Mausam, (1981), 32, 1, 85-92

551.526.64 : 551.465.41(267)

A case study on the northern Bay of Bengal subsurface thermal structure and ocean mixed layer depth in relation to surface energy exchange processes during Monsoon-77*

R. R. RAO, V. V. GOPALAKRISHNA[1] and S. V. BABU[2]

Naval Physical and Oceanographic Laboratory, Cochin

(*Received 15 October 1979*)

ABSTRACT. The short term variability of Mixed Layer Depth (MLD) in relation to the surface energy exchange processes over northern Bay of Bengal is examined using the data collected during Phase III of Monsoon-77. The day-to-day variations of the magnitude of MLD seem to depend on the net heat gain at the surface. Meridional gradient in the MLD in the head of Bay of Bengal due to boundary processes is highlighted. Daily variations in subsurface thermal structure and variability of heat potential are discussed in relation to the genesis of a monsoon depression.

1. Introduction

During the last few years, attempts have been rapidly progressing to understand the near-surface ocean thermal structure for better application in the fields of weather forecasting, fisheries, and acoustic propagation. The exact thermodynamics of the near-surface ocean are not well understood since the atmosphere and ocean are nonlinearly coupled in different scales, both in time and space. In addition, paucity of data further precludes one to investigate these interaction processes over tropical Indian Ocean. Even during International Indian Ocean Expedition (IIOE) (1959-65) subsurface temperature data collected in Bay of Bengal, during south-west monsoon season were only fragmentary to make use in investigating the short term variability of the physical processes of the upper ocean. In the Bay of Bengal, not much is known about the variations of the thickness of the surface layer. With the fresh water discharges into the Bay of Bengal, the surface salinities are low and a strong halocline is present over most of the region. Stratification in the water column is considerably more than that of in the Arabian Sea and vertical mixing is very much reduced. Recent Monsoon-77 experiment has given an unique opportunity to make an attempt to understand the temporal variability of the thermal structure of the upper ocean both in diurnal and daily scales.

The conditions in the first 150 metre change relatively rapidly, in the rythm of the change of the driving meteorological force at the surface. The Mixed Layer Depth (MLD) may be defined as the depth of the turbulent surface layer. The well mixed layer of the ocean usually constitutes the top 20-100 metres which interacts directly with the atmosphere on a time scale of hours to weeks. The depth of the mixed layer is variable both in time and space, and deviations of upto one-third of its average depth in a given area are rather common (Wyrtki 1971). The magnitude of MLD is known to depend on several factors as heat exchange at the surface, momentum input at the surface (mixing by wave action), advection by currents and internal waves in a complex manner. But it is difficult to estimate

*Paper presented at the Symposium on Applied Oceanography held at Cochin in February 1978.

[1]. National Institute of Oceanography, Goa.

[2]. Department of Meteorology & Oceanography, Andhra University, Waltair.

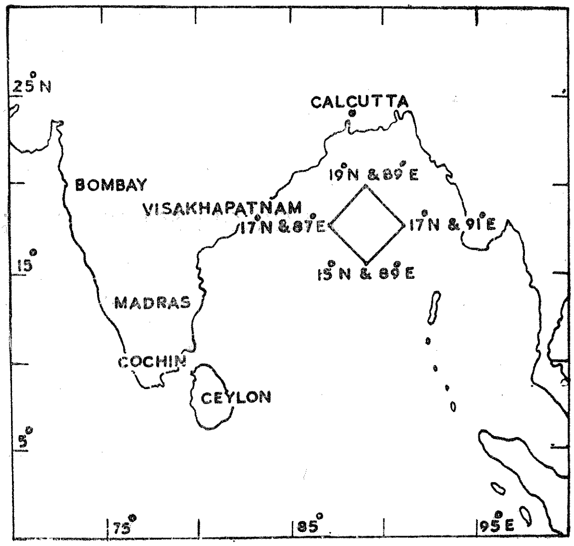

Fig. 1. Station location map

the individual contributions of these different physical processes which maintain mixed layer simultaneously. Heat gain at the surface results in the formation of a seasonal thermocline leading to shallowing of MLD and heat loss causes convective turnover, deepening the MLD. Kraus and Rooth (1961) found that changes in the mean depth of the isothermal layer are reflected in the changes in the heat balance at the surface at 35 deg. N and 48 deg. W during July to September of 1958 and 1959.

In the present study only the influence of surface heat balance is considered to expain the short term variability of MLD in northern Bay of Bengal during Monsoon-77. Further, the spatial variations in the upper ocean (200 m) thermal structure over a period of one week during August 1977 were presented.

2. Data

Fig. 1 shows the location of 4 USSR ship stationary polygon over northern Bay of Bengal during Phase III of Monsoon-77. Marine meteorological parameters collected at 3-hour interval as surface atmospheric pressure, dry bulb temperature, sea surface temperature, cloudiness, wind speed and moisture elements are used to evaluate the energy exchanges at the surface with the available empirical expressions. Excepting cloudiness the rest of the parameters are observed through instruments while the values of cloudiness are reported by visual observations. The cloudiness data may contain subjective error which can contaminate the radiation balance components which in turn affect the net heat gain values at the surface. Sub-surface bathythermograph data collected at every 3-hour interval are also made use of in this study to evaluate MLD and other thermal parameters. Though phase III is commenced just before noon of 11 August 1977, the present study is based on the data collected from 0500 IST of 12th to 0200 IST of 19 August 1977. This seven day time series data set gives an excellent opportunity to examine the variability of MLD in relation to the surface energy exchange processes. This study could not be extended to the eastern location of the polygon as the marine meteorological data were not available.

3. Methodology

Let Q represent the total heat transfer across air-sea interface (positive when the sea surface is gaining heat). Q can be expressed as a sum of different components:

$$Q = Q_i - (Q_a + Q_b + Q_e + Q_s) \quad (1)$$

$$Q_n = Q_i - (Q_a + Q_b) \quad (2)$$

where,

Q = Net heat gain (cal/cm²/day)

Q_n = Net radiation (cal/cm²/day)

Q_i = Net downward flux of solar radiation (cal/cm²/day)

Q_a = Reflected radiation (cal/cm²/day)

Q_b = Effective upward flux of long wave radiation (cal/cm²/day)

Q_e = Latent heat transfer (cal/cm²/day)

Q_s = Sensible heat transfer (cal/cm²/day)

The various components of Q are usually complicated functions of time, cloud cover, latitude, wind speed, air-sea temperature difference and vapour pressure. Empirical expressions for these (Laevastu and Hubert 1970) are given in equations (3) to (7) and their limitations were presented in detail (Ramanadham *et al.* 1977).

$$Q_i = 0{\cdot}014\, A_n\, t_d\, (1 - 0.0006\, C^3) \quad (3)$$

$$Q_a = 0.15\, Q_i - (0.01\, Q_i)^2 \quad (4)$$

$$Q_b = (297 - 1.86\, T_w - 0.95\, U_0)(1 - 0.0765 C) \quad (5)$$

$$Q_e = (0.26 + 0.077\, V)(0.98\, e_w - e_a)L, \text{ if } (e_w - e_a) > 0$$
$$= 0.077\, V (0.98\, e_w - e_a) L, \text{ if } (e_w - e_a) < 0 \quad (6)$$

$$Q_s = 39\,(0.26 + 0.077\, V)(T_w - T_a) \quad \text{if } (T_w - T_a) > 0$$
$$= 3\, V (T_w - T_a) \quad \text{if } (T_w - T_a) < 0 \quad (7)$$

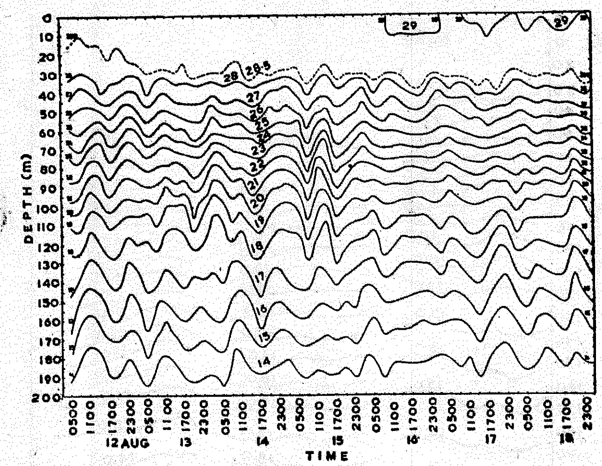

Fig. 2. Time-depth section of temperature at 19°N and 89° E from 12 to 18 August 1977

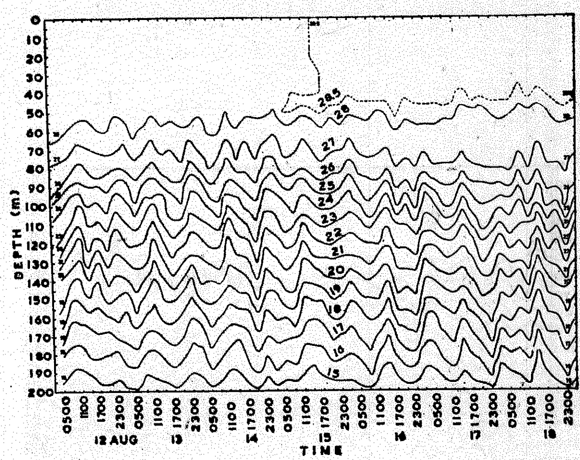

Fig. 3. Time-depth section of temperature at 17° N and 87° E from 12 to 18 August 1977

where,

A_n : Noon altitude of the Sun
t_d : Length of the day (min.)
T_a : Air temperature (°C)
T_w : Sea surface temperature (°C)
U_0 : Relative humidity (%)
V : Wind speed (m/sec)
C : Total cloud cover (in tenths)
e_a : Water vapour pressure of the air (mb)
e_w : Saturation vapour pressure of the sea surface (mb)
L : Latent heat of vapourisation

All the energy exchange parameters computed at 3-hourly interval are averaged for a day using the Eqns. (1) through (7). Only for the computation of Q_i the day time average of cloudiness is used.

The quantity heat potential (HP) is defined (Whitaker 1967) as the excess of heat over that in water at 26 deg. C. To compute at a given station, tht following equation is used:

$$HP = \rho\, c_p \int_0^{D_{26}} \triangle t \;\triangle z \qquad (8)$$

where,

ρ : Mean density of sea water from surface to D_{26} evaluated from temperature and salinity
c_p : Specific heat of sea water at constant pressure
D_{26} : Depth of 26°C isotherm
$\triangle t$: Average temperature difference above 26°C for a given depth increment, and
$\triangle z$: Depth increment (500 cm)

The product of these quantities are then summed through the layer having temperatures above 26 deg. C to obtain the total heat potential at the station.

The quantity heat content (HC) is defined as the total heat content of sea water in a volume of 1 cm² by a chosen depth.

$$HC = \rho\, c_p \int_0^{D} T\, dz \qquad (9)$$

where the symbols have standard meanings.

In the present study the Mixed Layer Depth is taken as the depth at which the temperature is 1 deg. C different, usually cooler from that at the surface. The mean temperature of mixed layer is obtained by averaging the temperature values at different depths of the mixed layer.

4. Analysis and discussion

Figs. 2-5 show the time-depth section of thermal field of upper 200 m layer at the four corners of the stationary polygon. All the four locations show near isothermal layers of different magnitudes from the surface. The shallowest mixed layer occurred at the northern location while the layer thicknesses at the other three locations are of similar magnitude. This exceptionally shallow nature of the mixed layer at the northern location can be explained due to the formation of a strong halocline resulted by the fresh water discharge from river *Hughly* leading

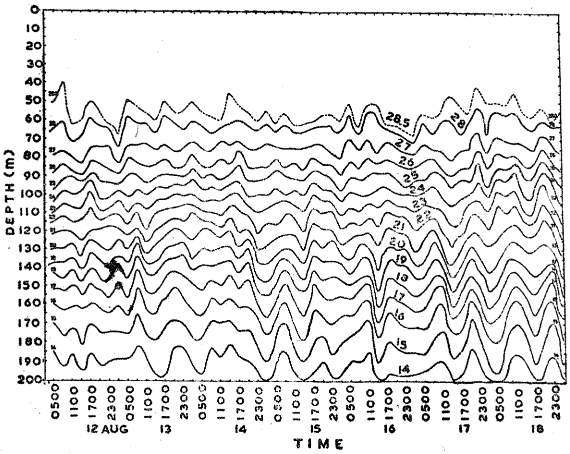

Fig. 4. Time-depth section of temperature at 15°N and 89°E from 12 to 18 August 1977

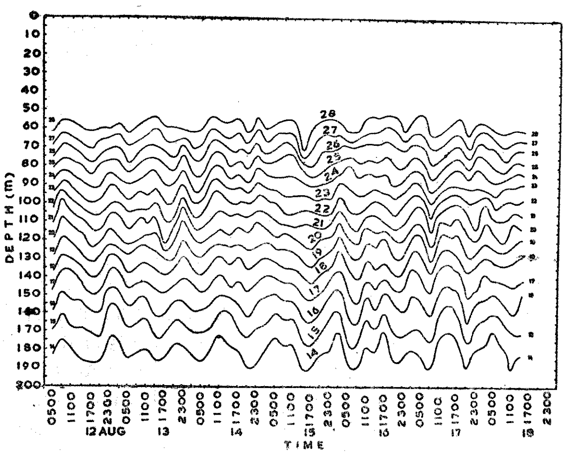

Fig. 5. Time-depth section of temperature at 17°N and 91° E from 12 to 18 August 1977

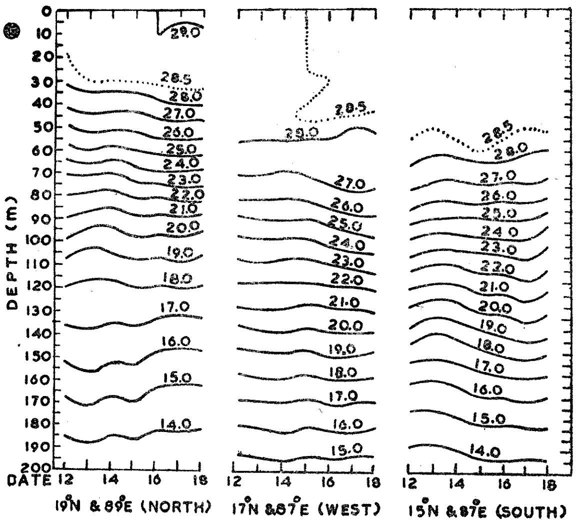

Fig. 6. Daily variation of subsurface thermal structure for the period 12-18 August 1977 in northern Bay of Bengal

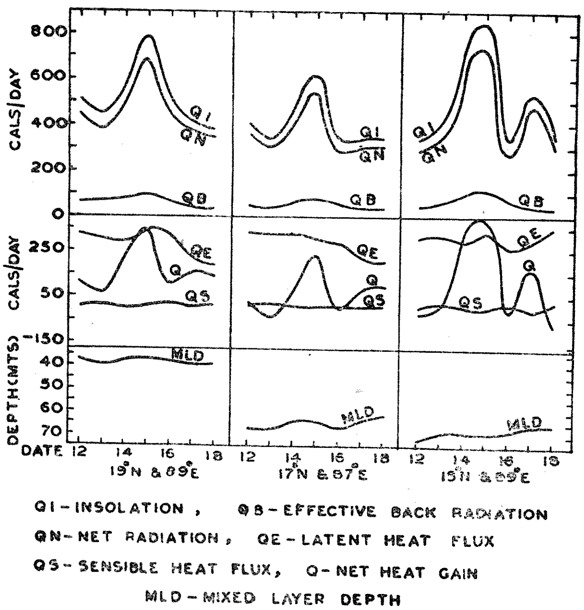

Fig. 7. Daily march of surface heat budget components and ocean mixed layer depth from 12 to 18 August 1977 in northern Bay of Bengal

to a stable stratification. The average surface salinity at the northern location is 23 ‰ and only at 30 m depth the value increased to 34 ‰. This vertical gradient in salinity causes a similar gradient in the pycnocline inhibiting the erosion of thermocline from entrainment processes.

The surface waters at the eastern location are cooler than all the other three locations as the 28.5 deg. C isotherm is completely absent only at the eastern location. Further a steady progressive deepening of 28.5 deg. and 28.0 deg. C isotherms and the occurrence of 29.0 deg. C isotherm leading to further accumulation of thermal energy can be noticed only at the northern location. This type of growing thermal contrast in the surface waters between the northern and eastern locations might have infused baroclinic instability in the overlying atmosphere which might have resulted in the formation of a monsoon depression at 0300 GMT on 19th within ½ deg. of 19 deg. N and 91 deg. E.

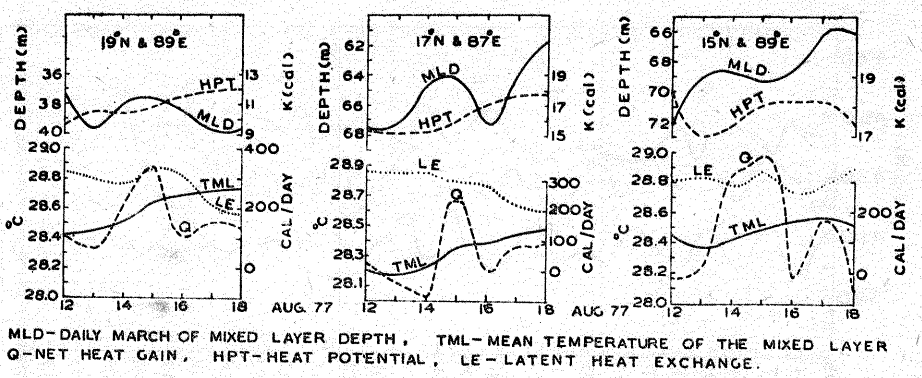

Fig. 8. Daily march of ocean Mixed Layer Depth (MLD), net heat gain (*Q*), mean Temperature of the ocean Mixed Layer (TML), ocean heat potential (HPT), and Latent heat Exchange (LE) during 12 to 18 August 1977

The maximum vertical temperature gradient is situated just below the mixed layer where the seasonal thermocline is formed. The thickness of this seasonal thermocline at the northern location smaller than the corresponding ones at any other location, *i.e.,* the isotherms below 100 m depth at the northern location are loosely packed compared to the other three locations. The oscillatory nature of isotherms in the thermocline is common at all the four locations. These short period oscillations are generally attributed to the combined influence of semi-diurnal tides, internal waves and inertial oscillations. LaFond (1954) found similar oscillations in the thermocline off Andhra coast (central part of east coast of India) and he attributed their existence to tidal forces. He also pointed out that these oscillations do not maintain a constant phase relation with the tides.

Fig. 6 depicts the daily variation of subsurface thermal structure at the northern, western and southern locations in Bay of Bengal. At the northern location the presence of 29 deg. C isotherm is conspicuous in the upper 10 metre from 16th onwards while the same is absent at the other two locations. The 28.5 deg. C isotherm appeared throughout the phase both at northern and southern locations but it can be noticed only from 15th onwards at the western location. The depth of occurrence of 28 deg. C isotherm is found to increase with decreasing latitude. In general, isotherms in the thermocline have descended at all the three locations from 14th onwards indicating the accumulation of heat energy in the upper layers with an exception at the southern location on 17th. The depth of 14 deg. C isotherm is minimum at northern location and it is maximum at the western location which shows the maximum heat content at the later location. Another important feature is the weak horizontal temperature gradient between the southern and western locations. For instance, at 100 m depth the average horizontal temperature difference between northern and western location is 4.6 deg. C while the corresponding value between the western and southern location is only 0.5 deg. C. This nonhomogeneous horizontal temperature distribution may result in similar shears in the motion field. Varadachari *et al.* (1968) found two anticyclonic cells with a zone of strong cyclonic shear between them in the western part of central Bay of Bengal during southwest monsoon season.

Fig. 7 shows the variation of daily averaged heat budget components. The input of net solar energy is above 400 cal/day on most of the days while the oscillations speak about the fluctuations in the cloud cover. The evaporative loss at any of the three locations on an average is about 300 cal/day and shows a decreasing trend at northern and western locations, and a mild increase on the last two days at the southern location. This dissimilarity in the evaporation in the north-south direction may be attributed to the saturation conditions of the atmosphere at the northern location before the formation of the depression. The net heat gain values are more or less positive with the pattern resembling that of net radiation. However, the estimation of heat budget components is not totally free from error in view of the unknown accuracy of the empirical coefficient values used in the Eqns. (3) to (7).

Fig. 8 shows the enlarged version of daily variation of MLD and surface heat gain, latent heat exchange, mean temperature of the mixed layer and the heat potential of the upper layers at northern, western and southern locations respectively.

The phase average mean Temperature of the Mixed Layer (TML) at northern location is higher compared to that of the any of the other two locations. A steady progressive increase in TML can also be noticed at all the three locations with

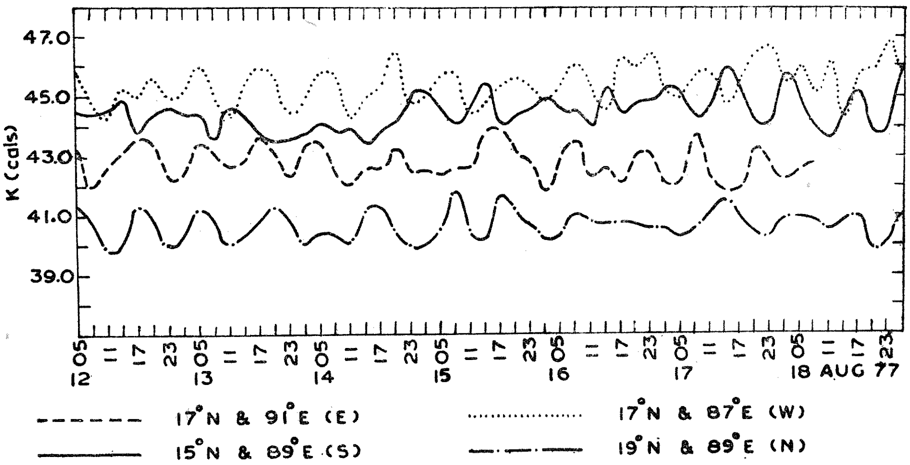

Fig. 9. Variation of heat content of upper 200 metre in northern Bay of Bengal during 12 to 18 August 1977

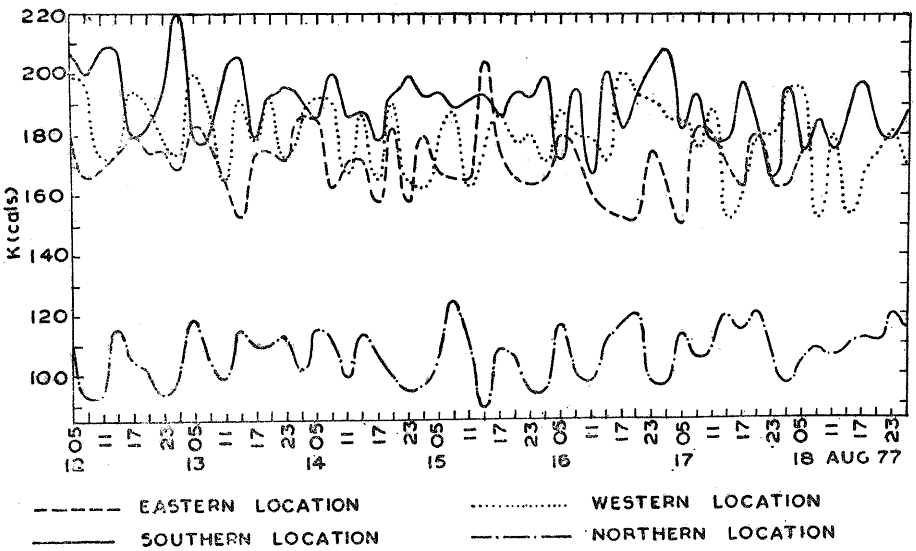

Fig. 10. Variation of heat content of ocean mixed layer in northern Bay of Bengal during 12-18 August 1977

the minor exception on the last day at the southern location confirming the accumulation of thermal energy in the upper waters before the formation of the depression. A corresponding similar pattern can also be seen in the case of heat potential. The close resemblance between the mixed layer depth and net heat gain curves supports the fact that the former is being mainly maintained by convective mixing processes while the contribution of other process may not be significant for the short period variability of mixed layer depth.

Fig. 9 shows the variation of heat content of 200 m at all the four locations. Highest values at the western and lowest values at the northern locations are observed. A mild increasing trend at western location can also be observed. The small period oscillations are present at all the four locations indicating the influence of vertical oscillations. One interesting feature is that the

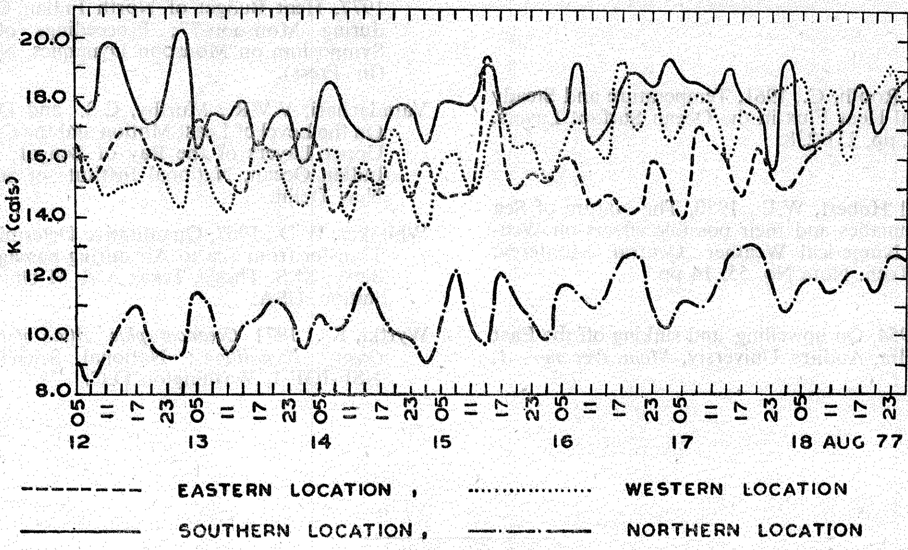

Fig. 11. Variation of ocean heat potential in northern Bay of Bengal during 12-18 August 1977

oscillations at western and eastern locations are approximately in phase while the oscillations at northern and southern locations are out of phase by approximately 180 deg.

Fig. 10 shows the distribution of heat content of the mixed layer at all the four locations. The highest and lowest values occurred at southern and northern locations respectively. This discrepancy is mainly due to the differences in the layer thickness. At northern location a mild increasing trend is observed from 15th onwards while a steady decrease is noticed at the other three locations from 12th onwards. These changes are mainly due to the variations caused in mixed layer depth. The increasing trend at northern location from 15th is of meteorological interest as a monsoon depression was formed. The out of phase relationship in the peaks is also seen between northern and southern locations in the heat content mixed layer also.

Fig. 11 shows the distribution of heat potential at all the four locations. The meridional gradient is seen with highest values occurring at southern and lowest values occurring at northern locations. A very prominent feature is the steady progressive increase of heat potential at the northern location. This accumulated heat in the surface waters of northern location might have had some bearing on the genesis of a monsoon depression. Similar increasing trend can also be noticed at the western location. Small period oscillations are also seen at all the our locations.

5. Conclusions

(*i*) The depth of the mixed layer shows marked differences between northern and all the other locations. The lower MLD observed at northern location is attributed to the boundary effects as fresh water discharge leading to thermal stratification. The depth of occurrence of 28 deg. C isotherm is found to increase with decreasing latitude.

(*ii*) The subsurface thermal structure shows both day-to-day diurnal variations in the thermocline. The short period fluctuations in the heat content of mixed layer, upper 200 m and heat potential show an approximately 180 deg. out of phase relationship between northern and southern locations.

(*iii*) This case study supports the dependence of mixed layer depth on the net heat balance at the surface over a period of one week.

(*iv*) A very prominent increase of heat potential observed at northern location might have had some bearing on the genesis of a monsoon depression over northeast Bay of Bengal at the end of the phase.

Acknowledgement

The authors wish to thank Dr. D. Srinivasan for his keen interest and encouragement throughout the course of this investigation.

References

Kraus, E.B. and Rooth, C., 1961, Temperature and Steady State Vertical Heat Flux in the Ocean Surface Layers, *Tellus*, **13**, 2, pp. 231-238.

Laevatsu, T. and Hubert, W.E., 1970, The Nature of Sea Surface Anomalies and their possible effects on Weather; Fleet Numerical Weather Central, Monterey, California, Tech. Note No. 55, 14 pp.

LaFond, E.C., 1954, On upwelling and sinking off the East Coast of India, Andhra Universiy, *Mem. Oceangr.*, **1**, pp. 117-121.

Ramanadham, R., Somanadham, S.V.S. and Rao, R.R., 1977, Heat Budget of North Indian Oceanic Surface during Monsoon-77; Proceedings of International Symposium on Monsoon Dynamics, New Delhi, 1977 (In Press).

Varadachari, V.V.R., Murthy, C.S. and Das, P.K., 1968, On the Level of Least Motion and the Circulation in the Upper Layers of the Bay of Bengal; Symposium on Indian Ocean, National Institute of Science of India, New Delhi.

Whitaker, W.D., 1967, Quantitative Determination of Heat Transfer from Sea to Air during passage of Hurricane Betsy; M.S. Thesis, Texas A & M University, College Station, USA.

Wyrtki, K., 1971 *Oceanographic Atlas of the International Ocean Expedition*; National Science Foundation, NSF-IOE-1, Washington D.C.