CHAPTER IV
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EQUATORIAL UNDERCURRENT IN THE INDIAN OCEAN

A critical review of the available information on the Equatorial Undercurrent has been carried out in the introduction of the present thesis. In that, the significance of the unique nature of the Indian Ocean from those of the other two major oceans, namely, the Pacific and Atlantic has been brought to focus. The distinction, mainly, being the contrasting atmospheric circulation that in turn reflects on the oceanic surface and subsurface currents has also been emphasised. In this chapter an attempt is being made to discuss the results of the present study on the Equatorial Undercurrent in the Indian Ocean with an objective of explaining the physical processes involved in its formation, establishment and termination, and also its deviation from the Undercurrent present in the Pacific and Atlantic.

4.1.1. From the distribution of temperature, salinity and oxyty at various transequatorial sections and the flux, it can be inferred that the Equatorial Undercurrent in the Indian Ocean is present only during January to early June with varied intensity and latitudinal shift in different
months, sometimes commencing even in December. During the rest of the period of the year, the Equatorial Undercurrent with its normal characteristic features is not identified in the Indian Ocean, although there is easterly flow observed both at the surface and subsurface levels with different structure in its magnitude as well as direction. Some of the important features associated with the presence or the absence of the Undercurrent are as follows.

4.1.2. The Equatorial Undercurrent in the Indian Ocean commences its development from the west in January or December and extends eastward with time. From the figures 1, 2 and 3, it is obvious that the Undercurrent is present slightly north of the equator along 58°E with the associated characteristic features of spreading of thermocline, high salinity core and penetration of oxyty to deeper levels, while such features are not conspicuous along 76° and 86°30'E. It can be seen that the core of the Undercurrent appears to be slightly north of the equator at 58°E which may be due to the upwind shift, resulted from the northerly winds prevailing at the equator. Such a wind shift was also reported by Leetmaa and Stommel (1980) while explaining the features of the current observations made in the western Indian Ocean in 1975 and 1976. The measurements of Duing et al. (1967) at 58°E during the end of January 1965 do not show the
evidence of an eastward flow above 100 m. Based on this observation Leetmaa and Stommel (1980) concluded that the Undercurrent either sets up extremely quick (from mid January to mid February) or 1965 was an unusual year. From the section along 76°E, a comparatively weak indication of Undercurrent is noticed, based on the salinity structure. The indication of the Undercurrent is still north of the one found along 58°E, probably, because of strong northerlies prevailing over in the western region. The surface flow at 86°30'E is easterly, penetrating to subsurface depth, as a result, the Undercurrent is not conspicuous (Fig. 3). An examination of the wind data between the east and western regions of the Indian Ocean reveal that the winds are northeasterlies in the western region and also strong while they are weakened towards the east and even reverse the direction in the easternmost region (Anonymous, 1952). It is, therefore, likely that the northeasterly winds prevailing in the western region are responsible for the development of the Undercurrent in this region, with a demarcation of the westerly flow in the surface and easterly in the subsurface layers, whereas, in the eastern region because of the westerly wind, the surface flow also is easterly and the Undercurrent is not at all conspicuous to be identified with the normal characteristics. It is further confirmed from the hydrographic properties that the sloping of the sea surface is steep between 76° and 86°30'E compared to that between 58° and 76°E. It is, perhaps,
possible that the variation in the sloping of the sea surface steepens from west to east.

4.1.3. From the distribution pattern of the hydrographic properties in February along 54°30'E, 65°E and 85°E, the Equatorial Undercurrent is conspicuously observed along the equator in all the three sections (Figs. 4, 5 and 6). It is, therefore, evident that the Undercurrent has shifted southward to the equator in the western region from January to February and also extended to the eastern region. The current measurements of Leetmaa and Stommel (1980) along 55°30'E in February 1975 and that of Ivanov (1964) in February 1961, along 93°E, confirm the presence of the Undercurrent with velocities 80 and 63 cm s⁻¹ at 75 m and 150 m respectively. But Taft and Knauss (1967) noticed an eastward current of only 15 cm s⁻¹ at a depth of 135 m along 85°E. The low value reported by Taft and Knauss (1967) can be due to a deviation in the atmospheric condition in 1963 compared to the other years (Taft and Knauss, 1967; Uda and Nakamura, 1973). The present results as well as the observations of Ivanov (1964) and Leetmaa and Stommel (1980) reveal that the Undercurrent is deepened from a depth of about 75 m at 55°30'E to a depth of 150 m at 93°E. According to Taft and Knauss (1967) also, the Undercurrent is shallower in the west (85 m at 61°E) than in the east (110 m at 92°E). Based on the zonal flux,
the Undercurrent appears to be present a steric level of 300 cl/t coinciding with the 20°C isotherm which runs slightly at a deeper level than that of the high salinity core.

4.1.4. The transequatorial distribution of hydrographic properties in March and April confirm the presence of the Undercurrent all along the width of the Indian Ocean. (Figs. 7 to 12). The distribution of the flux indicates the presence of the Undercurrent at the bottom of the thermocline between 200 and 280 cl/t in March and at 200 cl/t in April at 92°E. Both the distributions confirm the deepening of the Undercurrent towards the east. In these months the higher eastward flux is neither coinciding with the high salinity core nor is it within the thermocline but at the bottom of the thermocline. Knauss (1960), Montgomery and Stroup (1962) report that the core of the Undercurrent lies within the thermocline in the Pacific. Halpern's (1980b) observations at 152°W are also in agreement with the above results and his observations at 166°E indicate that the core of the Undercurrent is near the bottom of the thermocline. Stevenson and Taft (1971) conclude that there is no close association between the Undercurrent and the high salinity core.

Philander (1973), who made a critical review of the Equatorial Undercurrent in all the oceans remarks that
though the region of high salinity coincides with the region of strong eastward velocity, the two maxima need not coincide. Sturn and Voigt (1966) and Voigt et al. (1969) found that the maximum current to be below the salinity maximum which agrees with the present results.

The flux computed by Swallow (1964, 1967) based on the direct current observation in March 1964 comes to $14 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ while the present computation at $58^\circ \text{E}$ in March, based on the bivariate distribution, gives a total flux of $13.91 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ between the isanosteric surfaces of 200 and 400 cl/t (Fig. 33). Along $65^\circ \text{E}$ the total flux in the same month between these isanosteric surfaces is $18.38 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Fig. 34). In April, along $92^\circ \text{E}$, within the same isanosteric surfaces the total flux is $18.19 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Fig. 35). The eastward volume transport computed from the current measurement by Taft and Knauss (1967) at $92^\circ \text{E}$ within the Undercurrent came to $11 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. The difference in the mass transport computed by Taft and Knauss (1967) and the present computation may be due to the fact that their volume transport may be within the core of the Undercurrent while the present estimate of a total volume of $18.19 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ is within the isanosteric surfaces of 200 and 400 cl/t but not within the Undercurrent. From the above flux values at different longitudes, it appears that
the maximum mass transport takes place in the central region compared to the regions on either side. From the primary mode distribution of the zonal flux it appears that the Equatorial Undercurrent in the Indian Ocean is deepening from February to May.

4.1.5. The Equatorial Undercurrent appears to be absent during May in the eastern and central regions of the Indian Ocean while it is present in the western region (Figs. 13 to 15). In the place of the undercurrent strong westerly flow is conspicuous from the zonal flux distribution along $84^\circ E$ (Fig. 37). The mass transport at the surface is eastward and its total value is $48.15 \times 10^6$ m$^3$ s$^{-1}$, mostly confined to the upper layers. The zonal flux between 200 and 400 cl/t accounts to $29.44 \times 10^6$ m$^3$ s$^{-1}$ in the westward direction. Obviously, the Equatorial Undercurrent disappears in the eastern region by May itself, whereas in the western region the eastward flux between 200 and 400 cl/t isanosteric surfaces comes to $12.44 \times 10^6$ m$^3$ s$^{-1}$ (Fig. 36). It is, therefore, evident that the Undercurrent is present in the western region while it is absent in the eastern region in May. According to Swallow (1964), the Equatorial Undercurrent was still present even upto 7th June 1964 along $58^\circ E$, but some what weaker and shallower and it was distinctly assymetric about the equator with a maximum eastward speed at a depth of 50 m around $1^\circ S$. The flow is westward below 200 m, which
decreases with depth between 400 and 500 m. The measurements of Leetmaa and Stommel (1980) show a southward shift of the Equatorial Undercurrent in 1975 and 1976 along 55°30'E. But in the present investigation, while the salinity core with values greater than 35.6% is slightly north of the equator, the spreading of the thermocline is between the equator and 1°S (Fig. 13). The zonal flux indicates the primary mode between 200 and 400 cl/t surface is confined to the salinity range of 35.2 to 35.4%. Therefore, the core of the Undercurrent may not be in coincidence with the high salinity core but probably, with the spreading of the thermocline as the frequencies of the mode are within the thermocline. Hence, it can be construed that the core of the Equatorial Undercurrent is between the equator and 1°S agreeing with the observation of Leetmaa and Stommel (1980).

4.1.6. The transequatorial distribution of hydrographic properties in June at 65°E indicates the presence of the Undercurrent with the associated characteristics of spreading of the thermocline, high salinity core and penetration of oxygen rich water to deeper layers (Fig. 17). While there is no Undercurrent along 88°E, it is not very clear whether the Undercurrent is present or not along 58°E because there is spreading of the thermocline between 1°S and 3°S
without any associated high salinity core. However, the observations of Swallow indicate the presence of the Undercurrent at about 50 m along 58°E and also along 60° and 67°30′E. Along 67°30′E the strength of the Undercurrent decreased to a maximum speed of 44 cm s⁻¹ while it was more than 80 cm s⁻¹ in April.

4.1.7, During July, August and September there are no indications of the Equatorial Undercurrent in the distribution of hydrographic properties, although they indicate easterly flow extended to the deeper levels, probably, because of the Equatorial Countercurrent merging with the Southwest Monsoon Current except in the southern region where the flow is, invariably, westerly depicting the South Equatorial Current (Figs. 19 to 24). The zonal flux distribution in July along 54°30′E confirms that the westerly flow predominates over the easterly flow with values 30.33 x 10⁶ m³ s⁻¹ and 21 x 10⁶ m³ s⁻¹ respectively (Fig. 39). The easterly flow is, mainly, confined to the upper layers in the northern hemisphere associated with the high salinity water. In all the sections it seems that the easterly flow penetrates to deeper layers with increasing strength. The zonal flux along 91°30′E for September has been computed between 2°N and 2°S for the eastward flow only, as the Equatorial Countercurrent
dominates that region without much westerly flow (Fig. 40). From the total eastward flux of $16.46 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, it is clear that the currents are relatively weak. Of this total, 75% accounts for the easterly flow in the deeper layer alone, indicating very weak current at the surface. Taft and Knauss (1967) also noticed strong easterly flows along 79° and 89°E with values ranging from 34 to 67 cm s$^{-1}$, in the depth range 110 to 140 m during their observations in 1962. Although the current direction indicates an easterly, it cannot be identified as an Equatorial Undercurrent with normal characteristics. The deepening of the easterly flow was noticed by Kort (1977) and Erickson (1979).

4.1.8. The distribution of hydrographic properties do not indicate the Equatorial Undercurrent, on the contrary show very strong eastward flow particularly in the upper layers during October (Figs. 25, 26). This is further confirmed with the highest eastward flux of $70.05 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ in October at 84°E between 3°N and 3°S (Fig. 41). There is a total westward flux of $10.66 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ and it is of less significance. The zonal flux between 3°N and 3°S along 94°E in late November and early December confirms, the westerly flow is predominant over the easterly with values of 56.50 and $9.39 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ respectively, probably, because of the local westerly flow in Equatorial Countercurrent which shows an unsteady nature in the eastern Indian Ocean as evident from Anonymous (1952).
4.1.9. The distribution of hydrographic properties along $71^\circ E$ shows a clear spreading of thermocline between $2^\circ N$ and $1^\circ S$ (Fig. 30) indicating the possibility of commencement of an Undercurrent in this region. The commencement of Undercurrent is not associated with a high salinity core, perhaps, may be because it is in the transition of commencement only.

4.2. Comparison of Equatorial Undercurrent in the Indian Ocean with that of the other oceans

Unlike the other two major oceans, the Equatorial Undercurrent in the Indian Ocean is present only during the later period of the northeast monsoon season. For tracing the Undercurrent in Indian Ocean, the most reliable factor is the weakening of the thermal gradient as the high salinity core is not coinciding with the spreading of thermocline. In the Pacific, temperature is the main factor since the contrasting salinity structure is not observed between the western eastern Pacific Ocean. But in the Atlantic Ocean, due to very high saline water in the western region, salinity plays the major role in distinguishing the Undercurrent (Metcalf et al., 1962; Neumann and Williams, 1965; Rinkel et al., 1966).
In the present investigation, the Equatorial Undercurrent is present in the western Indian Ocean from January to May with a surface westerly flow. The core of the Undercurrent shifts from about 1°N to the equator from January to February and remains along the equator up to April. Beyond April, it shifts to about 1°-2°S. Such oscillation of the core of the Undercurrent is observed in the Pacific and Atlantic (Colin et al., 1971; Ivanov et al., 1976; Metcalf et al., 1962), which is explained to be due to wind shift (Charney and Spiegel, 1971).

The Equatorial Undercurrent is found to be well established all along the equator only during February, March and April. In the present study it is obvious that the thickness of the surface isothermal layer increases towards east on the contrary it is decreasing eastward in Pacific and Atlantic (Istoshine and Kalashnikov, 1965; Philander, 1973). Similarly, the observations of Neumann (1965) and Halpern (1980a) indicate shoaling of the core of the Undercurrent towards east, whereas deepening of the core is noticed from west to east in the Indian Ocean.

None of the sections in the present study indicates a double cell structure while it is a common feature in the Pacific and Atlantic, especially, in the
From the flux distribution, it is obvious that a maximum transport of $18.34 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, within 200 and 400 cl/t, is noticed during March in the central Indian Ocean. In the western Indian Ocean the value is much less. At $58^\circ \text{E}$ in March, within 200 and 400 cl/t, the Undercurrent has a flux of $13.94 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. But at $92^\circ \text{E}$ in April the transport does not vary much from that in the central Indian Ocean. Obviously, it shows an increasing tendency from western to the central region in the Indian Ocean. But the observations of Hisard et al. (1969) and Wyrtki et al. (1981) show a decrease of mass transport from western to the central Pacific in July, though, it increases in January and April. According to Voit and Strekalov, 1964; Stalcup and Parker, 1965 and Neumann and Williams, 1965; the transport increases from $14 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ in the western Atlantic to $37.4 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ in the central Atlantic. Both in the Pacific and Atlantic the transport decreases from the central to the eastern region (Knauss, 1962,1966; Christensen, 1971; Khanaichenko, 1974).