

Structure of the oceanic mixed layer in western Bay of Bengal during MONEX*

A. F. ANTO and Y. K. SOMAYAJULU

National Institute of Oceanography, Dona Paula, Goa-403004

(Received 2 February 1982)

सार—बंगाल की खाड़ी के पश्चिमी भाग में स्थित दो स्टेशनों से जुलाई 1979 में प्रति घंटा की टी तथा प्रति छः घण्टे सी एस टी डी आंकड़े इकट्ठे किए गए थे। जन्ही आंकड़ों के आधार पर, उपरिस्थित वायु मण्डल की मौजूदा सतह परत अवस्थाओं के फलन के रूप में, महासागरीय मिश्र परत (ओ एम एल) में तापमान के दैनिक परिवर्तन का विश्लेषण किया गया था। महा. मि. पं. की संरचना, जो गहराई के साथ तापमान के दैनिक परिवर्तन के संबंध में अंकित है, तीन उप-परतों : (i) मिश्रित तरंग (ii) दैनिक ताप प्रवणता तथा (iii) संक्रमण परत, को दिखलाती है। महा. मि. पं. को प्रथम दो उप परतों में सतह मौसमी प्रणोदनों में परिवर्तनों पर तुरन्त प्रतिक्रिया दिखाई। सतह तरंग मिश्रण, संवाही गति विधि तथा आन्तरिक तरंगों ऐसी मुख्य भौतिक संक्रियाएं पाई गईं जो मिश्र तरंग की मोटाई, दैनिक ताप प्रवणता तथा संक्रमण परत को अलग-अलग प्रभावित करती हैं।

ABSTRACT. Based on the hourly BT and six hourly CSTD data, collected from two stations in the western Bay of Bengal during July 1979, the diurnal variations of temperature in the oceanic mixed layer (OML) were analysed as a function of the prevailing surface layer conditions of the overlying atmosphere. Structure of OML, as delineated with respect to the diurnal variation of temperature with depth, revealed three sub-layers: wave mixed, diurnal thermocline and transition layer. The first two sub-layers of OML showed immediate responses to the changes in surface meteorological forcings. Surface were mixing, convective activity and internal waves were found to be the main physical processes to effect the thickness of wave mixed, diurnal thermocline and transition layer respectively.

1. Introduction

One of the major objectives of MONEX is to examine the coupling between the atmosphere and ocean. This coupling at the sea surface is mainly through two boundary layers (BLs), viz., surface layer (SL) of the atmosphere and oceanic mixed layer (OML) (Sarachik 1977). These two BLs have great roles in the dynamics and thermodynamics of surface and upper air circulations. Considering this importance, the SL conditions of atmosphere over the western Bay of Bengal during MONEX have been studied (Anto *et al.* 1982) for the three different synoptic scale circulations that prevailed during the period of observations. Studies on the structure of OML, for the same period and region, are important for understanding the different aspects of the coupling mechanism because the upper layers of ocean significantly influence the surface meteorological forcing and *vice versa*. In the present study the diurnal variations in temperature and the resulting structure of OML, were analysed as a function of the prevailing SL conditions of atmosphere over western Bay of Bengal during July 1979.

2. Materials and Methods

During the sixth MONEX cruise of *R.V. Gaveshani* the MBT/XBT at hourly intervals and CSTD data at six hourly intervals were collected from two stations (Fig. 1): 13° N, 85° E (Station A) and 16° N, 87° E (Station B). The oceanographic and surface meteorological observations were selected for the full day period of 20-22 July at Station A and 25-30 July 1979 at Station B. The BT data was checked with the temperature data available from the CSTD profiles. The weak temperature variations in OML, as observed from the MBT/XBT and CSTD data, motivated for the determination of the amplitude of diurnal variation of temperature through harmonic analysis. The amplitudinal variation of temperature with depth was adopted as the criteria here for delineating the layered structure of the weakly stratified OML. The diurnal variations in the structure and thickness of OML were compared with diurnal variations of sea-air temperature difference (SATD), wind stress and convective activity in SL (Anto *et al.* 1982). In the present study the weakly

*Paper was presented by the first author at the Symposium on "Environmental Physics and Atmospheric Boundary Layer", held at Indian Institute of Tropical Meteorology, Pune-411005, during 24-26 November 1981.

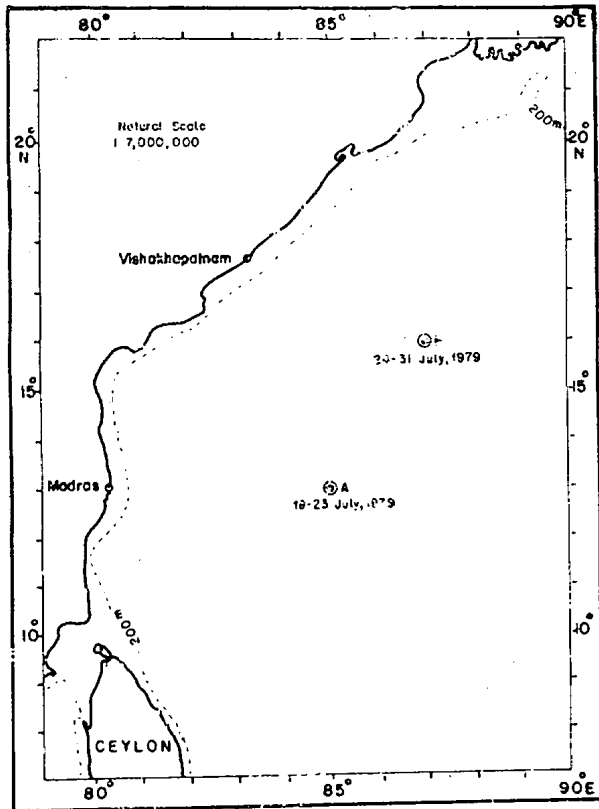


Fig. 1. Location of stations

stratified OML was demarcated from the strongly stratified thermocline for a temperature of 1°C less than the surface value (Colburn 1974).

3. Results and discussion

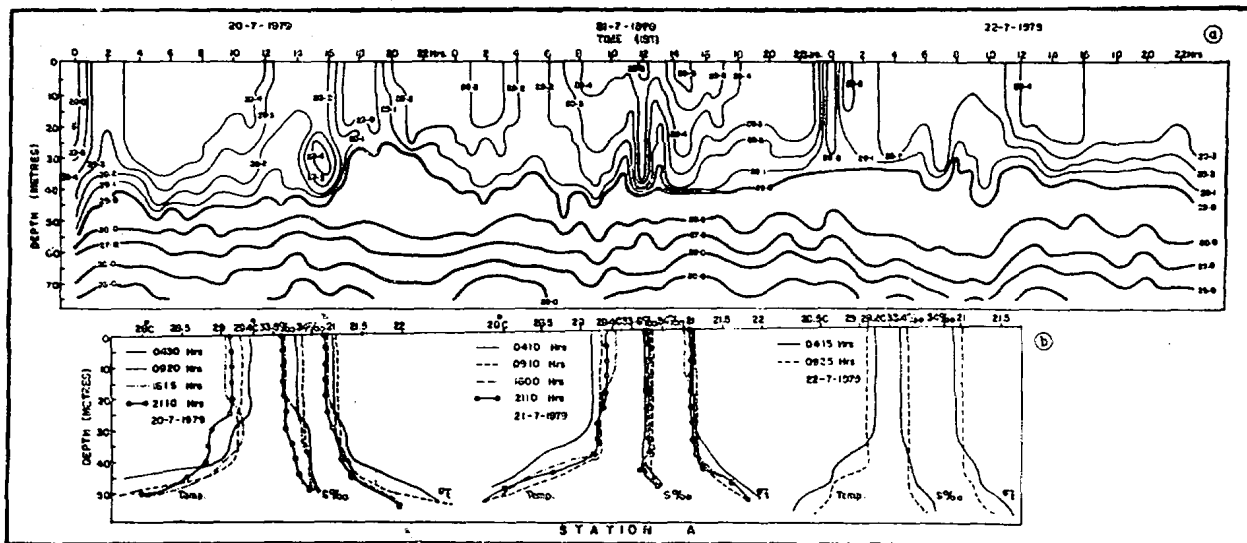
3.1. Atmospheric surface layer

The SL conditions of atmosphere over western Bay of Bengal during July 1979 were characterised by the veering and backing effects of surface winds. Based on the present weather (ww) conditions, surface meteorological data from Station B from two groups, *viz.*, GI and GII. Thus the available surface meteorological data from Stations A and B represent three periods, *i.e.*, 20-22 July at Station A, 25-27 July at Station B (GI) and 28-30 July 1979 at Station B (GII). These three periods, characterised by anticyclonic (Station A), precursor anticyclonic (GI) and cyclonic (GII) circulations in SL, will account for three different conditions of ww, atmospheric pressure, sea surface temperature (SST), etc. Air temperature and pressure were higher at Station A than that during GI and GII. The relatively warmer sea surface during GI reflects the precursor situation for the formation of cyclonic circulation. The low SST observed during GII appears to be the result of evaporative cooling by strong surface winds. Another important feature observed in SL is the convective activity which is low at Station A and high during GII. These surface meteorological conditions at Stations A and B (GI & GII) were compared

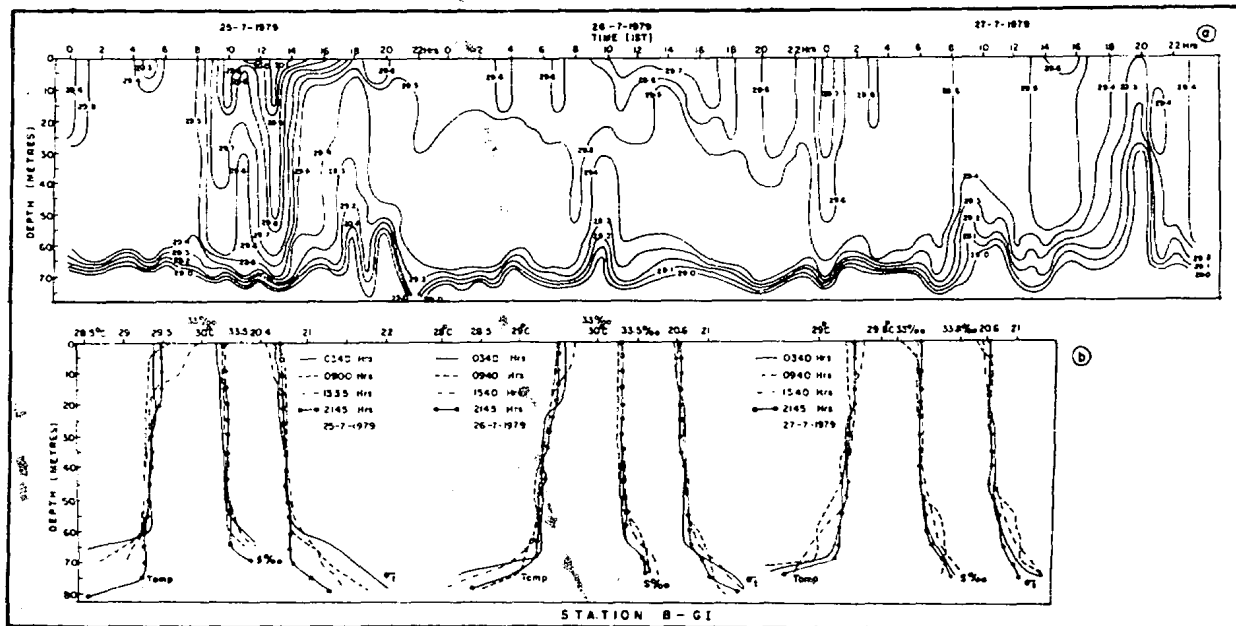
(Anto *et al.* 1982) to highlight the varying SL features under three different synoptic weather conditions. Averaging over the three-day period is sufficient to elucidate synoptic scale diurnal variations in the SL and OML which are mainly controlled by the energy exchange processes at the naviface (air-sea interface).

3.2. Diurnal temperature variations in OML

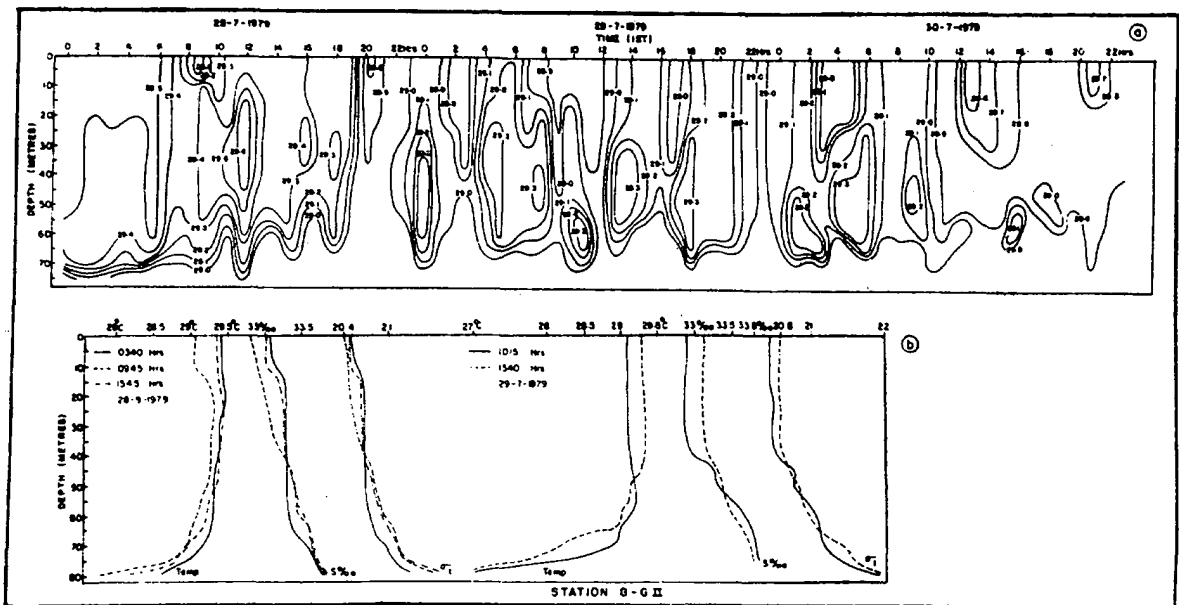
The diurnal variations of temperature in OML were analysed in terms of the studies on SL (Anto *et al.* 1982) for the same periods, Station A, GI & GII. Air temperature variation with depth is a good indicator of stability, the weak diurnal thermal stratification in OML and the temperature deviations (Hasse 1971) in the upper layers of OML were analysed as a function of the prevailing SL conditions like air circulation, wind stress variations, SATD, SST, convective activity etc. The diurnal temperature variations (Figs. 2, 3, 4 a) and the mean diurnal temperature variations (Fig. 5) showed weak stratifications in OML. These three figures show that the diurnal temperature variations in the three cases represent for the three different ww conditions. The internal wave activity is also seen in the transition layer between weakly stratified OML and strongly stratified thermocline. Thus OML was found to be weakly stratified by different SL conditions, day time heating and night time cooling at the surface and internal wave activity at the bottom. The mean diurnal variation of surface temperature at Station A and during GI and GII was of the order of 0.3°C . Higher values were observed on 25th and 28th (0.9°C - 0.4°C) when the SL circulations changed to precursor and cyclonic conditions. This signified the role of ww on the diurnal variation of surface temperature. During the precursor circulation of GI, there was a temperature inversion in the surface layers (Fig. 3b). The fall of surface temperature around 0925 hrs of 28th (Fig. 4b) was followed by the onset of cyclonic circulation. During GI, sea surface was relatively warmer than that at Station A and GII (Anto *et al.* 1982). The relatively warmer SST during the precursor SL circulation of GI and the colder SST during the cyclonic SL conditions of GII indicate the immediate response of SST to the prevailing ww changes in SL. Earlier studies (Shukla & Misra 1977) also show that the response of the surface layers to the cyclonic storm is to make the surface layers colder, as seen during GII, because of the heat loss to the atmosphere, due to vertical and horizontal heat advection and turbulent mixing. According to La Fond (1954), the predominant external environmental factors to produce or eliminate the vertical temperature gradients in OML are the energy transfer processes at the naviface and the advective transfer processes below the sea surface. The diurnal march of temperature in OML could be seen from the temperature profiles of CSTD records (Figs. 2, 3, 4b). The common features of diurnal heating and cooling effects were seen at Station A and during GI. The warmer sub-surface cells on 20th (Fig. 2a) around 1400 hrs extended to a depth of about 25-45 m. The upper warmer layers of OML at these two stations were almost stable, suppressing the downward wind mixing. In contrast, the thermal structure of OML (Figs. 4 a & 5 c) showed the colder layers over warmer ones, appearing to cause instability and convective mixing, during GII.



Figs. 2 (a & b). Diurnal variation of : (a) Temperature from MBT/XB Tdata, & (b) Temperature, S (‰) and σ_t from CSTD data



Figs. 3 (a & b). Diurnal variation of : (a) Temperature from MBT/XBT data, & (b) Temperature, S (‰) and σ_t from CSTD data



Figs. 4 (a & b). Diurnal variation of : (a) Temperature from MBT/XBT data & (b) Temperature, $S^{(‰)}$ and σ_t from CSTD data

TABLE 1

Mean values

	Station A	Station B GI	Station B-GII
Oceanic mixed layer thickness (m)	55	70	75
Wind stress (dynes/cm ²)	1.229	0.554	2.477
Wave mixed layer (m)	5	5	7
Diurnal thermocline layer (m)	40	55	55
Transition layer (m)	10	10	13

3.3. Salinity and density variations

Another factor that controlled the OML stability was the salinity. The observed features of diurnal variations in the salinity are given in Figs. 2, 3 & 4(b). At Station A and GI, there was little salinity gradient in the OML. The instantaneous positive salinity gradient in the surface was present during GII (as seen on 28th at a depth of 10m) because of the rain ($w_w = 02, 13, 21, 50$ and 60) (Anto *et al.* 1982) associated with the cyclonic circulation. The sudden salinity variations in surface layers obscure (Wortherm & Ostapoff 1976) the diurnal heating effects. This also contributed to lower the temperature of the surface layers as seen during GII. The resultant effects of temperature and salinity on stability could be seen from the σ_t variations which are mostly of neutral nature (Figs. 2, 3 & 4 b).

3.4. Thickness of OML

As a consequence of these diurnal temperature variations, the OML was thicker during GII than the other two cases — Station A and GI (Fig. 7a). The mean values of OML thicknesses are given in Table 1. The variations in OML thicknesses during the three periods (Station A, GI and GII) showed resemblances to the trend of the SATD variations (Fig. 7b) and appeared to be independent of the wind stress effects (Fig. 7c) which extended only to the upper layers of OML. SATD values were low at Station A and comparatively high during GII. The SATD indications confirmed the coupling mechanism at the surface and implied that the temperature variations at the surface were significant in the physical processes that controlled the depth of OML. For example, in Laevastu's model for the depth of mixing by waves, the significant wave height is formulated with the SATD (Geary 1961). The cyclonic effects appeared to contribute for the deepening of OML. As explained earlier (Anto *et al.* 1982), the three periods (Station A, GI and GII) of observations are considered to represent three different synoptic scale circulations in SL. Hence, the mean values of Table 1 are meant for the different w_w and the latitudinal variations in OML are not dealt with.

3.5. Layered structure of OML

Because of the different environmental factors, as mentioned above, OML was generally composed of layers of different temperatures, characterized by different physical processes like heating, cooling, mixing, advection, etc. OML can be divided into three sub-layers, *viz.*, wave mixed layer (WML) at the surface, diurnal thermocline layer within the OML and the transition layer at the bottom of OML (Wortherm & Ostapoff 1976; Ostapoff & Wortherm 1974; Garstang

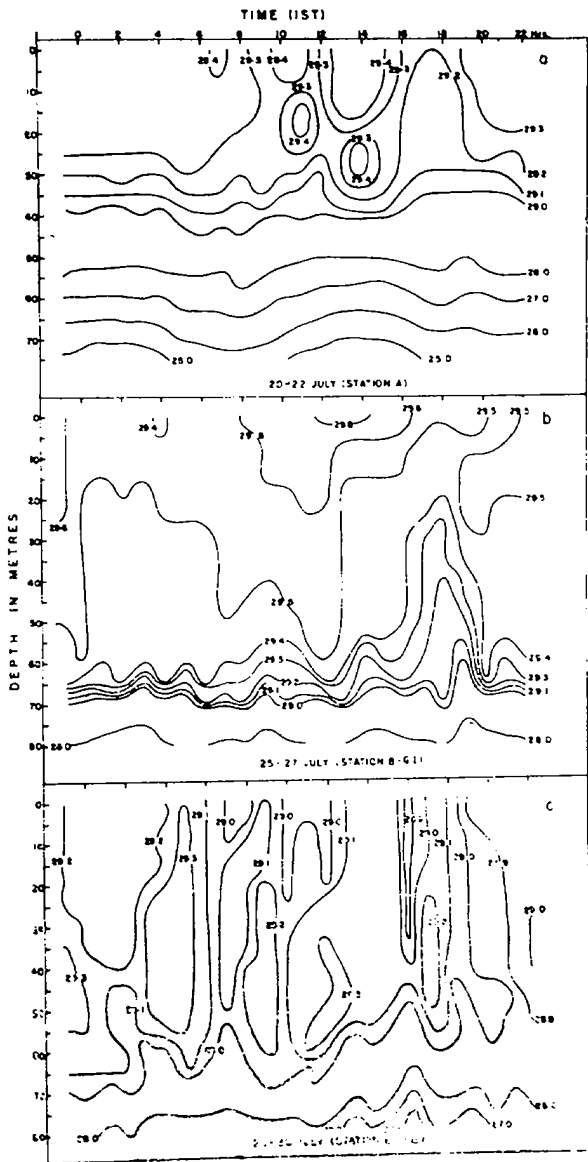


Fig. 5. Mean diurnal variation of temperature from MBT/XBT data

& Betts 1974). A schematic representation of these three sub-layers is given by Worthem and Ostapoff (1976). SATD at the surface, wave mixing in the WML, diurnal heating in the diurnal thermocline layer and internal waves breaking in the transition layer were the main physical processes to affect the characteristics of the sub-layers. These significant physical processes require further detailed investigations by refining the accuracy of temperature measurements.

(a) Wave mixed layer

The average WML thickness at Station A and during G1 and GII were found to be approximately 5 m (Table 1) and a larger value of 15 m was observed on 22 July. The WML thickness on 26, 27, 29 and 30 July was about 10 m (Fig. 6). The WML values from Fig. 6 were compared with the computed values of thickness of WML (Δ) when the wind speeds were low (Station B-GI). Such a computation was required to compare with the linearly extrapolated values. The average computed values of Δ was about 7 m. In the surface layer, the effect of waves extends to a depth of Δ (thickness of WML) which equals the wave length associated with the peak of the surface wave energy spectrum (Pierson 1964). The approximate wave length, Δ , of the dominating surface waves is given by Augstein $\Delta = 0.3 U^2$, where U is the wind speed. At Station A and Station B-GII, WMLs were conspicuous, whereas during G1, the upper layers constituted a sudden fall in amplitude causing uncertainty to determine the thickness of WML. Hence, the linear extrapolation method (Colburn 1974) was adopted to distinguish the WML during G1. The extrapolation method to demarcate the OML from thermocline is reasonable because of the large temperature gradient prevailing in the transition layer. Even though, such a large gradient may not prevail between the WML and diurnal thermocline layer, some large variations in the temperature amplitude at Station B-GI could be expected because of the transition stage (precursor anticyclonic) between anticyclonic and cyclonic circulations. The three different thermal structures of OML (Fig. 5) account for the effects of different SL meteorological forcings.

(b) Diurnal thermocline layer

The average thickness of diurnal thermocline layer in the three cases are given in Table 1. Compared to G1 and GII of Station B, Station A showed large variation of temperature in the diurnal thermocline. As

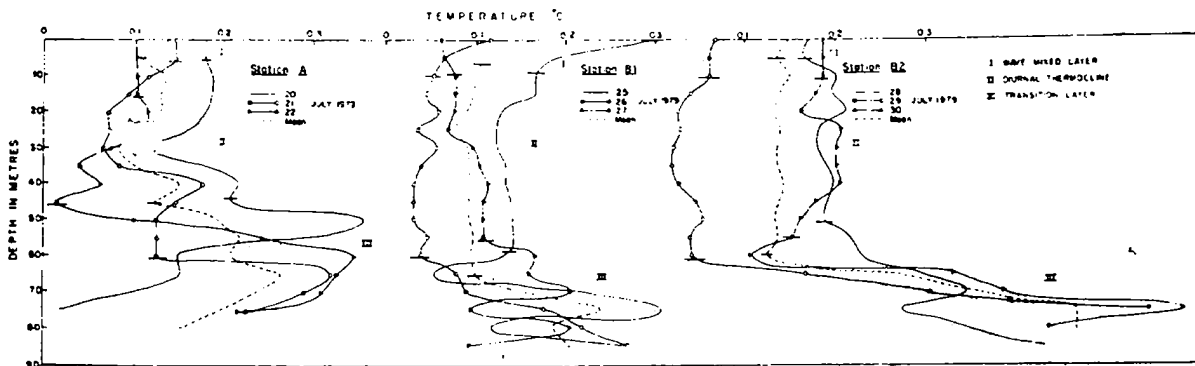
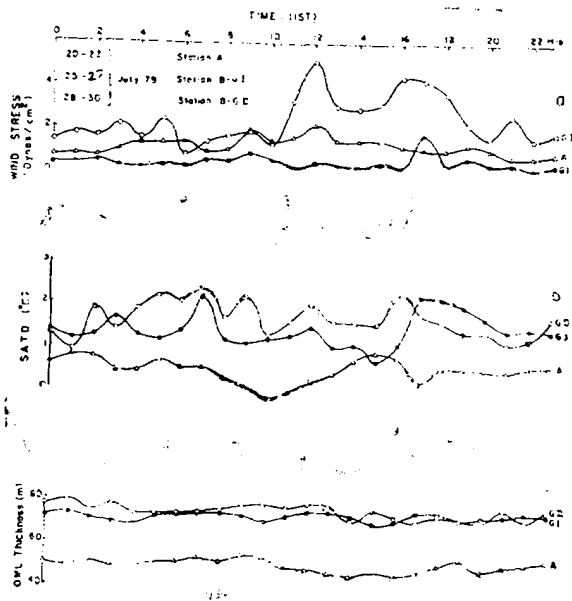


Fig. 6. Diurnal amplitudinal variation of temperature with depth



Figs. 7(a-c). Diurnal variation of mean : (a) OML thickness, (b) Sea-air temperature difference (SATD) and (c) Wind stress

mentioned above, Station A experienced both day time heating and night time cooling on 21 and 22 July, whereas surface layers showed only the cooling trend on 20 July. This led to the weak warmer cells and weak convective mixing as seen on 20 July (Fig. 2a). During GI and GII, diurnal thermocline layer was almost isothermal, because the precursor and cyclonic effects mainly controlled the thermal structure. Warmer surface and sub-surface layers of GI were in agreement with the precursor conditions of the sea. The colder surface layers over warmer cells (GII), a characteristic feature during cyclonic condition, might cause instability and convective mixing. The convective mixing appears to be the major physical process in controlling the thickness of diurnal thermocline layer, which was also subjected to the entrainment effects from the transition layer.

(c) Transition layer

The thickness of the transition layer was found to be equal at Station A and GI (Table 1). During GII, the mean thickness of transition layer was slightly higher. Further, GI showed less variations in layer III (Fig. 6). It appeared that these variations were related to the effect of convective mixing which controlled the weak and active entrainment effects of internal

waves at the boundary of OML and thermocline. The presence of higher SST and colder sub-surface layers reduced the convective mixing in the diurnal thermocline layer at Station B-GI.

Acknowledgement

We are thankful to Drs. S.Z. Qasim, V. V. R. Varadachari and J.S. Sastry for their interest and encouragement. We express thanks to our colleagues and the Scientists of India Meteorological Department for their participation in data collection on board *R.V. Gave-shani*. Thanks are also due to S/Shri L.V.G. Rao, M.J. Varkey and V. Ramesh Babu for their suggestions.

References

- Anto, A.F., Gangadhara Rao, L.V. and Somayajulu, Y.K., 1982, Surface layer conditions of the atmosphere over western Bay of Bengal during MONEX, *Indian J. mar. Sci.*, **11** (1), 15-20.
- Augstein, E., Development of the oceanic mixed layer particularly in conditions of strong solar heating and low wind speed, (In manuscript form).
- Colburn, J.G., 1974, The thermal structure of the Indian Ocean, *IIOE Oceanogr. Monogr.* No. 2.
- Garstang, M. and Betts, A.K., 1974, A review of the tropical boundary layer and cumulus convection: Structure, Parameterization and Modelling, *Bull. Am. Met. Soc.*, **55**, 1195-1205.
- Geary, E.J., 1961, The effect of wind upon the mixed layer, MS Thesis, U.S. Naval Postgraduates School, pp. 26.
- Hasse, L., 1971, The sea surface temperature deviation and heat flow at the sea-air interface, *Boundary Layer Met.*, **1**, 368-379.
- La Fond, E.C., 1954, Environmental factors affecting the vertical temperature structure of the upper layers of the sea, *Andhra Univ. Memoirs in Oceanogr.*, **1**, 94-101.
- Ostapoff, F. and Worthem, S., 1974, The intradiurnal temperature variation in the upper ocean layer, *J. Phy. Oceanogr.*, **4** (4), 601-612.
- Pierson (Jr.), W.J., 1964, The interpretation of wave spectrums in terms of the wind profile instead of the wind measured and a constant height, *J. Geophys. Res.*, **69** (24), 5191-5203.
- Sarachik, E.S., 1977, Boundary layers on both sides of the tropical ocean surface, *Review papers of Equatorial Oceanograph FINE workshop Proceedings*, held at Scripps Inst. of Oceanogr La Jolla, Calif., 27 June 12 August.
- Shukla, J. and Misra, B.M., 1977, Relationships between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India, *Mon. Weath. Rev.*, **105**, 998-1002.
- Worthem, S. and Ostapoff, F., 1976, The response of the tropical north Atlantic to meteorological forcing functions, *CICAR-II, Symp. on Progress in marine research in the Caribbean and adjacent regions*, held in Caracas, 12-16 July, 505-530.