

## Temperature oscillations in the upper thermocline region—A case study on internal waves off Kalpeni island in the southern Arabian Sea

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Temperature data were collected for 12 h in the thermocline region at an oceanic station off Kalpeni island (11°15'N and 69°E) from the stationary ship using a thermistor chain. These data were Fast Fourier Transformed (FFT) to examine the spectral characteristics of the temperature oscillations. The power spectra of temperature fluctuations at 11 depths in the upper thermocline from 80 to 100m with 2m interval, were computed for studying the short period internal waves. Power spectral density was higher at 90m at all frequencies compared to that at above or below this depth. An abrupt change in the degree of coherence occurred at 88m depth, in the sense that the oscillations above 88m showed very low degree of coherence, while below 88m depth the oscillations show very high degree of coherence. The low frequency oscillations (0.01667 to 0.2167 cpm) had higher coherence and very small phase shift whereas, high frequency oscillations (> 0.2167 cpm) had rather poor coherence and a large phase difference. Analysis of the coherence relations of the power spectral densities showed that the internal waves of periods longer than 10 min had higher coherence below 88m depth. The energy density spectra revealed a relation of  $f^{-2.7}$  fall off.

Internal waves are known to exist in the Indian seas<sup>1-3</sup>. Apel *et al.*<sup>3</sup> found the existence of predominant internal wave activity in the Andaman Sea from the remote sensing methods. Sarma *et al.*<sup>1</sup> used the time-series of wind, atmospheric pressure and upper ocean temperature to study the internal wave characteristics and their generating mechanisms off Andaman Islands in the Bay of Bengal. Murthy *et al.*<sup>4</sup> documented the wind and tide generated internal waves off Ratnagiri and Karwar in the eastern Arabian Sea using the time-series of bathythermograph profiles, wind and atmospheric pressure during summer monsoon. However, the internal wave studies in the Indian seas are very few, though they have several applications. Time-series of temperature measurements at a fixed location in the ocean can be used to study the internal wave characteristics<sup>5</sup> and for this purpose MBT, XBT data collected on space-time scales are commonly used. But only a few studies on the internal waves using the thermistor arrays are available<sup>6,7</sup>. In the present study, the internal wave characteristics off Kalpeni island in the southern Arabian Sea have been examined using thermistor chain measurements of temperature in the upper thermocline region. A thermistor chain, containing an array of 11 fast response thermistor beads (2K iso-curve Fenwall type GB 32 JM 19) equally spaced at 2m intervals that

provide very accurate (of accuracy  $\pm 0.1^\circ\text{C}$ ) and instantaneous measurements of temperature at different depths, was used. The data were collected at the fixed station over a period of 12 h. The spectrally analyzed oscillations observed in the thermal structure are attributable to short period (<5 h) internal waves<sup>5</sup>. The contribution of tides to the internal wave field at this location is not assessed since the data were available for 12 h only.

From theoretical considerations, the frequency limits for internal gravity waves are bounded by Brunt-Vaisala frequency on the higher side and by inertial frequency on the lower side. In the study location (11°15'N, 69°E) these limits for internal wave field are estimated to be 0.4167 cpm (maximum) and 0.00027 cpm (minimum). The frequencies of the observed internal waves lie within this range.

### Materials and Methods

A thermistor chain of Anderaa make was operated from *ORV Sagar Kanya* at an oceanographic station west of Kalpeni island (one of the Lakshadweep group of islands) in the southern Arabian Sea (Fig. 1) for about 12 h on 31 January 1989. An expendable Bathy Thermograph was operated and from the XBT record it was found that thermocline begins from 70m depth and extends downward to beyond 200m depth. Since the occurrence of internal waves is anticipated

in the maximum density gradient zone, the thermistor chain was deployed in the upper thermocline region (80-100m).

The thermistor chain system<sup>8</sup> was hung sufficiently away (using a boom) from the starboard side of the ship by a rope of correct length up to 80m depth from the sea surface. Attached to the rope is the recording unit and the array of equi-spaced thermistor beads at precisely 2m intervals. A suitable heavy weight was attached to the end of the thermistor chain to keep it taut and vertical. During the observation period the surface currents were negligibly small (as observed from the ship drift data) and the sea was calm (sea state = 1). Maximum error in the depth of the temperature sensors due to the swing of the chain, estimated taking into account the overall effects, is expected to be <0.5m. The internal wave field is also advected with current so that moored sensors observe an unknown Doppler shift in the waves. This in turn, produces a variation in energy density level in the frequency domain. By using an array which moves with the current, this Doppler shifting in the waves is minimized and more accurate measurements of wave frequencies were made<sup>7</sup>. In view of this, the present data set is considered to be reliable and the results are expected to yield fairly accurate estimates of the internal wave parameters.

The temperature data were collected from 0800 to 2000 hrs on 31 Jan. 1989 from depths of 80, 82, 84,..... 100m. The data were recorded at 1 min interval by an *in situ* recorder on a 1/4" magnetic tape

in the 10-bit coded format from all the 11 channels. The data were then transferred to ND-570 computer and processed to obtain the actual temperature values by feeding the sensor constants into an indigenously developed software programme.

The power spectra of the temperature fluctuations were computed for all the 11 data sets of temperatures using FFT method<sup>9</sup> to know the frequency composition of the internal waves. The data were divided into 12 ensembles of 60 data points each. Thus the spectral estimates have 24 degrees of freedom. Frequency resolution of the estimates is 0.024 cpm. Hanning window with a scaling factor of 0.0375 was used to achieve better resolution. The auto-spectra and cross-spectra were computed<sup>9</sup> at all depths to study the coherence and phase relations among the oscillations at different depths. For the purpose of coherence estimates 90m depth was taken as reference surface as this is the middle depth of the observation zone.

## Results and Discussion

Temperature distribution in the upper region of the thermocline between 80 and 100m depths is shown as a function of time in Fig. 2. Space-time section of temperature wherein, the variation of the isotherms in ocean-space as a function of time is shown in Fig. 3. The approximate mean position of the 2 isotherms (26°C and 25°C) which occurred in this depth range were also shown in the figure as smoothed curves. The observed temperature fluctuation can be seen as the short period oscillations riding on a long period wave. The temperature inversion was observed between 82 and 93m depths at 0800 hrs. The 27°C isotherm progressively shallowed with time and disappeared

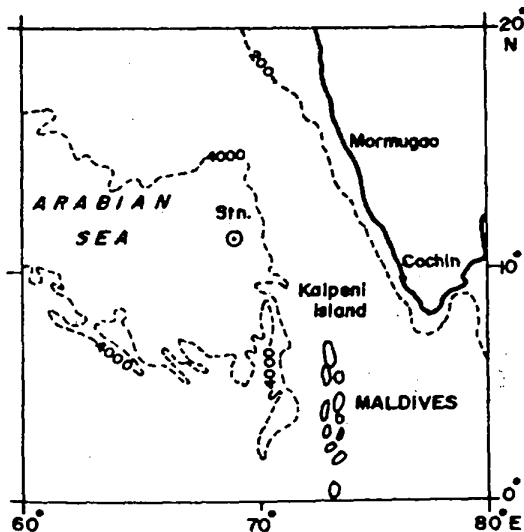


Fig. 1—Station location map

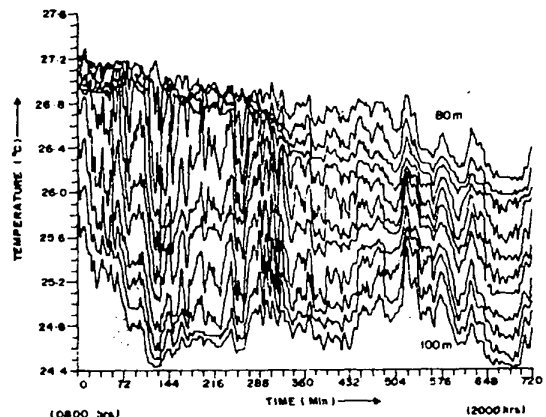


Fig. 2—Time-series of temperature fluctuations at observation depths at 2m intervals [80m (top) and 100m (bottom)]

from the scene after 1000 hrs due to shoaling of the thermocline. The trend of isotherms showed that they were diverging with time. The magnitude of the vertical oscillation of the isotherms has gradually decreased with time up to 1700 hrs and then started increasing. This feature might partly be due to the influence of semi-diurnal surface tide in this region.

Internal wave parameters were estimated from isotherm charts by an indirect method<sup>10</sup>. It was found from the space-time section of temperature (depth versus time plots of the isotherms) that the crest-to-trough wave height is 7m (estimated from 26°C isotherm) and the wave period estimated from the occurrence of successive peaks in the 26°C isotherm is 4.6 h. Woods and Fosberry<sup>10</sup> found a wave slope relation of  $2a:L = 1:25$  for short period (< 5 h) internal waves, where  $a$  = amplitude and  $L$  = wavelength. Assuming that such a relation exists

in this location, the wavelength of the internal wave was found to be 175m. From the relation  $L = C_p.T$ , where  $C_p$  is the phase speed and  $T$  the wave period (4.6 h), the internal wave phase speed was found to be approximately equal to  $1 \text{ km.d}^{-1}$  ( $1.057 \text{ cm.sec}^{-1}$ ). The crest-period obtained from the isotherms (Fig. 5) has a typical value of about 58 min (0.97 h). Using the relation (wave length / crest length) = (wave period / crest period) (i.e.,  $175:C.L = 4.6:0.97$ ), the crest length was estimated to be 37m.

**Power spectra**—Power spectra of temperature fluctuations at different depths were computed using the data from all 11 thermistors. All the spectra showed similar features and hence only three depths were selected for presentation and discussion. The log-log plots of the spectral density of temperature fluctuations at 80, 90 and 100m depths were presented along with 90% confidence limits in Fig. 4. Spectral density was higher at 90m when compared to the spectral densities above or below this depth. This depth coincided with the layer of maximum temperature gradient within the thermocline. The low frequency components in the depths below 90m were particularly predominant at frequencies 0.0167, 0.1667 and 0.2167 cpm corresponding to 60, 6 and 4.62 min periods respectively. In the higher frequency region, the spectral peaks occurred at 0.35, 0.38 cpm and at 0.47 cpm frequencies corresponding to 2.9, 2.6 and 2.1 min period respectively. The slope of the power spectra in the observed frequency domain of 0.0167 to 0.4667 cpm, was well represented by a  $f^{-2.7}$  fall off.

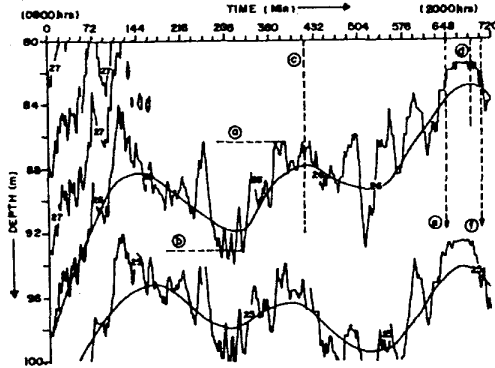


Fig. 3—Thermal structure of the upper thermocline at the study location [b-a = wave-height, d-c = wave-period, f-e = crest-period]

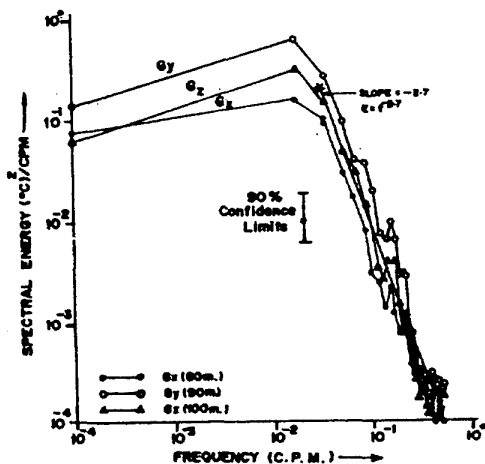


Fig. 4—Energy density spectra of temperature oscillations at 80m ( $G_z$ ), 90 ( $G_y$ ) and 100m ( $G_x$ )

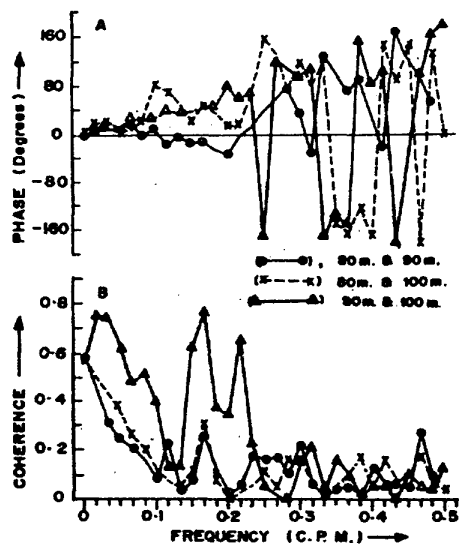


Fig. 5—(A) Phase and (B) coherence of cross-spectral estimates for temperatures at different depths

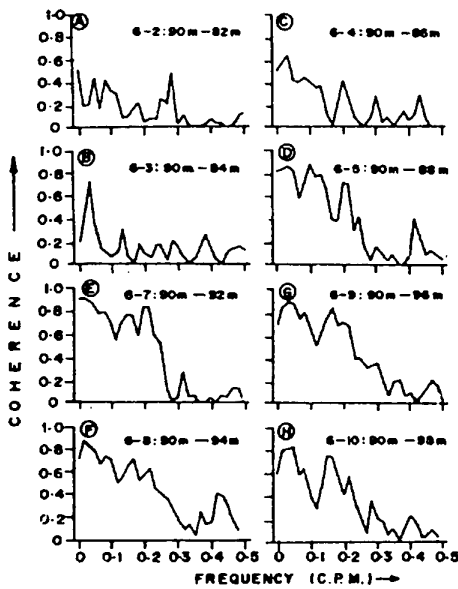


Fig. 6—Coherences of cross-spectral estimates for temperatures at various depths with respect to 90m in the range 80-100m

**Coherence and phase**—Coherence and phase relations of the temperature fluctuations at the 3 selected depths are presented in Fig. 5. The spectral peak corresponding to 0.0167 cpm (60 min) has high degree of coherence with very small phase difference ( $< 20^\circ$ ) from 80 to 100m depth. The oscillations at 90 and 100m depths have high coherence upto 0.2167 cpm (4.62 min) with gradually increasing phase difference towards high frequencies. It was found that a sharp change in the degree of coherence among temperature fluctuations occurs at 88m depth (Fig. 6) resulting in a discontinuity in the coherence between the oscillations above and below this depth. The oscillations below 88m depth showed a high coherence. Lack of significant coherence above 88m depth and the strong temperature gradient at this depth may possibly make this depth act as upper

boundary for the internal waves. The low frequency ( $< 0.0167$  cpm) fluctuations had high coherence in the entire column. Coherence gradually decreased towards high frequency region indicating that high frequency oscillations were unrelated.

This study shows that the thermistor chain measurements provide very useful information on the internal wave characteristics in the study region. As pointed out by Kaye *et al.*<sup>7</sup>, this type of measurement has advantages over the moored arrays and produce fairly accurate estimates of the internal wave characteristics.

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