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

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सार — "मानसून-77" के दौरान चार स्थिर सोवियत रूसी समुद्री जहाजों के बने बहुभुज द्वारा एकत्रित पृष्ठीय पवन तथा उच्च महासागरीय ताप आँकड़ा समुच्चयों की सहायता से मानसूनी आवेश पर उच्च मध्यवर्ती अरब सागर की तापीय अनुक्रिया का प्रलेखन किया गया है। 7 जून 1977 से लेकर पांच सप्ताह की अवधि में ग्रीष्मकालीन मानसून के आगमन तथा बहाव के कारण समीपवर्ती पृष्ठीय मिश्रित तल, 2° से० के लगभग ठण्डा हुआ और लगभग पचास मीटर गहरा चला गया। दैनिक औसत बी.टी. आँकड़ों द्वारा निर्मित ताप के गहराई-समय पार्श्विका उच्च थर्मोक्लाइन में नीचे धंसने की घटना की उपस्थिति प्रदर्शित करते हैं जो कि मात्रा के हिसाब से जून से जुलाई तक घटते जाते हैं। मिश्रित तल के गहरे होने और नीचे धंसने के दौरान ऊष्मा का नीचे की ओर बहाव के फलस्वरूप मानसून के बहाव के प्रभाव में मिश्रित तल के नीचे 2° से 3° से० तक गर्म होते पाया गया है। दो क्रोड़ीय ऊर्ध्वाधर तापीय प्रवणता जून से जुलाई तक एक क्रोड़ीय में रूपान्तरित हो गई। सबसे ऊपरी 100 मी० तथा 200 मीटर पट्टियों में ऊष्मा धारिता इन प्रेक्षित समय परिमापों पर ऊर्ध्वाधर अभिवहनीय संक्रियाओं द्वारा अधिकांशतः नियंत्रित रहती है।

ABSTRACT. The thermal response of the upper central Arabian Sea to the summer monsoonal forcing is documented with the aid of surface wind and upper ocean temperature data sets collected from a four-ship USSR stationary polygon during Monsoon-77. The near surface mixed layer cooled by about 2°C and deepened by about 50 m with the onset and sway of the summer monsoon over a five-week period from 7 June' 77. Depth-time sections of temperature, constructed with daily averaged BT data revealed the presence of downwelling phenomenon in the upper thermocline with a decreasing magnitude from June to July. Downward transport of heat in the wake of mixed layer deepening and downwelling below, has resulted in a warming of 2° to 3°C below the mixed layer under the sway of the monsoon. A double cored maxima in the vertical thermal gradient merged into a single core from June to July. Heat content of the uppermost 100 m and 200 m slabs is mostly governed by vertical advective processes on these observed time scales.

1. Introduction

The summer monsoon exerts strong thermal and mechanical forcing on the Arabian Sea surface. This redistributes the heat that is accumulated in the upper layers during pre-monsoon summer months. With the available historical bathythermograph (BT) data, Colborn (1975) documented the seasonal scale variability of the thermal structure observed in the Indian Ocean. His results indicate that the monsoon controlled northern Indian Ocean exhibits thermal structure variations in the upper 500 m that are unique to these latitudes in the oceans of the world. Sastry and D'sousa (1970), Ramesh Babu *et al.* (1976), Rao *et al.* (1976) and Ramam *et al.* (1979), have analysed the observed thermal structure in the Arabian Sea with the aid of variety of data sets. However, there has not been an adequate understanding of the time dependent thermal response of the Arabian Sea to the variable monsoonal forcing. In the present exercise, an attempt is made to document the thermal response of the upper 200 m water column to the monsoonal forcing over the central Arabian Sea on a synoptic scale.

2. Data

Four USSR ships occupied stationary positions forming a polygon in the central Arabian Sea during the Monsoon-77 experiment. The locations of the ships and the periods of deployment are shown in Fig. 1. Time series of BT data colleced at three hourly intervals and surface wind data collected at one hourly intervals from 7 June to 16 July 1977, with an intermediate break for 10 days from 21 June, form the data input to the present study. Daily averages of the observed sub-surface temperature are used in this study. The ships at the northern, eastern, southern and western corners of the stationary polygon are designated as UN, UE, US and UW respectively, in the following discussion.

3. Results and discussion

The observed near surface mixed layer deepening and the associated cooling of sea surface temperature (SST) with the progress of the monsoon at all the four stations is shown in Fig. 2. The mixed layer depth (MLD) is taken as the depth in the daily averaged BT

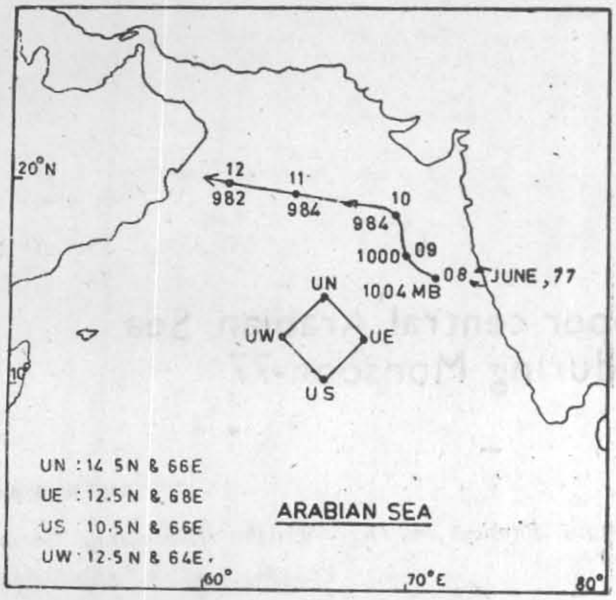

Fig. 1. Station location and track of monsoonal onset vortex

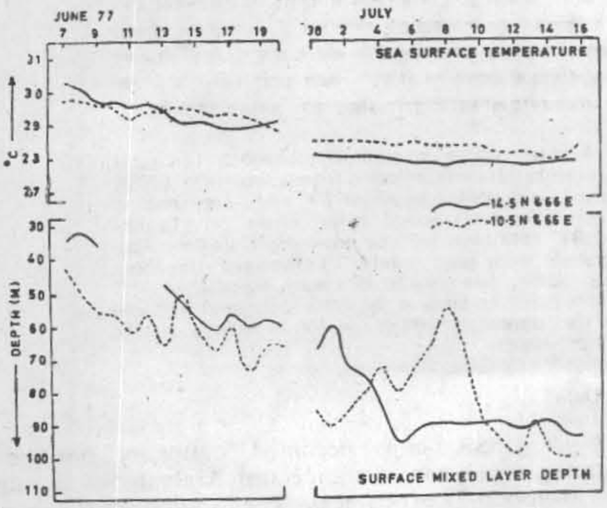

Fig. 2. Daily variation of sea surface temperature and mixed layer depth

TABLE 1

Station	SST (°C)			MLD (m)		
	(1) 7 Jun '77	(2) 15 Jul '77	Diff-erence	(3) 7 Jun '77	(4) 15 Jul '77	Diff-erence
UN (14.5N & 66E)	30.3	27.8	2.5	34	95	—62
UE (12.5N & 68E)	29.9	28.0	1.9	36	88	—52
US (10.5N & 66E)	29.7	27.9	1.8	43	102	—59
UW (12.5N & 64E)	29.7	27.4	2.3	48	98	—50
UN-US	0.6	—0.1	0.7	—9	—6	—3
UE-UW	0.2	0.6	—0.4	—12	—10	—2

profile where the temperature is equal to the SST *minus* 0. 2° C. The trends observed at all the four locations are similar with the only exception for MLD at US during the first week of July. Differences in the magnitudes of SST and MLD are apparent in both the zonal and meridional directions. This is over a distance of around 450 km and indicates a mesoscale response of the sea to the monsoonal forcing. The surface thermal gradient in the zonal direction reversed from June to July and increased in magnitude. However, the surface thermal gradients are only well established during July. Short period fluctuations with period of 2 to 3 days are apparent in the plots of MLD. Detailed analysis on this high frequency variability in the observed thermal structure will be reported elsewhere.

Table 1 summarizes the observed changes in SST and MLD. On 7 June, UN showed the highest SST of 30.3°C while both US and UW recorded 29.7°C. On this day, the horizontal surface thermal gradient was strongest in the meridional direction probably on account of greater solar heating towards north over the Arabian Sea in the absence of cloudiness prior to the onset of the monsoon. The near surface mixed layer was relatively deeper at both UW and US. On 7 June the shoaling tendency of MLD can be clearly noticed downstream the monsoon flow from southwest to northeast in the spatial domain of the polygon. With the onset of the monsoon and its sway over a period of five weeks, the response of the upper ocean is distinctly noticed in both SST and MLD. Highest cooling of 2.5°C was associated with the largest deepening of 62 m at UN. Although the cooling at UW was comparable in magnitude with that of UN, the mixed layer deepening was less. This probably indicates spatial variation either in the surface meteorological forcing and/or in the stratification below the mixed layer. During July the meridional and zonal gradients of SST became comparable. These cooling and deepening trends stand out above the short periods fluctuations. Rao *et al.* (1981) attempted to explain the observed deepening in terms of net heat loss at the sea surface, increased current shear across the base of the mixed layer and downwelling on account of the negative curl of the surface wind stress favouring convergence within the layer.

The averaged vertical profiles of temperature observed in the initial and final three-day periods of the observational programme are plotted for the stations in Fig. 3. The deepening and the cooling of the near

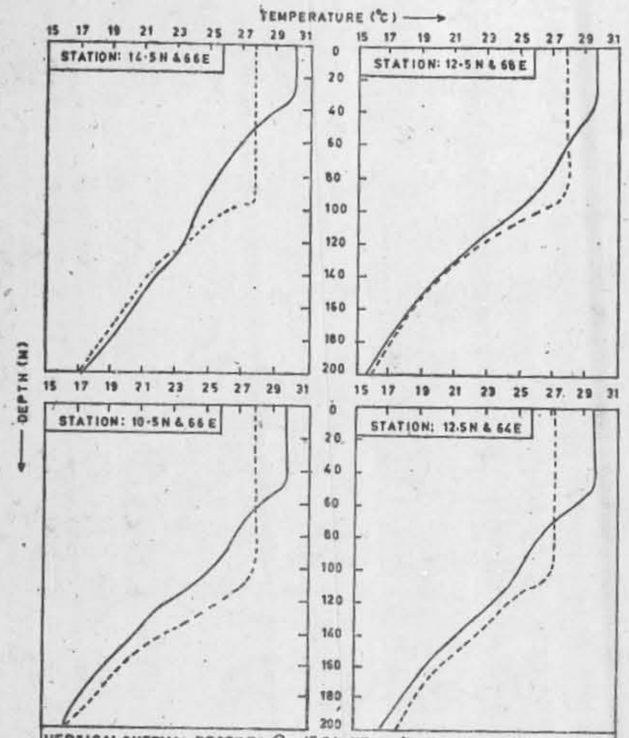

Fig. 3. Vertical temperature profiles of beginning and ending of three-day periods

surface mixed layer over five weeks with different magnitudes at all four locations is clearly seen. Heating in the upper thermocline was probably associated with the turbulent downward transport of heat as the warm surface layer deepened and downwelling within the thermocline. Heating below mixed layer was maximum at US and minimum at UE. The downward displacement of the thermocline was prominent only at UW and US. A mild uplifting occurred at UN. However, no significant changes in the slopes of the curves in the thermocline region occurred, perhaps, with the exception of US.

Daily averages of BT data sampled at every 5 m interval from surface to 200 m depth are used to draw temperature *versus* depth plots to show the evolution of thermal structure. The contours are spaced with 1°C interval for isotherms lower than 28°C and with 0.5°C interval for istotherms greater than 28 °C. Contours with superposed dots indicate the period without data. Fig. 4 (a) shows the thermal regime of the upper 200 m water column from 7 June to 16 July 1977 at UN and US. The progressive cooling in the near surface mixed layer is quite evident at both UN and US as evidenced by the gradual upward protrusion of isotherms from below, followed by their disappearance. The rate of cooling is higher during June than in July at both the stations. A severe cyclonic storm (known as the onset vortex) whose track along with the estimated daily central pressures (*derived from the* published *Indian Daily Weather Reports*) shown in Fig. 1, probably significantly affected the thermal structure at UN. During the stormy period, *i.e.*, 9 to 11 June, no BT data could be collected. During this period the isotherms between the base of the mixed layer and approximately 120 m depth deepened. The mixed layer at UN during this period also deepened significantly probably because of enhanced turbulent mixing caused by strong wind and wave action and buoyancy flux from the ocean. This depression of the isotherms is more conspicuous at UN as compared to US probably because the former location is closer to the storm. These results may indicate that only the upper 120 m of the water column or so is subjected to the influence of a severe cyclonic storm situated at a distance of about 400 to 500 km. After the passage of the storm and under the influence of the monsoonal forcing, the deepening of the isotherms is confined to the topmost 100 m at UN until 5 July and above 200 m at US until 1 July implying that the sinking continued to penetrate to deeper depths at US. After 5 July the depths of the isotherms changed little below 100 m at UN and below 150 m at US. At UN weak upwelling started after 7 July below120 m. This led to greater stratification in the upper thermocline around mid-July.

Fig. 4 (b) depicts the corresponding thermal structure at UW and UE. In addition to surface layer cooling and deepening at both the locations, a prominent bulging in the isotherms of the upper thermocline at UW is distinctly seen from 11 to 20 June. This feature is only seen at UW and it is also present in the salinity field, indicating the occurrence of strong mixing in the vertical on account of increased vertical shear in the horizontal currents. Rao *et al.* (1981) have reported the increase in the current shear between 50 m and 100 m depths from 13 to 20 June at this location. Woods and Wiley (1972) have attributed billow or shear turbulence to the observed patchy turbulent regions appearing in the seasonal thermocline of high internal wave activity. During July descent of the isotherms is observed throughout the upper thermocline at UW while at UE, the same process is replaced by ascent from 5 July throughout the upper thermocline. This type of ascent of isotherms is noticed from the beginning of June at the Indian station (13°N and 72°E) located in the eastern Arabian Sea (Rao 1986).

Yoshida and Mao (1957) have related the vertical velocity just below the mixed layer with the large scale surface wind stress curl. Fig. 5 shows the daily march of the curl of the surface wind stress over the polygon area derived from the wind vectors observed at the corners. The drag coefficient used in the calculation of wind stress is estimated following Kondo (1975). The curl of the stress was primarily anticyclonic during most of this period. This favours convergence of waters in the Ekman boundary layer and manifests sinking just below the mixed layer. Only during the first five days the curl was cyclonic because of the presence of the onset vortex system. After the system moved away from the central Arabian Sea area, the sign of the curl became negative. This switch over in the sign of the curl might have contributed to rapid deepening of the mixed layer during June. During July, the magnitude of the curl weakened steadily which may be responsible for the observed near steadiness in the mixed layer depth and in the depths of the deeper isotherms as shown in Figs. 4(a) and 4(b).

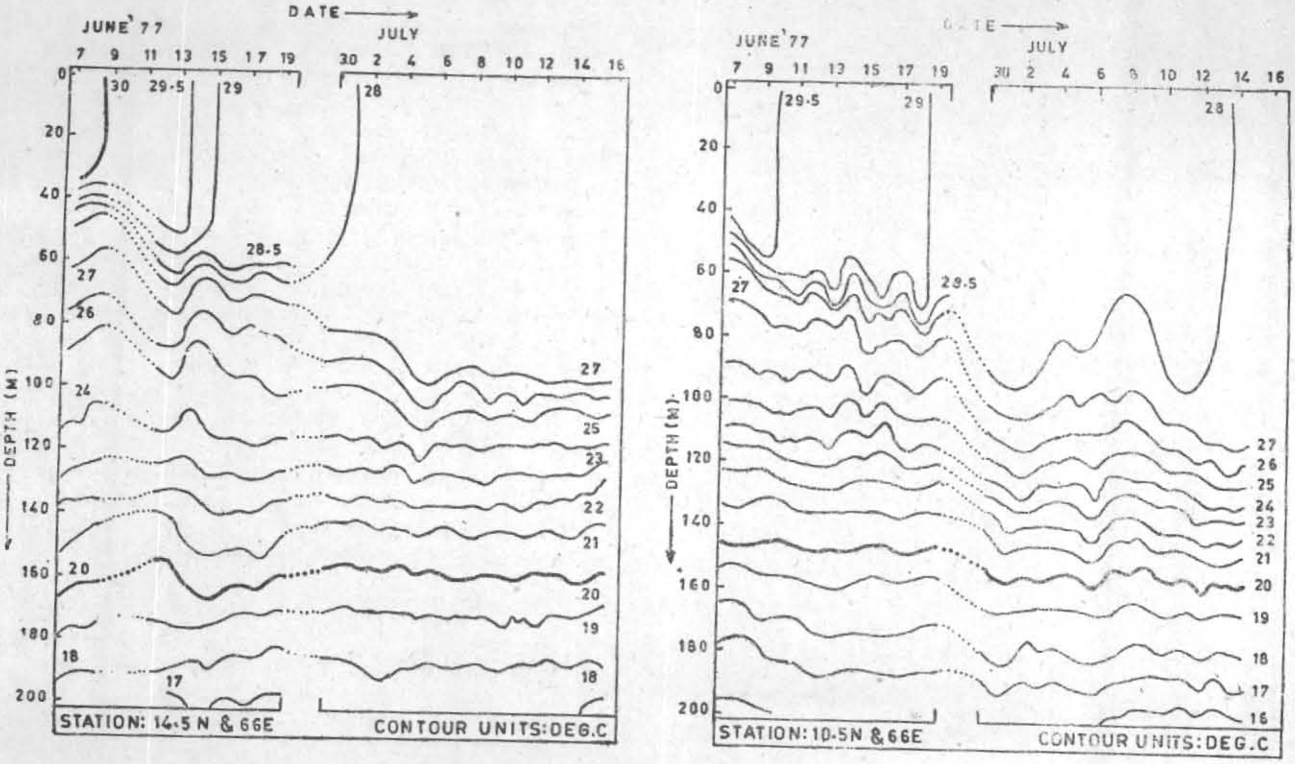

Fig. 4(a). Depth-time variation in the daily averaged temperature at stations UN and US

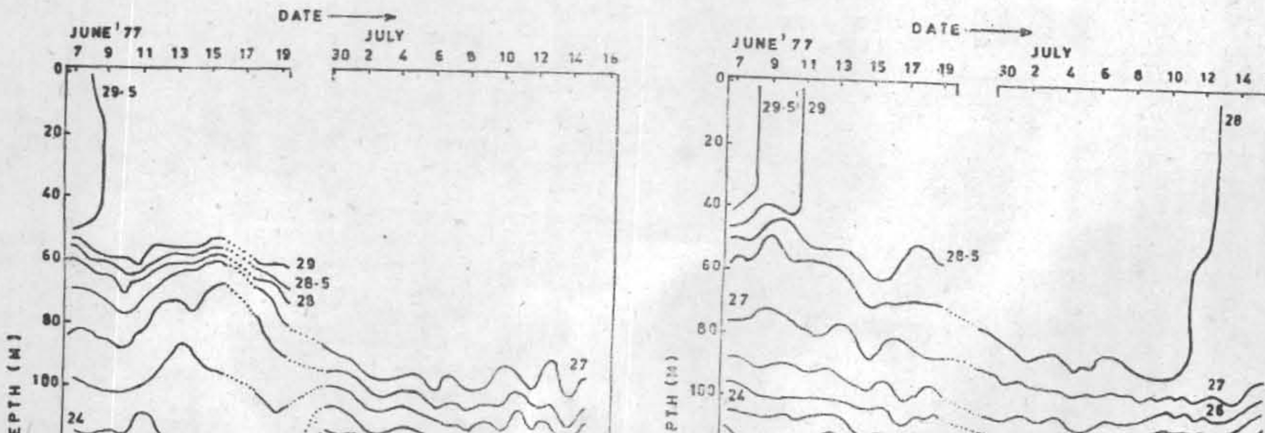

Fig. 4(b). Depth-time variation in the daily averaged temperature at stations UE and UW

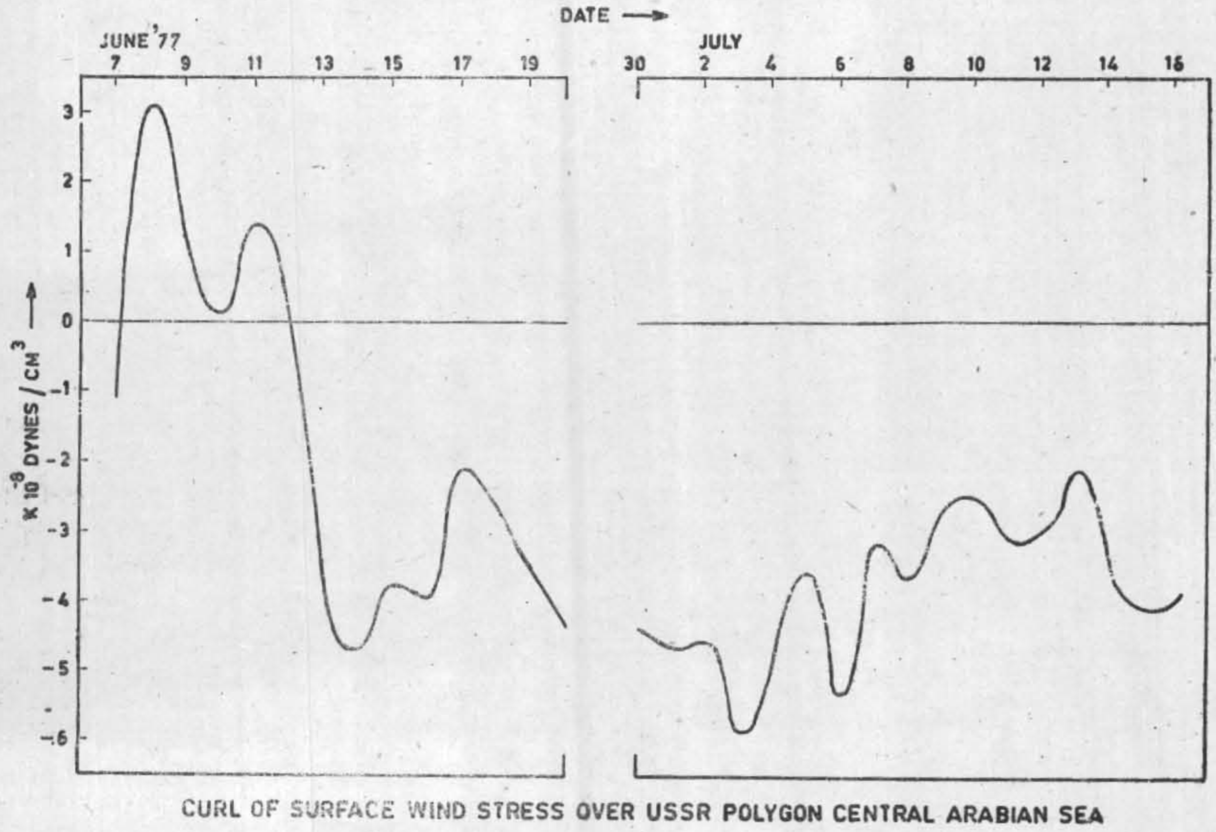

Fig. 5. Daily variation of curl of the surface wind stress over the polygon area

The changes in the vertical temperature gradient at all four stations are depicted in Fig. 6. A common feature observed at three locations during June is the two slabs of high stratifications one just below the mixed layer and the other located little deeper. Only at UE is no such double cored structure observed. These two stratified layers merged into a single one with time. This results as a consequence of deepening of the mixed layer. At UN, only the upper slab showed the downward trend while at US and UW both the slabs showed a sinking trend. This continued even after the merging has taken place. At UE during July a mild shoaling trend in the merged slab can be noticed, on account of the switching over to upwelling during the last few days. During July at US and UE no significant change is observed in the magnitude of the thermal gradient whereas at UW there is a mild decrease and at UN a mild increase. The resembling stucture at US and UE indicates that these two stations might have experienced similar conditions. The deeper stratified layer observed at the three locations in June may be viewed as the remnant of the merged stratified layer of the previous summer monsoon season.

The temperature deviations both in depth and time with respect to the daily averaged BT trace of 7 June are shown in Fig. 7. In the meridional direction near surface mixed layer cooling of 2.5°C at UN and of 1.5°C at US is evident. Just below the mixed layer, warming in the upper thermocline occurred at all the locations with unequal magnitudes. The magnitude and vertical extent of below layer heating is higher at US than at UN. This largest sinking occurred around 90 m and 120 m depths at UN and US respectively. Mild cooling occurred only at UN below 120 m on account of weak upwelling.

In the zonal direction the near surface layer cooled by 2.5°C at UW and by 2.0°C at UE. The vertical structure of the temperature changes at UW is different from that at the other three locations in view of the bulging of isotherms in the upper thermocline that was discussed earlier. At UW during June below 100 m heating up to 2°C has resulted because of the disappearance of the weakly stratified region in the thermocline. At UE the heating in the thermocline is similar to that at US. Maximum heating occurred about 10 days earlier at UE as compared to US. The reduction in the heating after 6 July occurred because of the initiation of upwelling (Fig. 4a). Upwelling seems to have started first on the eastern side of this array. Further indication that the upwelling seems to have spreaded from the eastern Arabian Sea westward is the observation that the two Indian stations located in the eastern Arabian Sea also showed ascent of isotherms in the thermocline mostly throughout this period (Rao 1986).

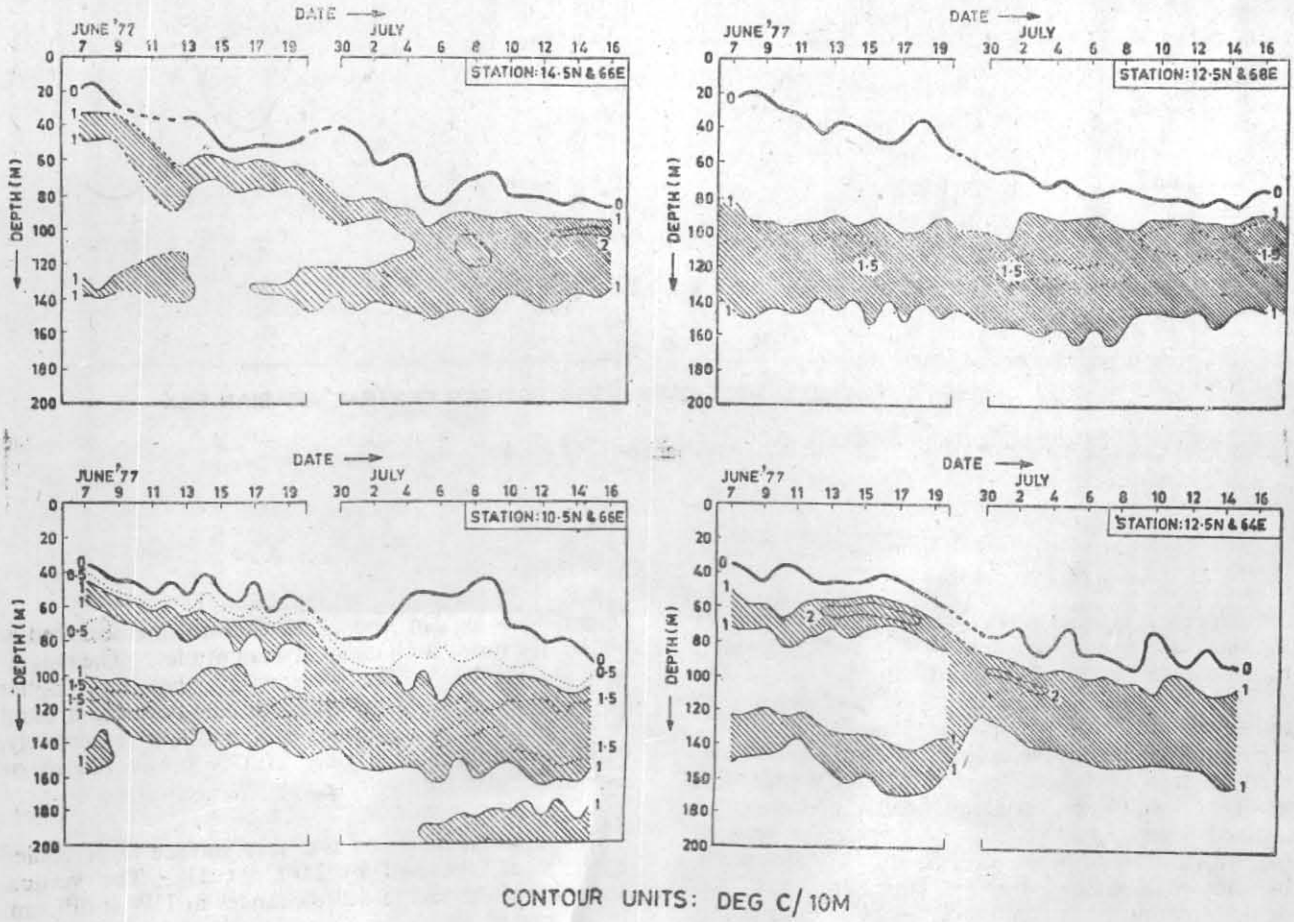

Fig. 6. Depth-time variation in the vertical thermal gradient

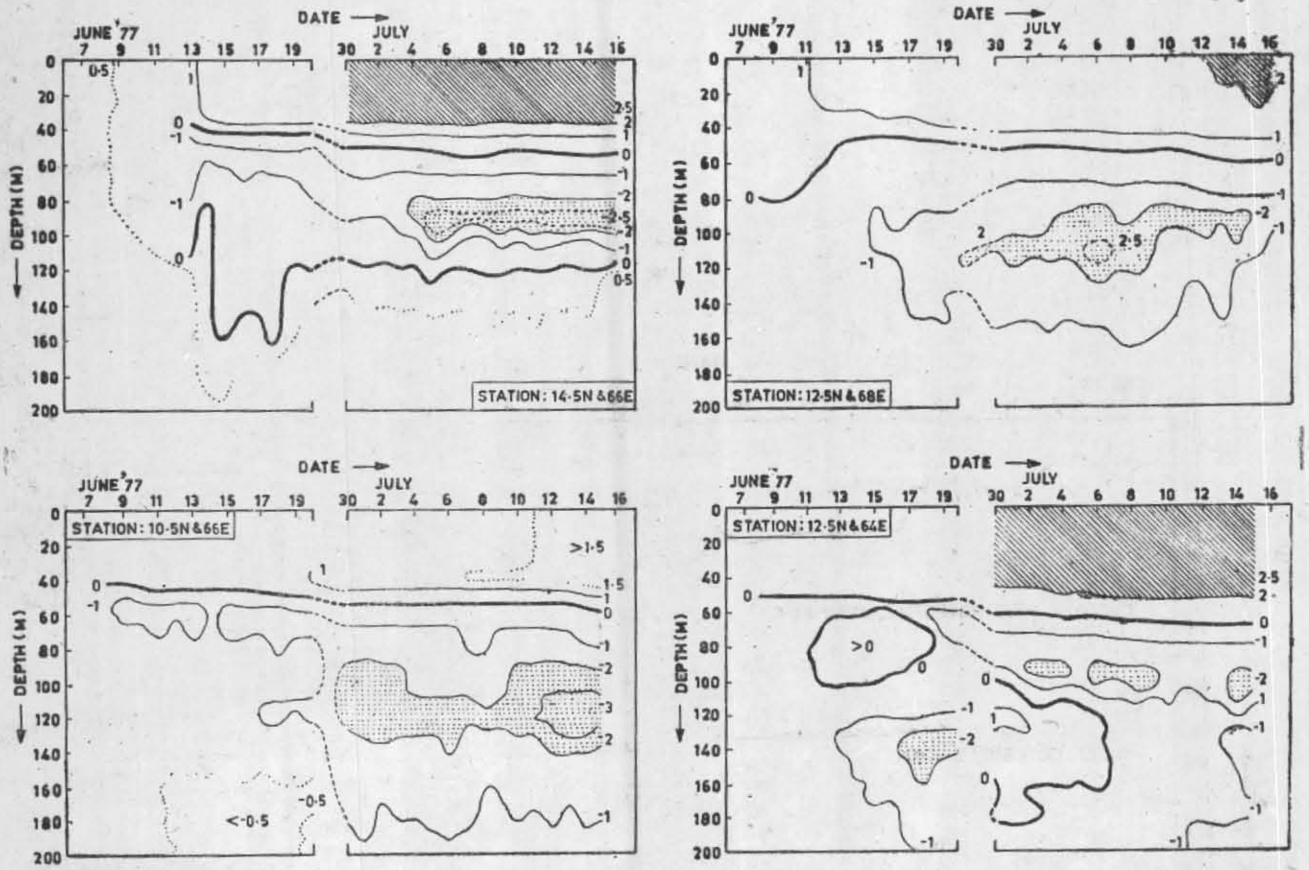

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Fig. 7. Depth-time variation in the deviation of thermal field from that of initial day

The heat content of the upper layers of the sea with respect to 28°C isotherm termed as cyclone heat potential (CHP) and the heat content (HC) of upper 10 m, 100 m and 200 m layers is depicted in Fig. 8 (a) for UN and US and in Fig. 8 (b) for UW and UE. A gradual lowering in CHP on account of the surface layer cooling is noticed. On 7 June all the four locations have shown the thermal capacity to sustain a cyclonic storm for a period of nearly one week with an assumed evaporation date of 2 cm/day from the surface. In the meridional direction, the CHP values are higher at US compared to UN throughout, with zero values during July at UN. In the zonal direction during June, CHP is higher at UW over that of UE and touched zero at UW during July.

The heat content of uppermost 10 m slab at all the four locations gradually decreased. While the heat content of upper 100 m and 200 m slabs has shown some interesting variations. The HC of upper 100 m at US has shown higher values over that of UN throughout. At US the HC of 100 m is of near steady nature during June but a gradual fall is noticed during July. Mixed layer cooling seems to be the major controlling factor for this observed fall. At US the HC of 200 m showed a marked increase from June to July mainly on account of large scale sinking of waters. But at UN the HC of 100 m and of 200 m during July is lower than that of June indicating mixed layer cooling and absence of sinking below 100 m. In the zonal direction, the HC of 100 m at both UE and UW show a diminishing trend due to mixed layer cooling. The HC of 200 m at UW gradually increased throughout with a sudden drop during intermittent periods. The HC of 200 m at UE has progressively increased from 13 June to 7 July when the fall began to occur on account of switching over from sinking to upwelling.

The temporal evolution of horizontal temperature differences in the zonal (upper panel) and meridional (lower panel) directions in the top 200 m water column is shown in Fig. 9. During June, UE was warmer than UW throughout the 200 m column with the minor exception of the slab from 60 to 100 m. The gradient was stronger in the upper thermocline compared to that of mixed layer. The gradient was building up during June in the upper thermocline reaching a maximum difference of 3°C mainly on account of the bulging of isotherms at UW (Fig. 4b). This strong negative gradient disappeared by the beginning of July giving

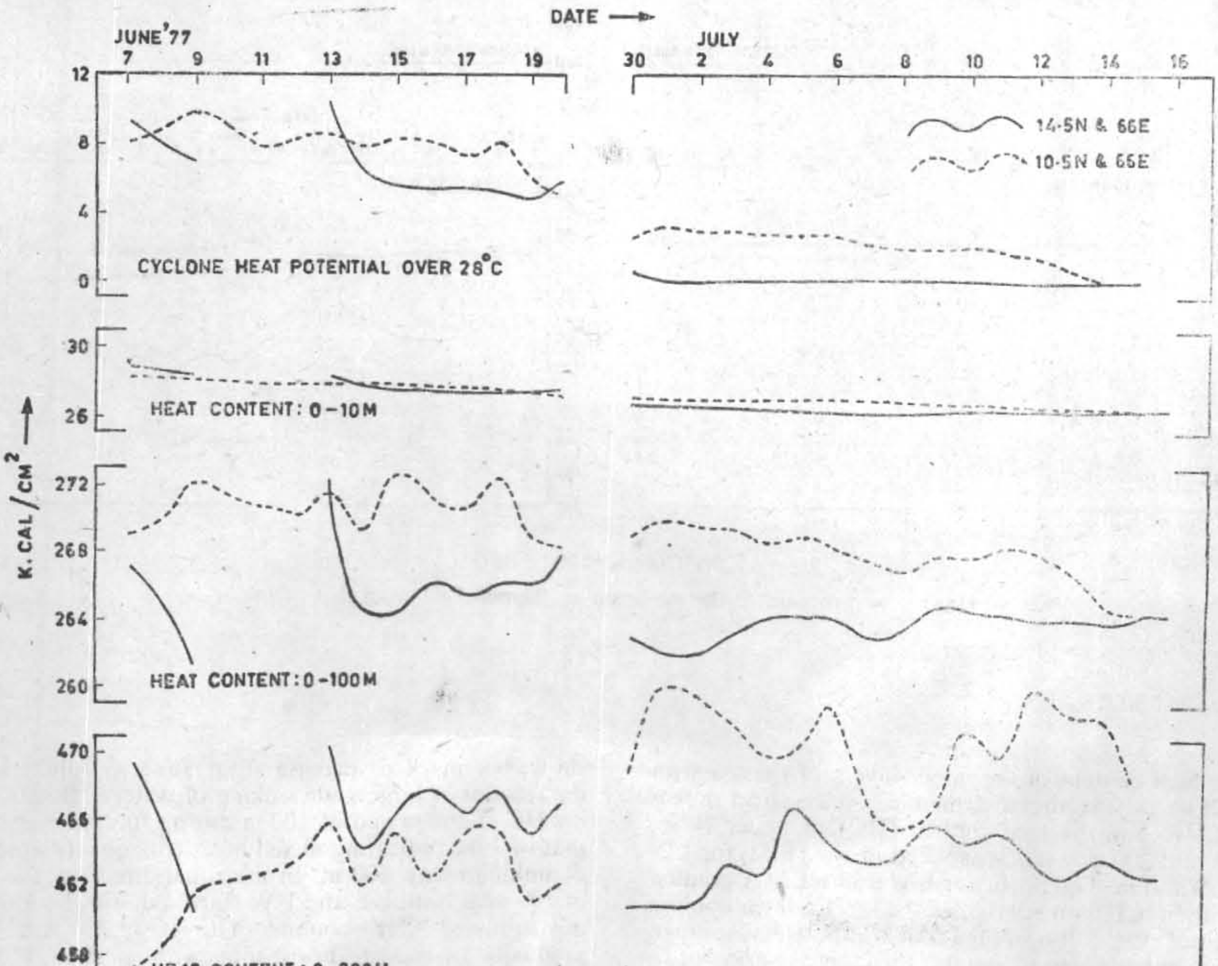

Fig. 8(a). Daily variation in cyclone heat potential and heat content of upper 10 m, 100 m and 200 m layers at stations UN and US

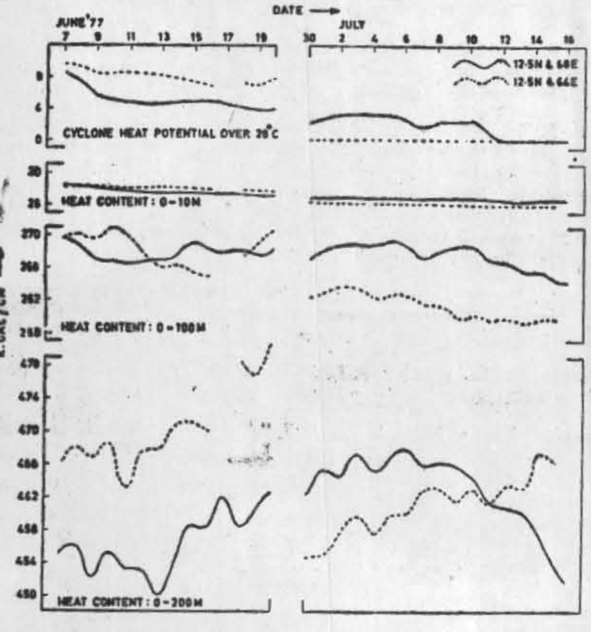

Fig. 8(b). Daily variation in cyclone heat potential and heat content of upper 10 m, 100 m and 200 m layers at stations UE and UW

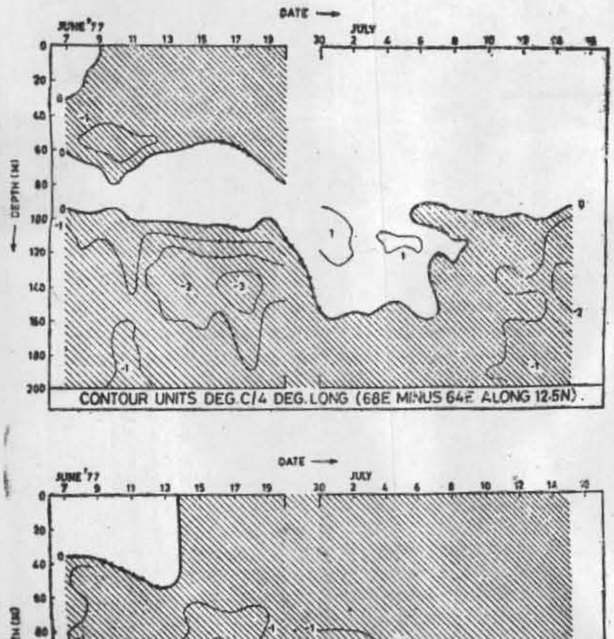

Fig. 9. Daily variation of zonal and meridional thermal gradient in the vertical

place to positive gradient at this depth. Towards mid-July the negative gradient again got strengthened on account of sinking at UW and upwelling at UE. The gradient in the upper 100 m was near zero during July. In the meridional direction, during June US was warmer than UN in the top 110 m column with the exception of top 40 m layer during second week of June. With the progress of time this negative gradient further strengthened especially below mixed layer due to unequal sinking rates at UN and US. Below this negative gradient layer, the gradient was of opposite nature but weaker in strength implying UN to be warmer than US. To summarise, the northwest sector of the polygon was warmer than southeast below 100 m throughout while the opposite was, by and large, true above 100 m depth.

4. Conclusion

(*i*) All the four stations over the central Arabian Sea showed near surface mixed layer cooling & heating in the thermocline just below layer under the onset and sway of the summer monsoon. The magnitude of these changes varied over this observational array.

(*ii*) The thermal response of the ocean to a moving severe cyclonic storm located at a distance of 400 to 500 km seemed to have felt only in the top 120 m layer.

(*iii*) The curl of monsoonal surface wind stress over the polygon was anticyclonic. This promoted convergence in the mixed layer and produced sinking of isotherms in the upper thermocline. This downwelling was stronger during June than in July. After mid-July the gradual change from sinking to upwelling is distinctly seen only at the eastern end of the polygon.

(*iv*) Downward transport of heat in the wake of the mixed layer deepening and sinking below resulted in below layer warming in the uppermost layers of the thermocline under the sway of the monsoon.

(*v*) Double cored maxima in the vertical thermal gradient were merged into a single core with an increase in the magnitude of the gradient under the sway of the monsoon.

(*vi*) The cyclone heat potential registered a gradual fall due to the cooling of surface layers under the sway of the monsoon.

(*vii*) The heat content of top 100 m and 200 m layers is strongly influenced by the near surface mixed layer cooling and deepening and the associated vertical advective processes in the upper thermocline.

(*viii*) The northwest sector of the polygon was warmer than southeast below 100 m throughout while the opposite was, by and large, true above 100 m depth.

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