

Anomalous circulation in the eastern equatorial Indian Ocean during southwest monsoon of 1994

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Abstract

Geostrophic circulation derived from hydrographic data collected during July-August, 1994 along 80, 84 and 88E between 5N and 3S latitudinal belt in the eastern equatorial Indian Ocean is presented. A broad westward flow north of the equator and an eastward flow, constituting the southwest monsoon current (SWMC), in the vicinity of the equator characterise the upper ocean circulation. While low salinity waters (33.5 -34.75) in the upper layer are advected westward from 88 E via the westward flow, the Arabian Sea High Salinity Water is advected eastward via the SWMC in the depth interval of 75-100 m. Strong (1.0-2.5 m/s) westward current is present in the upper 50 m at 1.25N at all the longitudes. Eastward flowing under-current is present north of the equator below 100 m depth whose velocity and depth are maximum (0.5 m/s and 150 m respectively) between 1.0-1.5N belt along 80 E. The surface wind field during the southwest monsoon of 1994 is anomalous and the surface layer circulation north of the equator does not appear to be wind-driven. The possible influence of remote forcing in driving the circulation is discussed.

1. Introduction

The eastern equatorial Indian Ocean (EEIO) is one of the least studied regions of world ocean. However, recently, there has been considerable interest in the study of this region. Reppin et al. (1999) analysed the monthly distribution of directly measured currents spanning from July 1993 to September 1994 along 80.6 E in this region. Vinayachandran et al. (1999) discussed the anomalous wind situation over this region and its effect on the ocean variability during the year 1994, the year of moderate warm El Nino Southern Oscillation (ENSO) event. Saji et al. (1999) described the existence of a dipole mode in the equatorial Indian Ocean linking the eastern end (off Sumatra) to the western end (off Somalia), which they showed to be independent of ENSO. However, hydrographic information in this region is lacking, except for a few sections (Wyrki, 1971) made during the International Indian Ocean Expedition (IIOE). In the present work, we document the upper ocean thermohaline variability and current structure during the southwest monsoon season (July-August) of 1994 in the eastern equatorial Indian Ocean.

2. Data And Methods

Hydrographic data were collected onboard ORV *Sagar Kanya* along three cross-equatorial sections 80, 84 and 88 E covering the region between 5 N and 3 S during 28 July - 21 August, 1994, at the peak of the southwest monsoon period. The stations were spaced at 1° interval, except between 2 N and 2 S, where they were spaced at 0.5° interval. A total of 49 stations were covered (shown as dots in Fig. 2). The Seacat CTD profiler

(SBE 19, Sea Bird Electronics, USA) was used to measure temperature and salinity upto 600 m. At some stations, surface water samples were collected and analysed for surface salinity using autosal (8400 A model GuidLine, Inc, Canada) in order to compare with the surface salinity values obtained from Seacat CTD. Three hourly wind observations along with other meteorological parameters were made to describe the prevailing wind field and weather during the observation period.

We examined the profiles of the geopotential anomaly difference between the station pairs and noticed that 500 db pressure surface can be chosen as a reference level. Beyond 1 S and 1 N, the currents were evaluated from the dynamic height field relative to 500 db. However, at the equator, the currents are evaluated using the differential form of the geostrophic equation, which can be written as

$$\beta u = (-1/\rho)(\partial^2 P / \partial y^2) \quad (1)$$

where $\beta = \partial f / \partial y$ is the meridional gradient of the Coriolis parameter (f); u is the zonal velocity; ρ is the water density; P is the pressure and y is the meridional distance. In order to apply equation (1), we followed the method of Hayes et al. (1982). The dynamic heights at the five stations between 1 N and 1 S (both inclusive), were subjected to a second order least square fit. The constants obtained from regression are used in solving equation (1) (see Hayes et al., 1982 for details) for zonal velocities at the equator.

3. Results and Discussion

Discussion of the results is presented in brief here, while the details are elaborated in Unnikrishnan et al. (2000).

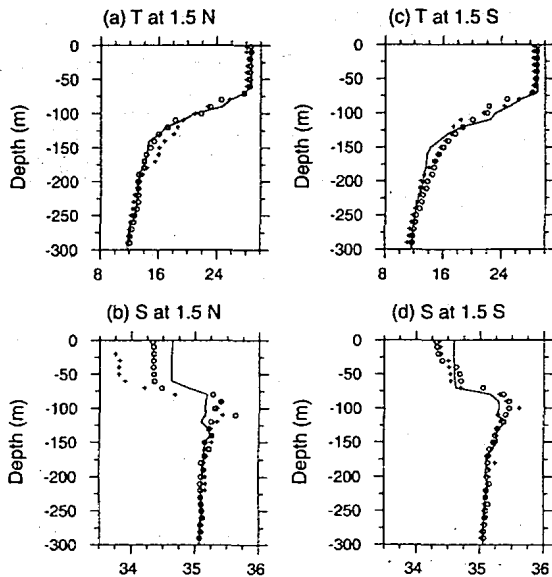


Fig. 1. Profiles of temperature and salinity at 1.5 N and 1.5 S at the three longitudes - 80 E (continuous line), 84 E (circles) and 88 E (crosses).

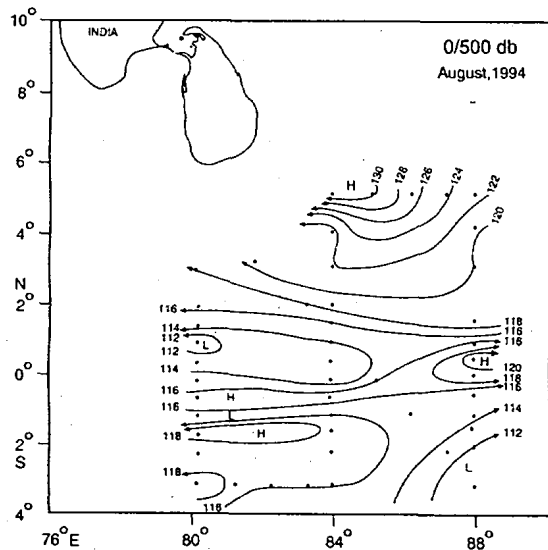


Fig. 2. Dynamic topography (dyn. cm) at sea surface relative to 500 db during August, 1994. The dots indicate the hydrographic stations.

3.1 Hydrographic features

Fig.1 shows the temperature and salinity profiles at 1.5 N (Figs. 1a,b) and 1.5 S (Figs. 1c,d) at the three longitudes respectively. The temperature profiles show a deep mixed layer (about 75 m) followed by a sharp thermocline. North of the equator, low salinities between 33.5 and 34.75 are noticed in the mixed layer (Fig.1b), with a gradual increase from 88 E to 80 E. At 1.5 S, the salinity profile (Fig.1d) indicates the presence of high salinity (35.5) water at subsurface depths (75-100 m).

3.2 Zonal currents

Fig. 2 describes the geostrophic surface circulation during August, 1994 in the study area (dots indicate the CTD stations), deduced from the distribution of dynamic heights at the surface with respect to 500 db. A broad westward flow north of the equator, a narrow eastward flow in the vicinity of the equator and an eastward flow south of the equator (1.5 S- 3 S) are the main features of surface circulation.

The profiles of zonal geostrophic velocities at the mean latitudes of 1.75 N, 1.25 N, Equator and 1.25 S respectively at the three longitudes are presented in Figs. 3a-d. A comparison of our estimates is made with the direct measurements of Reppin et al. (1999). Monthly mean distribution of zonal velocities along 80.6 E for August, 1994 (Fig.7, last panel in Reppin et al.) show an eastward undercurrent (75 m) of about 40 cm/s at the equator and south of it and reverses to a westward flow at about 200 m depth. Our estimates also show an eastward current of higher velocity of about 80 cm/s in the upper layers, which reverses to a gentle westward flow at about 200 m depth, similar to the pattern of direct current measurements. The direct current measurements show that north of the equator, at about 2 N, the surface flow is westward upto about 75 m depth, which reverses into a gentle eastward flow in the depth of 100-200 m. This finding is also consistent with our results. At 1.75 N (Fig. 3a), both at 80 and 84 E, the flow is westward in the upper layers and an eastward undercurrent (0.4 m/s) is present below 100 m depth. However, very high westward flow of velocity about 2.5 m/s is found in the geostrophic estimates (Fig. 3b) at 1.25 N which could not be compared with observed values, as direct measurements are not available in this narrow zonal belt. It is also noticed that the undercurrent present at 1.75 N extends southward and intensifies to 0.5 m/s at 1.25 N with the descent of velocity maximum to 125 m depth. This undercurrent is absent at the equator and further south (Figs.3c-d). This interesting high variability nature of currents in the equatorial region was missing in the direct measurement of currents.

The eastward flow found in the zonal belt of Equator - 1.25 S, constitutes the SWMC, and is characterised by higher salinity water at the subsurface depths and could be identified as the Arabian Sea High Salinity Water (ASHSW) following Murty et al. (1992). North of the equator, the SWMC is not detected within the study area, as anomalous westward flow occupies the upper layer between Equator and 5 N. However, the eastward undercurrent in the zonal belt of 1 N - 2 N represents the SWMC, as it is associated with ASHSW.

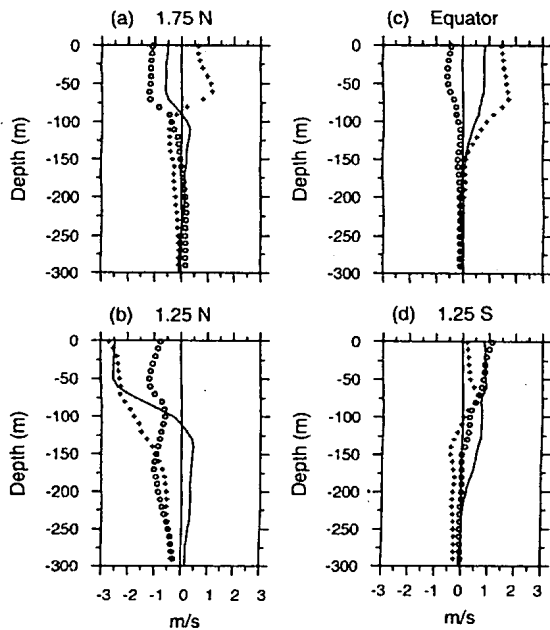


Fig. 3. Profiles of zonal velocity (m/s) at the mean latitude of (a) 1.75 N, (b) 1.25 N, (c) Equator (d) 1.25 S at the three longitudes - 80 E (continuous line), 84 E (circles), and 88 E (crosses).

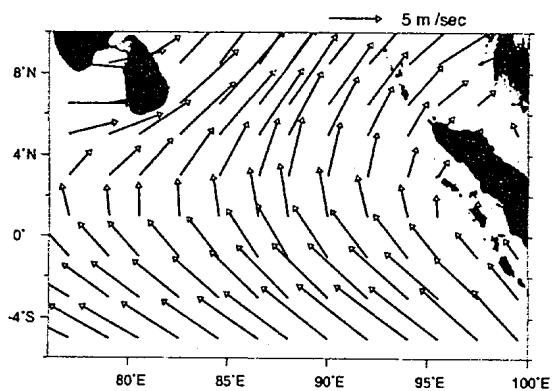


Fig. 4. NCEP/NCAR monthly mean wind field during August, 1994.

The ADCP measurements made during July, 1993 (Schott et al., 1994) showed the presence of SWMC north of 3 N with a magnitude of 1 m/s. They also noticed a strong shear in the velocity of SWMC in the upper 100 m. We presume that the northern branch of SWMC is shifted close to the Sri Lanka coast and then enters the southwestern Bay under the influence of the anomalous surface circulation during the southwest monsoon of 1994. This aspect has been examined in the following section through surface wind field and TOPEX/POSEIDON altimeter data for the period of the present study.

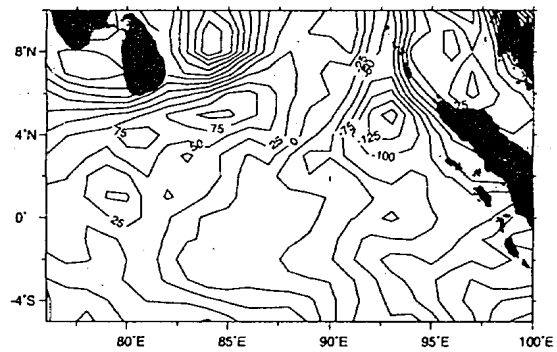


Fig. 5. TOPEX/POSEIDON altimeter derived sea surface height anomaly field (mm) on 13 August, 1994.

3.3 Wind and Topex/Poseidon sea surface height anomaly fields

Fig. 4 represents the monthly mean wind field from NCEP/NCAR for August, 1994. North of the equator, the winds are southwesterly with increasing magnitudes towards east. The fact that the zonal component of the wind stress north of the equator is eastward at all the three sections suggests that the observed westward flow in the surface layers is not wind-driven. This surface westward flow is also seen in the GCM simulations for the Indian Ocean for the year 1994 (Vinayachandran et al., 1999).

South of the equator, southeasterly winds prevail and are relatively strong off Sumatra, blowing parallel to the coast (Fig. 4). The sea surface height (SSH) anomaly field from the altimeter during August, 1994 (Fig. 5) clearly supports the presence of (i) the westward flow between 3 N - 5 N in the region of 80 to 88 E, (ii) anticyclonic eddy centred at 5 N, 84 E, (iii) the presence of SWMC south of Sri Lanka and its flow into the southwestern Bay (as presumed by us in above paragraphs) and (iv) northwestward flow between 4 S - 5 S that appears to feed the observed eastward flow south of 2 S.

The strong SE winds are favourable for coastal upwelling off Sumatra leading to a reduction in sea level as noticed in the large negative anomaly of SSH field (Fig. 5). This sea level pattern off Sumatra coast triggers the northward coastal current which upon reaching the equator contributes to the westward flow north of the equator. Thus, the observed anomalous winds off Sumatra (when compared to other years) appear to influence the near surface circulation north of the equator. Somayajulu et al. (2000) noticed that during the period 1992-'98, when warm ENSO events prevailed in the equatorial Pacific, the sea level dropped considerably off Sumatra coast and vice versa during the

episodes of colder La Nina events. However, the present study is inadequate to establish this point and further studies will be needed to examine the variability of the eastern equatorial Indian Ocean with respect to ENSO events (NIO Contribution No.3580).

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