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Summer cooling in the east central Arabian Sea — A process of dynamic response to the southwest monsoon

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सार — मॉनेक्स '79 और मानसून' 77 कार्यक्रमों के आंकड़ों का उपयोग करके ग्रीष्म मानसून ऋतु में पूर्वमध्य अरब सागर के शीतलन का परीक्षण किया गया है । इन अध्ययनों से पता चला है कि धारा अपरूपण क्षेत्र के गहन होने के साथ-साथ शीतल उप-पृष्ठ एवं गर्म पृष्ठ के जलों के मिश्रण के फलस्वरूप ऊष्मा का नीचे की ओर स्थानांतरण इस क्षेत्र में प्रेक्षित शीतलन की प्रमुख प्रक्रिया है । प्रबल मानसून पवनों की शुरूआत और प्रतिचक्रवाती पवन प्रतिबल कर्ल के विकास के तत्काल बाद शीतलन दर में वृद्धि हो जाती है । इससे भारत के पश्चिम तट से दूर दक्षिण-वर्ती धारा उत्पन्न होती है । नीचे की ओर ऊष्मा का अभिवाह स्थिर क्षेत्र में परिवर्तित होने लगता है। इसका मान सामान्यत: पश्चिमी क्षेत्रों में, जहां पृष्ठ स्तर में अधिकतम वृद्धि होती है, उच्च होता है । शोधपत्र में पूर्व मानसून एवं मानसून की दशाओं में चक्रवात ऊष्मा विभव का भी अध्ययन किया गया है ।

ABSTRACT. The cooling of the east central Arabian Sea during summer monsoon season is examined using data sets of MONEX '79 and MONSOON '77 programmes. These studies have revealed that downward transfer of heat due to the mixing of warm surface and cold sub-surface waters associated with deepening of the current shear zone is the predominant process for the observed cooling in the region. The rate of cooling is greater immediately after the onset of strong monsoon winds and the development of anti-cyclonic wind stress curl, which give rise to a southerly current off the west coast of India. The downward flux of heat is found to vary in the study area with generally higher values in the western regions where the growth of surface layer is maximum. The cyclone heat potential during pre-monsoon and monsoon conditions is also studied.

1. Introduction

The annual variation of sea surface temperature (SST) over most of the Arabian Sea shows a bimodal pattern with higher temperatures during May and October. The low surface temperatures are found in January-February and during July-August. This behaviour is anomalous. The water bodies which are similarly situated geographically with respect to the equator are known to show an increase in the SST with the advance of northern summer whereas in the Arabian Sea, the SST drops soon after the summer monsoon is established over the region. The quantum of lowering of the SST differs from region to region with largest reduction occurring off the African coast in the western Arabian Sea. Off the west coast of India, the fall in SST is about 2 deg. C whereas in the central Arabian Sea, surface cooling could be as much as 4 to 5 deg. C (Rao *et al.* 1976). The thickness of surface layer is also known to vary considerably in response to the reversal wind regimes affecting the heat storage in the upper layers of the Arabian Sea.

The sea surface temperature is one of the important parameters governing the air-sea interactions and forms one of the bottom boundary conditions for the development of prediction models of the southwest monsoon. The accuracy of these models would therefore, largely depends upon proper assignment of SST and its variations. Realising this feature, several investigations over the Indian Ocean in general and the Arabian Sea in particular have been carried out by meteorologists and oceanographers on various heat budget components such as incoming radiation, effective back radiation, sensible and latent heat exchanges, rate of heat storage, advective heat transport etc. (Colon 1964, Saha 1970 and 1974, Ramage, Miller and Jefferies 1972, Colborn 1975, Shukla 1975, Hastenrath and Lamb 1979, Ramanatham, Somanatham and Rao 1981). In the recent MONEX '79 which was conducted as a part of First GARP Global Experiment (FGGE) Programme, the studies related to the energy exchanges over the Arabian Sea have been given prominence. The purpose of present investigation is to study the temporal variations of the thermal structure in the upper layers of the east central Arabian Sea during pre-monsoon and monsoon weather conditions and to assess the causative factors for the anomalous behaviour of sea surface temperature in the eastern Arabian Sea.

2. Data and analysis

The National Institute of Oceanography, Goa had organised three cruises in the east central Arabian Sea (11 to 15 deg. N, 68 to 72 deg. E) on board RV *Gaveshani* during May, June and July 1979 as a part of MONEX '79 programme. It may be noted that owing to some operational problems, only a limited area could be surveyed during the third cruise (confined to 14 deg. N and 15 deg. N). Fig. 1 shows the study area along with the station locations during the three phases where the depth-temperature profiles were obtained using a bathythermograph. In order to aid the interpretation of results, the authors have further analysed bathythermograph and meteorological data collected in the region west of the present study area by the Russian ships forming a polygon (Fig. 2) during Monsoon '77 experiment.

During second phase of observations of MONEX'79, an atmospheric vortex had formed over the southeastern Arabian Sea which developed later into a depression and moved across the study area. Under its influence monsoon had advanced and Fig. 3 presents the track of onset vortex along with approximate onset dates of monsoon over India. With a view to study the available thermal energy in the sea for the maintenance of the atmospheric disturbance, the cyclone heat potential (Whitakar 1967) had also been evaluated using the following equation :

$$Q = \rho\, c_p \int_{0}^{Z_{26}} \Delta T\, dz$$

where ρ is the density of the water, c_p specific heat at constant pressure, ΔT average temperature difference above 26°C in the depth interval 'dz' and Z_{26} , depth of the 26°C isotherm. $\rho\, c_p$ was assumed constant and assigned a value of 0.977 cal cm^{-3} °C^{-1} (Bathen 1971). The lower temperature (26°C) was chosen since it is the mean surface air temperature in the tropical cyclones (Leipper and Volgenau 1972) and since the tropical cyclones do not usually form where the SST's are lower than 26°C.

3. Results

3.1. *Thermal structure in the MONEX '79 study area*

Fig. 4 presents the distributions of SST during the three phases. In May, the SST exceeds 30 deg. C west of 72 deg. E while lower temperatures (< 29 deg. C) are observed close to the west coast of India. During the second phase, the SST in general is slightly higher over the area whereas during the third phase, it is less than 28.5 deg. C. The thickness of surface layer during May and June varies between 30 and 40 m (Figs. 5A & 5B) while in July, it shows considerable spatial variation (30 to 60 m) (Fig. 5C).

Fig. 6 shows the mean depth-temperature profiles averaged for all stations west of 72 deg. E during the

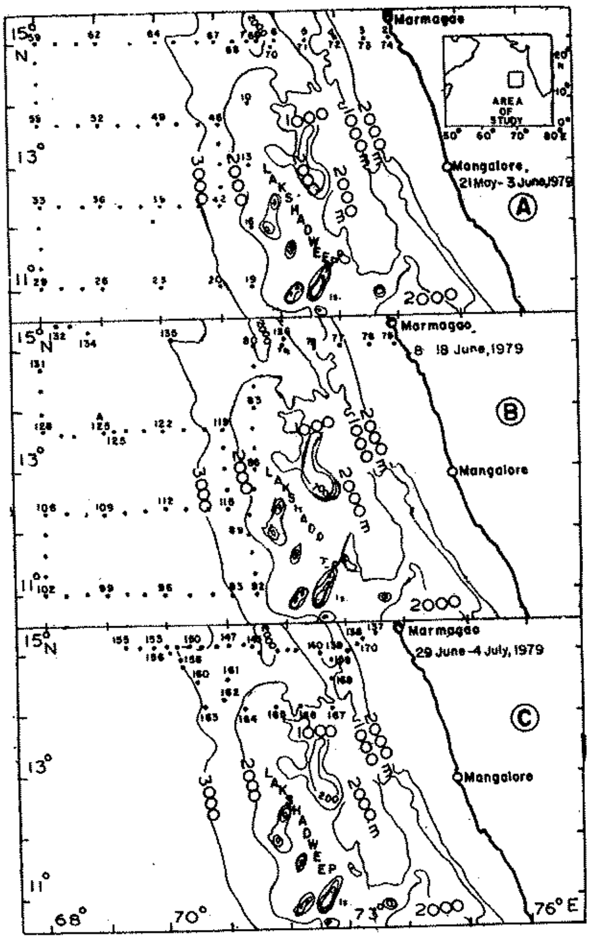

Fig. 1. Bathythermograph station locations in the east central Arabian Sea during MONEX'79 period

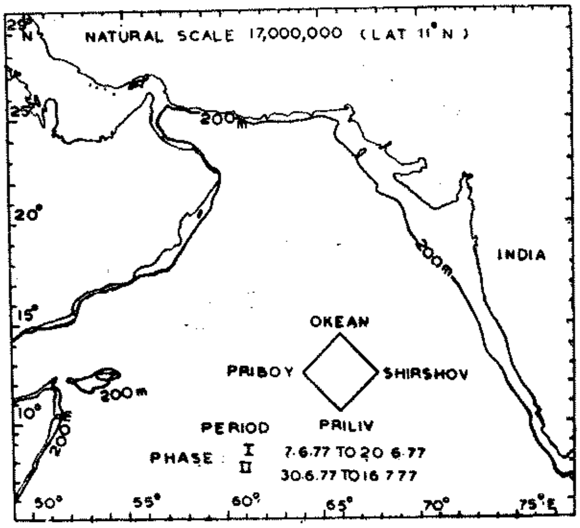

Fig. 2 Polygon formation of Russian ships in the central Arabian Sea during MONSOON'77 period

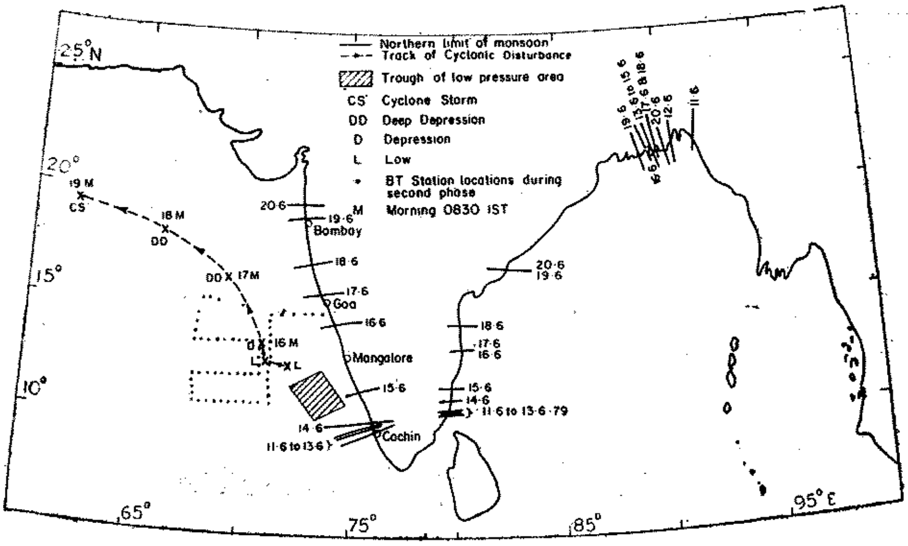

Fig. 3. Track of cyclonic disturbance over the eastern Arabian Sea and progress of summer monsoon of 1979 over India

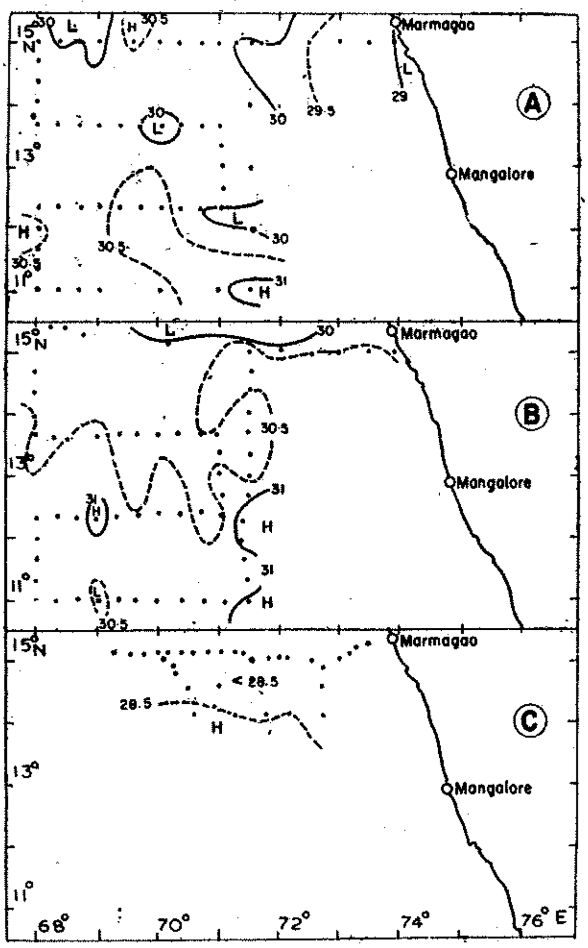

Fig. 4. SST (°C) in the east central Arabian Sea during the three phases

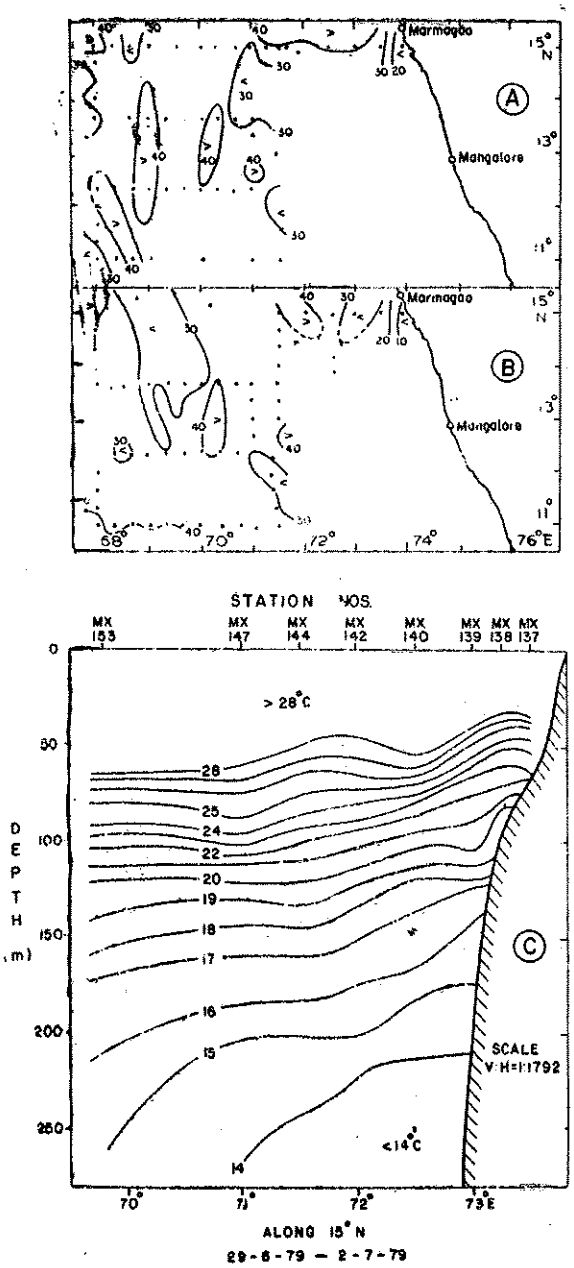

Fig. 5 (A–C). Thickness of surface layer (m) in the east central Arabian Sea during first phase (A), second phase (B) and along 15°N during third phase (C)

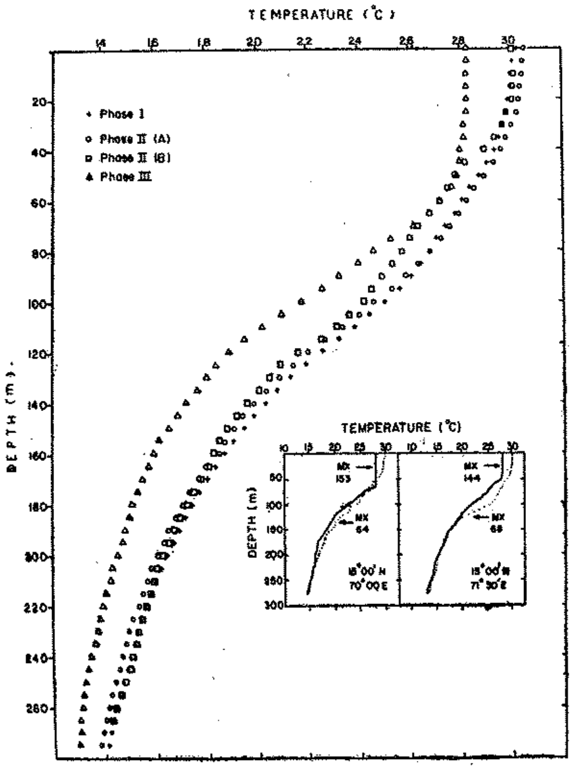

Fig. 6. Average depth-temperature profiles in the east central Arabian Sea during three phases

three phases. Also presented in this figure is an average depth-temperature profile (Phase II B) for stations 132 to 136 which were occupied soon after the atmospheric vortex crossed the study area. These profiles show that the water column upto a depth of 80 m is slightly warmer in June than in May indicating accumulation of heat energy in the upper layers. Below 80 m depth, June temperatures are slightly lower. By July, the entire depth-temperature curve has shifted to the left indicating lower temperatures at all depths. Comparison of the profiles for June and July indicates that the temperature falls by more than 2 deg. C at surface and by more than 3 deg. C at 100 m whereas the lowering is minimum ($\sim$1 deg. C) just below the surface layer.

3.2. *Cyclone heat potential*

Figs. 7A and 7B present the cyclone heat potential in the east central Arabian Sea during first two phases. In May, the cyclone heat potential exceeds 20 kilo cal cm^{-2} over most of the area while slightly low values ($<$ 20 kilo cal cm^{-2}) are encountered in the northern portions. Adjoining the west coast of India, the cyclone heat potential is very low due to the fact that 26 deg. C isotherm shoals up towards the west coast. During June, leaving the northwestern portions where the influence of vortex is felt, the heat potential shows a marginal increase by about 5 kilo cal cm^{-2} over that during May. However, by July after the onset of monsoon, the heat potential has decreased considerably and has values ranging from 10 to 15 kilo cal cm^{-2} along 15 deg. N (Fig. 7C).

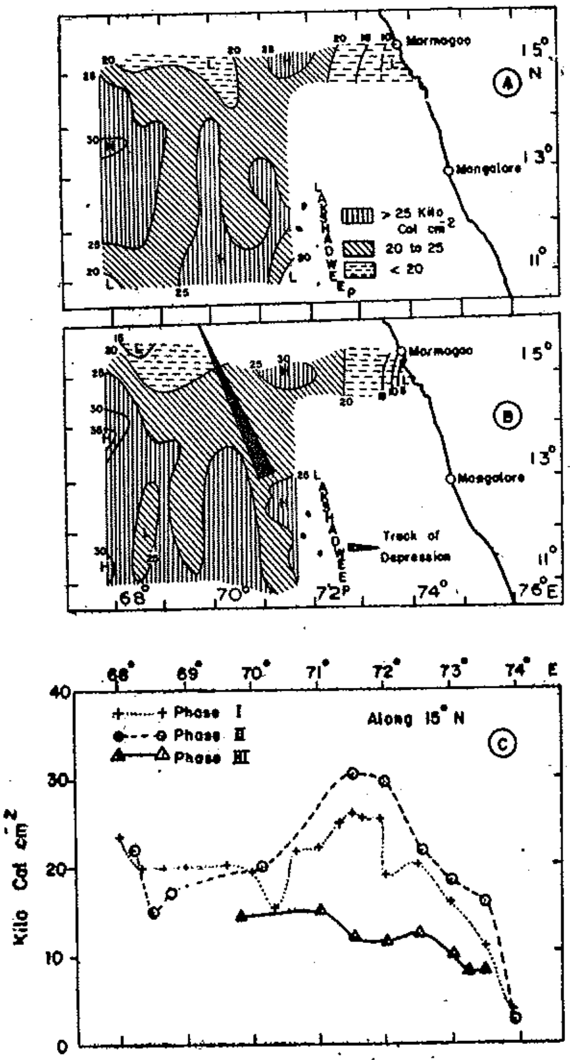

Fig. 7 (A–C). Cyclone heat potential (kilo cal cm^{-2}) in the east central Arabian Sea during first phase (A), second phase (B) and along 15°N during three phases (C)

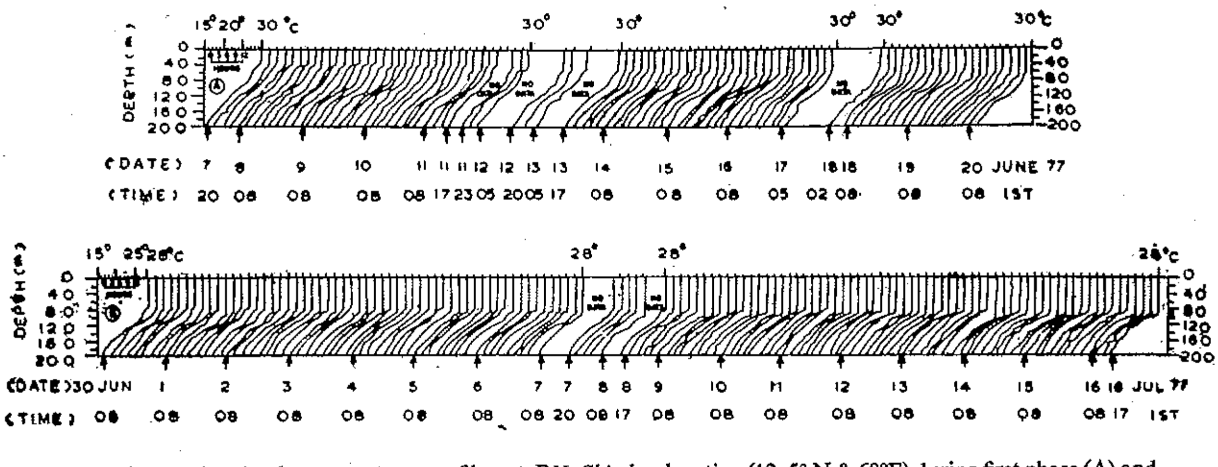

Fig. 8. Time series depth-temperature profiles at RV *Shirshov* location (12.5° N & 68°E) during first phase (A) and second phase (B) of MONSOON '77 programme

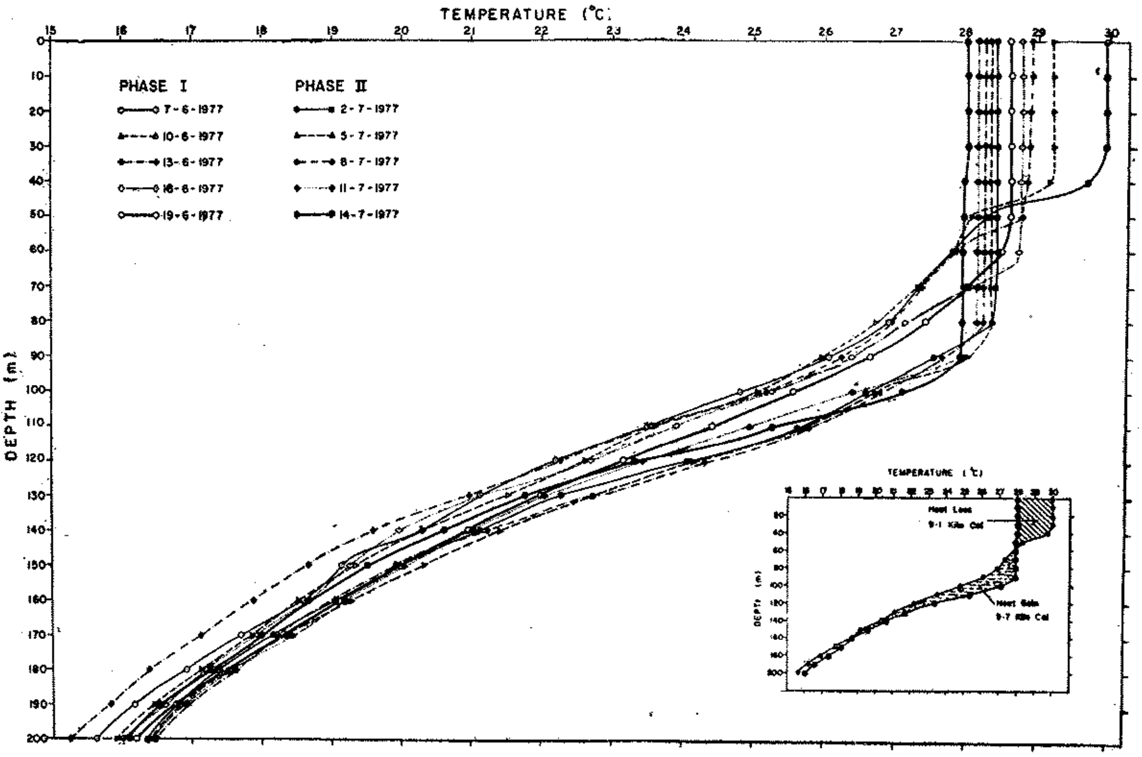

Fig. 9. Evolution of thermal structure at RV *Shirshov* location in relation to the summer monsoon of 1977

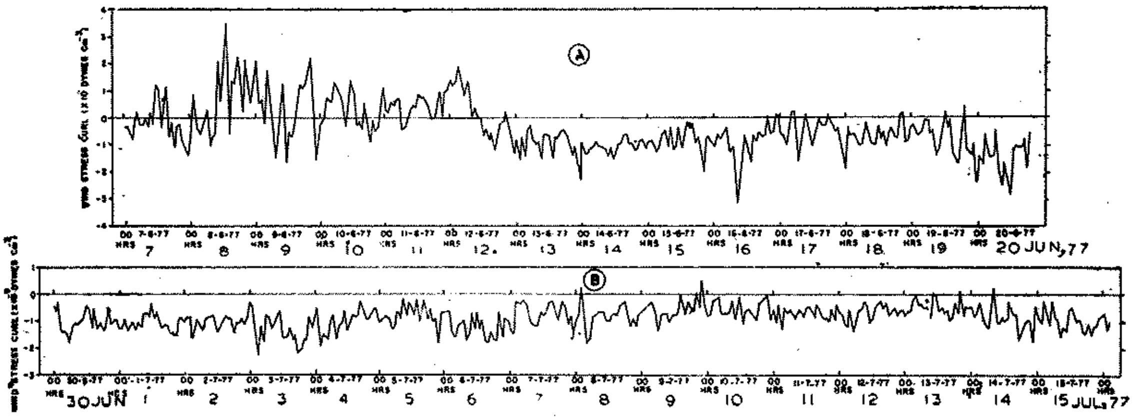

Fig. 10. Wind stress curl over the polygon area during first phase (A) and second phase (B) of MONSOON' 77 programme

3.3. *Thermal structure west of the present study area*

Time series bathythermograph data collected at three hourly intervals on board RV *Shirshov* at 12.5 deg. N and 68 deg. E during the periods 7-20 June 1977 and 30 June-16 July 1977 as a part of MONSOON '77 programme are presented in Fig. 8. The basic features of these depth-temperature profiles are summarised in Fig. 9 which shows the evolution of thermal structure with the advance of monsoon season. During early June, the sea surface temperatures are found to be 30 deg. C and thickness of surface layer is around 40 m. By mid July, the sea surface temperatures have decreased to around 28 deg. C and the thickness of surface layer has increased to 90 m. Fig. 9 further shows that the seasonal influences could affect the thermal structure upto depths of 150 m and probably more.

3.4. *Wind stress curl and currents in the polygon area*

The wind effect over the sea surface on the development of the surface layer has also been examined. The wind stress curl based on hourly wind data collected

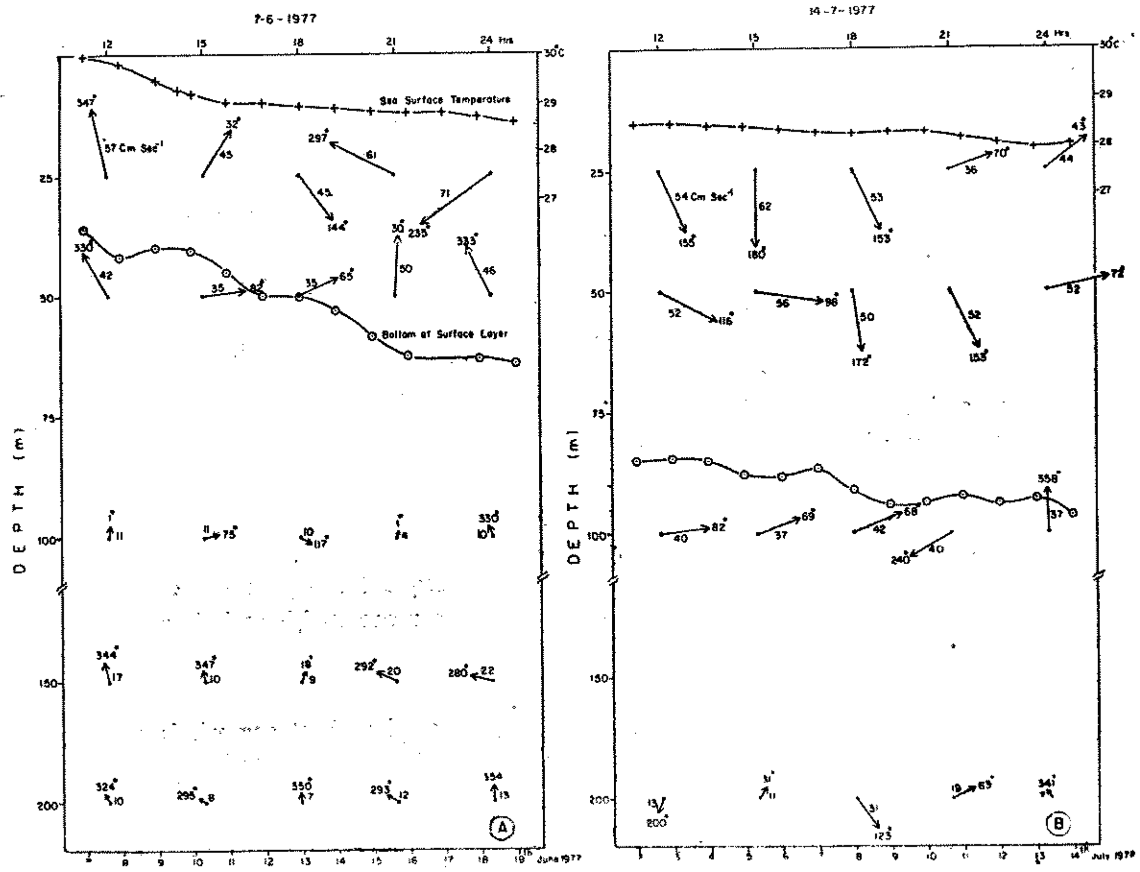

Fig. 11. Typical ocean current vectors in the polygon area during first phase (A) and second phase (B) of MONSOON '77 programme

on board the four Russian ships forming the polygon has been computed and presented in Fig. 10. During 8-11 June 1977, the wind stress curl has become predominantly positive and thereafter it has become negative indicating a change in the wind regime from cyclonic to anticyclonic.

Currents obtained by current meters moored to the anchored buoys in the vicinities of RV *Shirshov* (12.5 deg. N and 68 deg. E) during 7-16 June 1977 and RV *Priboy* (12.5 deg. N and 64 deg. E) during 30 June-14 July 1977 were also examined. Just before the onset of monsoon over the area, the currents are of the order of 40 cm sec^{-1} in the upper 50 m while they are weak below the surface layer. After the monsoon has established over the area, the winds have freshened and in response, the currents have strengthened and penetrated to deeper levels. Thus the vertical shear zone has shifted to deeper levels. Fig. 11 shows a typical example of currents in the polygon area prior to and after the onset of monsoon. The arrows in the figure show spot values of currents on 7 June and 14 July 1977 representing the two phases. The top scale of the figure gives time in hours on those two days. It is clearly seen from the figure that strong currents prevail only upto a depth of 50 m during pre-monsoon conditions. On the other hand, during July, the currents are stronger even at 100 m depth. The currents are relatively weak below the surface layer in both the cases. Also included in Fig. 11 are daily averages of SST and thickness of surface layer during the two phases (the bottom scale gives the day and vertical scale on the right shows the temperature). It is clear from this figure that the thickness of surface layer progressively increases with the advance of monsoon and the rate of fall in SST is greater immediately after the onset of monsoon.

4. Discussion

The results in the present study area reveal that there is a slight increase in SST during pre-monsoon period and after the onset of monsoon, a decrease of SST is about 2 deg. C (Fig. 3). The thickness of surface layer has showed minor fluctuations during first two phases and ranged between 30 and 40 m. In contrast the thickness of surface layer has varied in the region between 60 and 30 m after the onset of monsoon (Fig. 5). One can see that the 28 deg. C isotherm (which may be taken as the bottom of surface layer) slopes upward towards the Indian coast (Fig. 5C). This feature coupled with those in Fig. 9 (showing the evolution of thermal structure in the polygon area) indicates that the thickness of the surface layer increases further west of the present study area after the onset of monsoon. Sastry and D'Souza (1970) in their studies on thermal structure of the Arabian Sea have depicted similar features during southwest monsoon season. All these studies show that this is a regular feature even though inter-annual variability may be present.

With the onset of monsoon season, a change in the wind regime takes place. The variation of wind stress curl in the polygon area shows some interesting features (Fig. 10). An examination of sequence of satellite photographs of the Arabian Sea during June 1977 as published by Krishnamurti *et al.* (1981) indicates that an atmospheric vortex has formed on 7 June in a region southeast of polygon area. By 9th, it was located closer to the polygon and later it has moved northwest. Under its influence, the wind stress curl (which was found to be slightly negative when the vortex was located SE of the polygon) changed its sign. After 12th June (*i.e.,* when the vortex is moving northwest of the region), the wind stress curl is again negative. This is a characteristic feature in the eastern Arabian Sea during southwest monsoon season (Sastry and Ramesh Babu 1979). The upward shift of the thermocline on 9th June 1977 when the vortex is near to the polygon (Fig. 11) is associated with the positive wind stress curl of passing vortex. Leipper (1967) for example, has mentioned that waters would upwell from a depth of 60 m around the centre of hurricane and the corresponding decrease in SST would be about 5 deg. C when thermocline reaches the surface. Chang and Anthes (1978) have also predicted numerically the same orders. However, in the present case, thermocline does not reach the surface. After the vortex has passed over the area, negative curl in the wind stress could be expected as observed in the polygon area and a progressive increase in thickness of surface layer would result.

During the second phase of MONEX '79 programme, as mentioned earlier, an atmospheric vortex has formed on 14 June 1979 which crossed the study area (Fig. 3). Under its influence, a positive curl in the wind stress centred around the moving centre of the vortex could be envisaged which should help in raising the thermocline along its track. An examination of average depth- temperature curves of phases IIA and IIB (Fig. 6) suggests upwelling in the depth zone of 40-100 m and this seems to be clearly due to movement of depression. Following the atmospheric disturbance, the general southwest monsoon winds are established over the eastern Arabian Sea which give rise to a strong southerly current off the west coast of India which is a well documented feature. When the southerly current sets in, baroclinic adjustment takes place whereby isotherms slope upward to the left of an observer facing southwards. Thus the sloping of isotherms and the consequent readjustment of thickness of surface layer is a process of baroclinic adjustment to southerly flow.

Associated with strong winds during monsoon, the surface circulation deepens as can be seen from Fig. 11. Effectively the strong current shear zone has shifted downwards by about 50 m after the onset of monsoon. It may also be noted that currents in the surface layer are highly variable in direction just before the onset of monsoon reflecting the response of the sea to the changing wind patterns associated with moving vortex whereas they are predominantly southerly/easterly after the onset of the monsoon. In the current shear zone, entrainment of cold sub-surface waters into the surface layer takes place and subsequent mixing between the cold deep waters and warm surface waters results in the lowering of the SST and the transfer of heat downwards giving rise to general cooling of surface layer. Thus the lowering of SST in the polygon area could be attributed to this downward flux of heat across the thermocline. Recently Murthy, Rao and Sastry (1981) have sought a balance between the heat storage in the upper layers and the heat fluxes across the sea surface during passage of vortex in the present study area. According to them, the total heat losses across the sea surface by the processes of latent heat, sensible heat and effective back radiation works out to be about 45% of the total change in heat storage of the surface layer and the remainder has been attributed to the downward flux of heat across the thermocline which is in accordance with the above view.

In order to understand and quantify the downward flux, the depth-temperature profiles at *Shirshov* station on 7 June and 14 July 1977 were examined as shown in the inset map of Fig. 9. In the upper layers (58 m), the heat loss is estimated at 9.1 kilo calories and below this layer, the water column has gained heat upto about 160 m. The total heat gain is estimated at 9.7 kilo calories. Thus the downward transfer of heat is about 0.6 kilo calories more than the total heat losses in the upper layers in 38 days which shows that on an average during this period there is a net heat gain by the sea from the atmosphere. This result is not so surprising as it appears to be when one examines the heat fluxes across the sea surface. According to Colborn (1975) in June a net heat loss from the sea into the atmosphere takes place while a net heat gain by the sea from the atmosphere occurs during larger part of southwest monsoon season. Studies by Ramanatham, Somanatham and Rao (1981) in the polygon area indicate that the total incoming radiation absorbed at the sea surface is on an average balanced by the heat fluxes due to evaporation, sensible heat and effective back radiation. In the present case, the balance between the heat losses in the surface layer and heat gain in the sub-surface layer could be achieved by a net input of about 16 calories per day at the sea surface which compares well with the net heat balance derived by the above authors. Thus the progressive growth of surface layer with decreasing SST's is reflected as a downward flux of heat.

In the inset map of Fig. 6, the depth-temperature profiles during the first phase and third phase are shown at two locations around 15 deg. N separated by a distance of about 150 km. At the eastern location, the surface layer is about 50 m whereas at the western location, it is about 65 m by July. At the western location, the July curve intersects the May curve at about 55 m below which a slight increase in temperature is seen upto a depth of 75 m. This feature is not evident at the eastern location. In both the cases, the SST in July is about 28 deg. C. At the western station, downward flux of heat could be clearly visualised whereas at the eastern station, the July profile shows the development of knee at 55 m where the temperature differences between May and July curves is minimum. The downward flux of heat at this station is not clearly evident due to predominant upwelling in the region. Sastry and D'Souza (1971) have shown an anti-cyclonic cell at 100 m centred around 11 deg. N and 67 deg. E during southwest monsoon season even though the surface dynamic chart does not show this feature explicitly. In the centre of gyre, they have further depicted maximum thickness of surface layer of about 100 m. One can visualise the development of anticyclonic cell in response to the monsoon wind system and sloping of thermocline towards west coast of India may be viewed as upwelling closer to the Indian coast and sinking at the centre of the gyre. The depth-temperature profiles presented herein as well as those for *Shirshov* station indicate that downward transfer of heat is more prominent westward from the Indian coast.

The increase in heat storage which resulted in higher cyclone heat potential by about 5 kilo cal cm^{-2} prior to the onset of monsoon over the region is clearly due to the net influx of heat into the sea across its surface. It is interesting to observe that the genesis area of the atmospheric vortex which moved across the area of study coincides with that portion of the study area where surface temperature exceeds 31 deg. C prior to the onset of monsoon. The formation of atmospheric vortices over the eastern Arabian Sea has been established as a quasi-synoptic feature observed just before the commencement of rains over the Indian sub-continent (Ananthakrishnan *et al.* 1968 and Philip, Srinivasan and Ramamurthy 1973). The reduced cyclone heat potential as observed in phase II between 68 deg. and 70 deg. E along 15 deg. N seem to be clearly related to the movement of disturbance across the area. With the advance of disturbance into the region, the 26 deg. C isotherm has risen upward by about 20 m and a slight fall in temperature is noticed at the sea surface (Fig. 6). This is a fast moving cyclone and energy extraction seems to be very much limited as can be seen by a small decrease in temperature upto a depth of 40 m. The low cyclone heat potential in July is primarily a result of cooling of surface layer by about 2 deg. C and secondarily due to fluctuations in 26 deg. C isothermal surface.

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