Reprinted from:

SEAS AT THE MILLENNIUM: AN ENVIRONMENTAL EVALUATION

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Volume II
Regional Chapters:
The Indian Ocean to The Pacific

2000
PERGAMON
An imprint of Elsevier Science

AMSTERDAM – LAUSANNE – NEW YORK – OXFORD – SHANNON – SINGAPORE – TOKYO

Chapter 71

THE BAY OF BENGAL

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The Bay of Bengal has several remarkable features. It has a huge influx of fresh water from several major rivers, it is affected by intense northeast and southwest monsoon winds, of which the latter breed cyclones. In the bay there is a seasonal anticyclonic coastal current which is seasonally replaced by a cyclonic current, and unlike most coastal regions, there is a western boundary coastal upwelling.

The Bay supports various tropical biotopes such as brackish lakes, estuaries, mangroves, coral reefs, and offshore waters with a great diversity of marine fauna and flora. The steadily growing coastal population (~55 million) utilizes the coastal zone for several purposes. Increasing development pressure from urban settlements, industry, fishery, mariculture, ports and harbours has resulted in the alteration of coastline, loss of critical habitats, and pollution of the environment, giving rise to serious environmental and socio-economic problems. Massive education of the public about the environment, impending disasters, mitigation measures, and the need for conservation of resources and sustainable development are all crucial to our understanding or use of this unique sea. There is a need for the creation of a coastal zone management authority empowered to implement environmental regulations, and a need to establish regional scientific programmes.

Seas at The Millennium: An Environmental Evaluation (Edited by C. Sheppard)

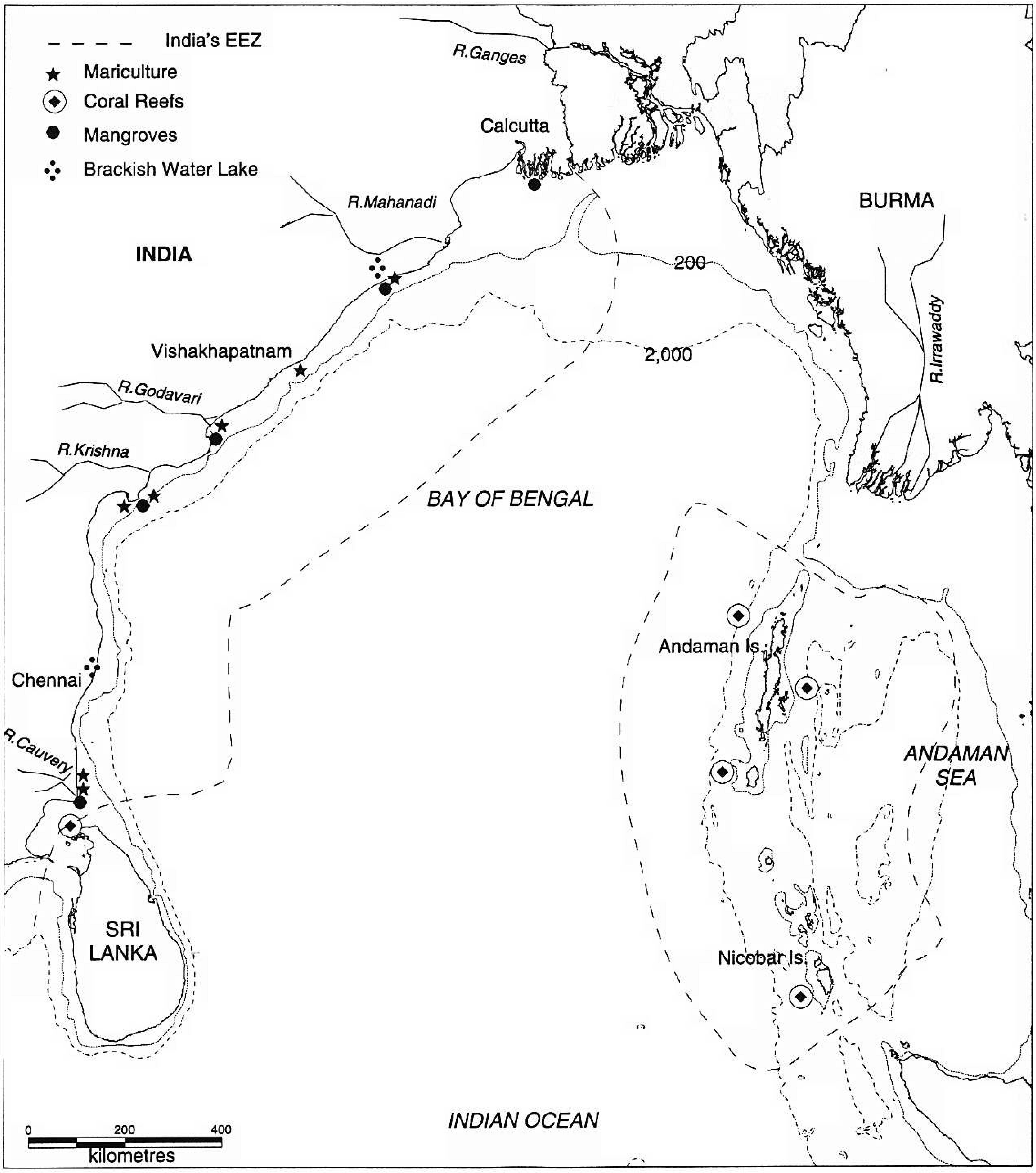

Fig. 1. Map of the Bay of Bengal.

THE BAY OF BENGAL

The Bay of Bengal stretches from the equator to 25°N and from 80°E to 100°E (Fig. 1) and has an area of about 4.09×10^6 km^2. Features such as alternating monsoon currents, upwelling of sub-surface waters and enormous river run-off provide an unusual combination of oceanographic features. Additionally, the Bay of Bengal offers diverse biotopes: estuarine waters and mangroves associated with several rivers, oceanic waters, brackish lakes and coral reefs around the 325 Andaman and Nicobar islands. The total population of the east coast of India i.e. Tamil Nadu, Andhra Pradesh, Orissa and West Bengal and the Andaman Nicobar Islands is 222 million, of which 25% live along the coast. The coastal population heavily utilizes the bay for fishing, mariculture, marine transport, recreation and waste disposal.

During the last 50 years India has acquired capabilities to study the Indian seas (Table 1) and also shows greater awareness of the value of marine sciences in this region. Most marine research publications address applications such as fisheries and aquaculture, and oil and gas exploration, but urbanization of the coast has also encouraged research into marine pollution, geology and geophysics.

The 0.44×10^6 km^2 shelf area (<200 m depth) of the Bay of Bengal (Table 2) approximates that off the British Isles or that off Peru and Chile. The total shelf and upper slope area of 0.62×10^6 km^2 approximates that of the Eastern Central Pacific (California to Colombia) or the Gulf of Mexico. Of the 2.02×10^6 km^2 Indian Exclusive Economic Zone, 59% is due to the Bay of Bengal (the eastern seaboard plus the Andaman, and Nicobar Sea) and covers $1.19\text{x}10^6$ km^2.

Table 1

Number of abstracts in *Aquatic Sciences and Fisheries* cited by Cambridge Scientific Abstracts

	1978–87	1988–96	1997–98
Indian Ocean	1853	2960	901
Andaman and Nicobar Sea	31	130	80
Bay of Bengal	397	856	188
Oceanography	38	161	37
Physical	14	38	6
Chemical	17	40	10
Biological	22	56	9
Geological and geophysical	8	78	10
Pollution	10	63	20
Fisheries	141	314	66
Aquaculture	24	102	15
Other	123	4	15

Table 2

Areas (10^6 km^2) in the Bay of Bengal based on Moiseev 1971

	Shelf <200 m	Continental Shelf >200–<300 m	Shelf and upper slope 0–1000 m	0–3000 m
Eastern India	0.19	0.84	0.33	1.03
Myanmar	0.25	0.20	0.29	0.45
Total	0.44	1.04	0.62	1.48

NATURAL ENVIRONMENTAL VARIABLES

River Run-off

The Bay of Bengal receives an annual precipitation of 11,000 km^3 and a run-off of about 126×10^{10} m^3 from the major rivers Brahmaputra, Ganges, Mahanadi, Godavari, Krishna and Cauvery (Table 3). The Bay of Bengal and Nicobar fan is the world's largest, being 2800–3000 km long, 830–1430 km wide and >16 km thick in the north (Chauhan et al., 1993). Fresh-water run-off, monsoon winds, cyclones and coastal currents modify the bay in several ways. Transport of sediment widens the shelf; muds from the Gangetic fan extend thousands of kilometres, and the thickness of the sediment cones exceed 1.5 to 2.5 km (Ewing et al., 1969). The sediment brought by the rivers amounts to 4×10^9 m^3, enough to cover the entire bay to a depth of 2 mm annually. A north to south decrease in the width of the continental shelf along the east coast can be attributed to deposition of sediments by the major rivers in the north, and the seaward edge of the continental shelf seems to be steadily spreading annually about 1.8 km (LaFond, 1957). The annual particle flux patterns correspond with the fresh-water discharge patterns of the Ganges-Brahmaputra rivers, being highest (>50g m^2 y^{-1}) in the central bay and least (37 g m^2 y^{-1}) in the south (Ramaswamy and Nair, 1994). The lighter illite-rich suspended sediments from Ganges–Brahmaputra are transported southwards along with the low salinity layer, an important sedimentary process in the Bay of Bengal. Some of these illite and chlorite rich clay sediments are transported as far as the southwestern peninsular continental margin on the Arabian Sea (Chauhan and Gujar, 1996).

Canyons

Opposite the mouths of the major rivers are deep canyons. At the head of the Bay, a deep Ganges Submarine canyon, known as 'Swatch of No Ground' cuts the plain in a northeast–southwest direction, and several others occur off Visakhapatnam (Andhra, Mahadevan and Krishna canyons). Their formation is attributed to turbidity currents (LaFond, 1957).

Shoreline Dynamics

Coastal currents and deposition of deltic muds affect the shoreline morphodynamics. Sediment transport can be very large (Fig. 2). Chilka inlet near Mahanadi is exposed to an annual littoral drift of about 1×10^6 m^3; as a result it

Table 3

Annual river inputs into the Bay of Bengal. Units for discharge are in $10 \times 10\ m^3$ for P,N,U and ^{226}Ra in 10^6 g; for DOC and POC and particulate metals in 10^{12} g. (Based on Kumar et al., 1992)

	Ganges	Brahmaputra	Mahanadi	Godavari	Krishna	Cauvery	Pennar	Total
Discharge	39.3	60.9	6.7	10.5	6.8	2.1		126
Na	395.6	128.8	68.0	182.0	234.0	468.3	1477	
K	105.6	113.4	10.0	27.0	18.0	44.1		318
Ca	998.0	857.7	70.0	274.0	136.0	483.0	2819	
Mg	274.7	233.4	64.0	64.0	52.0	77.7		766
Cl	195.0	67.4	98.0	153.0	176.0	199.5		889
SO_4	336.0	614.4	210.0	109.0	211.0	63.0	1543	
HCO_3	4995.9	3556.3	410.0	1380.0	977.0	294.011613		
SiO_4	324.4	474.0	6.0	230.0	95.0	38.1		1167
TDS	7626.0	6045.0	1039.0	2436.0	1911.0	668.020725		
Phosphate	45981	–	3900	–	–	17220		
Nitrate	51090	–	1600	–	–	–		
Uranium	711	384	17	65	78	–		
226 $Ra10^{10}$ dpm	2750	5480	–	420	340	–		
DOC	1.24							
POC	0.28							
Al	1.53		0.012	0.813	0.014	0.00019		
Fe	1.70		0.08	0.72	0.019	0.034		
Mn	0.035		0.007	0.022	0.003	0.0009		
Ni	0.005		0.00001	0.005	0.0003	–		
Cu	0.002		0.00008	0.001	0.0002	0.00002		
Zn	0.004		0.00009	0.0006	0.00003	0.00006		

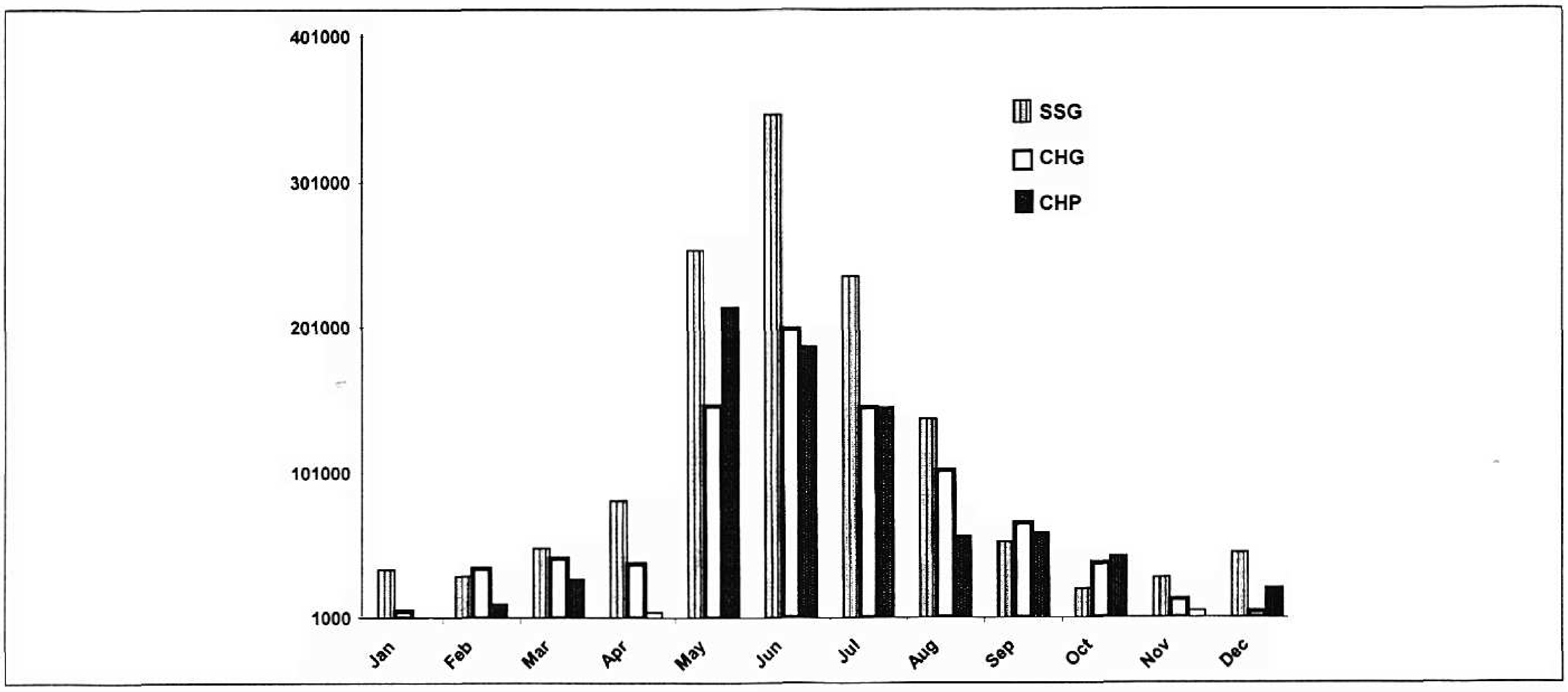

Fig. 2. Monthly sediment transport (m^3) off Orissa coast. SSG: off Gopalpur (Sundar and Sarma, 1992); CHG: off Gopalpur (Chandramohan et al., 1993); CHP: off Paradeep (Chandramohan et al., 1993).

migrates annually 500 m north (Chandramohan et al., 1993) and $0.16 \times 10^6\ m^3$ south (Sundar and Sarma, 1992). The Puri coast experiences active erosion amounting to $5.37\ m^3\ m^{-1}\ y^{-1}$ due to littoral currents, in addition to another $70\ m^3\ m^{-1}\ y^{-1}$ sediments per cyclone (Chauhan, 1992). Further south near Kakinada, a 16 km long sand spit named after the river Godavari, runs north–south. The spit seems to continuously lengthen and ultimately the bay will be converted into a lagoon (Prasad, 1990). Due to littoral drift, further south the coastline of Tamil Nadu undergoes significant changes due to both erosion and accretion (Ramaiyan et al., 1997).

Sediments

The inner shelves are dominated by sandy terrigenous muds that grade to finer clayey and silty sediments down to the 50 m isobath. Medium to coarse sediments with local pebble zones occur on the inner and middle shelf. In the outer shelf, some calcareous oolitic sand might represent a regressive phase of the sea level during the Pleistocene (Sen Gupta et al., 1992). Regional differences in the characteristics of the sediments exist (Table 3) although kaolinite illite, chlorite, smectite and montmorillonite are common. Based on the clay minerals along the shelf, Raman et al. (1995) distinguished from north to south (a) a Himalayan zone dominated by illite followed by chlorite, (b) an Eastern Ghats zone with mixed sediments, and (c) a Deccan Provinces zone rich in smectite.

River Impacts

On a global scale the Ganges–Brahmaputra river system alone ranks fourth in sediment transport. They contribute 118×10^6 tonnes of dissolved solids annually (Sarin and Krishnaswamy, 1984) which control the water chemistry. Surface discharge of fresh-water, excluding that from precipitation during the Southwest Monsoon (June–September) into the Bay of Bengal, amounts to $50 \times 10^3\ m^3\ s^{-1}$. When this is evenly spread, it raises the water level by 70 cm, but circulation in the Bay is essentially density (geostrophic) controlled (Murty et al., 1992). At the head of the Bay, a substantial amount of flood water, dependent on the relative strength of the wind and river discharge, is held back inside Bangladesh by the Southwest Monsoon (Ali, 1995). Known as the 'back water effect', this causes flooding, loss of life and damage to property.

In coastal waters detrital matter dominates the particulate organic carbon. In oceanic waters detrital matter correlates with protein and lipid (Sreepada et al., 1995). At the head of the bay, Subarnamukha river contributes to the heavy metal flux (Senapati and Sahu, 1996) while off Orissa, the ratio between calcium, magnesium and fluoride with chlorinity decreases both off-shore and from north to south (Das and Sahoo, 1996). These ratios were high in areas with pronounced fresh-water. The highest concentrations of quartz (80–90%) are in sediments between Mahanadi and Kalingapatnam, and are lowest (50–60%) in the south i.e. Krishna–Godavari and in the outer shelf off Visakhapatnam (Purnachandra Rao and Vijay Kumar, 1990).

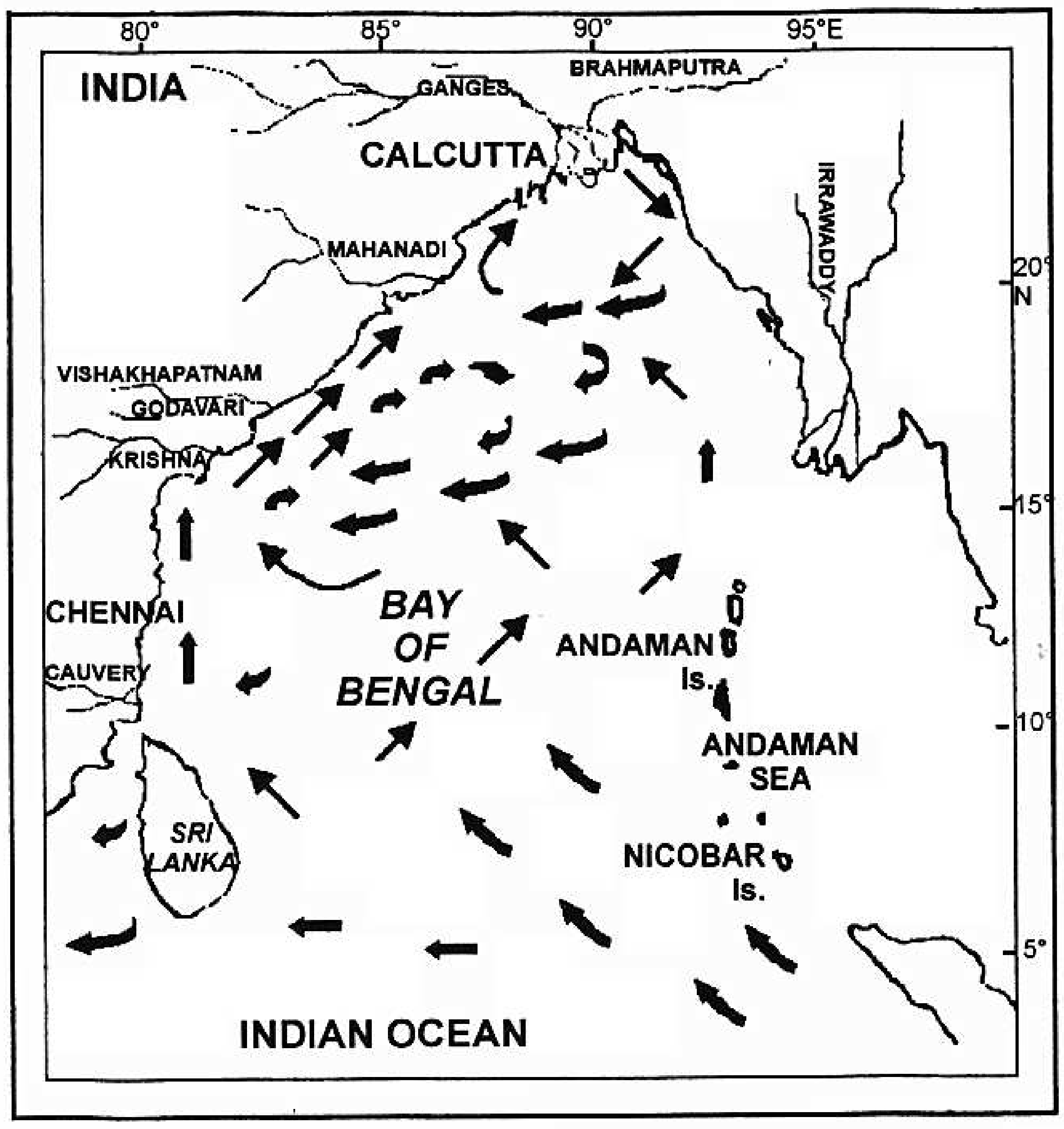

Fig. 3. Circulation during south west monsoon (summer).

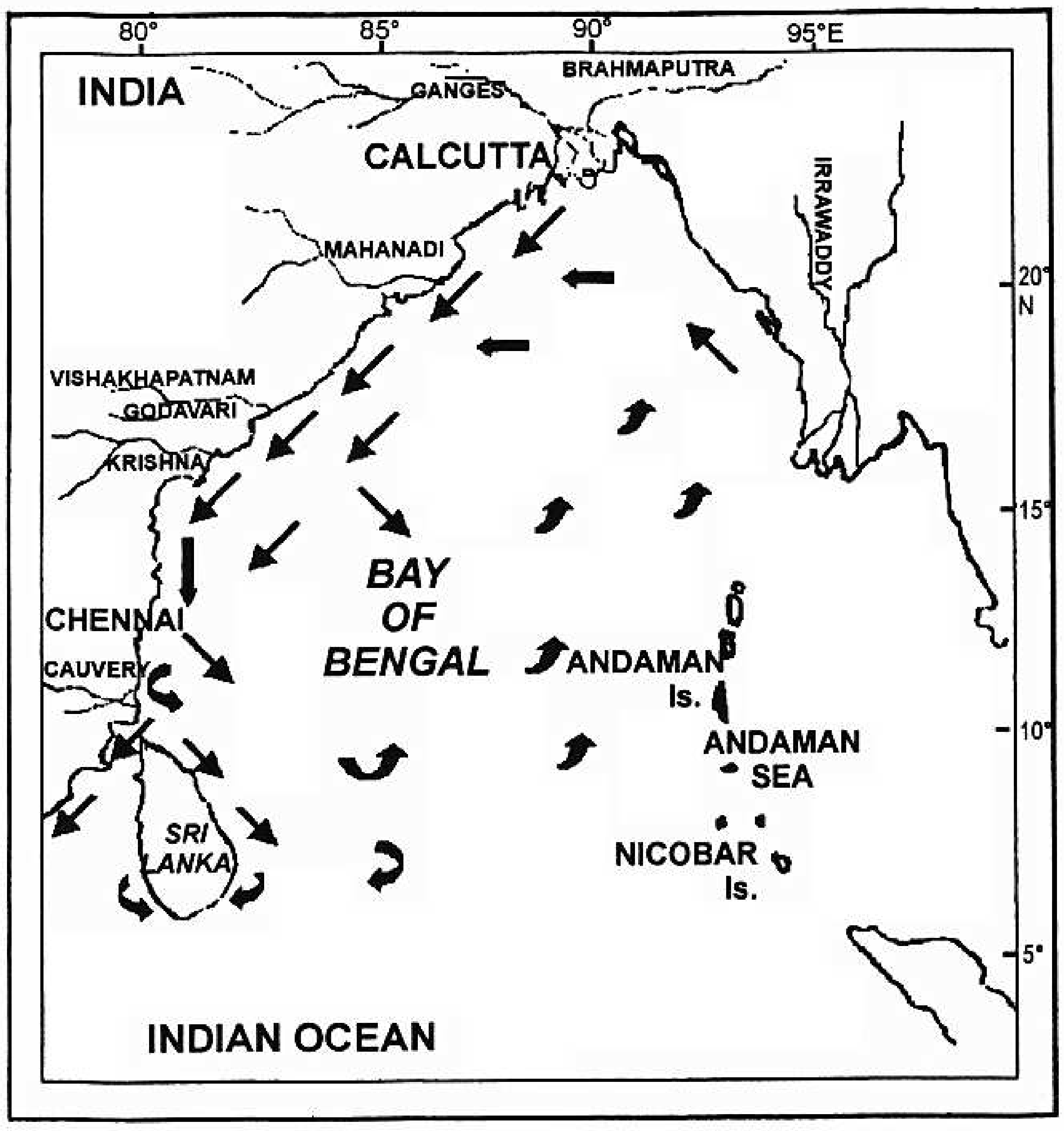

Fig. 4. Circulation during north east monsoon (winter).

Monsoons, Currents and Gyres

Seasonal land–sea heat fluxes change the atmospheric pressure over the Asian continent and result in monsoons. The Northeast Monsoon, also known as the winter monsoon, blows from land to sea whereas the Southwest Monsoon blows from sea to land. The latter sets in as early as March and may extend to October. Based on 10-year sensible heat (SHF) and latent heat (LHF) fluxes, Devi et al. (1994) showed that SHF of 40 $W\ m^2$ or more intensifies severe cyclonic storms. Good monsoon years have SHF of 20 $W\ m^2$ and poor years 10 $W\ m^2$ (Devi et al., 1994).

The east coast is influenced in a south to north sequence during the Southwest Monsoon and north to south during the Northeast Monsoon (Figs. 3 and 4). During the former, the Sri Lankan Coast will be influenced during February–

March, the Coramandel Coast during April, Orissa Coast during March–May and Calcutta Coast during April–July. A cyclonic gyre sets in at 5°N resulting in an eastward flow known as the Indian Monsoon Current (Molinari et al., 1990). At the head of the Bay the salinity remains as low as 26.0 psu due to freshwater influx, leading to a weak 2.0×10^6 m^3 s^{-1} northeast transport (Murty et al., 1992). The Northeast Monsoon passes along the east coast of India and Ekman pumping in the interior bay results in the East India Coastal Current (EICC) that flows southwards (Shetye et al., 1996). North of 15°, within 100 km from the coast, freshwater flow influences the circulation, and beyond this wind forcing is the dominant factor (Suryanarayana et al., 1992). During this monsoon the Calcutta, Orissa, Coramandel and Sri Lankan coasts will be influenced in September, October, November and December, respectively.

Numerical modelling studies (Potemra et al., 1991) agree with observations; temperature, salinity and flow data off the rivers Krishna, Godavari, Mahanadi and off New More Island during the Southwest Monsoon show south-southwest flows off Krishna and Godavari, whereas off Mahanadi it is north-northeast. Both flows are associated with gyres, clockwise off Mahanadi and anti-clockwise off Krishna and Godavari (Rao et al., 1987). Two anticyclonic gyres also develop in the central and southern parts of the Bay. The anticyclonic gyre during winter changes into a weak cyclonic gyre by late summer and is intensified into a western boundary current. Flow of river water results in a decrease in salinity and an increase in silicate, which is characteristic of these waters (Subba Rao, 1973).

Upwelling

During the Southwest Monsoon, a northerly current sets in and, due to Coriolis force, surface water is deflected to the right, away from the coast. As a result of Ekman transport, cooler subsurface waters upwell (LaFond, 1957; Gopalakrishna et al., 1996). In the southern part of the Bay the mean local temperature anomaly (LTA defined as the difference between coastal and mid-ocean sea surface temperatures) during the Southwest Monsoon is up to >2.0 due to upwelling (Naidu et al., 1999). However, in the northern Bay of Bengal it is negative (<–0.5) and so also is its correlation with Ekman transport ($r = -0.35, p = 0.05$). This is probably due to the presence of warm and freshwater discharges from the Brahmaputra and the Ganges (Naidu et al., 1999). The Hoogly and Mahanadi rivers (19°N) suppress coastal upwelling too (Sasamal, 1989; Shetye et al., 1991). Similarly, off the Godavari river, Johns et al. (1993) observed a marked cross-shelf spread of a plume of relatively low salinity water that weakens the local coastal upwelling.

Chemical Features

River discharge and the associated sediment and upwelling of bottom waters govern the chemistry of the Bay of Bengal. Mixed surface Bay waters (0–50 m) are saturated with oxygen, attributed to phytoplankton production (Satyanarayana et al., 1987; Sarma et al., 1988). Intermediate (100–500 m) waters have minimum oxygen suggesting active decomposition of organic matter (Satyanarayana et al., 1987). During the Southwest Monsoon, nutrients are brought up and tilt the isolines of oxygen-poor waters (Lafond, 1957; Sarma et al., 1988; Banse, 1990). Organic nitrogen and phosphorus were detected up to 3000 m deep indicating that supply of oxygen regulates oxidation processes in deeper waters (Sen Gupta et al., 1977). The rapidly sinking riverine matter contributes to biogenic silica that constitutes >80% of the total particulate silica (Gupta and Sarma, 1997). This reaches a maximum in mid depths of the euphotic layer, and its maxima deepens from north to south corresponding to the deepening of the thermocline and thickening of the surface layer. North of 15°N near the head of the Bay dissolved silicate levels were not high, suggesting that the contribution of the Ganges to the sea is insignificant (Rajendran et al., 1980).

Trace elements such as Ni, Zn, Cd, Cu, Mn, Pb and Fe are relatively higher in surface waters associated with low salinities than offshore (Satyanarayana and Murty, 1990). These grade from highest in the eutrophic harbour to lowest offshore (Satyanarayana et al., 1987).

COASTAL HABITATS AND BIODIVERSITY

The various biotopes in the Bay of Bengal offer a great biodiversity of fauna and flora (Table 4).

Table 4

Species diversity in the Bay of Bengal

Group	No. of species	Reference	Year
Diatoms	176	Subrahmanyan	1946
Dinoflagellates	108	Subrahmanyan	1971
Foraminifera	46	Reddy and Reddi	1994
Ciliates (Tintinnids)	47	Krishnamurty et al.	1979
Copepoda	58	Mishra and Panigraphy	1996
Hydromedusae	80	Santhakumari and Nair	1998
Mysidaceae	27	Tattersall	1922
Chaetognatha	19	Nair and Rao	1973
Euphausiaceae	22	Brinton and Gopalakrishnan	1973
Appendicularians	26	Fenaux	1973
Fouling organisms	54	Ganapati et al.	1958
Phytal fauna	80	Sarma and Ganapati	1975
Meiofauna	65	Sarma and Ganapati	1975
Sand dwelling fauna	30	Ganapati and Lakshmana Rao	1962
Coral reef fauna	120	Patterson and Ayyakkannu	1996
Bottom fauna	47	Ganapati and Lakshmana Rao	1962
Fish (commercially important)	45	James	1992

Phytoplankton Ecology

About 300 species of phytoplankton exist, mostly diatoms. Although tropical species dominate, a few temperate species such as *Chaetoceros affinae, Chaetoceros lorenzianum* also exist. There are at least eight floristic elements in the Bay (Table 5) (Thorrington Smith, 1971). The diatoms *Stephanopyxis palmeriana, Streptoptheca indica* and *Planktoniella sol* may be considered as indicators of upwelling off Visakhapatnam (Subba Rao, 1976).

Phytoplankton growth is bimodal, coinciding with the two monsoons. During summer, the crop is usually low but there are instances of a third, atypical non-seasonal bloom during June–August (Gopinathan et al., 1994). Observations in the Hoogly estuary (De et al., 1994) suggest exponential growth from February leading to a major peak during March. Off Visakhapatnam, initiation of phytoplankton growth coincides with upwelling (Subba Rao, 1974). The first signs of phytoplankton growth are in February in the 24–32 km zone, and it attains bloom proportions in the 0–16 km zone during early March. By April these blooms extend throughout the 0–32 km zone (Subba Rao, 1974). Heavy phytoplankton densities were reported in subsurface waters up to 122 m deep (Subba Rao, 1974). There is a time lag from north to south in the start of the maximum (Subba Rao, 1974; Gouda and Panigrahy, 1996; Gopinathan et al., 1994). Phytoplankton biomass is high and comparable to most productive coastal seas (Table 6) although in the northern Bay of Bengal it appears to be low (3.16 μg chl-*a* l^{-1}), probably because of the enormous river run-off.

Massive blooms of algae, mostly diatoms but sometimes with dinoflagellates, have been reported along the east coast (Murthy and Venkataramaiah, 1958; Mishra and Panigraphy, 1995; Subba Rao, 1969, 1973; Satpathy and Nair, 1996). Some are short lived and are a response to environmental perturbations such as dredging operations (Subba Rao, 1973), sudden lowering of temperature (Subba Rao, 1969) or dumping of fertilizer (Subba Rao, 1971), change in water quality (Satpathy and Nair, 1996) or due to organic pollution (Ganapati and Raman, 1979). Blooms cause red tides with 93.2×10^6 cells l^{-1} and 35.99 μg chl-*a* l^{-1} (Subba Rao, 1969). There were no fish kills or anoxic conditions associated with the algal blooms investigated, but the occurrence of euglenophyceae and cyanophyceae off river mouths and then in the brackish water lagoon at Chilka (Raman et al., 1990) flag a warning.

Primary production rates vary between 0.04–3852 mg C m^{-3} d^{-1} and 0.08–5.41 g C m^{-2} d^{-1} (Table 7). Annual primary production in coastal waters is about 250 g C m^{-2} while that of the coral reef waters off Mandapam and the Andamans has been measured at 2500 and 1200 g C m^{-2} (Nair, 1970). Surface production in the Bay is 4.9 t km^{-2} y^{-1} which is more than the 3.9 t km^{-2} y^{-1} for the Arabian Sea (Qasim, 1977). There is a significant increase from east to west (Pant, 1992). Qasim (1977) calculated that rivers contribute 33.6×10^6 tonnes of humus to the Bay of Bengal which would increase the phosphate in the upper 25 m by 0.03 μmol and nitrogen by 5.5 μmol. However, this enrichment and elevated production are limited to the top 25 m, unlike in the Arabian Sea. The calculated annual total column production for the Bay of Bengal is 394×10^6 t carbon compared to 1064×10^6 t for the Arabian Sea (Qasim, 1977).

Table 5

Phytogeographical distribution of phytoplankton in the Bay of Bengal

Floral element	Taxa
South equatorial	*Ceratium pulchellum, Chaetoceros diversum*
Southern side of the equatorial under-current	*Ceratium vulture*
Centred on 5°S	*Ceratium tripos, Coscinodiscus lineatus, Grammatophora sp., Navicula* sp.,
Equatorial under-current	*Ceratium teres*
Equatorial subsurface	*Asteromphalus heptactis, Bacteriastrum hyalinum, Coscinodiscus marginatus, Rhizosolenia cylindrus, Rhizosolenia hebetata, Bacteriastrum delicatulum, Chaetoceros affinae, C. pendulum, C. peruvianum, C. lorenzianum, Coscinodiscus excentricus, Coscinodiscus lineatus, Nitzschia closterium, N. seriata, Planktoniella sol, Rhizosolenia alata, Thalassionema nitzschioides*
South-west monsoon	*Chaetoceros affine, Gossleriella tropica, Guinardia flaccida, Pleurosigma* sp. *Rhizosolenia alata gracillima, R. styliformis, Schroderella delicatula,*
Fluctuating conditions	*Ceratium axiale, Chaetoceros affine* var *circinalis, C. compressum*
Other West India Ocean	*Actinoptychus undulatus, Bacteriastrum comosum, B. varians, Ceratium buceros, C. carriense, C. declinatum, C. extensum, C. furca, C. fusus, C. macroceros, C. pentagonum, C. trichoceros, C. tripos, Chaetoceros affine, C. messanense, C. pelagicum, Coscinodiscus centralis, C. excentricus, C. oculis-iridis, Eucampia zoodiacus, Fragilaria oceanica, Gonyaulax* sp., *Oscillatoria* sp., *Rhizosolenia acuminata, R. alata, R. calcar-avis, R. hebetata, R. imbricata, R. osolenia setigera, R. stolterfothii, Thalassiothrix frauenfeldii, T. longissima, Triceratium alterans, Triceratium* sp.

Probably the enormous discharge of fresh water reduces total column production in the Bay of Bengal. Carbonate fluxes in the Bay of Bengal increase from north to south and seem to be controlled by input from rivers (Ittekkot et al., 1991). The spread of freshwater by the surface currents controls the total carbon dioxide and results in low pCO_2 (Dileep Kumar et al., 1996) and as a result the northwestern Bay of Bengal acts as a sink for atmospheric CO_2.

Zooplankton

Zooplankton in the northwestern bay is most productive in the Northeast Monsoon (Mathew et al., 1996). Eighty species of hydromedusae occur, of which several are limited to the east coast (Shanthakumari and Nair, 1998). Copepod

Table 6

Phytoplankton biomass (Chl-*a*) in selected waters in the Bay of Bengal

Locality	Range mg m^{-3}	Range mg m^{-2}	Average mg m^{-2}	Reference	Year
Bay (Premonsoon)		1.0–34.0	8.1	Sarupria and Bhargava	1998
Bay (SW Monsoon)		1.1–93.2	14.8	Sarupria and Bhargava	1998
Bay			22.0	Sarupria and Bhargava	1998
N.E.Bay			23.2	Sarupria and Conkright	1998
Hoogly estuary	2.55–3.16			De et al.	1994
Chilka Lake	0.94–12.53			Raman et al.	1990
Gopalpur	0.19–17.22			Gouda and Panigrahi	1996
Tuticorin	1.2–11.8			Gopinathan et al.	1994
Chennai coastal waters	0.6–9.2			Nair	1990
Kalpakkam 12°33 N	<22.7			Satpathy and Nair	1996
Chennai backwaters	2.1–55			Nair	1990

Table 7

Primary production measurements in the Bay of Bengal

Locality	Range of production		Reference	Year
	mg C m^{-3} d^{-1}	g C m^{-2} d^{-1}		
Off Visakhapatnam	5–980	0.525–5.410	Subba Rao	1965
Visakhapatnam – Red water	537–1609		Subba Rao	1969
Dredging blooms				
Off Visakhapatnam	92–3380		Subba Rao	1973
Off Visakhapatnam	0.37–135.6	0.08–2.168	Ryther and Menzel	1964
Bay of Bengal	0.04–295.7	<3.495	Ryther and Menzel	1964
Bay of Bengal	2.1–44	0.19–0.63	Steeman Nielsen and Jensen	1957
Palk Bay	1.8–2342	1–8.68	Nair	1970
Gulf of Mannar	18–298		Raghu Prasad and Nair	1963
Vizinjam Bay	114–672		Jacob	1984
Vellar estuary	2940		Kawabata et al.	1993
Kalpakkam	36–3852		Nair	1990
Tuticorin	114–1600		Gopinathan et al.	1994
Shelf 16–20°N	74	2.9	Selvaraj and Srinivasan	1996
Slope 16–20°N	81	3.25	Selvaraj and Srinivasan	1996
Hoogly estuary	187–500		Bhunia and Choudhury	1982
Off Sagar Island	162–431		De et al.	1987
Bay	0.12–2988		Qasim	1977
Bay		0.3	Pant	1992

densities during the Southwest Monsoon are high (901 m^3) (Stephen, 1992). While some species avoid low salinity waters, members of the Centropagidae and Pontellidae seem to flourish in them.

Zooplankton biomass attains high densities, the maximum (92.25 cc10^6 l sea water) being around Andaman and Nicobars (Mathew et al., 1990), but in oceanic areas it is 36.55 ml in a million litres sea water. Maximum production is from July through October when 60–80% of the total occurs on the shelf. The balance between phytoplankton and zooplankton (Cushing, 1959 becomes overturned during periods of drastically lowered salinity, high temperature or lack of phytoplankton (Subba Rao, 1974).

In the southern region where hydrographical conditions are fairly stable, meroplankton and fishery production go hand-in-hand (Krishnamoorthy et al., 1999). In the northwestern Bay of Bengal peak zooplankton abundance coincides with maximum fishery landings (Mathew et al., 1996). Estimates of secondary production based on zooplankton biomass range between 0.5–5.98 g C m^{-2} y^{-1} on the East coast, and the maximum of 10.47 g C m^{-2} y^{-1} was around the Andaman and Nicobar Islands (Mathew et al., 1990). Assuming a 10% conversion efficiency from secondary to tertiary production, the calculated annual fish production for the Bay of Bengal, and Andaman Nicobar Sea is 1.38 and 1.39 million tonnes (Mathew et al., 1990).

Macrobenthos and Meiobenthos

Of 29 major taxa, polychaetes are the most dominant, followed by bivalves and amphipods (Ganapati and Lakshmana Rao, 1962; Harkantra et al., 1982; Jegadeesan and Ayyakkannu, 1992). Maximum population density and biomass were 12,572 individuals m^{-2} (mean 839) and 150.6 g m^{-2} (mean of 10.61 g m^{-2}), comparable with that of the west coast of India. Diversity decreases with increasing depth. Based on biomass, Harkantra et al. (1982) calculated an annual benthic production of 21.22 g m^{-2}, an organic carbon equivalent of 1.805 g C m^{-2} y^{-1}.

Meiofaunal abundance is affected by the annual cycles (Suresh et al., 1992; Rao, 1994), as well as by discharges of sewage. Groups vary with the monsoons; nematodes dominate during the post Southwest Monsoon, foraminiferans in the Southwest Monsoon and ostracods during the summer (Sunita Rao and Rama Sarma, 1990). Sandy interstitial habitats at Gopalpur are dominated by harpacticoid copepods (70%) followed by nematodes (Patnaik and Lakshmana Rao, 1990) with faunal densities of 323–525 cm^{-2} during March–May. In mangrove systems, the same groups were positively correlated with high organic matter (Sarma and Wilsanand, 1994). Offshore, varied meiofaunal densities have been reported (Rudnick et al., 1985; Patnaik and Lakshmana Rao, 1990; Suresh et al., 1992).

Mangroves

In estuaries the mangroves are mostly fringing. The largest area (4262 km^2) is the Sunderbans, off Sagar Island, near Hoogly River. *Rhizophora mucronuta, R. apiculata, Avicennia officianalis, A. marina, Ceriops* sp., *Exoecaria agallocha, Acanthus ilicifolius,* and *Acristucyn* sp. are the most dominant of the 59 mangrove species. Near the water's edge and with the highest plant density, *Rhizophora, Bruguiera, Sonneratia* and *Avicennia* dominate, with *Ceriops decandra, Aegiceros* sp. and *Clarodendrum* sp. in the middle of the forest. *Suaeda* sp. and *Lumnitzera* sp. grow landward. Mangroves are a natural coastal green belt which offers protection from cyclones, storms, winds and tidal excursions. They are highly productive and the litter fall beneath *Avicennia marina* of the Sunderbans is 1603 g m^{-2} y^{-1} dry weight (Ghosh et al., 1990). Detritus from the mangrove litter is a food for a variety of organisms, and commercially important crustaceans, fishes and shellfish use mangroves as spawning grounds. Additionally, mangroves are a source of fire wood, construction material, tannin for the leather industry, and the leaves are fodder for cattle and are used in herbal medicines. Increased exploitation, however, exerts severe stresses on the mangrove ecosystem.

Coral Reefs

About 20 coral islands cover 683 h in the southern part of the coast. There are 120 coral species of which 110 are hermatypic and 10 ahermatypic (Patterson and Ayyakkannu, 1996). *Montipora* and *Acropora* constitute 39% of the species. Most are fringing reef corals and provide important biological resources like finfishes, shell fishes and seaweeds. Although corals are fragile and critical ecosystems, there has been active destruction due to indiscriminate use as raw material for construction of houses, carbide and the white cement industry, and they are affected by pollution, aquaculture, fishing and tourism.

MARINE FISHERIES

In the EEZ the fish fauna includes 242 species of 87 families (Balachandran and Nizar, 1990). On the east coast, mackerel, sardines, anchovies, catfish, other clupeoids, coastal tunas, carangids, seer fish, ribbon fish, and pelagic sharks constitute the major pelagic fisheries (Sudarsan, 1993). The identity of species in landings varies regionally (Raja and Philipose, 1977). Annual fish catches on the east coast are 1.762×10^6 t of which 0.656×10^6 t are demersal and 1.106×0^6 t are pelagic. Potential fish stocks off the east coast EEZ are estimated to be 2.180×10^6 t (Somvanshi, 1998).

Demersal finfish are an important resource off Orissa and west Bengal (John and Sudarsan, 1990) (Table 8) and scope exists for increasing the catch, particularly offshore (Devraj et al., 1996). Cyclones which often hit Orissa adversely affect gillnetting (Pati, 1982).

On the east coast of India, nearly 60% of the total catch is of demersal finfish, nearly 70% of which is from depths >50 m (Vijayakumaran and Naik, 1991) and dominated by more than 20 carangid species (Sivakami et al., 1996). The highest densities were in the 60–80 m depth range, yielding about 150 kg h^{-1}. Also viable is a long-line tuna fishery, particularly during December to April (John et al., 1988). The tuna catch is particularly good between 65 and 120 m depth which is the boundary between the surface uniform layer and the sharp gradient layer of temperature and dissolved oxygen (Kurita et al., 1991). This is the shallowest tuna fishing in the world and Morinaga et al. (1992) attribute this to the location of a subsurface dissolved oxygen minimum

Table 8

Changes in fishing operation between 1961 and 1991

Mechanised vessels	1228 (1961)	12,223 (1991)
Potential fishing area	53 (inshore)	4,261 (1991)
Fish production	0.187 (1960–64)	0.634 (1990–94)
Potential yield for the continental shelf		1.5×10^6 t
Trawler catch		48.8%

layer. Altogether, estimated potential stocks in the Bay of Bengal EEZ are 1.106×10^6 t fish stocks, of which 0.0656×10^6 t are demersal (Somvanshi, 1998).

Brackish Water Fisheries

On the east coast off India there are several brackish water areas with a potential for fish farming. In West Bengal examples are the Hoogly estuary, in Orissa, Chilka Lake (790 km^2), in Andhra Pradesh several areas totalling about 0.2×10^4 km^2, and in Tamilnadu, Edaiyur and Lake Pulicat a total area of 461 km^2. In Lake Pulicat, the second largest lagoon of India, grey mullets (*Mugil cephalus* and *Liza macrolepis*) were cultured without supplementary feeding, yielding 617 kg ha^{-1} in 7 months in pens and 556 kg ha^{-1} in 10.5 months in cages (Prasadam and Kadir, 1988). Lake Pulicat supports large edible crabs and three species of penaeids, *Penaeus indicus, P. monodon* and *P. semisulcatus* which yield a total of about 500 tonnes annually (Sanjeevaraj, 1981). Potential also exists for culturing molluscs, particularly the clam *Meretrix casta* (Thangavelu and Sanjeevaraj, 1985). The green mussel *Mytilus viridis* occurs along the east coast and is ideally suited for rope culture because it tolerates wide fluctuations in salinity (Qasim et al., 1977). Annually three harvests are possible, yielding 181% return on investment.

Approximately 26% of the brackish water is under cultivation, with an annual yield of 0.2 million tons of shrimp. To meet demand, a potential annual production of 5.6 million tons of shrimp is required, though there is a targeted estimated production of 8 million tons. Of ten species of shrimp, the Tiger shrimp, Indian white shrimp and the Green tiger shrimp are cultured intensively, and requirements for shrimp seed tripled from 2.2 billion in 1992–93 to 6.8 billion in 1996–97.

POPULATIONS AFFECTING THE AREA

With increased industrialization there is rapid urbanization in certain regions of the East coast of India. The coastal population is about 55×10^6 and growing. Very few monitoring stations specifically for the marine environment exist here. The Central Pollution Control Board (CPCB) has declared North Arcot (Tamil Nadu), Visakhapatnam and Patancheru (Andhra Pradesh), Talcher (Orissa) and Howrah (West Bengal) as critically polluted from numerous industries. As an example, Tamilnadu has a 100-year-old tanning industry with 573 tanneries. More than 700 tonnes or 40% of the country's leather is processed, generating 25 tonnes of solid wastes and over 30 million l of effluents daily. The warning that they are an environmental threat came as early as in 1939. Some tanneries are trying to reduce the total dissolved salt to 4000 mg l^{-1} in the effluent, almost twice the permissible amount (2100 mg l^{-1}) set by the World Health Organization.

Coming from numerous sources, there are no precise estimates of the quality and quantity of pollutants entering the Bay of Bengal and baseline studies do not exist for this region. Strict enforcement of environmental laws becomes secondary when most locals are dependent on the local industries. Yet several coastal cities, particularly harbours, are experiencing environmental problems due to unrestricted disposal of treated or partially treated sewage, leading, on occasion, to the formation of H_2S and anoxia.

RURAL FACTORS

Shrimp Farming and its Collapse

On the east coast of India several areas are suitable for shrimp farming. In Andhra Pradesh with a 974-km coastline shrimp farming was modest around 1980. By 1990–91, 6000 hectares were used for shrimp farming which increased to 34,500 ha by 1994–95. Peak yield was 82,850 tonnes in 1993, fetching about $100 million. About 70,000 aquaculturists were employed on 200 farms, ranging from 0.4 ha to several hectares. It was hoped to generate $300 million by the turn of the century; the farm-raised shrimp harvest, often referred to as "dollar crop", constituted 30% of shrimp exported. Projected exaggerated claims are to increase the shrimp farms to 1.5 million ha in Andhra.

Big farms are intensive or semi-intensive monoculture farms. They are cement-lined, and their wastewater often cross-contaminates farms downstream. Shrimp are grown along with Roho, and Catla, though recently introduced Chinese Carp are taking over and are becoming a pest. In 1995, 76,589 ha in Andhra were rushed into shrimp culture, on fertile land traditionally used for cultivation of rice. However, during 1995–96 several shrimp farms were closed due to diseases. Nearly twenty viral shrimp diseases caused catastrophic outbreaks. Bacterial and fungal diseases, specifically White Spot Disease (WSD) and Brown Spot Disease (BSD) resulted in a heavy loss. Lack of a holistic scientific approach and severe lapses in the management policy led to the collapse of shrimp farming in Andhra. Cost-benefit analysis did not include the cost of environmental damage.

Heavy Metals, Pesticides

Hoogly River, a branch of the Ganges, is the most polluted in India. Large quantities of heavy metals particularly Hg, Cd and Pb enter, of which less than 9% are precipitated in the estuarine region, 45–50% at the river mouth, leaving 40% which reach the Bay (Qasim, 1998). Metal "hot spots" exist (e.g. Sasamul et al., 1987). Ganges and Brahmaputra river sediments also contain barium and radium (Carroll et al., 1993). The uranium in the Hoogly estuary ranges between 3.5 and 3.9 μg l^{-1}, the highest for any estuary (Somayajulu, 1994). At the sediment–water interface very likely 25% of the uranium in the estuary is removed into sediments (Somayajulu, 1994). The weighted mean uranium input from Mahanadi estuary is 36 t y^{-1} out of which 18.3% is in dissolved form (Ray et al., 1995). Most of the uranium input takes place during the NE monsoon season.

Persistent organochlorine residues occur in sediments and biota. Despite a ban on its usage, total DDT levels in the sediments ranged between 0.02 and 720 ng g^{-1} (Shailaja and Sarkar, 1992). Total DDT in zooplankton from Vellar estuary ranged from 1.2 to 47 ng g^{-1} (Rajendran et al., 1990) and from 0.04 to 2.38 ng g^{-1} in 14 species of fishes (Babu Rajendran et al., 1992). Assuming 2% of wet weight as dry weight, in the bottom-feeding fish total DDT ranged from 0.026 to 2.318 ng g^{-1} (Shailaja and Singbal, 1994). In blubber samples from dolphins netted in coastal waters of Porto Novo, total DDT was between 0.09 and 3.3 ng g^{-1} (Tanabe et al., 1993).

MINING, EROSION AND LAND FILL

Along the East coast of India, loss of crucial coastal habitats is a serious problem. A case in point is Chilka Lake—Asia's largest brackish water lagoon. Chilka Lake is a national concern because of heavy siltation, macrophyte growth and shrinkage. Nearly 100,000 fisher-folk earn a livelihood from Chilka Lake (Lakshmana Rao et al., 1994). During 1978 and 1987 more than 60 papers were published on the potential for aquaculture (Satpathy, 1992; Lakshmana Rao et al., 1994), but sadly lacking were holistic studies on the functioning of the ecosystem and its management. Since its origin around 3500 years BP, Chilka Lake has suffered a 50% reduction up to the beginning of the present century. A further reduction of about 255 km^2 took place between 1929 and 1988 due to soil erosion caused by active deforestation (Hema Malini et al., 1993). The estimated annual silt input is 30×10^6 tonnes contributed by alkaline soils of Daya and Bhargavi rivers (Mangala, 1989). In the 18 km stretch of shore between Gopalpur and Rushikulya river mouth, 2900 ha of sand dunes contain an estimated 230×10^6 t of heavy minerals, one of the world's largest deposits. The Orissa Sand Complex (OSCOM) has designed mining operations of 500 t h^{-1}, to produce annually 220,000 t ilemnite, 10,000 t rutile, 2000 t zircon, 4000 t monazite and 30,000 t sillimanite (Lakshmana Rao et al., 1994). The *Casuarina* and cashew plantations along the sand dunes prevent the migration of sand to agricultural fields, residential areas and the national highway.

Remote sensing studies have shown that 68% of the mangroves in Orissa state are in this area but that the mangals are getting depleted at a rate of 2 km^{-2} y^{-1} (Sarma and Wilsanand, 1994). In 1987 alone, 2000 ha of pristine mangrove land was brought under prawn culture, with an export target of 1500 tonnes. Areas up to 200 ha in one site were banded for reclamation of mangroves for shrimp culture, but ironically this failed due to acidification of the soil (Hatcher et al., 1989).

EFFECTS FROM URBAN AND INDUSTRIAL ACTIVITIES

Desalination Plants

To supply fresh water to villagers, several desalination plants have been built which use reverse osmosis to create 50–100 thousand m^3 fresh water each day (Qasim, 1998). Ironically in India—the land of rivers—clean potable water has become a scarce commodity. The effluent from desalination plants is discharged via an earthen canal to the sea. Salinity has increased in ground water and several wells due to seepage of brine (Rao et al., 1990).

Ocean Thermal Energy Plants

Due to chronic power deficiency, the Department of Ocean Development, Government of India has commissioned an Indian wave energy programme at Chennai. A 10 m wide module operates on the Oscillating Water Column principle, generates 150 kW (Ravindran, 1994). Under the Indian Ocean Thermal Energy Conversion (OTEC) Programme in collaboration with Sea Solar Power, USA, several thermal power plants (100 MW) probably will operate. The impact of thermal pollution on the biota needs to be evaluated, however, and thermal outfall from Ennore thermal power station near Chennai has had profound impacts on the hydrobiological conditions (Subrahmanian et al., 1990). It has elevated mean levels of temperature, nutrients and BOD and decreased pH and gross production.

Nuclear Power Station

For cooling purposes Kalpakkam Atomic Power Station near Madras uses coastal water which is chlorinated to 0.2 g l^{-1} to control biofouling. *Perna virisdis, Balanus reticulatus, Modiolus striatulus* still seem to cause severe blockage (Thiyagarajan et al., 1997), and to control this, shock chlorination is done that leaves 1.10 to 1.50 mg l^{-1} residual chlorine which adversely reduces (80–83%) primary production (Ahmed et al., 1993).

Mechanised Craft

On the East coast, mechanized trawling and bottom gillnets reduced catfish catches from 43.7 tonnes in 1972 to 17 tonnes by 1980–81 (Lakshmi and Srinivasa Rao, 1992). *Arius tenispinis* which once contributed 61% of the catfish catch disappeared by 1984 (Roy, 1997). For the collective good, the fishing communities recently banned the use of a new kind of fishing gear, a snail net, in spite of its profitability (Bavinck, 1996).

Shipping Impacts: Exotic Biota Introductions

Faunal surveys in the Indian seas, initiated by the British naturalists in 1878 and subsequently continued by local researchers, have made the fauna and flora in the Bay of

Bengal quite well known. However, in recent years several species were reported to occur for the first time (Subba Rao et al., unpublished). These include the polychaete *Sigambara tentaculata* (Achari, 1975) and the pelecypod *Mytillopsis sallei* (Rao and Rao, 1975) which now seem to flourish. These have fully established themselves in Visakhapatnam harbour where they are pests. The commercially important wood-boring isopods *Limnoria insulae, L. unicornis, L. platycauda* (Ganapati and Lakshmana Rao, 1960) and the pelycypod *Xylophaga mexicana* (Ganapati and Lakshmana Rao, 1961) are also new records from the Bay of Bengal. Some of these taxa occur in the West Atlantic, Pacific, Hawaii and the Mediterranean, Madagascar, Malayan Archipelago and could be considered truly exotic.

These may have been introduced via ballast water. Since 1947 (post-independence) the nation has been advancing industrially, and with it the sea trade. It was even necessary to construct a new port, Paradeep, to meet shipping demands. Besides ballast water and sediments, other possible dispersal vectors of exotic organisms are the scrapings of fouling organisms resulting from maintenance and dry-docking operations. There are several ecological impacts of these invaders. They may out-compete the native fauna and flora for resources, colonize, and cause shifts in populations. This in turn will cause changes in the trophodynamics of the ecosystems, leading to elimination of desirable species and the newly introduced pests may prevail, as in the temperate seas (Carlton and Geller, 1993; Subba Rao et al., 1994).

Marine Pollution

Several rivers contribute to the pollutants in the Bay of Bengal; its coastal zone is used as a receptacle for a variety of pollutants i.e. domestic sewage, agricultural wastes and pesticides, petroleum hydrocarbons and PCBs, and heavy metals. Nearly 357 MT of Gulf oil are transported along the EEZ of India, around Sri Lanka, southern Bay of Bengal to the Far East and Japan (Qasim, 1998). In the Bay of Bengal, north of 10°N, during 1978 to 1980, 61 oil slicks were sighted and floating tar ranged between 0–69.75 mg m^{-2} with a mean of 1.52 mg m^{-2} (Qasim, 1998). Besides bilge washings, damaged oil tankers contribute to large oil slicks and floating tar in the Bay of Bengal (Sen Gupta et al., 1995). Due to an oil spill from the Danish VLCC Maersk Navigator, in the Andaman Sea, dissolved petroleum hydrocarbon levels ranged between 0.31 and 1.85 $\mu g\, l^{-1}$ (Sen Gupta et al., 1995).

PROTECTIVE MEASURES

Central Pollution Control Boards (CPCB) and State Pollution Control Boards are responsible for enforcement of Acts for Prevention and Control of Pollution of Water (1974, 1977) and Environmental Protection Act (EPA, 1986). Laws for the prevention and abatement of pollution were adopted in 1992. Guidelines for technical support, training awareness programmes, waste minimization measures and promotion of clean technologies are provided. During 1997–98, 332 EPA projects were reviewed, 186 projects were granted site clearance and those concerned with water were mostly with fresh water resources. Under the Coastal Ocean Monitoring and Prediction Systems (COMAPS) along the Indian Coast 77 locations are now monitored. Of these, 32 are declared "hot spots" and were referred to State Pollution Control Boards. The Andaman and Nicobar Center for Ocean Development (ANCOD) is set up to monitor coastal ocean pollution, coral reef rejuvenation and enhancement of marine living resources through sea ranching and sea farming.

Public Awareness

Some of the developmental activities have resulted in environmental and socio-economic problems which have become issues of public concern and protest. In a few rare cases, regulatory measures were developed, for example the successful halting of the construction of a fishing jetty near Orissa which could have been a threat to the Olive Ridley sea turtle. About 50,000 Olive Ridleys (*Lepidochelys olivacea*) use 35 km of this sandy beach during December–January and March–April for nesting. These turtles enjoy protection under IUCN. Also, a major prawn farming venture in the periphery of Chilka Lake that would have necessitated clearance of prime mangrove forest was halted due to public pressure.

Diseases associated with shrimp farming on the East coast have cast long socio-economic shadows. Agitation by affected shrimp fishermen, championed by environmentalists in Tamil Nadu, Andhra Pradesh and Orissa, culminated in a few interim orders by the Indian Supreme Court on 11 December 1996. These include: (a) no shrimp farm may be placed within 500 m from high tide mark; (b) traditional and improved farmers are exempted; (c) any farm within 500–1000 m zone should be demolished; (d) a Government authority will enforce preparatory principles and the "polluter pays" principle; (e) fixed compensation for environmental damage, and (f) retrenched workers shall be compensated. Consequences of the above judgement are far reaching.

NEW MILLENNIUM: NEED FOR EAST COAST ZONE MANAGEMENT AUTHORITY

The key requirement for the management of the Bay of Bengal coastal waters is massive education of the public, mitigation measures and the need for conservation of resources and sustainable development. Various user agencies, advisory groups, joint task forces, and recognized NGOs should publicize that no coastal project will succeed without the willing participation and cooperation of the coastal communities. Cyclone and flood disaster mitigation is of prime importance. The large-scale alteration of the coastline due to human activity and the monsoons will raise the sea-level which will have serious impact. This expected sea-level rise (SLR) will submerge low-lying tracts of the Sunderbans and Chilka Lake. It may also enhance the frequency and magnitude of damaging storm surges, erosion of sandy shores away from river mouths, spread of saline waters in low-lying coastal lands and other effects of economic importance. Mangroves may flourish under rising sea level, but their wanton destruction in recent years may deprive the coast of defence against storms (Lakshmana Rao et al., 1994). The constitution of a coastal zone management authority and development of a regional scientific program to study the functioning of the ecosystems are essential.

DEDICATION

I dedicate this paper to the memory of the late M.V. Lakshmana Rao, my good friend, philosopher and a naturalist with a commitment to the coastal environment.

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