

Nature of the Observed Oscillatory Flows in Shelf Waters of the Western Continental Shelf of India

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ABSTRACT



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Time series data on currents obtained from three Aanderaa current meters moored at a station depth of 92 m in the waters of the western continental shelf of India during May 1984 indicated the presence of oscillatory flows. The spectral computations revealed maximum in the semidiurnal frequency band with its magnitude higher by one order compared to that of the other bands. An analysis of phase differences together with coherence of flows at different levels and their amplitudes showed dominance of internal waves with frequencies close to semidiurnal period (internal tide) controlling the flow structure. The temperature records at these levels together with the B.T. time series data collected in the vicinity of mooring site supported the presence of internal waves. Semidiurnal characteristics computed from hydrographic data collected during the period of mooring across the shelf combined with the distribution of phases and amplitudes of horizontal velocities are found to be consistent with the generation of internal tides along the slope region. The barotropic and baroclinic nature of these currents separated and decomposed by averaging the data from all sensors and using empirical orthogonal functions respectively revealed the dominance of the former in the longshore component and the latter in the cross-shore component.

ADDITIONAL INDEX WORDS: Coastal currents, internal tides, barotropic mode, baroclinic mode, semidiurnal tides.

INTRODUCTION

The nature and dynamics of shelf water flows along many parts of the world have been well documented. However, information over the continental shelves of India is meagre and is limited to description of flows deduced from the available hydrographic data except the study based on current observations off Bombay by VARKEY (1980). This communication presents the results of the study of the time series data obtained during May 1984 along 15°N Latitude over the western continental shelf of India. As the energy spectra computed indicated a maximum close to the semidiurnal frequency, the possible causes for these oscillatory flows close to this frequency have been addressed.

DATA

Three self recording Aanderaa current meters set at 5 min sampling interval were

moored at a location where the water depth is 92 m (Figure 1). The current meters were positioned at distances of 10 m (bottom), 50 m (middle) and 75 m (top) from the bottom. These depths represent near bottom, gradient and surface mixed layers based on the temperature profile taken prior to the deployment. The sensors have accuracies of about ± 1 cm/sec for current speed and $\pm 5^\circ$ for the direction. Taut mooring was maintained for a period of 8 days (11th to 19th May 1984). Simultaneously, B.T. observations were also carried out for the above duration at six hourly intervals from the ship anchored at a position close to the mooring site (about 3 km east). In addition, temperature and salinity data were also obtained along a section across the shelf (Figure 1) through conventional hydrocasts (using Nansen bottles and reversing thermometers) before the deployment and after the retrieval of mooring to examine the nature of the shelf waters.

The current vectors were decomposed into cross-shore (U) and alongshore (V) components

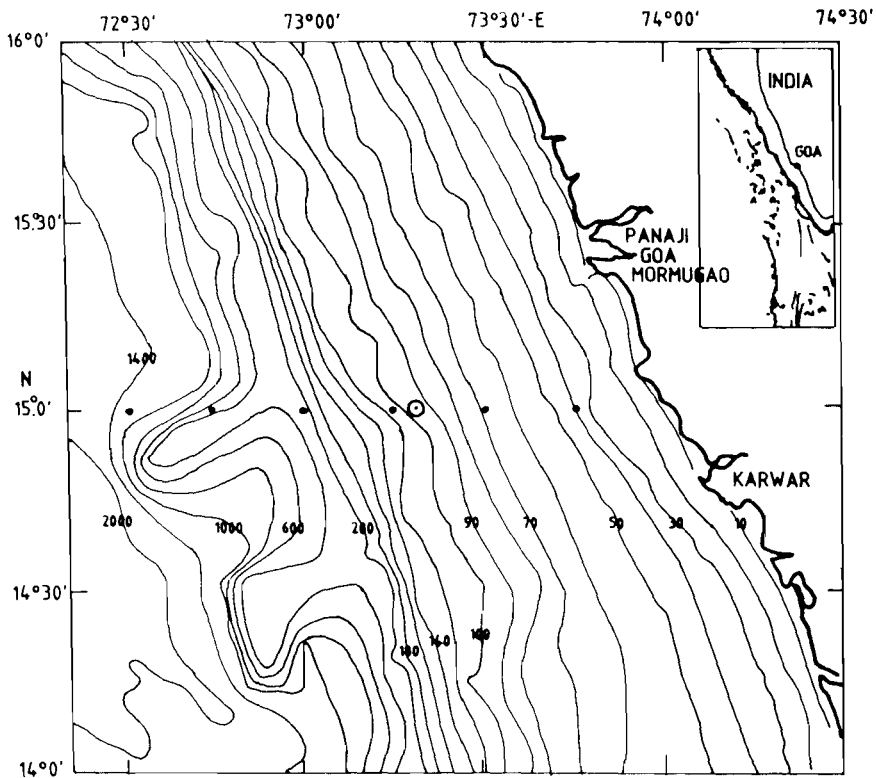


Figure 1. Bathymetry and locations of hydrographic stations and current meter mooring.

with X and Y coordinates oriented normal and parallel to the local isobaths. The U and V components along with temperatures recorded at 5 minutes interval were averaged to generate hourly values.

ENVIRONMENTAL SETUP

The general hydrographic features across the shelf show high saline waters with low temperature near the coast. The salinity varied from 34.95‰ to 35.51‰ while the temperature from 30.5°C to 29.4°C towards the coast. The computed density (σ_t) field (Figure 3) exhibit an upward tilt of the isopycnals towards the coast over a period of ten days. Within the top 140 m layers, vertical velocities of 6×10^{-4} cm/sec could be deduced from the shift of the isopycnals. The prevailing WNW-NW winds varying in strength from 2–10 m/sec favour upwelling along this coast.

OBSERVED FLOWS

The cross-shore (U) and alongshore (V) components of the observed currents at all the three levels exhibit oscillatory nature (Figures 4 & 5). These flows with magnitudes of 20–25 cm/sec, possess a semidiurnal periodicity. The phase of these oscillations are inconsistent with surface tide and between the flows at different levels. For example, while on-off shore flows prevail at the top current meter mostly onshore flows occur at middle depth.

Energy Spectra

The spectral density, estimated through the use of Fast Fourier Transforms for two components (U & V) at all the levels shows a maximum energy of $10^2(\text{cm s}^{-1})^2 (\text{cph}^{-1})$ for U and $10^1(\text{cm s}^{-1})^2 (\text{cph}^{-1})$ for V at the semidiurnal frequency (Figure 6). Significant energy still prevails at the lower frequency levels. How-

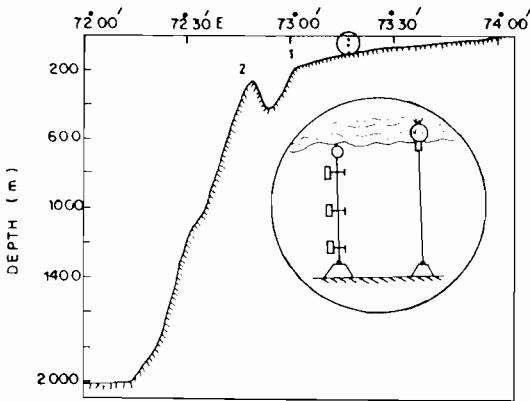


Figure 2. Cross-section of bathymetry along 15°N showing the location of mooring. The numbers 1 and 2 identify two sites of internal tide generation.

ever, one order of magnitude drop in the energy level is conspicuous for frequencies greater than 0.1 cph.

Analysis of Semidiurnal Frequency Oscillations

The observed semidiurnal oscillations could be due either to the surface tide (barotropic) or to the internal tide (baroclinic). If they are due to surface tide the currents should show consistency in phase and amplitude with depth except possibly near the bottom where friction may weaken the currents and should also exhibit high vertical coherence. If large internal

waves, with frequency close to that of prevailing surface tides (internal tides) control the flows the above may not be valid. Thus, the differences in amplitude, phase and coherence of these currents, at the semidiurnal frequency, observed at different levels have been examined to check this aspect.

Amplitudes and Phases

The amplitude and phase differences (Table 1) for the U and V components within this band, centered at 12.19 hours, have been computed through cross spectra (HARRIS, 1974). The computations show inconsistency in the amplitude and phase with depth for both the components. The variation in amplitude of the U-component from 13.40 cm/sec to 4.82 cm/sec occurred with a phase difference of more than 180° across the water column. This is larger than the expected phase difference for currents due to surface (barotropic) tide. For V-component the variations in magnitude (5.5 to 3.30 cm/sec) and phase (52 to 16°) are less compared to the U-component.

Coherence

The differences in phase between the components at different levels showed low values of coherence when checked additionally by coherence estimates. At semidiurnal frequency, for U-component, this value is 0.62 between the top

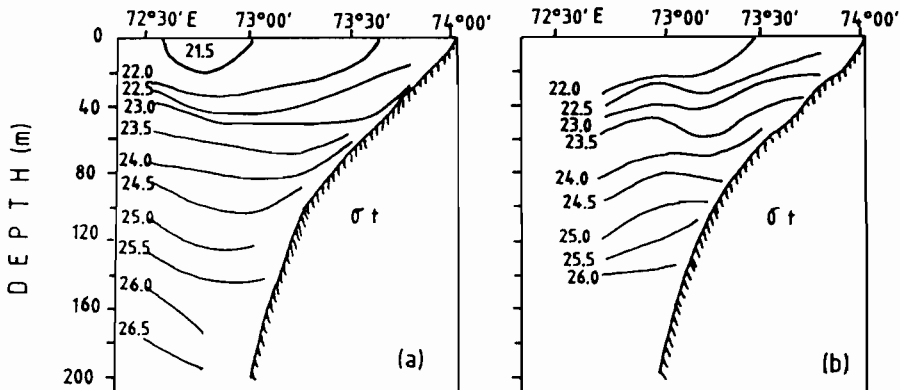


Figure 3. Sigma-t sections (a) before the deployment and (b) after the retrieval of the mooring.

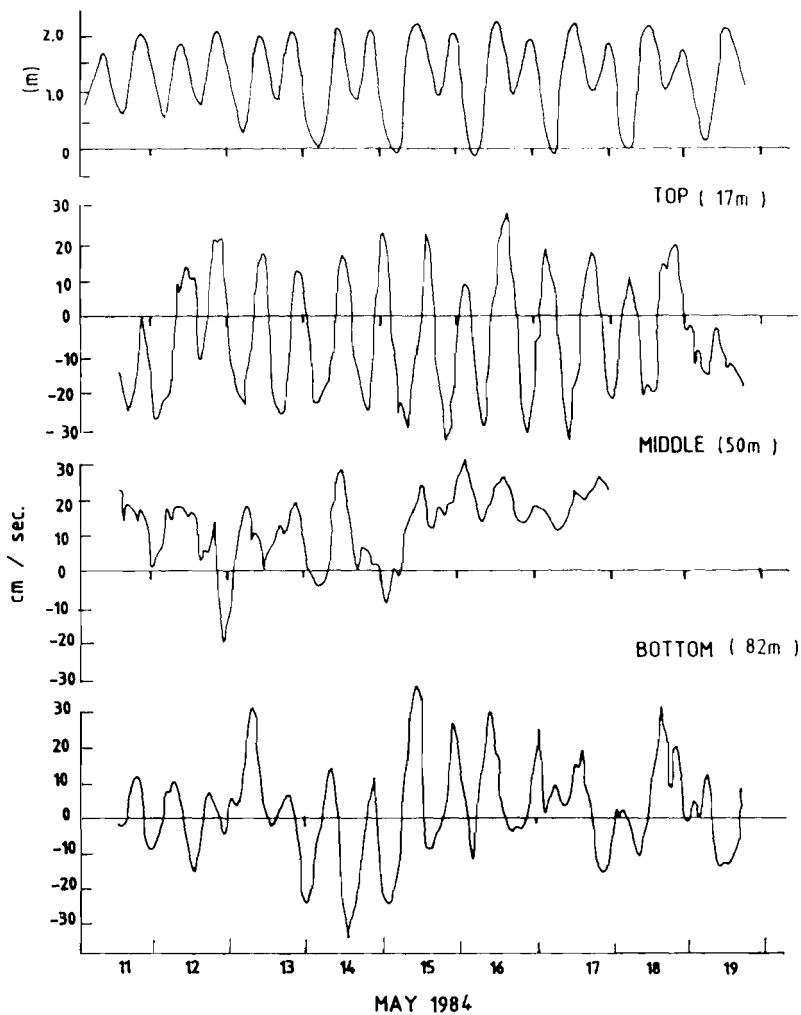


Figure 4. Cross-shore component (U) of currents and predicted tide for Marmugao during 11 to 19 May 1984.

and middle current meters and 0.54 between top and bottom current meters. However, slight improvements could be seen for alongshore components (V) where the corresponding values vary from 0.67 and 0.71.

These inconsistencies in phase and amplitude with low coherences over the water column are suggestive of the influence of internal waves with semidiurnal periodicity on the flow structure. Considering the bias due to poor signal to noise ratios which may characterise the observations as underlined by WUNSCH (1975), an

examination of the temperature records which are usually less susceptible for such problems has also been made.

Observed Temperature Time Series

The time series of temperature (Figure 7) obtained simultaneously with currents at the three levels clearly depicts the strong fluctuations with semidiurnal frequency. These fluctuations are less conspicuous at the top current meter and show an increase towards the inte-

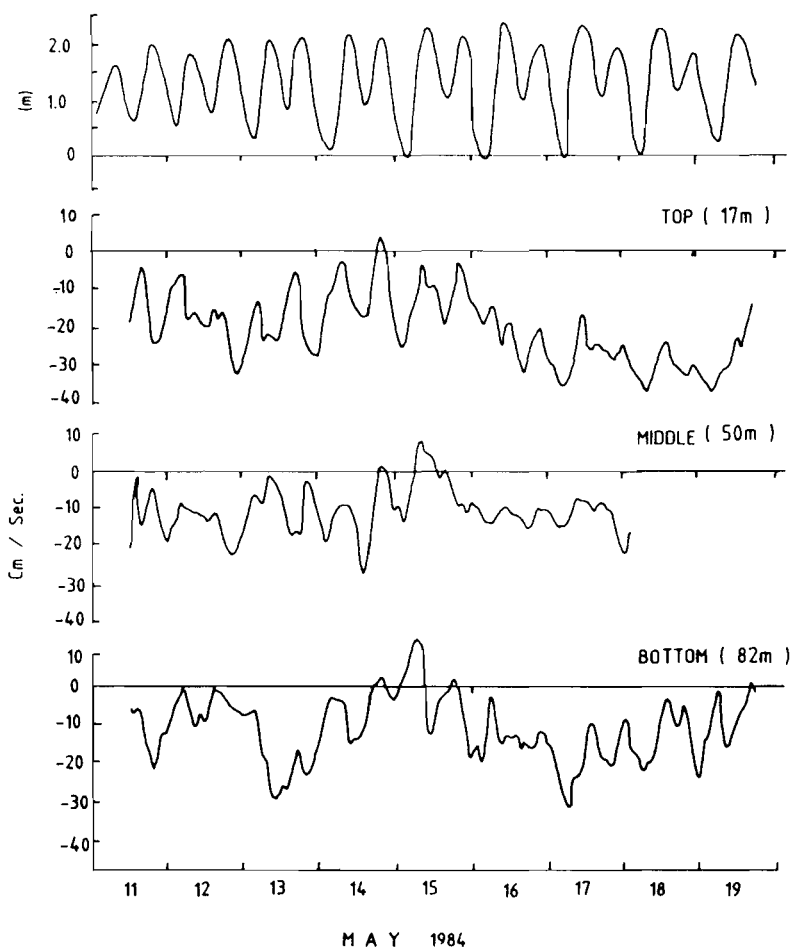


Figure 5. Longshore component (V) of currents and predicted tide for Marmugao during 11 to 19 May 1984.

rior of the water column. This variability in temperature also supports the presence of internal tides with semidiurnal frequency. Moreover, the additional information obtained on the thermal structure through the B.T. observations (Figure 8) at 6 hourly interval in the vicinity of mooring station also shows the presence of internal waves with semidiurnal frequency.

Thus, the inconsistency of the current amplitude and phase with low coherence along with the strong temperature signals are only due to the dominance of the baroclinic mode of semidiurnal frequency oscillations in the shelf water flows.

Baroclinic and Barotropic Components

The barotropic velocities (U & V) have been estimated by averaging current data from all the three current meters. This method was found more reasonable (TORGRIMSON and HICKEY, 1979) compared to the methods used by RATTRAY (1957) and PETRIE (1975). These estimates have been subtracted from the observed components at each level to obtain the baroclinic velocities. The amplitudes of barotropic and baroclinic semidiurnal components are shown in Table 2. In both the cases, U -components are relatively more energetic than V -components. The U -component is dominated by

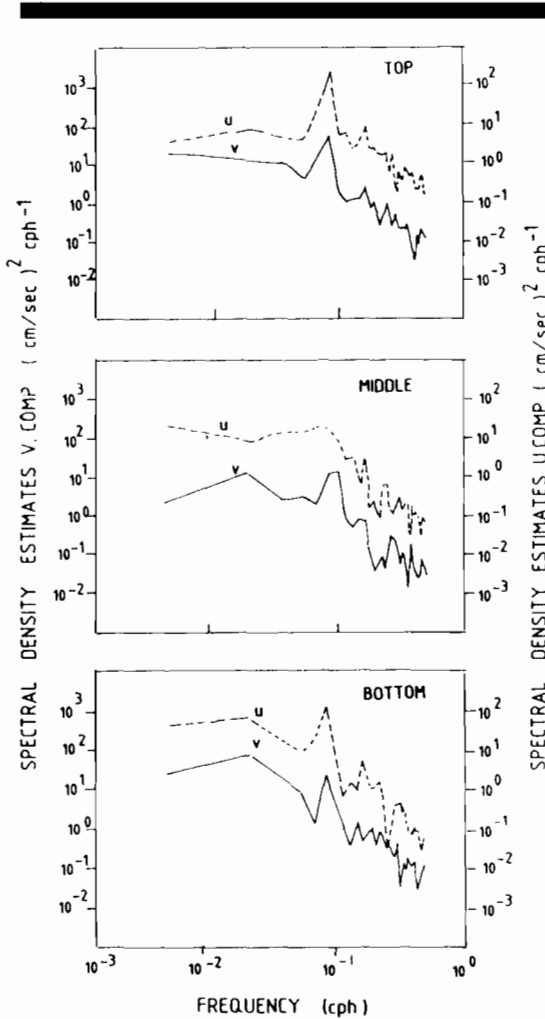


Figure 6. Spectral density estimates of cross-shore (U) and longshore (V) current components at (a) top, (b) middle and (c) bottom current meters.

the baroclinic field at the surface and bottom current meters whereas the barotropic field dominates the flows at the middle current meter. But the V-component at all the levels is dominated by barotropic field. Apparently, the lack of coherence in the U- and V-components of velocities observed could be due to the incidence of internal modes, thereby directing their energy towards the shore. On the other hand, the V-components are related to processes such as wind stress and tide, which are independent of the baroclinic modes.

The baroclinic and barotropic modes have

also been separated using empirical orthogonal functions. Following WINENT and OLSON (1976) a spatial correlation matrix A whose elements are made up of correlations between the velocity components U and V at each depth has been defined with elements

$$A_{ij} = \frac{1}{n_t} \sum_{t=1}^{n_t} X_{it} X_{jt}$$

where n_t samples of cross-shore velocity measured at current meter n are denoted by $U_n(t)$ and the n_t samples of longshore velocity are denoted by $V_n(t)$, and the data matrix X is defined with elements

$$X_{n,t} = U_n(t) - \bar{U}_n \quad n = 1, 3$$

$$X_{n+3,t} = V_n(t) - \bar{V}_n$$

The trace of A is equal to the total variance in the data set.

Two principal components of variability results from this analysis. The first eigen function corresponds to the baroclinic mode and the second eigen function to the barotropic mode.

The distribution of first eigen function (Figure 9) shows that U-velocities are out of phase by 180° across the water column. This phase reversal indicates strong baroclinicity of this component. The eigen functions of V-component does not show any such phase reversal over the water column. These findings are consistent with the phase differences presented in Table 1.

The constant magnitudes observed in the distribution of second eigen function (Figure 9) for both the components represent the barotropic mode of the velocities. Here, the magnitudes of V-components are more or less same as that in the baroclinic mode, but the U-components have lesser magnitudes than those of the first eigen function. This is also consistent with the magnitudes given in Table 2.

Propagation of Internal Tides

The most effective generation of internal tide takes place at the areas where the local bottom slope (β) matches with the slope of the characteristic (BAINS, 1973) given by

$$C(z) = \left(\frac{\omega^2 - f^2}{N_{(z)}^2 - \omega^2} \right)^{1/2}$$

where ω , f and N are the driving frequency,

Table 1. Amplitudes and phase differences of flow components at semidiurnal frequency.

Current meter	U-Component		V-Component	
	Amp. cm S^{-1}	Phase differ:	Amp. cm S^{-1}	Phase differ:
Top	13.40		5.51	
Middle	4.82	42.0	3.30	52.0
Top	13.40		5.51	
Bottom	10.99	192.0	4.05	16.3
Middle	4.82		3.30	
Bottom	10.99	150.0	4.05	- 36.4

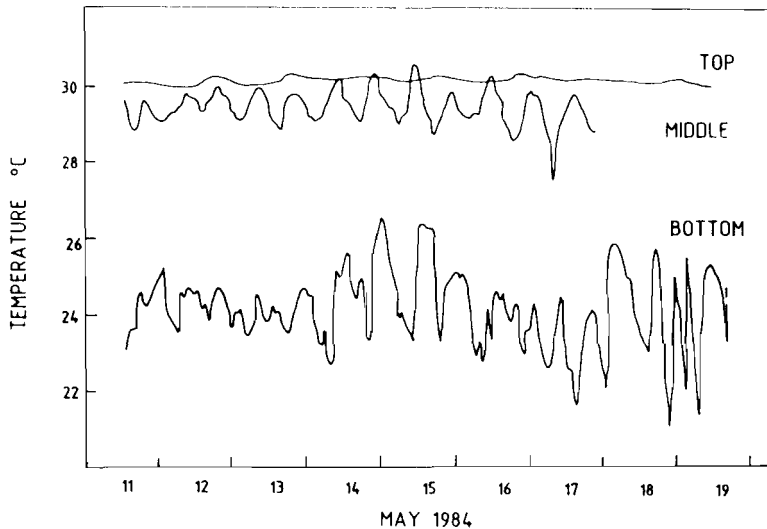


Figure 7. Temperature oscillations observed at top, middle and bottom current meters.

local inertial frequency and Brunt-Vaisala frequency respectively. The characteristic line along which the internal wave energy gets propagated is represented by $Z + CX = \text{Constant}$, where Z is the depth and X is the horizontal distance from the coast.

In the present case the cross section profile shows one such area near the shelf break (site 1) and another below the shelf break (site 2) on the main slope (Figure 2). The rays generated at these two sites were traced by constructing the characteristics based on the hydrographic data. Two rays from each of the two sites are shown in Figure 10. The rays generated at site 1 intersect with the surface and pass through the top current meter. Similarly the rays from site 2 gets reflected from the bottom near the

mooring site after passing the bottom current meter. Thus it is clear that the top and bottom current meters lie within the beam propagated from sites 1 and 2 respectively and the middle current meter lies outside the beam. The maximum baroclinic velocities observed at the top and bottom current meters (Table 2) could therefore be due to the siting of these current meters within the line of propagation of internal wave energy. However, the middle current meter is not completely free from the baroclinic mode, even though its position is not in the beam region. This may be because of the contamination with baroclinic velocities due to its proximity to the beams passing through the top and bottom current meter.

These ray paths may shift slightly due to cer-

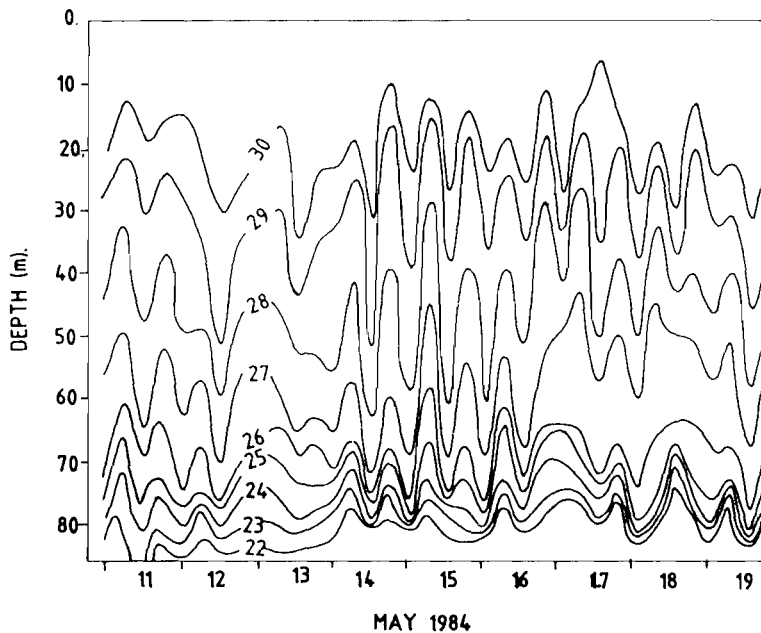


Figure 8. Temperature structure obtained during 11 to 19 May 1984 using B.T. at six hourly interval in the vicinity of mooring site.

Table 2. Baroclinic and barotropic components of flows at semidiurnal frequency.

Mode	Current meters	U cm/sec	V cm/sec
Barotropic		5.62	3.49
	Top	10.65	3.05
Baroclinic	Middle	3.86	2.14
	Bottom	9.30	2.69

tain errors involved in the computation of C . The horizontal stratification of the water column and the mean cross-shore shear of along-shore currents which are not considered while computing C are likely to induce errors in the ray paths. The errors involved due to these factors have been estimated by recomputing the slopes (C) of characteristics using the formula given by MOORES (1975)

$$C^2(z) =$$

$$\frac{M^2 \pm \{M^4 + [\omega^2 - f(f + \bar{V}_x)](N^2(z) - \omega^2)\}}{(N^2(z) - \omega^2)}$$

where, $M^2 = -\left(\frac{g}{\rho_0}\right) \frac{d\rho}{dx}$ is the horizontal analog

of Brunt-Vaisala frequency and $\bar{V}_x = \frac{dv}{dx}$ the horizontal shear in the mean alongshore velocity. The horizontal stratification can easily be computed from the hydrographic data set. But it is not possible to account for the cross-shore shear of longshore currents with a single array of current meters. Thus considering a maximum value of $5 \times 10^{-6} \text{S}^{-1}$ for \bar{V}_x the errors estimated did not exceed 15%.

The computed position of the characteristics can also vary significantly in time due to the changes in the density field over the shelf. Over periods of a month one expects changes in the density field in this area effecting the ray paths. As the positions of the characteristics alter, the phase difference and the amplitude of both barotropic and baroclinic flows fluctuate at any given location.

SUMMARY

In general, this study on the observed oscillatory flows over the shelf brings out the predominant semidiurnal periodicity and phase inconsistencies between different levels and

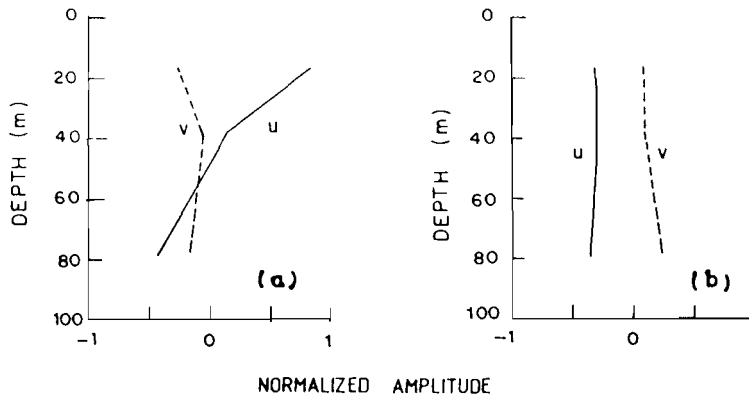


Figure 9. Depth dependence of first (a) and second (b) eigen functions of U- and V-components.

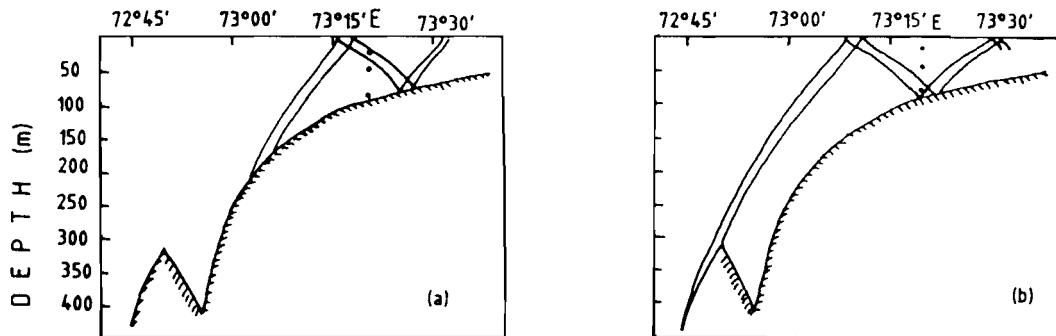


Figure 10. Characteristics for semidiurnal frequency during May 1984.

with that of the surface tide. This feature together with poor coherence between the flow components suggests the dominance of internal tides. The U-component is baroclinic and energetic than the V-component which is more barotropic. The characteristic rays traced from two potential areas of internal tide generation (at depths of 200–300 m) pass through the top and bottom current meters accounting for the maximum baroclinic velocities observed at these two levels.

CONCLUSIONS

(1) The flows over the western continental shelf of India have a strong semidiurnal signal with a barotropic component consistent with the surface tide and a baroclinic component,

best represented by the fundamental mode for internal waves generated along the continental slope.

(2) The uncoupled nature of the baroclinic U-component and barotropic V-component could be due to the fact they are controlled by two different forces. While the U-velocities are the result of incidence of internal modes, the V-velocities are influenced by the surface tide and wind stress which are independent of baroclinic modes.

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