

2 Observations

To define the monsoon currents and the associated circulation in the north Indian Ocean, we use climatological wind-stress data to estimate the surface Ekman drift, and hydrography and altimeter data from TOPEX/Poseidon to estimate the geostrophic contribution to the surface currents. The net surface current due to the two components is compared to the surface current represented by ship drifts. Defining the monsoon-current system requires more than one observational method because each method accentuates certain aspects of the flow field, thereby emphasizing a particular view of the surface currents.

2.1 Ekman drift

The Ekman drift is computed using the “Ekman spiral” method. The surface Ekman drift flows at 45° to the right (left) of the wind in the northern (southern) hemisphere and its magnitude is given by (Pond and Pickard, 1983)

$$V_E = \frac{\tau}{\rho (A|f|)^{\frac{1}{2}}}, \quad (1)$$

where τ is the magnitude of the wind stress, A the vertical eddy diffusivity, ρ the average density of sea-water, and $|f|$ the magnitude of the Coriolis parameter. We use $A = 10^{-2} \text{ m}^2\text{s}^{-1}$ (Hastenrath and Greischar, 1991) and τ from the wind-stress climatology of Hellerman and Rosenstein (1983) to obtain the monthly climatology of the surface Ekman drift in the Indian Ocean north of 5°S (Fig. 3); we exclude the region within 2.5° of the equator, where Eq. (1) does not apply.

The winter monsoon sets in during November (Fig. 1), and the Ekman drift is westward in the Arabian Sea and the Bay of Bengal. It is weak in the eastern Arabian Sea and the eastern bay. The winter monsoon strengthens in December; so does the Ekman drift, whose magnitude is $\sim 15 \text{ cm s}^{-1}$ in the western bay and $\sim 25 \text{ cm s}^{-1}$ in the western Arabian Sea. The winter monsoon peaks in January, with northeasterly winds over most of the north Indian Ocean, and the Ekman drift is westward. The current strength approaches 20 cm s^{-1} south of Sri Lanka and 30 cm s^{-1} in the southwestern Arabian Sea. The drift is weak in the eastern Arabian Sea and

northern bay. The winter monsoon weakens in February; so does the Ekman drift.

With the onset of the summer monsoon in May, the winds begin to blow from the southwest over most of the north Indian Ocean. The Ekman drift reverses to flow eastward over most of the Arabian Sea; it is southeastward in the eastern Arabian Sea, where the winds blow more from the west. In the bay, the Ekman drift is eastward, except in the north and the west, where it is parallel to the coast. The current strength is $\sim 25 \text{ cm s}^{-1}$ southeast of Sri Lanka and off the Somali coast. The Ekman drift strengthens all over the north Indian Ocean in June. It is eastward

Climatology of surface Ekman drift

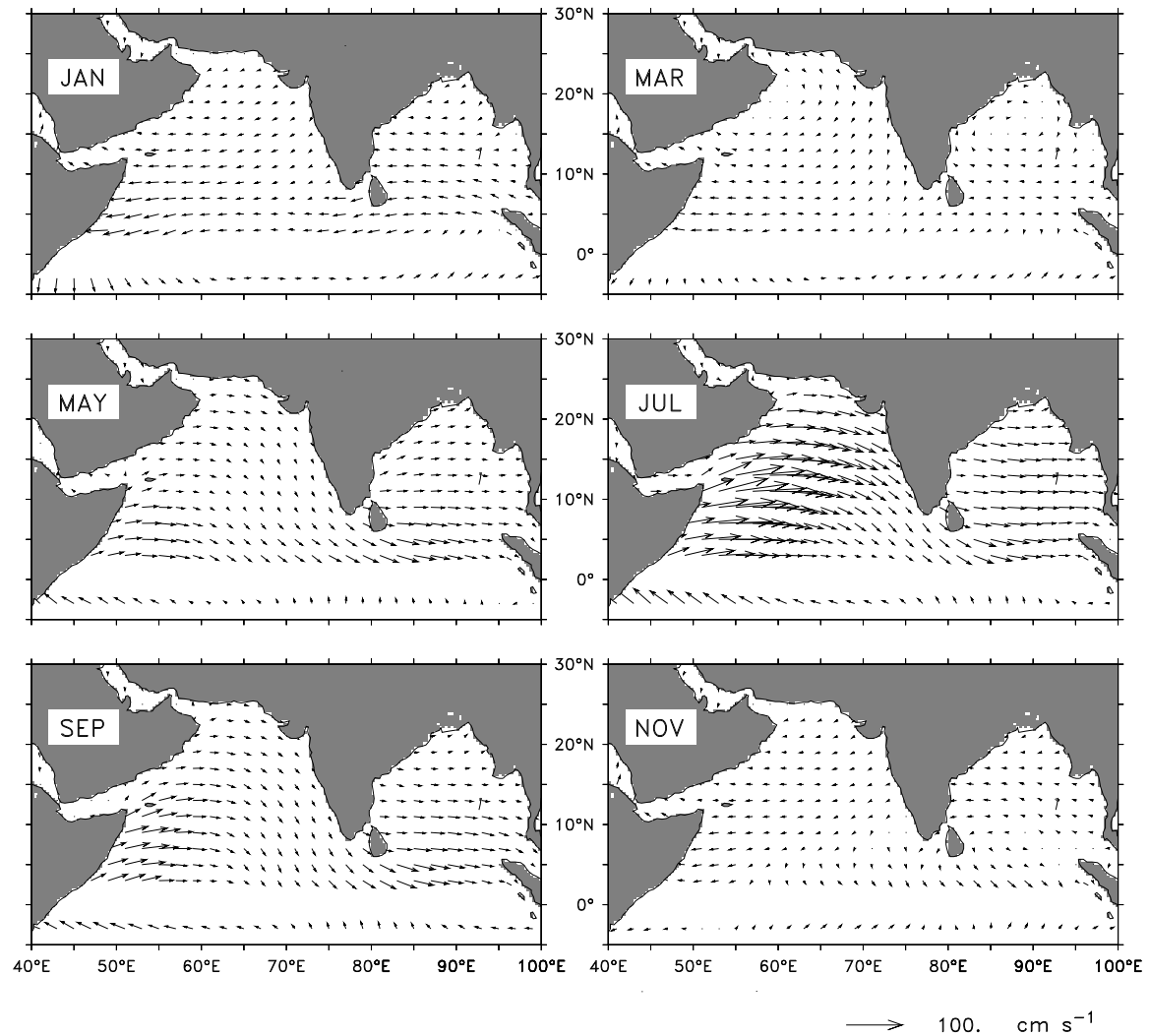


Fig. 3. Climatology of surface Ekman drift (cm s^{-1}) in the north Indian Ocean. The drift is estimated from the wind-stress climatology of Hellerman and Rosenstein (1983) and is based on the “Ekman spiral” formula.

and southeastward in the Arabian Sea, with a slight anticyclonic curvature; the drift is eastward in the bay. The direction remains the same from June to September, but the Ekman drift peaks in July, when current strength approaches $\sim 40 \text{ cm s}^{-1}$ in parts of the bay and $\sim 100 \text{ cm s}^{-1}$ off the Somali coast. October is the month of transition between the summer and winter monsoons, with weak winds all over the north Indian Ocean. The Ekman drift is weaker than 5 cm s^{-1} over most of the basin, with currents of $\sim 20 \text{ cm s}^{-1}$ seen only southeast of Sri Lanka.

During the summer monsoon, the Ekman drift is strong in the western and central Arabian Sea and south of Sri Lanka; it is relatively weak in the eastern parts of the Arabian Sea and Bay of Bengal. During the winter monsoon, the spatial variation in magnitude is much less. Most striking is the spatial uniformity of the Ekman drift in comparison with the eddy-like circulations seen in hydrography (Düing, 1970; Wyrтки, 1971; Murty et al., 1992). It strengthens and weakens almost all over the north Indian Ocean at the same time, in harmony with the seasonally reversing winds. This lack of spatial structure in the Ekman drift implies that geostrophy must make a significant contribution to the surface current in the north Indian Ocean.

2.2 *Geostrophic flow*

Climatological hydrographic data (Levitus and Boyer, 1994; Levitus et al., 1994) are incapable of resolving, in both space and time, the geostrophic component of the rapidly changing monsoon circulation of the north Indian Ocean. Hence, we use these data only to construct the annual-mean surface dynamic topography with respect to 1000 db and the corresponding geostrophic circulation, excluding the region within 2.5° of the equator (Fig. 4). The annual-mean dynamic height is higher in the bay than in the Arabian Sea (Wyrтки, 1971; Shankar and Shetye, 2001), and the annual-mean geostrophic flow is weak, the strongest current being a $\sim 10 \text{ cm s}^{-1}$ westward flow south of Sri Lanka. These hydrographic data appear to be too coarse to capture the mean poleward flow off Somalia.

To compute the deviations of the geostrophic flow from the annual mean, we use the sea-level anomalies from TOPEX/Poseidon altimetry, which are available on a $0.25^\circ \times 0.25^\circ$ grid (Le Traon, Gaspar, Bouyssel, and Makhmara, 1995; Le Traon

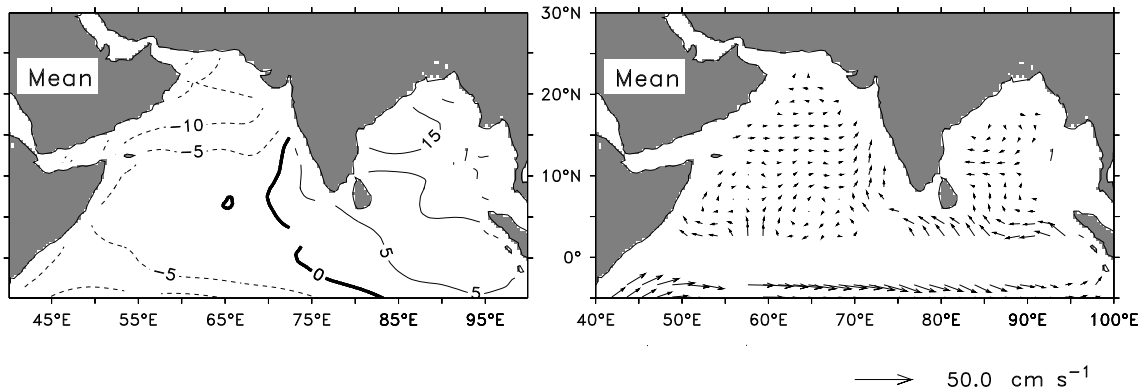


Fig. 4. Annual-mean surface dynamic height (dyn cm, left panel) and surface geostrophic flow (cm s^{-1} , right panel) estimated with respect to a level of no motion at 1000 db from the annual-mean climatologies of Levitus and Boyer (1994) and Levitus et al. (1994). The basin-wide mean (164 dyn cm) has been removed from the dynamic height field. Negative dynamic heights are indicated by dashed contours and the contour interval is 5 dyn cm.

and Ogor, 1998; Le Traon, Nadal, and Ducet, 1998). We construct a monthly climatology of sea-level anomalies using the 10-day repeat-cycle data for 1993–1997, and use this climatology to compute surface geostrophic currents in the Indian Ocean (Fig. 5), excluding the region within 2.5° of the equator. (Adding the annual mean dynamic height to the sea-level anomalies accentuates the annual-mean sea-level difference between the bay and the Arabian Sea at the expense of the seasonal cycle; hence, Fig. 5 shows only the sea-level anomalies from the altimeter data and the geostrophic currents derived from these anomalies.) Unlike the Ekman drift, which shows little spatial structure, the surface geostrophic flow is dominated by eddies. The geostrophic monsoon currents do not form, or decay, across the basin all at once. Instead, patches of the currents appear or decay at different times. The monsoon currents can be traced as continuous trans-basin flows only in their mature phase; the mature phase of the geostrophic WMC (GWMC) peaks during January–February and that of the geostrophic SMC (GSMC) during July. At other times, incipient or relic patches are identifiable in the surface geostrophic flow.

By November, with the onset of the winter monsoon, the GSMC breaks into separate currents in the Arabian Sea and the Bay of Bengal, this split into two relic currents being caused by the continuity of the flow along the coast of the Indian subcontinent, and by the relentless westward propagation of the sea-level anoma-

lies associated with the GSMC. In the Arabian Sea, the relic GSMC is restricted west of 72°E, and it appears as a geostrophic flow around a low in sea level; this low has propagated westward from the Indian coast, where it appeared during the summer monsoon as the Lakshadweep low. The relic GSMC flows southwestward to the west of the low and eastward to its south. In the bay, the relic GSMC flows northeastward as the eastern arm of a geostrophic flow around a low in sea level off the east coast of India; its western arm is the equatorward EICC. The GWMC first

Climatology of sea-level anomalies and surface geostrophic flow

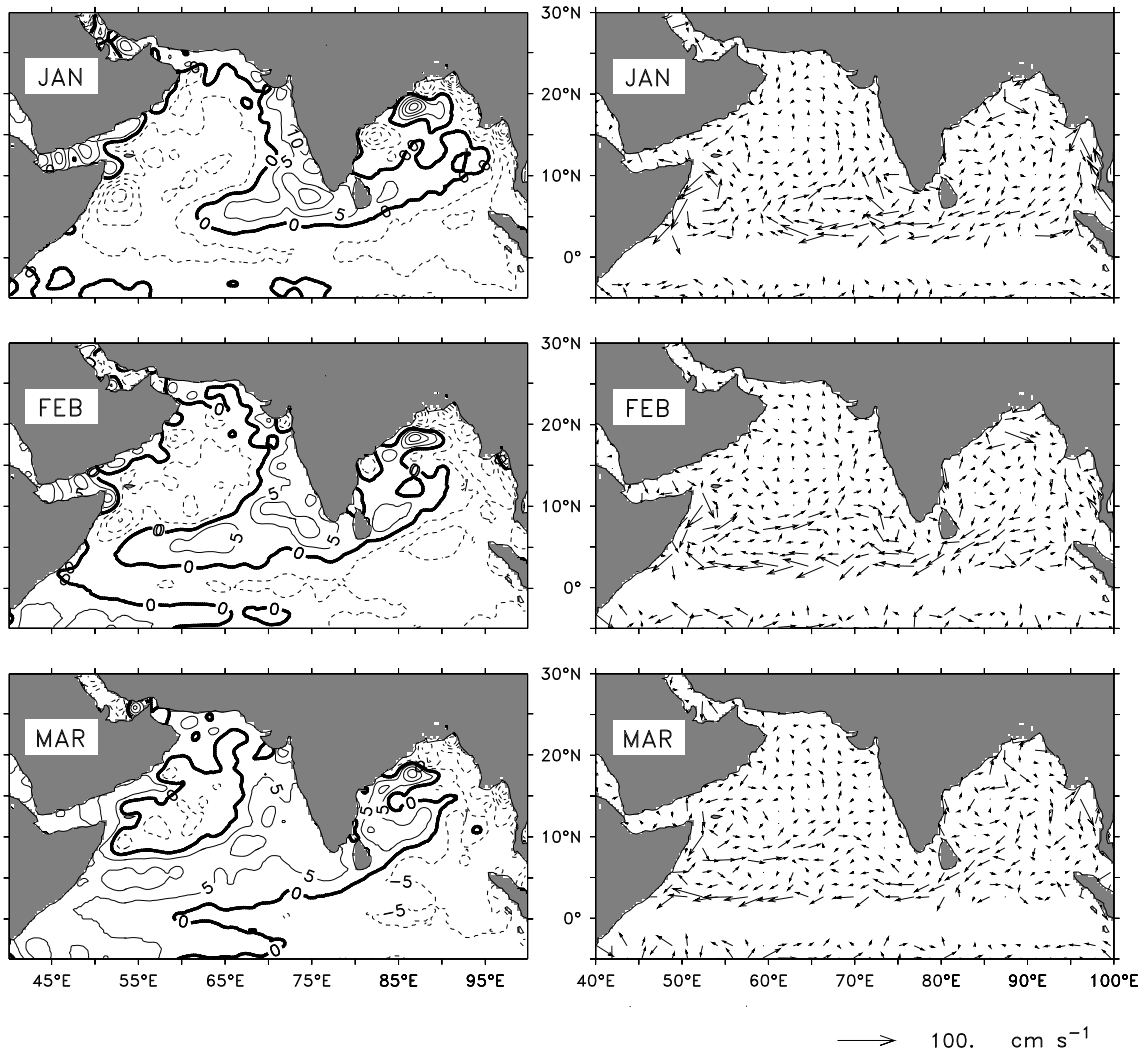


Fig. 5. Climatology of sea-level anomalies (cm, left panels) and surface geostrophic flow (cm s^{-1} , right panels) in the north Indian Ocean. Negative anomalies are indicated by dashed contours and the contour interval is 5 cm. The sea-level anomalies and geostrophic currents are derived from a monthly climatology constructed using the 10-day repeat-cycle TOPEX/Poseidon altimeter data for 1993–1997.

appears during November as a westward flow south of Sri Lanka. This incipient GWMC is fed by the equatorward EICC and it feeds, in turn, the poleward WICC.

The relic GSMC continues to shift westward, and by December, it is restricted to the west of 65°E in the Arabian Sea. The sea-level low abuts the Somali coast, and the southwestward GSMC to its west is now synonymous with the equatorward Somali Current. What remains of the GSMC in the bay is barely recognizable even as a relic. In December, the GWMC is fed by the EICC and has a velocity of $\sim 40 \text{ cm s}^{-1}$ southwest of Sri Lanka; it also appears in the southern bay as a weak westward flow southeast of Sri Lanka. It flows west beyond 70°E before turning to flow around the Lakshadweep high, which forms by this time off southwest India

Climatology of sea-level anomalies and surface geostrophic flow

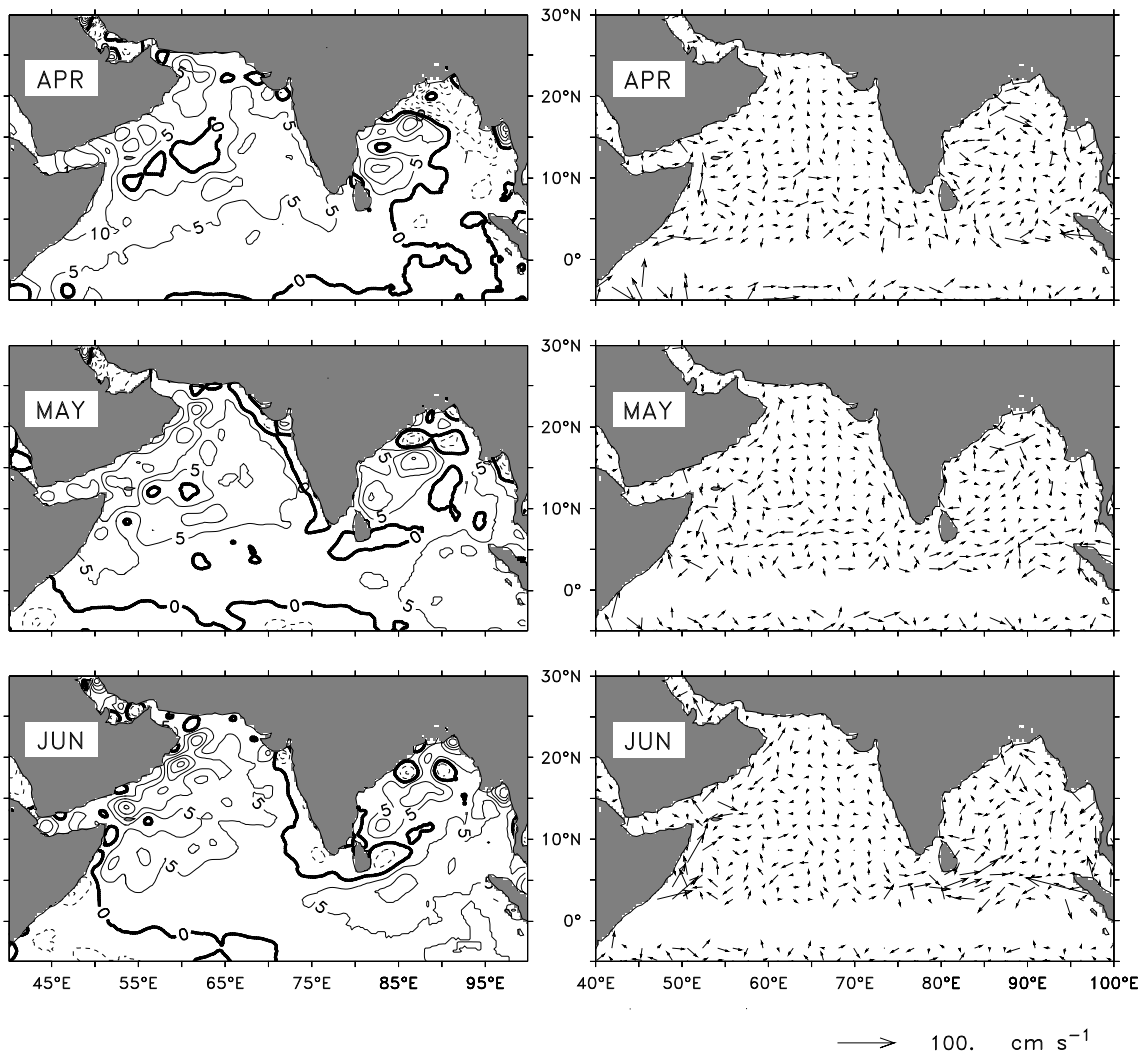


Fig. 5. (continued)

and Sri Lanka.

By January, the relic GSMC is restricted to a minor eastward flow west of 55°E , and the most significant geostrophic flows in the north Indian Ocean are the GWMC, the WICC, and the recirculation around eddies in the western Arabian Sea and the western bay. The EICC reverses to flow poleward off Sri Lanka, and the GWMC now appears as a westward flow across the southern bay at $\sim 6^{\circ}\text{N}$; it flows southwestward in the eastern bay. The GWMC flows westward halfway across the southern Arabian Sea at 5°N , where it turns to flow northeastward around the Lakshadweep high and into the WICC. There are two distinct sea-level highs embedded in the region of high sea level off southwest India. A branch of the GWMC also turns to

Climatology of sea-level anomalies and surface geostrophic flow

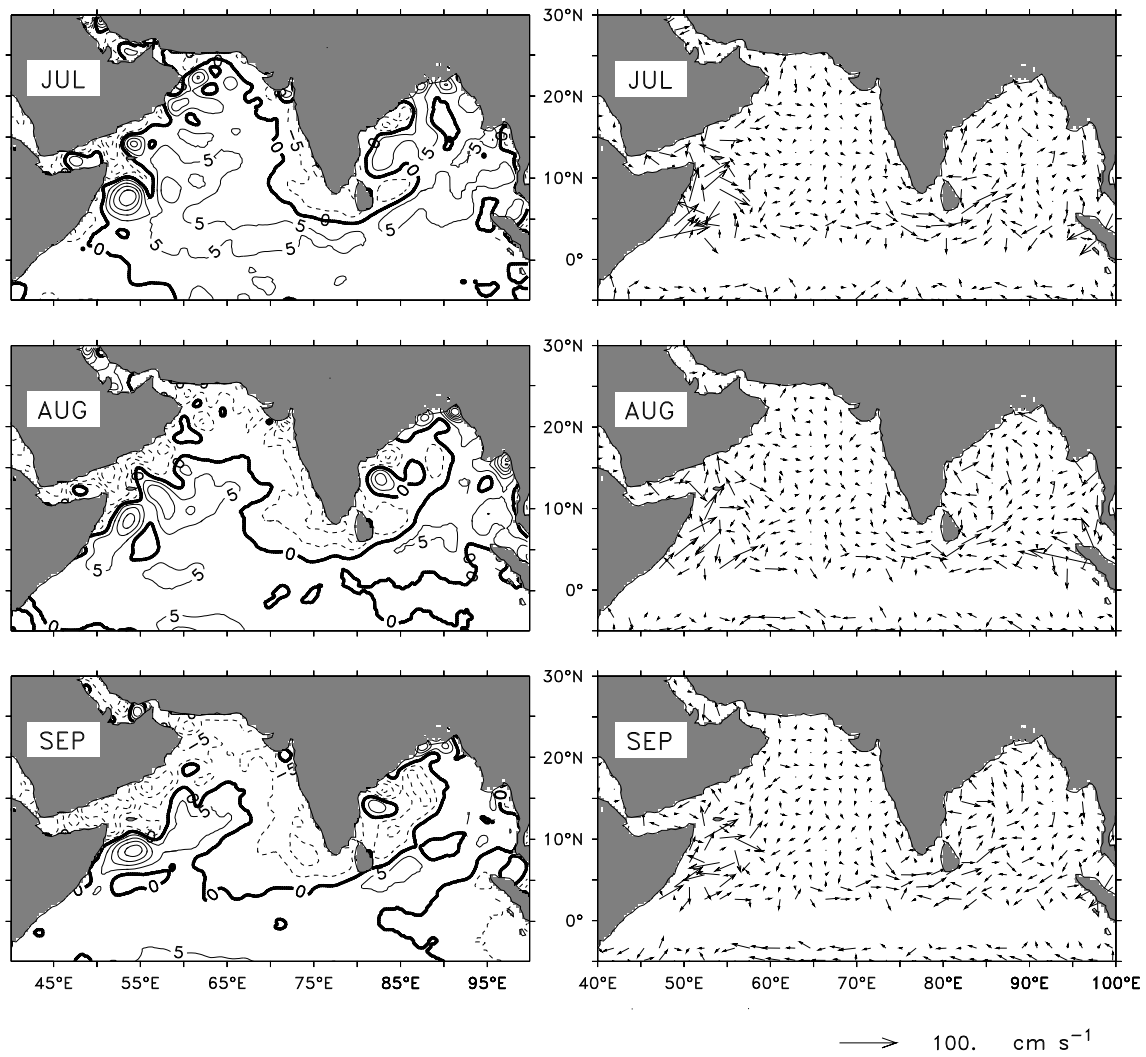


Fig. 5. (continued)

flow around the eastern sea-level high and into the WICC. Thus, the GWMC flows westward to the south of the sea-level high and eastward to its north.

The relic GSMC finally disappears in February. This period, January–February, marks the mature phase of the GWMC since it appears as a continuous, trans-basin current. Its strength south of Sri Lanka is $\sim 40 \text{ cm s}^{-1}$. The southwestward GWMC in the eastern bay has shifted west since January and is located at $\sim 93^\circ\text{E}$. Continuous geostrophic flow exists around a sea-level high in the southern Arabian Sea; the GWMC flows westward (eastward) to the south (north) of the high. The eastward part of the GWMC, as earlier in the season, feeds a current parallel to the Indian west coast; this poleward current was the WICC in January, but has since

Climatology of sea-level anomalies and surface geostrophic flow

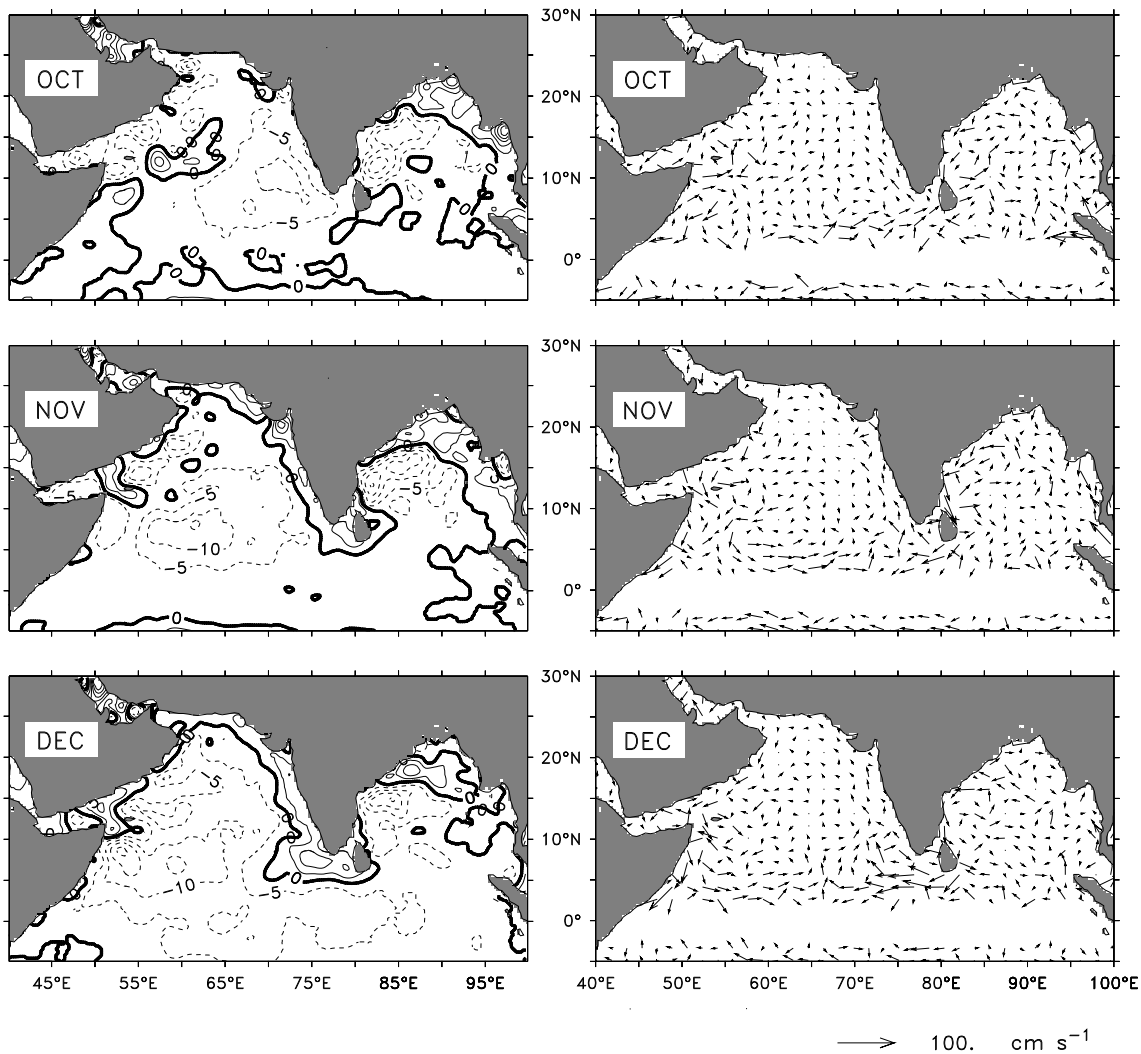


Fig. 5. (continued)

shifted offshore.

Westward propagation of sea-level anomalies continues during March. The GWMC no longer exists in the eastern bay and the southwestward GWMC is located at $\sim 83^\circ\text{E}$; this part of the GWMC is coupled to a distorted anticyclonic gyre in the western bay. The sea-level high in the southern Arabian Sea extends across the basin. The GWMC flows around the high, and, at the western boundary, it is synonymous with the poleward Somali Current between 4° – 6°N . The Somali current flows equatorward north of 6°N and feeds the eastward GWMC to the north of the high.

The geostrophic circulation during April is dominated by eddies. The GWMC in the bay has shifted westward and it now intersects the east coast of Sri Lanka; this breaks the GWMC into separate currents in the bay and the Arabian Sea. The relic GWMC in the bay is the eastern arm of an anticyclonic gyre. The relic GWMC in the Arabian Sea has weakened and meanders more, but its spatial structure is similar to that in March.

During May, the relic GWMC in the bay flows southwestward from the central bay to Sri Lanka. In the Arabian Sea, it appears primarily as a westward flow at $\sim 7^\circ\text{N}$ and is now fed by the equatorward WICC. The sea-level high is now well offshore, and the eastward flow to its north is weaker and meanders more than in April. An eastward flow appears in the southern bay between 4° – 8°N ; it flows across the basin, from Sri Lanka to the eastern boundary. This is the incipient GSMC, and it appears first in the bay even as the summer monsoon sets in.

In June, the relic GWMC is restricted in the central and western bay to a southwestward flow from (90°E , 16°N) to the northern tip of Sri Lanka, and in the Arabian Sea to a meander to the south and north of the sea-level highs in the southwest. The GSMC flows northeastward from the southern tip of Sri Lanka to (90°E , 14°N); an outflow from the GSMC also recirculates around a low in sea level to the east of Sri Lanka. The GSMC in the bay is pushed westward by the westward movement of a sea-level high from the eastern equatorial Indian Ocean. The GSMC also appears in the Arabian Sea as a flow around the Lakshadweep low off southwest India, and it is fed by the equatorward WICC. In the southern Arabian Sea, there is eastward flow at 5°N between 65° – 75°E , merging into the GSMC south of Sri Lanka.

The mature phase of the GSMC peaks in July and it exists as a continuous trans-basin current from the northern limits of the Somali Current to the southern tip of Sri Lanka and into the Bay of Bengal. It shifts westward in the bay, pushed by the sea-level high to its east. One branch of the GSMC appears as a northeastward flow from the southern tip of Sri Lanka almost to the northeastern boundary of the bay. Around 87°E , another branch flows due north and feeds into the relic GWMC, which has shifted westward and now appears as the eastern arm of an anticyclonic circulation around a high in sea level in the western bay. The GSMC south of Sri Lanka has a velocity of $\sim 40 \text{ cm s}^{-1}$. It is fed by a flow around the Lakshadweep low, this being a branch of the GSMC that is fed by the WICC, and by an eastward flow across the southern Arabian Sea. The eastward GSMC in the south is the continuation of the GSMC in the western and central Arabian Sea; this branch of the GSMC flows geostrophically around the sea-level high (low) in the western (eastern) Arabian Sea. It is the flow around the Lakshadweep low that provides greater inflow into the GSMC south of Sri Lanka.

Westward propagation of sea-level anomalies continues in the Bay of Bengal, and the GSMC is detached from its eastern boundary by August. It can be traced as a continuous current from the southern tip of Sri Lanka to the northern bay, though there are cyclonic eddies associated with it east of Sri Lanka and in the central bay. In the Arabian Sea, the Lakshadweep low propagates westward, taking the GSMC and WICC with it; the coastal current off the Indian west coast collapses. Westward propagation of the sea-level highs in the western Arabian Sea compresses them and strengthens the geostrophic flow around them. Except for this part of the basin and south of Sri Lanka, where it has a peak velocity of $\sim 50 \text{ cm s}^{-1}$, the GSMC is weaker in August than in July.

With the monsoon winds weakening during September, so does the GSMC, except in the western bay and, to a lesser extent, in the western Arabian Sea, where westward propagation compresses the sea-level lows and highs and strengthens the geostrophic flows associated with them. The Lakshadweep low is now detached from the coast and a part of the GSMC recirculates around it. The sea-level high that propagated westward across the southern bay is now almost at the southern tip of Sri Lanka, and the GSMC is squeezed against the coast. There is geostrophic flow around this high, and a westward current exists to its south, flowing from the

Andaman Sea to south of Sri Lanka.

The sea-level high that pushed the GSMC westward through the bay abuts the Sri Lankan coast in October, breaking the connection between the GSMC in the bay and the Arabian Sea. In the bay, the relic GSMC flows from the east coast of Sri Lanka into the northcentral bay, and it is associated with, and is fed by the recirculation around, sea-level lows in the western bay. The EICC reverses in October to flow equatorward as the western arm of these cyclonic geostrophic flows. The Lakshadweep low is now well offshore and the WICC also reverses to flow poleward off southwest India. The eddies and sea-level highs in the western Arabian Sea begin disintegrating, but the relic GSMC is still traceable as a distinct southwestward current in the western Arabian Sea; this relic current turns to flow eastward in the southern Arabian Sea.

Longitude-time plots of the sea-level anomalies (Fig. 6) show westward propagation at all latitudes, the speed of propagation decreasing with increasing latitude. Similar westward propagation has been noted earlier in hydrography (Kumar and Unnikrishnan, 1995; Unnikrishnan, Kumar, and Navelkar, 1997; Rao, 1998) and altimetry (Perigaud and Delecluse, 1992), and has been attributed to westward propagating Rossby waves. Most striking, however, is the phase shift in the westward propagating signal at 80.5°E , south of Sri Lanka, even though there is no land barrier there and the GSMC and GWMC form continuous currents from the Arabian Sea to the Bay of Bengal (and vice versa).

Latitude-time plots of the zonal component of the geostrophic current at 80.5°E (Fig. 7) show that the signal south of Sri Lanka is dominated by the annual harmonic north of $\sim 3^{\circ}\text{N}$; this is also seen in the zonal geostrophic current derived from the climatologies of Levitus and Boyer (1994) and Levitus et al. (1994) (Fig. 8), which also shows a strong semi-annual signal farther south in the regime of the Equatorial Current. This is in agreement with direct current measurements in this region (Schott et al., 1994; Reppin et al., 1999), and suggests that the monsoon-current system south of Sri Lanka is distinct from the Equatorial Current farther south, even though it is difficult to distinguish between these two regimes during, say, December–February, when the WMC flows westward, as does the Equatorial Current.

2.3 The net surface flow

The sum of the Ekman and geostrophic (annual mean from Fig. 4 plus monthly anomalies from Fig. 5) components constitutes, barring a residual, the net flow (NF) at the surface (Hastenrath and Greischar, 1991). We compare the NF with ship drifts (SD) (Fig. 9).

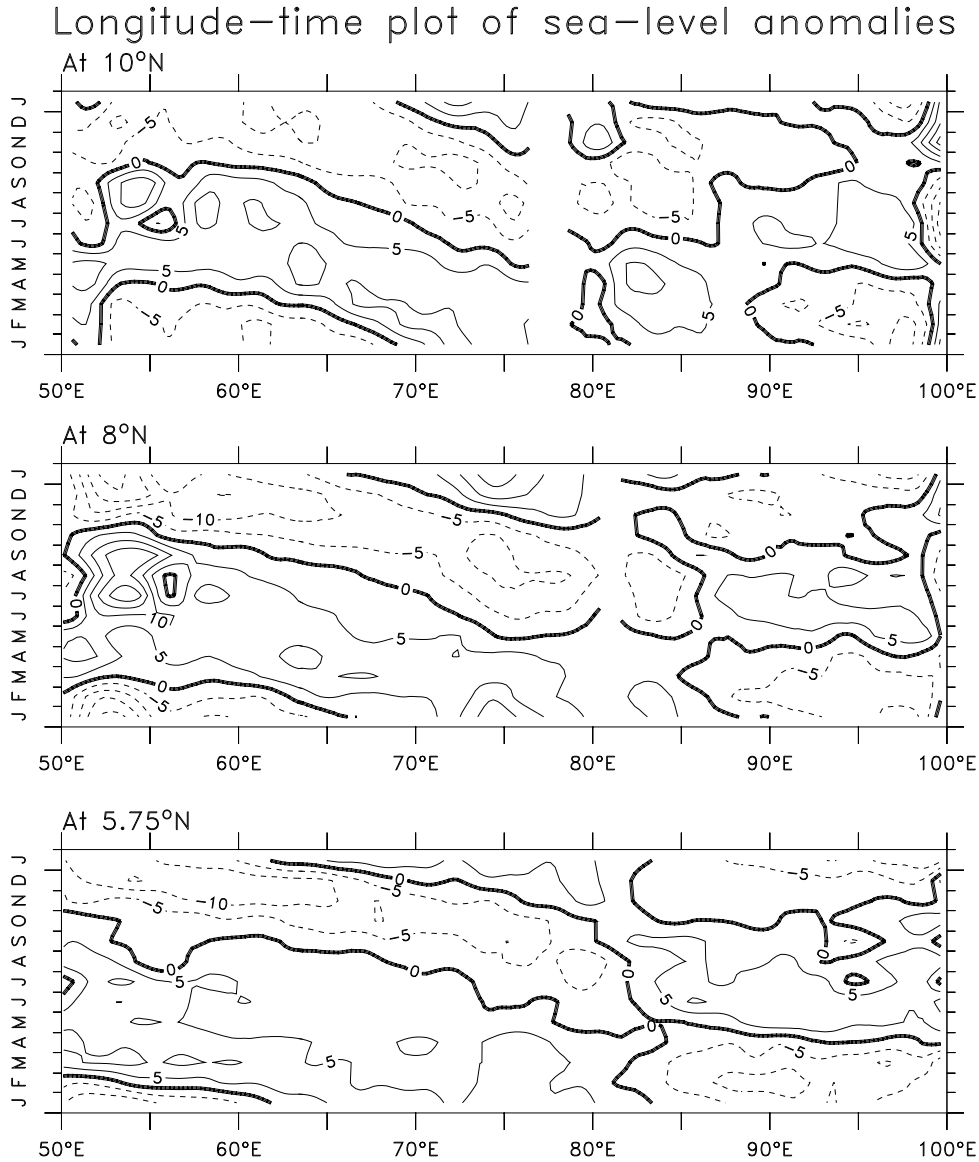


Fig. 6. Longitude-time plots of the monthly climatology of TOPEX/Poseidon sea-level anomalies (cm) at 10°N (top panel), 8°N (middle panel), and 5.75°N (bottom panel). Negative anomalies are indicated by dashed contours and the contour interval is 5 cm. Westward propagation is evident in both Arabian Sea and Bay of Bengal at all latitudes.

During November, geostrophy dominates in the Bay of Bengal and along the coast of the Indian subcontinent. The equatorward EICC, the westward WMC south of Sri Lanka, and the poleward WICC form a continuous current in both NF and SD; the SD, however, is stronger than the NF. The relic SMC in the Arabian Sea appears as a southwestward flow from ($\sim 65^\circ\text{E}$, 12°N) to ($\sim 55^\circ\text{E}$, 4°N), where it turns to flow eastward.

The Ekman drift strengthens in December, but it dominates geostrophy only in the northern Arabian Sea. The drift accentuates the strong westward GWMC in the southern bay and the westward geostrophic flow to the north of the sea-level low in southwestern Arabian Sea (Fig. 5). It attenuates the eastward GSMC to its south; as a consequence, the WMC appears farther north in western Arabian Sea compared to eastern Arabian Sea. It branches around 65°E , one branch flowing around the Lakshadweep high, the other continuing to flow westward. The latter branch of the WMC is synonymous with the relic SMC to the north of the sea-level low. South of Sri Lanka, the WMC attains its maximum strength, $\sim 50 \text{ cm s}^{-1}$, during December. This is due to the equatorward EICC and the Ekman drift, which also enables the WMC “to mature” before the GWMC does; the WMC is in its mature phase during December–March, but its spatial structure undergoes changes even during this phase.

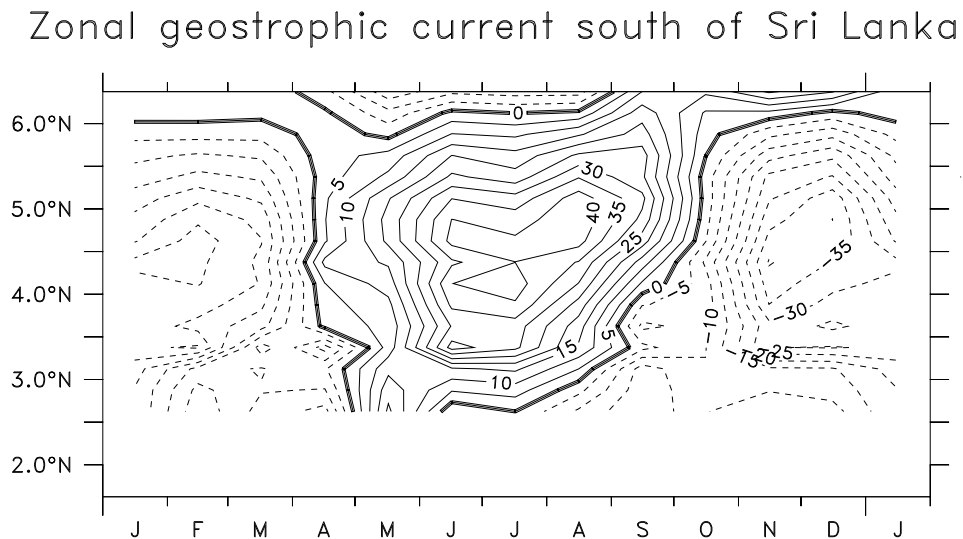


Fig. 7. Latitude-time plot of the monthly climatology of zonal geostrophic current (cm s^{-1}), derived from TOPEX/Poseidon altimetry, at 80.5°E (south of Sri Lanka). Westward flow is indicated by dashed contours and the contour interval is 5 cm s^{-1} .

The WMC in January is similar to that in December, but it is stronger, except south of Sri Lanka. Both geostrophy and Ekman drift contribute in the bay. In the Arabian Sea, the Ekman drift is responsible for extending the WMC west of 60°E, but geostrophic flow around the Lakshadweep high dominates in the east.

During February, the Ekman drift is weak, and the NF is dominated by eddies, resulting in relatively poor agreement with the SD outside the domain of the strong

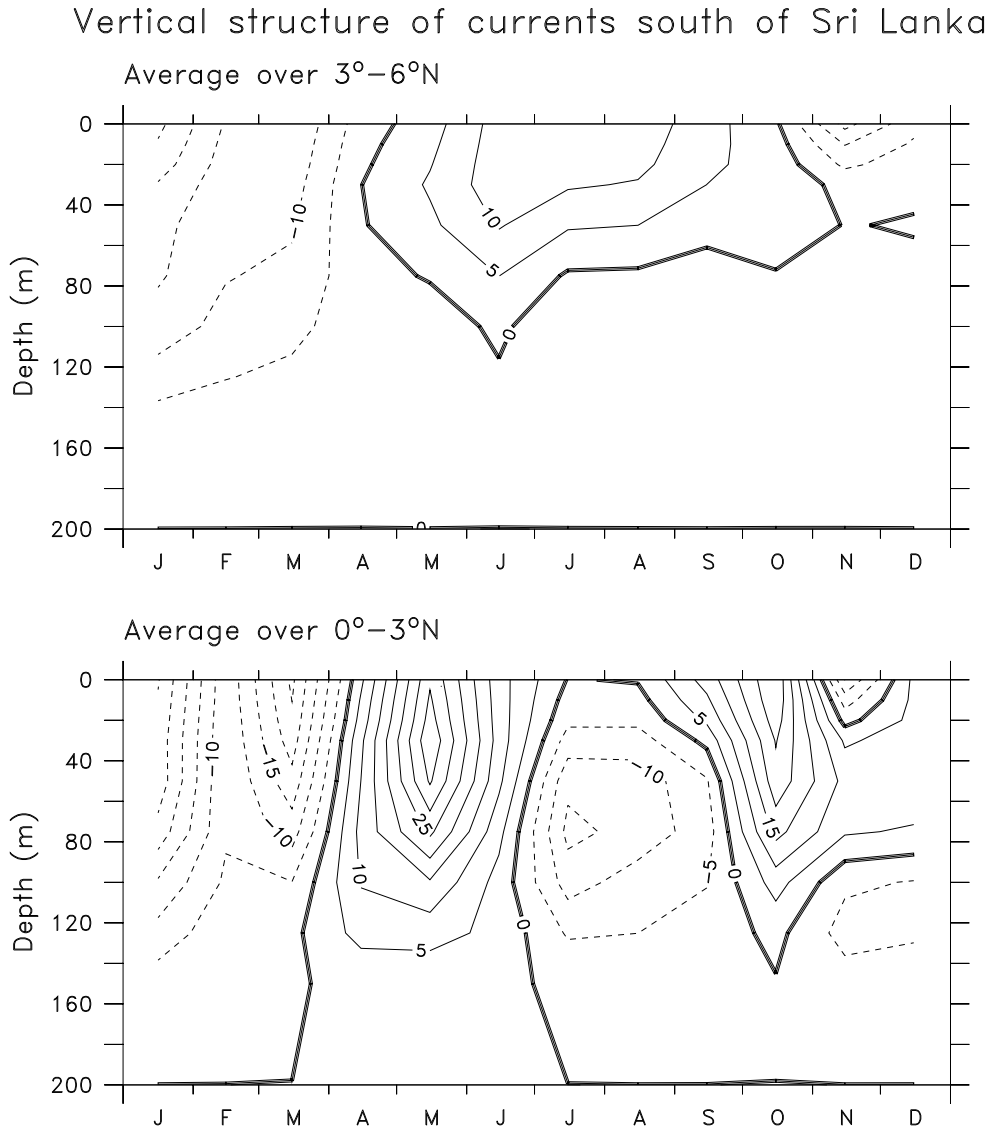


Fig. 8. Depth-time plots of the meridionally averaged zonal geostrophic current (cm s^{-1}) at 80.5°E derived from the climatologies of Levitus and Boyer (1994) and Levitus et al. (1994). The top (bottom) panel shows the current averaged over 0°–3°N (3°–6°N). Westward flow is indicated by dashed contours and the contour interval is 5 cm s^{-1} .

WMC. Owing to the dominance of geostrophy, which continues through to April, the WMC is almost identical to the GWMC.

During March, the Ekman drift contributes only in the southwestern Arabian Sea, where it accentuates the westward WMC to the south of the Lakshadweep high and attenuates the eastward WMC to its north.

The winds are weakest in April, and the WMC is almost identical to the GWMC.

Climatology of net surface flow and ship drifts

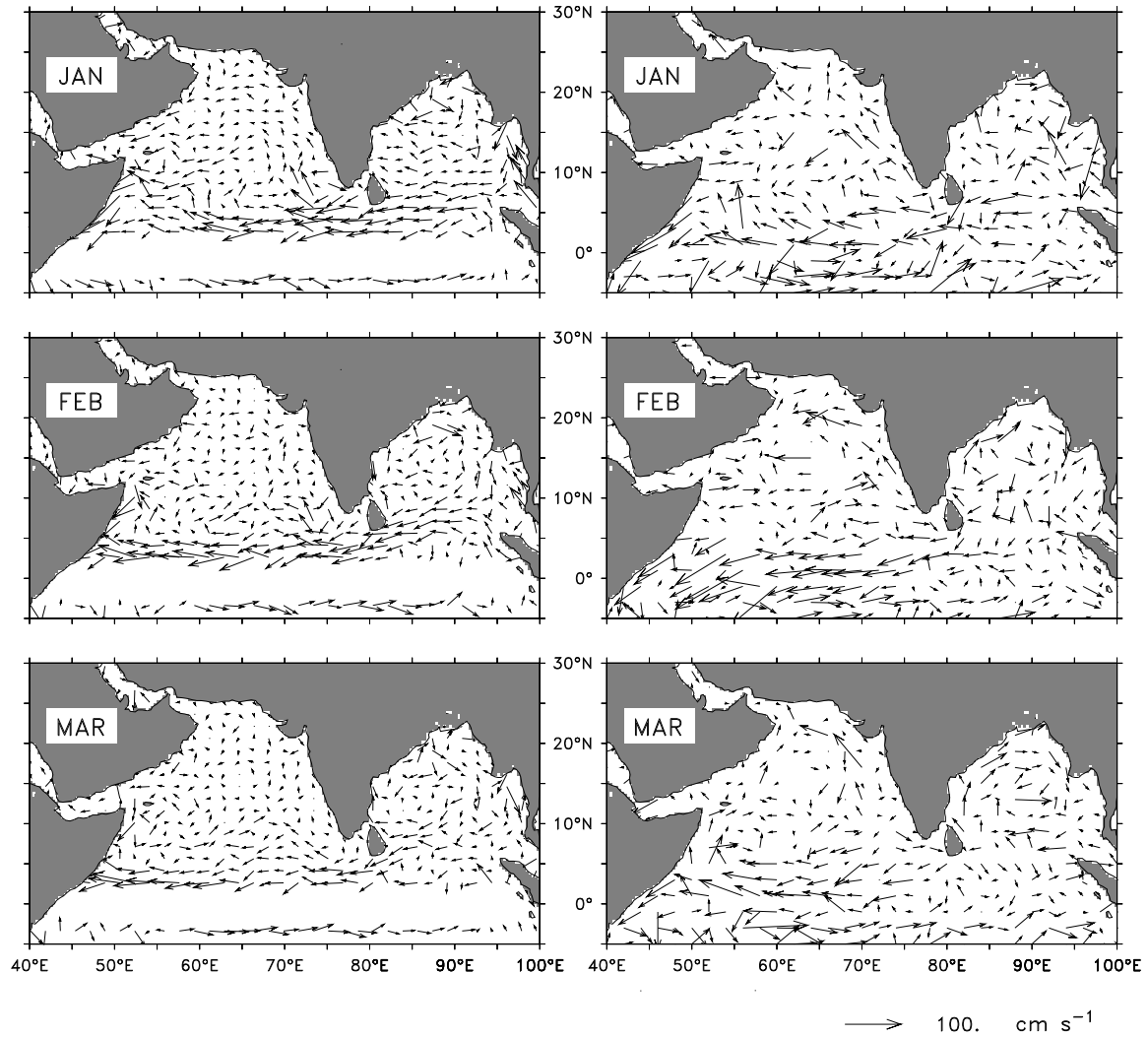


Fig. 9. The net flow (NF) at the surface (cm s^{-1} , left panels), computed as the sum of Ekman drift (Fig. 3) and geostrophic flow (Figs. 4 and 5), and ship drifts (SD) (cm s^{-1} , right panels). The source for the ship drifts are the Ocean Current Drifter Data CDROMs NODC-53 and NODC-54 (NODC, US Department of Commerce, NOAA).

It appears in three distinct parts: a southwestward relic in the western bay, a meandering westward flow south of a sea-level high in the southern Arabian Sea, and a meandering eastward flow to the north of the high. The two relics of the WMC in the Arabian Sea are connected by a poleward Somali Current. This is in agreement with the SD, in which too relics of the WMC appear as three separate currents; the Somali Current, however, flows poleward all along the coast in the SD, but not in the NF.

The SMC appears in the bay in both SD and NF during May, but it is broader in the latter because of the strong Ekman drift across the southern bay. The SMC can be traced as a continuous current from the northern limit of the poleward Somali

Climatology of net surface flow and ship drifts

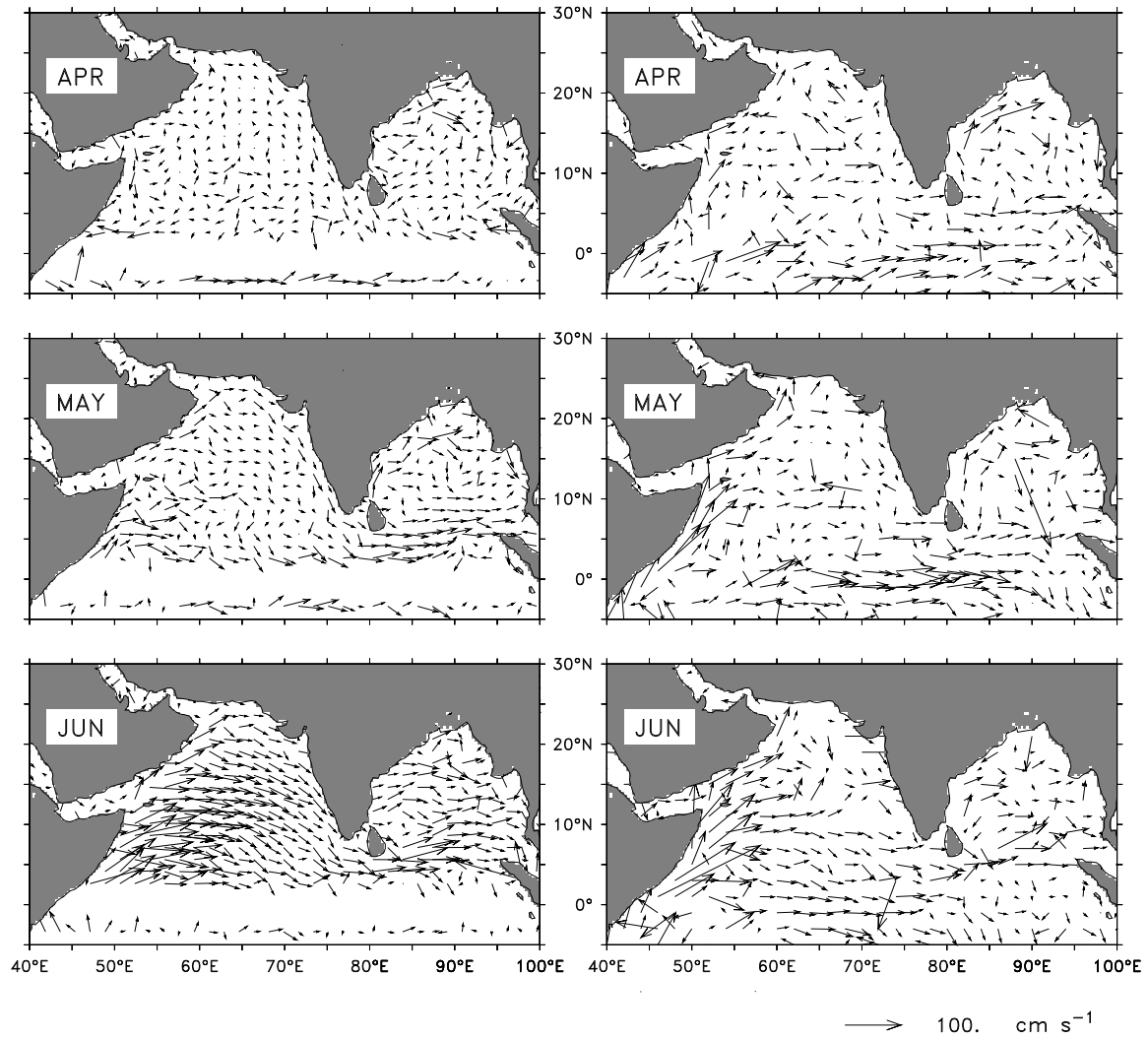


Fig. 9. (continued)

Current to the eastern bay in both data sets; this marks the beginning of its mature phase, which starts earlier than that of the GSMC because of the Ekman drift. An equatorward, geostrophic WICC feeds into the SMC in the NF, but the WICC is weaker in the SD. Ekman drift and geostrophic flow combine to produce the SMC in the Arabian Sea, the former dominating in the west and the latter in the east. In the NF, these two components combine to form a curving flow across the Arabian Sea, but this current flows zonally across the basin at 10°N in the SD.

The Ekman drift overwhelms geostrophic flow when the summer monsoon winds strengthen in June. This is more so in the Arabian Sea, where the currents cross the isolines of sea level, and a little less in the bay, where weaker winds compared to the

Climatology of net surface flow and ship drifts

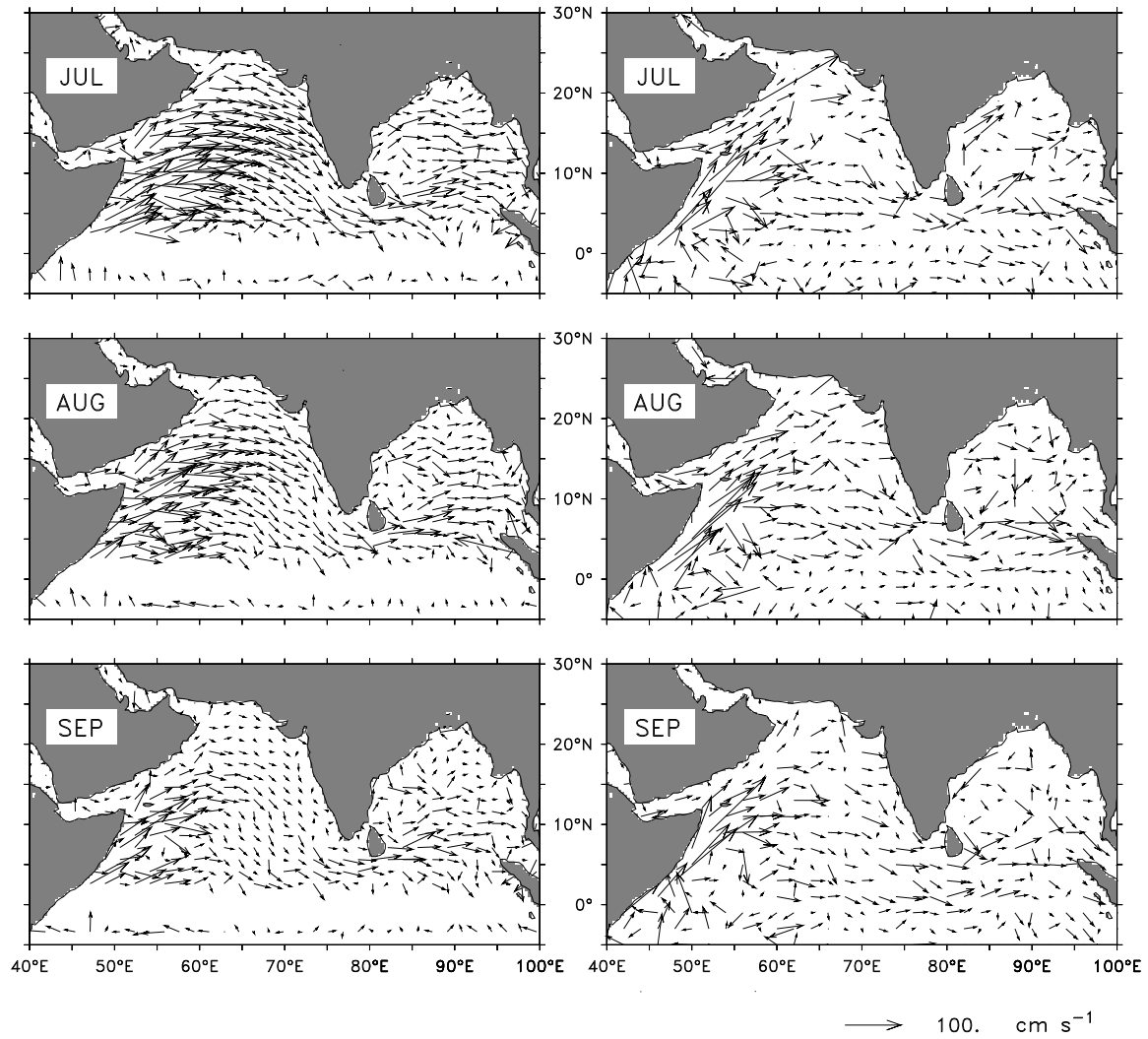


Fig. 9. (continued)

Arabian Sea (Fig. 1) combine with the multiplicity of eddies (Fig. 5) to make the NF different from the uniform eastward Ekman drift. Though the SD are noisier, the dominance of Ekman drift is seen in them too. In June, therefore, the SMC appears as an eastward or southeastward flow in the Arabian Sea and an eastward or northeastward flow in the bay.

The summer-monsoon winds peak in July; so does the Ekman drift. Geostrophy makes a significant contribution to the surface current only in the bay and south of Sri Lanka. Though there is agreement between the NF and the SD, the latter also show the effect of the winds on the ships. The mature SMC flows eastward or southeastward all over the Arabian Sea, and northeastward into the bay. There

Climatology of net surface flow and ship drifts

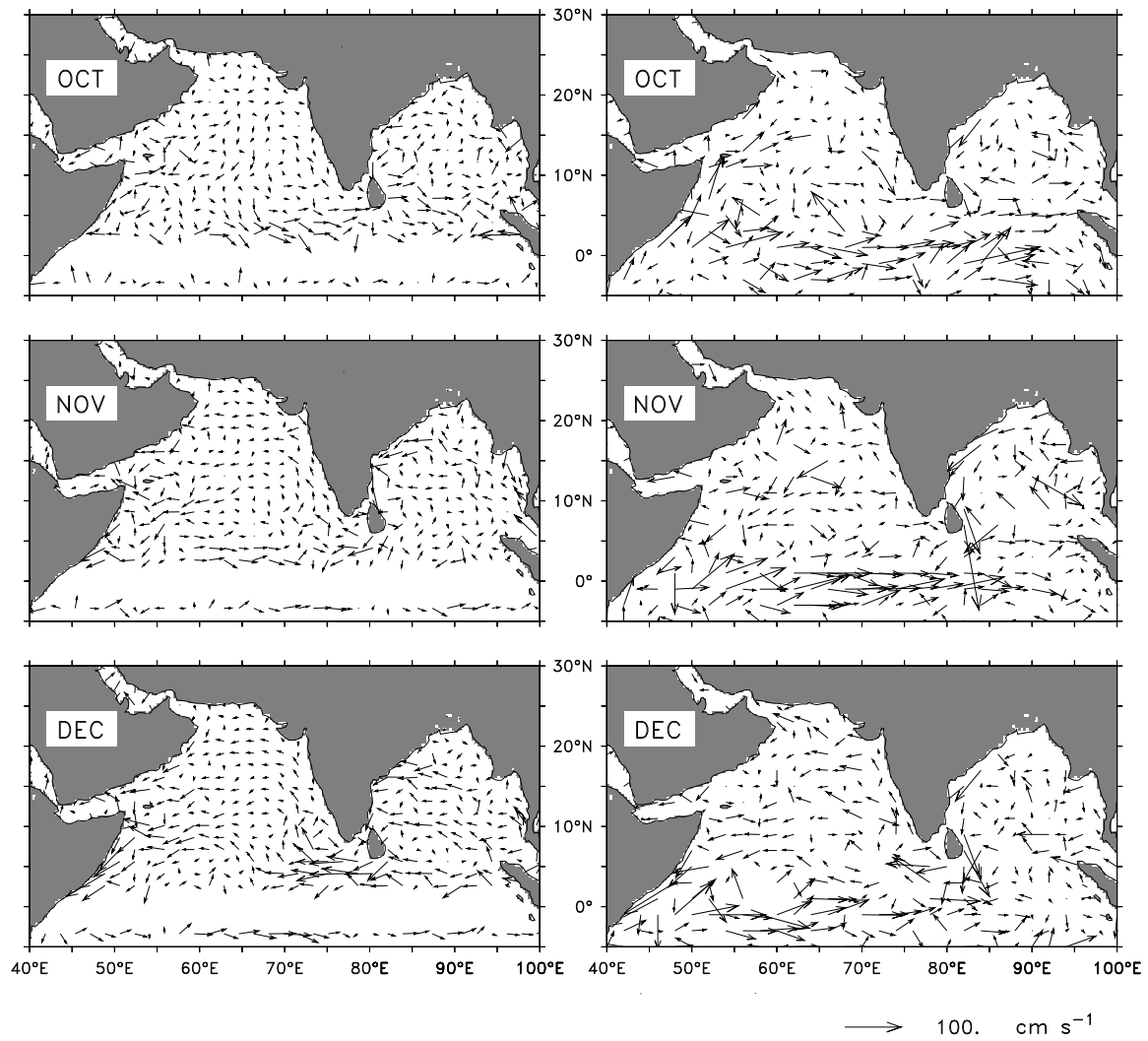


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is, however, a current branching off from the SMC south of Sri Lanka and flowing eastward-southeastward; a part of this flow, due to the Ekman drift, also crosses the equator in the SD (Fig. 9) and surface drifters (Shenoi et al., 1999a).

Apart from a weakening of the SMC owing to slightly weaker winds, the NF and the SD during August are as in July.

The summer-monsoon winds continue to weaken through September, making geostrophy more relevant to the surface flow field. In the Arabian Sea, the Ekman drift dominates, except in the southeast, where geostrophic flow around the Lakshadweep low is important, and in the vicinity of the Great Whirl off Somalia, where there is strong geostrophic flow around a sea-level high. In the bay, the Ekman drift dominates in the south, forcing a broad eastward SMC, but geostrophy is strong enough to make a part of the flow turn northeastward into the central bay. In the rest of the bay, geostrophic flow around eddies dominates.

October being a month of transition, the Ekman drift is negligible, except in the southern bay and to the southwest of Sri Lanka. Nevertheless, it combines with geostrophy to sustain the SMC as a continuous current from the Arabian Sea to the bay; the mature phase of the SMC therefore extends beyond the summer monsoon, unlike that of the GSMC. The SMC is split in the bay, a separate relic existing as a geostrophic northeastward flow from eastern Sri Lanka to the central bay. These features are also evident in the SD, except that the relic SMC is farther east.

Though there are differences between the NF and the SD, the major discrepancy being the greater strength of the SD, the two exhibit similar features in the domain of the monsoon currents. The Ekman drift dominates the surface circulation in the north Indian Ocean during the summer monsoon, with geostrophy being significant only south of Sri Lanka, around the eddies off Somalia, and in the Bay of Bengal. Both geostrophy and Ekman drift are important during the winter monsoon. During the transitions between the monsoons, in March–April and October, geostrophy dominates the circulation.