

CHAPTER 3

Hydrography

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HYDROGRAPHY

3.1 General oceanographic setting of the Indian Ocean

The northern Indian Ocean which is situated to the north of 10°S exhibits a unique oceanographic feature contrary to its counterparts, the north Atlantic and the north Pacific Oceans. It lies in the tropics below 30°N and is land-locked on the northern side hindering the source of deep convection of the cold waters of polar origin. The northern Indian Ocean experiences the semiannually reversing monsoon winds blowing from NE during December-February (NE monsoon) and SW during June-September (SW monsoon). Besides, there are intermonsoon periods in between the monsoons characterized by weak and variable winds and intense summer heating in May and mild heating during October. The surface circulation patterns of the Indian Ocean closely resembles that of the world oceans i.e., the Atlantic and the Pacific Ocean during boreal (Northern Hemisphere) winter season. However, it undergoes a drastic change during boreal summer when the circulation to the north of the equator is largely controlled by the prevailing winds (Shankar et al., 2004). The circulation pattern in the southern tropical Indian Ocean is characterized by a subtropical anticyclonic gyre (Wyrki, 1971).

Since the Bay of Bengal is a semi-enclosed basin in the North Indian Ocean, the seasonally reversing monsoon winds affect the Bay of Bengal circulation significantly (Cutler and Swallow, 1984; Hastenrath and Greischar, 1989). The above characteristics of the Bay and also its proximity to the equator together with immense quantity of fresh water influx from the rivers contribute to the formation of a highly complex circulation system.

The wind pattern over the Bay of Bengal is southwesterly during the northern summer which switches over to northeasterly during the northern winter (Figs. 3.1a and b). During the boreal winter (November-February), the dry northeasterly winds are coupled with cooling and evaporation. During the summer, the southwesterly winds are coupled with heating, precipitation, with

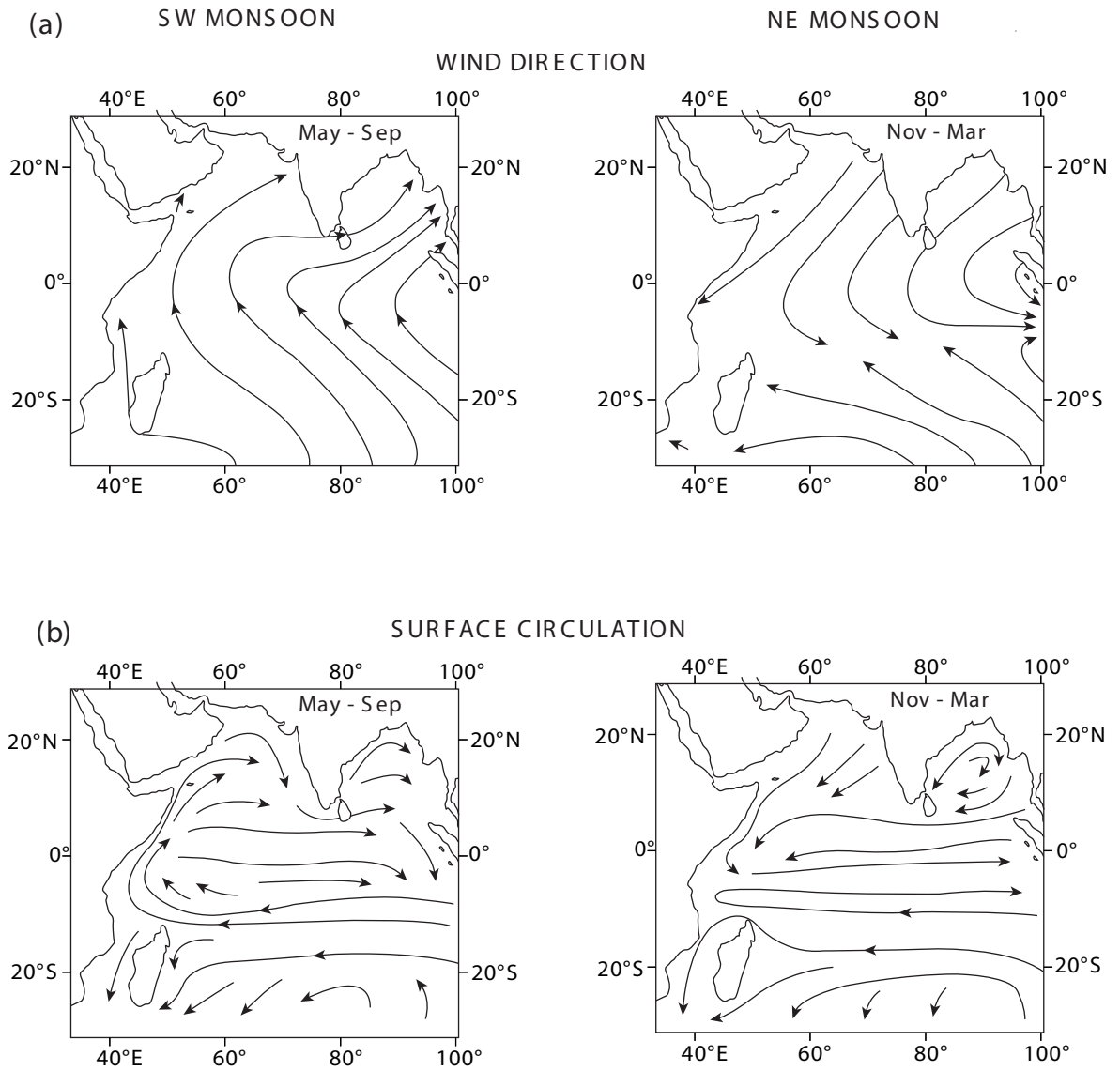


Fig. 3.1. (a) Mean surface wind direction (top panel) and (b) surface circulation (bottom panel) in the tropical Indian Ocean during the southwest (left panel) and northeast (right panel) monsoons.

an increased freshwater run off into the northern Bay (Varkey et al., 1996). During the boreal winter, the winds blow from the high pressure region over the Asian continent into the Bay of Bengal in a southwesterly direction which are strongest in December with an average speed of 5 ms^{-1} attaining a maximum speed of 6 ms^{-1} over the central western Bay (Hastenrath and Lamb, 1979). The highest wind velocities prevail along 6°N during January (Potemra et al., 1991). While, the winds are weak with variable magnitudes during March-April (NE-SW intermonsoon). During this period, an anticyclonic wind field is developed over the Bay with westerlies (eastward blowing winds) along the equator and easterlies (westward blowing winds) between 5°N and 10°N . In May, the winds are predominantly southwesterly, over the entire Bay of Bengal. This wind pattern intensifies by July attaining maximum velocities of 10 ms^{-1} over the central Bay. Generally, the SW monsoon lasts for four months from June to September. Following the summer monsoon, the winds during SW-NE intermonsoon (October – November) are weak and variable.

During the NE monsoon, the Northeast Monsoon Current (NMC) is developed between Equator and 10°N and flows westwards (Fig. 3.2a). Under the influence of the southeast trade winds, the South Equatorial Current (SEC) is developed and flows westwards between 20°S and 10°S throughout the year. The SEC gets divided and deflected upon reaching the African coast. During the NE monsoon, the SEC on reaching the African coast flows southwards as the Mozambique Current and northward as the East African Coastal Current (EACC). The eastward flowing Equatorial Counter Current (ECC), is fed by the EACC from the south and from the southward flowing Somali Current (SC) along the African coast. The ECC is observed between 10°S and equator during the NE monsoon season. During the SW monsoon, the NMC reverses and flows towards east combining with the eastward flowing ECC and the entire eastward flow from 15°N to 7°S is called the Southwest Monsoon Current (SMC) (Fig. 3.2b). The Somali Current now flows northward along the coast as the western boundary current under the influence of strong SW monsoon winds.

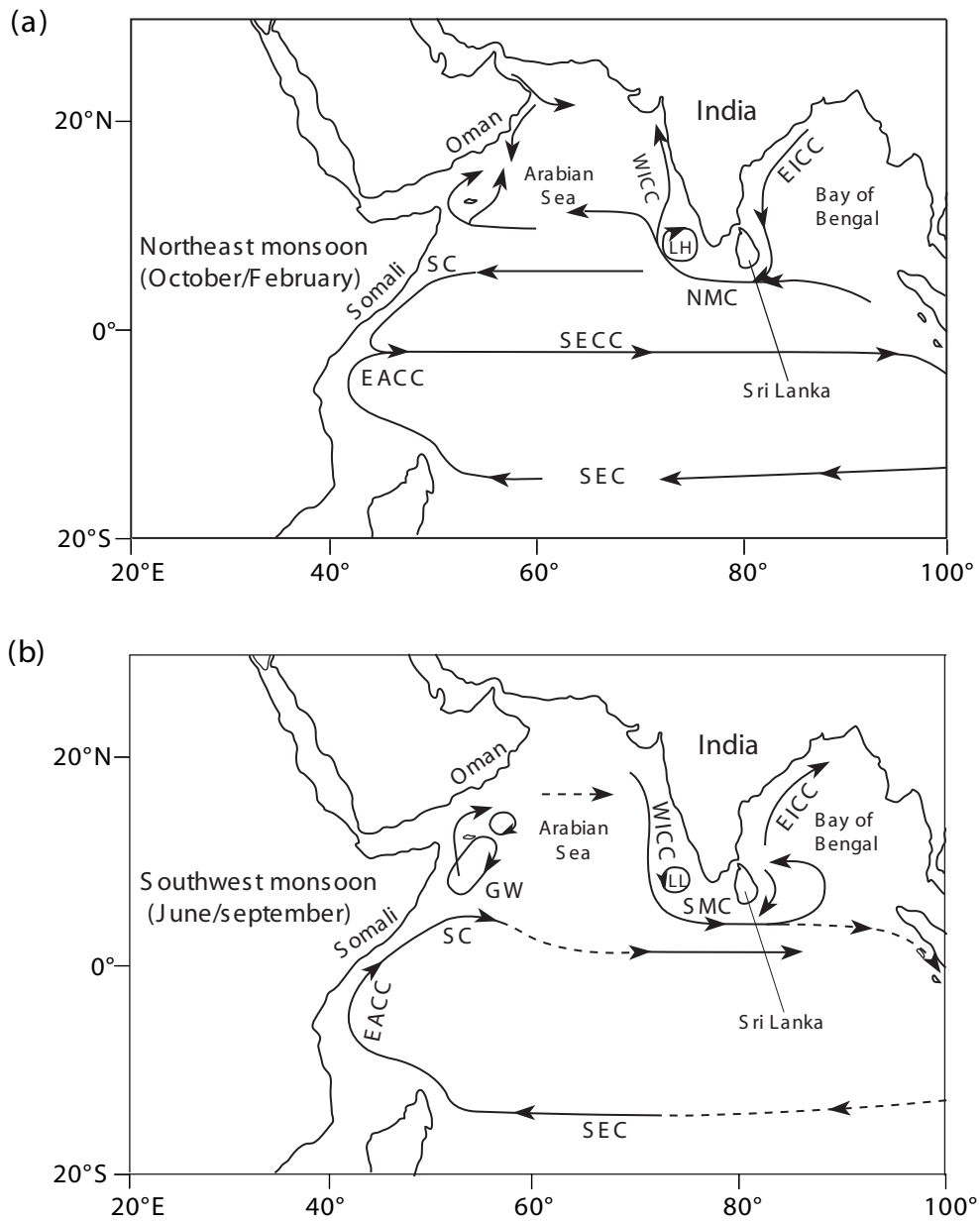


Fig.3.2. A schematic representation of Current patterns of the Indian Ocean during (a) Northeast monsoon and (b) Southwest monsoon. Abbreviations for the different currents indicated are: South Equatorial Current (SEC), South Equatorial Countercurrent (SECC), Southwest and Northeast Monsoon Current (SMC and NMC), Somali Current (SC), East African Coast Current (EACC), Great Whirl (GW), West Indian Coastal Current (WICC), East Indian Coastal Current (EICC) Lacadive High and Low (LH and LL) (after Schott and McCreary, 2001).

During the intermonsoons, strong (>1 m/s) eastward flowing equatorial jets, also popularly known as *Wyrтки jets* (Wyrтки, 1973), develop along the equator during April-May and October-November. These equatorial jets transport both heat and salt from the western basin to the eastern basin in the equatorial Indian Ocean.

3.2 General hydrographic setting of the Bay of Bengal

The Bay of Bengal (north eastern part of the Indian Ocean) is essentially a tropical one lying to the south of 22°N and is bordered by Sri Lanka, India, Bangladesh, Myanmar and the Andaman-Nicobar-Sumatra Islands.

The Bengal Fan floors the entire deep Bay and from 20°N the fan extends southward as far as 3000 km to south of the equator (Curry and Moore, 1971). Nath et al. (1989) have also reported the Bengal Fan extending as far as 8°S . The most prominent bathymetric high in the Bay of Bengal is the Ninety East Ridge. The Bay of Bengal receives enormous quantity of fresh water and sediment input from some of the world's largest rivers. The Ganges, the Brahmaputra, the Irrawaddy and the Godavari rivers are the four major rivers flowing into the Bay of Bengal, which discharge annually approximately $1.5 \times 10^{12} \text{ m}^3$ of fresh water into the Bay (Martin et al., 1981) compared to $0.3 \times 10^{12} \text{ m}^3\text{yr}^{-1}$ in the Arabian Sea (Subramanian, 1993). The enormous fresh water discharges from the rivers (Fig. 3.3) cause changes in the surface salinity of the Bay of Bengal over a wide range of values both seasonally and geographically (La Violette, 1967; Wyrтки, 1973; Ittekkot et al., 1985; Murty et al., 1990; Varkey et al., 1996). The oceanic precipitation results in salinity gradient in the upper layers (annual mean salinity is below 34). The large influx of fresh water brought in by the rivers Ganges and the Brahmaputra has a combined peak discharge of approximately $70 \times 10^3 \text{ m}^3\text{s}^{-1}$ in the month of August (Emery and Aubrey, 1989; Murty et al., 1992) forming a strongly stratified near-surface layer. The northern Bay of Bengal, which receives highest rainfall in the World Ocean, results in large amplitudes of seasonal variation of surface water salinity in the open ocean (Levitus, 1986). The physiographical conditions of South Asia are such that most of the land

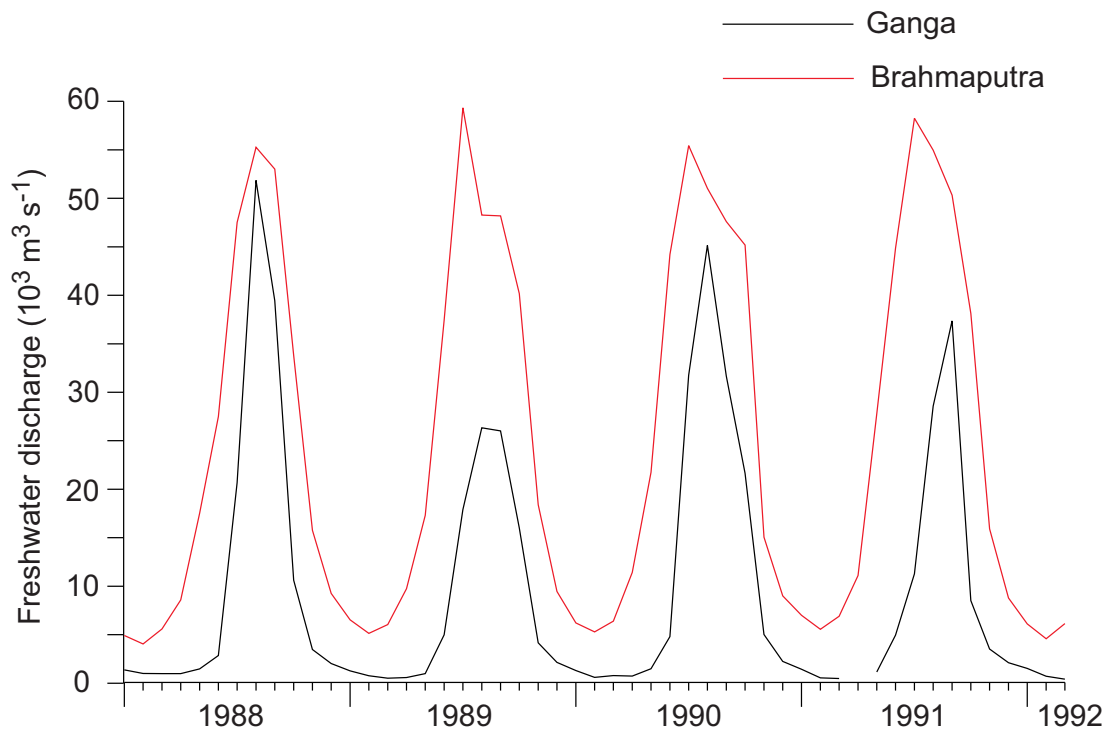


Fig. 3.3. Monthly water discharge of the rivers Brahmaputra and Ganges for the period January 1988-March 1992. Data provided by the the Global Runoff Data Centre, Federal Institute of Hydrology, Koblenz/Germany.

drainage during the SW monsoon is diverted into the Bay of Bengal, especially into the northern Bay, thus the land drainages have an even greater impact on the upper ocean salinity in the northern Bay than the oceanic rainfall.

Annually about 2×10^9 tons of sediment enters the Bay of Bengal with a major input from the major rivers draining through the Himalayas (Milliman and Meade, 1983), which exhibit seasonal variability with a peak discharge during SW monsoon. Besides, terrigenous material is also contributed into the Bay of Bengal by the peninsular Indian rivers such as the Mahanadi, the Godavari, the Krishna and the Cauvery, with a peak discharge occurring during the later phase of the SW monsoon (Schäfer et al., 1996). The suspended sediment discharge into the Bay is estimated to be about 1.4×10^9 tons compared to about 200×10^6 tons supplied in to the Arabian Sea. During the SW monsoon favorable winds and currents induce moderate upwelling along the east coast of India, despite the river runoff may partially compensate the offshore movement of surface water. The NE monsoon winds over the Bay of Bengal are relatively weaker than SW monsoon.

3.3 Circulation patterns in the Bay of Bengal

The annual variation (January to December) of ship drift surface currents (Mariano et al., 1995) between Equator and 24°N in the Bay of Bengal is shown in Figs. 3.4, 3.5 and 3.6.

a) NE monsoon (December-February)

During December, an equatorward surface current is well developed along the east coast of India under the influence of northeasterlies (Fig. 3.4a). This current is designated as the East India Coastal Current (EICC) (McCreary et al., 1993; Shankar et al., 1996) which continues to flow southward and eventually feeding the westward flowing NMC or Winter Monsoon Current (WMC). The WMC carries low salinity water ($S < 34$) that spreads as a tongue into the Arabian Sea (Wyrski 1971). A cyclonic circulation cell is noticed in the interior of the Bay of Bengal.

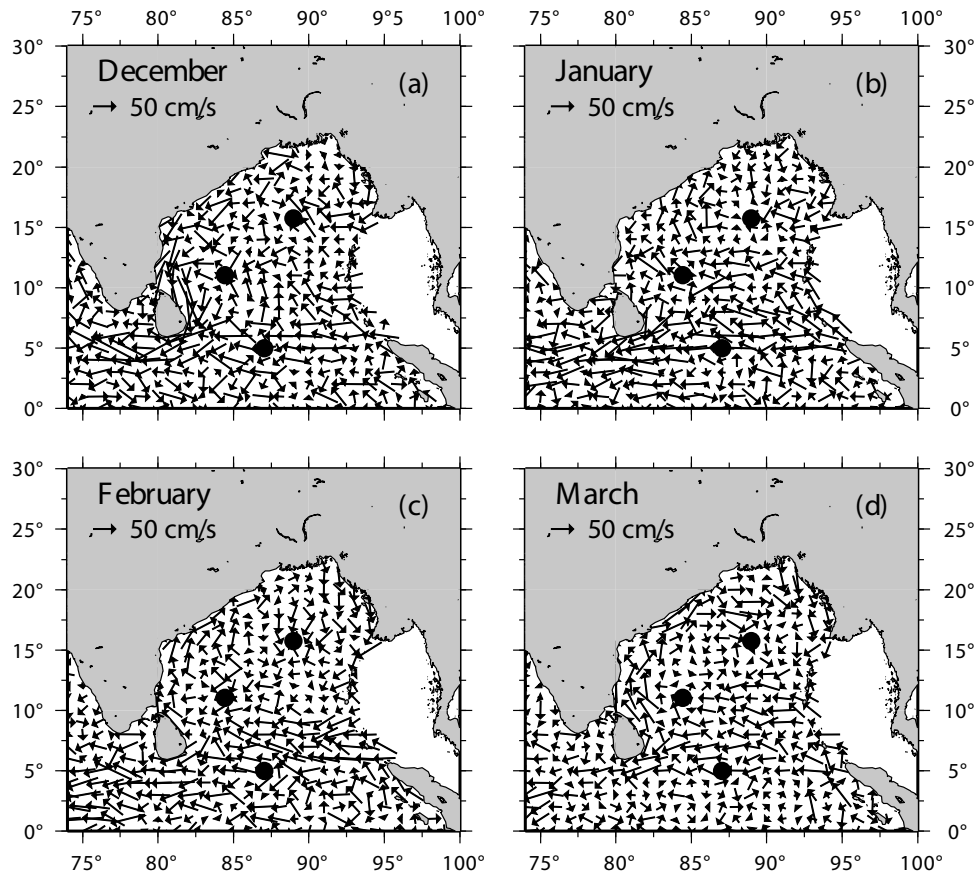


Fig. 3.4. Monthly mean ship drifts (cm/s) during (a) December, (b) January, (c) February and (d) March (after Mariano et al., 1995).

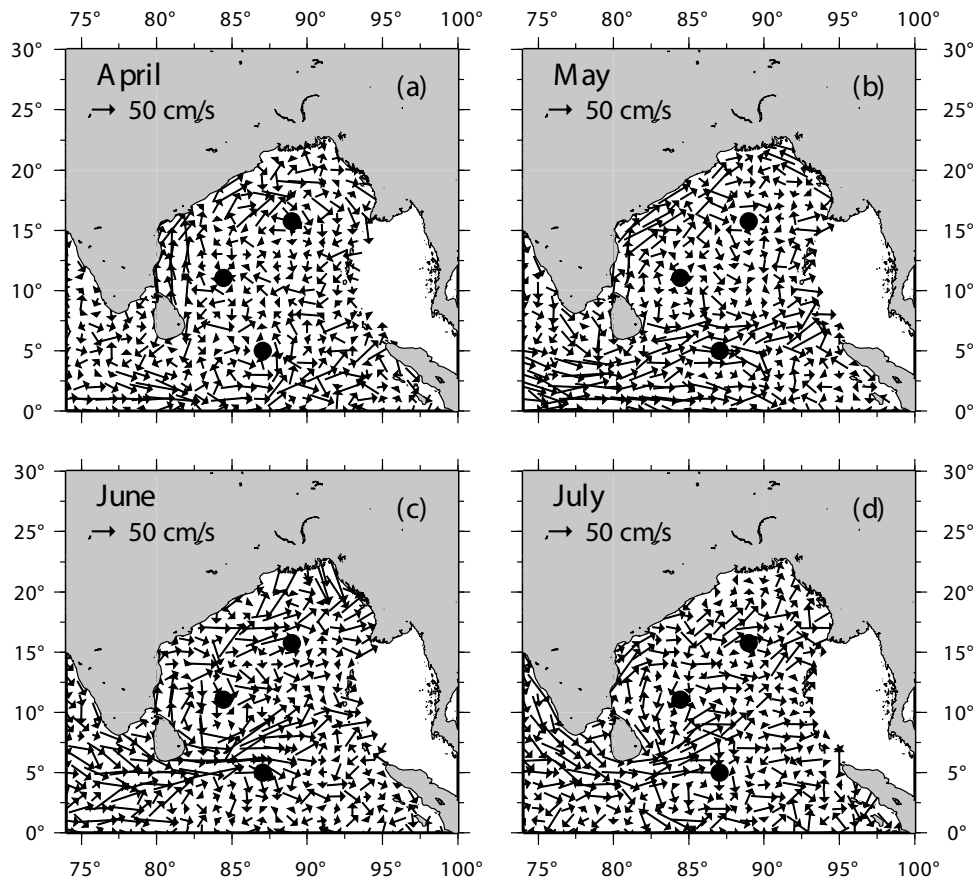


Fig. 3.5. Monthly mean ship drifts (cm/s) during (a) April (b) May (c) June and (d) July (after Mariano et al., 1995).

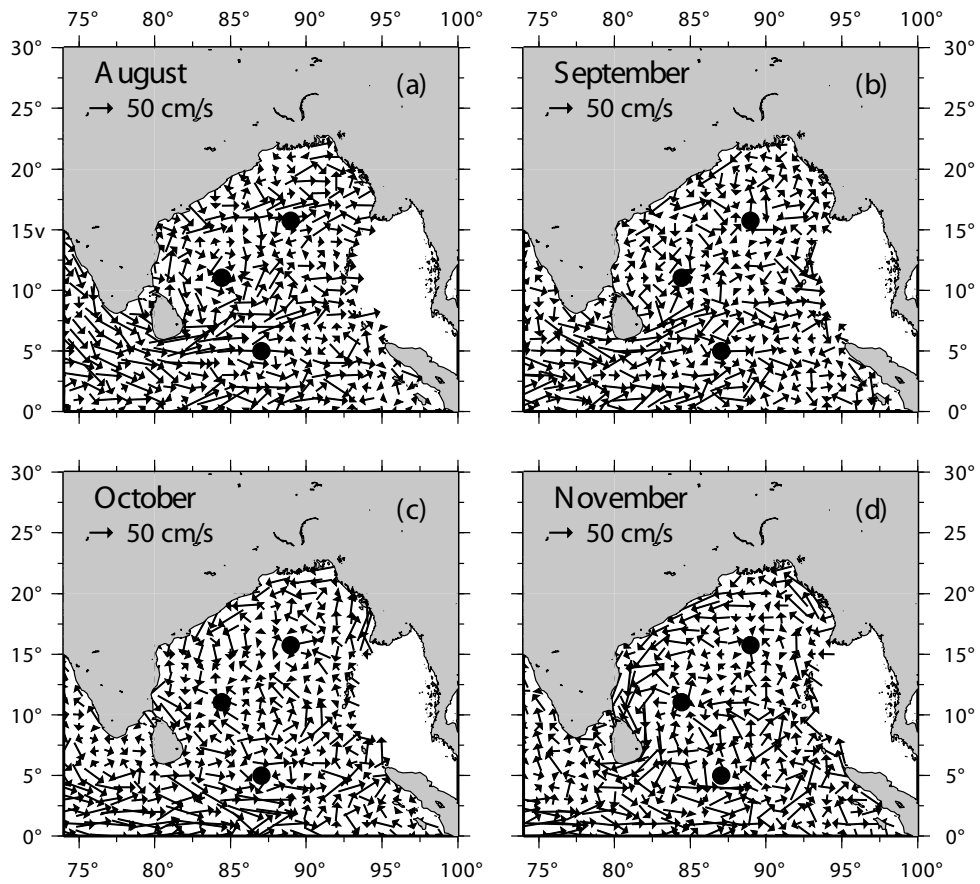


Fig. 3.6. Monthly mean ship drifts (m/s) during (a) August (b) September (c) October and (d) November (*after* Mariano et al., 1995).

During January, the strength of the EICC ceases rapidly and the WMC south of Sri Lanka is developed from the east south of 8°N (Fig. 3.4b). The cyclonic circulation cell in the interior of the Bay of Bengal in December weakens and moves towards the west and north.

During February, the surface currents along the east coast of India exhibit a reversal from the equatorward flowing EICC to the poleward flowing EICC (Legeckis, 1987; Shetye et al., 1993; Murty et al., 1993; Babu et al., 2004) (Fig. 3.4c). The interior cyclonic circulation cell replaces with an anticyclonic cell centered at 16°N, 87°E, which forms all over the basin between 9°N and 20°N. This change in surface circulation is attributed to the remote forcing from the equatorial region rather than changes in the local wind field (McCreary et al., 1993). Similarly, Legeckis (1987) also reported the appearance of the poleward flowing western boundary current in the Bay of Bengal from the satellite image of sea surface temperature (SST).

b) NE-SW intermonsoon (March-May)

During March, the poleward flowing EICC strengthens all along the east coast of India (Fig. 3.4d). Babu et al. (2004) described this as the seasonal (WBC) of the Bay. This BC forms the western part of two anticyclonic gyres centered at 11°N and 16°N. The flow south of Sri Lanka is seen reversing eastward.

During April, the pole ward flowing EICC is still evident all along the east coast and also the anticyclonic gyre in the interior of the Bay (Babu et al., 2004) (Fig. 3.5a). South of Sri Lanka the eastward flow forms a part of the SMC.

During May, with the onset of summer monsoon, the two anticyclonic gyres in the interior of the Bay during March-April merge together to form a large anticyclonic circulation cell that reaches from the Indian coast to the Andaman Islands (Fig. 3.5b). The SMC south of Sri Lanka continues to flow eastward as far as Sumatra coast.

c) SW monsoon (June-September)

During June, the EICC weakens and reverses its flow equatorward in the northern part (Fig. 3.5c). A cyclonic circulation cell is seen in the south eastern Bay of Bengal, which is fed by the eastward flowing SMC. However, anticyclonic circulation continues in the western Bay of Bengal.

During the peak of SW monsoon (July-August), the equatorward flowing EICC persists in the northern part (Figs 3.5d and 3.6a). Gopalakrishna and Sastry (1985) reported a southerly current in the northwestern Bay of Bengal during August. Further studies based on the hydrographic data during the SW monsoon documented that the circulation in the western Bay consists of alternating meso-scale cyclonic and anticyclonic cells (or eddies) (Murty et al., 1992; Varkey et al., 1996). From the hydrographic observations, Shetye et al. (1991) showed that the coastal circulation consists of two cyclonic eddies centered near 15°N and 18°N with southward flow near the coast and northward flow in between the two features. The SMC flows into the Bay in the northeasterly direction up to 12°N. The SMC passes through the Southern Bay of Bengal Sediment Trap (SBBT) location during the SW monsoon during May-August and similarly the Northern Bay of Bengal Sediment Trap (NBBT) comes under the influence of the eastward flowing current during the same period.

During September, the SW monsoon weakens and the EICC flows equatorward almost the entire length of the Indian coast (Fig. 3.6b). The northern cyclonic gyre develops further south and the southern cell is hardly visible any more. The flow south of Sri Lanka continues towards east and the SMC still persists in the southern Bay of Bengal.

d) SW-NE intermonsoon (October-November)

During October, a westward flow is developed in the northern Bay and feeds the equatorward flowing EICC, which is seen almost all along the entire east coast (Fig. 3.6c). It is also seen further south in the southern Bay of Bengal, but with decreased magnitude. A basin wide cyclonic circulation is evident west of the arc of the Andaman Island (Murty et al., 1993;

Suryanarayana et al., 1993) and feeds the EICC along the east coast of India. The EICC is relatively strong off the southeast coasts of India and Sri Lanka.

During November, a basin-wide cyclonic circulation west of the arc of the Andaman Islands persists (Murty et al., 1993; Suryanarayana et al., 1993) (Fig. 3.6d). The EICC continues to flow southward from north of 20°N to the east coast of Sri Lanka, with increased strength from 0.5 ms⁻¹ at 20°N to more than 1 ms⁻¹ at 8°N (Eigenheer and Quadfasel, 2000).