

### 3 The monsoon currents in an OGCM

The observations show that both Ekman drift and geostrophy contribute to the surface circulation in the north Indian Ocean. The former decays rapidly with depth, but the latter is expected to be significant even in the subsurface layers. We use a multi-level Oceanic General Circulation Model (OGCM) to ascertain the vertical structure of the monsoon currents and to estimate their transports.

#### 3.1 Numerical model

The OGCM is based on the Modular Ocean Model (Pacanowski, 1996). The model domain covers the tropical Indian Ocean ( $30^{\circ}\text{S}$ – $30^{\circ}\text{N}$ ,  $30^{\circ}$ – $115^{\circ}\text{E}$ ). The model has realistic coastline and topography based on the ETOPO5 data set. The horizontal resolution is  $0.33^{\circ} \times 0.33^{\circ}$  and there are 25 levels in the vertical, of which eight are in the top 100 m. Horizontal eddy viscosity and diffusivity are  $2 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$  and  $10^7 \text{ cm}^2 \text{ s}^{-1}$  respectively, and vertical mixing is parameterized using the scheme of Pacanowski and Philander (1981). The model is spun up for five years from a state of rest and climatological temperature (Levitus and Boyer, 1994) and salinity (Levitus et al., 1994) using the wind-stress climatology of Hellerman and Rosenstein (1983).

The model reproduces the monsoon circulation in the Indian Ocean reasonably well. Vinayachandran et al. (1999a) compared the SMC along  $6^{\circ}\text{N}$  in a similar model with TOPEX/Poseidon altimetry and geostrophic currents. They found that the model SMC near Sri Lanka compares well with that derived from TOPEX/Poseidon altimetry, but the core of the SMC east of Sri Lanka was weaker in the model compared to that derived from XBT data. Vinayachandran, Saji, and Yamagata (1999b) used the model to investigate the unusual conditions in the equatorial Indian Ocean in 1994 and noted that the model Equatorial Current is consistent with direct current measurements (Reppin et al., 1999).

### 3.2 *The model circulation*

The flow in the first 3 model levels is dominated by Ekman flow, geostrophy dominating below this. At each level, however, both contribute to the model flow field. Hence, we present the model circulation at 5 m and 35 m depths, comparing them with the Ekman drift and geostrophic flow. Then we present the depth-averaged flow in the top 50 m, which is more representative of the shallow monsoon currents than the surface flow alone.

As the model flow is a composite of both Ekman and geostrophic flows, there are several additional features in it at 5 m (Fig. 10) compared to the estimated Ekman drift (Fig. 3). For example, the model flow at 5 m contains strong coastal currents, including the Somali Current, the coastal current off Oman, the EICC, and the WICC. The EICC flows equatorward during November and feeds the westward WMC south of Sri Lanka, this flow standing out from the eastward Equatorial Current (the fall Wyrki jet). In the western Arabian Sea, there is a westward drift at  $\sim 9^\circ\text{N}$ ; this is the relic SMC or the incipient WMC. The mature, trans-basin WMC exists at the surface during December–March. Most of the flow is westward at  $\sim 5^\circ\text{N}$ , but a branch of the WMC turns to flow around the Lakshadweep high in the southeastern Arabian Sea; this branch of the WMC propagates westward. Apart from the WMC, the outstanding feature during the winter monsoon is the anticyclonic gyre in the bay. Thus, during the winter monsoon, when the winds are relatively weak, geostrophy dominates even at the surface, the Ekman drift modulating the geostrophic currents.

The Ekman drift dominates the model surface flow during the summer monsoon. Nevertheless, the coastal currents, the intrusion of the SMC into the bay, and the flow around the eddies off Somalia, which are due to geostrophy, are evident even at 5 m. At the surface, the mature phase of the SMC extends from May to October, like the NF and the SD. The model SMC south of Sri Lanka is fed by the southeastward drift across the Arabian Sea; unlike in the NF, the contribution from the flow due west is much less. As in the NF, a current branches off from the SMC south of Sri Lanka to flow eastward-southeastward and across the equator.

The model currents at 35 m (Fig. 11) compare well with the geostrophic flow

(Fig. 5). The genesis and decay of the (G)WMC and (G)SMC follow the pattern established from satellite altimetry. There does not, however, seem to be a clear link between the recirculation in the eddies off Somalia and the SMC south of Sri Lanka; the latter is fed more by the branch of the SMC that flows around the Lakshadweep low, and this flow, in turn, is fed by the WICC and the flow across the central Arabian Sea. The recirculation in the eddies off Somalia instead flows mostly into the eastward current in the western equatorial Indian Ocean. This eastward current feeds the SMC south of Sri Lanka in the SD (Fig. 9) and in the simulations of McCreary et al. (1993); it crosses the equator, however, in the OGCM

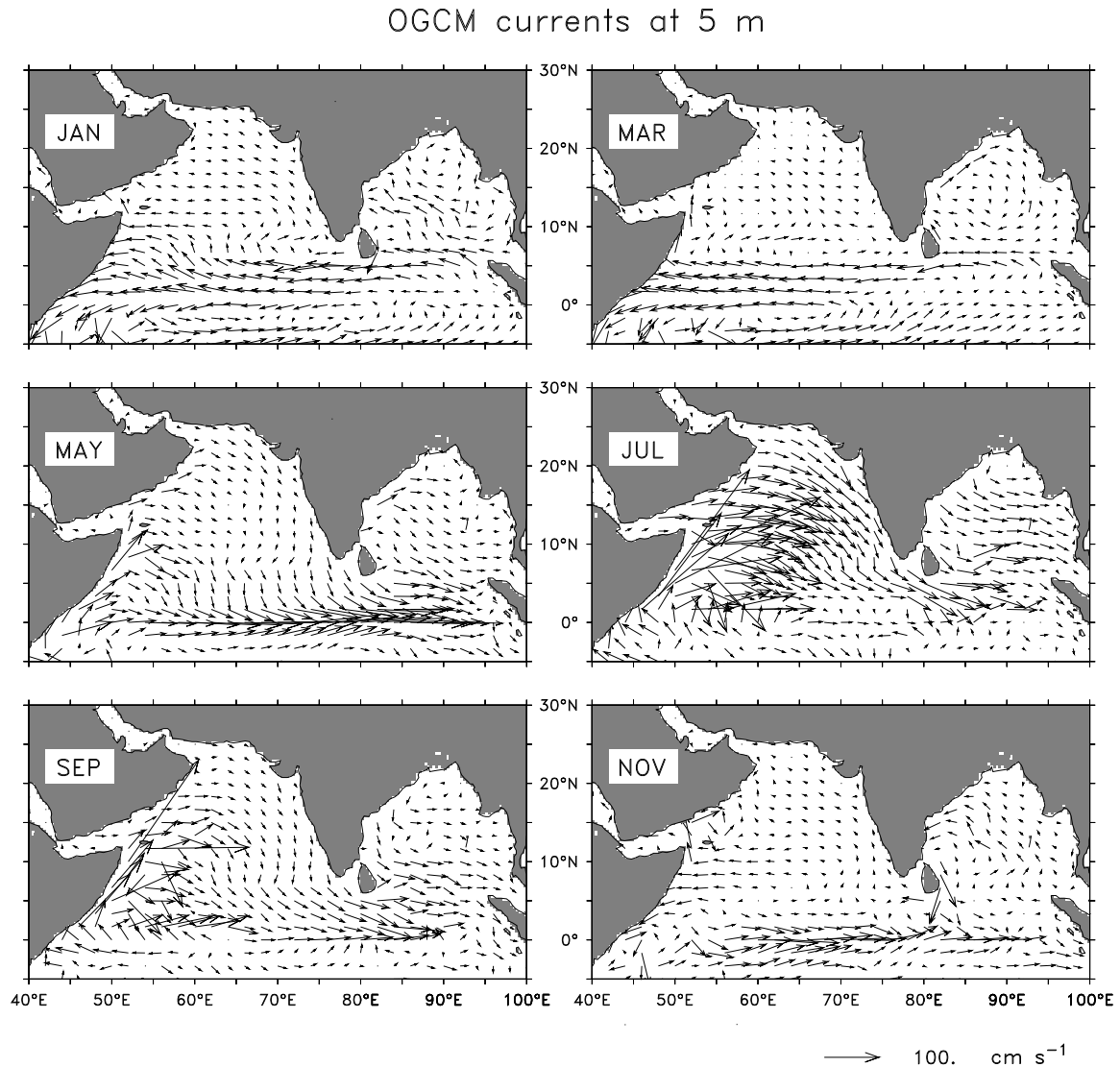


Fig. 10. OGCM currents ( $\text{cm s}^{-1}$ ) at 5 m. The model flow at this depth is dominated by Ekman drift.

simulations and in the surface-drifter data (Shenoi et al., 1999a).

In the depth-averaged flow (DAF) in the top 50 m (Fig. 12), the mature WMC is as in the NF and appears primarily as a geostrophic flow modulated by the Ekman drift; the mature phase of the depth-averaged WMC also extends from December to March. A part of the DAF around the eddies off Somalia feeds the eastward Equatorial Current in the western Indian Ocean, but, unlike in the 35 m flow field, most of it merges with the Ekman drift to form a broad, basin-wide, southeastward flow across the Arabian Sea; this current forms the broad western arm of the flow around the Lakshadweep low off southwest India, and feeds into the SMC south of

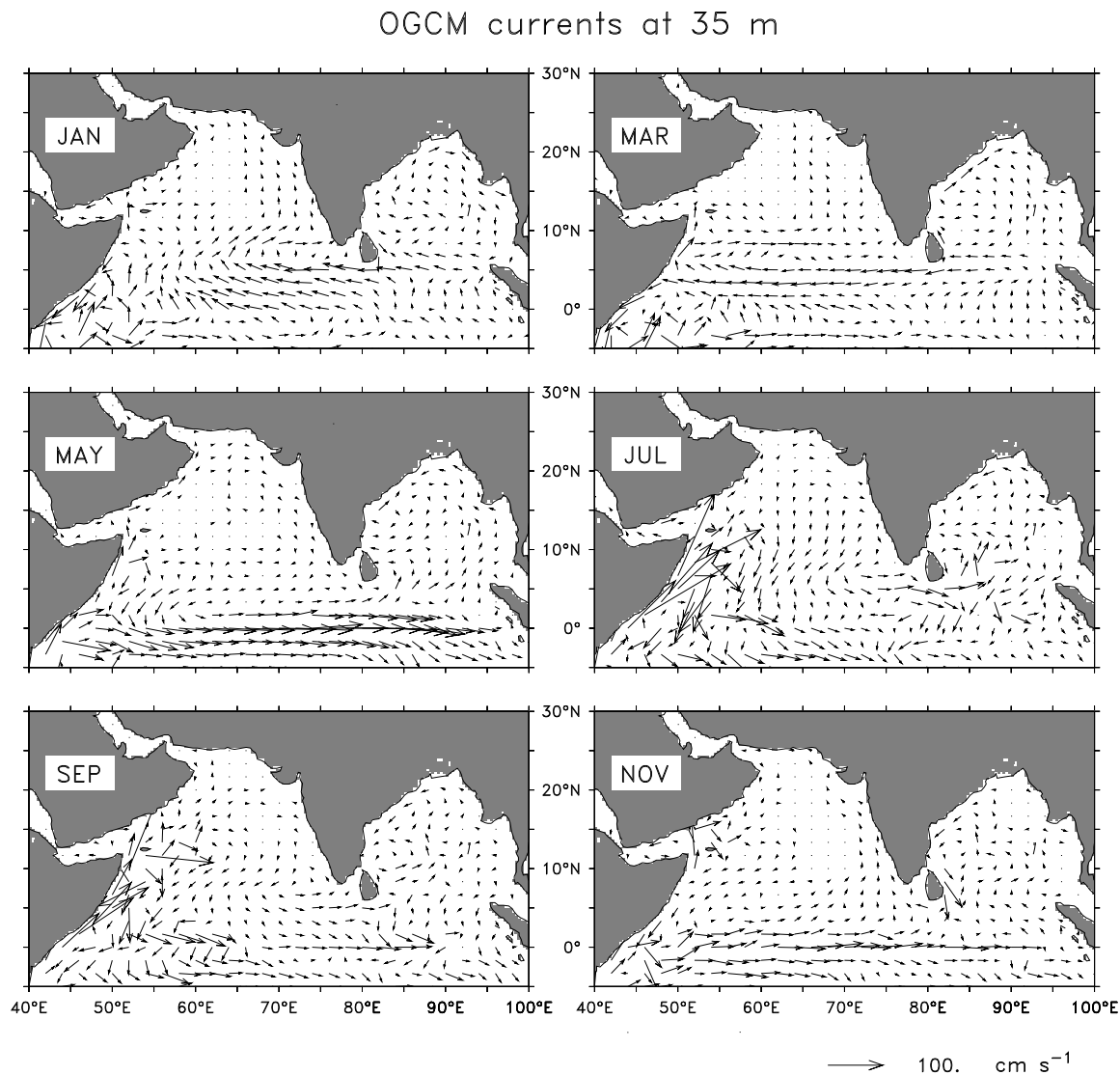


Fig. 11. OGCM currents ( $\text{cm s}^{-1}$ ) at 35 m. The model flow at this depth is dominated by geostrophy.

Sri Lanka. In the bay, the northeastward SMC is primarily geostrophic. The mature phase of the depth-averaged SMC extends from May to September, ending a month before that at the surface; this is because the Ekman drift is weaker in the DAF.

Westward propagation associated with Rossby waves forms an essential component of the monsoon circulation in the north Indian Ocean (Fig. 13); this is best seen in the flow at 35 m. In the bay, however, westward propagation is seen at all depths over the entire year, indicating the dominance of geostrophy there. During the summer monsoon, the dominance of the Ekman drift eliminates the Rossby wave signal at 5 m, but westward propagation is seen at 35 m; this signal, however, is weak, possibly because the strong eastward Ekman drift slows down the Rossby

OGCM currents averaged over top 50 m

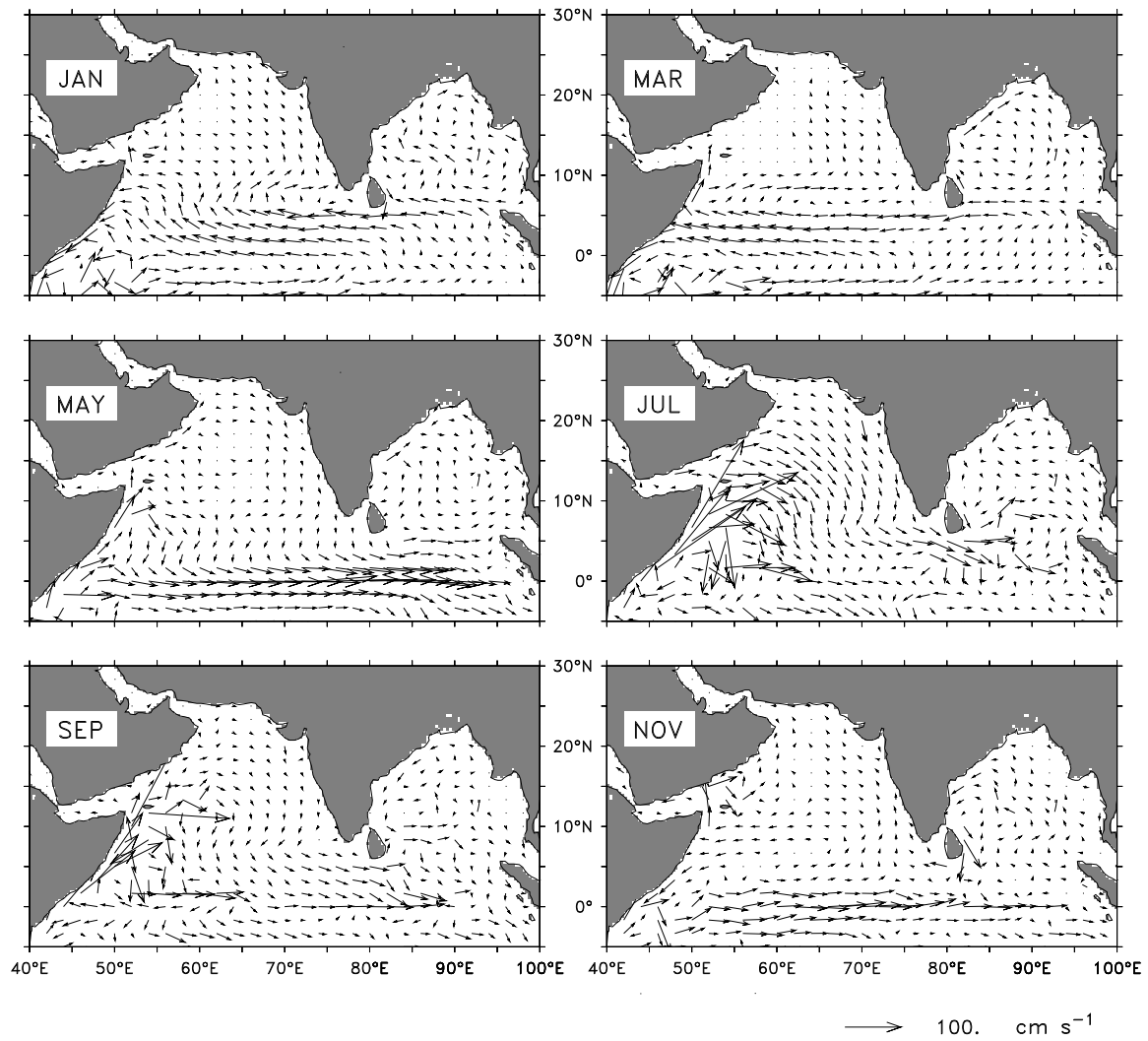


Fig. 12. OGCM currents ( $\text{cm s}^{-1}$ ) averaged over the top 50 m.

waves (Vinayachandran and Yamagata, 1998).

The monsoon currents are shallow, unlike the deep currents observed off Somalia during the summer monsoon (Schott and McCreary, 2001). The shallowness of the monsoon currents in the OGCM, especially the SMC, is seen in the depth-time plot of the zonal current at 80.5°E (Fig. 14). The SMC was shown by Vinayachandran and Yamagata (1998) to be trapped close to the surface because of the downwelling Rossby wave propagating westward from the eastern boundary of the equatorial Indian Ocean. This downwelling Rossby wave is associated with southwestward

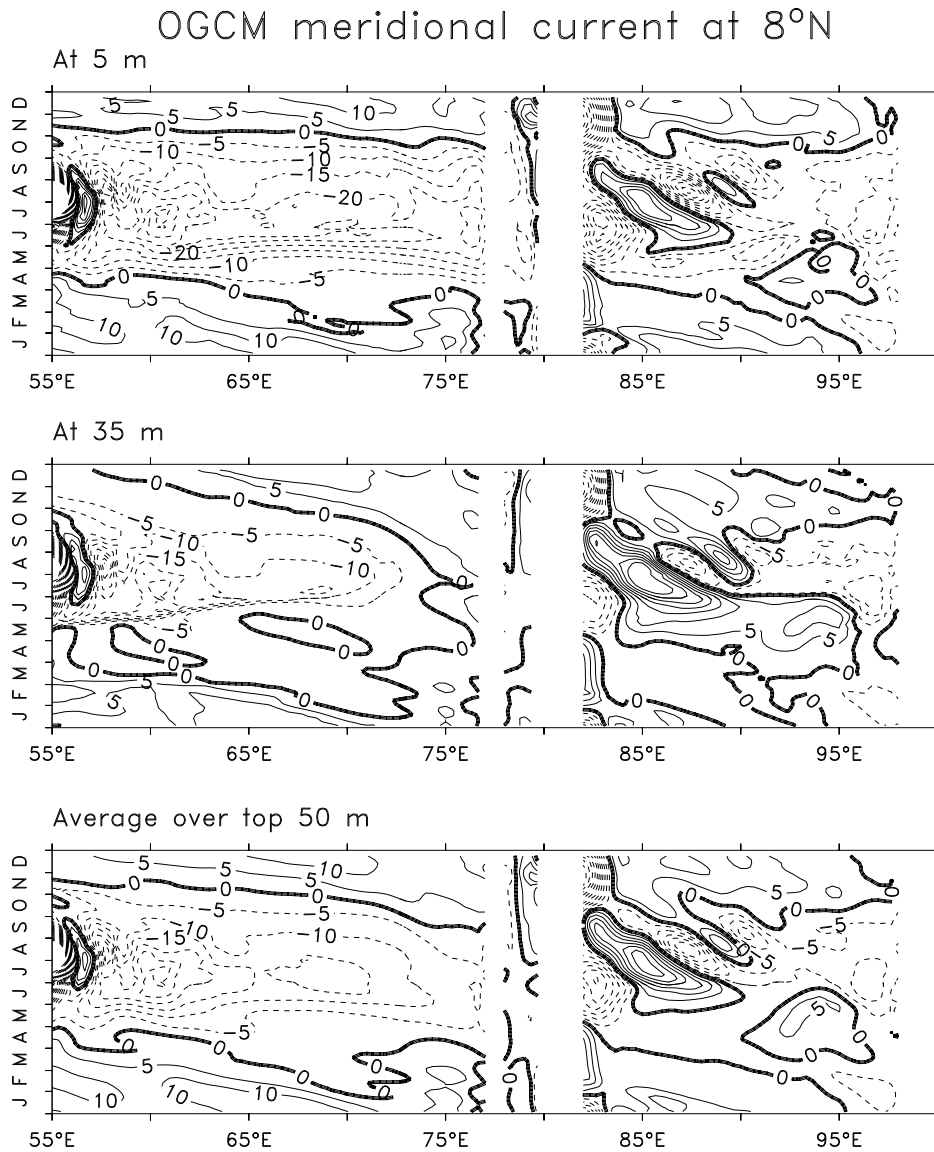


Fig. 13. Longitude-time plots of the OGCM meridional current ( $\text{cm s}^{-1}$ ) at 8°N. Southward flows are indicated by dashed contours and the contour interval is  $5 \text{ cm s}^{-1}$ .

geostrophic flow. As it propagates westward, the westward geostrophic flow dominates the eastward Ekman component, causing the latter to shallow. This signature of westward flow is seen in the westward flow below the eastward SMC during the summer monsoon; upward (downward) propagation of phase (energy) is evident (Fig. 14), as in the observations (Schott et al., 1994; Reppin et al., 1999), indicating the existence of free propagating waves.

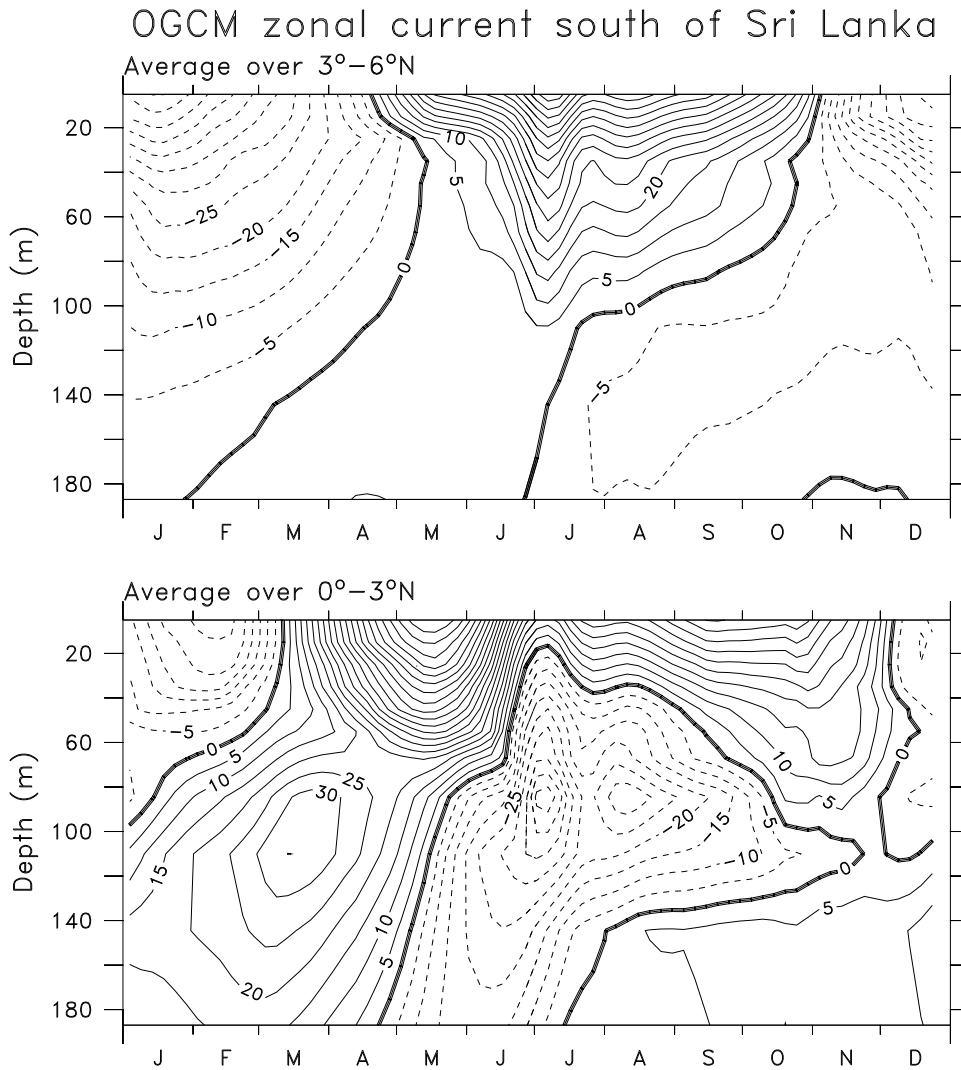


Fig. 14. Depth-time plots of the OGCM zonal current ( $\text{cm s}^{-1}$ ) at  $80.5^\circ\text{E}$  (south of Sri Lanka). The top (bottom) panel shows the current averaged over  $3^\circ\text{--}6^\circ\text{N}$  ( $0^\circ\text{--}3^\circ\text{N}$ ). Westward flows are indicated by dashed contours and the contour interval is  $5 \text{ cm s}^{-1}$ .

### 3.3 *Transport estimates*

Since subsurface observations of these seasonal, open-ocean currents are limited (see Table 2), numerical models that simulate well the observed surface circulation are an important source of information on the transports associated with them. Given the significant contribution of Ekman flow to the depth-averaged flow in the top 50 m, a comparison between the model transport and estimates based on hydrography is not meaningful. Hence, we choose to compare the model transports with those estimated from direct current measurements south of Sri Lanka (Schott et al., 1994). Given that the observations are from a particular year, while the model represents a climatology, the comparison is good (Table 3).

Latitude-time plots of the depth-integrated zonal current (Fig. 15) show that the WMC is relatively narrow and strong across the basin. In contrast, the SMC stands out only south of Sri Lanka and in the bay, where its eastward flow is seen to shift poleward with time, marking the westward propagation of the northeastward SMC across the bay. In the Arabian Sea at  $65^{\circ}\text{E}$ , the depth-integrated SMC is weak, but broad; the eastward flow extending from  $\sim 12^{\circ}$ – $20^{\circ}\text{N}$  during the summer monsoon; the weak westward flow between  $4^{\circ}$ – $6^{\circ}\text{N}$  and the weak eastward flow between  $0^{\circ}$ – $4^{\circ}\text{N}$  show the complicated spatial structure of the geostrophic flow associated with the SMC (Fig. 11). The model transports associated with the SMC and WMC are listed in Table 4.



Period	Observed	Model
10 Jan to 15 Feb	-12.8	-10
10 Jan to 15 Feb*	-10.4	-10
1 Jun to 5 Jul	8.4	9.1
10 Jul to 15 Aug	4.1	6.2
1 Jun to 15 Aug	7.8	7.9
1 Nov to 30 Mar	—	-7.1
1 May to 30 Sep	—	5.4

Table 3

Observed and model zonal transports (in Sv;  $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ) in the top 300 m between  $3^\circ 45' \text{N}$  and  $5^\circ 52' \text{N}$  at  $80.5^\circ \text{E}$  (south of Sri Lanka). Positive (negative) values indicate eastward (westward) flow, and the values listed are averages over the period indicated. All observations, except that marked (\*), are for 1991; the marked observation is for 1992. The observed transports are derived from the direct current measurements of Schott et al. (1994). The model was forced by climatological wind stress (Hellerman and Rosenstein, 1983). The last two values are average model transports for the winter and summer monsoons, respectively.

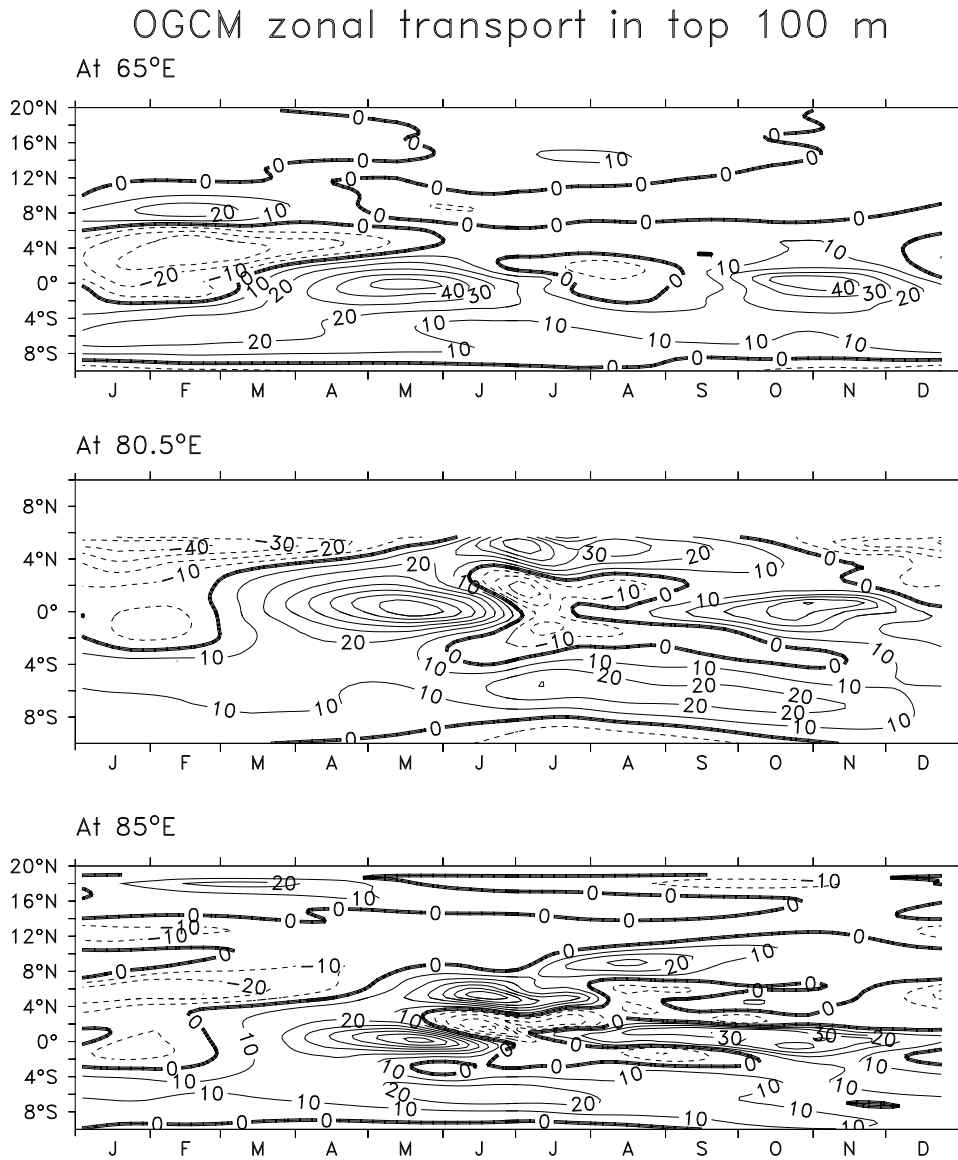


Fig. 15. Latitude-time plots of the depth-integrated zonal current ( $\text{m}^2 \text{s}^{-1}$ ) in the OGCM. The current is integrated over the top 100 m. Westward flows are indicated by dashed contours and the contour interval is  $10 \text{ m}^2 \text{ s}^{-1}$ . In the Arabian Sea ( $65^\circ\text{E}$ ), the core of the westward (eastward) part of the WMC is at  $4^\circ\text{N}$  ( $8^\circ\text{N}$ ); in the bay ( $85^\circ\text{E}$ ) and south of Sri Lanka ( $80.5^\circ\text{E}$ ), the core of the westward WMC is at  $\sim 5^\circ\text{N}$ . In contrast, the SMC has a more complicated spatial structure owing to the curvature of the geostrophic flow.

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Current	Location	Period	Transport
WMC	65°E, 2.5°–6°N	February	-13.1
WMC	65°E, 0°–6°N	February	-19.0
WMC	80.5°E, 3°–6°N	January	-10.1
WMC	85°E, 3°–7°N	January	-8.1
SMC	65°E, 12°–20°N	July	6.8
SMC	80.5°E, 3°–6°N	June–July	8.1
SMC	85°E, 4°–8°N	June	15.3
SMC	85°E, 7°–11°N	August	7.4

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Table 4

OGCM zonal transport (in Sv;  $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ) in the top 100 m in the domain of the monsoon currents. Negative values indicate westward flows and the transports are averages over the periods mentioned.