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A preliminary investigation on the summer monsoonal forcing on the thermal structure of upper Bay of Bengal during MONEX-79

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सार — समुद्र के पृष्ठ भाग के मौसम संबंधी एवं निमज्जन ताप आरेखी आंकड़ों की सहायता से कुछ चुने हुए स्थानों के जलयानों पर मई जून और जुलाई 1979 की तापीय परिसीमा के ग्रीष्म मानसून प्रणदन पर समुद्र को ऊपरी उपपृष्ठ तापीय संरचना की प्रतिक्रिया का अन्वेषण किया गया है । समुद्री पृष्ठ मिश्रित परतों पर मानसून के पूर्व के प्रचंड चक्रवाती झंझा के प्रणदन के अभिलक्षणों का अंकन किया गया है । पृष्ठीय उष्मा का विनिमय करने वाले अवयवों और मिश्रित परत के ठीक नीचे की ऊर्ध्वाधर ताप प्रवणता का उपयोग करके पृष्ठ मिश्रित परत के अभिलक्षण में देखे गए परिवर्तनों को स्पष्ट किया गया है । 200 मी० ऊपर के जलस्तंभ के तापमान के गहराई-समय क्षेत्र का विश्लेषण कर विवेचन किया गया है ।

ABSTRACT. The response of the upper oceanic subsurface thermal structure to the summer monsoonal forcing over Bay of Bengal in the temporal domain of May, June and July of 1979 at selected stationary ship positions has been investigated with the aid of surface marine meteorological and bathythermograph data collected during MONEX-79. Forcing of a severe pre-monsoon cyclonic storm on the ocean surface mixed layer characteristics is documented. Surface heat exchange components, vertical thermal gradient just below mixed layer are made use of to explain the observed variability in the surface mixed layer characteristics. Depth-time fields of temperature of the upper 200 m water column are analysed and discussed.

1. Introduction

The response of the upper oceanic subsurface thermal structure to the atmospheric flow at the surface is examined with the surface marine meteorological data and subsurface ocean temperature data collected at stationary positions over Bay of Bengal during the progress of monsoonal regime observed under MONEX-79. One of the main objectives of this investigation is to describe and qualitatively explain the observed temporal fluctuations in the upper 200 m of the oceanic thermal field at selected stationary positions. Mostly, the spatial variability in the subsurface thermal field of Bay of Bengal during summer monsoon season was documented in the literature by several authors (Anand *et al.* 1968, Wyrtki 1971 etc) but the corresponding information on the variability in the time domain is very meagre in the literature.

The oceanic surface mixed layer is a poorly understood region of the ocean. Many factors influence its development, including the wind, surface heating and cooling, the surface and internal wave fields, the stability of the underlying thermocline, frontal and intrusive structures in the thermocline, meso-scale deep ocean eddies and tides. Each factor separately can produce substantial variability on much the same vertical scales, upto the mixed layer depth, and on horizontal scales from few metres to hundreds of kilometers (JASIN 1977). The vertical temperature gradient will be quite sharp in the upper part of the thermocline (known as seasonal thermocline in summer) compared to that of the lower part. In addition, during heating season thin transient thermoclines also appear in the mixed layer which prevail for a shorter time. Vertical mixing within the turbulent boundary layer and entrainment mixing at its base occur in response

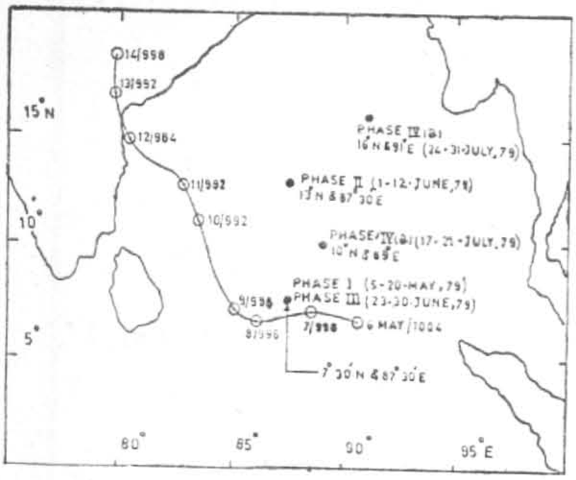

Fig. 1. Station location map of *INS Betwa* during MONEX-79

to the local atmospheric forcing — the surface wind stress and the net heat radiated and turbulent fluxes across the sea-air interface. The mixed layer together with the seasonal thermocline act as a very effective thermal buffer shielding the interior of the ocean from the seasonal changes of the heat budget. As relatively slight variations in the mean temperature of such a layer represent substantial amount of heat, an accurate representation of the thermal structure of the mixed layer is therefore of immense value.

2. Data

The stationary positions of *INS Betwa* are shown in Fig. 1 along with the periods of deployment for all the four phases of MONEX-79. The track of the pre-monsoon May 79 cyclonic storm with estimated central pressures against dates is also shown. Marine meteorological data as the sea surface temperature and surface atmospheric pressure, air temperature, wet bulb temperature, wind speed at 10 m height are measured on board with appropriate instruments every one hour while the cloudiness values are collected through visual observations. Only during Phase III the marine meteorological data are collected at 3-hourly interval. Three-hourly sampling of bathythermograph data are made use of to investigate the variability of upper oceanic thermal fields.

3. Methodology

For estimating the insolation at the sea surface we have taken the average of the values obtained by the schemes proposed by Tabata (1964) and Reed (1977) as the two authors have arrived at similar empirical coefficients and also as the values obtained by the schemes proposed by several other authors have shown considerable scatter. The equations used in this paper after Tabata (1964) and Reed (1977) are given below:

$$Q_T = Q_0 \ (1.0 - 0.716 \ C + 0.00252 \ A_n)$$

$$Q_R = Q_0 \ (1.0 - 0.62 \ C + 0.0019 \ A_n)$$

$$Q_i = (Q_T + Q_R)/2.0$$

where,

Q_T and Q_R are the insolation values estimated after Tabata & Reed respectively.

Q_0 : radiation at the top of the atmosphere which is a function of season and latitude.

C : day time average cloudiness in tenths.

A_n : noon altitude of the sun in degrees.

Q_i : the insolation at the surface (cal/cm^2/day)

The evaluation procedures are followed for net radiation after Reed (1976) and for sensible heat and latent heat fluxes after Kondo (1975). The net heat gain by the ocean surface boundary layer can be written as :

$$Q = Q_i - (Q_l + Q_s + Q_e)$$

where, Q : the net heat gain by the ocean

Q_i : the effective insolation

Q_l : net long wave radiation from sea to air taken as positive

Q_s : sensible heat flux from sea to air taken as positive

Q_e : latent heat flux from sea to air taken as positive

The units of all the above mentioned fluxes are cal /cm^2/day. It is presumed that the heat input at the surface of this upper mixed layer is to be distributed uniformly throughout the layer by turbulent diffusion. One of the aims of this study is to examine the influence of these boundary exchanges on the thermal characteristics of the mixed layer and of the thermocline below. In the literature different criteria were used to define mixed layer depth (MLD) and it is rather difficult to make a rational selection. Ostapoff and Worthem (1974) have examined the question of defining the criterion for the mixed layer depth using GATE (GARP Atlantic Tropical Experiment) data. Their definition of MLD as the depth

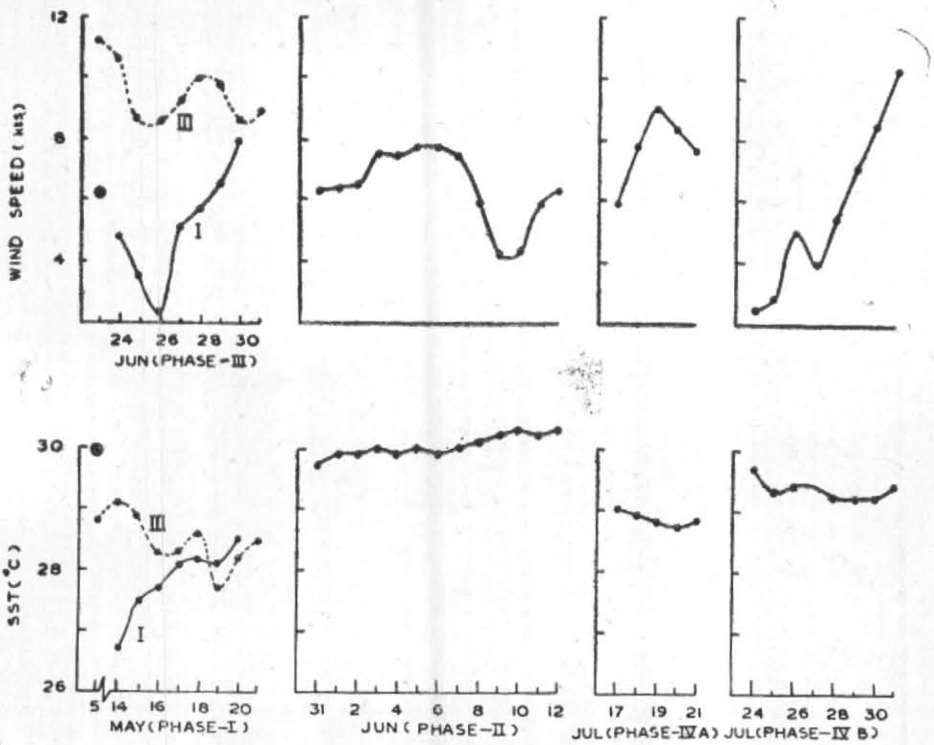

Fig. 2. Daily march of wind speed and sea surface temperature at the stationary positions of *INS Betwa* during MONEX-79

where the temperature is lower by 1.0 deg. C from the value at 10 m depth is used here in demarcating the mixed layer depth. As the deepening rate of MLD is inversely proportional to the magnitude of the density just below the layer, due to non-availability of salinity data the vertical temperature gradient at the base of the mixed layer is also presented in addition to the vertically averaged temperature of the mixed layer.

4. Analysis and discussion

Fig. 2 shows the temporal variation of daily averages of wind speed in knots and sea surface temperature in deg. C for all the four phases. As the ship occupied the same position during Phase I (continuous) and Phase III (broken) lines are drawn together for easier comparison purposes. For convenience the dates of Phase III are marked in the upper panel of the diagrams. During Phase I the discontinuity in the time axis caused in the observational programme with the formation of a severe cyclonic storm may be noted. This notation is followed throughout.

A trough of low pressure was formed over the southeast Bay of Bengal on 3 May 1979 and concentrated into a depression on 5th at 7 deg. N, 90 deg. E. It intensified into a deep depression on 6th and became a cyclonic storm on 7th with its centre near 7 deg. N, 88 deg. E. Moving slowly westward it intensified further into a severe cyclonic storm and lay near 7 deg. N, 85 deg. E on 9 May. On 12th the system crossed the south-east coast of India and got weakened. The observed data during Phase I mostly represent the conditions after the passage of the cyclonic storm. All the data of 5 May is marked with a dot in a circle for a clearer distinction. No significant discontinuity in the wind field is seen from 5 to 14 May as very strong winds might have occurred in association with the cyclonic storm in between and dampened out. The same is not the case with SST which shows a very conspicuous fall by more than 3 deg. C from 30 deg. C. This significant fall in the temperature of surface layers of the sea in the wake of cyclonic storm is well documented in the literature (Leipper 1967). During the passage of the storm, in addition to cooling in the upper ocean there will be warming at the base of the mixed layer caused by downward heat flux across the base of the layer due to turbulent mixing. In these strong storms the downward heat flux at the base of the layer can be 5-10 times the value of the upward heat flux that is lost to the atmosphere through the surface (Camp & Elsberry 1978). Both effects tend to cool the near surface layer and account for the rapid cooling rates. Another interesting feature that is to be noted is the rapid rise of SST from 14th onwards till the end of the Phase I leading to a warming of nearly 2 deg. C over a period

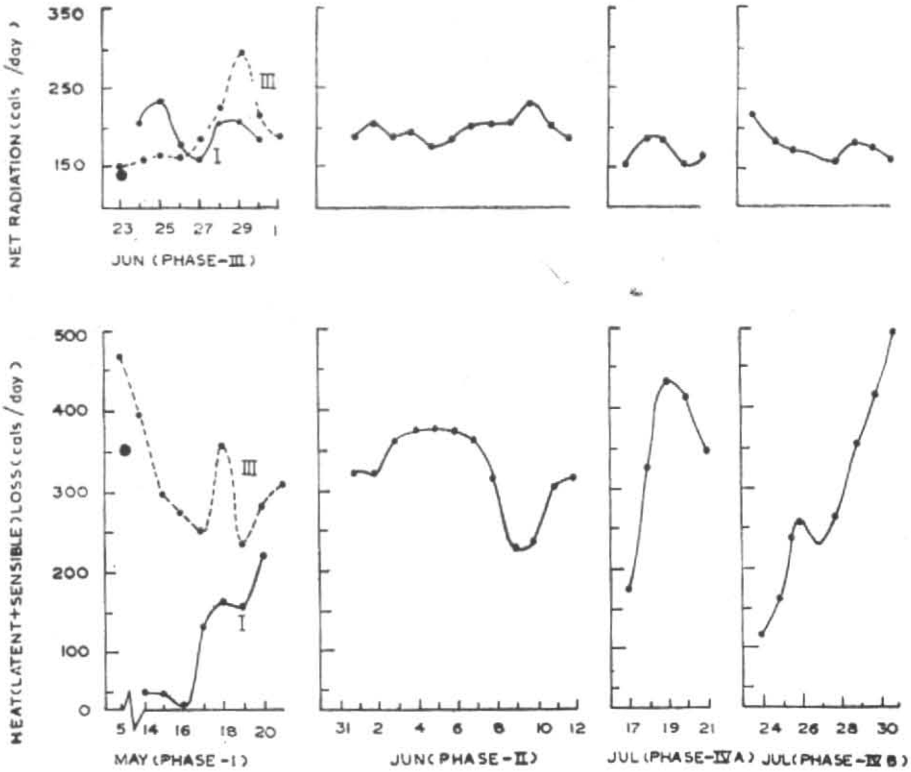

Fig. 3. Daily march of net radiation and heat loss at the stationary positions of *INS Betwa* during MONEX-79

of one week. This sharp rise cannot be explained by taking only the vertical heat fluxes into account which are in the opposite direction in this case. This will be discussed later in detail. During Phase II the ship occupied a different position about 600 km north along the same longitude. During this phase due to the delayed onset of monsoon no increase in the wind or fall in SST is noticed. On the other hand SST values with the increasing trend are of the similar magnitude of the pre-storm conditions at the southern location during Phase I. The rising trend cannot alone be explained as a result of the vertical heat fluxes at the air-sea interface. The qualitative agreement in the increasing trend of SST (shown in Fig. 2) and the decreasing trend in the net heat loss (shown in Fig. 5) probably indicate that the insolation values obtained after Tabata and Reed are under estimated. During Phase III the ship occupied its earlier position of Phase I. On the first day wind strength nearly double in magnitude is noticed at this area on account of the established monsoosal flow while the SST values did not change much. Only during this phase the SST values followed a declining trend with an approximate fall of 1 deg. C over a period of one week due to the prevailing monsoonal onset. During Phase IVa the SST values are also slightly less than 29 deg. C showing near homogeneous surface thermal conditions over Bay of Bengal. During Phase IVb over north-east Bay wind field has shown a steady rise almost throughout the phase as a low pressure was formed on 27 July. During next few days this low pressure system seems to have had some influence on lowering the SST.

Fig. 3 depicts the temporal variation of the computed net radiation and turbulent heat fluxes at the surface. During Phase I the net radiative input at the surface roughly varied between 150 to 200 cal/day while the sum of latent and sensible heat fluxes are around 350 cal/day during the formation of the storm. After the intensification and dissipation of the storm the ocean surface boundary layer properties are considerably changed. The significant reduction in the heat loss of 300 cal/day from 5th to 14th can be explained due to the lowering of SST by 3.0 deg. C, the reversal of temperature gradient from atmosphere to ocean (sea *minus* air temperature on 5th was 1.0 deg. C and on 14th, —1.0 deg. C) and the fall of vapour pressure difference from 10 mb to 3 mb — all the conditions favouring stable equilibrium. With the progress of time the magnitude of the stability of the atmospheric surface layer got weakened which simultaneously resulted in the steady progressive increase in the surface heat losses. By the end of the phase a near balance is reached between radiative and

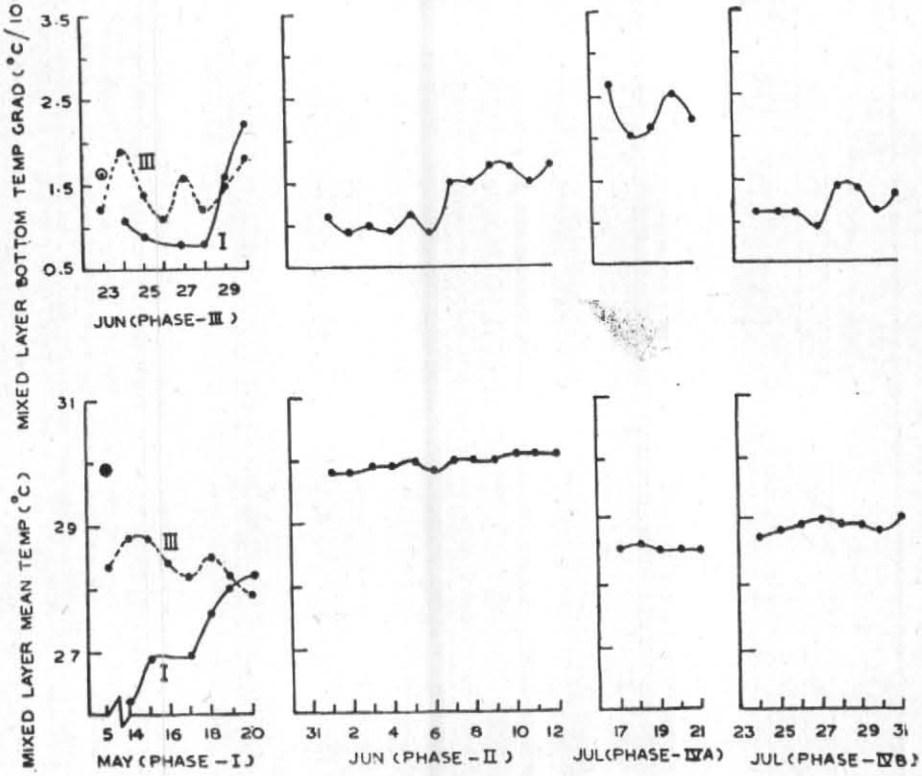

Fig. 4. Daily march of temperature gradient below the base of mixed layer and mixed layer mean temperature at the stationary positions of *INS Betwa* during MONEX-79

turbulent energy fluxes at the surface. During Phase II the net radiation is of similar magnitude as that of Phase I. The minor oscillations speak about variability in the daily day time averages of cloudiness. But the corresponding turbulent heat fluxes are about 300 cal/day with a dip on 9th and 10th. On these two days though there is a mild increase in the vapour pressure gradient, the reduction in the wind speed contributed to the lowering of heat losses from the sea surface. During Phase III the net radiation values are low in the first half in association with increased cloudiness caused by the formation of a monsoon depression over north-west and adjoining west-central Bay of Bengal on 23 June. The net radiative input increased during the second half of the phase when the cloudiness values are reduced following the dissipation of the depression over central part of India on 27 June. With the formation of another depression in the north Bay at 21 deg. N & 90 deg. E on 28 June again the net radiation values began to lower with the increased cloudiness. The heat losses show a declining trend as corresponding trends for wind speed and vapour pressure gradient are also in the same direction. The higher losses during the first half might have been resulted due to the occurrence of the depression on 23rd, over northern Bay of Bengal. During Phases IVa and IVb though there is change in observing position, no significant changes in the net radiation are noticed. But the decreasing trend in Phase IVb was attributed to the corresponding rise in cloudiness in association with a low pressure area which was formed over north-east Bay on 27 July. The increasing heat losses during Phase IVa are caused by the overall strengthening of the monsoonal flow over central Bay of Bengal. The steady steep rise during Phase IVb has been resulted due to the formation of the above mentioned low pressure system.

The cooling of the mixed layer while deepening can also occur on account of entrained colder waters across the base of the layer. This entrainment rate or mixed layer deepening directly depends on the surface frictional velocity and inversely on the density just across the base of the layer. In order to visualise this phenomenon the temporal variation of vertical temperature gradient below the base of the layer in Fig. 4 and MLD variation in Fig. 5 are shown. During Phase I, after the passage of the storm, the gradient shows a mild weakening trend from 14th to 18th and then a marked rise till the end of the phase. The weak gradients observed during 14th to 18th may be explained in terms of the stronger vertical diffusion of heat across the base of the

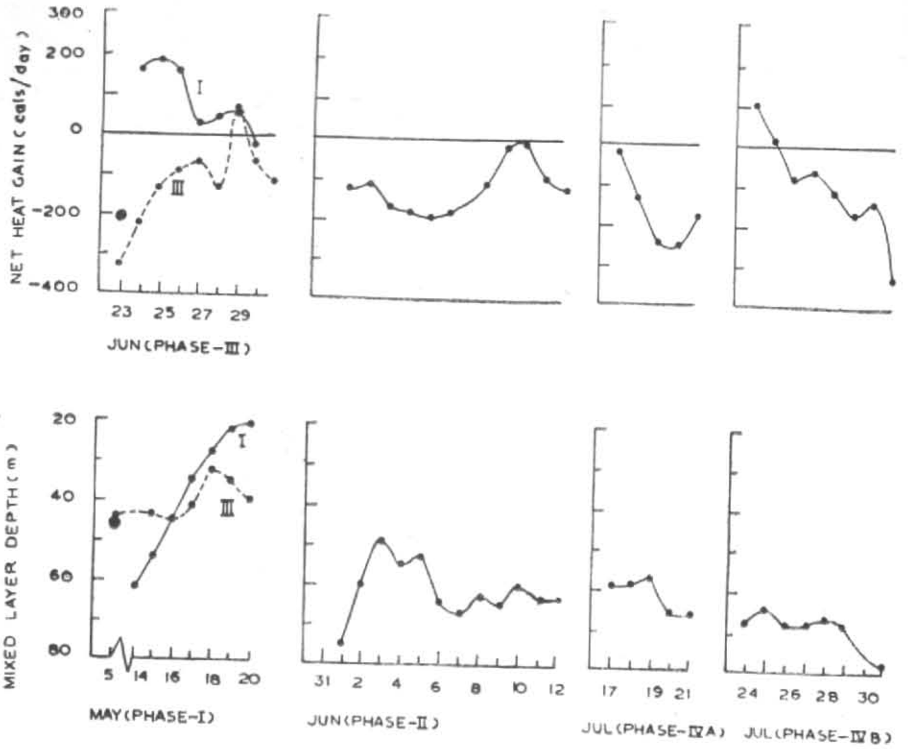

Fig. 5. Daily march of net heat gain and mixed layer depth at the stationary positions of *INS Betwa* during MONEX-79

mixed layer on account of inertial oscillations in the mixed layer caused by the cyclonic storm. With the decay of these oscillations over a period of one week, vertical thermal gradients got built up with a steady progressive rise. There is a good agreement on the shoaling of MLD and sharpening of the vertical temperature gradient during the last three days. In Phase II, during first half though no significant trend is noticed in the bottom gradient, MLD got deepened from 3rd to 7th. But in the latter half a very good support is available to the theory, *viz,* mixed layer shoals when the bottom gradient strengthens. During Phase III the bottom gradient is mainly of oscillatory nature. During Phase IVa the phase averages of the gradient value is highest of all the phases. Opposing trends in MLD and gradient are noticed in Phase IVb. Detailed discussion will not be made on the temporal variability of mixed layer mean temperature as the curves very much resemble SST curves and therefore the discussion made for SST holds good here.

Since the heat flow in the vertical at the sea surface plays an important role on regulating MLD variations, the daily march of net heat gain at the surface and MLD are shown in Fig. 5. During Phase I after the passage of the storm, the net heat gain shows a diminishing trend leading to near balance at the surface. This phenomenon, however, should not encourage the layer shoaling but a very steady lowering of the layer depth is observed. As the layer was considerably deepened in the wake of the storm, after the passage of the storm, it appears as if the layer depth is tending to occupy its pre-storm position. In this case it even shoaled beyond its pre-storm position. This shoaling of around 40 m within six days cannot be accounted only by considering the vertical heat fluxes alone but vertical advective processes seem to have played a significant role, as below the cyclones the wind stress pattern causes the Ekman or mixed layer transport to be divergent resulting upwelling at the base of the mixed layer. During Phase II the layer shoaled from 1st to 3rd, while there is an increasing heat loss which opposed the shoaling tendency. But the subsequent layer deepening from 3rd to 7th and shoaling tendency from 7th to 10th are in good corroboration with the increasing and decreasing heat losses respectively. The agreement in the layer deepening on last three days is also supported by the increasing heat loss at the surface. During Phase III there is a steady decrease in the heat loss during the first 5 days, with corresponding shoaling tendency in MLD. However, the layer shoaled from 26th to 28th indicating a lag of 4 days. The layer shows a deepening trend from 28th while increasing heat loss can be noticed only from 29th onwards. The MLD is deepened by around 25 m from the end of Phase I to the beginning of Phase III while there is no such corresponding

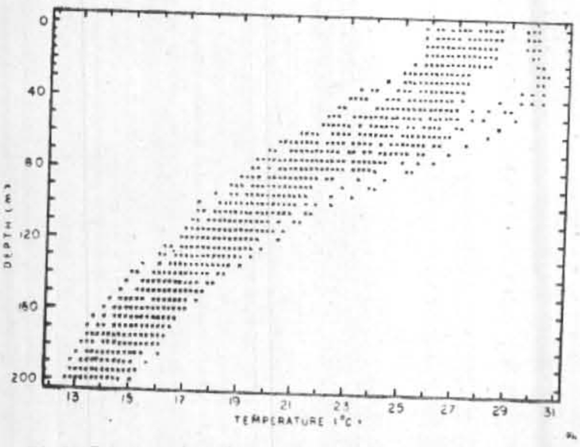

Fig. 6. Composite of vertical temperature profiles at 7.5°N and 87.5° E from 5 to 20 May 1979

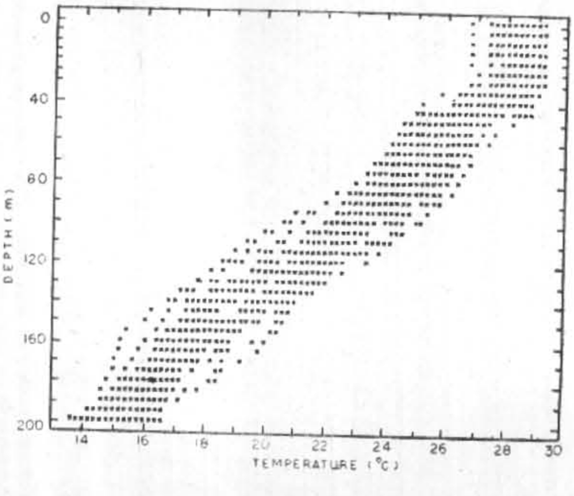

Fig. 7. Composite of vertical temperature profiles at 7.5° N and 87.5° E from 23 to 30 June 1979

reduction in the mixed layer mean temperature. This fact indicates that heat content of the mixed layer got nearly doubled during a course of one month before the monsoonal onset. During Phases IVa and IVb the deepening trends of the layer depths are in agreement with general increasing layer depth with increasing latitudes (Phases III, IVa & IVb) if near stationarity is assumed. A corresponding mild increasing trend in the mixed layer mean temperature can also be noticed from Fig. 4 with increasing latitude. These factors may be of great consequence for the genesis of monsoon depressions over northern Bay of Bengal.

Fig. 6 shows the composite of vertical temperature profiles from surface to 200 m depth for the period 5 and 14 to 20 May 1979 at the stationary position 7.5 deg. N & 87.5 deg. E. No data could be collected during 6 to 13 May on account of a severe cyclonic storm whose track is shown in Fig. 1. The composite trace shows large variance in the surface waters (upper 40 m) with the highest temperatures around 30 deg. C occurring before the intensification of the cyclonic storm (*i.e.*, on 5 May) and lowest values around 26 deg. C occurring soon after the dissipation (*i.e.*, 14 May). A very clear discontinuity in the temperature is noticed on account of missing data, during the period of storm intensification when the cooling is quite significant. On the day of highest temperatures around 30 deg. C a mild positive temperature gradient in the vertical at 20 m depth can be noticed on account of intense surface cooling associated with storm growth. Fig. 7 shows the corresponding pattern at the same location for the period 23 to 30 June, *i.e.*, nearly one month after the end of Phase I. During this period the composite traces are shifted towards increasing temperatures. As shown in Fig. 8 the rise in temperature is about 1 deg. C in the mixed layer and around 1 deg. C to 3 deg. C in the thermocline. The increase in the mixed layer temperature may be accounted due to downward flow of net accumulation of heat at the surface in association with mechanical mixing. In the thermocline as there is no significant change in the temperature gradient it is surmised that advective flow of heat in the horizontal is more dominant than that of downward diffusion of heat in increasing the mean temperature of the profile. It may be further argued that downward diffusion of heat does not seem to be responsible as the surface waters also have not exhibited any cooling trend. The relative levels of the respective isotherms from end Phase I to beginning of Phase III (shown in Figs. 9 and 11) show a marked deepening. This type of lowering of isotherms might have been resulted due to Ekman type of convergence as a result of wind stress curl. This increase of temperature over a period of one month shows a net accumulation of heat of an amount of 40 k cal/cm^2 in the upper 200 m water column while the net heat exchange across the sea surface can account less than 25% even at the rate ocean gaining 300 cal/cm^2/day. It is, therefore, imperative that advection of heat in the horizontal might have contributed to this observed rise in temperature of the upper thermocline.

Fig. 9 shows the time depth field of temperature during phase I. The isotherms are drawn at 1 deg. C interval for the values less than 28 deg. C and with 0.5 deg. C interval for the values greater than 28 deg. C. No attempts have been made to generate data when BT casts were not taken and hence the isotherms are discontinuous in the time domain. This section very clearly reflects the oceanic response in its thermal regime to an atmosphere forcing of a synoptic scale cyclonic

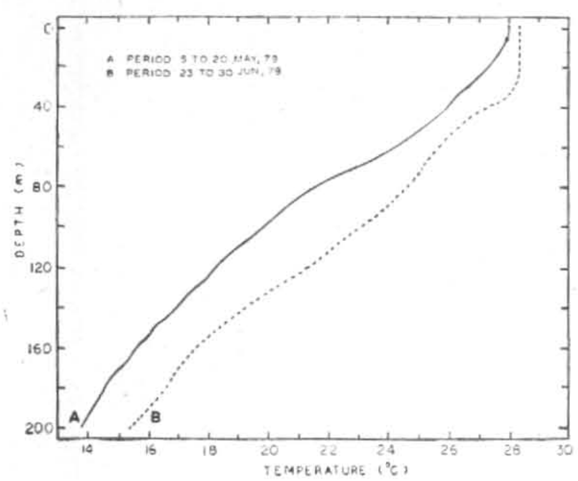

Fig. 8. Mean vertical temperature profiles at 7.5° N & 87.5° E

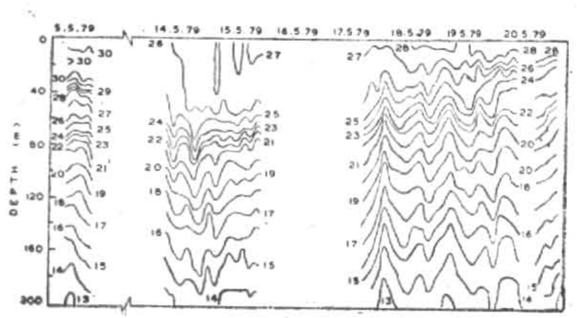

Fig. 9. Depth-time section of temperature at 7.5° N & 87.5° E from 5 to 20 May 1979

storm. On 5 May a deep depression was formed with its centre at an approximate distance of 300 km east-southeast of the stationary position. Though the data during the occurrence of the storm are available for only one (*i.e.,* 5 May) day the following inferences could be made. The SST values on this day are slightly less than 30 deg. C with its daily average of 29.9 deg. C. But the temperature values between roughly 10 m and 30 m depths are greater than 30 deg. C leading to instability conditions on account of thermal inversion. This subsurface warm slab can be accounted by the intense surface cooling caused by strong surface heat losses. The observed mean daily mixed layer depth is 46 m. The centre of the intensifying system is nearest to the observation point on 7th (*i.e.,* within around 60 km). After 7 days of the passage of the storm, *i.e.,* on 14th the surface temperatures showed a cooling by more than 3 deg. C associated with the layer deepening to 60 m depth. With the progress of time, a steady progressive rise in surface temperature is noticed with the gradual reappearance of 27 deg. C and 28 deg. C isotherms. This surface heating is not commensurate with the trend of net heat again at the surface. It may, therefore, be surmised that both horizontal and vertical advective processes seemed to be quite predominant than the local vertical turbulent fluxes across air-sea interface.

As expected in accordance with the increase in the temperature of surface layer waters, the mixed layer depth also followed a shoaling trend. The strong vertical temperature gradient in the seasonal thermocline is persistent throughout the phase but occupying different depths during the period of observations. From 14th onwards, the shoaling trend of this seasonal thermocline is very clearly seen. Below this seasonal thermocline the vertical gradients are relatively weaker. The wavy natured small period undulations which are present throughout in the vertical indicate the presence of vertical oscillatory forces caused by semidiurnal tides, internal waves and inertial oscillations. The coherence in the vertical of these high frequency fluctuations is quite significant throughout. Similar oscillatory nature in the subsurface isotherms in the northern Bay of Bengal were reported based on the data collected by 4 ship USSR stationary polygon during August 1977 (Rao *et al.* 1981).

Fig. 10 shows time-depth field of temperature during Phase II approximately at a location 600 km north of the Phase I position during the first 12 days of June 1979. The temperature of surface waters is throughout greater than 29.5 deg. C and the 30 deg. C isotherm appeared mostly in the day time as a consequence of day time solar heating. The mixed layer depth shows a rapid shoaling during the first three days and then deepening during the next four days followed by a tendency to shoal. There is a corresponding increase in the temperature gradient at the base of the mixed layer from 1 deg. C to 1.5 deg. C/10 m from first half to latter half. One interesting feature is the presence of comparatively thicker column of water between 28 deg. C and 27 deg. C isotherms. This weak temperature gradient between these two isotherms may be attributed to stronger vertical shear in the horizontal flow evidenced by the relatively larger amplitudes of 28 deg. C isotherm oscillations probably caused by internal waves. Woods and Wiley (1972) have attributed billow or shear turbulence to the observed patchy turbulent regions appear in the seasonal thermocline of high internal wave activity. Below the depth of occurrence of 27 deg. C isotherm the vertical gradients are again stronger in the upper thermocline ($\leqslant 150$ m) while the gradients are weaker below 150 m depth. The vertical oscillations are also present throughout with an approximate number of 24 peaks indicating the dominance of semidiurnal tides. A mild upwelling of isotherms in the thermocline is seen throughout during Phase II. The ship occupied the same position of Phase I during Phase III. Fig. 11 depicts conditions of nearly after one month. From the end of Phase I to the beginning of Phase III the following changes are noticed. The mixed layer depth is deepened from 20 m to nearly 45 m and with no significant variation in the mean temperature of the mixed layer. This indicates that greater amount of heat is accumulated in the upper boundary layer during this one month period. During Phase III two depressions of short life are formed over northern Bay on 23rd and 28th respectively. The isotherms in the upper thermocline are loosely packed during Phase III compared to those of Phase I, indicating an increase in the vertical downward diffusion of heat caused by increased wind mixing. Further at 200 m depth the occasional appearance of 13 deg. C isotherm during Phase I is displaced by 15 deg. C isotherm. This clearly shows an increase in the heat content of 200 m layer from Phase I to Phase III. This increase may be attributed to the advective processes whereby heat might have got transported by the driving southwesterlies. Higher temperatures prevailed at 13 deg. N and 87.5 deg. E. during early June compared to the corresponding ones at 7.5 N & 87.5 deg. E during May. This type of meridional gradient supports Ekman type of heat transport towards the southern location under the drive of southwesterlies. The surface temperatures are always around 28.5 deg. C with occasional appearance of 29 deg. C caused by solar heating. The MLD is around 40 m with a mild shoaling trend. The stronger vertical gradient in the upper thermocline is no longer situated just below mixed layer unlike that of Phase I but occupied relatively deeper position. A careful examination of this strong gradient layer shows a wavy nature in the time domain especially embedded between the isotherms 24 deg. C and 18 deg. C with its ridge occurring on 25th in this series probably indicating the passage of a wave disturbance. Short period fluctuations are also present throughout the 200 m water column.

Fig. 12 shows the time-depth field at 10 deg. N, 89 deg. E for a period of 5 days from 17 July onwards. The position corresponds to the southern position of the first stationary Indian ship polygon. In the surface waters the 28.5 deg. C isotherm is occasionally present, may be mainly on account of day time solar heating. The upper thermocline gradient from the base of the mixed layer to 100 m depth is steeper than that of the layer below. This stable upper thermocline indicates further accumulation of heat in the surface mixed layer as evidenced by the deepening of 28 deg. C isotherm. The isotherms below 40 m depth are also showing deepening trend from 19th onwards. Small period oscillations are also present throughout with good vertical coherence. The amplitude of the vertical oscillations have grown with the increasing depth. Fig. 13 shows the time-depth field at 16 deg. N & 91 deg. E during the last week of July 1979. This position corresponds to the eastern location of the second stationary Indian ship polygon. In this area the surface temperatures are further higher than the previous locations even after the onset of summer monsoon over Bay of Bengal, values being greater than 29 deg. C on most of the occasions. The gradual increase of mean temperature of the mixed layer shows the accumulation of heat in the surface layers. The vertical gradient in the upper thermocline is steep throughout with a maximum in the layer 80 m to 120 m with relatively weak gradients on either side. The small period oscillations are present in this section as in the earlier phases.

5. Summary and conclusions

1. The severe pre-monsoon cyclonic storm exerted a profound influence on the surface mixed layer characteristics with a cooling of 3 deg. C and deepening of around 15 m. But with the passage of this storm away from the observing stationary position, a recovery in the mixed layer characteristics towards the pre-storm situation is noticed within the following one to two weeks.

2. Before the monsoonal onset, the increase in the bulk heat content of upper 200 m water column over an interval of one month from end Phase I to beginning of Phase III, of the order of 40 deg. k cal/cm^2 is mostly attributed to convergence of heat as the surface exchange processes can hardly contribute to less than 25% with an assumed surface heat gain of 300 cal/cm^2/day.

3. Though the onset of summer monsoon is delayed beyond normal in 1979, a steep fall of 1 deg. C in SST over a period of one week is noticed under the influence of increased wind strength in association with the monsoonal onset during Phase III.

4. The strong vertical thermal gradient situated just below the mixed layer before the onset of monsoon shifted downwards with the progress of the monsoon probably on account of increased downward heat flow due to mixing and diffusion in the upper most layers.

5. Depth-time fields of temperature of the 200 m water column revealed the presence of short period vertical oscillations (with good coherence in the vertical) resembling the nature of semi-diurnal tides.

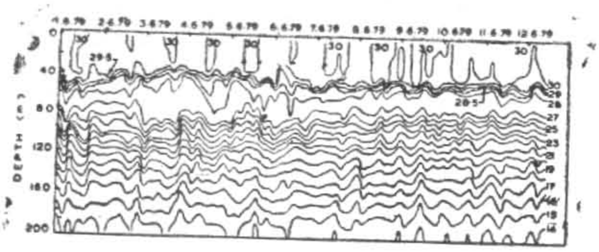

Fig. 10. Depth-time section of temperature at 13°N & 87.5° E from 1 to 12 June 1979

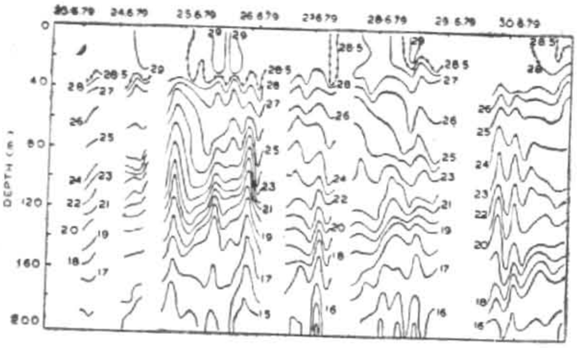

Fig. 11. Depth-time section of temperature at 7.5° N & 87.5° E from 23 to 30 June 1979

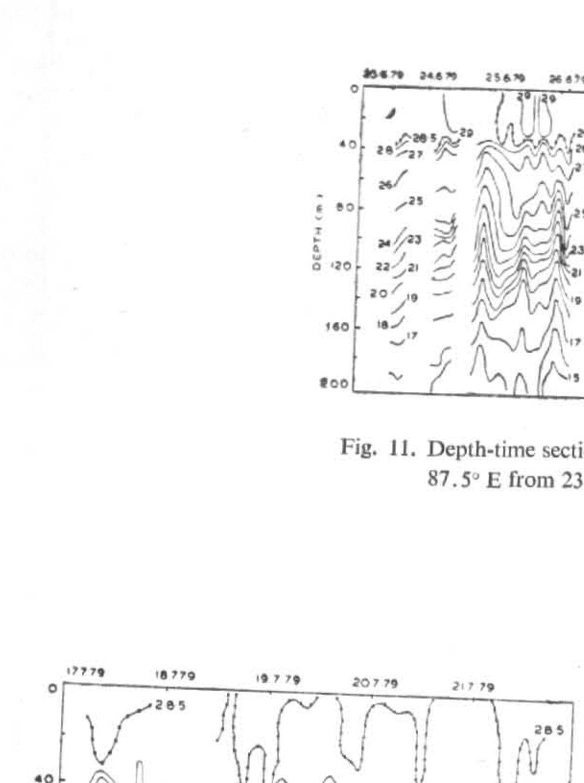

Fig. 12. Depth-time section of temperature at 10° N & 89° E from 17 to 21 July 1979

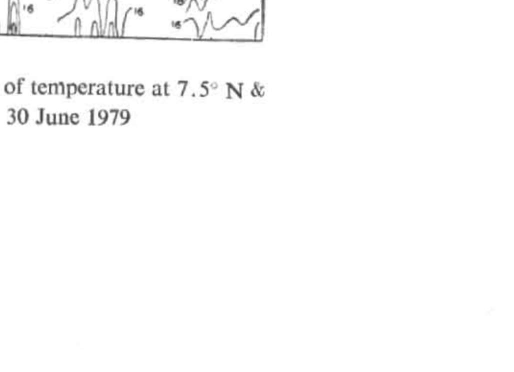

Fig. 13. Depth-time section of temperature at 16°N & 91°E from 24 to 31 July 1979

TABLE 1

Phase averages of upper Bay of Bengal thermal parameters during MONEX-79

Location (°N & °E) 1979	Period (Dates)	MLD (m)	MLT (°C)	TCGRAD (°C/m)	HC_{ml} (k cal)	HP_{27} (k cal)	HC_{200} (k cal)
7.5 & 87.5	5-5-79 20-5-79	38.5	27.7	0.075	102	2	412
7.5 & 87.5	23-6-79 30-6-79	40.7	28.4	0.072	110	5	453
13.0 & 87.5	1-6-79 12-6-79	50.5	30.0	0.096	144	17	447
10.0 & 89.0	17-7-79 21-7-79	50.7	28.5	0.087	138	6	422
16.0 & 91.0	24-7-79 31-7-79	54.6	28.9	0.100	150	10	417

MLD : Mixed layer depth,

TCGRAD : Vertical temperature gradient in the thermocline,

HP_{27} : Heat potential above 27°C,

MLT : Mixed layer mean temperature,

HC_{ml} : Heat content of the mixed layer,

HC_{200} : Heat content of upper 200 m layer.

APPENDIX

Table 1 shows the phase averages of different upper ocean thermal parameters at all the five stationary positions. The mean temperature of the mixed layer is taken as the vertical average of the layer. The temperature gradient in the thermocline is taken for the layer with the base of the mixed layer as the upper boundary and 200 m depth as the lower boundary. Heat content of the mixed layer and upper 200 m depth are defined as :

$$HC_{200} = \rho C_p \int_0^{200} T \, dz$$

and heat potential above 27°C is taken as

$$HP_{27} = \rho C_p \int_0^{D_{27}} \triangle T \, dz$$

where,

ρ is the density of sea water

C_p is the specific heat at constant pressure

$\triangle T$ is the temperature. difference above 27°C for a given depth increment

D_{27} is the depth of 27°C isotherm and

dz is the depth increment (500 cms)

In the table the units for all the parameters are given in the brackets.

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