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On the observed intra-diurnal variability in the thermal structure of the upper layers at a station in the eastern Arabian Sea before the onset of summer Monsoon-77

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सार — 1977 के दौरान ग्रीष्म मानसून के आरम्भ होने के पूर्ववर्ती 12 दिनों के दौरान पूर्वी अरब सागर में एकल स्टेशन (13° उ०, 72° पू०) में अल्पावधि क्रम में ली गई मापों की सहायता से सतही मौसम विज्ञान संबंधी तत्वों में प्रेक्षित अन्तर दैनिक परिवर्तिता और सतह मिश्रित परत की गहराई का चित्रण करने वाली उर्ध्वाधर ऊष्मीय संरचना और दैनिक ताप प्रवणता का विश्लेषण किया गया है। विभिन्न सतह मौसम विज्ञान संबंधी अवस्थाओं और आंतरिक महासागरीय प्रक्रमों के प्रकाश में सतह और उपसतह प्राचलों में संबंधित अन्तरदैनिक परिवर्तिता पर विचार विमर्श किया गया है।

ABSTRACT. The observed intra-diurnal variability in the surface meteorological elements and the vertical thermal structure depicting the surface mixed layer depth (MLD) and diurnal thermocline are analyzed with the aid of short time series measurements made at a single station (13°N, 72°E) in the eastern Arabian Sea during the preceding 12 days of the onset of the summer monsoon during 1977. The associated intra-diurnal variability in the surface and subsurface parameters is discussed in the light of varying surface meteoroloigcal conditions and internal oceanic processes.

1. Introduction

The vertical thermal structure of the upper layers of the sea is known to exhibit variability on a diurnal scale. The amplitude of this diurnal heat wave is quite small in the open ocean (rarely more than 0.3° C), but may be larger in sheltered and shallow coastal waters (2°-3°C) (Pickard and Emery 1982). Variations in the amplitude of this diurnal wave are known to differ with season and place. Factors like surface heat exchange processes, wind and wave mixing, thickness of the mixed layer and below—layer stratification are expected to play an important role in determining the structure of the diurnal wave. The variability of the mixed layer depth (MLD) on the diurnal scale is known to be governed by the diurnal march of net accumulation/depletion of heat through heat exchange processes and vertical displacement of stratified waters below caused by the tidal forces and internal waves.

Several authors have attempted to document and explain the observed diurnal scale variability in the open ocean with a variety of data sets (Stommel and Woodcock 1951; Lafond 1954; Poornachandra Rao 1960; Kraus and Rooth 1961; Satyanarayana Rao and Chalapathi Rao 1962; Shonting 1964; Roll 1965; Howe and Tait 1969; Stommel *et al.* 1969; Bowden *et al.* 1970; Leavastu and Hela 1970; Delnore 1972; Hoeber 1972; Leetmaa and Welch 1972; Ostapoff and Worthem 1976; Hareesh Kumar and Rao 1987). Price *et al.* (1986) modelled the observed diurnal cycle with a simple one-dimensional model with some success. More recently Peters *et al.* (1987) noticed that the average turbulent energy dissipation rate was 100 times larger at night than in the day time both in the mixed layer and in the thermocline during November 1984 over the equatorial Pacific Ocean. For the Indian seas, information on this diurnal scale variability in the upper layers is extremely sparse, due to non-availability of systematic time-series measurements with short sampling intervals.

In the present study an attempt is made to document the observed intra-diurnal scale variability in the surface marine meteorological elements and the vertical thermal structure of the top 200 m water column at a stationary position in the eastern Arabian Sea (13° N, 72°E) with the aid of time series data sets collected during 26 May to 6 June 1977 under the Monsoon-77 observational program (Fig. 1). No attempt is made here to look into the balance between net surface heat gain and heat storage rate in the upper layers as the direct measurements of insolation which are very important are not available. Unfortunately, no dependable

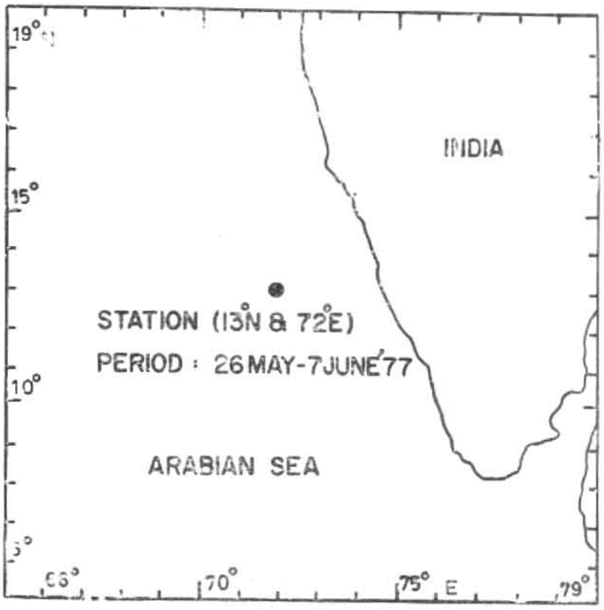

Fig. 1. Station location map

empirical relationships giving corrections for various cloud types and thicknesses are also available to indirectly estimate insolation on a diurnal scale. The period under study mostly reflects typical pre-monsoonal conditions before the onset of the monsoon.

2. Data

Time series measurements of surface marine meteorological elements such as surface pressure, wind speed and direction, dry and wet bulb temperatures of air, SST, visually-observed cloudiness and the vertical temperature profiles of the top 200 m water column were made at one hourly intervals. No measurements of solar and terrestrial radiation could be made. The ship used to be brought to the stationary position twice a day to minimize the error caused by the ship's drift. Measurements were carried out with some brief interruptions. Missing data are interpolated through linear interpolation. All the data are scanned for outliers and the appropriate corrections are made. All the observed data are smoothed with 1 : 2 : 1 filter, *i.e.*,

$$x(t_i) = \frac{1}{4}\left[x(t_{i-1}) + 2x(t_i) + x(t_{i+1})\right]$$

where, x=variable; t_i=time.

3. Weather summary

The data collected during the observational period represent conditions mostly of pre-onset regime of the summer monsoon. A well marked trough of low formed over Laccadive and off Kerala and Karnataka coasts on 28 May 1977. South of the observational station the monsoon progressively advanced northward during the rest of the observational period. On the whole, relatively calm conditions prevailed at the observational station with wind speeds around 4 m/s

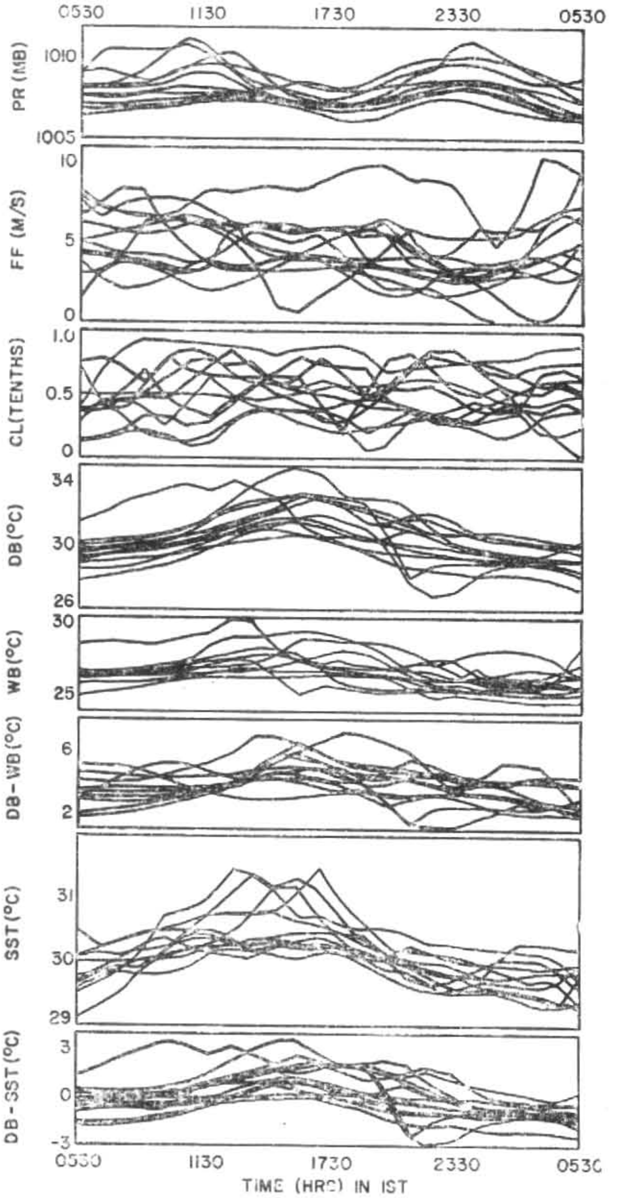

Fig. 2. Intra-diurnal march of surface marine meteorological elements

until 4 June. During the following two days, the wind shot up to 10 m/s in association with the onset of the monsoon.

4. Analysis and discussion

The observed hourly surface marine meteorological data are shown in Fig. 2 as composite plots to depict the diurnal scale variability. The dispersion of the curves reflects the intra-diurnal range during the observational period. Surface pressure (PR) shows a bimodal distribution with an average amplitude of 3 mb influenced by the semi-diurnal tides which is prominent in the tropics. Wind speed (FF) and cloudiness (CL) do not show any well defined diurnal variation but the intra-diurnal spread is evident due to undisturbed and disturbed weather regimes. Air temperature (DB) and SST show a well defined diurnal variation

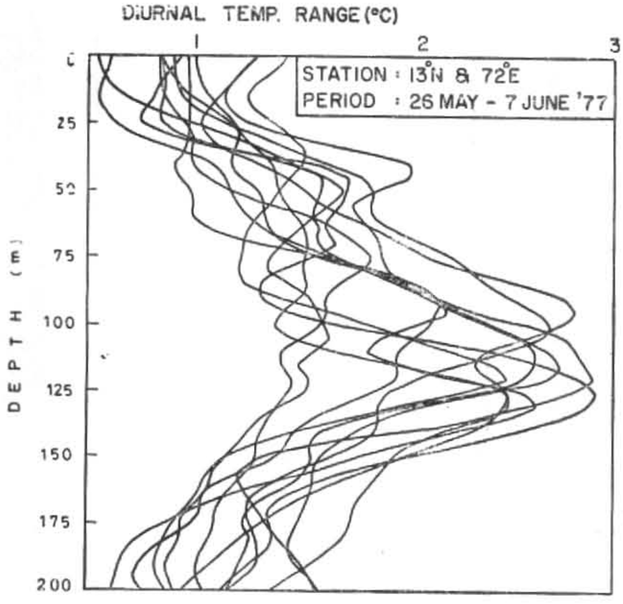

Fig. 3. Intra-diurnal temperature range in the top 200 m water column

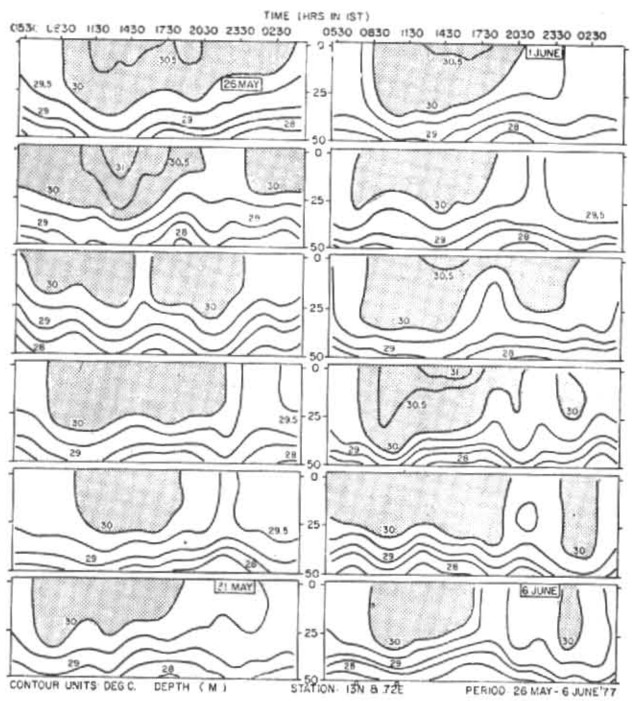

Fig. 4. Depth-time sections of temperature in the top 50 m water column

with an average amplitude of 4°C and 1.3°C respectively, mostly controlled by radiative heating and turbulent heat exchanges at the air-sea interface. The maxima in DB and SST did not appear to have occurred at the same time, but there appears to be a lag of a few hours. The occurrence of DB maxima a few hours later than SST maxima suggests the importance of longwave radiative heat flux and sensible heat flux. The wet bulb temperature (WB) and the wet bulb depression (DB—WB) also exhibit similar trends with an average amplitude of 3° C and 3.5° C respectively. The wet bulb depression progressively increased due to growing moisture holding capacity of air under solar heating. For major portion of the day, the air-sea temperature difference (DB—SST) is negative with the only exception from noon to a few hours before midnight. These differences ranged between —3° C & 2°C. The distribution of this temperature difference indicates a strong unstable regime around local sunrise and a strong stable regime around local sunset.

The observed diurnal ranges of the temperature at each 5 m depth for the top 200 m water column for each day during the observational period is depicted in Fig. 3. The intra-diurnal range is of the order of 1°C in the topmost 25 m water column. This progressively increased to 1.5°-2.0°C in the depth range of 100 to 125 m and then decreased downward. In the surface layers, the values of larger diurnal amplitude correspond to undisturbed days, while the values of smaller amplitude correspond to disturbed days. This influence of surface meteorological forcing seems to have been limited to the top 25 m water column or so and the range below this depth might have been caused by the vertical displacements of isotherms in the thermocline influenced by the tides and internal waves. Stronger vertical temperature gradients noticed in the depth range of 75 to 150 m might have been responsible for greater vertical displacement of isotherms caused by internal tides. Interestingly, the larger intra-diurnal spread also coincided at this same depth range.

The depth-time sections of the thermal structure for the top 50 m water column for all the days from 26 May to 6 June 1977 is shown in Fig. 4. Contours are drawn through linear interpolation at 1° C intervals. Water column warmer than 30° C is hatched for better perception. Formation of diurnal thermocline due to intense solar heating during daytime is conspicuously noticed with the appearance of isotherms 30° C and above during undisturbed days due to weak wind and buoyancy mixing. For example, the depth-time sections corresponding to 26 May, 27 May, 1, 3 and 4 June show the transient appearance of the isotherms 30.5°C and 31.0°C mostly confining only to daytime. The vertical extent of the 30.0°C isotherm which is of the order of 25 m probably suggests the penetrative depth of solar heating. The vertical displacements of the isotherms lesser than 30°C are manifested due to short period internal waves. The reasons for the secondary appearance of the 30°C isotherm during night-time on 27 May and 3-6 June are not clear. Ship drift into heterogeneous waters caused by the local circulation could also probably result in such a phenomena.

The vertical mixing in the upper layer is generally caused by wind and wave action, net depletion of energy across the air-sea interface causing surface cooling

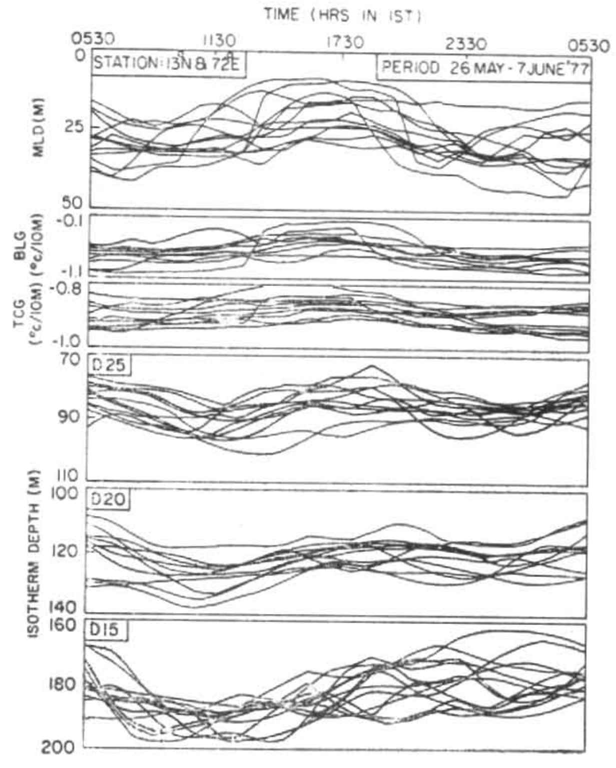

Fig. 5. Intra-diurnal march of MLD, BLG, TCG and isotherm depths

which leads to convective overturn. Accumulation of energy through radiative processes promotes the formation of diurnal thermocline under weak wind stress conditions. If surface winds are strong, this accumulated heat will be mixed and distributed in a relatively deeper water column. Hence the MLD can also exhibit a strong diurnal signal. In the present study MLD is viewed synonymous to the isothermal layer depth. It is defined as the depth where the temperature is lower than 0.2°C from SST. The derived MLD distribution on a diurnal scale is shown for all the days during the observational period in Fig. 5. MLD is found to be deepest around sunrise and shallowest around sunset with a diurnal range of about 10 m. The intra-diurnal spread is found to be about 20 m owing to differences in wind and buoyancy mixing under both disturbed and undisturbed weather conditions. The shoaling of MLD from sunrise to sunset and deepening thereafter appears to be governed by the net cumulative accumulation of heat on the diurnal scale. The diurnal variability of the bulk vertical thermal gradient in the 30 m water column just below the mixed layer (BLG) and of the thermocline (TCG) also exhibit similar but weaker trends of (MLD). The topography of the isotherms 25°, 20° and 15°C is also depicted in the bottom panel of Fig. 5. The vertical displacements are know to be caused by the tidal forces on a diurnal scale. The differences on the intra-diurnal mode are to be viewed as manifestations due to inertial oscillations whose period at the observational station is about 2.2 days. The topography of the 25°C isotherm shows a double peak caused by a semi-diurnal tide while that of the 15°C isotherm exhibits a single peak probably under the influence of the diurnal tide. The 20°C isotherm shows combined influence of the above mentioned tides. On an average, the intra-diurnal variations at the depth of these isotherms range between 10 and 20 m.

Fourier analysis of the observed temperature at the surface and at depths 50, 100, 150 and 200 m is carried out for each 24-point sample (one day) and then these spectral estimates are averaged for the observed 12-day period. The distribution of the spectral power in percentage with period is shown in Fig. 6. At the surface, the dominance of the diurnal period with a peak at 24 hours under the influence of daytime heating and nocturnal cooling is distinctly seen. Below the 50 m depth a combination of diurnal and semi-diurnal periods is noticed. At 100 m depth, the 12-hr period shows highest power with a decrease on either side and the 24-hr period shows lowest power with an increase on either side probably under the influence of diurnal and semi-diurnal tides respectively.

5. Conclusion

(*i*) The surface marine meteorological elements as surface (3 mb), dry bulb (4°C) and wet bulb (3°C) temperatures and SST (1.3°C) exhibited well defined diurnal signals.

(*ii*) Significant differences are noticed in the intra-diurnal range of the temperature in the top 25 m water column under the influence of varying surface meteorological conditions.

(*iii*) The surface mixed layer depth exhibited diurnal variations with its maxima occurring around sunrise and minima around sunset with an approximate diurnal range of 10 m and an approximate intra-diurnal range of 20 m, owing to varying surface meteorological forcings.

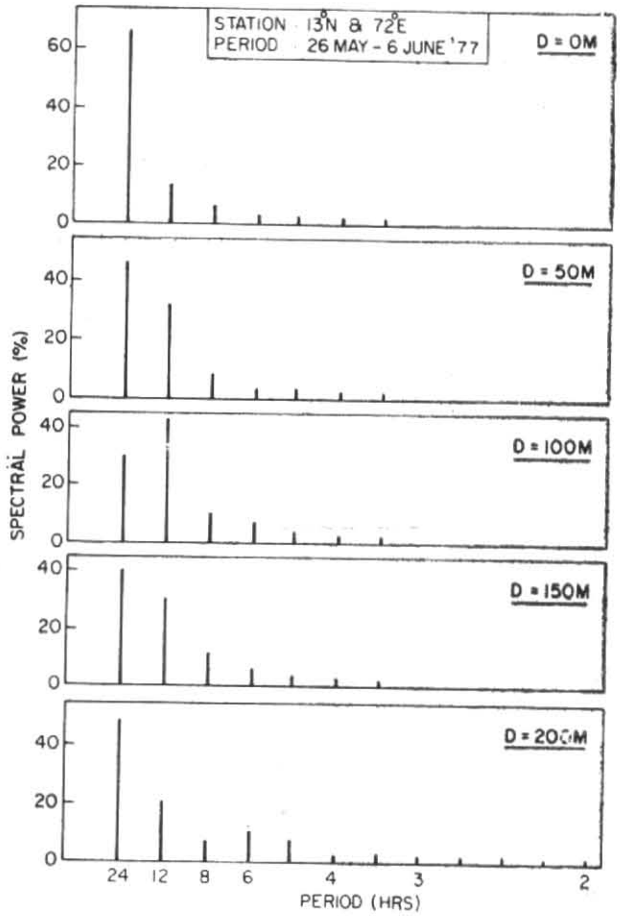

Fig. 6. Fourier line spectra of temperature at selected depths in the top 200 m water column

(*iv*) Highest intra-diurnal range of 1.5°C to 2.0°C in the depth range of 100 to 125 m is caused due to vertical displacement of isotherms on account of the influence of internal tidal and inertial oscillations.

(*v*) Fourier analysis of temperature at 100 m depth suggest a stronger signal corresponding to 12 hr period with decreasing magnitude on either side and a relatively weaker signal corresponding to 24 hr, with increasing magnitude on either side owing to the influence of semi-diurnal and diurnal tides respectively.

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