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Diurnal Scale Variability in Vertical Thermal Structure of Coastal Waters Off Southwest Coast of India during May 1985

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Diurnal scale variations observed in the vertical thermal structure at 3 stations on the continental shelf (off Cape Comorin, Vizhinjam and Cochin) during May 1985 are analysed with short time series data sets collected onboard *R V Gaveshani* (cruise 154). Heating and cooling cycles observed in the surface layer are qualitatively discussed in terms of surface heat exchange processes. Large amplitude variations noticed in the thermocline suggest the prominence of internal waves. Vertical eddy diffusivity coefficient evaluated at one of the stations showed a value of 72 $cm^2.sec^{-1}$.

Advance knowledge on the short-term variability in the thermal structure of coastal waters is required for fisheries exploration, monitoring pollutant dispersal as oil slicks, underwater acoustic surveillance operations, etc. Variability of vertical thermal structure is known to be prominent on a diurnal scale in the coastal waters due to shallow water columns with high turbidity[1]. In general, formation of the surface mixed layer is mostly governed by radiative and turbulent heat exchange processes at air-sea interface while the gradient in the thermocline is known to be controlled by diffusion of heat and upwelling/sinking processes. However, the temperature distribution in coastal waters may not be totally governed by the local surface heat exchange process alone. Tidal effects and fresh water discharges may also become more important on a regional mode. In addition, internal waves whose frequencies range between Brunt-Vaisala frequency and inertial frequency which propagate along/towards the coast influence the thermal structure. The cause of the subsurface oscillations in coastal waters with periods of the order of hours can be due to internal waves[2]. These internal waves not only raise and lower the water layers, but also compress and stretch them along the vertical in such a way that the vertical density gradient continuously changes within certain depth intervals[3]. These waves occasionally get trapped and traverse along the coast on the continental shelf. The vertical temperature profile is therefore expected to exhibit complex patterns in the space-time domains. Information on the variability of the vertical thermal structure on the diurnal scale off Indian coasts is relatively meagre[4,5]. In the present study the observed diurnal scale variability in the surface meteorological elements and the vertical thermal structure at 3 selected stations off the southwest coast of India is documented.

Methods

The time series stations (TS1, TS2 and TS3) were chosen on the continental shelf off the southwest coast of India (Fig.1), during cruise 154 of *R V Gaveshani* [8-22 May 1985]. The ship was anchored at all the stations for observational periods extending over 12 h. Short time series measurements of standard surface marine meteorological elements (pressure, wind direction, wind speed, cloudiness, dry and wet bulb temperatures and sea surface temperature) and vertical temperature profiles (with the aid of MICOM bathythermograph) with sampling intervals of 1 to 2 h were made. The accuracy of MICOM bathythermograph is ± 0.05°C. The time is reported in IST.

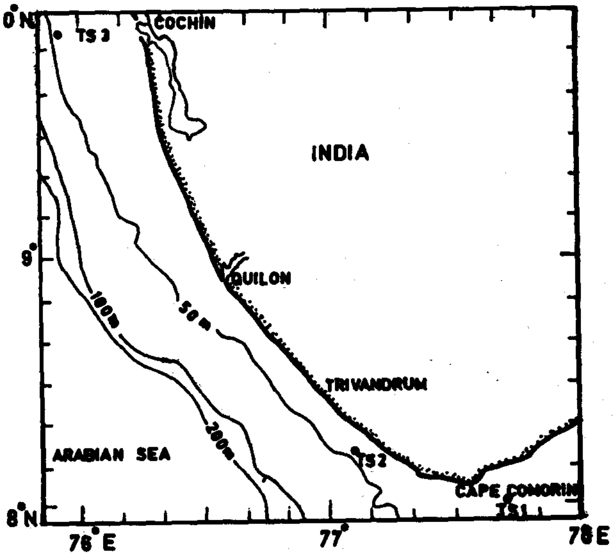

Fig. 1 — Station locations [Depth (m): TS1, 30; TS2, 38; and TS3, 50]

Results and Discussion

Time series st TS1— The observations were made from noon to mid-night on 12 May 1985 at TS1. The observed surface marine meteorological elements are shown in Fig.2. The surface atmospheric pressure (PR) fluctuated around 1006 mb with minimum around 1600 hrs and maximum around 2200 hrs reflecting the influence of atmospheric tides. The winds (D) were predominantly from west southwest with an average speed (FF) of 20 knot. Cloudiness (CL) showed a mild decreasing trend during this period. Air temperature (DB) dropped by about 2°C. The wet bulb depression (DB-WB) also registered a similar drop. The sea surface temperature (SST) cooled by about 0.25°C. The sea minus air temperature was mostly positive except around 1300 hrs, implying an unstable regime during observational period.

The corresponding vertical temperature profiles from 1200 to 2300 hrs at TS1 are shown in Fig.3. The origin is shifted by 0.5°C towards right for each profile. In general, these profiles exhibited a weak isothermal layer extending from surface to 20 m depth capped over a very strong thermocline. The profiles, from noon to 1500 hrs, did not exhibit well defined mixing but showed a transient diurnal thermocline from surface to 15-20 m depth under the influence of strong solar heating. In the coastal waters, due to high turbidity, the solar radiation will be mostly absorbed in the top 10-15 m water column[6]. After 1500 hrs, with increasing time cooling due to turbulent heat exchange processes has dominated. The diurnal thermocline in the surface layers gradually disappeared leading to the formation of well defined mixed layer due to the onset of cooling at the surface. The profiles for 2000-2300 hrs showed a sharp reduction in the temperature in 2 to 3 m water column, probably due to surface cooling.

The depth-time section of temperature field corresponding to TS1 is shown in Fig.4a. Contours are drawn at intervals of 0.2°C for the top 25 m water column. The gradual descent of 30°C isotherm from noon to 1730 hrs is a clear indication of warming of surface waters under the influence of solar heating. After 1900 hrs, the 30°C isotherm has disappeared and by 0030 hrs, the surface layer has cooled by 0.2°C. Isotherms below 15 m depth showed a packed

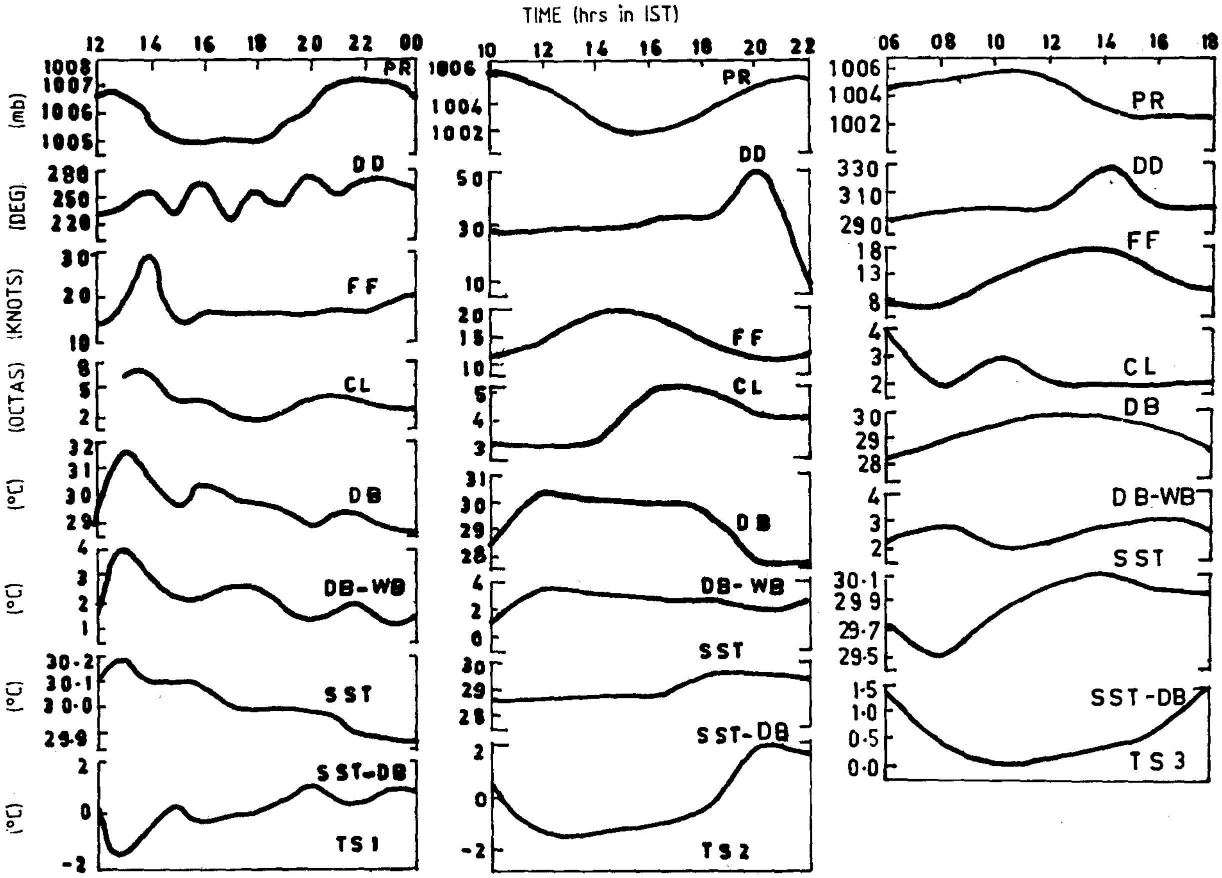

Fig. 2— Diurnal march of surface meteorological elements (PR - pressure, DB - dry bulb temperature, WB - wet bulb temperature, CL - cloud amount, FF - wind speed, DD - wind direction, SST - sea surface temperature)

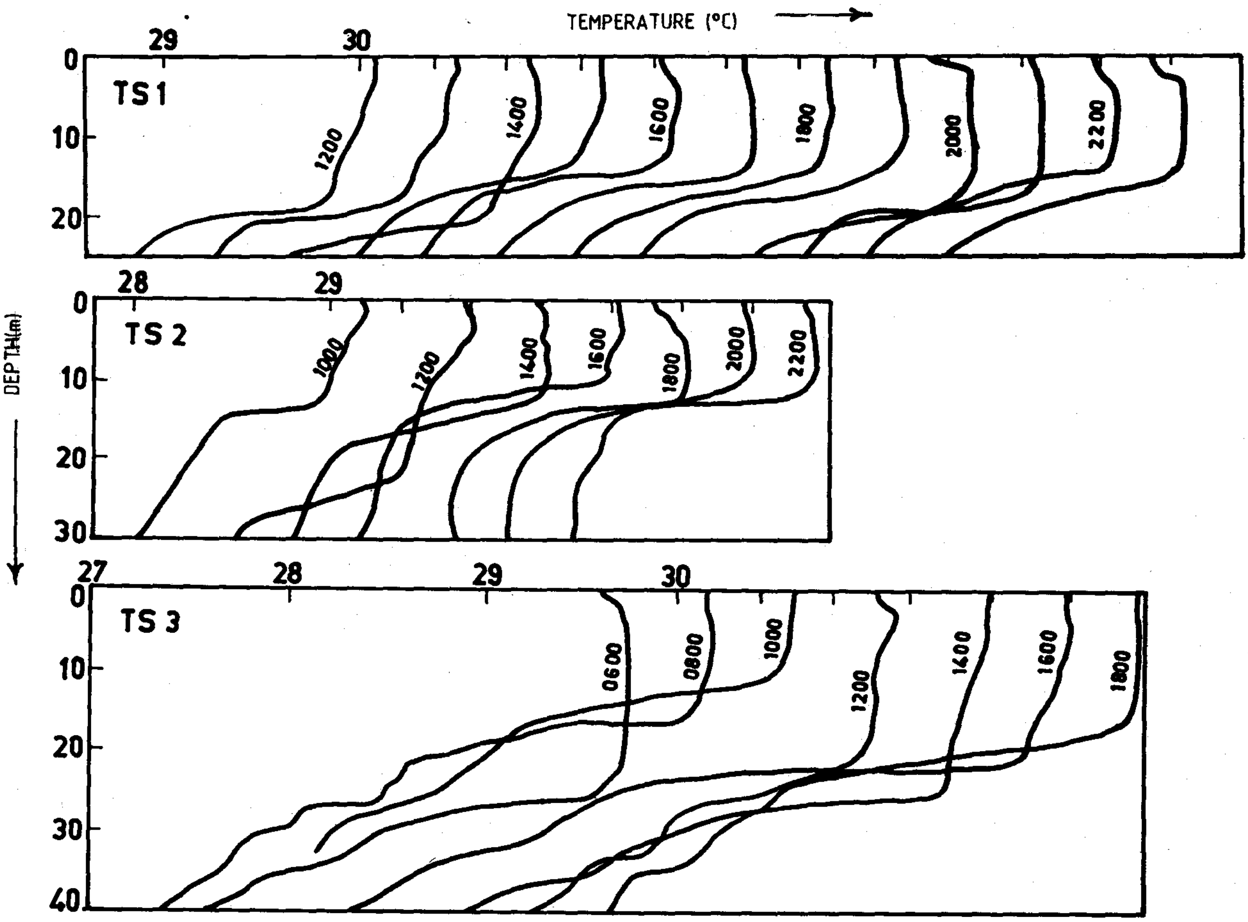

Fig. 3—Diurnal progress of vertical temperature profiles

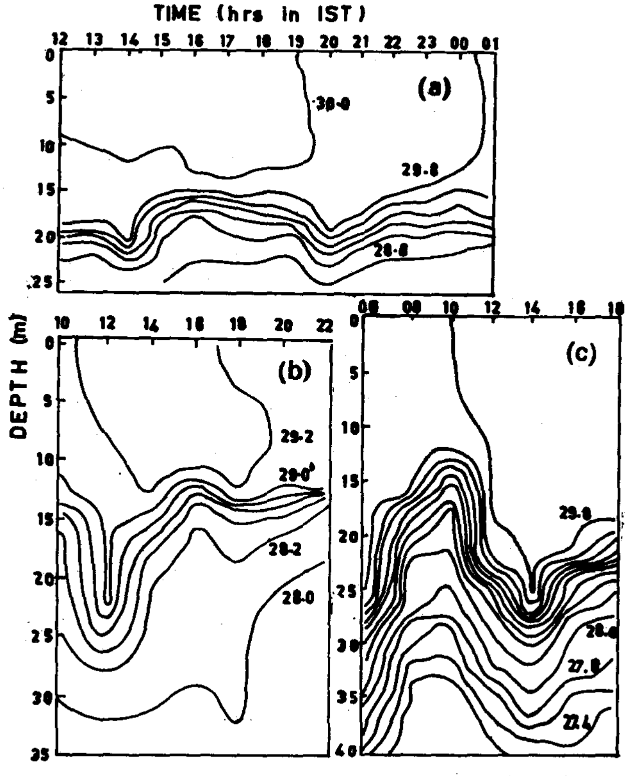

Fig. 4—Depth-time section of temperature at TS1(a), TS2(b) and TS3(c)

nature due to strong vertical thermal gradient. The influence of a propagating internal wave seems to be apparent with the occurrence of troughs in the isotherms around 1400 and 2000 hrs. The amplitude of the internal oscillation was of the order of 5 m.

The temperature recorded at the surface, 10, 15 and 20 m depths at TS1 are shown in Fig.5. While the top layer is primarily influenced by atmospheric forcing and probably advective processes, the water below 10 m depth showed a strong signal penetrating upward from the thermocline into the bottom of the mixed layer. At 10 m depth, the temperature record was relatively flat under the weak influence of surface heat exchange processes. This figure illustrates the influence of diurnal heating/cooling in the mixed layer and of internal waves in the thermocline.

For understanding the variability of SST, studying the heat content to isotherm depths is a better measure than that of fixed depths[7]. The heat content with respect to 29° and 28°C isotherms (Fig.6) registered a steady decrease. It was lowered by 0.7 kcal.cm^{-2} over

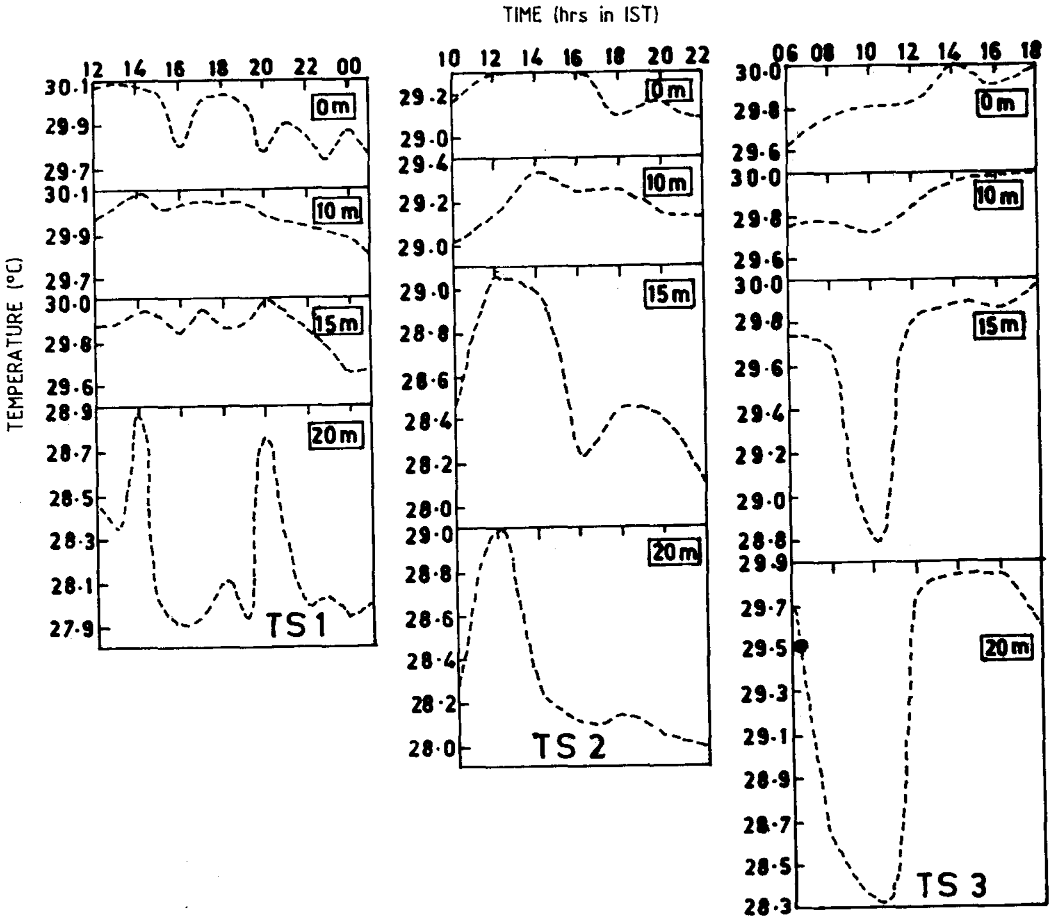

Fig. 5— Diurnal progress of isobaths at selected depths

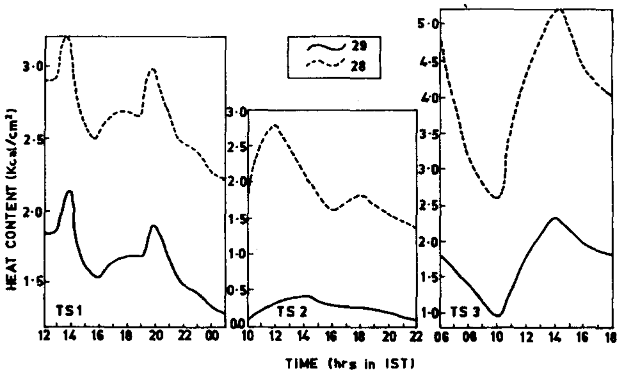

Fig. 6— Diurnal progress of heat content

the 12 h period. This reduction might have been caused by the mixing and surface heat losses produced by the existing 20 knot winds. However, the contribution from the advective processes probably due to tidal currents cannot be ignored.

The action of winds and waves and the net depletion of energy at the sea surface leading to convective overturn cause vertical mixing in the upper layers. Under fair weather conditions with weak surface winds, the net accumulation of heat in the surface layers can produce a diurnal thermocline. With the strengthening of winds, the accumulated heat will be distributed over a deeper water column. Hence, the mixed layer depth (MLD) can also exhibit a diurnal signal. In the present study, MLD is defined as the deepest depth where the temperature is lower by 0.2°C from SST[8]. The distribution of MLD at TS1 is shown in Fig.7. Except at 1400 and 2000 hrs, MLD was approximately 15 m with a diurnal range of 5 m. The increase in MLD at 1400 and 2000 hrs can be attributed to the propagating internal wave.

Time series st TS2— Observations were made from 1000 hrs to mid-night on 16 May 1985. The observed marine meteorological parameters are shown in Fig.2. The surface atmospheric pressure fluctuated around 1004 mb, with maximum around 1000 hrs and minimum around 1600 hrs. The winds were from northwest with 12 knot average speed. The cloudiness showed an increasing trend from 1400 hrs to 1800 hrs. The air temperature dropped by about 2°C and the wet bulb depression did not show any significant variation. The SST increased by about 0.5°C and reached maximum by 1800 hrs. The sea minus air temperature was negative up to 1200 hrs and thereafter showed a positive trend. The stable regime was replaced by the unstable regime around 1800 hrs. The vertical temperature profiles from 1000 to 2200 hrs at TS2 are shown in Fig.3. The profiles for 1000 and 1200 hrs showed an increase in temperatures in the surface layers caused by solar heating. This accumulated heat appears to have been mixed up in the vertical under the influence of strong winds of about 20 knots at 1400hrs. Cooling in the surface (of about 5 m) water column is evident from the last 3 profiles with decreasing magnitude. Thermocline occurred at relatively deeper depth in the case of 1200 h profile probably caused by a propagating internal wave.

The depth-time section corresponding to TS2 is shown in Fig.4b. The gradual descent of the isotherms 29.2°C from 1100 to 1800 hrs is a clear indication of warming up of the surface waters under the influence of solar heating. After 1800 hrs, the isotherm 29.2°C disappeared. Isotherms below 10 m depth reflected strong vertical thermal gradient. The influence of internal waves was apparent with the occurrence of troughs in the isotherms at 1200 and 1800 hrs. However, the amplitude of the waves was much larger at 1200 hrs compared to 1800 hrs. Interestingly this oscillation was confined to a maximum depth of 27 m or so. Further, the vertical thermal gradient below 28.5°C isotherm was also very weak. The amplitude of the internal oscillation was around 10 m.

From the observed temperature distribution at selected depths for TS2 (Fig.5), the influence of strong diurnal signal at the surface and 10 m depth can be clearly seen. The range of variation increased with depth under the influence of propagating internal waves.

The heat content (Fig.6) showed a steady increase with time. It was lowered by about 1.2 kcal.cm^{-2} with respect to 28°C isotherm and by about 0.2 kcal.cm^{-2} with respect to 29°C isotherm. This large difference suggests that stronger advection under tidal influence might have been confined to the water column warmer than 28°C. Distribution of MLD at TS2 is shown in Fig.7. MLD fluctuated around 12 m depth with weak diurnal range.

Time series st TS3— The observed marine meteorological parameters from 0600 to 1800 hrs on 21 May 1985 for TS3 are shown in Fig.2. The surface atmospheric pressure fluctuated around 1004 mb with the maximum around 1000 hrs and the minimum around 1800 hrs. The winds were from northwest with 13 knot average speed. Cloudiness showed a decreasing trend from 0600 to 1800 hrs. Air temperature increased to a maximum value of 29°C around noon and decreased thereafter. A minimum of 29.5°C in SST was noticed at 0800 hrs probably under the continued influence of nocturnal cooling and weak solar heating due to clouds. SST increased by 0.4°C and reached its maximum by 1500 hrs. The sea minus air temperature was positive throughout the observational period indicating strong unstable regime.

The vertical temperature profiles (Fig.3) exhibited large variations in the time domain especially in the thickness of surface mixed layer. The influence of nocturnal cooling is clearly reflected in the topmost 5 m water column corresponding to 0600 hrs which disappeared with increasing time. The reasons for the occurrence of mild inversion at 1200 hrs are not clear. Warming under the influence of solar heating is evident in the 1400 and 1600 hrs profiles. By 1800 hrs, the layer was well mixed.

Depth-time section of thermal structure is shown in Fig.4c. The appearance of 29.8°C around 1000 hrs and the deepening of isotherm during the following 4 h indicate the influence of solar heating in the top 20 m water column. Very strong thermal gradients were apparent below the surface mixed layer. A well defined wave regime with its ridge occurring around 1000 hrs and trough occurring around 1400 hrs was also evident. The observed pattern of the thermal structure in the thermocline probably suggests the presence of a propagating internal wave.

Progressive increase of temperature of the order of 0.4°C at the surface and of the order of 0.2°C at 10 m depth is clearly evident (Fig.5) due to solar heating. The heating appears to have commenced at the surface by sunrise, but the same is noticed with a time lag of 4 h at 10 m depth. Very large variations are noticed at 15 and 20 m depths under the influence of a propagating internal wave.

The variability of the heat content with respect to 29°C and 28°C, (Fig.6) appears to have been governed by the vertical displacement of isotherms caused by the propagating internal wave. However, the amplitude increased with depth.

Accumulation of heat in the top layers under the influence of the propagating internal wave is clearly indicated in the observed pattern of MLD (Fig.7). The mixed layer depth varied between 12 and 25 m; the minimum coinciding with the ridge of the wave and the maximum with the trough of the wave.

The stabilising effect of solar radiation during day time, mixing caused by winds, waves and buoyancy flux are the important processes that occur in the upper layers of the ocean[9]. The surface wind stress produces turbulence leading to forced mixing while the surface heat losses produce convective overturn leading to free mixing in the upper layers. This turbulence is usually manifested in the form of eddies which characterise the mixing in the vertical. The accumu-

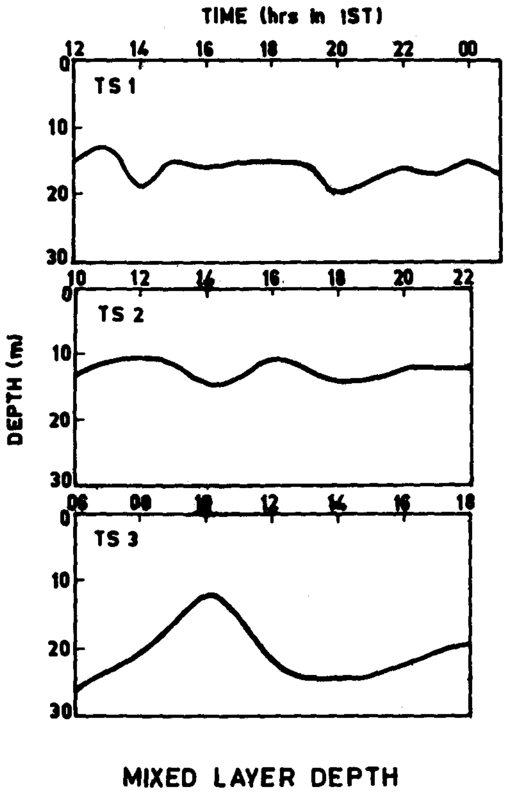

Fig. 7 — Diurnal progress of mixed layer depth

lated heat in the topmost layers through the absorption of solar radiation is redistributed through this thermal eddy diffusion mechanism. Two different methods have been employed to determine the value of thermal diffusivity (K) at TS3 on 21 May 1985, due to availability of the data from sunrise to sunset.

Method I: This method follows a scale analysis approach[9]: $K = L^2/T$. The scale length L is the distance from surface to the appropriate sensor depth, and the scale time T is the time lag between maximum SST and maximum temperature at appropriate sensor depth.

Method II: Here one dimensional heat conduction equation is employed[9].

$$K = \frac{Z^2\pi}{P}[\ln\{T(z)/T(o)\}]$$

where T(o) and T(z) are the amplitudes of the temperature at the surface and at a depth $Z, P = 2\pi/\omega$ and ω is the frequency of diurnal heat wave. For a diurnal heat wave P = 24 h. Although data on one complete diurnal cycle is required to adopt this method, the data set collected at TS3 was chosen in view of the availability of maximum temperature occurring in the afternoon and minimum temperature occurring in the morning hours. The amplitude derived from this 12 h record fairly represents that of a diurnal wave and accordingly P was chosen as 24 h.

Table 1 — Computed K Values

Depth (m)	Method I	Method II	Average
2.5	10	20	15
5.0	35	60	47
7.5	80	110	95
10.0	70	190	130

The computed values of K obtained by both the methods are given in Table 1. Both the methods showed a qualitative agreement with a progressive increase of K from surface to 10 m depth. The value of K (Method I) are in general lower than those of K (Method II). The average value of K for the 10 m water column is 72 $cm^2.sec^{-1}$ which coincide with an earlier estimate[9].

Acknowledgement

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