Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 101, No. 4, December 1992, pp. 317–327.

Internal wave characteristics in the eastern Arabian Sea during summer monsoon

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MS received 13 February 1992; revised 23 September 1992

Abstract. The time series BT profiles and surface winds and atmospheric pressure, collected in the deep waters off Ratnagiri and Karwar during summer monsoon were utilized to document the characteristics of internal waves (IW). Low-frequency ($\leqslant 2$ cycle per day (cpd)) IW off Ratnagiri are found to propagate at 83 cm/s with wavelengths of 45 km and wave heights upto 40 m. These parameters for high-frequency (> 2 cpd) IW off Karwar correspond to 99 cm/s, 3 km and 23 m. The IW off Karwar appear to leave the station at 70° ($\pm 10°$) (measured from the horizontal). The data sets were further analysed to address the harmonic composition of the IW and identify the possible sources for the observed IW fields. Power spectra of the IW indicated energy peaks at inertial (0·6 cpd) and tidal (1 and 2 cpd) frequencies off Ratnagiri and in the high-frequency band of 0·5–2·0 cycles per hour off Karwar. The coherence between the IW and wind/tide is found to be good at several frequencies within the IW spectrum. This feature probably suggests tides as a source for the IW of tidal frequencies and winds and tides as a joint source for the IW at the remaining frequencies.

Keywords. Internal waves; buoyancy frequency; inertial frequency; spectral density; coherence.

1. Introduction

Internal waves (IW) occurring in the stratified waters of the sea have a variety of applications. On mesoscales (few hours to few days) fish concentrations (Laevastu and Hela 1970), offshore drilling operations (Osborne *et al* 1978), underwater acoustic intensity fluctuations (Murthy and Murty 1986), density currents (Pond and Pickard 1978), ocean thermohaline fine structure (Federov 1978) and pollutant dispersal are some of the areas that are directly affected by the IW. The studies on IW in the seas around India started way back in the early sixties (La Fond and Purnachandra Rao 1954; La Fond and La Fond 1968). However in the absence of long-term time series data sets on ocean parameters, which are used for extracting the IW characteristics, no studies were undertaken for quite a period of time. The advent of MONEX and other subsequent programmes generated time series of temperature profiles and marine meteorological data from stationary ships in the Arabian Sea and the Bay of Bengal. These data sets were mainly analysed for the mixed layer and thermocline studies. However, a few sporadic attempts were also made to document the IW parameters (Raman *et al* 1979) and understand the response of the IW to a deep depression (Murthy and Hareesh Kumar 1991).

The data collected during the MONEX program by Russian research vessels and subsequent field programmes by Indian scientists have created an important base for carrying out studies related to different aspects of the IW. Accordingly, several investigations (Varkey 1980; Antony *et al* 1985; Sanil Kumar *et al* 1989; Rao *et al* 1991; Shenoi and Antony 1991) made attempts to understand the general characteristics and harmonic composition of IW.

The time series of temperature and salinity profiles along with surface wind and atmospheric pressure are measured for sixteen days (sampled at three hours), off Ratnagiri and half a day (sampled at ten minutes) off Karwar during the summer monsoon. In this paper these data sets are analysed to document the characteristics and spectral composition of the IW in two frequency bands namely from inertial frequency to semidiurnal frequency and from semidiurnal frequency to buoyancy frequency respectively, as classified by Roberts (1975). An attempt is also made to examine the possible sources that excite the IW fields.

2. Data

The surface wind, atmospheric pressure and vertical profiles of temperature and salinity were collected at two stationary positions in the eastern Arabian Sea during the summer monsoon. The location of these stations is shown in figure 1 and the details of the data collection are given in table 1. Both recording (on Sagar Kanya) and indicating (on Betwa) sensors were used to measure the surface wind and pressure. MBT and hydrocasts (at synoptic hours for standard depths) were operated to generate vertical profiles of temperature and salinity. The salinity of water samples was measured using Autosal/Kahlsico Salinometer. Although the ships were kept stationary at their positions during these programs they used to drift because of wind

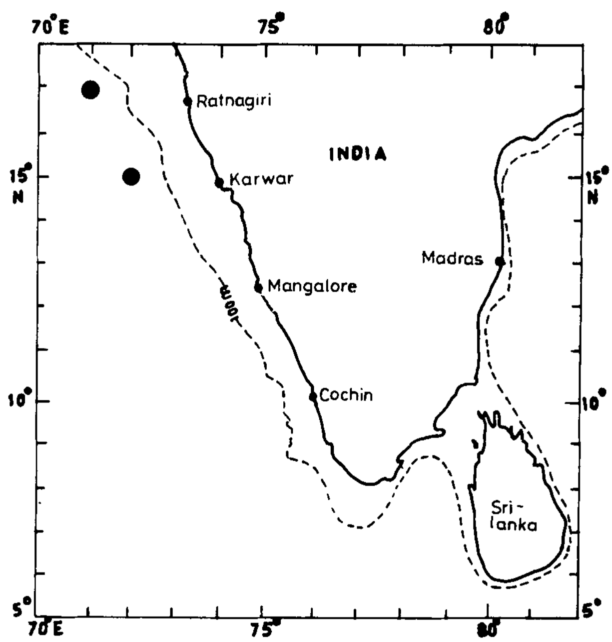

Figure 1. Location map showing station positions (●).

Table 1. Details of the field programme.

Station	Depth to bottom (m)	Ship	Duration	Sampling interval (min)	Parameters
Off Ratnagiri (T_1:17°N, 71°E)	> 2500	INS Betwa	4–19 Aug '77 (16 days)	180	Wind, pressure, temperature and salinity
Off Karwar (T_2:15°N, 72°E)	> 2000	ORV Sagar Kanya	1 Sep '83 (1/2 day)	10	Wind, pressure, temperature and salinity

and current. The ship drift off Karwar was observed as 6·5 km per half day, while the mean daily drift off Ratnagiri was around 10 km. The drift was corrected by bringing the ship back to the site once in a day.

3. Analysis, results and discussion

3.1 *IW Parameters*

The temperatures extracted from the BT profiles at 5 m intervals were used to construct vertical thermal structures that are presented in figure 2A for the site T1 (off Ratnagiri) and in figure 2B for the site T2 (off Karwar). Since the focus of this paper is to document the IW characteristics in the thermocline region, the thermal structure in these figures, contoured at 1°C interval was depicted without the surface mixed layer (temperature change of about 0·5°C is noticed within the mixed layer). From these structures one can clearly see the prominent and regular isotherm oscillations in the stratified water column (i.e. thermocline zone). Such oscillations in temperatures within the inertial periods (41 hours off Ratnagiri and 46 hours off Karwar) are caused by the local IW field (Roberts 1975). Hence each isotherm in the thermocline zone represents an internal wave. As such, the terms isotherms and IW are synonymously used in this paper.

The frequency (f) and wave height of the IW were estimated from the vertical displacements of the isotherms. For a two-layer model the phase speed (c) and wavelength (λ) of the IW at the interface (Defant 1961) were computed from the following formulae

$$c = \left(gh_1 \frac{\rho_2 - \rho_1}{\rho_2}\right)^{1/2} \tag{1}$$

$$\lambda = c/f \tag{2}$$

where, h_1 is the thickness of the upper layer and ρ_1 and ρ_2 are the mean densities of the upper and lower layers.

At a depth of 50 m low-frequency ($\leqslant 2$ cpd) IW off Ratnagiri are found to move with a speed of 83 cm/s and wavelength of 45 km (for $f = 1{\cdot}6$ cpd). They reach peak wave heights upto 40 m (mean = 16 m) in the frequency band of 1·0 – 2·0 (mean = 1·6) cpd. The corresponding parameters for high-frequency (> 2 cpd) IW off Karwar are observed to be 99 cm/s (at a depth of 60 m), 3 km (for $f = 0{\cdot}7$ cph; nearly four times

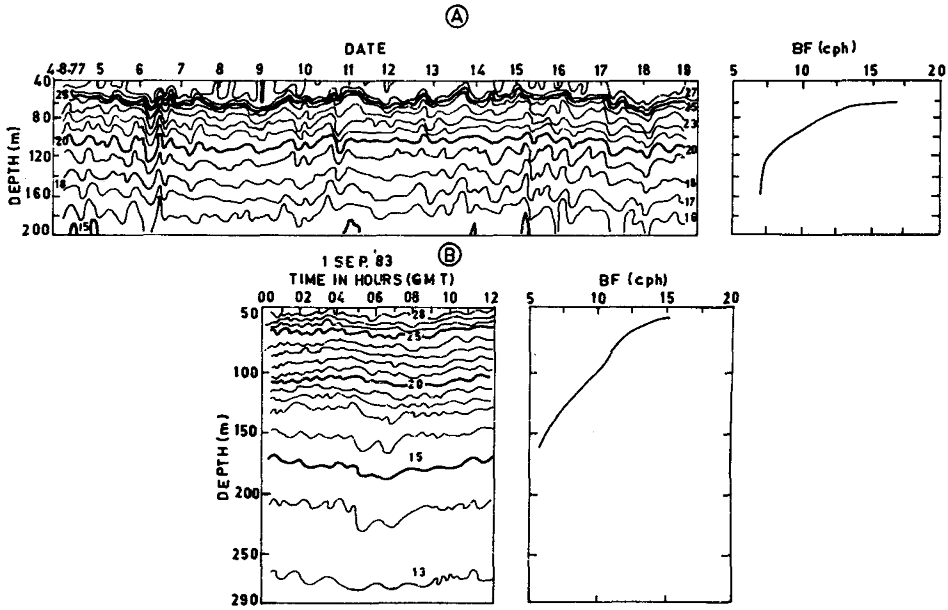

Figure 2. Thermal structure fluctuations and the buoyancy frequency (BF) profiles. (**A**) Off Ratnagiri. (**B**) Off Karwar.

ship drift), 23 m (mean = 7 m) and 0·5 – 3·0 (mean = 0·7) cph respectively. The energy (proportional to the wave height) aspects of the IW are further discussed in § 3·3.

The buoyancy frequency (N) denotes the natural frequency of the fluid with which it oscillates when disturbed by a force. It also becomes the maximum frequency for an IW field. The values of N at different depths (Z) were computed (Roberts 1975) from

$$N = \left(\frac{g}{\rho}\frac{\partial \rho}{\partial Z}\right)^{1/2} \tag{3}$$

where, g is the acceleration due to gravity; ρ is the mean density of the layer; and $\partial\rho/\partial Z$ is the density gradient of the layer.

The densities were computed using the temperatures from the BT profiles and salinities from the nearest hydrocasts. (The temperatures from hydrocasts were not used in computing N, because the mean computations of ρ off Karwar become unreliable as only two hydrocasts were available). The vertical profiles of N at both the sites were computed at intervals of the BT measurements and then averaged at each site before presenting in figure 2 for the depth range from 60 to 160 m. These profiles contain a peak (16·5 cph off Ratnagiri and 15·5 cph off Karwar as compared to 4 and 3 cph in the surface layer respectively) in the pycnocline region due to high stratification. The number of peaks in the profile of N also indicates the number of significant modes in the IW structure (Roberts 1975) although they cannot really define the mode composition of the IW. Thus the solitary maximum or N (maximum not clear as the profiles have not started from the surface) around 60 m suggests that the IW fields are of predominantly first mode.

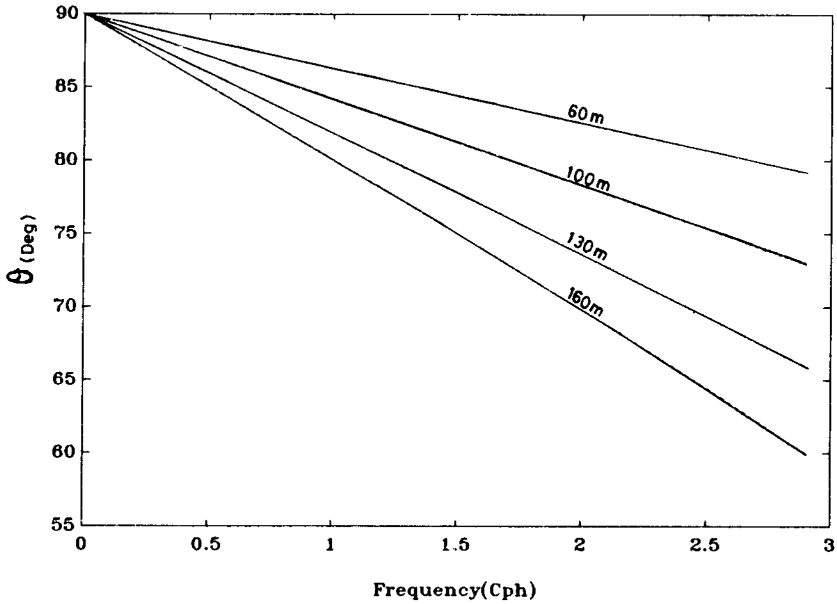

Figure 3. Propagation of the IW at different depths off Karwar.

3.2 *IW Direction*

For short IW, whose wavelengths are much shorter than 600 km, at a given depth the angle (θ) measured from the horizontal (conventionally east) along which the IW propagate (LeBlond and Mysak 1980) is given by

$$\theta = \cos^{-1}(\omega/N) \tag{4}$$

where ω corresponds to the IW frequency at that depth. The values of θ were computed for the high-frequency range of IW off Karwar and the results are presented in figure 3. Such computations were not attempted for the low-frequency IW off Ratnagiri because equation (4) is valid for short IW only.

In the depth range of 60 to 160 m the IW off Karwar appear to leave the site between 80° and 60° with the angle decreasing with depth. The direction of propagation of IW energy is normal to the phase vector (i.e. θ) of the IW (LeBlond and Mysak 1980). This means that the IW energy propagates along 170° to 150° from the horizontal.

3.3 *Spectral density*

Among the surface wind and the atmospheric pressure, the latter closely follows the tidal rhythm (Mitra 1952 and Roll 1965). As the tide data could not be collected at the measurement sites the atmospheric pressure changes are substituted for tide. Hence the atmospheric pressure will be hereafter referred to as tide. It is now examined whether the winds and tides are responsible for the observed IW. The zonal (U) and meridional (V) components of winds, tides and isotherm displacements (internal waves) at the two sites were subjected to Fourier analysis to obtain their harmonic

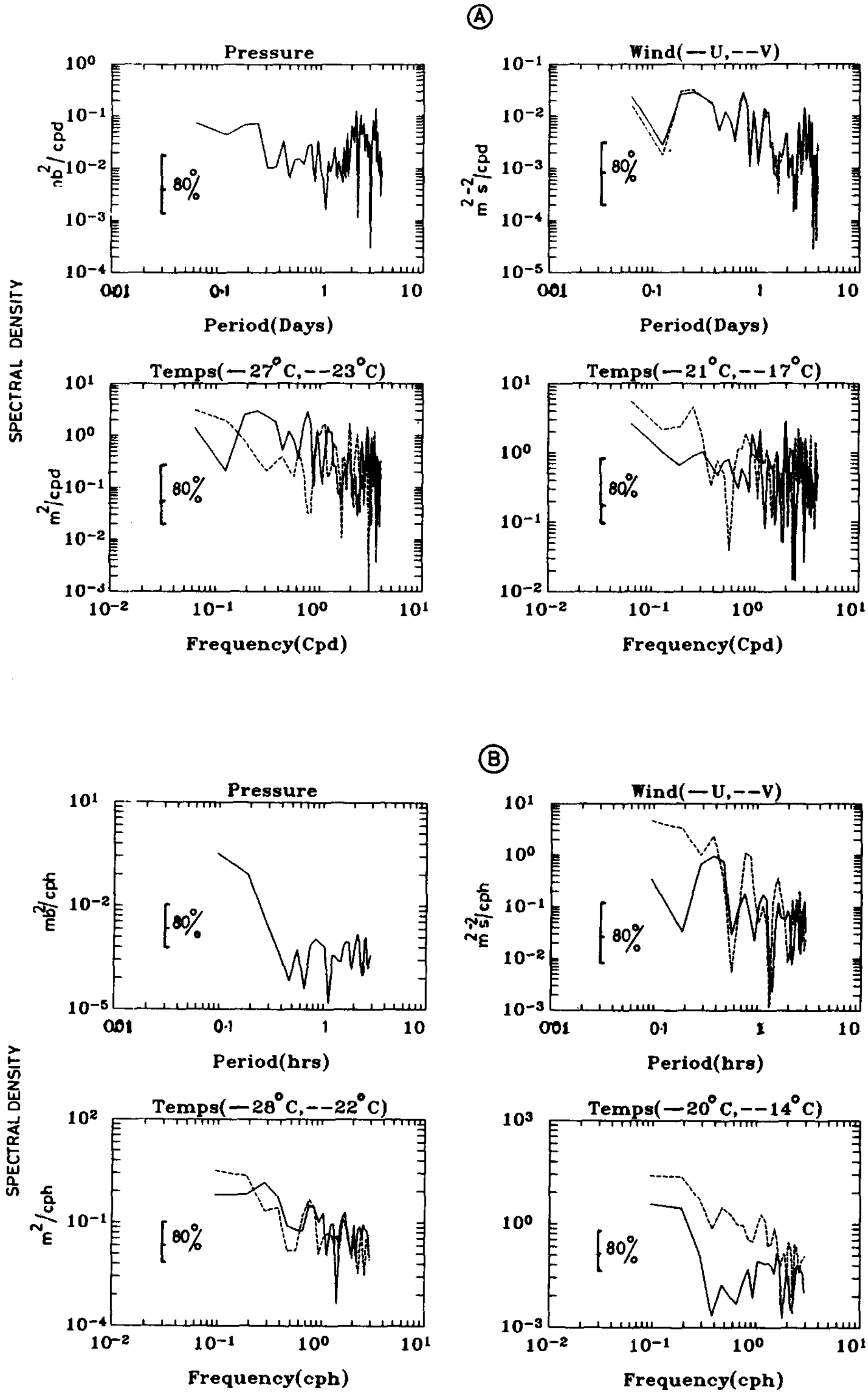

Figure 4. Power spectra of wind, tide (pressure) and the IW (vertical bars - confidence limits). (A) Off Ratnagiri. (B) Off Karwar.

compositions. The spectral densities (SD) were computed with FFT following the Welch method and applying Hanning window (Jenkins and Watts 1968). Due to short records, all the data points (128 off Ratnagiri, 64 off Karwar) were used as a single segment. The SD plots are shown in figures 4A and 4B for the sites T1 and T2 respectively along with confidence limits as vertical bars. Although the analysis was done for all the isotherms, presentation was restricted for selected isotherms. But, it may be noted that the rest of the isotherms also exhibit similar features.

3.3a *Off Ratnagiri*: The SD plots are in general red showing a gradual fall of energy with increasing frequency (figure 4a). Within the IW spectrum – bounded by inertial and buoyancy frequencies – the spectra of tide, wind and IW contain peaks at 0·5, 0·8, 1·0, 1·3, 2·0 and 3·0 cpd with 2·0 cpd (semidiurnal) as more energetic for tides and IW. Out of them the first SD peak is closer to the inertial frequency of 0·6 cpd, where a shift of 0·1 cpd occurs because of sampling resolution. This component is probably forced by the varying local wind field (Pond and Pickard 1978). The internal tides of 1 and 2 cpd are perhaps generated by the interaction of tidal flows with the continental slope (Roberts 1975). Although we do not have any direct computational evidence for these forcing mechanisms we interpret the genesis of the IW from the similarity in the harmonic composition among tide, wind and IW. Gill (1982) reports much of energy concentration of the IW spectrum at tidal frequencies. Varkey (1980) and Shenoi and Antony (1991) notice similar spectral peaks at inertial and tidal frequencies in the coastal waters of Bombay and Karwar. In deep waters in the Bay of Bengal Rao *et al* (1991) also find similar features. Outside the IW frequency band temperature spectra showed peaks at 0·3 cpd (period = 3·3 days) and 0·2 cpd (5 days). Rao *et al* (1991) also document similar peaks in the currents over northern Bay of Bengal during summer monsoon. The slopes of the IW as read from the SD plots correspond to $-0{\cdot}5$ to $-0{\cdot}8$ with an average of $-0{\cdot}6$.

3.3b *Off Karwar*: At this site the SD plots (figure 4b) are similar to those at the other station. A close similarity exists in the harmonic composition among tide, wind and IW. The SD peaks for tide, wind and IW spectra are observed at frequencies of 0·3/0·5, 0·8, 1·7, and 2·0 cph (corresponding to respective periods of 3·3/2·0, 1·25, 0·6 and 0·5 hours) with the maximum energy still around semidiurnal frequency (0·08 cph). However, significant energy can also be seen at subtidal ($>0{\cdot}5$ cph) frequencies, although it falls in this band by 1 to 2 orders as compared to the energy at 0·08 cph, indicating the importance of high-frequency (subtidal) IW. Antony *et al* (1985) and Shenoi and Antony (1991) also observe similar energy peaks at 0·5 to 1·0 cph in the coastal waters of Machilipatnam and Karwar respectively. At the sites T1 and T2 the IW spectra do not show any clear tendency of energy decay with depth. The slopes of the IW spectra vary between $-0{\cdot}9$ and $-2{\cdot}2$ with a mean of $-1{\cdot}4$. It may be noted that the slopes of the IW at both the sites of measurement do not represent the true slopes of the IW because the field measurements have not covered the entire frequency band of the IW.

3.4 *Coherence and phase*

The similarity in the spectral composition, as described above, prompts us to examine the coupling between wind and IW and tide and IW with a view to know whether

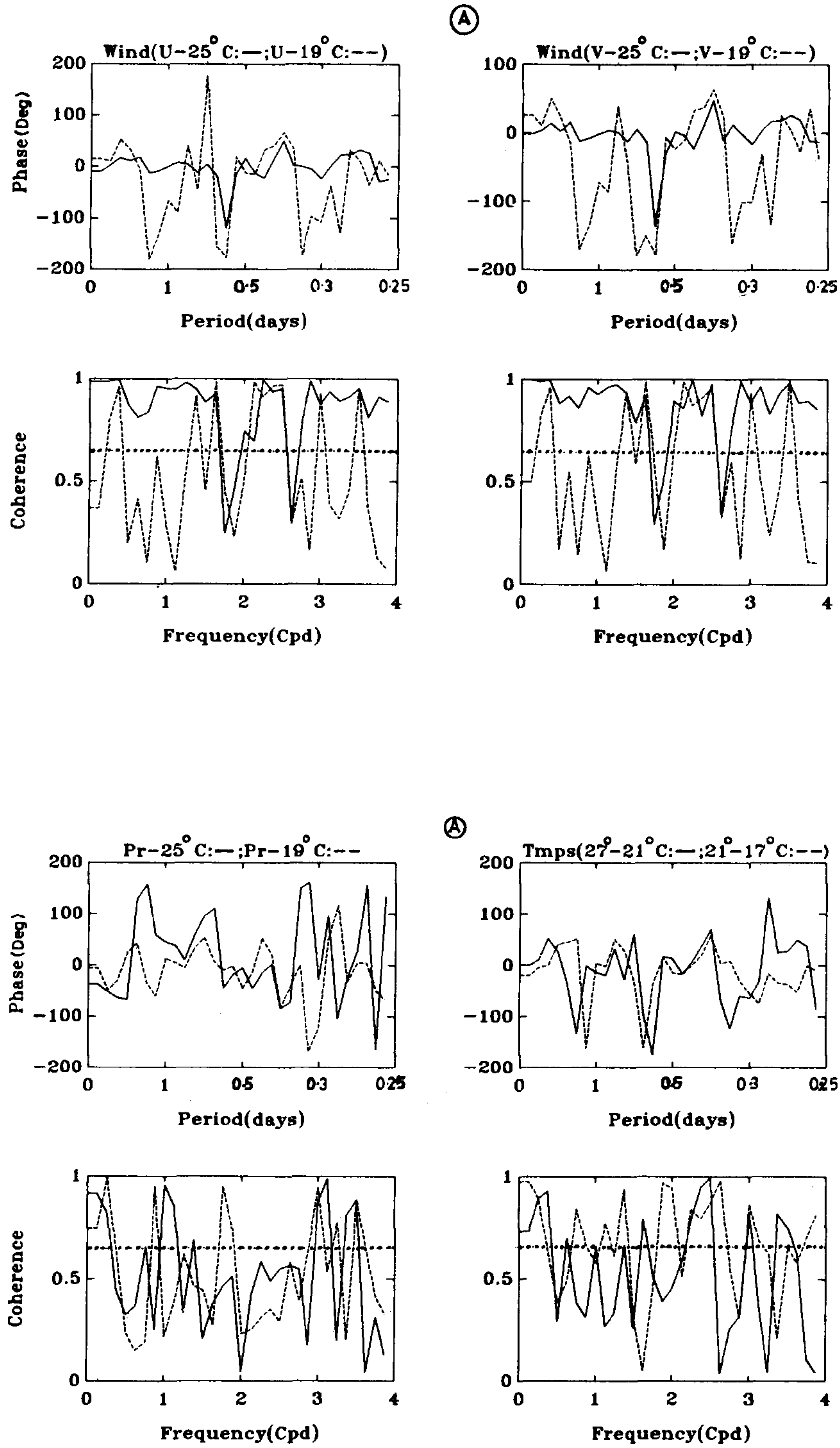

Figure 5. Frequency spectra of coherence and phase between winds and IW, tide (pressure) and IW and within IW (...95% confidence limit). (A) Off Ratnagiri. (B) Off Karwar.

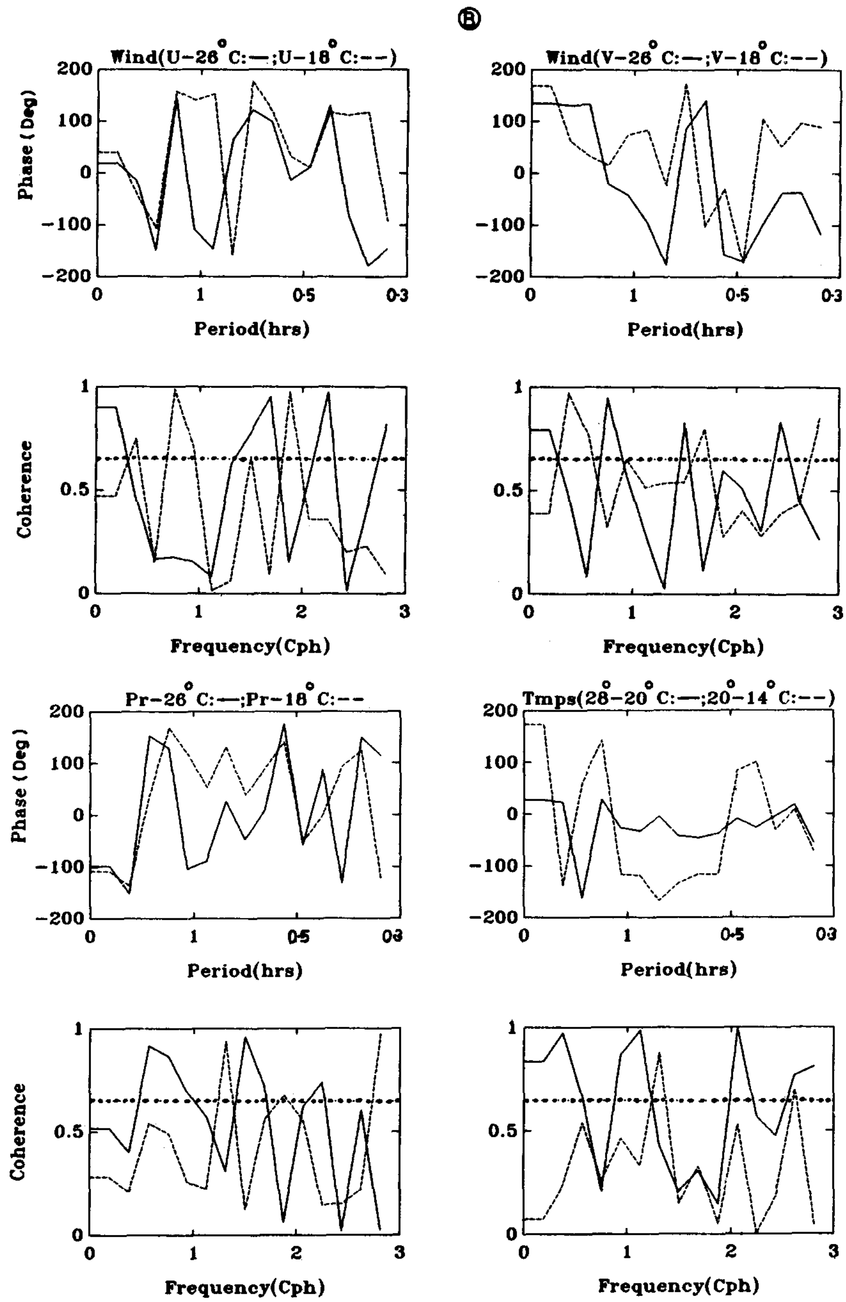

Figure 5(B).

the local winds or tides are responsible for the observed IW fields. The coupling is analysed by looking at the coherence and phase obtained from the cross spectra between wind and IW and tide and IW.

The data of each of these combinations were divided into four segments with lengths of 32 (data) points off Ratnagiri and 16 points off Karwar. The coherence and phase were computed for each segment using the Welch method (Jenkins and Watts 1968) and averaged. The results at both the sites are presented in figure 5 for selected combinations of winds, tides and IW. Other combinations between them also showed similar features.

3.4a *Off Ratnagiri*: The frequency spectra of coherence show good coherence (> 0·5) at 0·6, 1·1, 1·4, 2·1, 2·5, 3·0 and 3·7 cpd for all the considered combinations. This feature, like SD spectra, suggests that the inertial (0·6 cpd) and tidal (1·1 and 2·1 cpd) frequencies are triggered possibly by the local wind field and tidal flows (atmospheric pressure changes) respectively, while the remaining frequency components (i.e. > 2·1 cpd) are perhaps generated jointly by these two mechanisms. Outside the IW frequency band coherence peaks are also noticed at 0·2 and 0·3 cpd (3–5 day oscillations) between tide and IW (i.e. pressure and 19°C) and within IW (i.e. 27° and 21°C; 21° and 17°C). Coherence computations among the IW also showed good coherence within the IW frequency band indicating a symmetrical nature in their vertical structure. In general the phase values at the frequencies of high coherence are found to vary within ± 30°.

3.4b *Off Karwar*: On an average, high coherence between tide and IW, wind and IW and within IW can be noticed at frequencies of 0·5/0·7, 1·5/1·7, 2·1 and 2·7 cph. Wind combinations contain an additional peak at 0·2 cph. Although all the SD plots of IW exhibit an energetic peak at semidiurnal frequency, it is seen irregularly among coherence spectra. Contrary to the other site, the phase values at the above frequencies are highly variable at this station. Thus, the coherence results suggest that the high-frequency IW at this site might have been created by the combined effects of tides and winds.

3.5 *Limitations*

The BT operations are carried out from stationary ships. As such the temperature profiles might be perturbed by the random motions of the ship by waves at the surface. Also within the scales of ship drift (< 10 km) the IW field is presumed to be ubiquitous. The analyses of this investigation are based on short record lengths and hence the findings can at best act as preliminary results with least emphasis on their consistency. It may be noticed that the sources for the observed IW fields are suggested based on the SD and coherence estimates and not supplemented by any other computational evidence. Probably a strong data base, preferably from moored sensors, can provide a more vivid picture on these findings.

4. Conclusion

Internal waves (IW) of low-frequency and high-frequency bands are noticed in the eastern Arabian Sea during summer monsoon. Their spectra exhibit energetic peaks at inertial, tidal and subtidal frequencies. The crossspectral (coherence) estimates between the IW and their generating mechanisms suggest winds and tides as the possible sources for the observed IW.

Acknowledgement

We record our appreciation to our colleagues Dr R R Rao for permitting us to use part of his processed material and Dr Tatavarti Rao for useful suggestions in this work. We also acknowledge the help received from the scientists and technicians in the data collection onboard the ships and unknown referees for improving the quality of the paper.

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