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Thermal structure variation in the Arabian Sea (May-July 1973)

K. V. S. RAMAM, P. G. K. MURTY and C. K. B. KURUP

Naval Physical and Oceanographic Laboratory, Cochin

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ABSTRACT. Temperature data collected by the Russian research vessel R.V. *Priliv* over Arabian Sea during three cruises of ISMEX 1973 from May to July 1973 have been analysed. Thermal conditions of two zonal sections along 11° 30'N and 16° 00'N and at buoy station (18°N, 67°E) have been depicted. Layer thickness increases from May to July. Linear regression equations have been developed between mixed layer depth (MLD) and depth of 21°C isotherm below MLD. Internal waves have been identified in these areas and the wave parameters reported.

1. Introduction

Indian Ocean has been under active and rigorous study for the past one decade. Much of this study is centred around equatorial and northern latitudes of the ocean, covering various aspects of hydrographic features, major and minor current systems, water masses, etc. Apart from these studies, some work has also been directed towards the studies on internal waves and their effects on thermal structure and underwater sound propagation (Lee 1961, Perry and Schmike 1961). The present study emerged from a collection of oceanographic data during the joint Indo-Soviet programme, designated as ISMEX 1973 (Indo-Soviet Monsoon Experiment). The results of the analysis of the temperature and salinity data, collected on board Russian vessel *Priliv* over two zonal sections and at the buoy station, which were covered prior to and during the monsoon period (from May to July 1973) are reported in this paper.

2. Data analysis

The data coverage along two zonal sections and at the buoy station with duration are indicated in location map (Fig. 1). The ship's drift at the buoy station in the first phase , *viz.*, during 28 May to 6 June 1973 is observed to be 5.5 and 3 nautical miles in the N-S and E-W directions respectively, while the corresponding figures in the second phase, *viz.*, during 26 June to 3 July 1973 being 4 and 5 nautical miles.

(a) *Thermal structure*

From the digitized BT data, the depths of isotherms at 1°C interval are estimated. The vertical thermal structure along the two zonal sections within the upper 200 m is presented in Figs. 2 (i to iv). In the same figure corresponding station locations together with dates are indicated at the top of each section. Similarly variations of the vertical thermal structure at the buoy station are presented in Figs. 3 (i to v) along with its location at the top of each diagram. It may be noted that two different time scales have been used in the two cases, *viz.*, for Figs. 3(i) and (ii), and Figs. 3 (iii), (iv) and (v) to illustrate the thermal features in detail.

(b) *Internal waves*

The periods and heights of internal waves at different depths at the buoy station are obtained by following individual isotherms at respective depths and these are given in the Table 1. Fig. 4 shows plots of internal wave energy (proportional to square of wave height) against corresponding wave periods. From the available hydrographic data at the buoy station, assuming two layer model (Sverdrup *et al.* 1949, Defant 1961) internal wave velocity, C, is computed from the following equation at a depth of 70 m:

$$C^2 = gh \frac{\rho - \rho'}{\rho}$$

where,
- g : Acceleration due to gravity
- h : thickness of the top layer, *viz.*, surface isothermal layer, where density gradient is small.
- ρ' : The mean density of the top layer,
- ρ : The mean density of the bottom layer, *viz.*, layer extending from bottom of isothermal layer to 200 m.

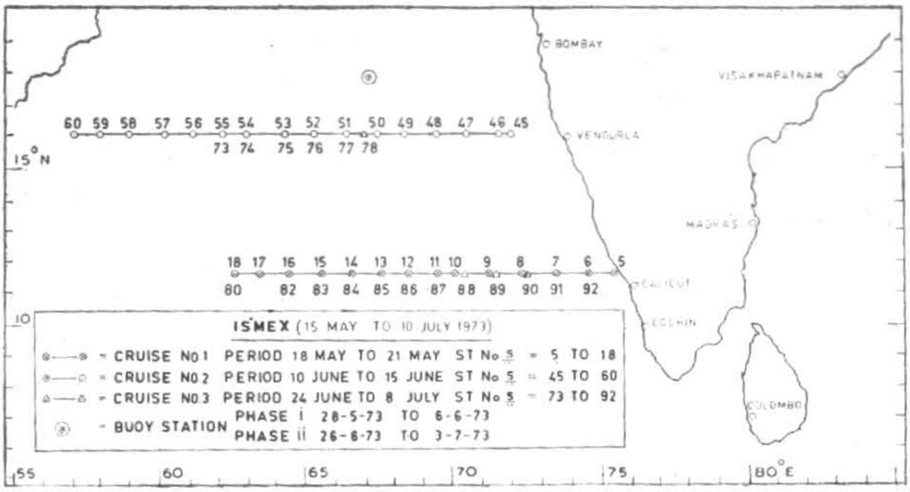

Fig. 1. Location map of stations and dates of cruises

TABLE 1

Internal wave characteristics at different depths at buoy station

Late May				Early June				Early July				
Depth (m)	Wave period (hr)	Wave period (min)	Wave height (m)	Depth (m)	Wave period (hr)	Wave period (min)	Wave height (m)	Depth (m)	Wave period (hr)	Wave period (min)	Wave height (m)	Wave length (km)
60	9	20	3	50	9	00	12	70	6	40	8	51·1
	8	30	4		8	50	15		6	00	9	46·1
	6	10	8		9	20	14		6	20	22	48·6
	10	10	11		5	50	7		5	30	5	42·2
	11	30	13		11	00	14					
100	11	00	20	120	12	20	36	150	7	40	12	
	11	10	17		7	10	16		9	10	29	
	9	00	21		10	40	35		8	50	9	
	8	40	32		6	00	18		8	40	50	
	6	50	20		9	20	20					
160	9	15	22	190	6	50	8	190	6	30	3	
	7	00	28		8	20	6		11	10	19	
	7	10	14		6	00	7		9	50	[illegible]	
190	11	00	11		11	40	14		8	30	24	
	7	00	6									
	7	50	5									
	6	00	10									
	6	00	9									

From this velocity, the wave length, λ is calculated from the equation $\lambda = CT$ where T corresponds to internal wave period.

(c) *Mixed layer depth (MLD)*

MLD is taken as the depth at which a negative temperature gradient exceeds 0.1°C/10 m and persists over depth intervals of 30 m. Mixed layer depths are evaluated for all the bathythermograms at the buoy station, Simultaneously, corresponding depths of 21°C isotherm below MLD are evaluated. A scatter diagram, between these two parameters is shown in Fig. 5 and two regression equations corresponding to pre-monsoon and monsoon conditions have been obtained.

3. Discussion of results

For convenience of discussion the zonal sections along 11° 30′ N and 16° 00′ N are designated as southern and northern sections respectively.

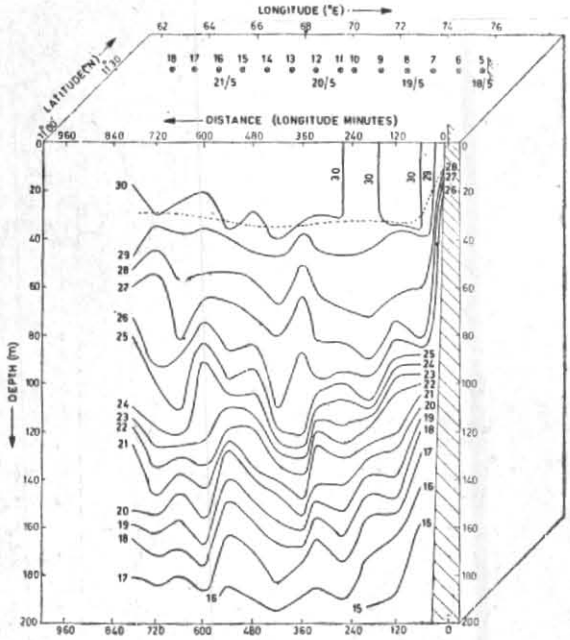

Fig. 2 (i)

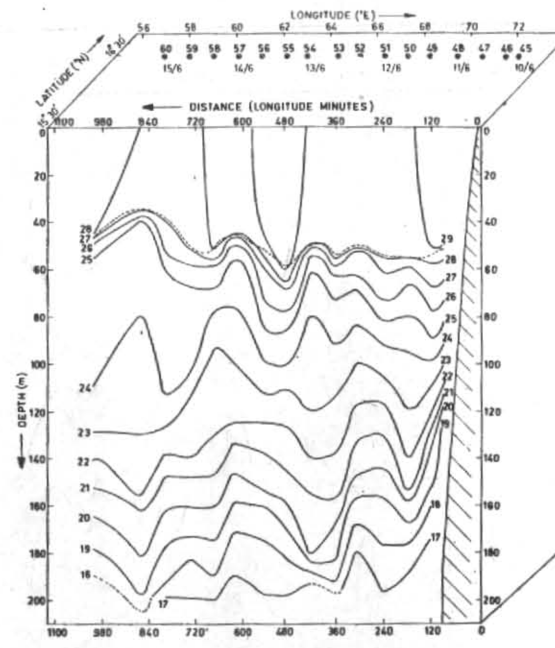

Fig. 2 (iii)

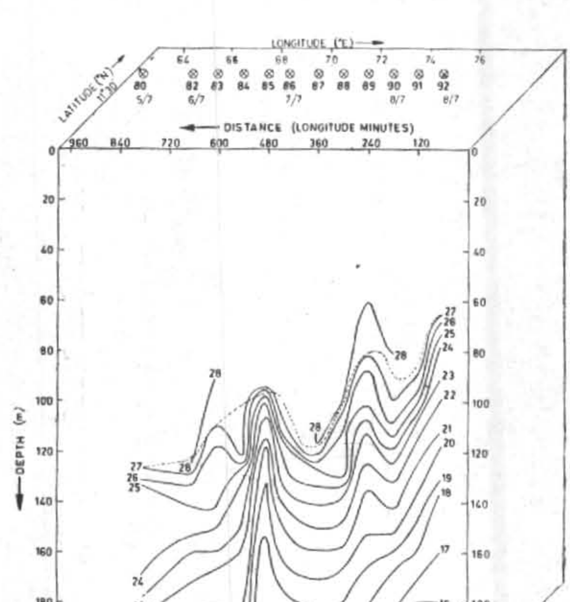

Fig. 2 (ii)

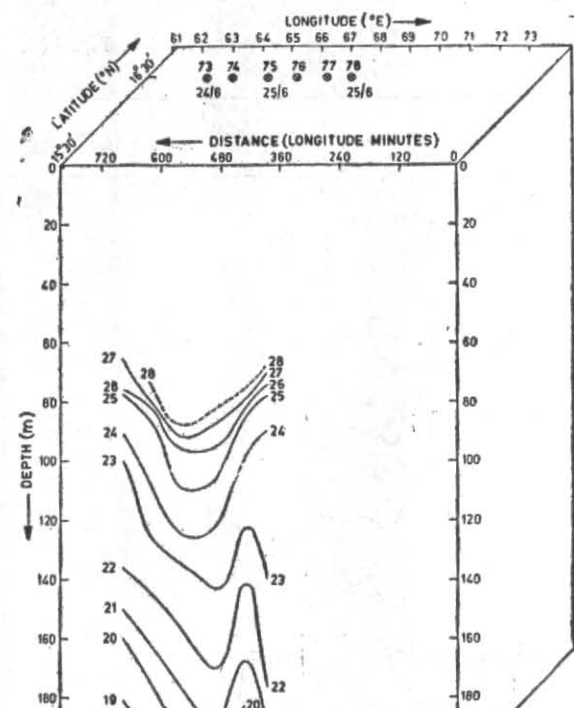

Fig. 2 (iv)

Fig. 2. Zonal sections — Vertical distribution of thermal structure (Dotted line : Layer depth)

(i) Along 11° 30′N for May

(ii) Along 11° 30′N for July

(iii) Along 16°00′N for mid-June

(iv) Along 16°00′N for end-June

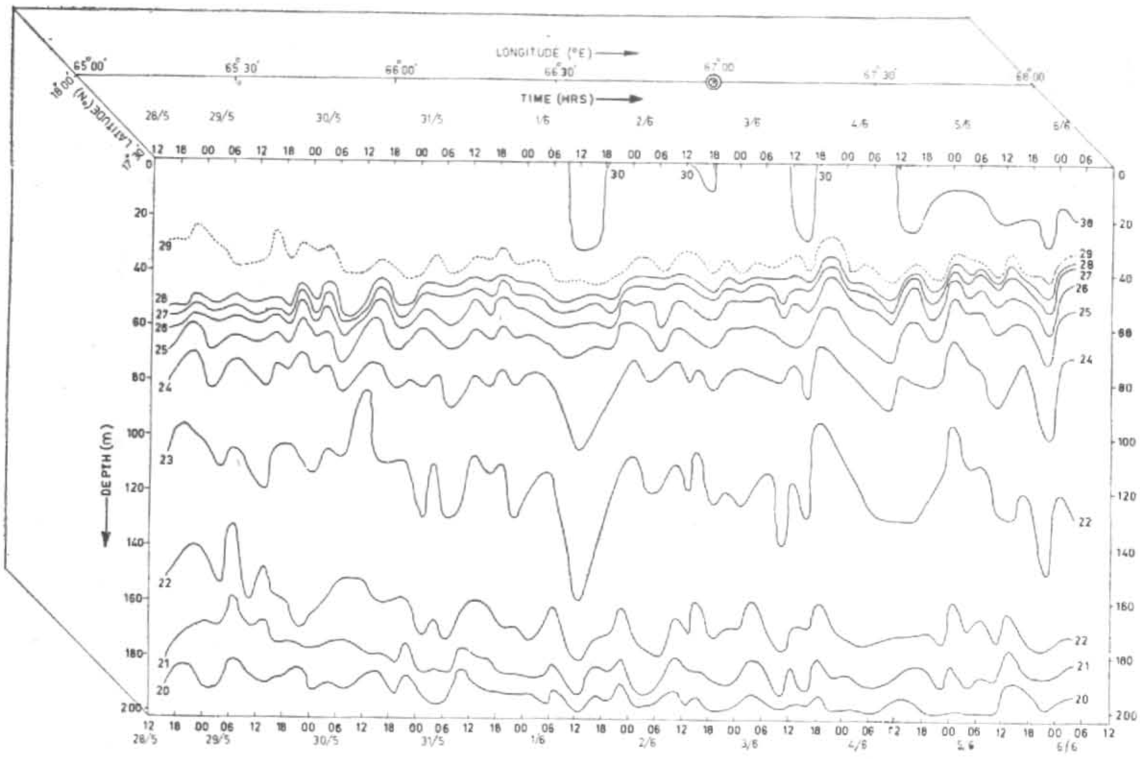

Fig. 3 (i). For phase I

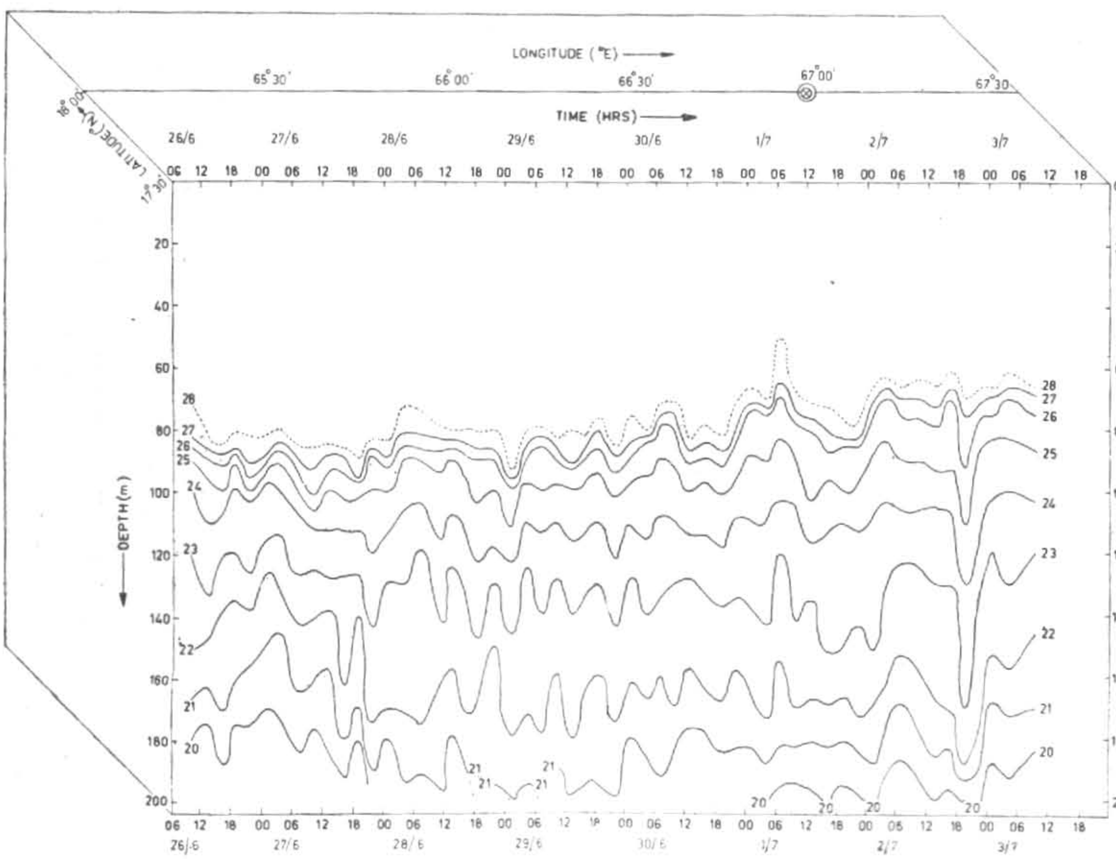

Fig. 3 (ii). For phase II

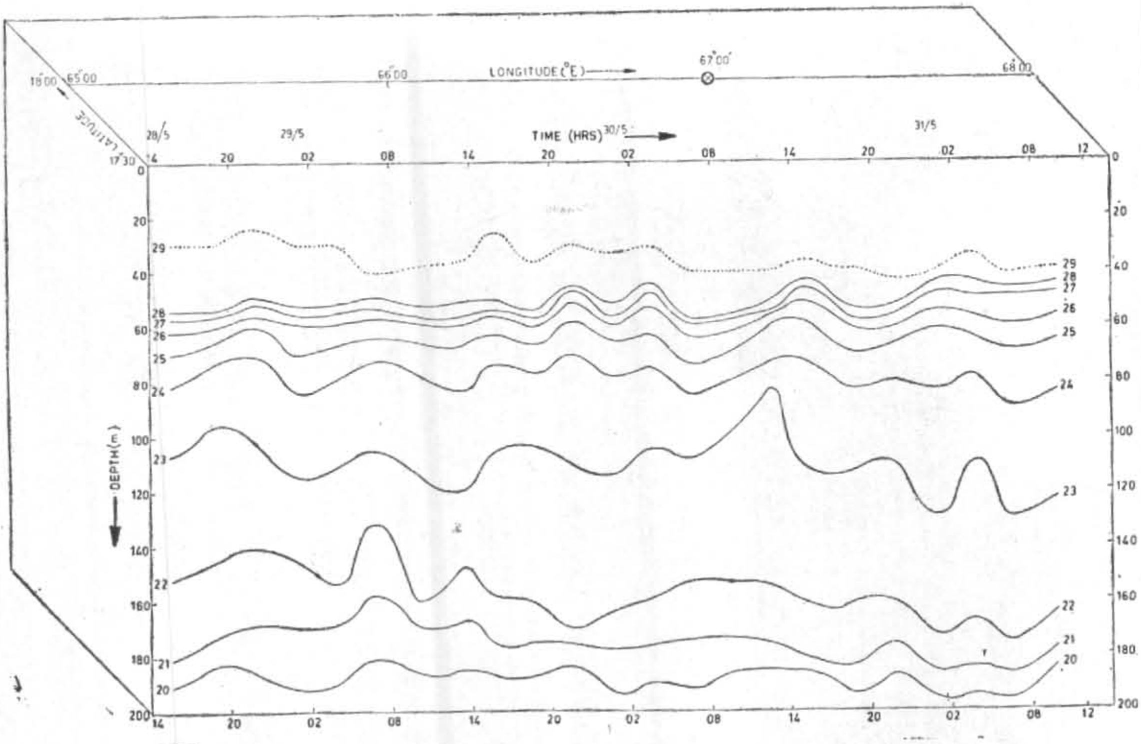

Fig. 3 (iii). Portion of phase I on expanded time scale

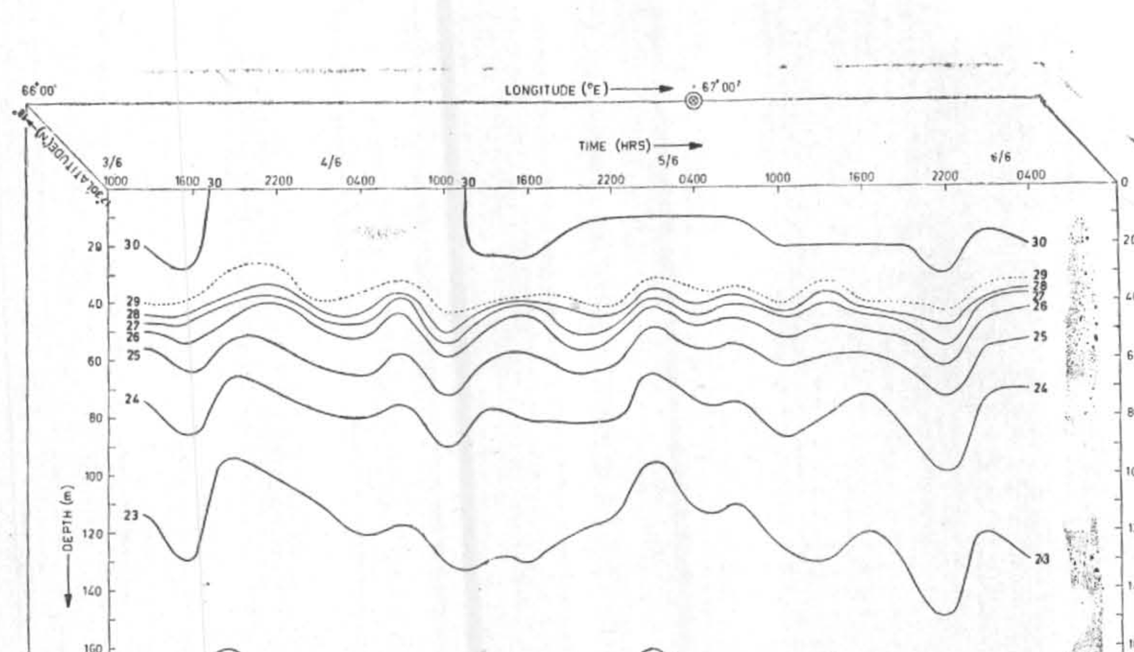

Fig. 3 (iv). Portion of phase I on expanded time scale

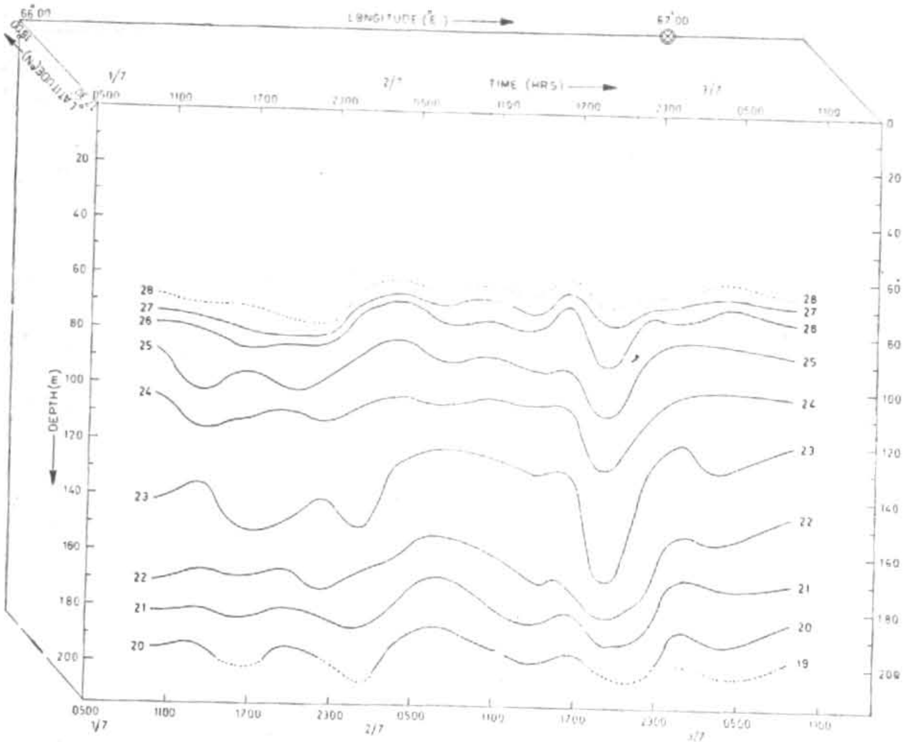

Fig. 3 (v). Portion of phase II on expanded time scale

Figs. 3 (i-iv). Time sequence of vertical thermal structure at buoy stations (Dotted line: Layer depth)

(i) For phase I

(ii) For phase II

(iii) & (*iv*) Portions of phase I on expanded time scale

(v) Portion of phase II on expanded time scale.

3.1. *Thermal structure along southern section (May and July)*

In May (Fig. 2 i) surface temperature varying from 30.6 to 28.6°C whereas in July (Fig. 2 ii) they vary from 28.2 to 27.4°C. The ranges of vertical temperatures from surface to a depth of 200 m during May and July are 15° and 12°C respectively. The layer thickness increases from 30 m in May to 110 metres in July with superimposed oscillations of amplitude varying from 9 to 15 m. Overcast skies and persistent strong winds, with occasional gales, during this period are responsible for these conditions (Ramesh Babu *et al.* 1976). During May the orientation of isotherms in the off-shore waters suggests weak northerly flow upto 80 m and moderately strong southerly flow at depths exceeding 80 m. The upward tilting of isotherms towards the coast may be due to the effect of bottom configuration on the flow pattern of internal waves. Alternatively, this upsloping reveals the possible southerly flow along the coast during this period (Sharma 1966). Similar features were noticed along Californian coast also (Lafond and Lafond 1971). If this southerly flow is considered as the cause for upwelling, it can be concluded that the upsloping may be due to the combined effect of upwelling and bottom configuration on the existing flow pattern.

3.2. *Thermal structure along northern section (June)*

This section was covered partially during June, *viz.*, first time during middle June (Fig. 2 iii) and second time end June (Fig. 2 iv). The surface temperature variations for middle and end June are from 29.7° to 27.2°C and from 28.5° to 27.2°C respectively. Corresponding vertical temperature ranges from 0 to 200 m are 12 and 9°C. At all depths except at the surface, the water is found warmer by 1° to 2°C during the later half of the month. The layer depth increases from 55 to 75 m. From these results, it appears that during time interval of only 10 days (between these two sets of observations) the thermal features have considerably changed indicating the need for more detailed studies in this area. The wavy pattern of isotherms with significant amplitudes, seen in Fig. 2, indicates the presence of internal waves (Defant 1950). The wide spacing of isotherms between 25° and 22°C is regarded as the result of mixing due to internal waves (Haurwits 1950, Lafond and Lafond 1971, Ramesh Babu 1976).

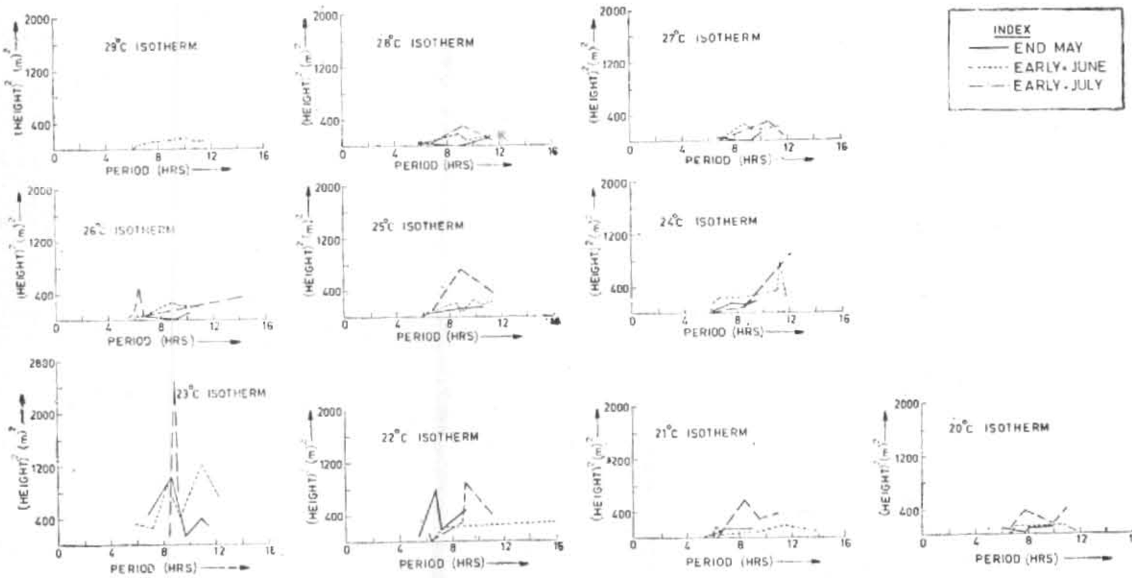

Fig. 4. Spectral distribution of internal wave energy at buoy station

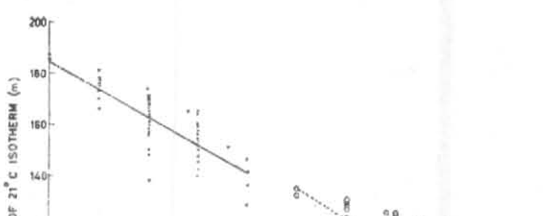

Fig. 5. Relationship between depth of 21 °C isotherm below MLD and Mixed Layer Depth (MLD)

3.3. *Thermal distribution at buoy station*

It is seen from Fig. 3(i) that during Phase I, surface temperatures change from 30.7° to 29·3°C (1.4°C) while during Phase II (Fig. 3 ii) they are reduced from 28.4° to 28.1°C (0.3°C). During these two phases, the range of vertical temperatures from surface to 200 m falls from 10° to 8°C. Further, thickness of the layer depth increases from 20 to 60 m. The seasonal thermocline appears to have been split into two parts with distinctive thermocline characteristics. The temperatures of the upper boundaries of these two parts, *viz.*, 30°/29°C and 22°C isotherms occur within two depth regions 20 to 60 m and 140 to 170 m respectively. The layer separating these two is characterized by weak thermal gradient, due to mixing of internal waves (Lafond and Lafond 1971). Therefore, these two parts of sharp thermal gradients are termed as primary and secondary seasonal thermoclines. They occur along northern zonal section also, where internal waves are noticed. This leads to the conclusion that whenever internal wave mixing dominates in the thermocline, primary and secondary seasonal thermoclines occur.

3.4. *Internal wave characteristics*

The periodic variations of the thermal structure at the buoy station indicate the presence of internal waves. From the analysis of the three hourly data, study was made of internal waves of periods exceeding 3 hours. It can be seen from the table that wave periods range from 5 hours 50 min to 12 hours 20 min with period around 8 hours 30 min being more frequent. The wave periods at different depths within the same time interval are observed to differ. The wave heights are found to vary from 2 to 50 m. The velocity corresponds to 213 cm/sec at a depth of 70 m and wave length for the prevailing periods fall within the range 42-51 km.

From Fig. 4 it is inferred that the energy of the internal waves is generally concentrated around wave period 9 hours and for 23°C isotherm. It diminishes on either side of 23°C isotherm.

3.5. *Correlation between mixed layer depth (MLD) and depth of 21°C isotherm below MLD*

From the thermal distribution at buoy station 21°C isotherm corresponds to the lowest isotherm recorded on all the bathythermograms. In addition to this it exhibits minor depthwise fluctuations. Basing on these two criterion an attempt is made to establish a relation between MLD and the depth of 21°C isotherm below MLD. The two following linear regression equations are obtained between MLD (L) and the depth (D) of 21°C isotherm below it for pre-monsoon and monsoon conditions.

For pre-monsoon $D = 184.73 - 1.0912L$

For monsoon $D = 194.45 - 1.2000L$

Although the correlation coefficients for the above two equations came to 0.80 and 0.64 with confidence level being 99 per cent for both the periods, yet their validity has to be confirmed by further observations over different regions during these seasons. If this type of regression relations can be established, it may be possible to predict the characteristics of the thermocline and the thermal structure in sub-surface layers.

4. Conclusions

(*i*) From May to July, there is a decrease in both the surface and vertical (0-200 m) temperature ranges. However, an increase in the layer depth is noticed during the same period.

(*ii*) The upward sloping of the isotherms near the coast indicates a possible southerly flow along the coast, which may give rise to upwelling. It is also likely that the upward tilt of isotherms may be due to the effect of bottom topography on internal waves.

(*iii*) A definite wavy pattern with periods from 5 hours 30 min to 14 hours 10 min and amplitudes 1 to 25 m indicates the presence of internal wave moving towards the coast with velocities around 213 cm/sec and wave lengths 42 to 51 km.

(*iv*) A weak thermal gradient extending over a thickness of 50 m around a depth of 100 m results out of the mixing due to internal waves. Primary and secondary seasonal thermoclines are observed.

(*v*) Much of the energy of observed internal waves, centres around wave period of 9 hours and corresponds to 23°C isotherm.

(*vi*) Two linear regression equations with negative slopes are obtained between mixed layer depth (MLD) and depth of 21°C isotherm below MLD, one for the pre-monsoon and the other for the monsoon periods.

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