

# The monsoon currents in the north Indian Ocean

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## Abstract

The monsoon currents are the seasonally reversing, open-ocean currents that flow between the Arabian Sea and the Bay of Bengal, the two wings of the north Indian Ocean. The Summer Monsoon Current (SMC) flows eastward during the summer monsoon (May–September) and the Winter Monsoon Current (WMC) flows westward during the winter monsoon (November–February). We assemble data on ship drifts, winds and Ekman drift, and geostrophic currents derived from altimetry and hydrography to describe the observed climatological seasonal cycle of the monsoon currents. We then use an Oceanic General Circulation Model (OGCM) to simulate these currents and estimate their transports, and a  $1\frac{1}{2}$ -layer reduced-gravity model to investigate the processes that force them.

The monsoon currents extend over the entire basin, from the Somali coast to the eastern Bay of Bengal. They do not, however, come into being, or decay, over this entire region at a given time. Different parts of the currents form at different times, and it is only in their mature phase that the currents exist as trans-basin flows.

The westward WMC first forms south of Sri Lanka in November and is initially fed by the equatorward East India Coastal Current (EICC); the westward WMC in the southern bay appears later. In its mature phase during December–March, the WMC flows westward across the southern bay; it divides into two branches in the Arabian Sea, one branch flowing westward, the other turning around the Lakshadweep high (a sea-level high off southwest India) to flow into the poleward West India Coastal Current (WICC). The WMC is primarily a geostrophic current, with Ekman drift modulating it.

The eastward SMC first appears in the southern bay during May. In its mature phase, which peaks with the summer monsoon in July, the SMC in the Arabian Sea is a con-

tinuation of the Somali Current and the coastal current off Oman. It flows eastward and southeastward across the Arabian Sea and around the Lakshadweep low (a sea-level low off southwest India), eastward south of Sri Lanka, and into the Bay of Bengal. The strong winds during the summer monsoon ensure that Ekman drift dominates at the surface, leading to a more complex vertical structure in the SMC than in the WMC. In the depth-averaged flow over 50 m, the mature phase of the SMC extends from May to September.

The numerical experiments show that the dynamics of the north Indian Ocean on seasonal time scales is explicable by linear wave theory. Circulation at any point is decided by both local forcing and remote forcing, whose signals are carried by equatorial and coastal waves. Superimposed on the currents associated with these waves is the local Ekman drift. The geostrophic component of the monsoon currents is forced by several processes. In the Bay of Bengal, the monsoon currents are forced by Ekman pumping and by the winds in the equatorial Indian Ocean. In the eastern Arabian Sea, the major forcing mechanisms are the winds along the east and west coasts of India and Sri Lanka; these processes link the parts of the SMC in the Arabian Sea and the bay during the summer monsoon, and of the WMC early during winter. Ekman pumping in the central Arabian Sea and off the Somali coast force the monsoon currents in the central and western Arabian Sea, with the Rossby waves radiated from the Indian west coast also playing a role. Therefore, the monsoon currents consist of several parts, each of which is forced by one or more processes, which act in concert to produce the continuous currents seen flowing across the breadth of the north Indian Ocean.

*Key words:* Summer Monsoon Current. Winter Monsoon Current. Coastal Kelvin wave. Equatorial Kelvin wave. Equatorial Rossby wave. Tropical Oceanography. Arabian Sea. Bay of Bengal. Equatorial Indian Ocean.

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# 1 Introduction

The winds over the Indian Ocean north of 10°S reverse direction twice an year (Fig. 1). Over the north Indian Ocean, they generally blow from the southwest during May–September (summer monsoon) and from the northeast during November–February (winter monsoon), March–April and October being the months of transition with weak winds. The winds are much stronger during the summer monsoon than during the winter monsoon. These seasonally reversing monsoon winds over the north Indian Ocean force a seasonally reversing circulation in the upper ocean (see the schematic in Fig. 2).

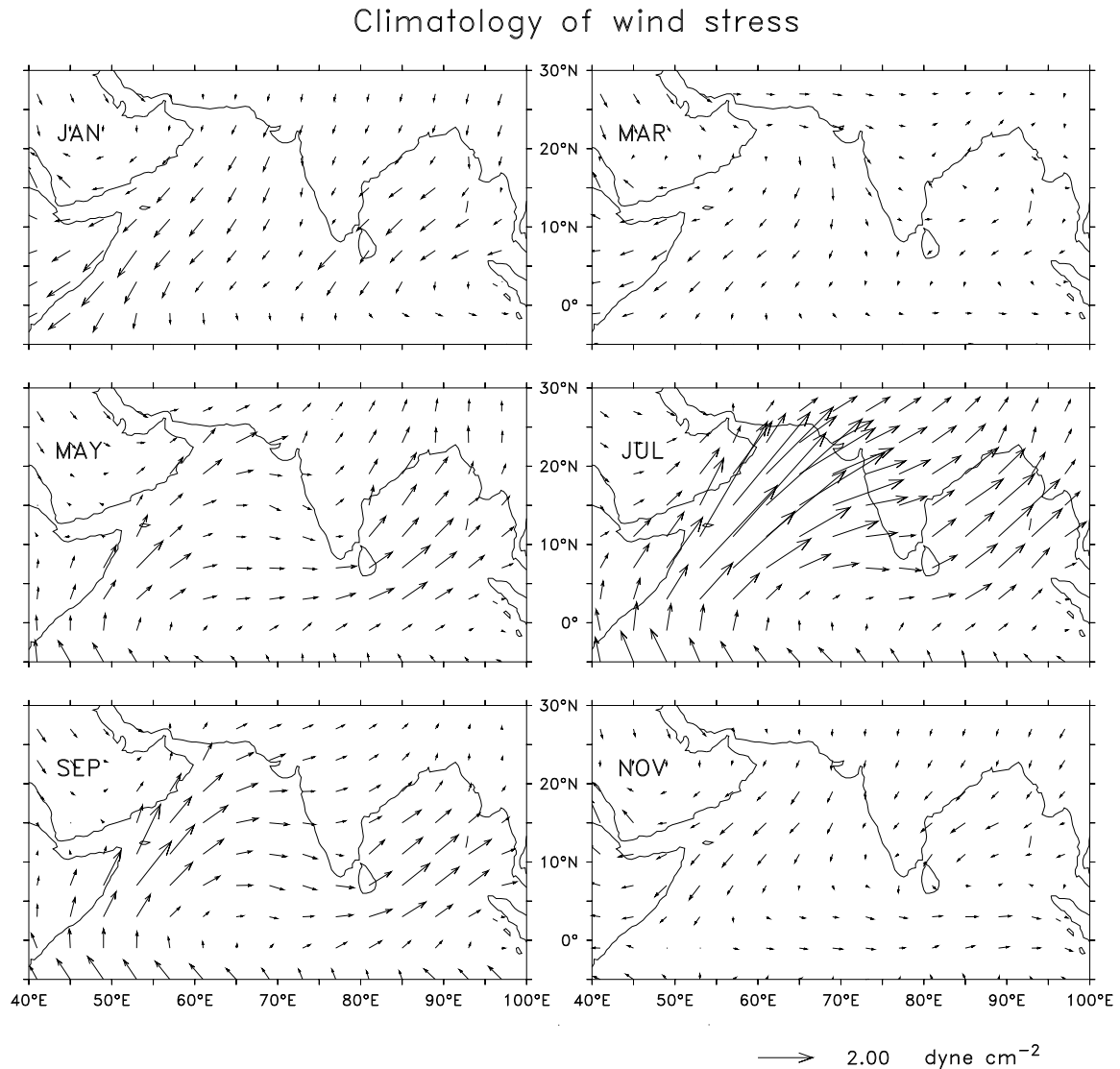


Fig. 1. Wind stress (dyne cm<sup>-2</sup>) from the climatology of Hellerman and Rosenstein (1983).



The best studied of the seasonally reversing currents are the Somali Current, which flows poleward (equatorward) along the coast of Somalia during the summer (winter) monsoon (see the reviews by Schott, 1983; Shetye and Gouveia, 1998; Schott and McCreary, 2001, and the many references therein), and the current along the equator (called Equatorial Current in this paper), where eastward surface jets are

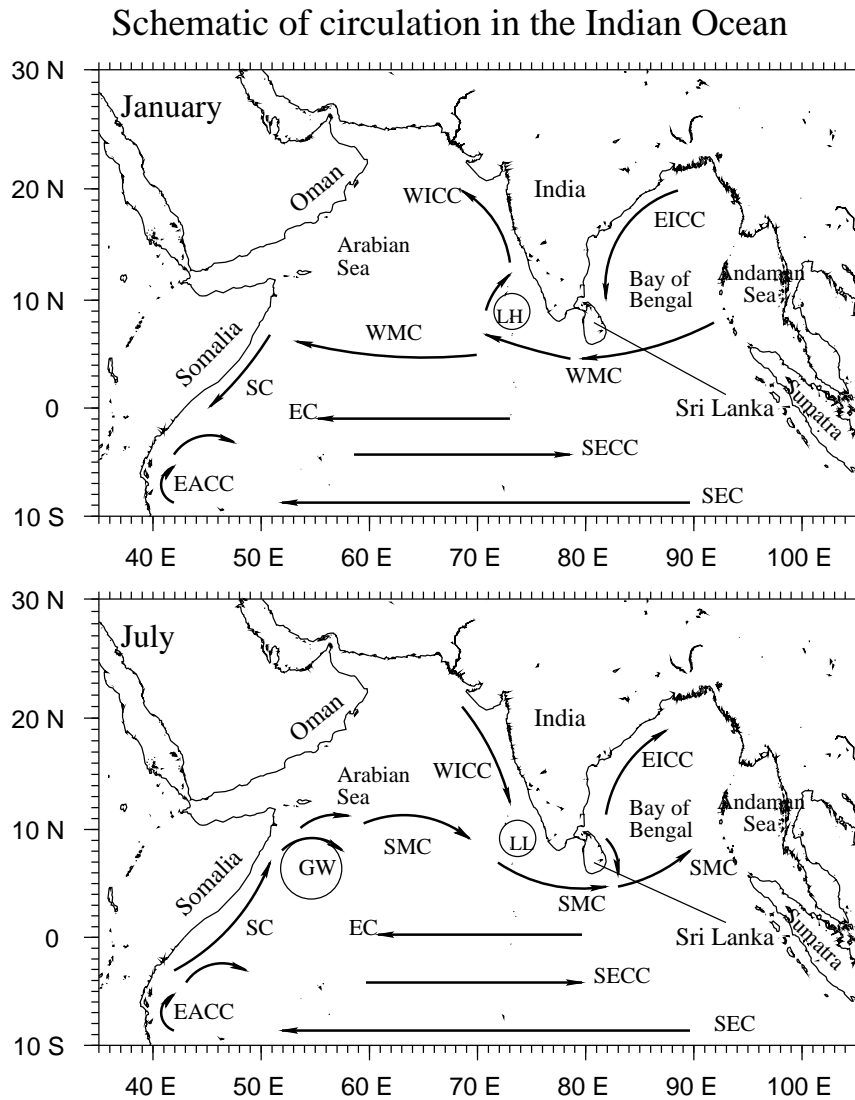


Fig. 2. Schematic representation of the circulation, as described in the literature, in the Indian Ocean during January (winter monsoon) and July (summer monsoon). The abbreviations are as follows. SC, Somali Current; EC, Equatorial Current; SMC, Summer Monsoon Current; WMC, Winter Monsoon Current; EICC, East India Coastal Current; WICC, West India Coastal Current; SECC, South Equatorial Counter Current; EACC, East African Coastal Current; SEC, South Equatorial Current; LH, Lakshadweep high; LL, Lakshadweep low; and GW, Great Whirl.

observed during April–May and October–November (see, for example, Wyrski, 1973a; O’Brien and Hurlburt, 1974; Reverdin, 1987; Jensen, 1993; Han, McCreary, Anderson, and Mariano, 1999; Schott and McCreary, 2001, and the many references therein). In the last decade, however, other coastal currents have also received attention. These include the currents along the east coast of India, called the East India Coastal Current (EICC) (Shetye, Shenoi, Gouveia, Michael, Sundar, and Nampoothiri, 1991b; Shetye, Gouveia, Shenoi, Sundar, Michael, and Nampoothiri, 1993; Shetye, Gouveia, Shankar, Shenoi, Vinayachandran, Sundar, Michael, and Nampoothiri, 1996; Shankar, McCreary, Han, and Shetye, 1996; McCreary, Kundu, and Molinari, 1993; McCreary, Han, Shankar, and Shetye, 1996; Vinayachandran, Shetye, Sengupta, and Gadgil, 1996; Shetye and Gouveia, 1998; Schott and McCreary, 2001), the current along the west coast of India, called the West India Coastal Current (WICC) (Shetye, Gouveia, Shenoi, Sundar, Michael, Almeida, and Santanam, 1990; Shetye, Gouveia, Shenoi, Michael, Sundar, Almeida, and Santanam, 1991a; McCreary et al., 1993; Stramma, Fischer, and Schott, 1996; Shankar and Shetye, 1997; Shetye and Gouveia, 1998), and the current along the Arabian-Sea coast of Oman (McCreary et al., 1993; Shetye and Gouveia, 1998; Böhm, Morrison, Manghnani, Kim, and Flagg, 1999; Shi, Morrison, Böhm, and Manghnani, 2000; Schott and McCreary, 2001). There are no observational studies of the coastal current along the eastern boundary of the Bay of Bengal. Apart from these coastal currents, the most significant large-scale currents known in the north Indian Ocean are the open-ocean, seasonally reversing monsoon currents. During the summer monsoon, the monsoon current flows eastward as a continuous current from the western Arabian Sea to the Bay of Bengal; during the winter monsoon, it flows westward, from the eastern boundary of the bay to the western Arabian Sea. We call these currents the Summer Monsoon Current (SMC) and Winter Monsoon Current (WMC), respectively. It is these currents, which transfer water masses between the two highly dissimilar arms of the north Indian Ocean, the Bay of Bengal and the Arabian Sea, that form the subject of this paper.

### *1.1 Observational background*

The existence of seasonally reversing currents in the Arabian Sea has been known for long (see Warren, 1966, for references to medieval Arab sources), but the first

major description of the monsoon currents followed the International Indian Ocean Expedition (IIOE) (Düing, 1970; Wyrтки, 1971, 1973b). Based on these hydrographic data, Wyrтки (1973b) highlighted what he called “the seasonally changing monsoon gyre” as a gyre unlike those found in the other oceans. In his scheme of circulation, the monsoon gyre during the winter monsoon consists of the “westward North Equatorial Current, a southward flow off the Somali coast, and the Equatorial Counter Current, which runs east between the equator and 8°S across the entire width of the ocean.” During the summer monsoon, his monsoon gyre consists of the “northern portions of the South Equatorial Current, which now extends almost to the equator, the strong Somali Current flowing north as a western boundary current, and the monsoon current, into which the Counter Current has merged.” There is no standard nomenclature for the monsoon currents (Table 1); in this paper, we shall stick to the terminology used above, i.e., SMC and WMC.

Wyrтки (1973b) noted that the circulation in the Indian Ocean is complex; the winter monsoon gyre did not close cleanly in the east, with most of the flow from the South Equatorial Counter Current (SECC) flowing into the South Equatorial Current (SEC), and a strong branch of the WMC turning north to flow along the Indian west coast, transporting low-salinity water from the Bay of Bengal into the eastern Arabian Sea. The circulation during the winter monsoon was shallow compared to that during the summer monsoon, when intense upwelling was observed in several places and the circulation penetrated deeper, affecting the movement of water masses below the thermocline, especially in the western Arabian Sea. The complexity of the circulation represented by the hydrographic data was seen in the large number of eddies (Düing, 1970; Wyrтки, 1973b), which were found to be connected intimately to the dynamics of the monsoon gyre. The most vigorous of these eddies lay about 300 km offshore of the Somali coast; large parts of the Somali Current were recirculated around this eddy, the “Great Whirl” (Bruce, 1968).

A different picture emerges from the ship-drift data (Defant, 1961; Cutler and Swallow, 1984; Rao, Molinari, and Festa, 1989) or surface-drifter data (Molinari, Olson, and Reverdin, 1990; Shenoi, Saji, and Almeida, 1999a), which show broad eastward (westward) or southeastward flows across the Arabian Sea during the summer (winter) monsoon. Hastenrath and Greischar (1991) used ship drifts, hydrography, and Ekman drift computed from wind-stress climatologies to study the monsoon

currents in the Arabian Sea. They concluded that the monsoon currents are essentially Ekman drifts forced by the monsoon winds, the geostrophic contribution to these flows being negligible. Shenoi et al. (1999a) compared hydrography based on the climatologies of Levitus and Boyer (1994) and Levitus, Burgett, and Boyer (1994) to currents from surface drifters, and concluded that the role of geostrophy

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| Name of current (acronym)               | Other commonly used names (acronyms)   |
|---|--|
| Winter Monsoon Current (WMC)            | Northeast Monsoon Current (NMC),<br>North Equatorial Current (NEC)                   |
| Summer Monsoon Current (SMC)            | Southwest Monsoon Current (SMC),<br>Indian Monsoon Current (IMC),<br>Monsoon Current |
| Equatorial Current                      | Equatorial jet or Wyrcki jet (when<br>flowing eastward)                              |
| South Equatorial Counter Current (SECC) | South Equatorial Counter Current (SECC, SCC), Equatorial Counter Current (ECC)       |
| Somali Current                          |  |
| West India Coastal Current (WICC)       |  |
| East India Coastal Current (EICC)       |  |

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Table 1

Nomenclature used for currents in this paper. Many of the currents in the Indian Ocean have been referred to by different names in the literature; these are listed here. The first column lists the name and acronym used by us. The second column lists names and acronyms used earlier; this column is blank if no other name is known to have been used by other authors. The names used are based on the geographical location of the current; the monsoon currents are the exceptions. Except in the case of the monsoon currents, no allowance has been made for a change in direction with season.

in representing the surface flows varies both geographically and seasonally. The agreement between the drifter data and hydrography was worst during the summer monsoon, when the drifters showed southeastward flows all over the Arabian Sea, unlike in hydrography.

Hydrographic data, however, were also used in later studies (Bruce, Johnson, and Kindle, 1994; Bruce, Kindle, Kantha, Kerling, and Bailey, 1998; Donguy and Meyers, 1995; Murty, Sarma, Rao, and Murty, 1992; Murty, Sarma, Lambata, Gopalakrishna, Pednekar, Rao, Luis, Kaka, and Rao, 2000; Gopalakrishna, Pednekar, and Murty, 1996; Vinayachandran, Masumoto, Mikawa, and Yamagata, 1999a), which showed strong geostrophic flows and transports associated with the monsoon currents. These estimates (Table 2) yield current strengths of  $\sim 40 \text{ cm s}^{-1}$  and transports of  $\sim 10 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  in the upper 400 or 1000 m, which implies that the geostrophic flows associated with the monsoon currents are not small, even if they are weaker than the surface Ekman flows in some regions during some seasons. The geostrophic flows estimated by Hastenrath and Greischar (1991) are weak probably because of the poor resolution of the data and the averaging they did to obtain climatological currents and transports in a region; in contrast, except for the IIOE atlas (Wyrтки, 1971), the hydrographic data are usually from individual cruises. These data, which yield higher estimates for the geostrophic transports, show that the monsoon currents are not found in the same location during a season or in different year. For example, Vinayachandran et al. (1999a) showed that the SMC in the Bay of Bengal intensifies and shifts westward as the summer monsoon progresses; this westward shift with time is also seen in the surface geostrophic flow inferred from TOPEX/Poseidon altimetry (Eigenheer and Quadfasel, 2000).

In spite of these differences, all the observations — hydrography, ship drifts, and surface drifters — show that the monsoon currents flow across the breadth of the north Indian Ocean. The branches of the SMC and WMC that flow around the Lakshadweep high and low in the southeastern Arabian Sea (McCreary et al., 1993; Bruce et al., 1994; Shankar and Shetye, 1997) link the circulations in the Arabian Sea and the Bay of Bengal (Fig. 2). The SMC flows eastward south of Sri Lanka and into the bay. It is fed by a flow from the southwest near the equator and by the flow around the Lakshadweep low. East of Sri Lanka, the SMC flows northeastward into the Bay of Bengal. An outflow from it, however, appears to flow southeastward and

| Cur-<br>rent/Transport<br>and direction | Location and period   | Remarks  |
|---|---|--|
| 9 Sv (E)                                | 78°E, 3°–5°N; June 1992.  | Geostrophic transport with respect to 400 db; based on XBT data, with salinity from T-S relation based on climatology (Levitus, 1982); Source: Murty et al. (2000). SMC.                         |
| 14 Sv (E)                               | 80°E, 3°–5°N; July 1992.  | As above. SMC.   |
| 9.3 Sv (E)                              | 68°E, 4°–7°N; July 1995.  | As above. SMC.   |
| 6 Sv (E)                                | 68°E, 2°–6°N;<br>September 1993.  | As above. SMC.   |
| 14 Sv (W)                               | 72°–79°E, ~ 6°–8°N;<br>February 1993.   | As above, but WMC.   |
| 7–8 Sv (W)                              | 2°–5°N; January 1996,<br>February 1993,<br>March 1992.                        | As above, but average values for the given months over three different transects. WMC.   |
| 13 Sv (W)                               | ~ 6°N, east of Sri Lanka;<br>January–February<br>climatology                  | Geostrophic transport with respect to 400 db; based on TOGA XBT data for 1985–1989, with salinity from T-S relation based on climatology (Levitus, 1982). Source: Donguy and Meyers (1995). WMC. |
| 11 Sv (NE)                              | West of Lakshadweep<br>high (see Fig. 2);<br>January–February<br>climatology. | As above. WMC.   |
| 19 Sv (N)                               | 10°N, ~ 66°–70°E;<br>Winter monsoon, 1965.                                    | Geostrophic transport with respect to 1000 db, evaluated from IIOE data; Atlantis II, Cruise 15. West of Lakshadweep high. Source: Bruce et al. (1994). WMC.                                     |
| 15 Sv (S)                               | 10°N, ~ 67°–72°E;<br>Summer monsoon, 1963.                                    | As above, but for IIOE data from Atlantis II, Cruise 8. SMC.   |

Table 2

Currents and transports ( $1 \text{ Sv} = 10 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ) associated with the monsoon currents. The direction is given in parentheses in the first column; N implies northward flow, S southward, E eastward, W westward, and NE northeastward. The acronym (SMC/WMC) listed in the last column indicates the current referred to.

| Current/Transport and direction                          | Location and period                      | Remarks   |
|--|--|---|
| 35 cm s <sup>-1</sup> (S),<br>5.2 Sv (S)                 | 8°N, 72°10'–75°E;<br>August 1993.        | Current from ADCP; geostrophic transport with respect to 1000 db from hydrography. West of Lakshadweep low (see Fig. 2). Source: Stramma et al. (1996). SMC.  |
| ~8 Sv (E), with a peak transport of 24 Sv                | 80.5°E; Summer monsoon, 1991.            | Transport estimated from current-meter moorings and ADCP. Moorings located south of Sri Lanka between 5°39'N and 4°10'N (transport estimated over top 300 m between 3°45'N and 5°52'N). Source: Schott, Reppin, Fischer, and Quadfasel (1994). SMC. |
| ~12 Sv,<br>~10 Sv (W),<br>with a peak transport of 25 Sv | 80.5°E; Winter monsoon, 1991, 1992.      | As above. The first value is for 1991, the second for 1992. WMC.  |
| 40 cm s <sup>-1</sup> (N)                                | 87°–89°E, 14°N;<br>Summer monsoon, 1984. | Maximum of geostrophic current between 50–100 m depth, estimated from hydrographic data with respect to 1000 db. Source: Murty et al. (1992). SMC.  |
| 40 cm s <sup>-1</sup> (N),<br>17 Sv (N)                  | 87°–89°E, 11°N; July 1993.               | Geostrophic current and transport with respect to 1000 db, estimated using hydrographic data. Source: Gopalakrishna et al. (1996). SMC.   |
| 40 cm s <sup>-1</sup> (N),<br>14 Sv (N)                  | 87°–89°E, 12°N; August 1991.             | As above. SMC.  |
| 40 cm s <sup>-1</sup> (N),<br>12 Sv (N)                  | 81°–85°E, 6°N; July climatology.         | Geostrophic current and transport with respect to 400 db, estimated from TOGA XBT data during 1985–1996. The current is restricted to the top 200 m and moves westward as the season progresses. Source: Vinayachandran et al. (1999a). SMC.        |

Table 2  
(continued)

crosses the equator near Sumatra in the surface-drifter data (Shenoi et al., 1999a); recent hydrographic data (Unnikrishnan, Murty, Babu, Gopinathan, and Charyulu, 2001) also show that the eastward current between  $80^{\circ}$ – $88^{\circ}$ E flows close to the equator and even to its south. The SMC transports high-salinity water (Arabian Sea High Salinity Water) into the bay (Wyrтки, 1971; Murty et al., 1992; Gopalakrishna et al., 1996; Han and McCreary, 2001). The WMC flows westward south of Sri Lanka, where it divides into two branches, one flowing westward into the southern Arabian Sea, the other flowing around the Lakshadweep high into the WICC. The WMC transports low-salinity water (Bay of Bengal Water) into the eastern Arabian Sea, where it is entrained into the Lakshadweep high and spread along the Indian west coast by the WICC (Wyrтки, 1971; Bruce et al., 1994; Han, 1999; Shenoi, Shankar, and Shetye, 1999b; Shankar and Shetye, 1999; Han and McCreary, 2001; Han, McCreary, and Kohler, 2001; Howden and Murtugudde, 2001).

The passage between Sri Lanka and the equator is therefore significant because the monsoon currents have to flow through it, making it the only location where they are geographically frozen, unlike in the open ocean, where they meander a lot. Hence, it is not surprising that the only direct current measurements of the monsoon currents have been made between Sri Lanka and the equator along  $80.5^{\circ}$ E (Schott et al., 1994; Reppin, Schott, Fischer, and Quadfasel, 1999). The current-meter and ADCP (Acoustic Doppler Current Profiler) observations show that the SMC and WMC transport  $\sim 10 \times 10^6 \text{ m}^3\text{s}^{-1}$  in the upper 300 m. These direct measurements also confirm the observation in hydrography that the monsoon currents are shallow, with most of the variation being restricted to the upper 100 m. The moored array shows upward phase propagation, implying downward propagation of energy. Most striking is the difference between the Equatorial Current and the monsoon currents, even though both flow together in the same bottleneck. The Equatorial Current includes a large semiannual harmonic and reverses direction four times an year, unlike the monsoon currents, which are dominated by the annual harmonic and reverse direction twice. Superimposed on these seasonal changes are large intraseasonal oscillations (Schott et al., 1994; Reppin et al., 1999).

Though the observations differ in their presentation of the monsoon-current system in the north Indian Ocean, they show that the open-ocean currents in the north Indian Ocean extend all across the basin, reverse direction with season, and are



relatively shallow compared to the deep western boundary current off Somalia.

## *1.2 Theoretical background*

Given that there are many different interpretations of the monsoon currents (contrast, for example, Hastenrath and Greischar (1991) with Wyrski (1973b)), it is not surprising that more than one hypothesis exists to explain the observations. Early ideas attributed the monsoon currents as seen in ship drifts to direct Ekman forcing by the monsoon winds (for example, Defant, 1961; Hastenrath and Greischar, 1991), and as seen in hydrography to the local curl of wind stress (for example, Murty et al., 1992).

Matsuno (1966), Moore (1968), and Lighthill (1969) showed that baroclinic waves propagate fast in the tropics, and it is now appreciated that the open-ocean, equatorial, and coastal currents in the north Indian Ocean, all of which reverse seasonally, are manifestations of direct forcing by the monsoon winds (Ekman drift), and of equatorial and coastal long, baroclinic waves generated by the winds (Cane, 1980; Potemra, Luther, and O'Brien, 1991; Yu, O'Brien, and Yang, 1991; Perigaud and Delecluse, 1992; McCreary et al., 1993; Jensen, 1993; Shankar et al., 1996; McCreary et al., 1996; Vinayachandran et al., 1996; Shankar and Shetye, 1997; Shankar, 1998; Vinayachandran and Yamagata, 1998; Han, 1999; Han et al., 1999; Shankar, 2000; Han and McCreary, 2001; Han et al., 2001). The small size of the basin and its confinement to the tropics, with its northern boundary around  $25^{\circ}\text{N}$ , implies that these waves can traverse the basin in a few months. This is unique to the north Indian Ocean. This framework, which has evolved in the last decade, suggests a unity of dynamics in the north Indian Ocean. Circulation at any point is decided by both local forcing and remote forcing, whose signals are carried by the equatorial and coastal waves. This is seen in numerical simulations using both layered models and multi-level general circulation models. The layered models, in particular, emphasize the quasi-geostrophic dynamics that leads to the eddies and meanders so typical of hydrographic observations of the monsoon currents. In these models, the monsoon currents appear as the fronts of Rossby waves.

Thus, there appears to be more than one definition of the monsoon currents in cur-

rent literature, common to them being the idea of these currents serving as the link between the circulations in the Bay of Bengal and the Arabian Sea. In this paper, we use both observations and numerical simulations to define them more precisely. In section 2, we assemble observations to define the surface circulation associated with the monsoon currents. Numerical simulations with an OGCM follow in section 3. In section 4, we use a  $1\frac{1}{2}$ -layer reduced-gravity model to investigate the mechanisms that force the monsoon currents. Section 5 concludes the paper.