Mausam, (1986), **37,** 1, 77-84

551.558.1 : 551.553.21

On the thermal response of upper eastern Arabian Sea to the summer monsoonal forcing during Monsoon-77

R. R. RAO

Naval Physical & Oceanographic Laboratory, Cochin

(*Received 29 September 1984*)

सार — इस लेख में ग्रीष्म कालीन मानसूनी प्रणोदन के प्रति ऊपरी पूर्वी अरब सागर की तापीय प्रतिक्रिया को लिपिबद्ध किया गया है इसके लिये 'मानसून-77' के दौरान दो स्थिर भारतीय जलयानों से इकट्ठे किए गए सतह-समुद्री मौसम विज्ञानी तथा ऊपरी महासागरीय तापमान (बी. टी.) समय श्रृंखला आंकड़ों की सहायता ली गई है। सतह के पास मिश्रित परत 2° सेल्सियस पर ही ठण्डी हो गई तथा मानसून शुरू होते ही 25 से 35 मीटर तक अभेद्य रूप से गहरी होती चली गई। दैनिक बी. टी. आंकड़ों के औसत द्वारा निर्मित तापमान के गहराई-समय काटों ने मिश्र परत के नीचे से उत्स्रवण का पता दिया जिसके परिणाम-स्वरूप 2° से 3° सेल्सियस तक ठण्डक हो जाती है। केवल उत्तरी स्थल पर ऊर्ध्वाधिर तापीय प्रवणता में एक द्विगुण क्रोडित उच्चिष्ठ देखा गया था और दक्षिणी स्थल में सम्पूर्ण रूप से एकल क्रोडित उच्चिष्ठ देखा गया था। सबसे ऊपर की 100 से 200 मीटर की परतों में तापीय अवयव के लुप्त होने का कारण नीचे से ठण्डे पानी का उत्स्रवण है।

ABSTRACT. The thermal response of upper eastern Arabian Sea to the summer monsoonal forcing is documented with the aid of surface marine meteorological and upper ocean temperature (BT) time series data collected from two Indian stationary ships during Monsoon-77. Near surface mixed layer cooled over 2 deg. C and deepened non-penetratively of the order of 25-35 m with the onset and progress of monsoon. Depth-time sections of temperature constructed with daily averaged BT data revealed upwelling below mixed layer resulting a cooling of 2 deg. to 3 deg. C. A double cored maxima in the vertical thermal gradient was noticed only at the northern location while at the southern location a single cored maximum was noticed throughout. Diminishing tendency in the heat content of top most 100 m and 200 m layers was attributed to the upwelled colder waters from below.

1. Introduction

In response to the wind stress exerted by the summer monsoonal flow during May to August, the Arabian Sea exhibits surface cooling and deepening of the near surface mixed layer with varying magnitudes in its spatial domain. The sea surface temperature (SST) drops over 10 deg. C in the western, 4 deg. to 5 deg. C in the central and 2 deg. C in the eastern Arabian Sea with the onset and progress of summer monsoon, (INDEX 1977). However, the phenomenon of mixed layer deepening does not exhibit such as well defined longitudinal asymetry from west to east but it deepens maximum in the central Arabian Sea (around 10 deg. N & 60 deg. E) and with a decreasing magnitude towards the coasts around during the same period. The mixed layer even shoals off the west coast of India from May to August. The surface cooling is mostly attributed to the coastal upwelling, advection of colder waters from upwelled areas, net oceanic heat loss mostly through evaporation and entrainment of colder waters from below through erosion of thermocline etc. The deepening of the mixed layer is usually attributed to the influence of mixing caused by wind and wave action, convective turn over caused by buoyancy flux, dynamic instability/stratification below the base of the mixed layer and sinking/upwelling caused by the large scale wind stress curl.

The seasonal (summer monsoon) anticlockwise wind stress curl causes Ekman transport leading to convergence in the surface layers of central Arabian Sea which results in the thickening of the warm surface mixed layer. Conversely, the coastal oceanic belt of north Arabian Sea, experiencing cyclonic wind stress curl, manifests in the thinning of the surface layer. On a seasonal scale these broad features are well portrayed in the Atlases of Hastenrath *et al.* (1979) and Robinson *et al.* (1979). However, on a synoptic scale in the temporal damain of summer monsoon, the variability in the characteristics of the surface mixed layer and upper thermocline in the eastern Arabian Sea is not well reported in the literature. In the present study advantage is taken of the time series measurements made at two selected stationary positions in the eastern Arabian Sea during a monsoon experiment (Monsoon-77) in 1977, to document the thermal response to the summer monsoonal forcing.

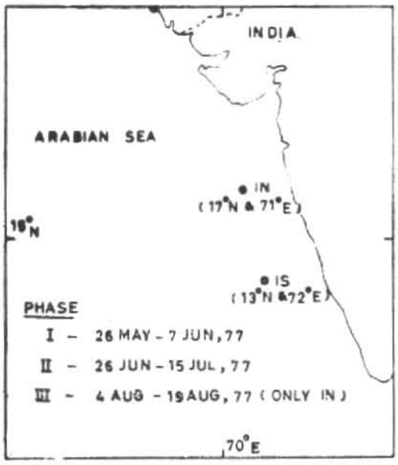

Fig. 1. Indian station locations map during Monsoon-77

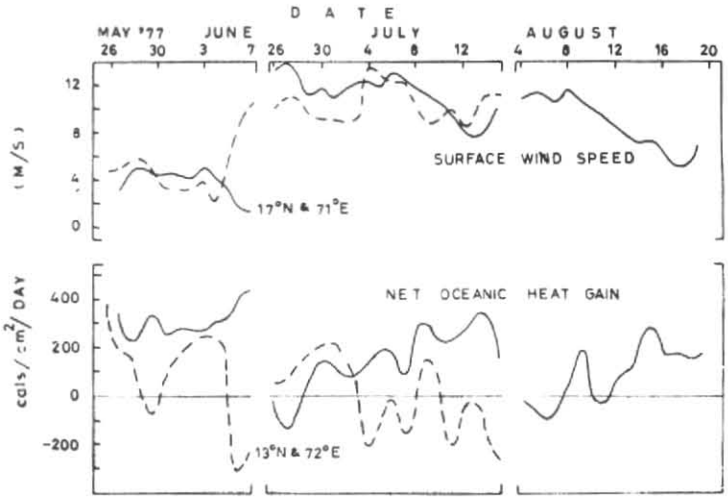

Fig. 2. Daily averages of surface wind speed and estimates of net oceanic heat gain

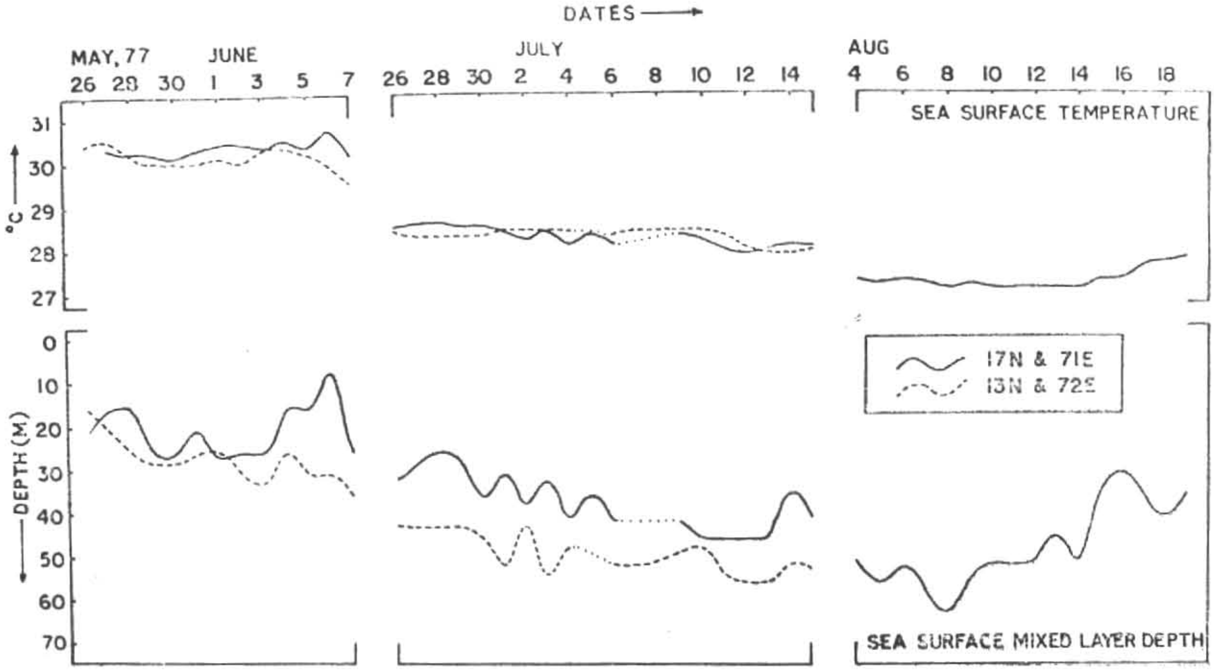

Fig. 3. Daily averages of SST and MLD

2. Data

To Indian ships occupied stationary positions in the eastern Arabian Sea during Monsoon-77 experiment. The geographic locations of the ships and the periods of deployment are shown in Fig. 1. The three observational phases considered in this study correspond to pre-monsoon (phase-I : 26 May to 7 June), established monsoon (phase-II : 26 June to 15 July) and break monsoon (phase-III : 4 Aug to 19 Aug) periods. The two ships occupied the same positions in all the phases with the exception of southern ship which occupied a stationary position in northern Bay of Bengal during phase-III. Time series measurements of routine surface marine meteorological parameters and bathythermograph data collected at three hourly intervals from these two stationary ships form the main data input to the present study. Only daily averages of the observed data are used. The stationary locations 17 deg. N & 71 deg. E and 13 deg. N & 72 deg. E are designated as IN and IS respectively in the following discussion.

3. Analysis and discussion

3.1. The distribution of observed near surface wind speed at both IN and IS is shown in the top panel of Fig. 2. During phase-I, the winds were weak with

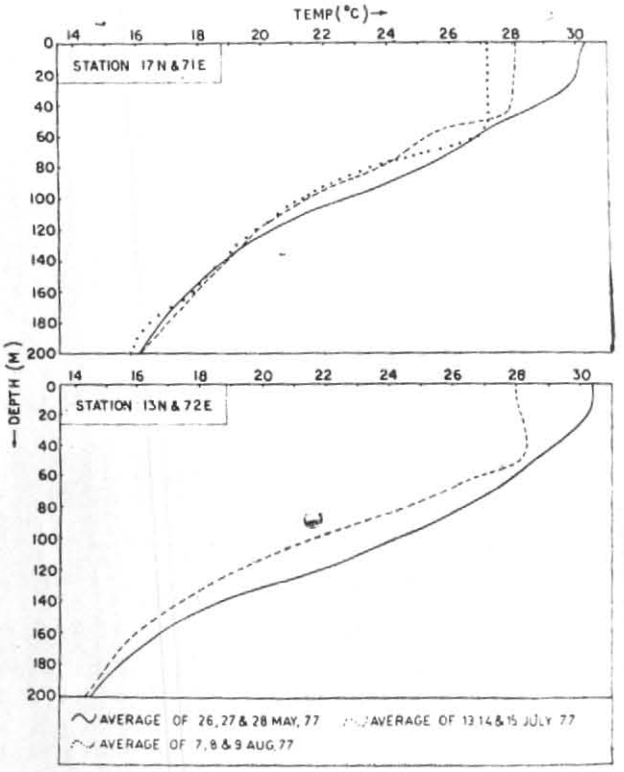

Fig. 4. Typical BT profiles of pre and post regimes of monsoonal onset and progress

an average speed of 4 m/s. Towards the end of phase-I, sudden increase in the speed can be noticed only at IS, on account of the onset of monsoon around 5 June when wind strength got early doubled during the last two days. The wind speed at both the stations was consistently more than 8 m/s during phase-II. During 4 to 7 July a peak in the speed can be attributed to the strengthened monsoonal flow in association with a depression over Bay of Bengal. At IN the wind speed progressively decreased from 8 Aug till the end of the phase-III on account of prevailing break conditions in the monsoonal flow.

Surface heat budget estimates (Fig. 2) are derived by calculating the latent, sensible heat losses and net long wave radiation following the procedure described in the Rao *et al.* (1985). As no direct measurements of solar radiation were available, the observed radiation data from the nearest coastal stations (Bombay 19.1 deg. N & 72 .9 deg. E for IN and Mangalore 12.9 deg. N & 74.9 deg. E for IS) were made use of in estimating the net heat gain by the oceanic surface. As the observed radiation depends upon the cloud cover, a comparison is made for ship and coastal station cloud data. On the whole the cloudiness at Bombay and IN matched very well while the values at IS were found to be little higher over those of Mangalore. No usage of empirical equations was made in view of non-availability of reliable equations to compute short term varying solar radiation. Hence the net gain values may have to be viewed only as the best approximations. Positive values indicate heat gain to the ocean. IN recorded a gain of 200 to 300 cal/cm^2/day before the onset of monsoon while IS exhibited two negative maxima around 30 May and 6 June respectively. The former dip at IS was associated with a well-marked trough of low pressure over Lakshadweep and off the southwest coast of India. The latter steep fall of — 300 cal/cm^2/day resulted on account of the sudden burst of the monsoon. During phase-II IN showed a progressively increasing heat gain while IS recorded heat gain only during the first eight days and mostly heat loss during the following period. The heat loss at IS can be accounted to the strengthening winds in association with the depression over head Bay of Bengal. Decreased insolation due to heavy clouding in the ITCZ might have also contributed to the heat loss. The increasing tendency of heat gain at IN might have spuriously resulted on account of over estimation of solar radiation. During phase-III oceanic heat gain was positive at IN probably on account of clear skies associated with the break conditions in the monsoonal flow.

3.2. *Variability of SST & MLD*

The variability of SST and MLD at IN and IS in the temporal domain is shown in Fig. 3. The dotted lines correspond to missing data. The SST was over 30 deg. C at both the stations before the onset of the monsoon. A mild heating tendency was seen during the first week of June only at IN mostly due to clear skies. IS occupying a southern latitude experienced onset of the monsoon around 5 June lowering SST from 3 June. When the ships occupied the same respective stationary positions on 26 June, *i.e.,* after the complete onset of summer monsoon, SST dropped by about 1 deg. C at IS and 1.5 deg. C at IN, over a period of 3 weeks. This was the period when the cooling rates were highest associated with the onset of the monsoon. During the following three weeks (*i.e.,* during phase-II) the SST further lowered at both the stations but with a lesser magnitude of 0.5 deg. C due to the prevailing near saturated atmospheric conditions. At IN, SST showed further cooling around 1 deg. C from 15 July to 14 Aug. The trend was, however, reversed from 14 Aug, leading to an increase in SST due to increased insolation under break monsoon conditions.

The variability of near surface Mixed Layer Depth (MLD) at both the stations is shown in the bottom panel of Fig. 3. The MLD is demarcated as the depth where SST *minus* 0.2 deg. C has occurred in the daily averaged BT profiles. Before the onset of monsoon, MLD was around 20 m and with the progress of monsoon by 15 July the layer deepened to 40 m and 55 m respectively at IN and IS. At IN, the deepest MLD was 60 m around 8 Aug followed by shoaling. This shoaling was resulted on account of reduction in the wind speed and accumulation of heat in the surface layers associated with break monsoon conditions. During phase-I the deepening tendency in MLD was evident only at IS on account of the local atmospheric disturbances during the monsoon onset process. During phase-II, the deeper MLD at IS over that of IN may be viewed in terms of greater heat loss from the ocean compared to that of IN. The embedded oscillations of 2 to 3 day period might have resulted due to the inertial oscillations caused by monsoonal wind stress.

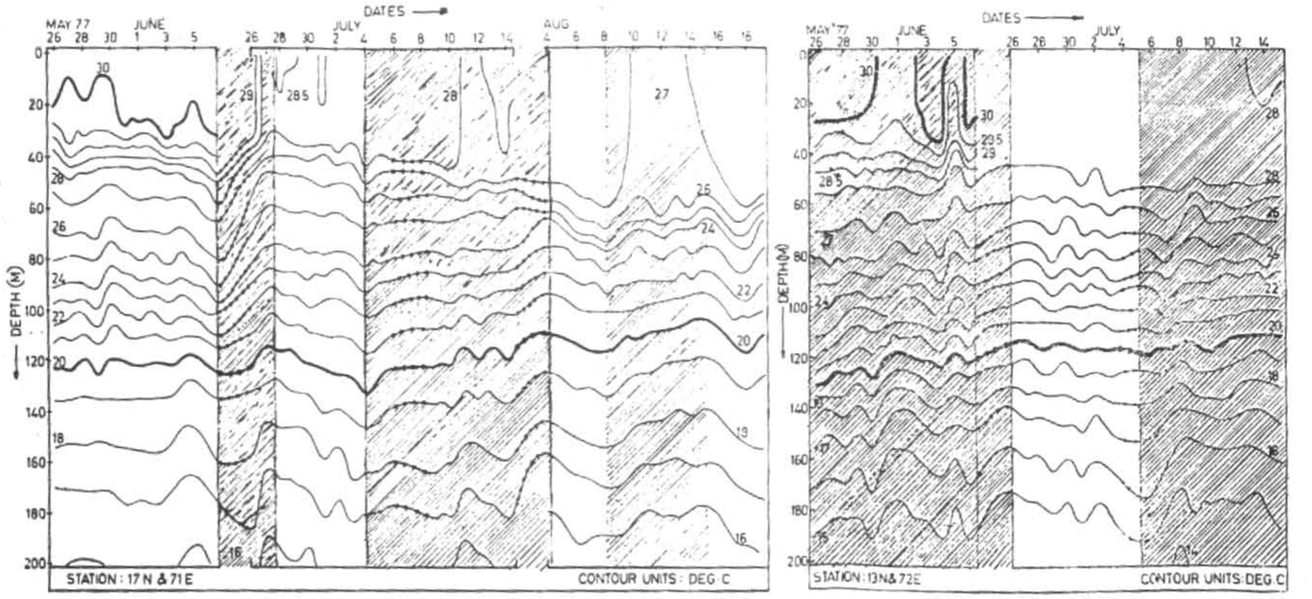

Fig. 5. Depth-time sections of temperature

Three-day averages of vertical BT profiles at both the stations for different regimes of the monsoon are shown in Fig. 4. Three-day averaging was done to minimise the influence of inertial oscillations. The changes brought about with the onset and progress of monsoon were prominent in the surface mixed layer than in the thermocline. Deepening of the mixed layer was non-penetrative on account of upwelling in the thermocline, unlike the corresponding pattern in the central Arabian Sea where sinking was noticed (Rao 1984). Summer type pre-monsoonal heating was noticed only at IN in the surface layers due to clear skies before the onset of monsoon. In phase-II around 14 July a mild positive gradient within the mixed layer at IS might be viewed as a manifestation in terms of severe surface heat loss as shown in Fig. 2. At 100 m depth, over a 50-day period from 26 May, the cooling caused below mixed layer due to upwelling was almost double at IS compared to that of IN, with a approximate values of 2.5 deg. C and 1.25 deg. C respectively. With the further progress of monsoon for another 25 days from 14 July, the mixed layer at IN further deepened penetratively mostly due to surface heat losses in the absence of significant upward or downward motion below during this period. No data was, however, available for IS to estimate further changes in the mixed layer with the progress of the season.

3.3. *Evolution of temperature in the 200 m deep layer*

The temporal evolution of temperature in the top 200 m layer at both the stations is shown in Fig. 5. Daily averages of BT data were used to contour the isotherms. Contours were drawn at 1 deg. C interval for temperature lesser than 28 deg. C and at 0.5 deg. C interval for temperature greater than 28 deg. C. Lines with dots correspond to missing periods. Progressive deepening of the mixed layer was quite evident at both IN and IS. Before the onset of monsoon warm surface layer of 30 deg. C extended from surface to 20-30 m depth during phase-I at both the stations. Following the onset and progress of monsoon (by 15 July 1977) the layer cooled by 2 deg. C and the mixed layer depths got doubled from 20 m to 40-50 m range.

TABLE 1

Nature of isotherm slopes and weather

Period	Days	IN	IS	Weather in eastern Arabian Sea from satellite pictures
26 May-7 Jun	13	descending	ascending	cloudy
7 Jun-26 Jun	19	ascending	ascending	cloudy
26 Jun-4 Jul	8	descending	descending	fair
4 Jul-15 Jul	11	ascending	ascending	cloudy
15 Jul-4 Aug	20	ascending	—	
4 Aug-8 Aug	4	descending	—	
8 Aug-15 Aug	7	ascending	—	
15 Aug-19 Aug	4	descending	—	fair

On the whole, isotherms with values lower than 26 deg. C in the upper thermocline showed an ascending trend at both the locations. However, embedded alternate ascending and descending regimes of unequal and irregular periods can also be noticed at both the locations. Only before the onset of monsoon, *i.e.*, during phase-I the trends at IN and IS were of opposite nature. This feature may be attributed to the premonsoonal disturbed weather and early onset of monsoonal conditions at IS. Coherence in the nature of

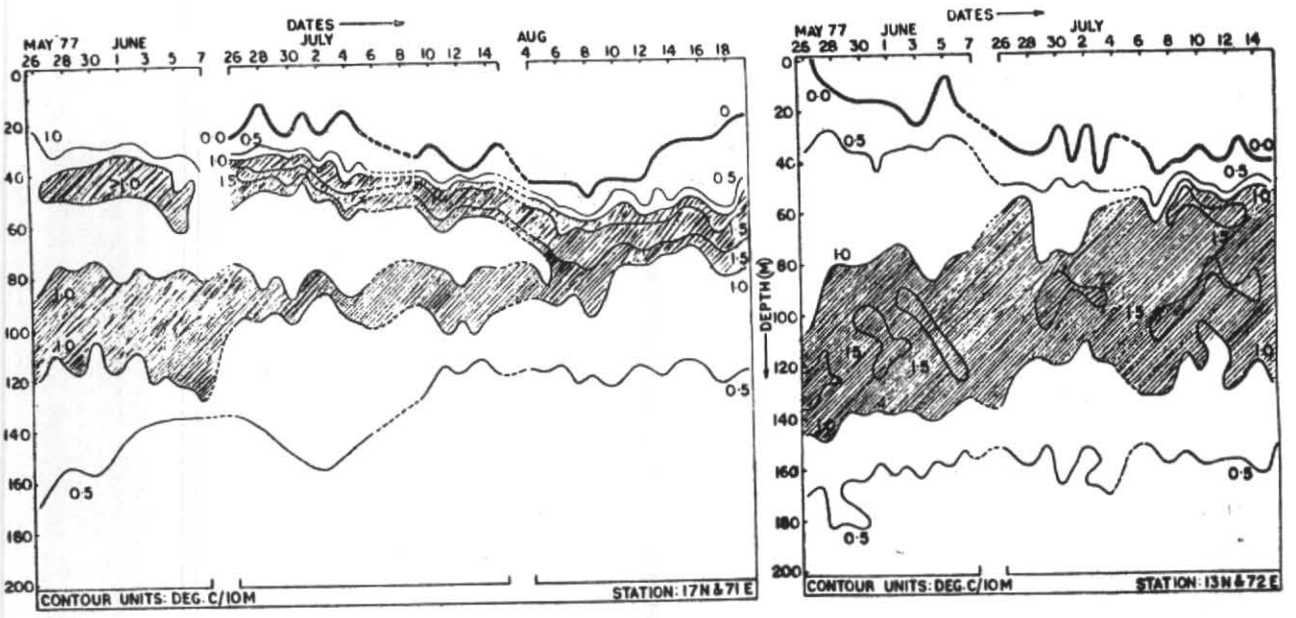

Fig. 6. Depth-time sections of vertical thermal gradient

slopes of isotherms between the two stations during the intervening periods of phase-I and phase-II and during phase-II was good. Since the periods shown in the Table 1 appear to be irregular, the possibility of interactive wave propagation in the thermocline cannot be ruled out. Alternately, the manifestation of bands of ascending and descending isotherms may be attributed to the vergence patterns caused by Ekman transport caused by the forcing of the surface wind stress curl. Data are not adequate to quantify either of the phenomenon proposed. There exists a good correspondence between periods of disturbed/fair weather (indicated by satellite cloud cover) and ascent/descent of isotherms (Table 1). This may imply the rapidity of the upper oceanic dynamic response to the prevailing wind stress curl even on a synoptic scale. The short period oscillations superimposed on the isotherms be viewed as internal waves in the frequency domain of inertial range. Coherence in the vertical for these short period oscillations is consistently seen throughout. The amplitude of these oscillations is higher below 120 m compared to the corresponding ones above 120 m on account of differences in the vertical stratification. Though the temperature of surface waters at both the stations was of equal magnitude, the waters of 200 m depth were relatively warmer at IN compared to IS.

The thermal gradient for every 10 m interval in the vertical is evaluated and its temporal evolution is contoured at 0.5 deg. C/10 m interval as shown in Fig. 6. The patterns were contrasting at IN and IS. Doubled cored maxima of 1.0 deg./10 m were noticed at IN whereas only a broad single cored maximum was seen at IS. At IN there was a seasonal tendency for the upper cored maximum to penetrate downward (from about 40 m to 60 m) upto about 10 Aug and the second maximum near 100 m to propagate upward to about 70 m during the same period. For the IS the single maximum near 130 m at the beginning of the period showed an upward tendency and reached about 90-100 m at the end of the season. The gradient situated just below mixed layer was stronger at IS compared to the corresponding one at IN. Rao (1984) reported a similar double cored maximum in the central Arabian Sea during Monsoon-77 experiment. He hypothesised that the top strong gradient-layer was resulted due to mixed layer deepening while the bottom strong gradient-layer was the remnant of the preceding year's descended below mixed layer gradient. At IN, with the progress of the monsoon both these two strong gradient layers merged on account of mixed layer deepening from above and rising of isotherms from below. At IS the single cored maxima showed a steady progressive rising tendency throughout. Pockets of 1.5 deg. C/10 m gradient embedded in this layer appeared in a transient manner.

Temporal changes in the heating/cooling regimes brought about in the vertical 200 m water column with respect to initial day, *i.e.*, 26 May were contoured for the deviations arrived by successively differencing the BT profiles with respect to the initial day (Fig. 7). Positive values indicate cooling with respect to 26 May. Mixed layer cooling of 3 deg. C and 2 deg.C was clearly seen at IN and IS respectively. The cooling was rapid at IS as 2 deg. C contour as seen throughout phase-II while the same was seen at IN only towards the end of the phase-II. In the upper thermocline the cooling with unequal magnitudes occured due to the uplift of the isotherms. By end of phase-II greater cooling occurred at IS compared to the corresponding cooling of < 2 deg. C at IN. Only during phase-III cooling > 2 deg. C has occurred at IN. Further the depths of the cores of maximum cooling in the thermocline were situated around 90 m and 110 m at IN and IS respectively.

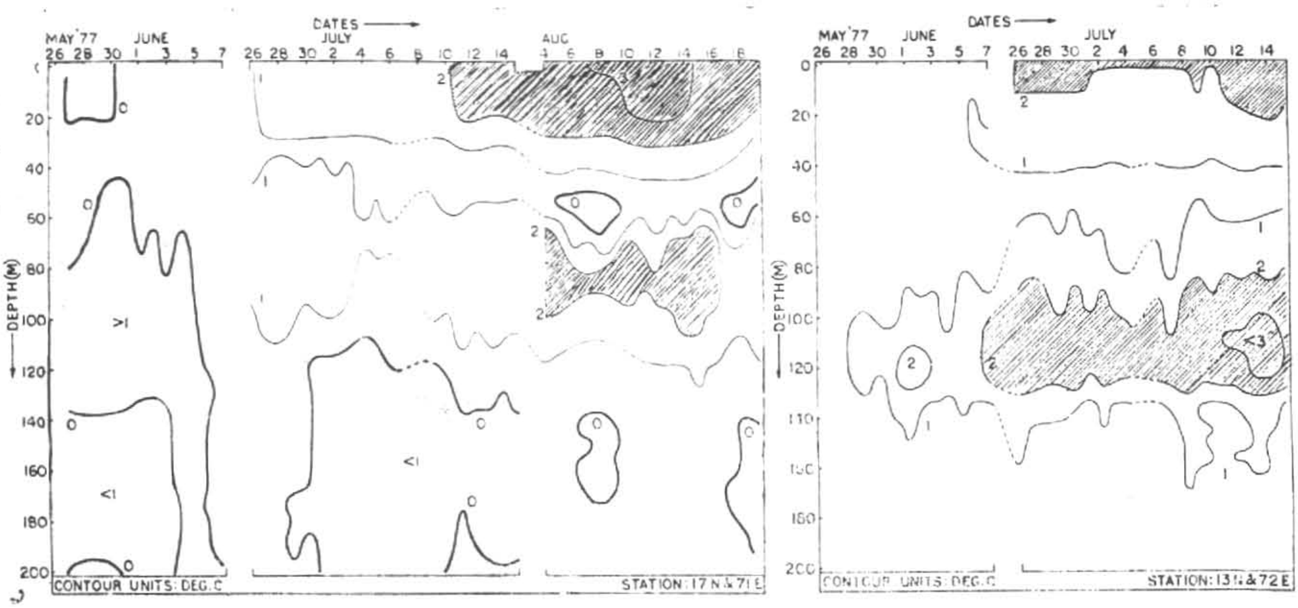

Fig. 7. Depth-time sections of heating/cooling regimes

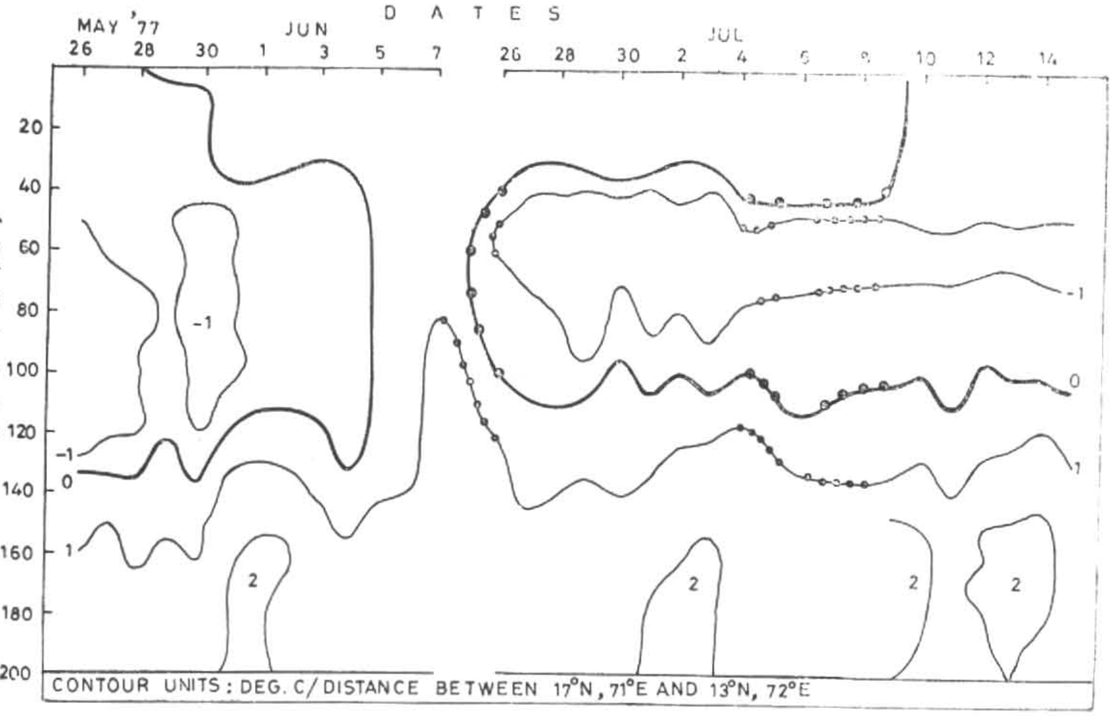

Fig. 8. Depth-time section of horizontal temperature difference

The variability in the horizontal temperature difference between IN and IS in the top 200 m water column in the temporal domain is shown in Fig. 8. Positive value inicates IN warmer than IS. Two distinct regimes in the horizontal thermal gradient in the meridional direction can be noticed separated around 130 m and 100 m depth during phases-I and II respectively. At IS, the upper layer was warmer than that of IN while the reverse prevailed in the bottom layer. The magnitude of the horizontal gradient in the top layer was weaker than that of bottom one. The core of — 1 deg. C contour shifted upward from phase-I to phase-II with a reduction in the vertical extent due to mixed layer deepening from above and upwelling from below. The meridional temperature gradient was generally negative (— 1 deg. C) in the

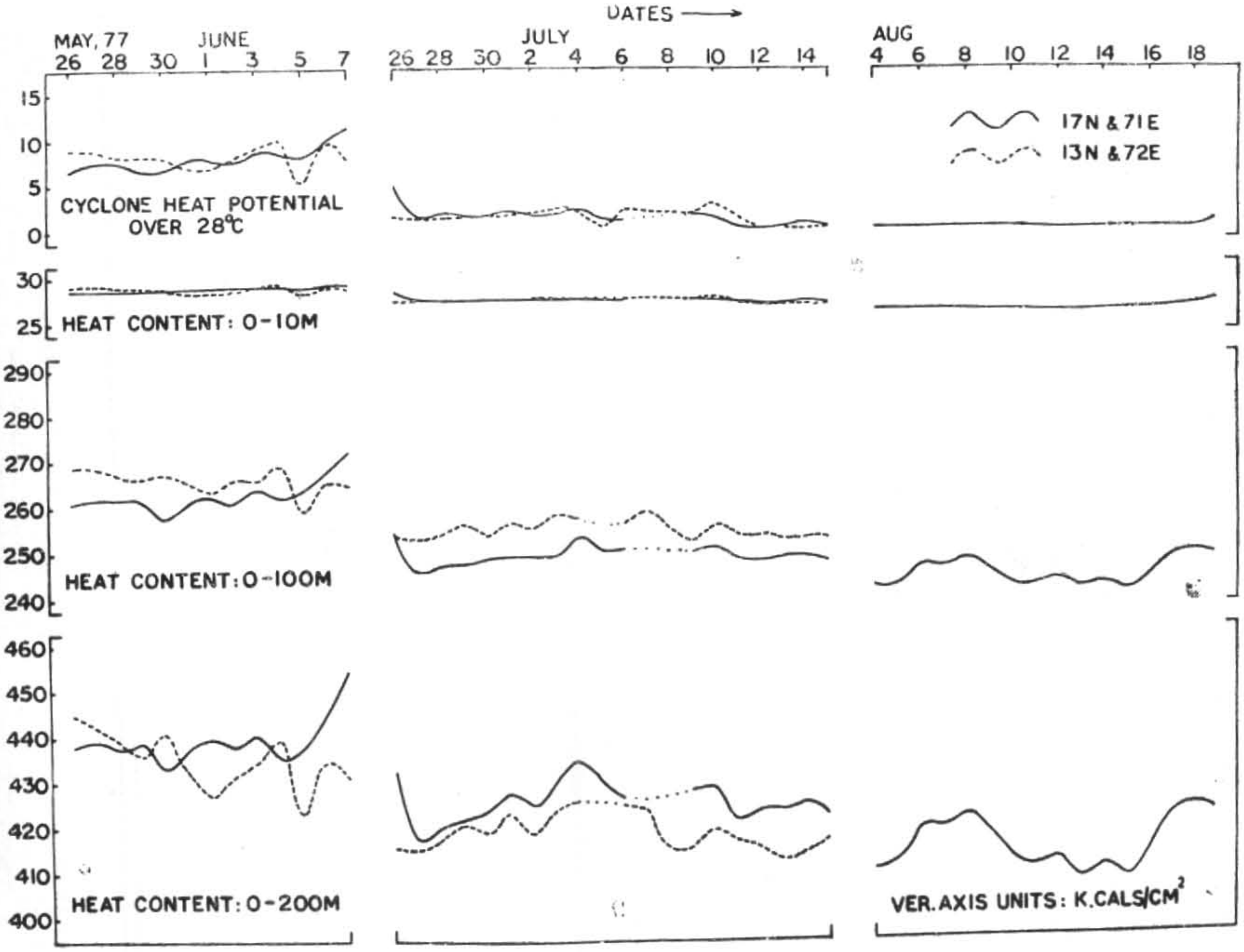

Fig. 9. Daily averages of heat potential and heat contents of topmost 10 m, 100 m and 200 m layers

layer 60-100 m and positive in the layer 180-200 m (2 deg. C). The two layers were separated by about 120 m in depth. The bottom layer gradient can induce thermal circulation in a direction opposite to the wind driven surface circulation.

3.4. *Variation of Cyclone Heat Potential* (*CHP*)

The variation of CHP defined as the heat content in the upper layer with respect of 28 deg. C and of the Heat Content (HC) of the top 10 m, 100 m and 200 m slabs at IN and IS is shown in Fig. 9.

$$\mathrm{CHP} = \rho c_p \int_0^{D_{28}} (t - 28^\circ\mathrm{C})\, dz$$

$$\mathrm{HC} = \rho c_p \int_0^{D} t\, dz$$

where, ρ = density of the sea water
c_p = specific heat at constant pressure
t = temperature at a particular depth
dz = depth increment
D_{28} = depth of 28° isotherm
D = (10 m, 100 m and 200 m)

The average CHP value at both IN and IS during phase-I was around 8 K cal/cm², which can sustain an intense tropical synoptic disturbance for about a week with an assumed evaporation of 2 cm/day. During the onset of the monsoon, *i.e.,* 7 June to 26 June (20 days) the ocean lost around 7 K cal/cm² at an average of 350 cal/cm²/day. During phase-III the value of CHP was zero at IN. The HC of the top 10 m layer showed progressive decrease throughout on account of surface cooling. The variations in the HC of top 100 m and 200 m layers were governed by vertical advective processes in addition to net surface heat loss. In general the HC values showed a declining tendency from beginning of phase-I to end of phase-II/III at IS/IN on account of uplift of the isotherms in the upper thermocline. The increasing/decreasing tendency during any phase was in conformity with the descending/ascending tendency of the isotherms. The HC values of 100 m layer at IS were higher over the corresponding values of IN and *vice-versa* for 200 m layer, during phases I and II. This reversal was due to the prevalence of warmer waters above 100 m depth at IS over IN and of colder waters below 100 m depth at IS over IN (Fig. 8). On 15 July 77, the HC values in the eastern Arabian Sea were lower by 15 K cal/cm² and 15 K cal/cm² in the top 100 m and 200 m layers respectively over the corresponding ones in the central Arabian Sea (Rao 1984).

TABLE 2

S. No.	Parameter	17° N & 71°E			13° N & 72° E	
		26-28 May' 77	13-15 Jul '77	7-9* Aug '77	26-28 May '77	13-15 Jul '77
1	Sea surface temperature (°C)	30.3	28.1	27.2	30.4	27.9
2	Mixed layer depth (m)	18	41	59	18	54
3	Depth of 20° C isotherm (m)	123	118	117	130	112
4	Heat potential over 28° C (K cal/cm²)	7.3	0.2	0.0	8.8	0.0
5	Heat content of 10 m layer (K cal/cm²)	28.8	26.8	25.9	29.0	26.7
6	Heat content of 100 m layer (K cal/cm²)	261.7	247.6	246.0	268.2	252.3
7	Heat content of 200 m layer	438.3	423.4	419.7	442.0	414.3

*7-9 Aug '77 was chosen as a reference period in view of the observed minimum SST and maximum MLD at IN instead of 17-19 Aug '77.

These spatial differences may be attributed to the vertical advection of waters of opposite nature (sinking in the central Arabian Sea and upwelling in the eastern Arabian Sea) in the upper thermocline.

4. Conclusions

Table 2 shows various typical thermal parameters at IN and IS in the eastern Arabian Sea for the pre- and post-onset regimes of the monsoon. Based on this and what is discussed in the preceding sections, the following conclusions can be drawn :

(1) In the eastern Arabian Sea the surface temperature cooled over 2 deg. C and near-surface layer deepened nonpenetratively by about 25-35 m with the onset and progress of monsoon over a period of seven weeks.

(2) In the thermocline (waters cooler than 26 deg. C) a broad trend of upwelling embedded with unequal regimes of alternate ascending and descending motion was noticed.

(3) A double cored maxima in the vertical thermal gradient (which subsequently merged into a single core) was seen only at IN while at IS a single cored maximum was seen throughout.

(4) Cooling below mixed layer on account of upwelling in the thermocline was higher at IS compared to IN.

(5) Waters were relatively warmer at IS over IN in the upper half of 200 m water column and *vice versa* in the lower half.

(6) Eastern Arabian Sea supplied 7 K cal/cm² to the atmosphere during the onset of the monsoon over a period of 20 days implying an average net heat loss of 350 cal/cm²/day from the surface.

(7) Diminishing tendency in the heat content of the topmost 100 m and 200 m layers was attributed to the upwelled colder waters from below.

Acknowledgements

The author wishes to record his gratitude to Dr. D. Srinivasan for his encouragement and for providing the facilities to carry out this investigation. The author is grateful to his colleagues who collected and processed the BT data and to scientists of India Meteorological Department who collected marine meteorological data during Monsoon-77 experiment. Thanks are due to Director General of Meteorology, India Meteorological Department for making available the solar radiation data observed at Bombay and Mangalore. The author wishes to thank the referee for his valuable comments towards the improvement of the paper.

References

Hastenrath, S. and Lamb, P.J., 1979, *Climatic Atlas of the Indian Ocean* (Parts I & II), University of Wisconsin Press, Madison, U.S.A.

INDEX, 1977, An Oceanographic contribution to International progress in the monsoon region of the Indian Ocean. Report No. ID 075-01571, National Science Foundation, Washington D.C.

Rao, R.R., Ramam, K.V.S., Rao, D.S. and Joseph, M.X., 1985, Surface heat budget estimates at selected areas of north Indian Ocean during Monsoon-77, *Mausam*, **36**, 1, pp. 21-32.

Rao, R.R., 1984, On the thermal response of upper central Arabian Sea to the summer monsoonal forcing during Monsoon-77, communicated to *Mausam*.

Robinson, M.K., Bauer, R.A. and Schroeder, E.H., 1979, *Atlas of North Atlantic—Indian Ocean*. Monthly Mean Temperatures and Mean Salinities of the Surface layer, Naval Oceanographic Office Reference Publication 18, Department of the Navy, Washington, D.C. 20373.