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The observed thermal response of the upper northeastern Arabian Sea to the onset of the summer monsoon during ISMEX—73

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सार — इसमैक्स-73 के दौरान एक स्थिर सोवियत जलयान से 29 मई से 5 जून '73 तथा 26 जून से 2 जुलाई '73 की अवधियों के बीच 18° उत्तर तथा 67° पूर्व की स्थिति पर ऊपरी महासागरीय तापमान के समय श्रृंखला माप लिये गये थे। इन मापों का उपयोग अन्तः स्थापित भ्रमिल प्रणाली वाले ग्रीष्मकालीन मानसून के आरम्भ के प्रति उत्तर-पूर्वी अरब सागर की प्रेक्षित तापीय प्रतिक्रिया के वर्णन एवं व्याख्या के लिए किया गया है। अन्तः स्थापित भ्रमिल प्रणाली उत्तरी अरब सागर पर 6 से 13 जून '73 तक उपस्थित थी। प्रारंभिक भ्रमिल के निर्माण तथा उसके गुजर जाने के साथ ही मिश्रित परत तीन सप्ताह की अवधि में 50 मीटर की गहराई तक 1.7° सेल्शियस के आस-पास तक ठण्डी हो गई। परत के ठण्डा होने का मुख्य कारण समुद्री सतह पर होने वाला ताप-विनिमय तथा नीचे से ठण्डे पानी का संरोहण है। परत के गहरा होने में प्रमुखता एकमैन अभिसरण की होती है जिसकी वजह से सतही परत गहरे डूबती जाती है। भ्रमिल आरंभ होने के बाद के एक सप्ताह में 20 मीटर की परत गहराई में निवर्तन, भ्रमिल प्रणाली के पथ में निश्चित प्रत्यावर्ती उत्स्रवण एवं डूबते हुए पैटर्नों की बैरोक्लिनिक विधियों के कारण होता है।

ABSTRACT. Time series measurements of upper ocean temperature made during ISMEX-73 at 18°N & 67° E from a stationary USSR ship during the periods 29 May-5 June 1973 and 26 June-2 July 1973 are utilised to describe and to explain the observed thermal response of northeastern Arabian Sea to the forcing of summer monsoonal onset with an embedded vortex system prevailed over the northern Arabian Sea during 6-13 June 1973. With the formation and the passage of the onset vortex the mixed layer cooled around 1.7°C and deepened by 50 m over a three week period. The cooling is mostly attributed to heat exchanges at the sea surface and vergence compared to the entrainment of colder waters from below. The layer deepening had its largest component from the Ekman convergence resulting sinking in the surface layer. During the observed post-onset vortex regime of one week, retreat in the layer depth of 20 m is attributed to the baroclinic modes of alternate upwelling and sinking patterns set up in the track of the vortex system.

1. Introduction

The annual variation of the sea surface temperature (SST) in most parts of the Arabian Sea is of bimodal nature (Colborn 1975). Seasonal reversing monsoons are mostly responsible for this observed bimodal distribution of SST. The annual ranges in SST differs with geographic location depending upon the 'exposure' conditions to the summer and winter monsoons. The heating and cooling cycles of SST are intimately coupled with the behaviour of both the monsoons in a complex manner. The phenomenon of pre-monsoon heating and monsoonal cooling of the sea surface influencing the behaviour of the monsoon has attracted the attention of several workers in the recent past. However, the exact coupling between Arabian SST and Indian summer monsoon has not been established due to paucity of adequate observations over the sea. A major field experiment under international auspices, MONEX (Monsoon Experiment) was, therefore, organised as a regional component of FGGE* in 1978-79 to address this important problem. As a prelude to this, a pilot joint experiment ISMEX-73 (Indo-Soviet Monsoon Experiment) was carried over the Arabian Sea during the summer monsoon season of 1973. These experiments provided an unique opportunity to the oceanographic community to look at the observed temporal variability of some of the oceanic features at selected stations with the onset and progress of the summer monsoon.

Using Indian ship data collected during ISMEX-73 Ramesh Babu *et al.* (1976) documented the changes in the upper ocean thermal structure brought about by the summer monsoon along a zonal and a meridional section of the Arabian Sea. With the data collected on USSR ships during ISMEX-73 along two other zonal sections and a stationary position in the Arabian Sea, Ramam *et al.* (1979) have reported the observed changes in the upper ocean thermal structure with a greater emphasis on the high frequency variability. Ramesh Babu *et al.* (1981) further described the observed ocean thermal variability in terms of mean differences and auto correlation coefficients at the USSR stationary position during ISMEX-73. However, these studies have not adequately

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*First Global GARP Experiment.

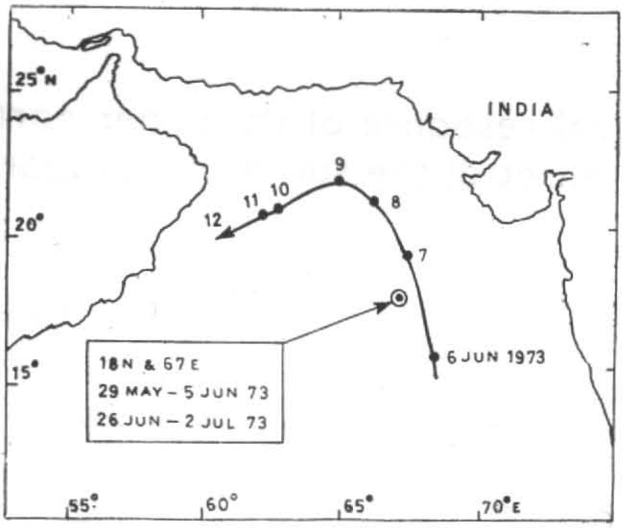

Fig. 1. USSR ISMEX-73 stationary position and the track of the summer monsoonal onset vertex

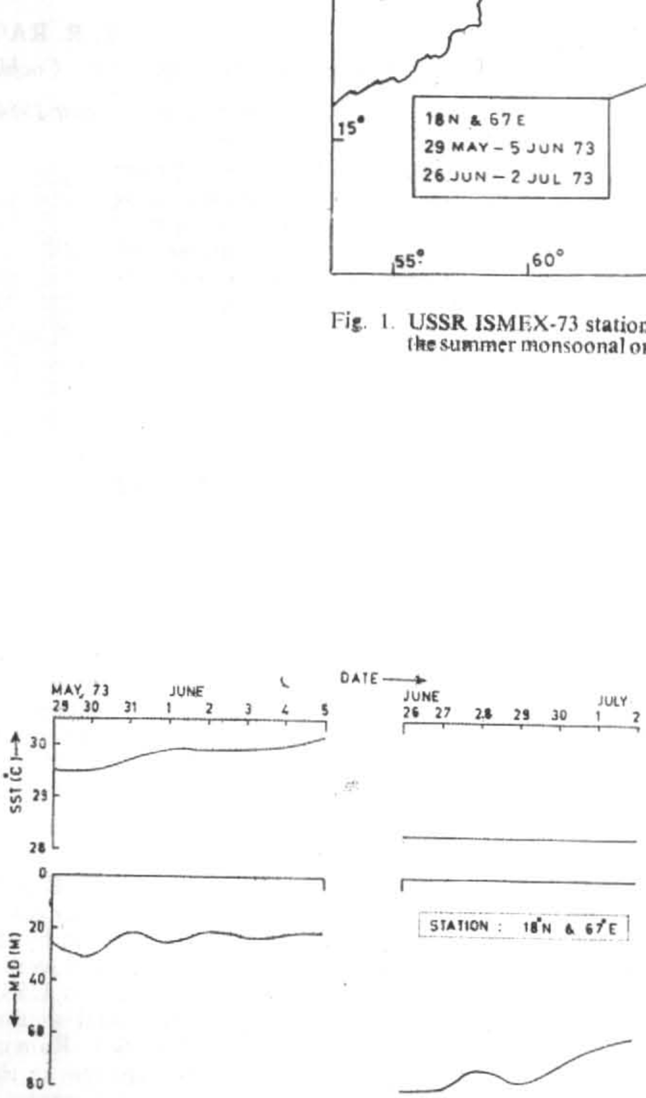

Fig. 2. Daily variation of SST and MLD at ISMEX station

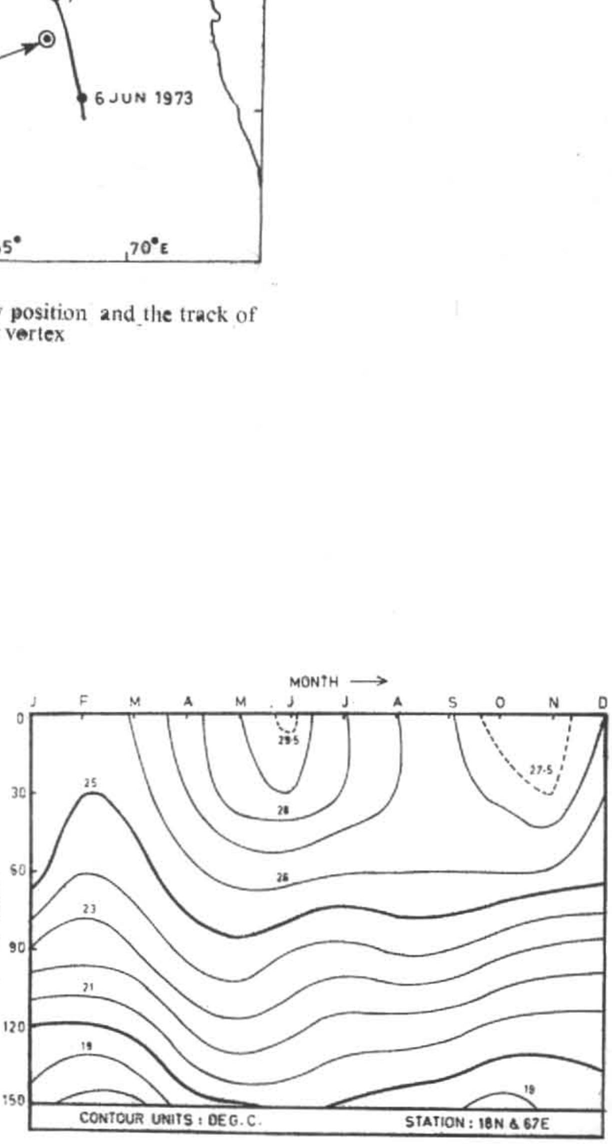

Fig. 3. Annual variation of upper ocean thermal structure at ISMEX station

highlighted the role of the onset vortex as a responsible agency in modifying the observed thermal features of the upper ocean. In the present exercise advantage is taken of the time series measurements made from the USSR stationary ship in the northeastern Arabian Sea to describe the thermal response of the sea to the forcing of the summer monsoonal onset vortex system.

2. Data

One USSR ship *RV Priliv* occupied the stationary position at 18° N and 67° E during the following periods :

(a) 29 May-5 June 1973

(b) 26 June-2 July 1973

During these two periods time series of bathythermograph (BT) data were collected at 3 hourly intervals. The associated surface marine meteorological data are not available for analysis purposes here. During the intervening period, the monsoon set in with an embedded vortex system over the North Arabian Sea. The track of this system was laid very close to the observing station (Fig. 1).

A low pressure area developed off Kerala coast on 2 June 1973. Moving northwestward, it concentrated into a deep depression on the evening of 6th near 16°N and 68.5° E. It further intensified on the evening of 7th. Continuing to move northwest upto 9th and later southwestward it intensified into a cyclonic storm on the morning of 10th. It weakened into a depression by 12th and dissipated off the Oman coast by 13 June 1973 (Alexander *et al.* 1979). There was a lull in the monsoon in the second week of June. Monsoon was particularly weak during 19-25 June 1973 and was active during 4-8 July 1973.

3. Analysis and discussion

A brief summary of the upper ocean thermal climate of this region is presented here. The monthly mean SST (Hastenrath & Lamb 1979) at 18° N & 67° E is of bimodal type with a primary maximum in May/June, a secondary maximum in October. The sea surface cools by 2.2° C from June to August in response to the summer monsoonal forcing. Fig. 2 shows the daily march of observed SST and derived mixed layer depth (MLD: depth where SST *minus* 0.2 °C occurs in the daily averaged BT profile) during the observed periods. The discontinuity in the time domain from 5 to 26 June may be noted. A mild warming of 0.7 °C over a week (29 May to 5 June) before the onset of the monsoon is seen due to intense pre-monsoon solar heating. This heating could have resulted in the ocean gaining approximately 250 cal/cm ^{2}/day for a mixed layer of $\sim$ 25 m.

With the onset, over a peiod of three weeks (5 to 26 June 1973), the SST dropped by 1.9° C with a corresponding deepening of the mixed layer from 30 to 80 m. This drop in SST accounts for about 85% of the seasonal summer monsoonal cooling. During the post-onset regime the MLD gradually retreated by 20 m. Anthes (1982) has shown that baroclinic modes of alternate upwelling and sinking regimes prevail in the track of a storm. This retreat might have been manifested due to the upwelling tendency at the base of the mixed layer. However, no change in the SST is seen during the post-onset regime probably due to mild surface heat losses with deep mixed layer.

The annual march of observed thermal structure in the topmost 150 m layer is shown in Fig. 3. Contours are drawn at 1° C interval for the long term averaged BT data extracted from Robinson *et al.* (1979). A clear bimodal heating and cooling regime confining to the upper 60 m layer is prominently seen. Pre-monsoon heating is of the order of 3.5° C from March to June while the summer monsoon cooling accounts 2.5°C until August. A similar but weaker cycle followed during the northeast monsoon season. Below this active layer, the thermocline appears to be nearly steady with mild slopes. The ascent and the descent of isotherms in the upper thermocline is mostly governed by the driving atmospheric wind stress curl (Yoshida & Mao 1957). The curl estimates by Hastenrath & Lamb (1979) indicate that this station is located in the vicinity of the zero curl contour during the seasons (January & July) of strong atmospheric forcing. The weak slopes of the isotherms in the thermocline may imply the same. The observed sinking from February to May followed by upwelling during the rest of the year can only be explained qualitatively with the aid of the analysis of Hastenrath and Lamb (1979).

The daily averaged BT data collected during ISMEX-73 are contoured in the depth-time domain with 1°C interval to depict the evolving thermal structure of the topmost 200 m layer (Fig. 4). During the pre-onset regime, a shallow mixed layer capped over a 40 m thick highly stratified thermocline is evident. The packed isotherms in this stratified layer show a mild ascending tendency. Below this stratified layer, waters with very weak vertical gradients are noticed. Such weak gradients in the thermocline are not observed in the long term averages (Fig. 3). These weak gradients might have been resulted due to weak monsoonal forcing during the preceding year 1972 (declared as a global drought year). The author has compared the vertical thermal gradient in this area before and after the onset of the monsoon during ISMEX-73, MONSOON-77 and MONEX-79. He found weak vertical thermal gradient in the 100-160 m depth range only in the ISMEX-73 profile.

After the onset of the monsoon, the shallow steady mixed layer during the pre-onset regime was replaced by a deep, shoaling mixed layer. This layer deepening was also associated with sinking of waters just below the base of the mixed layer. For example, the 28°C isotherm descended by nearly 40 m in 3 weeks from 5 June implying an approximate sinking rate of 2 m/day. The 24° C isotherm descended only at the rate of 1 m/day. This sinking rate progressively decreased with depth indicating its causative factor to lie probably near the surface. Anthes (1982) summarises the sequence of events associated with the storm forcing on the upper ocean. As the storm approaches, the increasing winds produce stronger turbulence, deepening and slight cooling of the mixed layer. Outside the radius of maximum wind, the anticyclonic relative vorticity is associated with a stress field with negative curl. Convergence is induced in the mixed layer and downwelling occurs, which also acts to deepen the mixed layer. During the post-onset regime the general nature of the isotherm slopes remained same with some changes in the resulting

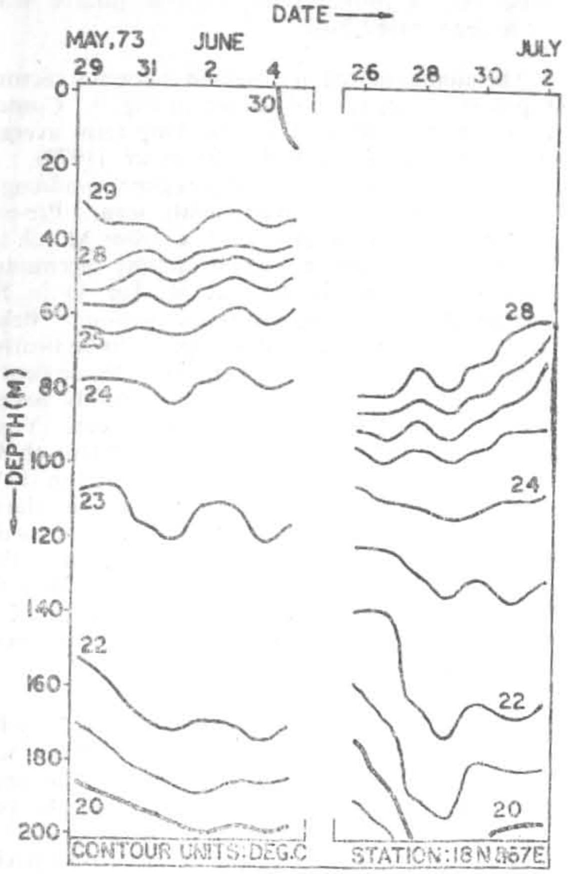

Fig. 4. Daily variation of upper ocean thermal structure at ISMEX station

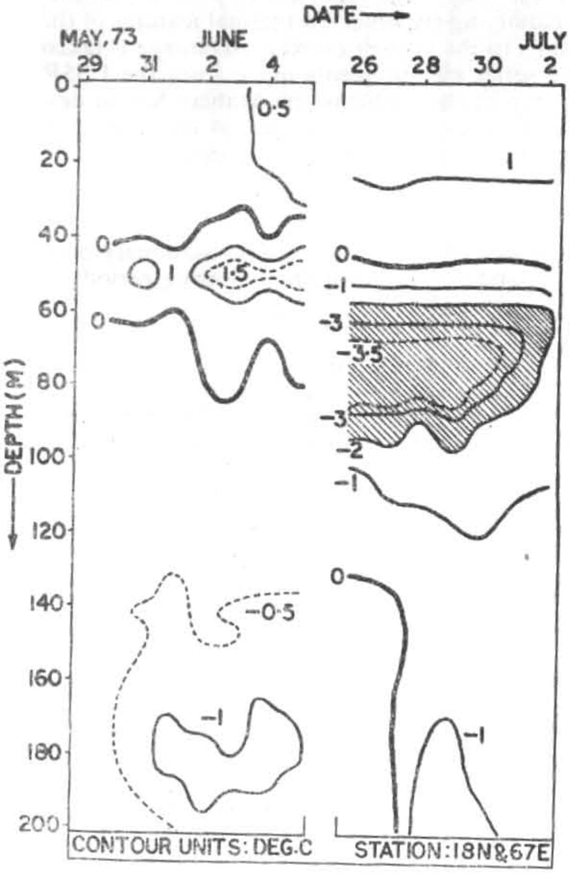

Fig. 5. Daily variation of heating/cooling regimes at ISMEX station

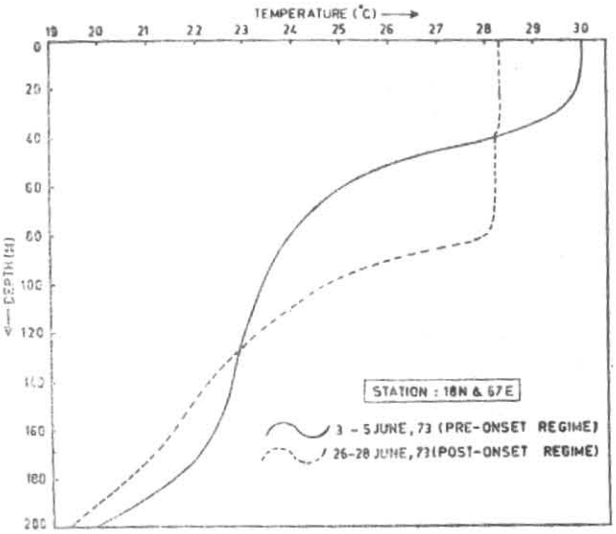

Fig. 6. Pre and post-onset BT profiles

TABLE 1

S. No.	Heat budget of mixed layer	Temp. (°C)
(1)	Average temperature of the 0-25 m layer of the pre-onset profile	29.9
(2)	Average temperature of the 0-40 m layer of the pre-onset profile	29.6
(3)	Probable entrainment cooling : (1) *minus* (2)	0.3
(4)	Average temperature of the 0-75 m layer of the post-onset profile	28.2
(5)	Mixed layer cooling : (1) *minus* (4)	1.7
(6)	Probable cooling due to net surface heat loss and vergence (5) *minus* (3)	1.4

TABLE 2

Thermal parameter	Pre-onset regime (3-5 June 1973)	Post-onset regime (26-28 June 1973)
Mixed layer mean temperature (°C)	29.9	28.2
Mixed layer depth (m)	25	75
Vertical thermal gradient below mixed layer (°C/30 m)	4.2	4.1
Heat potential with respect to 28°C (K cals/cm^2)	6.3	1.8
Heat content top 10 m (K cals/cm^2)	28.6	26.7
Do. (,, 100 m)	255	265
Do. (,, 200 m)	467	474

gradients. A mild ascent of isotherms in the lower region with the onset of monsoon is noticed. No perceptible change in the below layer vertical thermal gradient is noticed from pre-onset regime to post-onset regime. However, the gradient between 24° and 22° isotherms got nearly doubled due to descent of isotherms above 24°C and ascent of isotherms below 22° C from pre-onset regime to post-onset regime.

The thermal changes brought about in the topmost 200 m layer with respect to 29 May (initial day of observations) are shown in Fig. 5. Positive values indicate cooling with respect to 29 May. In the surface layer a mild pre-monsoon solar heating of over 0.5°C by 4 June and monsoon cooling of over 1°C throughout the post-onset regime is evident. In the upper strata of the thermocline, cooling of 1.5°C is present during thg pre-onset regime due to the upwelling of waters. During the post-onset regime warming of 3.5°C resulted due to the descent of these highly stratified waters as a consequence of surface convergence caused at larger radii of the onset vortex during the onset of the monsoon. During this post-onset regime a fast retreat during the last three days has resulted due to the upward tendency of the stratified layer below MLD. This strong upward tendency cannot be accounted in terms of seasonal surface wind stress curl ($\nabla \times \tau$). A rise of 20 m during this 6-day period warrants $\nabla \times \tau$ to be one order higher than the classical estimates of Hastenrath and Lamb (1979) for July. This ascent can be viewed as a segment of baroclinic mode as proposed by Anthes (1982). No prominent changes are noticed in the lower layers excepting a warming of 1°C due to descent of waters around 180 m depth.

Fig. 6 shows the BT profiles of pre-onset (average of 3-5 June 1973) and post-onset regimes (average of 26-28 June 1973). Here three day data closest to the onset event are averaged to minimize the influence of inertial oscillations at this location. Mixed layer cooling and deepening is evident. The profiles intersected at 40 m and 125 m depths. The area above the top intersection point, (through graphical integration) showed a net heat loss of 5.3K cals over the three week period. This heat loss might have occurred across the sea surface and entrainment of colder waters embedded between the base of the mixed layer and 40 m depth in the pre-onset profile. The relative importance of these two processes is shown in Table 1. This heat loss of 5.3 K cals accounts for a cooling of 1.3° C/3 weeks for this 40 m water column. This accounts over 75% of the observed drop in mixed layer temperature of 1.7° C/3 weeks. The large separation noted between 40 m and 125 m depths is mostly attributed to the descent of waters in response to the prevailing anticyclonic wind stress curl outside the eyewall of the onset vortex system. Analysing the temperature changes due to the passage of 14 storms Federov (1973) proposed a two cell vertical circulation in the plane perpendicular to the track of the storm. The inner cell with upwelling at the centre and downwelling at about 200 km is consistent with the observations of Leipper (1967). The descent of isotherms can be further supported by looking at the vertical thermal gradients just below the mixed layer in both the profiles. These values during pre-onset regime (4.2° C/30 m in the depth range of 25 m to 55 m) and that of post-onset regime (4.1°C/30 m in the depth range of 80 m to 110 m) are almost identical.

A crude heat budgeting of the mixed layer is done and the estimates are shown in Table 1.

If entrainment of colder waters from the base of the mixed layer to 75 m depth were to occur in the pre-onset profile, the mean temperature of the topmost 75 m layer of post-onset profile should be cooler than the corresponding one of pre-onset profile. This is not the case as the mean temperatures of topmost 75 m layer of pre and post-onset profiles are 27.7°C and 28.2°C respectively. This further confirms that the erosion of thermocline did not extend upto 75 m but the highly stratified waters only descended (Fig. 4). The convergence of waters due to Ekman transport thickened the mixed layer, thus pushing down the stratified waters below (Note the descent of 28°C to 25°C isotherms by 40 m in Fig. 4).

The cyclonic heat potential (CHP) and heat content (HC) of the topmost 10, 100 and 200 m layers as defined in Rao *et al.* (1983) have been computed and are shown in Fig. 7. During the pre-onset regime the CHP oscillated around 6 K cals/cm^2. Following the onset a marked drop of 4.5 K cals/cm^2 is registered implying an average net oceanic heat loss of 210 cal/cm^2/day during the period of three weeks from 5 June. Heat content of topmost 10 m layer mostly corresponded to SST variation shown in Fig. 2. The HC of top 100 m layer during pre-onset regime showed a mild decrease on account of upwelling

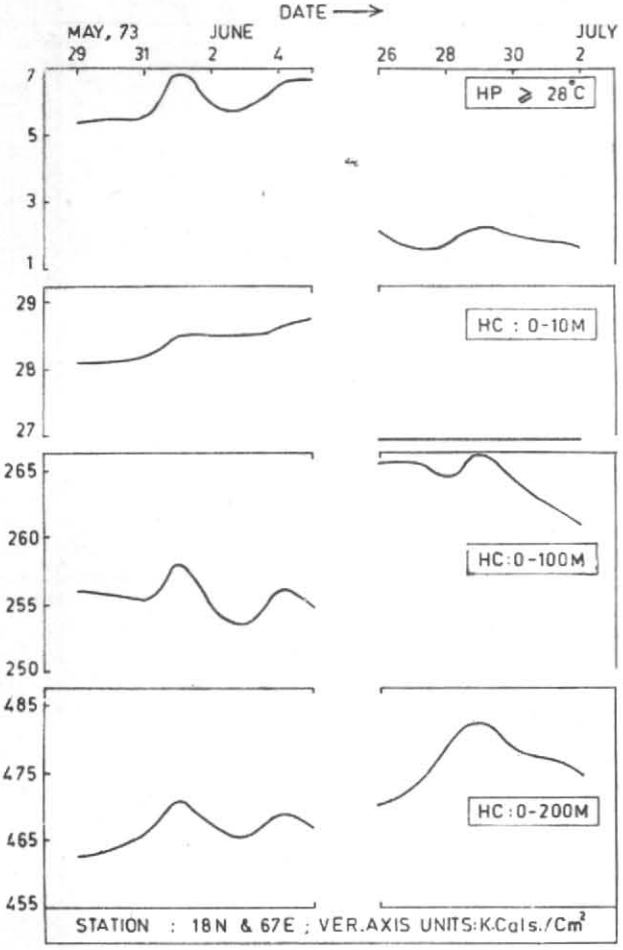

Fig. 7. Daily variation of cyclonic heat potential and heat content of top 10, 100 and 200 m layers

of colder waters from below. After the onset of the monsoon, the phenominal increase is due to sinking of warmer waters and deepening of the mixed layer. During the last four days of the post-onset regime, the lowering tendency due to ascent of colder waters is again noticed. The HC of top 200 m layer also is governed by the vertical advection of waters. The progressive increase throughout the observational periods can be accounted to the overall sinking of isotherms. The vertical redistribution of the bulk heat content in the upper 200 m layer with the onset of the monsoon is clearly noticed. Table 2 summarises the salient thermal features of the pre and post-onset regimes.

4. Conclusions

(*i*) The onset vortex and progress of the monsoon during a three week period cooled the sea surface by 1.7° C and deepened the mixed layer by 50 m at the observing station. The cooling is mostly attributed to the surface heat losses and vergence while the deepening for the sinking of waters due to Ekman type of convergence. Drop in SST of 1.7° C with the onset of the monsoon has accounted for nealy 85 % of seasonal summer monsoonal surface cooling of 2.2°C.

(*ii*) With the formation and passage of the onset vortex system the upper boundary of the thermocline (*say* 28° C) descended by about 40 m implying an approximate sinking rate of 2 m/day. This sinking decayed with depth. This sinking is attributed to the surface convergence caused by anticyclonic wind stress curl outside the radius of maximum winds of the onset vortex.

(*iii*) During the post-onset regime the mixed layer shoaled by 20 m over one week. This type of shoaling might have resulted due to the baroclinic modes of alternate upwelling and sinking patterns set up in the track of the disturbance. Such a strong shoaling cannot be explained by the classical seasonal estimates of the surface wind stress curl.

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