

## **Sub-surface Temperature Oscillations and Associated Flow in the Western Bay of Bengal**

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*Received 25 June 1984 and in revised form 23 January 1985*

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**Keywords:** temperature variations; coastal currents; internal waves; shear; Richardson number; stratification; continental shelf; Bay of Bengal

Unusual temperature variations at subsurface depths were noticed while making continuous observations (for 13 h) on temperature, salinity and currents at a point in the vicinity of river Krishna in the western Bay of Bengal. Sharp temperature oscillations recorded at four different levels between 14 and 20.1 m had an average periodicity of about 1.6 h. Similar periodicities were also observed in the case of flow components. Computed Brunt-Vaisälä frequency, vertical shear and Richardson number showed remote possibilities of vertical mixing occurring in this area. These oscillations showed features of internal waves propagating with a speed of about  $13.3 \text{ cm s}^{-1}$  and wavelengths between 0.8 and 1.3 km and apparently generated as a result of flood current passing over a submarine obstacle in the presence of stratification.

### **Introduction**

Temperature oscillations of periodicity ranging from 12 h to a few minutes have been observed in the waters of the continental shelves of the oceans by various authors on many occasions (LaFond, 1962, 1966; Leipper, 1955; Cairns, 1967). These oscillations, sometimes erratic, are triggered generally by tidal forces, flow over irregular bottom, atmospheric disturbances, shear flows, etc. The growing importance of these oscillations in studies pertaining to biological productivity, underwater acoustics, vertical mixing etc., have created an increased interest in the investigation of this feature recently.

Some unusual variations in water temperature at depth have been encountered by the present authors while making continuous temperature observations at a fixed point off the River Krishna in the Bay of Bengal before the onset of the SW Monsoon in 1982. Similar temperature oscillations observed around this area have been attributed to the presence of internal waves on a few earlier occasions (LaFond, 1954; LaFond & LaFond, 1968). Apart from these early works, reports describing such oscillations in the shelf waters of India are few, probably due to the lack of continuous temperature observations. The present paper deals with such observed temperature oscillations, their characteristics and probable generating mechanisms.

### **Observation**

The data for the present investigation were collected approximately 15 km off the river Krishna (Figure 1) where the water depth is around 25 m. The bottom topography is free

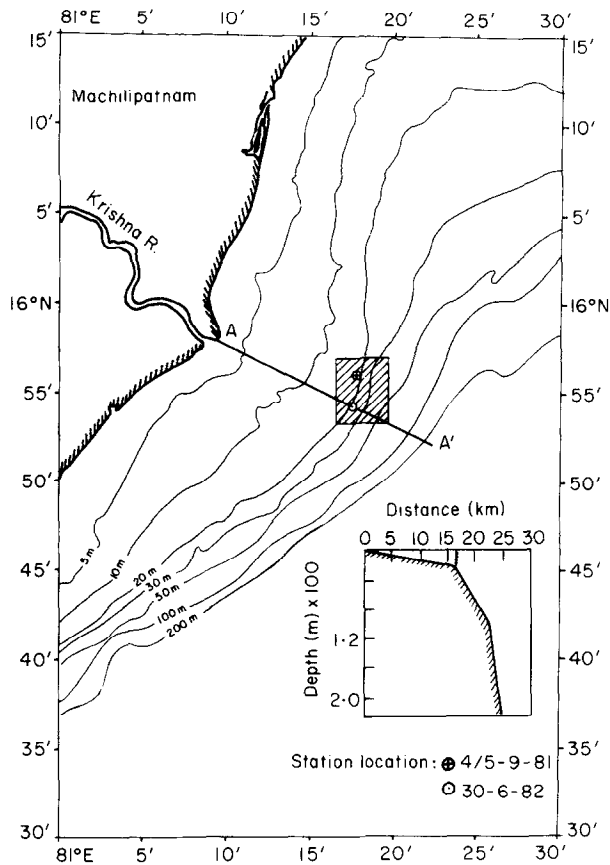


Figure 1. Location of the observation point with inset showing the cross-sectional bathymetric profile along AA'.

from any irregularities except that the shelf is very narrow and our observation point was very near to an increase in slope within the shelf (Figure 1, inset). The tide in this area is of mixed semi-diurnal type with a range of 1.2 m (nearest tidal station is 50 km north of Machilipatnam).

Four Aanderaa RM-4 current meters were suspended at depths of 14, 16.7, 18.4 and 20.1 m from an anchored ship, R.V. *Gaveshani* and continuous measurements of current speed and direction, temperature, salinity and depth were made at 5-minute intervals for 13 h from 12.00 h on 30 June to 01.00 h on 1 July 1982. Though the selection of the depths may appear to be arbitrary, observations prior to current meter lowering have shown a temperature discontinuity layer around 15 m at this station. The data collection system could introduce a source of error, arising from the fact that the current meters were suspended from an anchored vessel the oscillations of which could interfere with the recordings. However, the absence of rough seas during these observations helped to maintain the vertical movements of the current meter array at a minimum.

#### Observed temperature time series

Temperature time series data obtained at the four levels are presented in Figure 2. One interesting feature noticeable from this figure is the sharp temperature fluctuations with a periodicity of about 1.5–2 h. These fluctuations are so sharp at times that within a span

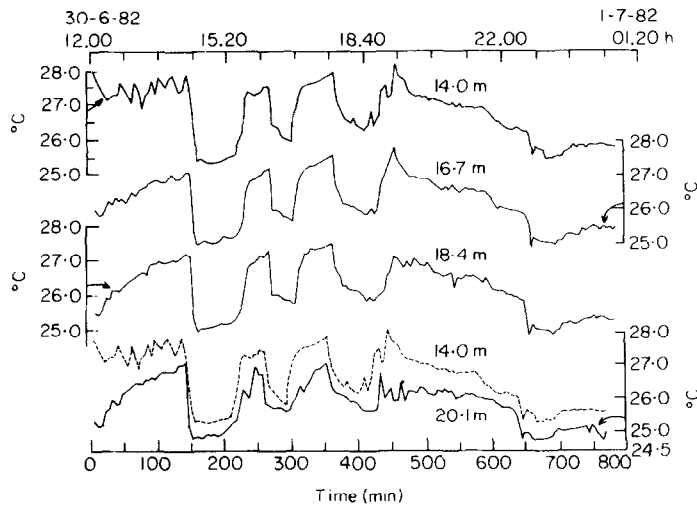


Figure 2. Observed temperature time series.

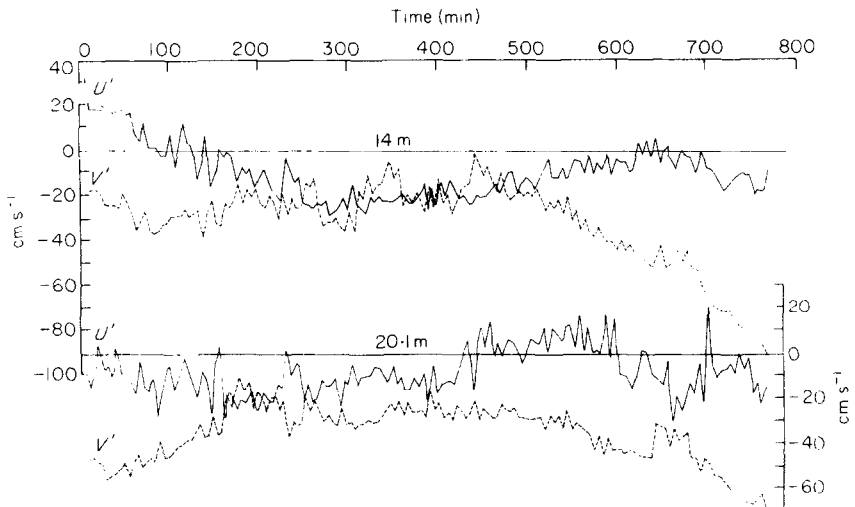


Figure 3. Shore normal ( $U'$ ) and alongshore ( $V'$ ) components of the observed flows at the 14.0 m and 20.1-m levels.

of 10 min, the temperature drops by about  $2.5^{\circ}\text{C}$ . The magnitude of temperature variations remains more or less the same at all levels. It may be noticed that the temperature fall is more sharp than the rise with the crests and troughs of the temperature curve almost flat. The temperature difference between the upper and the lower levels remains at a minimum during the time of fall and rise, but increases at the crests and the troughs. The maximum temperature difference ( $2.7^{\circ}\text{C}$ ) between these two levels occurred at the beginning of the observation. The sharp fluctuations, however, did not persist throughout the period of observation.

### Currents

The flow components  $V'$  (alongshore) and  $U'$  (offshore/onshore) for the upper and the lower current meters are presented in Figure 3. Both the components exhibit variations

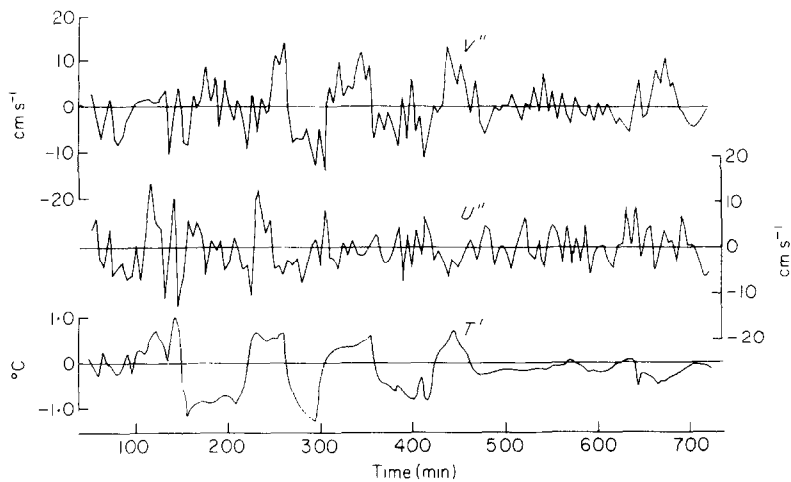


Figure 4. Deviations of 90-min moving averages from the original data of shore normal ( $U''$ ), alongshore ( $V''$ ) components of the flow and temperature ( $T'$ ) and 14.0 m depth.

with more than one frequency. At both levels  $V'$  indicates oscillations of a low frequency comparable to that of the tide and an intermediate one with a period of about 90–100 min.  $U'$  on the other hand, does not show the intermediate frequency clearly, though the tidal frequency is conspicuous. Further,  $V'$  seems to be at a maximum when  $U'$  is at a minimum and vice versa. As to the amplitudes,  $V'$  attains a maximum value of about  $90 \text{ cm s}^{-1}$  at 14 m and  $70 \text{ cm s}^{-1}$  at 20 m, both occurring towards the end of the observation, while  $U'$  attains a maximum value of about  $30 \text{ cm s}^{-1}$  at both levels.

### Relation between temperature oscillations and currents

To explore the existence of any inter-relationship between the observed temperature oscillations and the variations in the flow, the high and low frequency oscillations have been separated using a 19-point (95-min) moving average which corresponds to the observed period of these oscillations.

#### *High frequency oscillations*

The higher frequency oscillations (deviations of the averages from the original value) of the temperature ( $T'$ ) and the  $U''$  and  $V''$  components (Figure 4) are closely related. The trend is that the alongshore flow (which is always southwards) increases when temperature falls suddenly and decreases when the temperature rises. Whereas, the  $U''$  component (which is mostly towards the coast) decreases when temperature falls and increases when temperature rises. The contrast in the behaviour of the flow components, i.e. the decrease of  $V''$  when  $U''$  increases and vice versa, must be of manifestation of the to-and-fro movements of the current vector in the horizontal plane. In short, when the temperature oscillations occur, similar oscillations in the current vector also take place.

#### *Low frequency oscillations*

Figure 5 shows the low frequency oscillations of temperature ( $T$ ) and  $V'$  and  $U'$  components along with the tide as predicted for the nearest tidal station. The observations were started when the tide was rising and the flow components show a mean increase

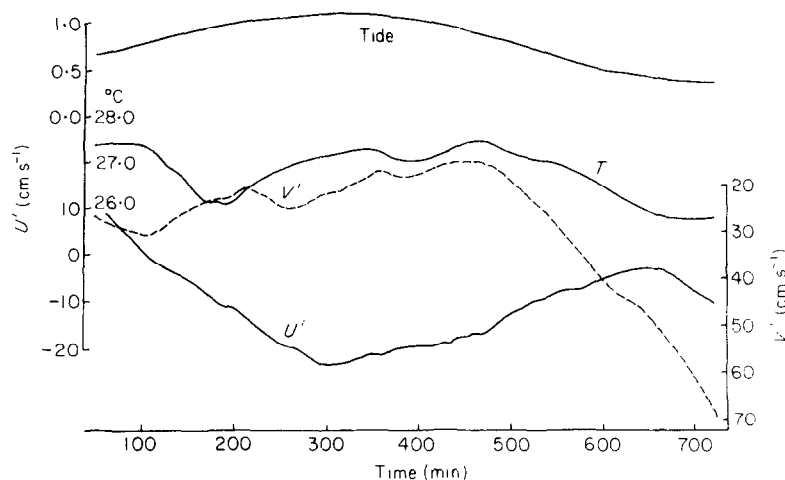


Figure 5. The 90-min moving average of  $V'$ ,  $U'$  and temperature at the 14.0-m level together with the predicted tide.

in magnitude onshore and a decrease alongshore. The mean temperature also shows an increasing trend. The reverse happens with all the three parameters when the tide is falling. One may tend to attribute the increase in the mean temperature during the rising phase of the tide either to the increase in the magnitude of the onshore current or to the slackening of the alongshore flow. Similar observations relating the alongshore current fluctuations with frequencies close to semi-diurnal tide to the surface tide, and the coherence between the temperature and the onshore flow to the internal tide, have been reported by Winant & Olson (1976). We, however, have no evidence to show the presence of warm water offshore leading to this observed increase. On the contrary, Figure 4 shows the possible relation between the temperature drop and the increase in the alongshore flow. Also, from Figure 5, we find a substantial drop in the temperature when  $V'$  increases considerably towards the end of the observation. From these we are inclined to associate the cold water with the alongshore flow and attribute the general rise in temperature to the decrease in the alongshore flow, in preference to the increase in the onshore flow. We further presume that these variations are due to the surface tide than to the internal tide.

It can also be seen from Figures 4 & 5 that the temperature oscillations started when  $U'$  was increasing, i.e. when the water was flowing towards the shore, and they disappeared when the onshore flow began to decrease. This trend prompted us to examine the vertical shear both alongshore and offshore to understand the role of vertical shear in the generation of these motions. Though the onshore shear was found to be greater than the alongshore shear it was strange to find that the above-temperature oscillations occurred when the vertical shear along both these directions remained low (Figure 6). We also noticed that the shear components tend to be greater when the temperature difference between the top and the bottom levels shows an increase.

#### *Power spectra*

Power spectra of temperature and flow components for the upper level were computed using an FFT algorithm. Due to restrictions on the number of data points to be used in an FFT algorithm the data length had to be limited to a duration of 10.5 h instead of the

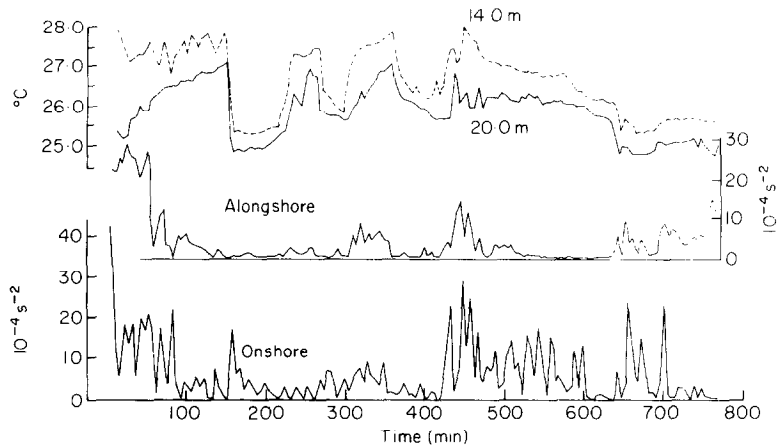


Figure 6. Alongshore and shore normal current shear together with the observed temperature at 14 m and 20.1 m.

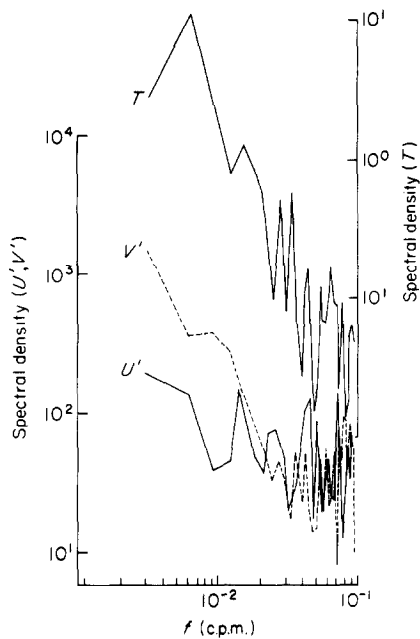


Figure 7. Power spectra of  $U'$ ,  $V'$  and  $T$  at 14 m.

original data length of 13 h. The temperature spectrum (Figure 7) shows a greater rate of fall of energy with frequency compared to the  $V'$  spectrum. In the case of  $U'$ , though the energy level is low compared to  $V'$ , the rate of change of energy is not appreciable. All three spectral curves show a small peak around the frequency band of  $9 \times 10^{-3}$  to  $1.6 \times 10^{-2}$  c.p.m. and correspond to the observed higher frequency oscillations of the temperature and flow components in Figure 4. The absence of well defined peaks in the spectra at frequencies otherwise identifiable in the time series data may partly be attributed to the fact that (i) the low frequency trend has not been filtered from the

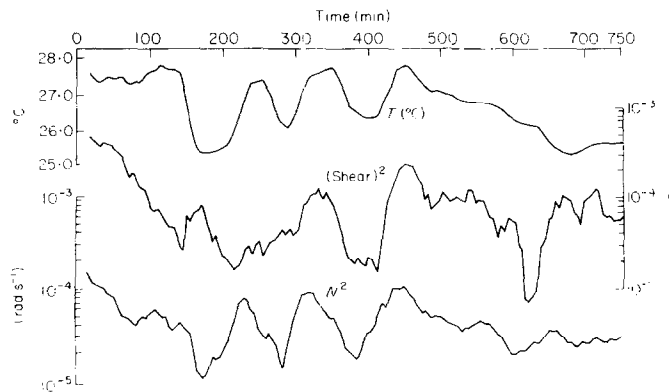


Figure 8. The 5-point moving averages of temperature (14.0 m), shear and  $N^2$  between 14 and 20.1 m.

original data and (ii) the length of the data had to be limited because of the FFT algorithm used for this analysis.

### Stability of the water column

In order to know the stability of the water column at the observation site and the probable mixing taking place during the study period, Brunt-Vaisälä frequency ( $N^2$ ), vertical shear and Richardson number (Ri) were computed using the data from the upper and the lower current meters. The formulae used and the values obtained are presented below:

$$N^2 = -\frac{g}{\rho_0} \frac{d\rho}{dz}, \quad (1)$$

where  $g$  is the acceleration due to gravity,  $\rho_0$  is the average density and  $z$  is the vertical co-ordinate (positive upwards). The average density,  $\rho_0$ , has been computed from the temperature and salinity recorded every 5 min:

$$R_i = \frac{N^2}{\left(\frac{\Delta U}{\Delta z}\right)^2 + \left(\frac{\Delta V}{\Delta z}\right)^2}, \quad (2)$$

where  $N$  is the Brunt-Vaisälä frequency in  $\text{rad s}^{-1}$  and  $\Delta U'$  and  $\Delta V'$  are the differences in the  $U'$  and  $V'$  components of the flow in the upper and the lower current meters, and  $\Delta z$  represents the distance between the rotors of the current meters.

The denominator of the above equation (2),

$$\left(\frac{\Delta U'}{\Delta z}\right)^2 + \left(\frac{\Delta V'}{\Delta z}\right)^2$$

is the vertical shear squared, and the variations in this parameters were utilized for comparison with the temperature oscillations to understand the vertical stability of the water column. The shear values presented here have only a qualitative importance as the vertical shear computations using data obtained from instruments like Aanderaa current meters may lead to artificial or instrumental shear, especially in the upper 50 m of water (Winant, 1979).

The computed values of  $N^2$  and the vertical shear are plotted against the temperature time series (Figure 8) for comparison. To make the study easier, a 5-point moving

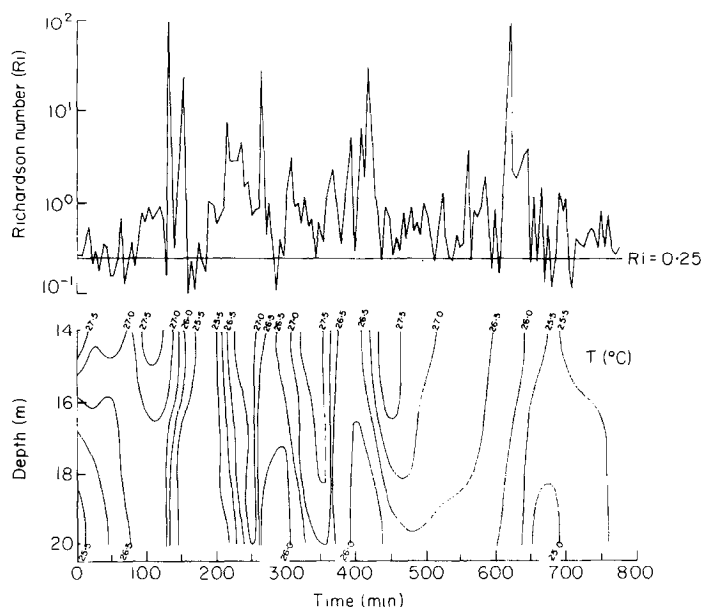


Figure 9. Variation of Ri and temperature between 14 and 20.1 m with time.

average of these parameters was used to eliminate very high frequencies. Ri was presented along with the vertical temperature structure with time which was prepared using every 5th value of the observed temperature. This was done to make the contouring easier while sacrificing certain irrelevant details.

$N^2$  shows wide variations with time ( $1.6 \times 10^{-3}$  to  $6.5 \times 10^{-5}$   $\text{rad s}^{-1}$ ) indicating that the stability of the water column increases and decreases alternately. When temperature drops sharply,  $N^2$  exhibits a sudden decrease and when temperature rises, it shows an increase.  $N^2$  is maximum when the temperature recorded is at a maximum. This pattern shows the dependence of  $N^2$  on temperature alone and the marginal contribution from salinity (33.7–34.1‰) during the period of the study.

Vertical shear was found to vary considerably during the period of observation. In general, it was found to decrease with a sudden fall in temperature and increase with increase in temperature. Also, the variations in the shear were found to coincide with those of  $N^2$  except during the first temperature drop.

Figure 9 displays the variations of Ri and the vertical temperature structure with time. It is seen from this that Ri decreases when cold water is present and increases when warm water appears. Though Ri varies widely, it rarely falls below 0.25. Phillips (1966) and Munk (1966) identify the transition from waves to turbulence with Ri equal to 0.25, so that shear instability would occur. The reason why Ri seldom falls below the above limit could be either due to the high values of  $N^2$  or the low vertical shear. But from Figure 10 we note that the shear remains low compared to  $N^2$  indicating the possibility of minimum shear instability taking place during the temperature oscillations.

## Discussion

The findings of this study on subsurface temperature oscillations and the associated flow characteristics that have been described above, along with some stability parameters and



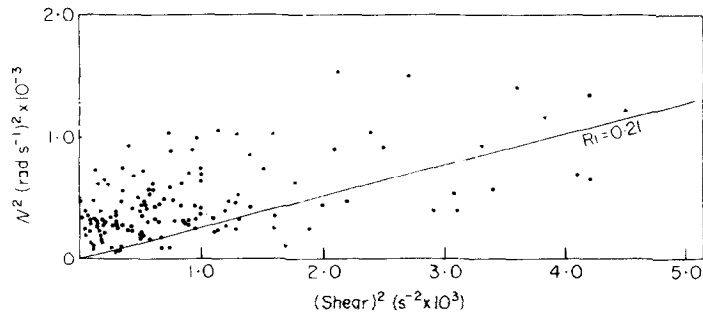
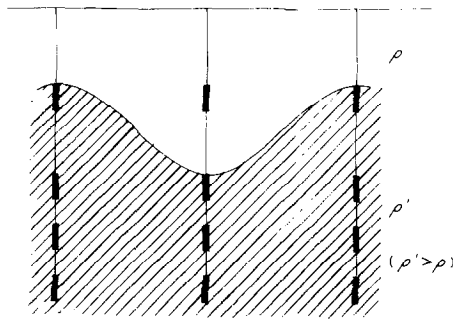
Figure 10. Plot of  $N^2$  vs.  $(\text{shear})^2$ .

Figure 11. Schematic presentation of the internal wave with reference to the current meter array.

the sudden drop and gradual increase in temperature associated with these oscillations, could possibly be explained through the following. If a current meter array, like the one we used in the present study, occupies the lower layer of a two-layer system, where considerable velocity shear and density gradient exists across the interface (Figure 11), one may not encounter appreciable shear or high vertical stability between the top and bottom sensors. On the other hand, if the current meter array is distributed both in the upper and the lower layers, it would be possible to notice the presence of high shear and vertical stability. It is likely that this is what could have happened in the present case and we have some evidence to support it. A temperature difference of about  $2.7^\circ\text{C}$  observed between the upper and the lower levels at the beginning of the observations suggests the existence of a density discontinuity. The vertical stability and the shear were also very high. We also found that the shear was greater when the temperature difference between the upper and the lower levels was greater. These results substantiate the above explanation and the possibility that the top current meter could have been very near to the interface. In addition, the fact that  $Ri$  seldom fell below a value of 0.25 perhaps shows that the shear associated with the flow is not sufficient enough to overcome the effects of stratification, and there is not much evidence to assume that turbulence and vertical mixing take place during the oscillations, though patches of turbulence may be associated with the surge of cold water. This prompts one to believe that the up-and-down movements of cold and warm waters could be the manifestation of internal waves.

Considering these as internal waves we find that, due to shoaling, an internal wave appears to shorten or steepen on its shoreward side rather than its trailing end, as was

also observed by Cairns (1977) off the coast of California. The speed of the internal wave,  $C$ , computed from the relation

$$C^2 = g \frac{h h_1}{h + h_1} \left( \frac{\rho - \rho'}{\rho} \right), \quad (3)$$

where  $\rho'$  and  $\rho$  are the densities of the upper and the lower levels respectively and  $h$  and  $h_1$  are the thicknesses of the two layers, gave a value of  $13.3 \text{ cm s}^{-1}$ . For these computations, we used 14 and 11 m for  $h$  and  $h_1$  respectively, with average densities of 1.02197 (upper current meter) and 1.02227 (lower current meter). The observed absence of mixing shows that the waves do not become unstable at this depth, because the breaking would have given rise to mixing of the waters. Generally, the frequency of the internal waves would lie in between the Brunt-Vaisälä frequency ( $N = 10.5 \text{ c.p.h.}$  in the present case) and the local inertial frequency ( $\sim 0.023 \text{ c.p.h.}$ ). The frequency of the internal wave that we observed was about  $0.63 \text{ c.p.h.}$ , and it falls within the above limits. For this frequency, considering internal wave of the first mode, the theoretical value of the wave length would be around 1 km. The computed wavelength from the observed values using the relation,  $L = CT$ , assigning  $13.3 \text{ cm s}^{-1}$  for  $C$  and 1.6 h for  $T$ , is about 0.8 km. This is true only in the absence of any flow. But if it is presumed, as before, that the waves are moving with the current towards the coast, we may have to take into consideration the average speed of the flow. In the present case, the mean  $U'$  is about  $9.7 \text{ cm s}^{-1}$  and, if we substitute  $C$  by  $(C + U')$  in the relation  $L = CT$ , we obtain a value of about 1.3 km for  $L$ . Therefore, the wavelength of the observed internal wave would lie in between 0.8 and 1.3 km, which is close to the theoretical value of 1.0 km.

However, what is the mechanism that generates these internal waves in this area? The frequency of the temperature oscillations observed do not permit us to link them directly to the tides. However, the occurrence of a series of internal waves of relatively high frequency following the tide have been reported in the waters off the California coast (Lee, 1961). Also, observations on high frequency temperature oscillations have been attributed to the horizontal shear of the tidal currents over the shallow irregular bottom in the presence of stratification (Leipper, 1955). Experimental studies by Gargett (1968) show that long waves passing over a submarine obstacle can degenerate by bore formation into a number of waves of much shorter wavelength. Do any of these mechanisms hold good in our case? It appears that Gargett's study can provide some insight into our problem. As mentioned earlier, our observation point lies just on the edge of a submarine slope (Figure 1, inset) and we have noticed that the temperature oscillations started when offshore water started advecting towards the shore. Therefore, it is possible that the above oscillations were initiated when the flow was passing over the edge of the slope in the presence of stratification (maximum temperature difference of  $2.5^\circ\text{C}$  observed at the beginning). Halpern (1971) also arrived at a similar conclusion in the case of high frequency temperature oscillations observed in the Massachusetts Bay. The disappearance of these oscillations towards the end of the observation may partly be due to the erosion of the stratification, presumably due to the strong, almost uniform alongshore flow rather than shear-induced mixing.

At this stage, examination of winds—one of the environmental factors considered important and pertinent in this type of problem—showed (Table 1) no abnormal features. Steady, moderate winds were blowing for two consecutive days prior to this observation. In addition, the absence of movement of the frontal systems associated with

TABLE 1. Summary of wind observations at Machillipatnam (India Meteorological Department)

Date	Wind (08.30 h)		Wind (17.30 h)	
	Speed (kt)	Direction (°TN)	Speed (kt)	Direction (°TN)
27 June 82	03	270	03	260
28 June 82	06	290	08	290
29 June 82	08	290	05	320
30 June 82	02	270	03	270

land and sea breeze circulation (evident from the table) also points to the remote possibility of the generation of these oscillations by winds.

We further presume that the correlation observed between temperature oscillations and the flow (especially the  $V'$  component) is mainly due to the interaction between the internal wave and the existing flow – though the nature and the extent to which such interactions take place is not clear.

The very low vertical shear observed at the time of these oscillations is curious in the light of a recent study in the Black Sea by Ivanov & Serebryanny (1982) where the importance of vertical shear in the generation of internal waves has been pointed out. Their conclusions were based on a higher peak that was observed at internal wave frequencies in one of the two temperature spectra where the vertical shear was greater than in the other. Though details regarding the behaviour of the vertical shear during the internal oscillations are not clear in their study, our observations show that, though the vertical shear was high during the initial stages, it remained very low during the oscillations. However, for confirmation of various suggestions made in this study more observations are needed.

### Acknowledgements

The authors wish to thank the Director and Dr R. Sen Gupta, Scientist, National Institute of Oceanography for their interest in this study. They express appreciation to their colleagues and the Master & Officers on board R.V. *Gaveshani* for their help. This study forms part of the Department of Environment's (Government of India) grant-in-aid programme.

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