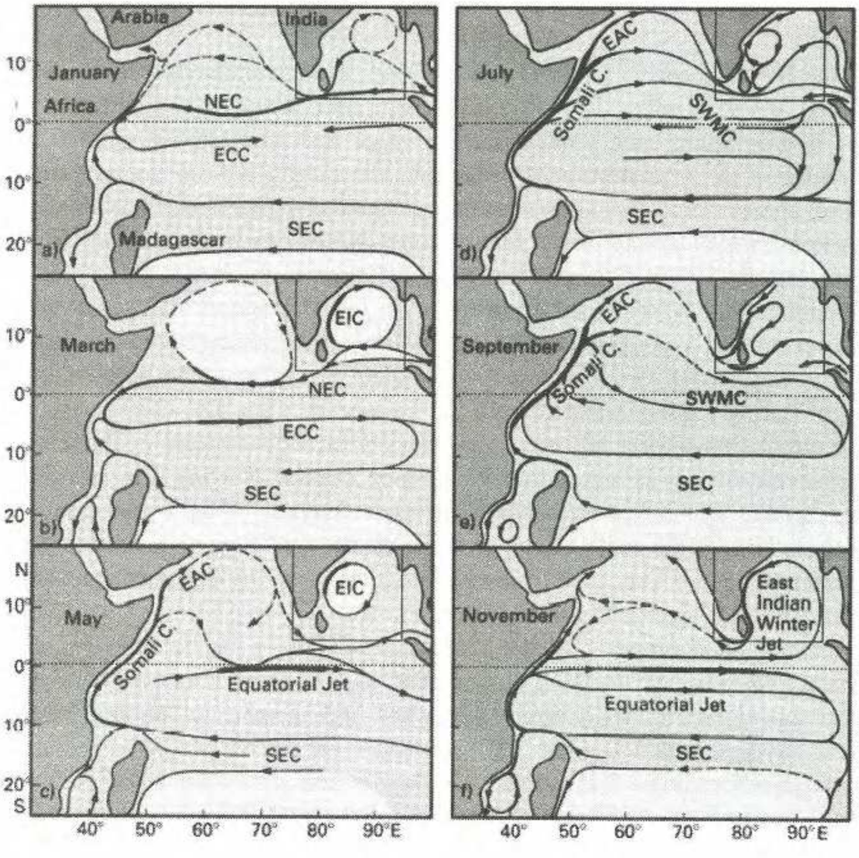

Figure 6: Surface Currents in the Indian Ocean. Notice the seasonal changes in the Bay of Bengal region (highlighted in square box). Adapted from Tomczak and Godfrey (2001) after Cutler and Swallow (1984).

3.1 Seasonal Circulation

The Bay of Bengal is distinguished by strong near-surface stratification. Hence, it is anticipated that the physical properties of the upper layers, for example, surface currents and temperature, would exhibit large variability in the spatial domain. According to Potemra et al. (1991), the seasonal circulation in the Bay of Bengal can be separated into four stages:

(a) A large anti-cyclonic gyre across the whole Bay during December until March;

(b) This is followed by two counter-rotating flows, anticyclonic on the western side and cyclonic on the eastern side, producing northward currents along both coasts and southward flow down the middle;

(c) The previous pattern persists until early summer (April-June), when the anti-cyclonic flow extends across the whole Bay, and in the SW monsoon months (July and August) is characterised by counter-clockwise flow; and

(d) Finally, in the autumn, two rotating flows develop again, with southward current along both coasts and northward flow in the centre.

Varkey et al. (1996) explained the seasonal circulation by a three-gyre circulation pattern (G1, G2, G3) in a schematic way for the two monsoons – summer or SW monsoon and winter or NE monsoon (Fig. 7).

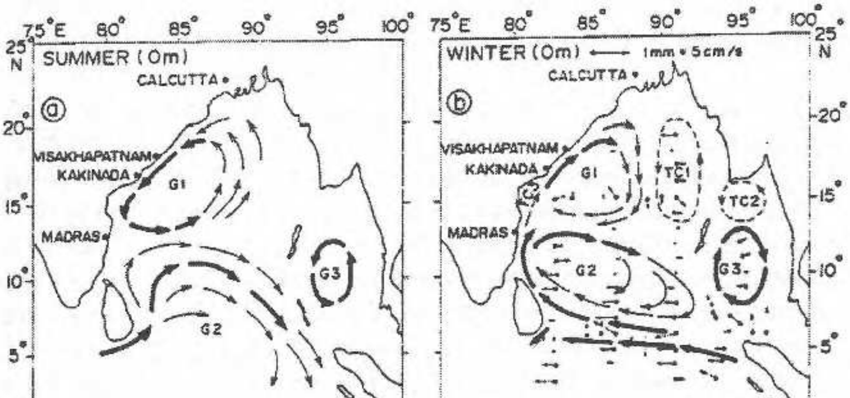

Figure 7: Schematic of the seasonal surface circulation in the Bay of Bengal (After Varkey et al., 1996).

The northern gyre (G1), between the western boundary and 13°N/89°E, is clockwise during winter and anticlockwise in summer. They observed a reversal of G1 at depths greater than 500 m during winter (not illustrated here), which needs further explanation. A southern gyre (G2) in the area south of 13°N is clockwise during both winter and summer. The gyre in the

Andaman Sea (G3) has clockwise and anticlockwise flows in winter and summer, respectively. The steadiness and strength of these gyres and other currents in the Bay seems to depend on the development and shift of the *North Equatorial Current* (NEC) and the *Indian Monsoon Current* (IMC). In numerical experiments Yu et al. (1991) showed that the seasonal reversal of gyre G1 in the northwestern Bay is caused partly by remote forcing due to monsoon winds in the equatorial Indian Ocean. They, using a reduced-gravity model, found that the long *Rossby waves* excited by the remotely forced *Kelvin waves* contribute substantially to the variability of the local circulation.

Cutler and Swallow (1984) compiled (averaged) the historical surface current data collected by the British Meteorological Office for over a century (1854-1982) with 1° × 1° space and 10-day time grid, which confers a precise awareness about the seasonal cycle of the near-surface circulation in the Bay. At the outset of the NE monsoon, the Bay has a basin-wide cyclonic circulation. Schott et al. (1994), from the shipboard current measurements and from moored instruments during 1991-92, observed a reversal and reduction of the near-coastal transport, which they suspected to be a result of the *Kelvin waves* from the Bay of Bengal.

3.2 The Monsoon Currents

The monsoon currents are essentially Ekman drifts forced by the monsoon winds, the geostrophic contribution to these flows being negligible. The monsoon current varies round the year. In January (peak NE monsoon), the westward flowing Indian Monsoon Current (IMC) south of Sri Lanka is supplied from the east (south of 8°N), which weakens during the inter-monsoon (March) period but still fed by the well-developed southern gyre. The reverse flow (eastward) of the Monsoon Current is observed throughout the SW monsoon period following the onset with a slight break during July, picking up in speed again in August. Shankar et al. (2002) demonstrated the monsoon currents as a trans-basin phenomenon in the northern Indian Ocean using an Oceanic General Circulation Model (OGCM). They showed that the westward flowing *Winter Monsoon Current* (WMC) develops south of Sri Lanka in November that is initially fed by the equatorward East India Coastal Current (EICC).

The WMC in the Bay appears later in the following months (Fig. 8). The eastward flowing *Summer Monsoon Current* (SMC) continues to flow from the Arabian Sea passing through the Lakshadweep low and splits into two branches after crossing the Sri Lankan coast—one into the Bay of Bengal and the other in the eastward direction. Net transport due to the shallow monsoon currents is attributed to both Ekman drift and geostrophic flow. In the Bay of Bengal, the monsoon currents are generally forced by Ekman pumping and by the winds in the equatorial Indian Ocean. However, the hydrographic data show that the monsoon currents are not found in the same

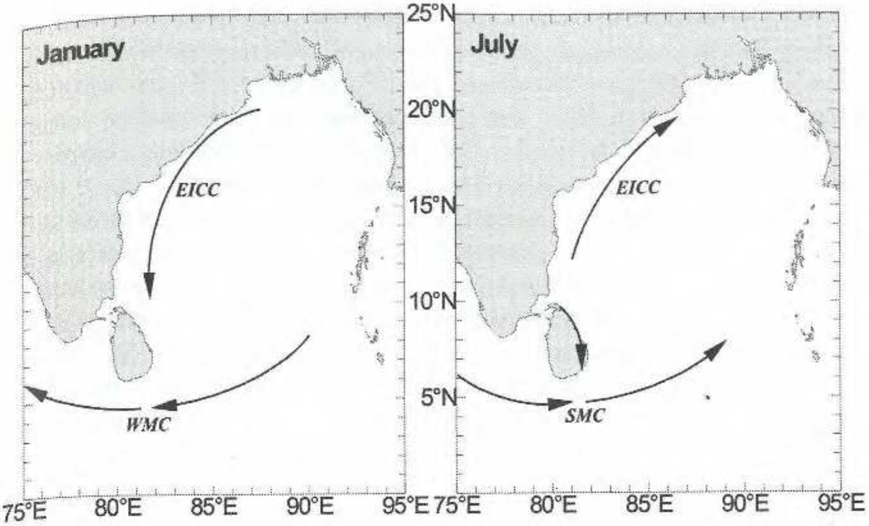

Figure 8: Schematics of the current systems in the Bay of Bengal during January (winter monsoon) and July (summer monsoon) modified after Shankar et al., 2002. Legends: WMC – Winter Monsoon Current, SMC – Summer Monsoon Current, EICC – East India Coastal Current, SL – Sri Lanka.

location during a season or across different years; for example, Vinayachandran et al. (1999) showed that the SMC in the Bay of Bengal intensifies and shifts westward as the summer monsoon progresses.

3.3 East India Coastal Current (EICC)

During last few years a number of studies have helped to identify the principal mechanism that drives the general circulation in the Bay of Bengal (Potemra et al., 1991; Yu et al., 1991; McCreary et al., 1993) and the East India Coastal Current (EICC) as an extension of the western boundary currents (Shankar et al., 1996; McCreary et al., 1996). Western Boundary Currents (WBCs) persist in response to the large-scale zonal wind systems along with the combined effect of the curvature and rotation of the Earth. The WBCs in the major oceans have always fascinated oceanographers by virtue of their well-developed and intense flow patterns and they have potential for generating warm/cold core eddies which are an integral part of the general circulation. Though numerous studies have been made on WBCs viz. the Gulf Stream and the Brazilian Current in the Atlantic, the Kuroshio and East Australian Current in the Pacific, the Aghulas Current in the Southern Indian Ocean, and the Somali Current in the western Indian Ocean, such studies are meagre in the Bay of Bengal where the surface flow reverses seasonally. However, based on the size of the oceanic basin, the Bay of Bengal is a possible location for WBCs. But the currents in this basin are variable due to the biannual cycle of the monsoon winds. Like the Somali Current in the Arabian Sea, the currents along the east coast of India reverse their directions twice a year, flowing northeastward from February until September with a strong peak in March-April and south-eastward from October to January with strongest flow in November. Recently the western boundary current in the Bay of Bengal has been named as the East India Coastal Current (EICC). The current along the east coast of India is hereafter referred to as EICC. It is observed that the EICC changes its direction twice a year (see Fig. 8) flowing north-eastward from February until September with a strong peak in March-April and southwestward from October to January with strongest flow in November (Shankar et al., 1996; McCreary et al., 1996). The current extends to a depth of 200 m and has a transport of ~10 Sv. The recent study using NOAA AVHRR imagery by Ratna Reddy et al. (1995) showed the current about 900 km in length, usually lying close to the coast but occasionally shifting offshore (Shetye et al., 1993), with an average speed of 30-55 cm s^{-1}. The SST within the boundary current is reported as ~27°C, and the temperature on either side of this current is lower (~26°C). This western boundary current is also a part of an eddy field like the Somali Current in the SW monsoon (Shetye et al., 1993). Yu et al. (1991) proposed a bifurcation of the WBC along the East Indian coast at ~12°N with a warmer poleward and a colder equatorward current. There are some hydrographic studies (e.g. Shetye et al., 1993; Shetye et al., 1996; Sanilkumar et al., 1997) and numerical studies (McCreary et al., 1996; Shankar et al., 1996) further describing the EICC and its driving mechanism. Studies made in the recent past (Yu et al., 1991; Potemra et al., 1991; McCreary et al., 1993; Shankar et al., 1996; Shetye et al., 1996; McCreary et al., 1996) have suggested four different principal mechanisms that drive the EICC:

(a) Interior Ekman pumping over the Bay;
(b) Local alongshore winds adjacent to the east coast of India and Sri Lanka;
(c) Remote alongshore winds adjacent to the northern and eastern boundaries of the Bay;
(d) Remotely forced signals that propagate into the Bay from the equator.

4. COASTAL PROCESSES AND SEDIMENT DISPERSION

4.1 Tides and Fronts

The processes in the coastal waters are greatly complicated by factors peculiar to the coastal zone, viz., the shallowness, the presence of tidal currents, river run off, and the barrier to advection posed by the coastline itself. In the presence of strong tidal currents that create turbulence in shallow waters, tidally induced mixing may extend all the way to the surface. This, in conjunction with the flow of freshwater from the land, makes the dynamics more complicated in the Bay. The less haline (~0 psu) and much lighter freshwater by lying on the top of the dense seawater creates a stratification that can be independent of temperature difference of the layers, and forms the buoyancy-driven currents. So, one way of trying to understand the complex relationship existing between physical and biological processes in coastal waters is to view freshwater run-off as a mechanism tending towards greater stratification while wind-driven and tidal currents are mechanisms tending to cause turbulence in the water column and to breakdown stratification. In the shallower regions (e.g., head of the Bay), the effects of tidal mixing lead to the formation of distinct fronts of different space and time scales which often overlap with the shelf-break fronts. These shallow-water fronts have biological importance since they account for high densities of phytoplankton concentrations. Since the east coast of India has a very narrow and stiff continental self in the central and southern sectors, local plume fronts are observed as a consequence of seasonal reverine discharge. It is worth mentioning here that the fronts can also be created by large turbulent eddies, or by the coastal upwelling.

Both semi-diurnal (M_2, principal lunar) and diurnal (K_1, principal lunar/solar) constituents contribute to the tides along the coasts surrounding the Bay of Bengal (Fig. 9). Tides in the Bay are mixed semi-diurnal in nature (two high and two low tides every lunar day, i.e. 24 hours 50 minutes). The highest tide is seen where the influence of bottom relief and the configuration of the coast are prominent, i.e. in shallow water and in the northern Bay and estuary. The mean height of tidal waves near the coast of Sri Lanka is around

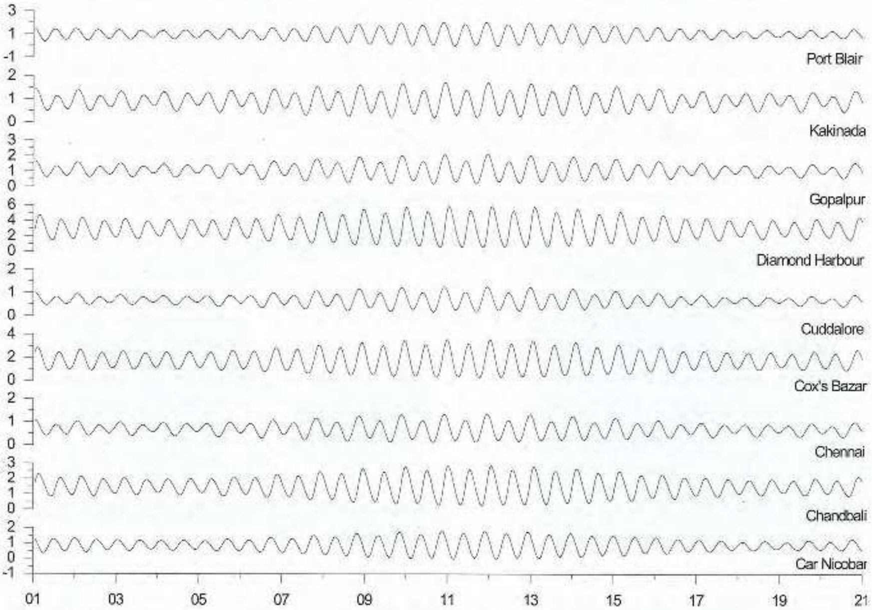

Figure 9: Typical tide curves over a period of three weeks at selected ports along the coasts surrounding the Bay of Bengal.

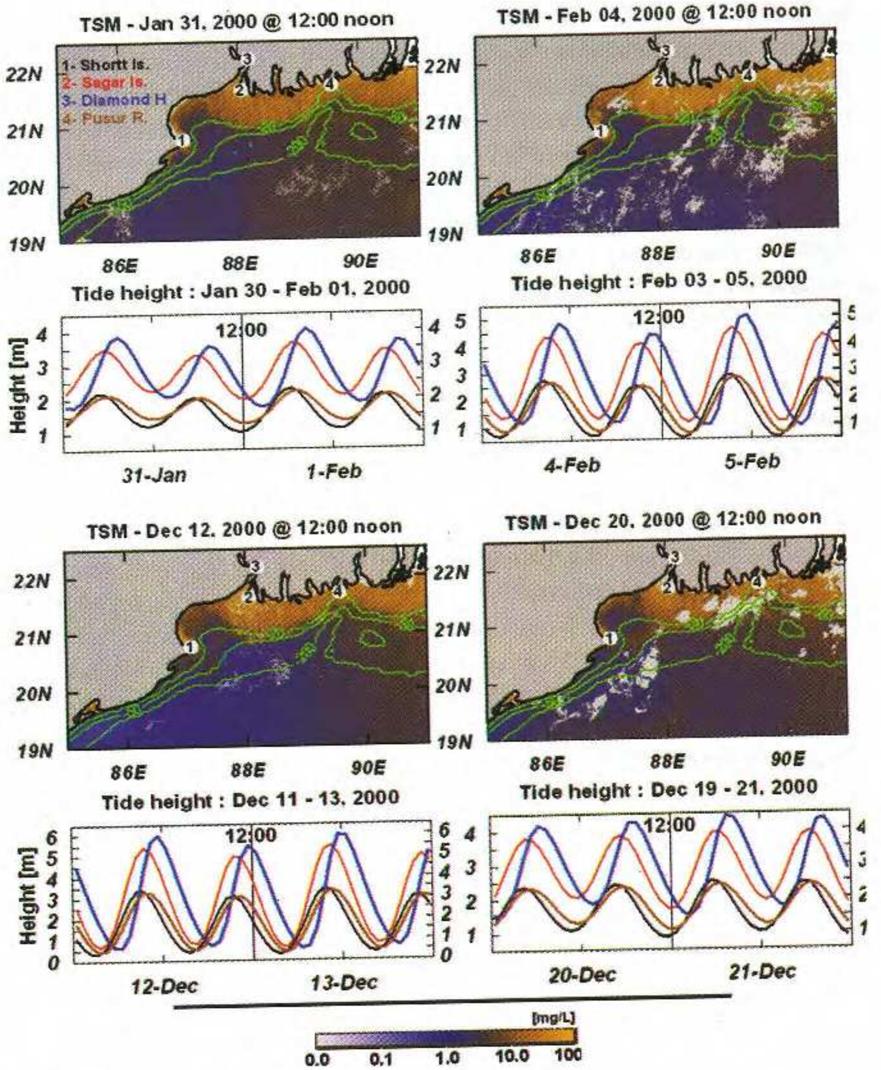

Figure 10: Total Suspended Matter (TSM in mg ℓ^{-1}) derived from IRS-P4 Ocean Colour Monitor (OCM) data. Bathymetry contours for 20 m, 50 m and 200 m are overlaid on the TSM maps. Tide curves at four different locations (1–Shortt Island, 2–Sagar Island, 3–Diamond Harbour and 4–Pusur river) for corresponding dates are plotted below the TSM maps.

0.7 m whereas it is 4.71 m near the deltaic coast of the Ganges. In the Bay of Bengal tidal currents specially develop in the mouths of the rivers, for example the Hooghly. The currents associated with the semi-diurnal tides play significant role in material transport and distribution along the coasts in the Bay of Bengal. Figure 10 shows the surface distribution of TSM, during low-tide and slack period between high and low tides, at four selected locations in winter 2000. Tide heights range at Shortt Island and Pusur River mouth are almost half of the range at Sagar Island and Diamond Harbour.

Frequent excursion of suspended matters keeps the shelf zone (below 20 metre depth) ever turbid with TSM values exceeding 50 mg ℓ^{-1}. The TSM snaps on 31st January and 20th December were taken during near low-tide conditions (when the magnitude of tidal stream currents are minimum), which reveal the shoals and their elongated patterns more clearly as the water level recedes although the exposure of these shoals are partially hindered by clouds on 20th December. On the other hand, the TSM images on 4th February and 12th December were taken during the transition between high and low tides when the tidal current is at the peak and offshoreward. Sediment plumes near station 1 are observed to be stretched towards the 50 m depth isoline. The plumes in the north which were strong within the 20 m depth contours have now stretched up to 50 m. This observation sets two ideas regarding sediment transport across the northern Bay – (1) the elongated NE-SW and NW-SE shoals across the *Swatch of no Ground* essentially indicate the tunnelling of the materials and (2) a branch of the plume west of 88°E also moves southwestward along the 20-50 m bathymetry track which often hugs the coast.

4.2 Surface Current: Role of Ocean Colour Data

The patterns of ocean colour on sequential images can be used as tracers, to a better extent than SST, to measure displacements of surface waters. Garcia and Robinson (1989) first showed the use of ocean colour data to extract sea surface velocities in shallow seas. The objective method is used to estimate the surface currents from OCM derived TSM maps. The method is based on matching suspended sediment dispersal patterns in two sequential time lapsed images. The movement of the pattern can be calculated knowing the

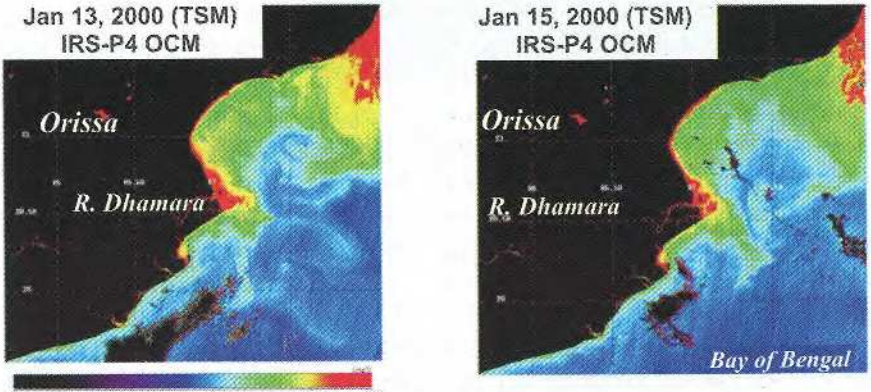

Figure 11: IRS-P4 OCM derived TSM images for January 13th and 15th, 2000 near Dhamara estuary, north Bay of Bengal.

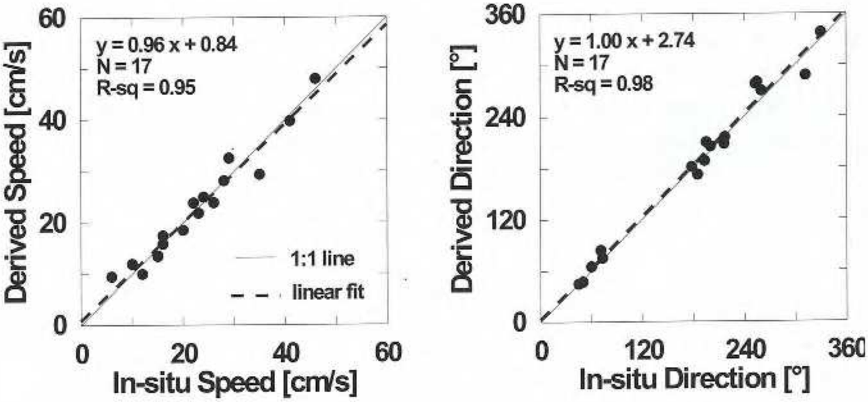

Figure 12: Scatter plots of in-situ vs derived surface current speeds (left panel) and directions (right panel).

displacement of windows required to match patterns in successive images. Figure 11 shows the TSM images of 13th and 15th January 2000, on which the Maximum Cross Correlation (MCC) scheme was applied and the currents were retrieved. The scatter plots between retrieved and measured current speeds and directions (only during local noon) are shown in Fig. 12 that essentially explains the validity of this technique. The study also demonstrates the feasibility of ocean colour data to understand the transport velocity and pathways of optically active near-surface tracers.

4.3 Effects of Oceanic Eddies in Coastal Waters

To improve the observational strategy in understanding the effects of medium-large eddies on coastal circulation, satellite data from different disciplines are used in this section.

Figure 13 shows the net surface flow vectors (estimated from T/P and QS data) on OCM derived TSM map. The surface currents are generated from the weekly data. The TSM maps give reliable pictures on the surface advection in the nearshore waters. In the top panel of Fig. 13, an elliptical anti-cyclonic eddy of about 400 km diameter along its major axis is seen near 86°E/ 18.5°N during the first week of March. Away from the northern-most shelf (where tides control the flow), the sediment plumes off the Mahanadi delta, follows the surface currents along the northern periphery of the eddy as far as 100-120 km from the mouth. Similarly, in the bottom panel three distinct plumes are visible at the Godavari, the Krishna and Pennar river mouths. Interestingly, the plumes off the Godavari and the Krishna moves at right angle to each other (southward off the Godavari and eastward off the Krishna). This is true since the coastal circulation during this period was affected by an eddy triplet. A large cyclonic eddy (centred near 86°E/16°N), sandwiched between the two anti-cyclonic eddies (off the Chilika lagoon and Pennar

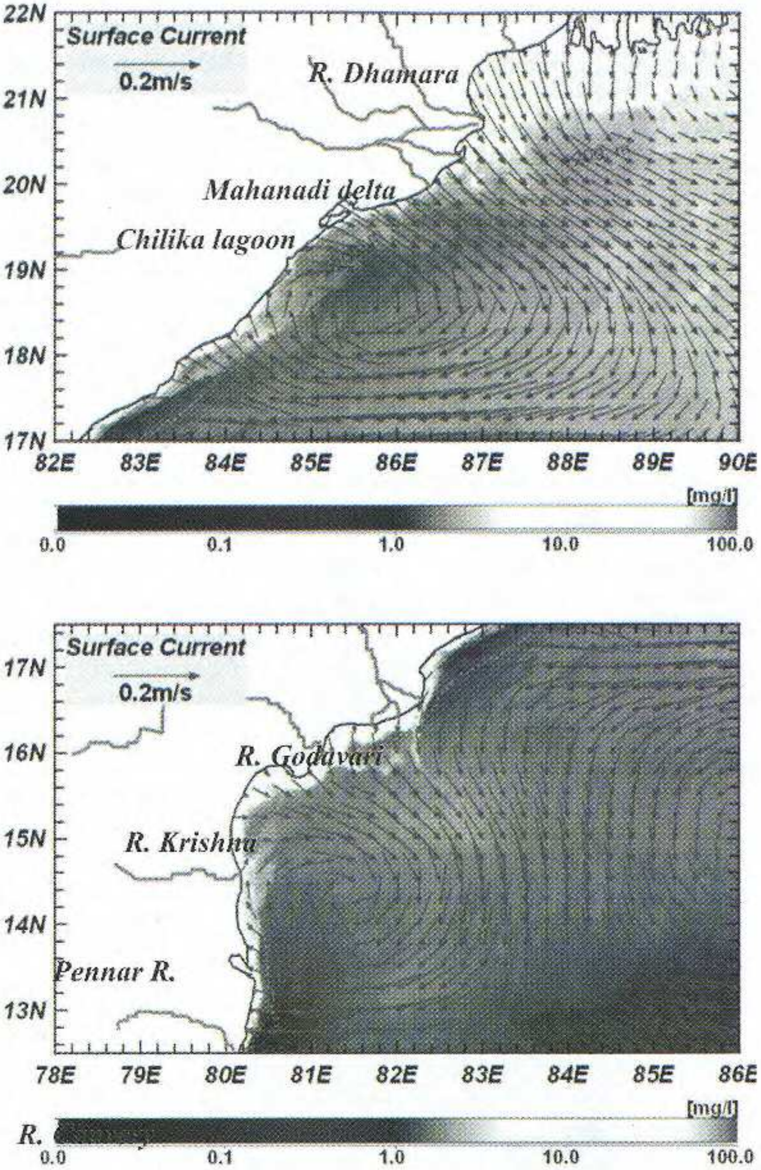

Figure 13: Net surface flow (in m.s^{-1}) estimated from T/P-QS data for March week#1, 2000 overlaid on OCM TSM (in mg.l^{-1}) maps of March 01, 2000.

river) seems to drive the Godavari plume towards south whereas the southern eddy moves the plumes off the Pennar, the Krishna northward and eastward, respectively. Hence it would be quite valuable to understand the dispersal pathways through the estimation of surface currents using microwave data during the cloudy seasons.

5. DISPERSAL PATHWAYS

It was reported in the past that sediments from the G-B system are transported into the southern hemisphere (Nath et al., 1989) as far as 8°S, covering a distance of more than 3000 km. The *Swatch of no Ground*, also known as the *Ganga Trough*, has a comparatively flat floor 5-7 km wide and walls of about 12° inclination (Fig. 14). At the edge of the shelf, depths in the trough are about 1200 m. The *Swatch of no Ground* has a seaward continuation for more than 2000 km down the Bay of Bengal in the form of fan valleys with levees. The sandbars and ridges near the mouth of the G-B delta pointing toward the *Swatch of no Ground* suggest that sediments are tunnelled through this trough into the deeper part of the Bay of Bengal. Thus, the *Swatch of no Ground* is a potential region to transport the sediments beyond the continental shelf into the deep Bay. Some of the shoals and sand ridges

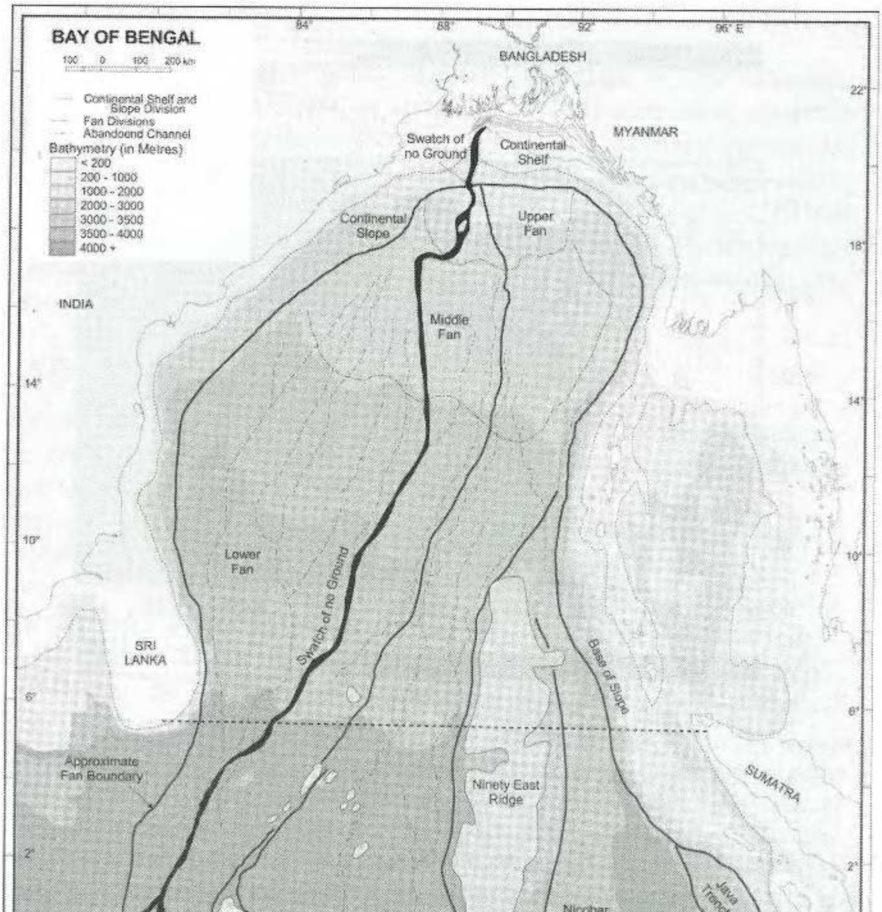

Figure 14: The Bay of Bengal and the environs showing the different regions of the Bengal Fan and the Swatch of no Ground.

present on this part of the continental shelf show an elongation pattern pointed towards the *Swatch of no Ground*. Bengal Deep Sea Fan, also known as Bengal Fan, is the world's largest submarine fan. The Bengal Fan has been built up principally by turbidite deposits of the G-B origin (Emmel and Curray, 1984). Together with its eastern lobe, the Nicobar fan, it covers an area of 3106 sq km with approximate length and width of 2800-3000 km and 830-1430 km, respectively and a thickness of more than 16 km beneath the northern Bay of Bengal.

Sediments are tunnelled to the fan via the delta-front trough, the *Swatch of no Ground*. The Bengal Fan can be divided into three parts - upper fan, middle fan and lower fan. Most of the fluxes seem to get accumulated within the upper and the middle fan. The Bengal Fan is underlain by thick sequence of sediments derived from the peninsular and Himalayan rivers. More than one billion tons of sediments are discharged into the Bay annually, mostly from the G-B system (Milliman and Meade, 1983). Average sedimentation rate on the fan is 20-30 cm per 1000 years (Wetzel and Wijayananda, 1990).

In order to understand seasonal variations in source to sink pathways of fluvial influx into the Bay, from time series sediment trap observations, it had been inferred that concurrent with riverine flux maxima, the Bay witness a maximum terrigenous influx during the SW monsoon, the main source of which is the Himalayan rivers (Ittekkot et al., 1991). These fluxes dwindle during rest of the year. Therefore, it was thought that the influx of terrigenous sediments into the bay is broadly regulated by precipitation or melting pulses from the Himalayas (Ittekot et al., 1991). Moreover, a long distance dispersal of these sediments by low salinity Bay of Bengal waters into the southeastern Arabian Sea and along the equatorial region, mostly during the NE monsoon, has also been documented (Shetye et al., 1991; Chauhan and Gujar, 1996). The occurrence of high magnitude, short-lived, cyclones/depressions in the Bay is a common phenomenon during the NE monsoon (Chauhan, 1995), which brings torrential rains with sporadic fluvial discharge. Dispersal mechanism of the fluvial discharge into the Bay is, therefore, complex, especially during short (weekly) events associated with depression/cyclones or large spatial and temporal variability in the rainfall. In order to understand the dispersal pathways of the suspended sediments discharged by the G-B river system during the winter (NE) monsoon, a sequence of 64 TSM images (OCM) during October 1999-March 2001, synchronous sea truth data with the aid of salinity variations have been used to construct dispersal pathways of the surficial fluvial flux in the northern Bay. As part of in situ measurements about 100-150 litres of seawater were filtered for each station for acquiring about 200-300 mg of TSM during November of 2000 at eight stations along Orissa Coast (Fig. 15). Owing to very small amount of samples for clay mineral analysis a fraction of these samples were passed through a membrane filter of ~2 mm. Clays are identified and quantified using the methods of Biscaye (1965).

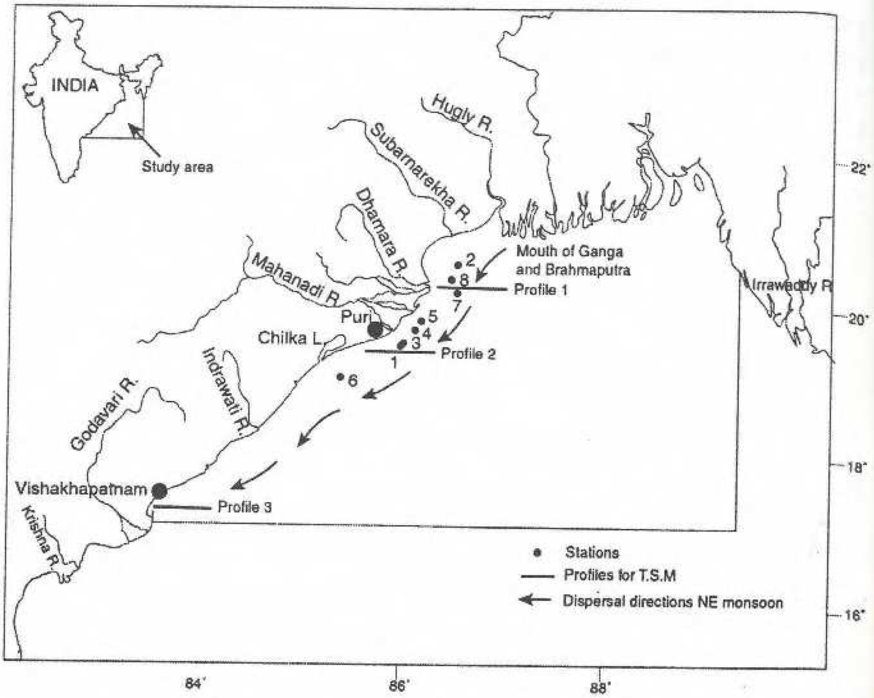

Figure 15: The study area and location map of the sampling stations for clay analysis. Sites of TSM profiles off Dhamara river, Chilika and Vishakhapatnam are also shown.

The generalised TSM patterns have large spatial and temporal variations during NE monsoon. During the month of October, there is gradual reduction in the spatial extents of the plumes of major rivers, except off the mouth of G-B system which has been traced for 120-160 km offshorewards. During the month of November, however, there are frequent, short duration pulses of high TSM. Gradually, the influx of TSM is reduced during December-January. The dispersal pattern derived from the sequential scenes and from the in situ TSM measurements is south-southwest.

The correlation between the sea truth and imageries data of TSM by and large is moderate ($r = 0.51$ $p = 0.001$) (Anuradha et al., 2000) because of complexities and inherent limitation of available algorithms. TSM values derived from the image are underestimated compared to in situ measurements in coastal waters. However, imagery derived dispersal patterns have high correlation with measured in situ currents magnitude and direction (Fig. 16). TSM patterns derived from the images in the study area (Fig. 15), though have limitation for the accurate quantification of fluxes, yet can be used in conjunction with measured TSM and current parameters for reconstruction of regional dispersal pattern of the fluvial flux, pending availability of an improved algorithm.

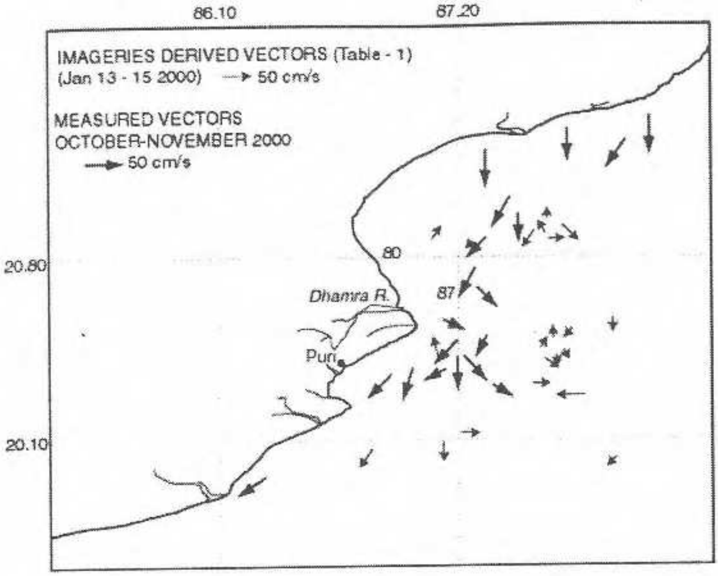

Figure 16: Surface currents estimated from sequential ocean colour images (in January 2000) and from ship board measurements (in October-November 2000) showing the equatorward advection along the coast.

The sequential variations in the TSM along the three W-E profiles along the northern, central and southern regions between 8 and 14 November, 1999 (Fig. 17) are also evaluated to further elaborate the pathways of TSM dispersal. On all individual profiles, from the north (off the Dhamara River) to the south (off Visakhapatnam), in the inland waters, there was a distinct localised area of high TSM, which decreases offshoreward on all the profiles, except on Profile 1 where a high TSM band existed 100 km offshore. On the subsequent profiles of 10 November 1999, in addition to the inland TSM enrichment, an additional band of high TSM, located about 50-100 km offshore was also observed. Between these two TSM enriched waters, lay the waters of reduced TSM values. These two waters, therefore, have different sources of TSM–deeper one from the pluses of the G-B system.

At all the profiles, the coastal waters have higher TSM. However, being in the vicinity of the G-B, the area off the Dhamara river continues to have much wider spatial extent and with higher TSM during the entire NE monsoon. In the offshore waters, however, the TSM is much reduced, except few isolated areas of high contents. It is, therefore, inferred that the fluvial discharge of the Himalayan rivers advects alongshore in narrow localised bands. The time lag of the advection of this TSM among profiles 1-3 was rather four days, which implies that dispersal rate is rather rapid (over 250 km in six days). These results distinctly suggest high dynamic nature of equatorward hydrography to disperse and distribute the fluvial influx along the shelf in short span of time.

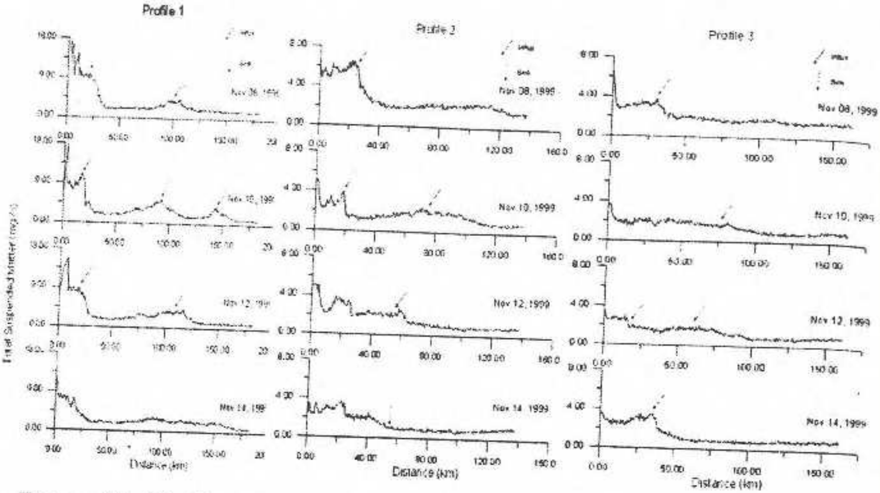

Figure 17: Weekly spatial and temporal variations in the TSM along W-E (Profile 1 off the mouth of Mahanadi-Dhamra shows the inland shift of plume in coastal waters during 8-14 November 1999. Profile 2 south of Paradeep shows sequential increase of TSM from offshore into inland waters and time lag of two days. Profile 3 at Visakhapatnam shows sequential delay in the enrichment of TSM in coastal waters). Arrows indicate influx and sink of the TSM.

Clay minerals transported in the seawaters were evaluated during November of 2000 which further elucidates the advection of G-B fluxes. Since the clay minerals (mean grain size <2 μm) (i) regulated by geology and drainage characteristics of catchment area, have fluvial source specific assemblages, and (ii) have a potential to be transported regionally in suspension, they have potential to be used as tracers of a specific source. The clays present in the surface waters along the study area are illite, chlorite, kaolinite, and smectite (traces) in the order of abundance (Table 3). Because the clay assemblage of illite, chlorite, and kaolinite are characteristics of the load of the G-B system (Konta, 1985), which is similar to one observed in the surface sea water

Table 3: Clay abundance in the suspended sediments (water depth 0-2 m) at selected locations (Refer Fig. 15 for station locations)

Station	*Location*	*Water depth*	*Illite*	*K+C*	*K/C*	*Smectite*
1	19° 40.1'N, 85° 50.1'E	22	61	17.9	1.58	5.1
2	21° 05.5'N, 87° 09.8'E	20.4	67	17.3	1.48	5.6
3	19° 40.1'N, 85° 50.2'E	32	61	16.9	1.51	5.4
4	20° 04.0'N, 86° 50.0'E	52.5	70.9	19.8	0.56	5.8
5	19° 55.1'N, 86° 28.4'E	32	73.1	15.5	0.61	6.4
6	19° 03.3'N, 85° 28.6'E	29.5	61.4	17.9	0.78	6.5
7	20° 42.6'N, 87° 19.1'E	28	69.4	19.8	0.63	5.1
8	20° 50.0'N, 87° 12.9'E	24.2	67.2	17.8	0.68	5.8

samples, it is inferred that fluvial flux of the G-B system is dispersed and distributed along the shelf by equatorward hydrography.

Considering the observed illite and chlorite in the surficial sediments along the continental shelf off Orissa, the study suggests that the source of chlorite is from the distributaries of the River Mahanadi. In general, chlorite (clay) is produced under arid, cold climate, and is mostly found in the load of Himalayan rivers G-B (Konta, 1985). The suspended load of the river Mahanadi and its distributaries is dominated by the smectite, kaolinite with minor illite and, therefore, the source of chlorite appears to be of not local origin. The integrated results of the present study, for the first time, distinctly suggest higher influence of the G-B system onto the coastal regions on the northern Bay of Bengal. The reduced terrigenous flux into the central and the northern traps of the Bay of Bengal during the NE monsoon, therefore, appears linked with the dispersal mechanism, rather than linearly related with magnitude of the flux from the G-B.

6. CONCLUSIONS

Surface oceanic circulation, besides turbidity currents and the bottom topography, affects the dispersal of materials within the Bay. Influx from the Himalayan and the Peninsular rivers reaches maximum by August; however, the perennial nature of the G-B system feeds the northern Bay even after the cessation of the summer monsoon. The seasonal trends of freshwater discharge in the Bay remain consistent over decades as evidenced from the climatology. However, the inter-annual variability of flux by the Himalayan rivers, unlike the Peninsular rivers, does not show one-to-one correlation with the Indian summer monsoon indices. The northern shelf of the Bay, being a macro-tidal region, remains ever-turbid due to the round the year discharge from the Himalayan rivers. The *Swatch of no Ground* is a prospective track to carry the sediment loads from the G-B source into the Bengal Fan and as far into the southern Indian Ocean; however, the dispersal of sediments along the Indian coasts needs further investigation. Satellite ocean colour data is extremely useful to trace the surface sediment dispersal pathways.

As a major contribution to understand and delineate the source-sink pathways of the G-B flux during off-summer monsoon periods, the combined experiment using in situ and remote sensing data confirms that: (1) during the NE monsoon the suspended sediment influx of the Ganga-Brahmaputra system influences the coastal processes with much higher spatial variability along the northern region, than hereto before thought and (2) the supply of the terrigenous sediments to the deeper offshore regions of the central Bay during the NE monsoon is not related with the magnitude of influx of the sediments into the Bay, but the prevalent dispersal by the hydrography. A schematic of the general dispersal of the spread of G-B flux is depicted in Fig. 18. During the NE monsoon, influx of the G-B moves N-S initially, off

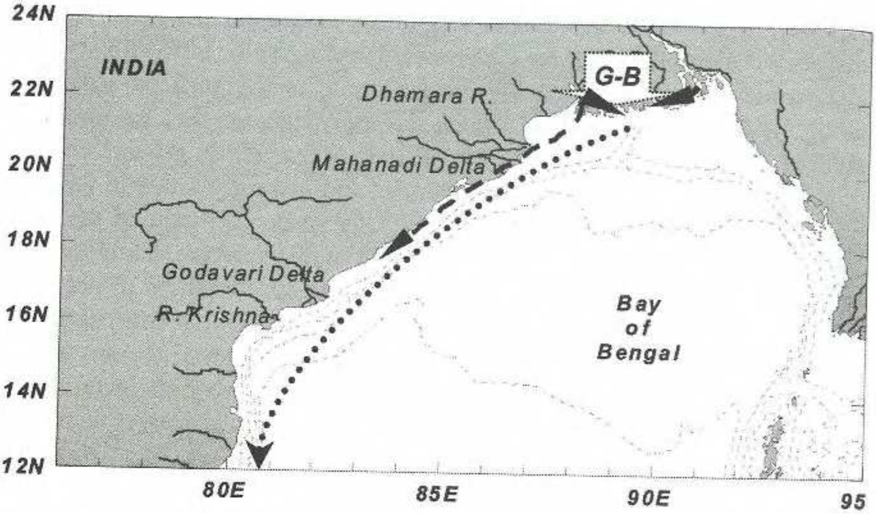

Figure 18: Conceptual depiction of sediment dispersal in the northern Bay. Solid and dashed arrows represent sediment pathways in the summer (SW) and the winter (NE) monsoon periods. The generalised surface current pattern along the east coast during the winter monsoon is shown with the dotted arrow. Bathymetry contours overlaid are for 200 m, 1 km, 2 km and 3 km from the coast.

the mouth, and thereafter advects southwest alongshore in the form of coastal sediment plumes, reducing the salinity of the coastal waters along the entire northern Bay during October-December. A strong relation exists between enhanced episodic discharges of the Ganga-Brahmaputra and augmented coastal turbidity during weekly events. It is observed that during short (weekly) events of very high pulse of TSM discharge by the G-B system, the fluvial fluxes do not advect offshoreward into the deeper offshore regions of the north-central Bay, but are transported alongshore and distributed along the shelf. These observations have implications for a possible different sink pathway, and biogenic processes associated with stronger/weaker monsoon activities.

REFERENCES

Anuradha, T., Suneethi, J., Dash, S.K., Pradhan, Y., Prasad, J.S., Rajawat, A.S., Nayak, S.R. and Chauhan, O.S., 2000. Sediment dispersal during NE monsoon over northern Bay of Bengal: Preliminary Results using IRS–P4 OCM data. *In: Proceedings of PORSEC*, **2:** 813-815.

Biscaye, P.E., 1965. Mineralogy and sedimentation of recent deep-sea clays in the Atlantic Ocean and adjacent seas and oceans. *Bull Geol Society of America*, **76:** 803-832.

Chauhan, O.S. and Gujar, A.R., 1996. Surficial clay mineral distribution on the south western continental margin of India: Evidence of input from the Bay of Bengal. *Cont. Shelf Res.*, **16(3):** 321-333.

Chauhan, O.S., 1995. Monsoon induced temporal changes in the beach morphology and associated sediment dynamics, central east coast of India. *J. Coastal Res.*, **11:** 776-787.

Cutler, A.N. and Swallow, J.C., 1984. Surface currents of the Indian Ocean (to 25°S, 100°E) compiled from historical data archived by the Meteorological Office, Bracknell, U.K., *Rep. 187*, Inst. of Oceanogr. Sci., Wormley, Surrey, England, 1-8.

Duing, W., 1970. The monsoon regime of the currents in the Indian Ocean, *IIOE Oceanogr. Monograph No. 1*, Univ. Hawaii, East-west Central Press, Honolulu, 68 pp.

Emmel, F.J. and Curray, J.R., 1984. The Bengal Submarine fan, North eastern Indian Ocean. *Geo-Marine Letters*, **3:** 119-124.

Ganapathi, P.N. and Murty, S.V., 1954. Salinity and temperature variations of the surface water off Visakhapatnam coast. *Andhra University Memoirs in Oceanography,* **1:** 125-142.

Garcia, C.A.E. and Robinson, I.S., 1989. Sea surface velocities in shallow seas extracted from sequential Coastal Zone Colour Scanner Satellite Data. *J. Geophys. Res.*, **94(C9):** 12681-12691.

Goodbred, S.L. and Kuehl, S.A., 1999. Holocene and modern sediment budgets for Ganges –Brahmaputra river: Evidence for highstand dispersal to floodplain, shelf, and deep-sea depocenters. *Geology*, **27(6):** 559-562.

Ittekkot, V., 1993. Particle flux studies in the Indian Ocean. *EOS, Trans. of the American Geophysical Union*, November 19, 1991, 527-530.

Ittekkot, V., Nair, R.R., Honjo, S., Ramaswamy, V., Bartsch, M., Manganini, S. and Desai, B.N., 1991. Enhanced particle fluxes in Bay of Bengal induced by injection of freshwater. *Nature,* **351:** 385-387.

Ittekkot, V., Safiullah, S., Mycke, B. and Seifert, R., 1985. Seasonal variability and geochemical significance of organic matter in the river Ganges, Bangladesh. *Nature*, **317:** 800-802.

Kolla, V., Henderson, L. and Byscaye, P.E., 1976. Clay mineralogy and sedimentation in the western Indian Ocean. *Deep-Sea Res.*, **23:** 949-961.

Kolla,V. and.Kidd, R.B., 1982. Sedimentation and sedimentary processes in the Indian Ocean. *In:* The Ocean Basins and Margins: The Indian Ocean, (eds. A.E.M. Nairn and F.G . Stehli), Plenum, New York, **6:** 1-45.

Konta, J., 1985. Mineralogy and chemical maturity of suspended matter in major rivers samples under SCOPE/UNEP, Transport of carbon and minerals in major world rivers. Part III (eds T. Degens and S. Kempe), Mitteilungen aus dem Geologisch - Paleontologischen Institut der Universitat Hamburg, pp. 569.

La Fond, E.C. and La Fond, K.G., 1968. Studies of Oceanic circulation in the Bay of Bengal. *Proc. Symp. Indian Ocean. Bull. Natl. Inst. Sci. India*, Vol I, 169-183.

LaViolette, P.E., 1967. Temperature, Salinity and Density of the World's Seas: Bay of Bengal and Arabian Sea. *Informal Rep. No. 67-57*, Naval Oceanographic Office, Washington D.C.

McCreary, J.P., Kundu, P.K. and Molinari, R.L., 1993. A numerical investigation of dynamics, thermodynamics and mixed-layer processes in the Indian Ocean. *Prog. Oceanogr.*, **31:** 181-244.

McCreary, J.P., Han, W., Shankar, D. and Shetye, S.R., 1996. Dynamics of East India Coastal Current, 2. Numerical solutions. *J. Geophys. Res.*, **101(C6):** 13,993-14,010.

Milliman, J.D. and M. Syvitski, J.P., 1992. Geomorphic/Tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. *J. Geol.*, **100:** 525-544.

Milliman, J.D. and Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. *J. Geol.*, **91:** 1-29.

Murty, V.S.N., Sarma, Y.V.B., Suryanarayana, A.S., Babu, M.T., Santhanam, K., Rao, D.P. and Sastry, J.S., 1990. Some aspects of physical ocenography of the Bay of Bengal during the southwest monsoon. NIO Technical Report No. NIO/TR-8/90, National Institute of Oceanography, Goa.

Nath, B.N., Rao, V.P.C. and Becker, K.P., 1989. Geochemical evidence of terrigenous influence in deep sea sediments up to 8°S in the central Indian basin. *Mar. Geolo.*, **87:** 301-313.

Potemra, J.T., Luther, M.E. and Obrein, J.J., 1991. The seasonal circulation of the upper ocean in the Bay of Bengal. *J. Geophys. Res.*, **96(C7):** 12,667-12,683.

Ramaswamy, V., Kumar, B.V., Parthiban, G., Ittekkot, V. and Nair, R.R., 1997. Lithogenic fluxes in the Bay of Bengal measured by sediment traps. *Deep Sea Res. I*, **44(5):** 793-810.

Rao, D.P. and Murty, V.S.N., 1992. Circulation and geostrophic transport in the Bay of Bengal. *In:* Physical processes in the Indian Seas (eds G.N. Swamy, V.K. Das and M.K. Antony), Proc. First convention of the Indian Society for Physical Sciences of the Ocean, NIO, Goa.

Rao, D.P., 1977. A comparative study of some physical processes governing the potential productivity of the Bay of Bengal and Arabian Sea. *Ph.D. Thesis (Unpublished manuscript)*, Andhra University, Waltair, pp. 135.

Rao, D.P. and Sastry, J.S., 1981. Circulation and distribution of some hydrographic properties during the late winter in the Bay of Bengal. *Mahasagar, Bull. Natl. inst. Oceanogr.*, **14:** 1-15.

Ratna Reddy, S., Easton, A.K., Clarke, S.R., Narendra Nath, A. and Rao, M.V., 1995. Gyres off Somali coast and western boundary currents in the Bay of Bengal during the south-west monsoon. *Int. J. Remote Sens.*, **16(9):** 1679-1684.

Sanilkumar, K.V., Kuruvilla, T.V., Jogendranath, D. and Rao, R.R., 1997. Observations of the Western Boundary Current of the Bay of Bengal from a hydrographic survey during March 1993. *Deep Sea Res.*, Part I, **44(1):** 135-145.

Schott, F., Reppin, J., Fischer, J. and Quadfasel, D., 1994. Currents and transport of the Monsoon Current south of Sri Lanka. *J. Geophys. Res.*, **99:** 25,127-25,141.

Shankar, D., McCreary, J.P., Han, W. and Shetye, S.R., 1996. Dynamics of the East India Coastal Current 1. Analytic solutions forced by interior Ekman pumping and local alongshore winds. *J. Geophys. Res.*, **101(C6):** 13,975-13,991.

Shankar, D., Vinaychandran, P.N., Unnikrishnan, A.S. and Shetye, S.R., 2002. The monsoon current in the north Indian Ocean. *Progr. Oceanogr*, **52(1):** 63-119.

Shankar, D. and Shetye, S.R., 2001.Why is mean sea level along the Indian coast higher in the Bay of Bengal than in the Arabian Sea? *Geophysical Res. Lett.*, **28(4):** 563-566.

Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Sundar, D., Michael, G.S. and Nampoothiri, G., 1993. The western boundary current of the seasonal gyre in the Bay of Bengal. *J. Geophys. Res.*, **98:** 945-954.

Shetye, S.R., Shenoi, S.S.C., Gouveia, A.D., Michael, G.S., Sundar, D. and Nampoothiri, G., 1991.Wind driven coastal upwelling along the western boundary of the Bay of Bengal during the southwest monsoon. *Continental Shelf Res.*, **11:** 1397-1408.

Subramanian, V., 1993. Sediment load of Indian rivers. *Curr. Sci.*, **64(11&12):** 928-930.

Tomczak, M. and Godfrey, J.F., 2001. Regional Oceanography: An Introduction, online version at *http://www.es.flinders.edu.au/~mattom/regoc/pdfversion.html.*

UNESCO, 1971. Discharge of selected rivers of the world, Vol. II and Vol. III, Paris.

Varadachari, V.V.R., Murty, C.S. and Das, P.K., 1968. On the level of least motion and the circulation in the upper layers of the Bay of Bengal. *Bull. Natl. Inst. Sci. India*, **38(I):** 301-307.

Varkey, M.J., Murty, V.S.N. and Suryanarayana, A., 1996. Physical Oceanography of the Bay of Bengal and Andaman Sea, *Oceanography and Marine Biology: an Annual Review* (eds A.D. Ansell, R.N. Gibson and Margaret Barnes), **34:** 1-70.

Vinaychandran, P.N., Masumoto, Y., Mikawa, T. and Yamagata, T., 1999. Intrusion of Southwest Monsoon Current into the Bay of Bengal. *J. Geophys. Res.*, **104:** 11077-11085.

Vorosmarty, C.J., Fekete, B.M. and Tucker, B.A., 1998. Global River Discharge Database (RivDIS) V. 1.1. Available online (http://www-eosdis.ornl.gov) and on CD-ROM from the ORNL Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Wetzel, A. and. Wijyananda, N.P., 1990. Biogenicsedimentary structures in the outer Bengal Fan deposits drilled during leg 116. *Pro. of Ocean Drill Progress, Science Research*, **116:** 15-24.

Wyrtki, K., 1973. An equatorial jet in the Indian Ocean. *Science*, **181:** 262-264.

Wyrtki, K., 1971. Oceanographic atlas of International Indian Ocean Expedition. National Science Foundation, Washington, D.C., pp. 531.

Yu, L., O'Brien, J.J. and Yang, J., 1991. On the remote forcing of the circulation in the Bay of Bengal. *J. Geophys. Res.*, **96(C11):** 20,449-20,454.