

## Seasonally reversing current bands across 15°N in the Arabian Sea and their implications

M K Antony, S S C Sheno, V V Gopala Krishna, C S Murty, D P Rao, V S N Murty & J S Sastry  
National Institute of Oceanography, Dona Paula, Goa 403 004, India

Received 17 May 1991; revised 15 November 1991

Geostrophic currents computed from hydrographic data collected in different months from a section along 15°N in the Arabian Sea show alternate N-S current bands. Flow directions of these bands are found to reverse with the change in season. Analysis of ship drift data (KNMI atlas) supports the existence of such bands in this area. Evidences suggest the possibility that these current bands can be due to westward propagation of planetary (Rossby) waves of annual periodicity with a probable speed of 1-2 cm.sec<sup>-1</sup> and wave length varying between 200 and 500 km. Generation of these waves is thought to be linked to the SW and NE monsoon winds in this region.

Information on surface currents in the Arabian Sea is based mainly on the ship drift data compiled in the form of atlases<sup>1,2</sup>. These atlases show that along the west coast of India, there is a southward current during SW monsoon season and a northward current during NE monsoon season. Sheno and Antony<sup>3,4</sup> and Antony and Sheno<sup>5</sup> have made use of short term current measurements along the shelf region at 15°N in the eastern Arabian Sea to work out certain characteristics of the observed currents. Shetye *et al.*<sup>6</sup> have studied the hydrography along the west coast of India during the SW monsoon of 1987 and proposed that the circulation in this part of the Arabian Sea is dynamically similar to wind driven eastern boundary currents. Obviously, a lot more are yet to be understood, especially on the main driving force and on the nature of current reversals. In this context, it is felt desirable to make use of some of the available data on hydrography in order to derive information on nature and behaviour of currents in the eastern Arabian Sea. In this paper, some observed features of the computed flow across a section along 15°N in the eastern Arabian Sea between the period 1979 and 1983 are presented.

### Materials and Methods

On several occasions between 1979 and 1982 hydrographic surveys were made along lat. 15°N by R. V. *Gaveshani* in the Arabian Sea. This survey was between long. 68° and 73°E except, on 2 occasions when it extended westward to 60°E (Fig. 1). The hydrographic stations occupied during these cruises

had a maximum separation of about 110 km and temperature and salinity data were obtained through CSTD (Guildline, Canada) and hydrocasts (Table 1). Hydrocast data were subjected to standard corrections for depth and temperature and salinity samples were analysed using an Autosol (Guildline, Canada) on board the vessel. The procedure adopted for checking the quality of hydrocast data includes routine steps like preparation of L-Z graphs for accepted depths, T-S curves, etc. Vertical plots of temperature and T-S curves were also examined for the presence of abnormal values. CSTD data were cross checked with hydrocast data collected for the purpose during each cruise and as there was good agreement between them, no corrections were applied to CSTD data set.

Dynamic computations were carried out using

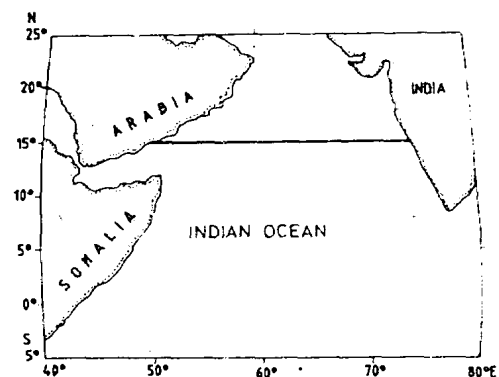


Fig. 1—Map showing the section along 15°N in the Arabian Sea

standard method taking a reference level of 1000 m. Though selection of reference level was arbitrary, earlier workers had used the same reference level in this area with a certain amount of justification<sup>7</sup>. Also, this had an added advantage that it makes the inter-comparison easier. The computed flow, using

the geostrophic relation, across this section at different depths was plotted in depth vs longitude graphs, and, these formed the basic reference for this study.

From the ship drift data presented in the KNMI atlas monthly current vectors for every 2° square between lat. 14° and 16°N were read out and N-S components were computed. These components were utilised for comparison with computed geostrophic flow.

Table 1—Details of data used (along 15°N)

Ship and cruise No.	Date	Length of section	Mode of data collection
<i>R V Gaveshani</i>			
Cruise No. 54	May-June 1979	73-68 E	Hydrocast
Cruise No. 59	October 1979	72,30-68 E	C S T D
Cruise No. 69	February 1980	74-68 E	Hydrocast
Cruise No. 91	April 1981	74-68 E	C S T D
Cruise No. 97	October 1981	74-68 E	C S T D
Cruise No. 103	February 1982	73-60 E	C S T D
Cruise No. 114	December 1982	73-60 E	Hydrocast
Cruise No. 118	April 1983	72-67 E	Hydrocast
<i>O R V Sagar Kanya</i>			
Cruise No. 2	September 1983	72-66 E	C S T D

## Results

*Opposite flowing current bands*—Geostrophic flow computed across lat. 15°N showed alternate current bands flowing northward and southward with moderate speeds (Fig. 2). The flows were almost unidirectional in vertical and change only in their magnitudes. These opposing flows were consistently present during all surveys but with displacements in their positions. Therefore, in order to understand spatial and temporal variations of these bands, N-S

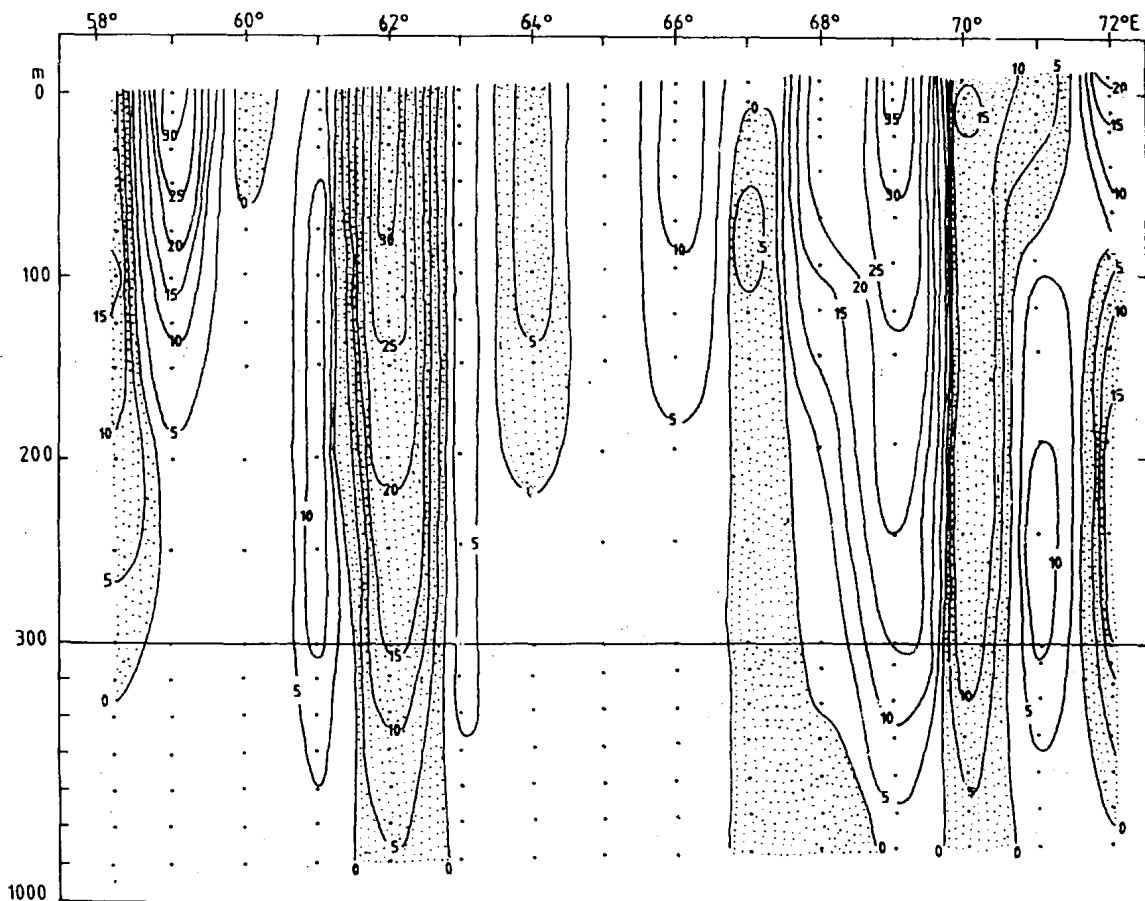


Fig. 2—Vertical structure of N-S geostrophic current across 15°N in February 1982 (Numerals indicate speed in  $\text{cm}\cdot\text{sec}^{-1}$ . Shaded portion shows flow towards south and unshaded, towards north)

surface geostrophic current vectors in between each pair of longitudes (stations) of each survey were plotted (Fig. 3). As the data were not sufficient enough to show vectors for every month in any single year, whole data were arranged monthwise (except for monsoon months) without considering the year to which they belong.

The two most important facts that emerge from Fig. 3 are: (i) there is a seasonal reversal in the direction of the flow across this section in between all longitudinal (station) pairs. Accordingly one can identify seasons as February-May and September-December and (ii) during the same season flows in between different pairs of longitudes (stations) oppose each other. Both these features are very prominent during the first half of the year and these flow bands appear to have space scales of 1°-2° long.

Seasonwise grouping of flows across this section during different cruises shows a wave-like pattern which is prominent during February-May (Fig. 4A) but less so during September-December (Fig. 4B). However, the southward flow, between 70° and 72°E during February-May, shows a definite reversal during September-December. The mean seasonal variability (Fig. 5A) gives the impression of a standing wave being present here (Fig. 5B) with an antinode on the eastern end close to shelf edge and its amplitude decreasing in the offshore direction.

The flow along 2 extended sections up to 60°E shows existence of band structure throughout its length (Fig. 6). Incidentally, these 2 sections fall in 2 different seasons mentioned earlier and as seen before, these current bands are also out of phase with each other throughout.

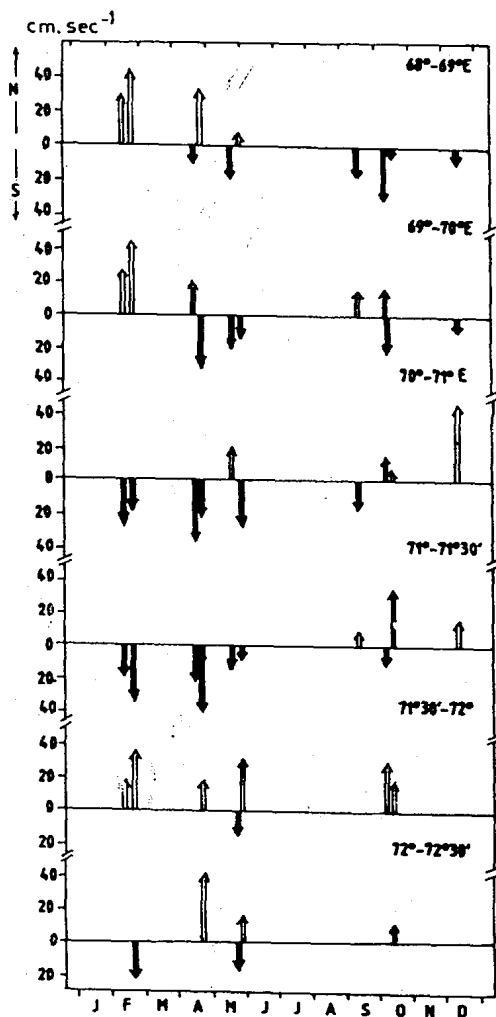


Fig. 3—Monthly surface geostrophic current vectors across 15°N for each pair of longitudes (stations)

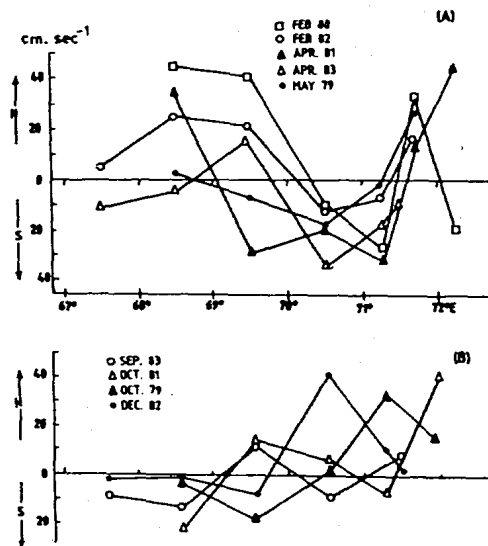


Fig. 4—Geostrophic flow across 15°N during different months grouped into seasons (A) February-May (B) September-December

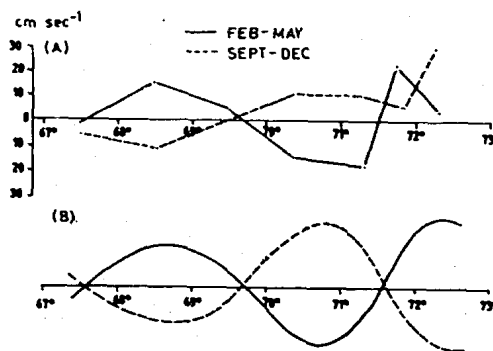


Fig. 5—Mean seasonal variability of geostrophic flow across 15°N from the observed data (A) and schematic presentation (B)

**Reversals of the bands**—From a careful analysis of available data approximate time of reversal of current bands can be ascertained while assuming that the year to year variability is at a minimum (Fig. 7). The moderate southward flow between 70° and 71°E during February increases in magnitude by April. The reversal which started in September completed in October and by December it gets intensified. This

northward flowing current, however, slows down over a comparatively short period of time and by February it again turns towards south. This pattern is almost reversed west of 70°E extending up to 68.5°E beyond which the flow pattern presents a mixed picture. This shows that reversals occur in September-October and in January-February. Considerable asymmetry in the duration of northward and southward flows has also been observed. For example, between 70° and 71°E, duration of southward flow is about 8 months, whereas, northward flow appears to be of about 4 months only. The current reversals shown in the KNMI atlas (ship drift) in February and in October are very close to those mentioned above.

**Geostrophic band structure and ship drift data**—It is interesting to know how the geostrophic band structure observed in this study agrees with the ship drift data. An attempt to compare present results with the KNMI data has been made though a direct comparison could not be attempted because of differences in spatial resolution and data source. Fig. 8 presents N-S components of monthly ship drift data between lat. 14° and 16°N from January to December. The ship drift data also exhibit N-S bands which appear to be more prominent on the eastern half. The seasonal reversal patterns are also clearly visible in this figure. Thus it can be more for less confirmed that the band structure observed in this investigation is a near stationary phenomenon for this area.

**Implications of the band structure**—It may be noticed from Fig. 7 that the southward flow centered around 71°E in February 1982 shifts towards west slowly and by December it reaches around 69°E. This gives an impression that the mesoscale variability of computed currents travel towards west. This westward shift of the disturbance prompts to speculate that these are induced by the propagation of Rossby waves. Alternatively, it could be argued that the band structure may be due to eddies present in this area. To verify this, geostrophic flows have been computed across 4 adjacent sections along 15°, 17°, 19° and 21°N from a single cruise of *ORV Sagar Kanya* during September 1983 (Fig. 9). If the bands are due to eddies, as presumed, it could be possible to identify them by geostrophic computations provided their size scales fall within these latitudinal limits. However, from these computations a southward flow is observed between 66° and 68°E which is almost continuous between 15° and 21°N and on either side of this there are continuous flows towards north. These features do not probably support the possibility that the current bands are due to eddies.

It is known that for  $T \gg f/2\pi$ , the flow due to Rossby

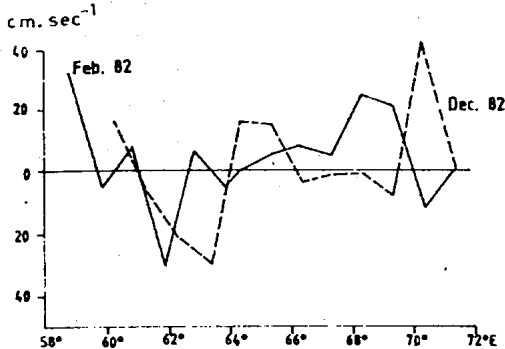


Fig. 6—N-S surface geostrophic flow across 15°N during February and December in 1982

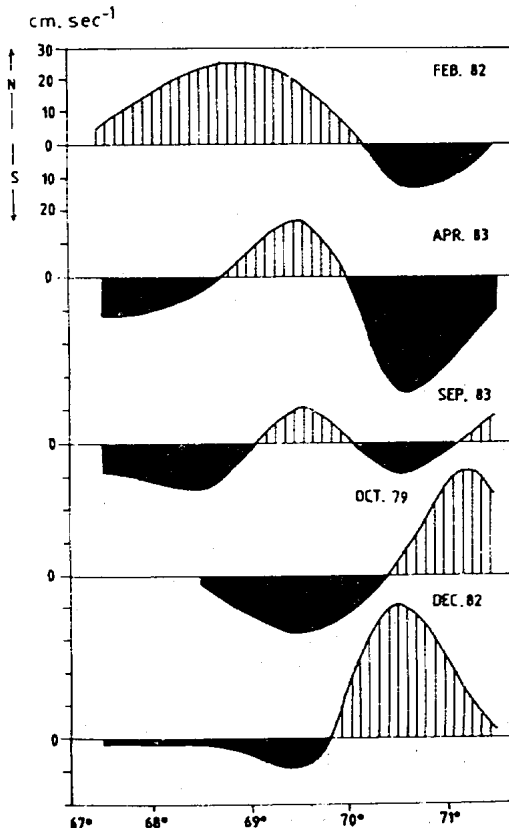


Fig. 7—A near-time series of the computed flow showing reversal with season

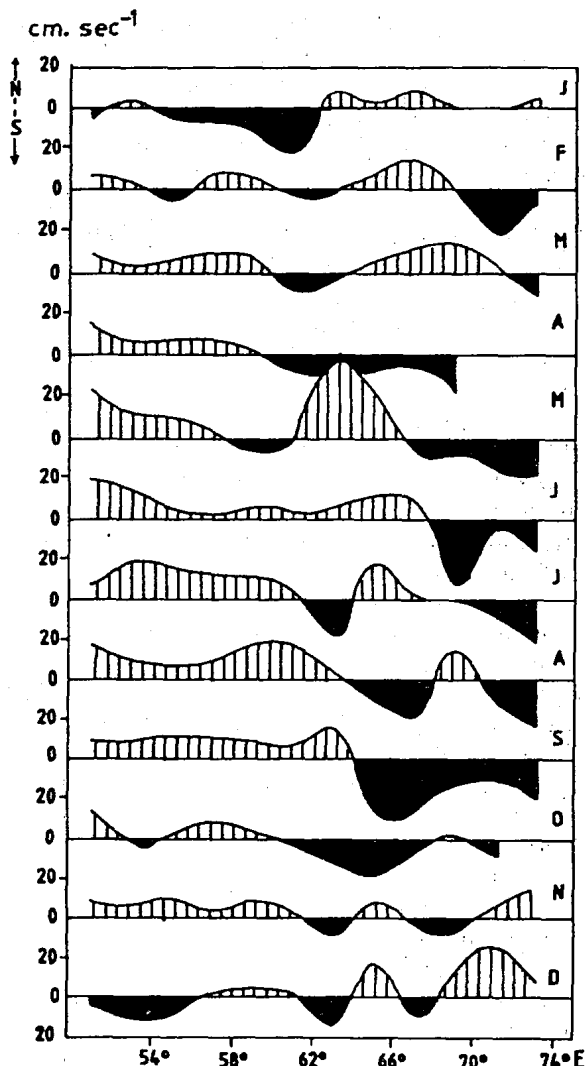


Fig. 8—N-S component of ship drift data between 14° and 16°N (January-December) showing alternate (N-S) flow bands

waves will be essentially geostrophic and that with detailed observations, these can be shown by geostrophic computations. Thus, it was tried to derive some of the Rossby wave characteristics which are apparent in the present data set.

The observed westward shift in Fig. 7 requires a speed of about  $1.2 \text{ cm. sec}^{-1}$ , which is comparable with the typical speed of planetary wave propagation. These disturbances have wave lengths (approximated from Fig. 7) varying between 200 and 500 km and the periodicity of propagation appears to be annual. For forcing period of 1 y, the response is both barotropic and baroclinic. Considering barotropic mode and a wave length less than the external Rossby radius of deformation, the speed,  $C$ ,

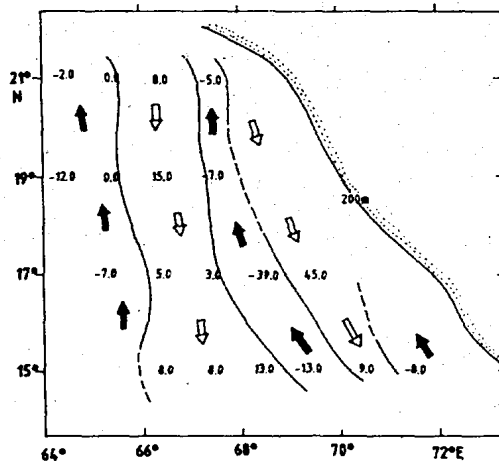


Fig. 9—Surface geostrophic flow between lat. 15° and 21°N

can be computed from the relation<sup>8</sup>,

$$C = -\beta/K^2$$

where  $K$  is the wave number,  $2\pi/L$  and  $\beta = \partial f/\partial y$ . With  $\beta = 2 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$  and  $L = 200 \text{ km}$ ,  $C$  has a value of  $-2.02 \text{ cm. sec}^{-1}$ . The negative sign indicates that the wave propagation is towards west. The group velocity is of the same order but directed in the opposite direction. This computed value of  $C$  is very close to the speed derived from Fig. 7 earlier. However, for a wave length of 500 km, the computed speed has a value of  $12.6 \text{ cm. sec}^{-1}$  which is higher than the value derived from Fig. 7.

**Discussion**

An attempt has been made in the present study to describe alternate N-S current bands along 15°N in the Arabian Sea as induced by propagation of Rossby waves. The consistent nature of current bands and their seasonal reversals give indications of propagating waves of annual periodicity. Occurrence of current bands throughout the extended sections (Fig. 6) and also in the ship drift data supports this proposition. Lighthill<sup>9</sup> has proposed that the Somali current can be due to accumulation of energy from the westward propagating equatorially trapped planetary waves generated by the onset of SW monsoon. Apart from this fundamental work proposing propagation of Rossby waves (near the equator), there are not many studies relating to Rossby waves in the Arabian Sea. Incidentally, Lighthill's<sup>9</sup> proposed waves has a speed of about  $1 \text{ m. sec}^{-1}$  which is more than the speed anticipated in this study.

Generation of the Rossby waves is linked to Ekman pumping by wind stress curl and eastern boundary

influence induced either locally by wind stress or coastally trapped internal Kelvin waves<sup>10</sup>. It is not clear which factor(s) is responsible for the generation in the present case. Fig. 7 gives an impression that the duration (about 8 months) of the southward flow is more than the duration (about 4 months) of the northward flow. This asymmetry is matching with the durations of SW and NE monsoons in this area. This resemblance in the periodicities suggest the importance of wind forcing as a possible cause of generation of Rossby waves. The opposing current patterns during February-May and September-December (Figs 4 and 5) then could be the manifestation of opposing winds during SW and NE monsoons.

Distribution of the N – S components of ship drift data at different latitudinal belts in the Arabian Sea (results not presented here) shows a tendency for the number of bands to increase while moving towards north. This indirectly shows an increase in the wave number which results in a decrease in the phase speed of Rossby waves while moving northwards.

It appears that the amplitude of the wave tends to be higher at the eastern boundary (Fig. 5). It is not clear whether this feature is related to the energy travelling towards east (group velocity) or dissipation of energy while moving away from the coast.

It would have been desirable to carry out some of the quantitative estimates/cross spectral fit as performed by Emery and Maggard<sup>11</sup> and Kang and

Maggard<sup>12</sup>, however, such analyses could not be made partly due to insufficient data.

#### Acknowledgement

Authors thank the Director for encouragement and keen interest in this study. They express their appreciation of the services rendered by the scientists, officers and crew on board *RV Gaveshani* and *ORV Sagar Kanya*.

#### References

- 1 Koninlijk Nederlands Meteorologisch Instituut, *Indian Ocean oceanographic and meteorological data*, Publication No. 135, (Royal Netherlands Meteorological Institute, De Bilt) 1952.
- 2 Cutler A N & Swallow J C, *Surface currents of the Indian Ocean*, (Institute of Oceanographic Sciences, U K) 1984, pp 88.
- 3 Shenoi S S C, Antony M K & Sundar D, *J Coastal Res*, 4 (1988) 617.
- 4 Shenoi S S C & Antony M K, *Cont Shelf Res*, 11 (1990) 81.
- 5 Antony M K & S S C Shenoi, Communicated to *Cont Shelf Res*.
- 6 Shetye S R, Gouveia A D, Shenoi S S C, Sunder D, Michael G S, Almeida A M & Santanam K, *J Mar Res*, 48 (1990) 359.
- 7 Duing W, *The monsoon regime of the currents in the Indian Ocean*, (East West Centre Press, Honolulu) 1970, 63.
- 8 Pond S & Pickard G L, *Introductory dynamical oceanography*, (Pergamon Press, London) 1983, 241.
- 9 Lighthill M J, *Phil Trans Roy Soc London*, A265 (1969) 45.
- 10 White W B, *J Phys Oceanogr*, 15 (1985) 403.
- 11 Emery W J & Lorenz Maggard, *J Mar Res*, 34 (1976) 365.
- 12 Kang Y Q & Lorenz Maggard, *J Phys Oceanogr*, 10 (1980) 1159.