

# VM-ADCP Measured Upper Ocean Currents in the Southeastern Arabian Sea and Equatorial Indian Ocean during December, 2000

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## ABSTRACT

The Vessel-Mounted Acoustic Doppler Current Profiler (VM-ADCP) measured currents in the upper 200 m along the cruise track covering the southeastern Arabian Sea and the Eastern Equatorial Indian Ocean during northern winter monsoon (10-31 December) of 2000 are presented. In the study area, the westward flowing North Equatorial Current is identified at 4°N southeast of Sri Lanka and its northwestward flow into the southeastern Arabian Sea over a wider zonal belt 4°N-7°N west of 80°E. It attains higher speed (>50 cm/s) outside the Gulf of Mannar augmented by the strong northeasterly winds blowing over the Gulf. With the eastward flow north of 7°N towards the Gulf, a clockwise eddy (early stage of the Lakshadweep High) is formed off south-southwest coast of India due to local wind forcing. A strong (>50 cm/s) eastward flowing North Equatorial Counter Current (NECC) is developed in the zonal belt 0-3°N due to prevalence of the equatorial west wind forcing through December and retroflection of NEC. The transport of the NECC in the upper 100 m varies from  $4 \times 10^6$  m<sup>3</sup>/s at 83°E to  $7 \times 10^6$  m<sup>3</sup>/s at 93°E. The data details the structure of the South Equatorial Counter Current south of the equator from 83°E to 93°E.

**Keywords:** VM-ADCP currents, Equatorial currents, Gulf of Mannar, Southeastern Arabian Sea, Equatorial Indian Ocean, winter monsoon.

## INTRODUCTION

The surface circulation in the equatorial Indian Ocean is documented through ship drift currents<sup>1</sup>, drifter trajectories<sup>2-3</sup>, observations<sup>4-9</sup> and numerical simulations<sup>10-11</sup>. Recently, the Physical Oceanography and the monsoon circulation of the Indian Ocean have been reviewed based on the field data analysis<sup>12-13</sup> and models<sup>13</sup>. All these studies<sup>1-13</sup> highlight the seasonal change in the surface currents of the equatorial Indian Ocean - the westward flowing North Equatorial Current (NEC) during northern winter monsoon and the eastward flowing Southwest Monsoon Current (SMC) during northern summer monsoon. During the inter-monsoons, northern spring and fall periods, eastward flowing narrow Equatorial Jets (EJ) are documented<sup>14,7,8</sup>. Luis and Kawamura<sup>15-16</sup> studied the winter monsoon wind forcing and the associated sea surface cooling events in the Gulf of Mannar - oceanic region between Sri Lanka and southern tip of India. Hacker *et al.*<sup>6</sup> described the upper layer circulation using the Vessel-Mounted Acoustic Doppler Current Profiler (VM-ADCP) measured currents along WOCE (World Ocean Circulation Experiment) sections in the area of 20°N-15°S; 80°-95°E during the northeast monsoon of 1995. Unnikrishnan *et al.*<sup>9</sup> documented the anomalous upper ocean circulation in the Eastern Equatorial Indian Ocean during the southwest monsoon of 1994 and identified the presence of

Equatorial Undercurrent (EUC) at 75-100 m depth range. Reppin *et al.*<sup>7</sup> noticed strong current speeds for the Fall EJ (FEJ). In this paper, we present the VM-ADCP measured currents and discuss the upper ocean circulation during the northern winter monsoon of 2000 in the southeastern Arabian Sea and Eastern Equatorial Indian Ocean.

## MATERIALS AND METHODS

Under the Indian national Ocean Observing System (OOS) program, a cruise was undertaken from Goa (west coast of India) to the Eastern Equatorial Indian Ocean onboard *ORI Sagar Kanya* during 10-31 December, 2000. During this cruise, the broadband (153 kHz) VM-ADCP (RD Instruments, USA) was operated along the ship's track (Fig. 1) besides occupying hydrographic stations along 83°E and 93°E sections and recording the underway measurements of the near-surface temperature and salinity (at 3 m depth) using the Thermosalinograph (TSG). The VM-ADCP currents data were acquired using RDI TRANSECT program at 2 minutes averaging interval and at 4 m depth (bin) intervals. The ship's heading and GPS navigational information were logged into the PC while acquiring the raw data for processing the data internally at the averaging interval. The first bin record of currents started at 15 m depth and the last bin record was at 171 m depth. Spurious values of currents at some bins with U- and V- components of velocity 100 cm/s simultaneously

were discarded from the processed data at 2 minute interval. Then the processed data were averaged at 2 hour interval (equivalent to 20 km spatial average approximately) and used for construction of the zonal (U) and meridional (V) current structure sections (gridded at 0.25° in X-direction and 10 m in Y-direction) along five sections of the cruise track (Fig. 1).

## RESULTS AND DISCUSSION

### *Near-surface circulation*

The VM-ADCP currents at 15 m depth along the ship's track represent the near-surface circulation (Fig. 2a) in the study area. Strong (>50 cm/s) westward currents are noticed between 4°N and 7°N (76°-80°E) in the southeastern Arabian Sea at the outward edge of the Gulf of Mannar, separating the Sri Lanka and Indian sub-continent. Extension of this westward flow to the east is seen at 4°N between 84° and 85°E and towards equator between 4°N and 2°N (from 79°E to 83°E). This westward flow between 2°N and 7°N is identified as the North Equatorial Current (NEC) of the northern winter monsoon<sup>1,2,6,8</sup>. Between 7°N and 10°N, an east/southeastward flow towards the Gulf is present. This eastward flow and the northern part of the NEC at 6°-7°N constitute the anticyclonic eddy representing the early formation of the Lakshadweep High (LH) by second week of December 2000. Earlier investigators reported that the LH off the southwest coast of India is the feature of the northeast monsoon season<sup>17-20</sup>. This study shows that the NEC branches at 4°N, 80°E to flow west/northwestward with a larger velocity at the outer edge of the Gulf of Mannar and equatorward between 2°N and 4°N. The TSG measured salinity at 3 m depth shows marginal variation between 4°N, 80°E to 2°N, 83°E with a low salinity of 35.08 PSU (Practical Salinity Unit) in the equatorward branch of the NEC. These relatively low salinity waters are due to mixing between the very low salinity waters (33.8 PSU) advected by the NEC from the southern Bay and relatively high salinity (35.22 PSU) of the southeastern Arabian Sea. In the Equatorial region, a strong (>50 cm/s) eastward flow is seen between 2°N and equator at 83°E. It occurs over a wider zonal belt (0-3°N) at 93°E. This all-along eastward flow might represent the continuation of the northern Fall Equatorial Jet (FEJ), extending beyond the fall season into winter monsoon. This occurrence of the FEJ for a longer period may be an anomalous feature of the winter monsoon of 2000. Alternatively, this strong narrow eastward flow might represent the presence of the North Equatorial Counter Current (NECC), first proposed by Hacker *et al.*<sup>6</sup>. It appears that the southern part of the NEC between 2°N and 4°N from 79°E to 83°E bends equatorward and feeds the FEJ to form the NECC. Hacker *et al.*<sup>6</sup> identified the NECC around 2°N at 80°E and between 3°N and 7°N along 93°E. In this study, the NECC, however, is well

defined in the equatorial region (Fig. 2a). It is seen in the zonal belt 0-2°N at 83°E and 0-3°N at 93°E. Branching of the NECC into the southern Bay is faintly evident from the northeastward currents at 3°N, 88°E (Figs. 2a-b) and is supported by the subsurface high salinity in the CTD salinity profile there. However, a large part of the NECC flows towards east along the equator. The upper ocean thermohaline structures along 83°E and 93°E sections show that the NECC at 83°E advects the high salinity waters of the Arabian Sea origin. However, the waters at 93°E in the NECC are relatively fresh. This suggests that the western high salinity waters did not reach the eastern part of observations within the survey period, though the eastward flow is established quickly due to local wind forcing and retroflexion of the NEC into the NECC from 83°E to 93°E. Between the equator and 5°S, the eastward flowing South Equatorial Counter Current (SECC) is identified across the 83°E and 5°S sections.

### *Upper layer mean circulation*

Figure 2b shows the upper layer mean flow in the depth range of 15-100 m. The anticyclonic eddy disappears off the south-southwest coast of India suggesting the shallow nature of the eddy during its early formation. The NEC is strong (>50 cm/s) between 4°N and 7°N off south-southwest coast of India, at 4°N between 83° and 86°E in the southern Bay. South of Sri Lanka, the NEC flows southwestward in the zonal belt 3°-7°N. The location and extent of the NECC are similar to that at 15 m depth indicating that the NECC extends up to 100 m depth both at 83°E and 93°E. The flow pattern between the equator and 4°N suggests the presence of a cyclonic gyre with the eastward flowing NECC at the equator and the west bound NEC off the equator. South of the equator, the layer mean flow pattern is similar to that at near surface (15 m depth).

### *Current structure along 83°*

The zonal and meridional current structures are shown for 83°E section in Figs. 3a-b. The zonal component of the current structure shows a two-layer flow, with an eastward flow in the upper 90 m and westward flow below 90 m between 2°S and 2°N (Fig. 3a). While the eastward flow north of the equator represents the NECC, the eastward flow south of equator is that of the SECC. The current shear is intense at the base of the mixed layer (~90 m thick). The NECC extends up to about 90 m depth at 83°E and to 100 m depth at 93°E while its zonal extent increases to 0-3°N belt at 93°E (Fig. 2b). At 93°E, its surface (15 m depth) velocity is relatively high (35 cm/s) at 1°N and less (16 cm/s) at the equator. The two-layer flow pattern is absent between 3°S and 5°S and is replaced by a deep eastward flow. The meridional velocity field shows weaker speeds compared to the zonal speeds and also a three-layer

structure with an embedded southerly flow in the subsurface depth range (Fig. 3b). However, the vertical extent of this southerly flow narrows towards north, except at 2°S and 1°N. South of 3°S, one can see a southeastward flow in the entire depth range identifying the SECC.

#### Dynamics

For understanding the response of the study area to the local wind forcing, we have examined the weekly wind stress data at 1°x1° grids derived from Sea Winds scatterometer on QUIKSCAT for the period beginning from October 3-10 to December 26-31, 2000. These data are routinely produced at COAPS/FSU<sup>21,22</sup>. The distributions of surface wind stress and the wind stress curl for the weeks of November 7-14 (Julian day 315) and December 5-12 (Julian day 343) are shown in Figs. 4a-d. The wind stress in the southeastern Arabian Sea during these weeks is from the northeast with maximum stress over the Gulf of Mannar (Fig. 4a). This stress distribution is opposite to that prevailed prior to October 24-31. In between these weeks, the wind stress and curl fields in the southeastern Bay are weak. Luis and Kawamura<sup>16</sup> reported a 14 day variability in the wind stress field over the southeastern Arabian Sea based on the NCEP/NCAR surface wind reanalysis. In the equatorial region, westerly wind stress prevailed between 70°E and 80°E with a maximum stress south of the equator in November 7-14 (Fig. 4a). The equatorial westerly wind stress intensified towards east (east of 78°E) by the week November 21-28 and further eastwards (east of 83°E) by the week December 5-12 (Fig. 4b). The wind stress curl field, restricted to 2°-10°N, shows the existence of negative curl in the southeastern Arabian Sea (Figs. 4c-d). This negative curl field is responsible for the generation of the observed anticyclonic eddy off the south-southwest coast of India. This emphasizes that the early formation of the LH at the beginning of second week of December off the south-southwest coast of India is primarily due to local wind forcing. Earlier studies report the presence of the LH off the southwest coast of India during the northern winter monsoon from December to March<sup>17-20</sup>. With the progress of winter monsoon, remote forcing due to propagating coastal Kelvin waves and radiating Rossby waves in the southeastern Arabian Sea also play a major role for the LH off the southwest coast of India<sup>10,19,20</sup>. While the westerly wind stress along the equator during northern fall (October-November) leads to formation of the fall equatorial Jet<sup>14</sup>, the persistence of the westerly wind stress through December intensified the FEJ. It is the retroflexion of the westward flowing NEC between 2°-4°N and 76°-80°E into the FEJ forms the NECC in the 0-2°N at 83°E and 0-3°N at 93°E. The computed volume transport associated with the NECC in the upper 50 m is about 3 x 10<sup>6</sup> m<sup>3</sup>/s both at 83°E and 93°E. However, in the upper 15-100 m, its transport

is 4x10<sup>6</sup> m<sup>3</sup>/s at 83°E and increases to 7 x10<sup>6</sup> m<sup>3</sup>/s (Table 1). This transport of NECC is in agreement with that reported<sup>6</sup>. Table 1 also shows that the upper layer transports of the flows associated with the LH are at 7-9 x10<sup>6</sup> m<sup>3</sup>/s, while the transport of the NEC is 9 x10<sup>6</sup> m<sup>3</sup>/s at 4°N and at 4°-7°N (westward flow of the LH). The transport of the SECC shows an enormous increase from 8 x10<sup>6</sup> m<sup>3</sup>/s at 83°E to 28 x10<sup>6</sup> m<sup>3</sup>/s across 5°S section. This increase is due to length of the section as well as higher velocities around 90°E across 5°S section (Fig. 2b). Murty *et al.*<sup>8</sup> reported a value of 37 x10<sup>6</sup> m<sup>3</sup>/s (0-400 m layer) for the SECC during northern winter (January) along a XBT trackline at 63°E between 3°S and 7°S. The distribution of surface currents derived from the TOPEX/POSEIDON sea surface heights<sup>23</sup> in the equatorial belt (5°N-5°S) for December 2000 supports the NEC at 4°N, NECC at 2°N and SECC at 4°S. The climatological drifter trajectories<sup>3</sup> and the ship drifts<sup>11</sup> for December do partly support the flow pattern of the VM-ADCP measured currents in December, 2000, particularly the eastward flow along the equator. However, the VM-ADCP currents show a broad (200-300 km width) eastward NECC north of the equator in December. While the local wind forcing quickly establishes the NECC over a wide longitudinal belt, the thermohaline structures along 83°E and 93°E do not suggest advection of western high salinity waters to the east by the NECC during the survey period. It is, however, evident that the NECC reaches the southern Bay at 3°N, 88°E during the survey period. Intense ADCP measurements in the Eastern Equatorial Indian Ocean are essential to describe the variability of the current systems during winter monsoon.

#### CONCLUSIONS

This study presents the analysis of VM-ADCP measured currents in the southeastern Arabian Sea and the Eastern Equatorial Indian Ocean during the northern winter monsoon (December) of 2000. It reveals the early formation of the LH off the south-southwest coast of India due to local wind forcing over the Gulf of Mannar and the branching of the NEC into the southeastern Arabian Sea in early December. A part of the NEC also retroflects into the eastward flowing Fall Equatorial Jet to form the North Equatorial Counter Current in the zonal belt 0-2°N at 83°E and 0-3°N at 93°E. The transport of the NECC varies from 4 x 10<sup>6</sup> m<sup>3</sup>/s at 83°E to 7 x 10<sup>6</sup> m<sup>3</sup>/s at 93°E.

Table 1. Upper layer (15-100 m) volume transport ( $\times 10^6 \text{ m}^3/\text{s}$ ) associated with the Lakshadweep High flows and equatorial current systems. The limits of the current systems and direction of transport (E-eastward, W-westward, SW-southwestward and SE-southeastward) are also given.

Current System	Lat. & Long. Limits	Transport ( $\times 10^6 \text{ m}^3/\text{s}$ )
LH	7°-10°N (73°-75°E)	7 E
	4°-7°N (75°-79°E)	9 W
NEC	2°-4°N (76°-80°E)	3 SW
	4°N (83.8°-86.3°E)	9 W
NECC	Equator -2°N (83°E)	4 E
	Equator -3°N (93°E)	7 E
SECC	Equator -5°S (83°E)	8 E
	3°-5°S (83°-93°E)	28 SE

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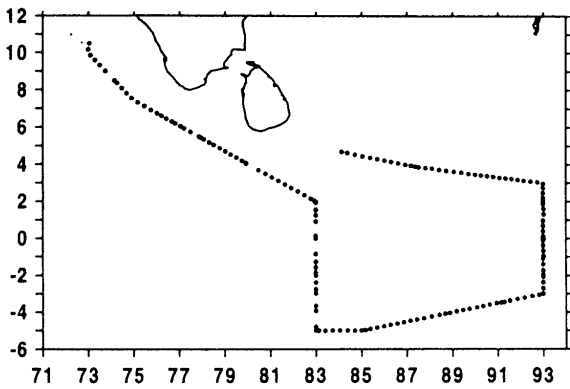


Figure 1. Study area showing the sections of VM-ADCP current measurements along the Ship's track during 7-29 December, 2000.

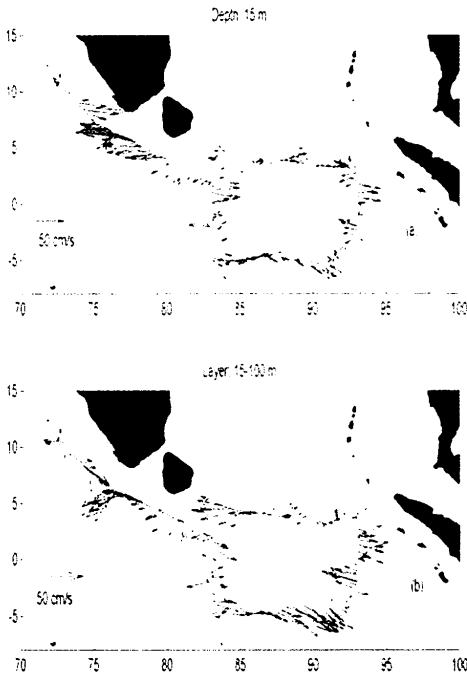


Figure 2. VM-ADCP measured currents (cm/s) showing (a) near-surface (15 m depth) circulation and (b) upper layer (15-100 m depth) mean circulation during December 2000.

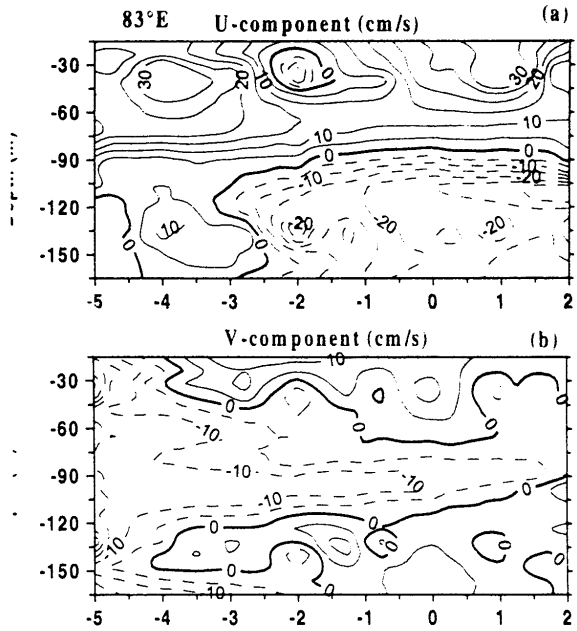


Figure 3

Figure 3. VM-ADCP measured upper ocean (15-165 m depth) current structure along 83 °E section (a) zonal component of velocity (cm/s) and (b) meridional component of velocity (cm/s).

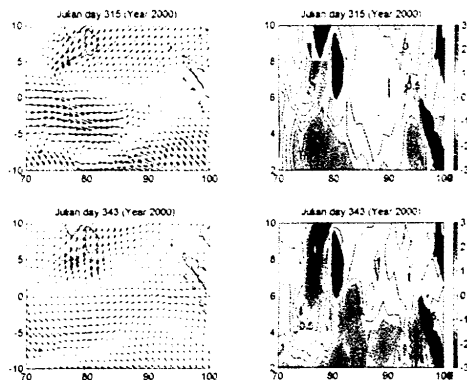


Figure 4. Sea Winds Scatterometer on QUIKSCAT derived weekly surface wind stress ( $N/m^2$ , left panel) and wind stress curl ( $\times 10^7 N/m^3$  right panel) for the weeks (a) November 7-14, 2000 (Julian day 315) and (b) December 5-12, 2000 (Julian day 343).