

5 Summary

We have described the climatological seasonal cycle of surface circulation associated with the open-ocean monsoon currents in the north Indian Ocean. Both Ekman drift, estimated from climatological wind stress, and surface geostrophic currents, derived from hydrography and TOPEX/Poseidon altimetry, contribute to the net surface current. The monsoon currents extend over the entire basin, but they do not come into being, or decay, over this region at a given time. Different parts of the currents form and decay at different times, and it is only in their mature phase that the monsoon currents exist as continuous, trans-basin currents. Both Ekman drift and geostrophy make significant contributions to the monsoon currents and to the transports associated with them.

Observations and numerical simulations using an OGCM show that the WMC, in its mature phase during December–March, is primarily a geostrophic current, with Ekman drift modulating it. It flows westward from the eastern Bay of Bengal to Sri Lanka and beyond. In the Arabian Sea, the WMC branches, one branch flowing westward, the other turning around the Lakshadweep high in the southern Arabian Sea to flow eastward into the poleward WICC. The Ekman drift, in contrast to the geostrophic flow, is unidirectional (westward); hence, at the surface, it accentuates the westward flow of the WMC to the south of the Lakshadweep high, and attenuates the eastward flow of the WMC to its north. The curving flow of the WMC around the high is, therefore, clear only below ~ 20 m. This definition of the WMC differs from that in earlier work, which considered only the westward flow to be the WMC; we do not differentiate between the two parts of this continuous current because they form the front of the westward propagating Rossby wave radiated from the Indian west coast, and are, therefore, dynamically indistinguishable.

In its mature phase, the SMC flows eastward, from the western Arabian Sea to the eastern Bay of Bengal. The strong winds during the summer monsoon ensure that Ekman drift dominates at the surface, with geostrophy dominating below ~ 20 m. This leads to a more complex vertical structure than is associated with the WMC. Hence, the mature phase extends from May to October at the surface, but ends a month earlier in the depth-averaged flow over the top 50 m. At the surface, the mature SMC in the Arabian Sea flows eastward and southeastward over most of

the basin, feeding into the eastward SMC south of Sri Lanka; this current flows eastward and northeastward into the bay. The geostrophic SMC, which dominates below ~ 20 m, is a continuation of the Somali Current. A part of the recirculation around the eddies off Somalia merges with the flow to the west of the Lakshadweep low off southwest India to form a curving current that flows into the eastward SMC south of Sri Lanka; this flows northeastward into the bay. In our definition, the mature SMC in the Arabian Sea is the broad, basin-wide, east-southeastward flow whose signature is seen in both surface flow and depth-averaged flow. The core of this current lies in the central Arabian Sea, where the geostrophic outflow from the eddies off Somalia accentuates the Ekman drift. It is this core that was considered the SMC in earlier work. We do not distinguish between the core and the rest of the flow because both are forced by the same set of processes. The mature phase of the monsoon currents, as defined in this paper, is summarised in a schematic (Fig. 27).

Numerical simulations with a reduced-gravity model show that the monsoon currents are composed of several parts, each of which is forced by one or more processes. In the Bay of Bengal, the major processes are Ekman pumping and remote forcing from the equatorial Indian Ocean. The continuity of the SMC south of Sri Lanka is primarily due to remote forcing by the winds along the east coasts of India and Sri Lanka, which force the Lakshadweep high off southwest India and contribute significantly to forcing the monsoon currents in the eastern Arabian Sea. In the rest of the Arabian Sea, Ekman pumping combines with Rossby waves radiated from the west coast of India to produce the curving flows associated with the geostrophic monsoon currents. Superimposed on these geostrophic flows is the local Ekman drift. Thus, a simple linear framework based on three linear, baroclinic waves — the equatorial Kelvin wave, the equatorial Rossby wave, and the coastal Kelvin wave — and the Ekman drift is sufficient to explain the seasonal cycle of the monsoon currents.

That the monsoon currents, despite their complexity, are seen in climatology is due to the regular seasonal cycle associated with the monsoon. This — regularity, bordering on predictability — is one facet of the monsoon. Another facet of the monsoon is fickleness: the monsoon varies a lot from one year to another. This results in considerable interannual variability in the monsoon currents (Fig. 28). There are also variations on the sub-monthly time scale superimposed on the seasonal

monsoon, forcing sub-monthly variability in the monsoon currents (Fig. 29). The sea-level anomalies and geostrophic currents from each TOPEX/Poseidon cycle (Fig. 29) show a much richer structure than do the monthly averages or climatology (Fig. 28). Though still identifiable as continuous trans-basin flows in these “snap-

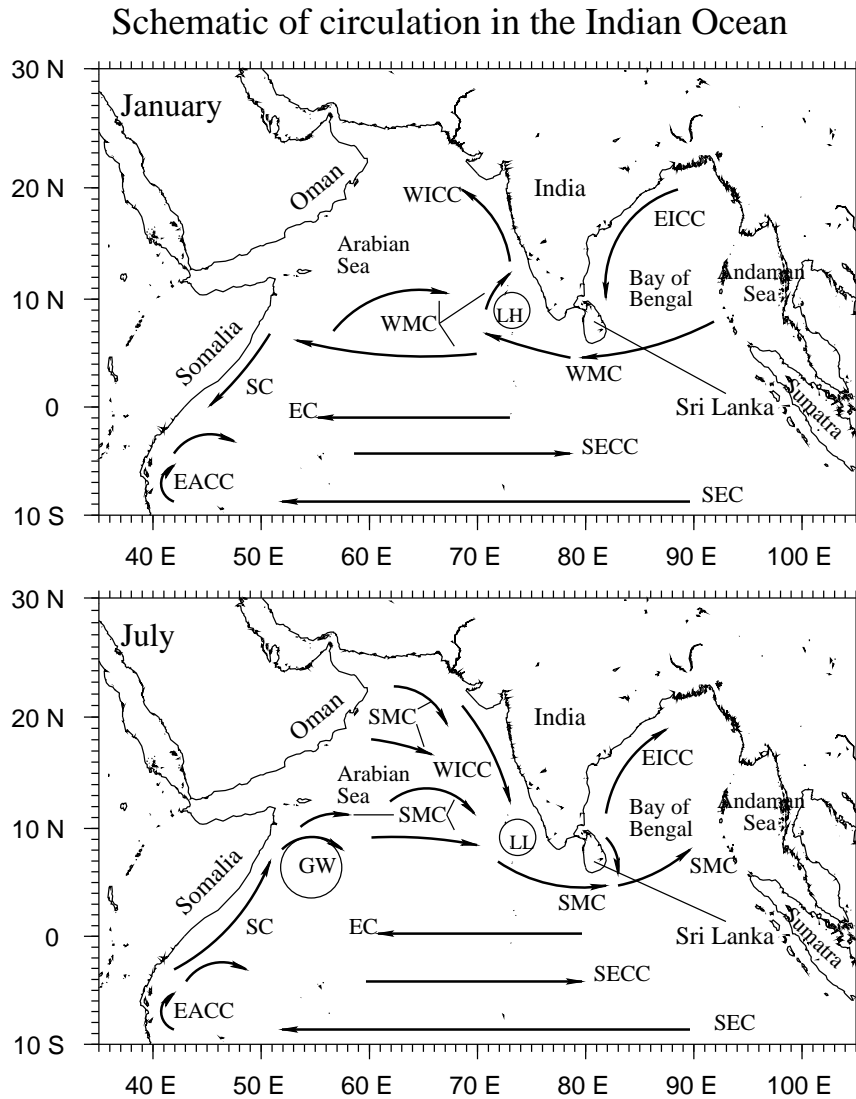


Fig. 27. Schematic representation of the circulation, as described in this paper, in the Indian Ocean during January (winter monsoon) and July (summer monsoon). A comparison with the schematic in Fig. 2 shows the differences between earlier descriptions of the monsoon currents and the description in this paper. 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.

shots,” the currents meander much more in flowing past the many eddies that dominate the flow field. The climatological geostrophic monsoon currents are therefore the weaker ensembles of these meandering currents.

The multiplicity of eddies in the TOPEX/Poseidon sea-level anomalies is reminiscent of the eddy-dominated flow seen in the hydrographic data of the IIOE (Düing,

Interannual variability in surface geostrophic flow

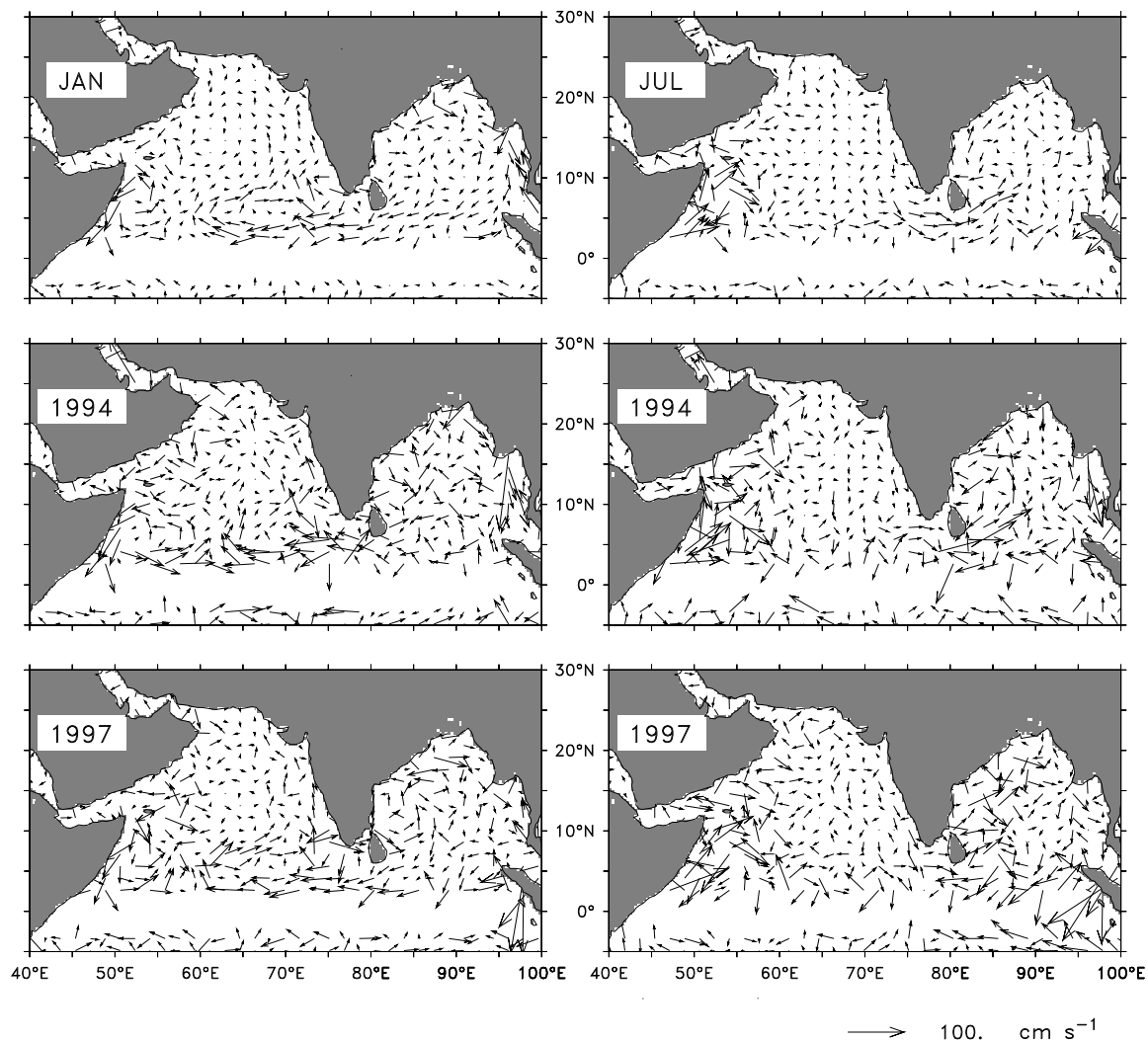


Fig. 28. Monthly-mean geostrophic current (cm s^{-1}), derived from TOPEX/Poseidon altimetry, for January (left panels) and July (right panels). The top panels show the monthly climatology (1993–1997), as in Fig. 5. The middle panels show the monthly-mean geostrophic currents for 1994 (January on left and July on right), and the bottom panels for 1997. The monthly averages for the years 1994 and 1997 differ from climatology, even though the monsoon currents can be traced in both these years.

1970; Wyrki, 1971). Those eddies, however, were due to sparsity of data, which prevented the mean currents from standing out. The eddies seen in altimetry are, on the other hand, due to the better resolution that the satellite data afford in both space and time. The vast amount of such “near-synoptic” data being made available by satellites reveals more complex structures in the domain of the monsoon currents as the resolution of the data becomes finer in space and time. That eddies are common in the north Indian Ocean is obvious from these data, which reveal

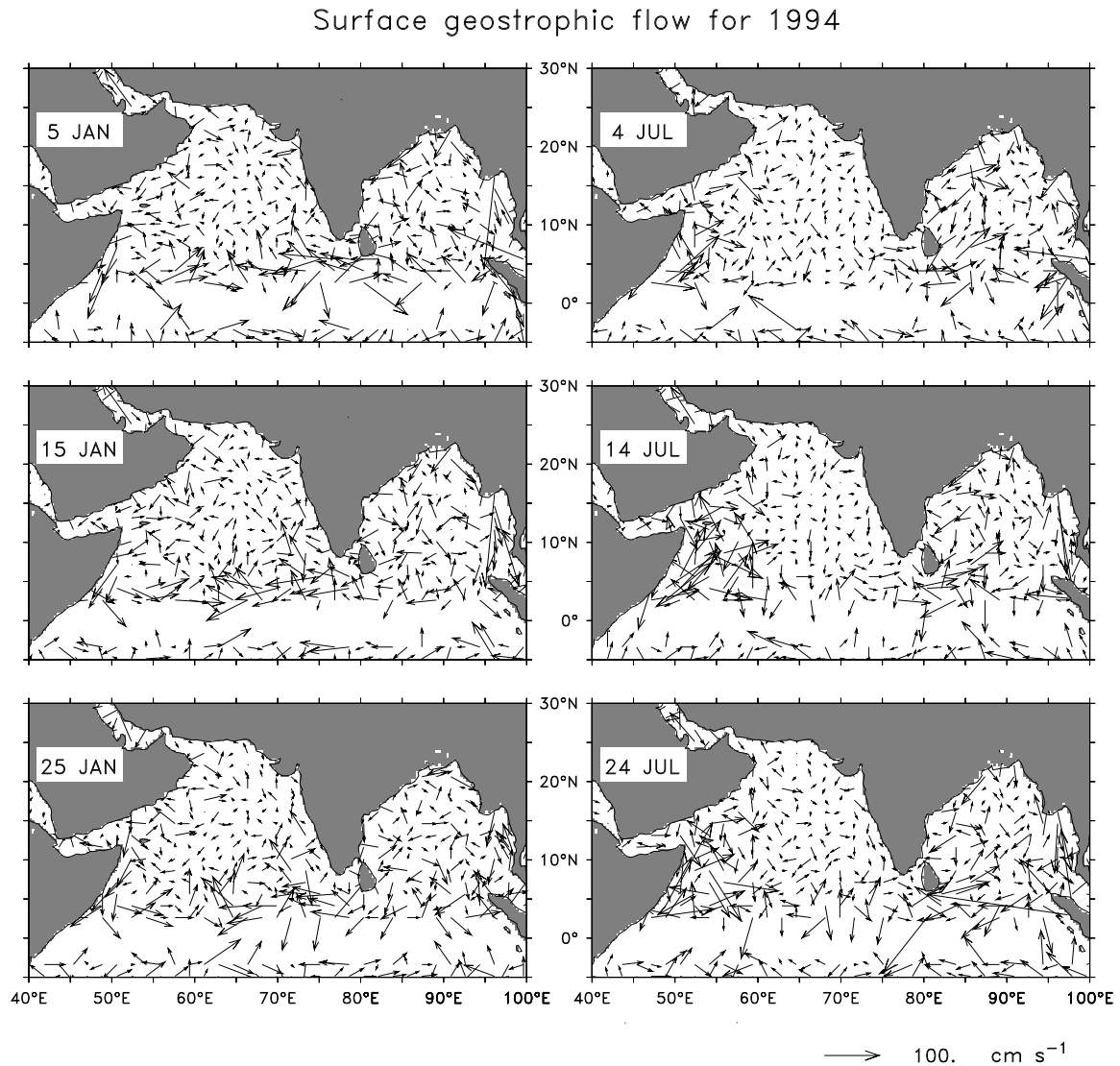


Fig. 29. Geostrophic currents (cm s^{-1}) from TOPEX/Poseidon altimetry for three cycles each during January (left panels) and July (right panels) of 1994. The GWMC and GSMC can be traced even in individual TOPEX/Poseidon cycles, even though the currents are more noisy and meander more than in climatology or in monthly averages (Fig. 28).

a picture of the surface circulation that is quite different from the smooth currents seen in climatology or monthly means, or in the simulations described in this paper. It remains to be seen if the linear theoretical framework described herein will hold even for the eddying motion evident at these spatial and temporal scales, or if its applicability is restricted to the ensemble of these eddies that is represented by the seasonal cycle.

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