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Watermass modification in the upper layers of the Arabian Sea during ISMEX-73

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सार — भारत सोवियत मानसून परीक्षण (इस्मेक्स-73) के पूर्व और पश्च मानसून, आरंभ वाले क्षेत्रों के दौरान आच्छादित कुछ प्रतिरूपी मंडलीय और याम्योतरी अनुभागों सहित सोवियत संघ और भारतीय पोतों द्वारा किए गए पुनरावर्त ट्रांसेक्टों की सहायता से 1973 को ग्रीष्म मानसून ऋतु के दौरान अरब महासागर के ऊपरी स्तरों में थर्मोहेलाइन लक्षणों में पाई गई अन्तर मौसमी विभिन्नता को बताया गया है। सीमित उपलब्ध आंकड़ा सैटों के साथ 1971, 1972 और 1973 की ग्रीष्म मानसून ऋतुओं के दौरान इस प्रेक्षित विभिन्नता की तुलना करने की कोशिश की गई है। एक स्टेशन में भूमध्यरेखा (60° पू०) पर और दूसरे स्टेशन में उत्तरपूर्वी अरब महासागर (18° उ०, 67° पू०) पर पूर्व और पश्च मानसून आरंभ वाले क्षेत्रों के दौरान प्रेक्षित अल्पावधि विभिन्नता का वर्णन किया गया और विविध मौसमी मानसूनी बलकृत को अपने आकाशीय प्रभाव क्षेत्र में अरब महासागर बेसिन की अनियमित अनुक्रिया की विशिष्टताओं पर विचार विमर्श किया गया।

ABSTRACT. The intra-seasonal variability noticed in the thermohaline characteristics in the upper layers of the Arabian Sea during the summer monsoon season of 1973 is described with the aid of repeat transects made by USSR and Indian ships along some typical zonal and meridional sections covered during the pre and post onset regimes of Indo-Soviet Monsoon Experiment (ISMEX-73). An attempt is made to compare this observed variability during the summer monsoon seasons of 1971, 1972 and 1973 with the limited available data sets. The observed short-term variability during the pre and post onset regimes at one station (60°E) on the equator and another station (18° N, 67° E) in the northeastern Arabian Sea is described and discussed to highlight the uneven response of the Arabian Sea in its spatial domain to the variable seasonal monsoonal forcing.

1. Introduction

The summer monsoon produces large scale variations in the watermass characteristics of the upper layers of the Arabian Sea. Most of the description on the observed variability in the thermal regime of the upper layers of the Arabian Sea documented by several workers (Wooster *et al.* 1967, Wyrtki 1971, Colborn 1975, Robinson *et al.* 1979, Duing and Leetma 1980, Levitus 1982, Molinari *et al.* 1986, Rao 1988, Rao *et al.* 1989) provide information on climatological annual cycle from multi-year averaged data sets. Relatively few studies (Sastry & D'Souza 1970, Rao *et al.* 1976, Swallow *et al.* 1983, Sastry & Ramesh Babu 1985) were carried out to highlight the observed variability in the thermal regime of the upper layers of the Arabian Sea during summer monsoon season. These investigations were, however, based on observations made from research ships which usually do not have space-time continuity. In these studies considerable smoothing in space-time could have smeared out some interesting features. Further, sufficient information is not available on these aspects for any single year due to lack of adequate measurements. The corresponding information on the variability in the salinity field is still meagre due to lack of salinity measurements in the Arabian Sea (Sastry and D'Souza 1971, Levitus 1986, Rao and Sanil Kumar 1989). The transects repeated during May (pre-onset regime) and July/August (post-onset regime) were few even during International Indian Ocean Expedition (IIOE) to discern the temporal changes in the thermal and salinity fields in the Arabian Sea (Duing 1970, Wyrtki 1971). The field experiments conducted during the summer monsoon seasons of 1973, 1977 and 1979 provided very useful data on the observed intra-seasonal variability in the watermass structure at some stationary positions and along some typical zonal and meridional transects in the Arabian Sea. Different physical processes with varying importance in the space-time domain appear to play significant role in producing these observed variations. Coastal upwelling, lateral advection from boundary areas into interior of the basin, surface heat exchange processes, entrainment across the mixed layer base are all identified as important mechanisms responsible for the observed changes. Under the monsoonal drive, the clockwise gyral circulation advects high saline waters from the northern Arabian Sea southward. These high saline waters form a tongue shaped trajectory with a downward slope towards south while maintaining its *in situ* equilibrium. This high saline sub-surface core (> 36 ppt) below the mixed layer is usually observed in the east central Arabian Sea before the onset of the monsoon. With the onset and progress of the monsoon the vertical mixing penetrates downwards and destroys this sub-surface salinity

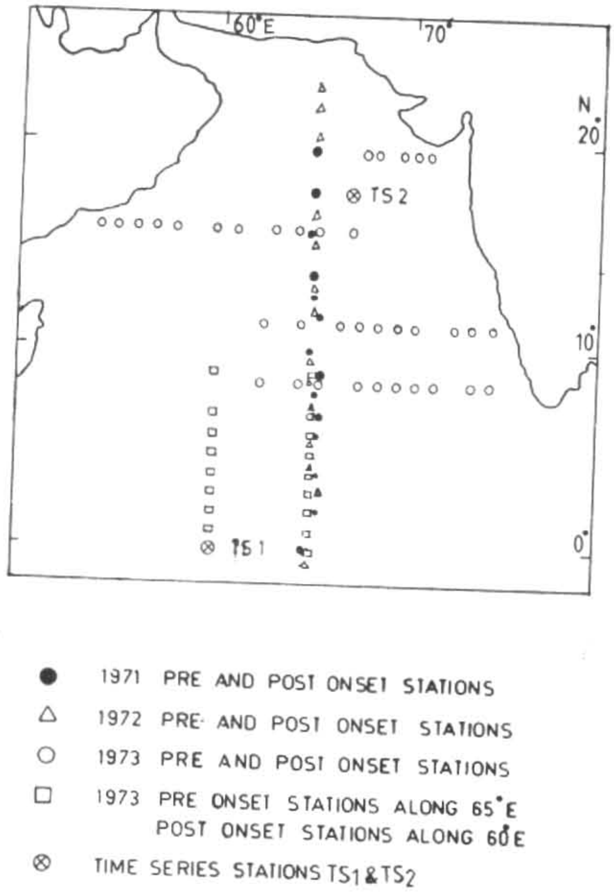

Fig. 1. Station location map

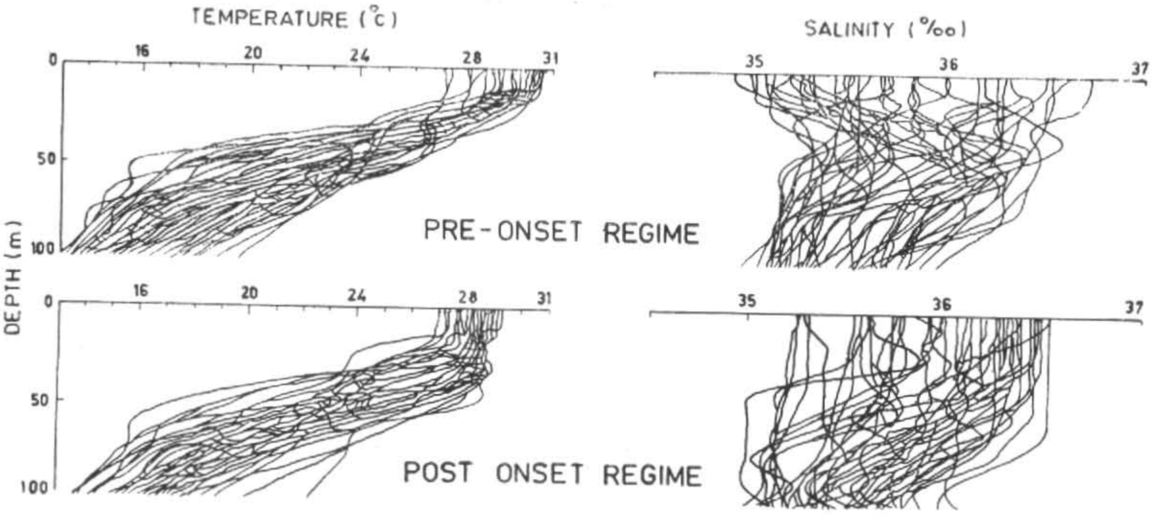

Fig. 2. Composites of vertical temperature and salinity profiles in the Arabian Sea for pre and post onset regimes during ISMEX-73

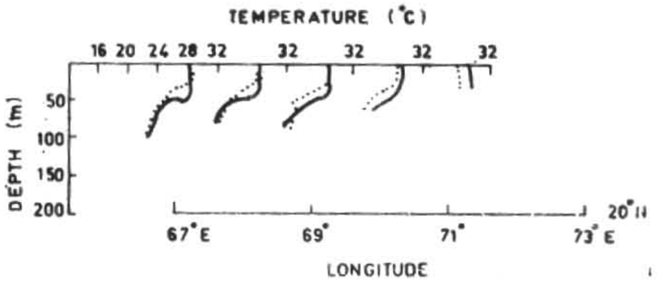

Fig. 3. Vertical profiles of temperature during pre (dotted line) and post onset (continuous line) regimes along 20° N

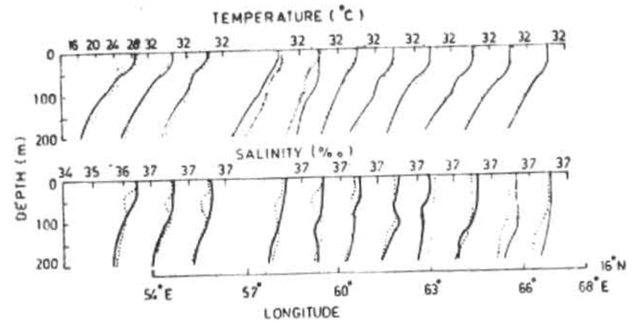

Fig. 4. Vertical profiles of temperature and salinity during pre (dotted line) and post onset (continuous line) regimes along 16° N

maximum enhancing the mean salinity of the upper layers. The local rainfall and evaporation also modify the salinity regime of the mixed layer. However, adequate data are not available to parameterise the relative importance of various processes which produce the observed changes in the temperature and salinity regimes in the upper layers of the Arabian Sea. Some studies were reported utilising limited data sets collected during ISMEX-73 (a joint Indo-USSR field observational programme) to explain the space-time variability either at a time series station or along few sections (Ramesh Babu *et al.* 1976, Ramam *et al.* 1979, Ramesh Babu *et al.* 1981, Gangadhar Rao *et al.* 1981, Rao 1986b, Rao & Hareesh Kumar 1989). In none of these studies an attempt was made to describe the basin scale response of the Arabian Sea to the variable summer monsoonal forcing utilising all the available data sets collected during ISMEX-73. In the present study advantage is taken of all the available repeat transects made along some typical zonal and meridional sections during ISMEX-73 to describe the observed variability in the thermal and salinity regimes of the upper layers of the Arabian Sea. Data sets collected along 65 °E during 1971 and 1972 corresponding to pre and post onset regimes were also utilised to compare the year to year variations in the observed thermohaline variability caused by the variable monsoonal forcing. In addition, short time series measurements made at one station on the equator and another in the northeastern Arabian Sea were also utilised to describe the short-term variability and to highlight the uneven response of the Arabian Sea in its spatial domain.

2. Data

Three zonal transects along 8° 30′ N, 11° 30′ N and 16°N latitudes and one meridional transect along 65°E longitude (Fig. 1) were repeated by 4 USSR ships during end May 1973 and end June/early July 1973. Hydrographic data at standard depths at an approximate interval of 1° Lat./Long. were collected along these transects. From these soundings data at every 5 m depth interval were generated following cubic spline interpolation scheme limiting to a maximum depth of 200 m. One Indian ship repeated bathycasts along a short zonal transect (20° N). Two stationary positions designated as TS1 (0° N, 60° E) and TS2 (18°N, 67°E) were occupied by two USSR ships during both the pre and post onset regimes. The data sets collected from the repeat transects were utilised to describe the basin scale variability in the near surface watermass characteristics. The short time series data sets collected during the pre and post onset regimes were utilised to describe the variations brought about in the upper layer characteristics with the onset of the monsoon. These data sets were also utilised to show the spatial differences in the nature of response between the equatorial and northeastern regions.

2. Analysis and discussion

3.1. *Temperature variability along east-west direction*

In order to gain a comprehensive idea on the changes brought about in the temperature and salinity fields in the topmost 200 m water column, all the available temperature and salinity soundings made during ISMEX-73 were assembled for pre and post onset regimes. The composites of these profiles are shown in Fig. 2. Cooling and deepening of the mixed layer are evident from pre to post onset regime. These composites suggest relatively weak horizontal temperature variations in the upper 30 m water column. The dispersion noticed in the near surface layer is reduced from pre to post onset regime suggesting the influence of monsoonal forcing mostly limited to the uppermost layers. The corresponding variability below 100 m depth is not perceptible (not shown in the figure).

The smoothed profiles of temperature corresponding to pre (dotted line) and post onset (continuous line) regimes collected along 20° N zonal transect are shown in Fig. 3. The origin is shifted to the right for the stations covered eastward. These profiles were repeated after an interval of about 6 weeks. The temporal changes observed in the thermal regime are distinct from this figure. A warming of 0.5° to 1°C within the mixed layer is noticed only at the eastern stations. The temperature of the mixed layer practically did not show any variation at the western stations, although the layer deepening was significant. The zonal section along 16° N (Fig. 4) was repeated over an interval of only 2 weeks. The variations were practically minimum in the profiles made off the Arabia coast with a moderate cooling (0.5°C) and penetrative deepening of the mixed layer (10-20 m) noticed in the central Arabian Sea. The profiles along 11°30′N repeated

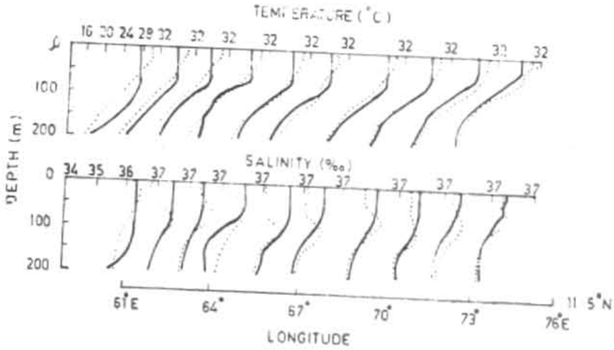

Fig. 5. Vertical profiles of temperature and salinity during per (dotted line) and post onset (continuous line) regimes along 11° 30 N

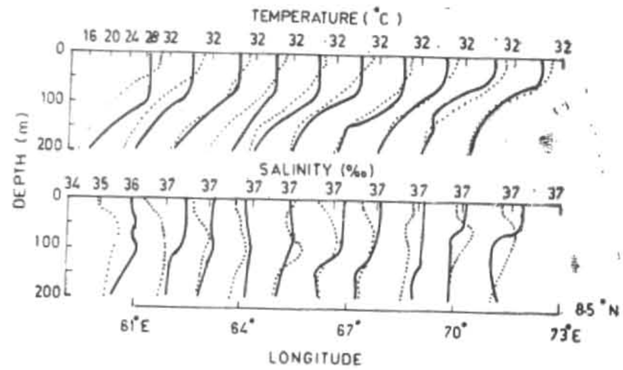

Fig. 6. Vertical profiles of temperature and salinity during pre (dotted line) and post onset (continuous line) regimes along 08° 30′ N

after an interval of 7 weeks are shown in Fig. 5. Large differences in the mixed layer cooling and deepening are noticed along this section compared to those of 20° N or 16° N. West of 70° E the deepening was strong (>50 m) while it was relatively weak (<30 m) east of 70° E. One remarkable feature of the pre and post onset profiles is that the cooling was confined to the uppermost layers in the central Arabian Sea while it was evident even up to 200 m depth at the two locations in the eastern Arabian Sea. Coastal upwelling off the southwest coast of India (Narayana Pillai *et al.* 1980) appeared to have inhibited deepening of the layer east of 70° E. Utilising time series data sets collected during MONSOON-77 observational programme from end May to mid-August 1977 (Rao 1986a) also showed a similar upwelling tendency in the thermal structure at a nearby station (17° N, 71° E). The profiles along 8°30′N were also repeated during the same period of the 11°30′N zonal section (Fig. 6). The temporal differences noticed along this section are comparable to those of 11° 30′N. Layer deepening was maximum in the central Arabian Sea which decreased eastward from about 100 to 50 m depth. Deepening of the layer was comparatively less at the two eastern stations off the southwest coast of India, suggesting the influence of coastal upwelling. In the central Arabian Sea, noticeable warming is observed in the upper thermocline as warmer near surface waters downwelled in association with mixed layer deepening and Ekman type of convergence. Such a downwelling phenomenon occurs in the central Arabian Sea as a dynamic response (Yoshida and Mao 1957) to the clockwise wind stress curl at the surface (Sastry and Ramesh Babu 1979). Bruce (1982) also showed a good geographic correspondence between the maxima of the surface wind stress curl and the mixed layer deepening on a seasonal scale in the central Arabian Sea.

3.2. *Temperature variability along north-south direction*

The temperature profiles along 65° E (pre-onset) and 60° E (post-onset) are shown in Fig. 7. As the ship traversed along 65° E and 60° E longitudes, repeat transects are not available. In this case the meridional sections were separated by about 300 nautical miles and were covered over an interval of 6 weeks. Under the assumption of weak zonal variations in the thermal

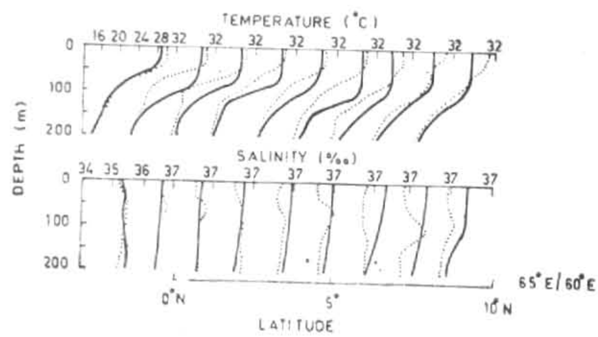

Fig. 7. Vertical profiles of temperature and salinity during pre (dotted line) and post onset (continuous line) regimes along 65 °E in 1973

response in the central Arabian Sea (*i.e.*, within 5° longitude), the profiles made along these two sections may be compared to evaluate the thermal response of the central Arabian Sea from the equator to 10° N. Mixed layer cooling increased from the equator (1° C) to 10° N (2.5° C). On the equator practically no difference in the mixed layer depth is noticed while the profiles at 10° N showed an increase of about 70 m in the layer depth. The deepening of the layer and downwelling observed in the thermocline produced significant warming beneath the mixed layer in the central Arabian Sea.

3.3. *Year to year variability along north-south direction*

Brown and Evans (1980) have reported large interannual variability in the seasonal surface cooling of the Arabian Sea. Joseph and Pillai (1986) also reported large differences in the summer monsoonal cooling between good (1973) and weak (1972) monsoon seasons. During 1973 the cooling in the western Arabian Sea was not only wider in extent but also intense compared to that of in 1972. To gain some insight into the year to year variability in the Arabian Sea summer cooling, data sets collected corresponding to pre and post onset regimes along 65° E during 1971 and 1972 are analysed (Fig. 8). During 1971 the ship started from northern end and traversed southward and then returned. Hence the repeat interval decreased southward with a minimum of 5 weeks at the southernmost station and a maximum

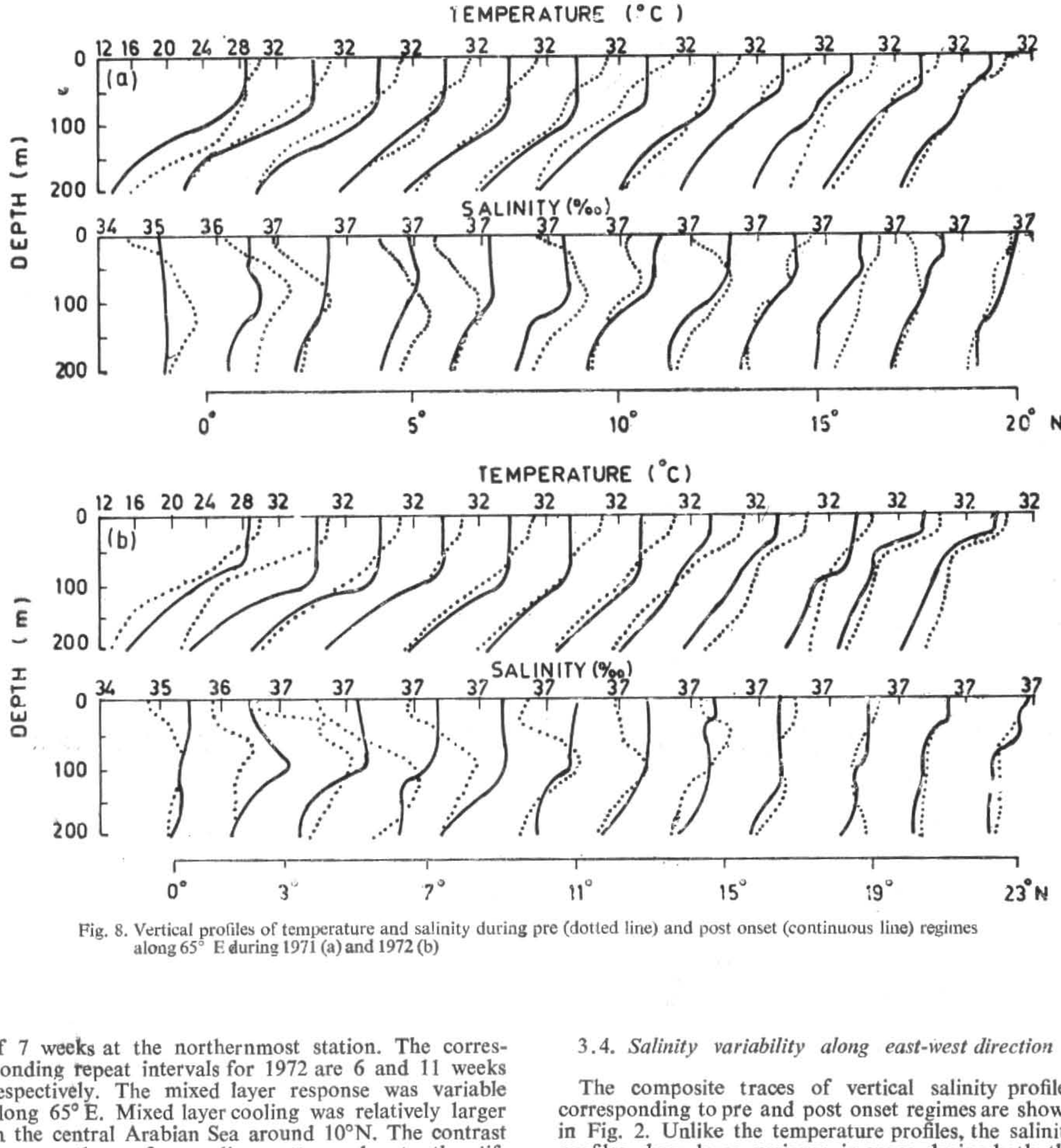

Fig. 8. Vertical profiles of temperature and salinity during pre (dotted line) and post onset (continuous line) regimes along 65° E during 1971 (a) and 1972 (b)

of 7 weeks at the northernmost station. The corresponding repeat intervals for 1972 are 6 and 11 weeks respectively. The mixed layer response was variable along 65° E. Mixed layer cooling was relatively larger in the central Arabian Sea around 10°N. The contrast between the surface cooling patterns due to the differential monsoonal forcing during 1971 and 1972 is evident from Fig. 8. The region of maximum cooling shifted northward during 1972 when compared with that of 1971. The monsoonal performance during 1972 was below normal producing drought conditions over India (Pharthasarathy and Mooley 1978). A delay of two weeks in the commencement of cruise during 1972 at the northern end compared to that of 1971 must also be taken into account while interpreting the observed differences between 1971 and 1972.

3.4. *Salinity variability along east-west direction*

The composite traces of vertical salinity profiles corresponding to pre and post onset regimes are shown in Fig. 2. Unlike the temperature profiles, the salinity profiles show large variance in space during both the regimes. This spatial variability is generally attributed to various watermasses, *viz.*, the Arabian Sea watermass, the southequatorial watermass and the Bay of Bengal watermass. But the sub-surface maxima noticed during the pre-onset regime almost disappeared during the post-onset regime.

The distribution of vertical salinity profiles corresponding to pre and post onset regimes made along 16°N is shown in Fig. 4. During the pre-onset regime a mild salinity minimum is noticed just below the isohaline

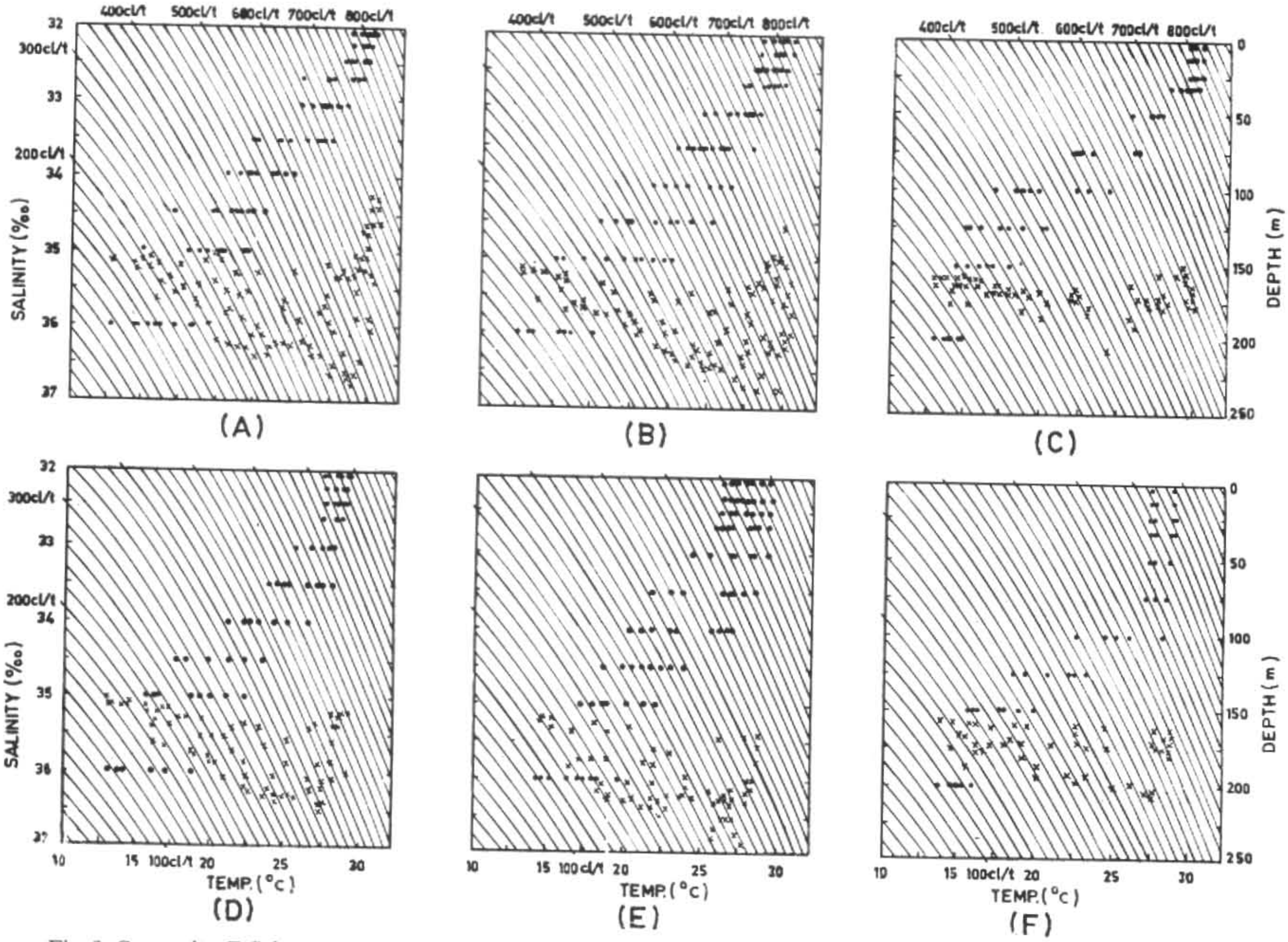

Fig. 9 Composite *T-S* (××××) and *T - D* (....) diagrams representing the pre and post onset regimes along 8° 30′ N (a & b), 11° 30′ N (c & d) and 16° N (e & f)

layer. This minimum diffused with its depth of occurrence increasing eastward. This salinity minimum practically disappeared east of 60°E. Swallow *et al.* (1983) suggested the presence of low saline waters near the surface in the Somali basin during southwest monsoon of 1979. It is not clear whether these low saline waters have encountered any mixing while advecting northeastward. This minimum disappeared during the post-onset regime when the isohaline layer deepened due to strong vertical mixing caused by the monsoonal wind stress. In general a relative increase is noticed in the mean salinity profile. The profiles corresponding to pre and post onset regimes along 11° 30′ N are shown in Fig. 5. During the pre-onset regime the sub-surface maximum in the salinity field is evident. This maximum is attributed to the southward advection of high saline Arabian Sea watermass (Rochford 1964, Wyrtki 1971). This maximum disappeared during the post-onset regime producing an increase in the salinity of the near surface water column. This increase may be viewed as a combined contribution from advection of high saline waters from north and vertical mixing of the sub-surface high saline waters. The rise in the mean salinity of the near surface water column showed a decrease eastward, thus implying the contribution of advection of high saline water mostly limiting to east central Arabian Sea. This pre-onset maxima descended eastward occupying deepest depth around 72°E and further east of it this maximum ascended under the influence of upwelling off the southwest coast of India. The profiles corresponding to pre and post onset regimes made along 8° 30′N are shown in Fig. 6. During the pre-onset regime the sub-surface salinity maxima were less organised along this section compared to those of 11° 30′ N. During the post-onset regime the salinity increased in the near surface water column with deeper isohaline layers. The sub-surface maxima did not completely lose its identity but diffused considerably. However, some very notable differences are evident at the two easternmost stations off the southwest coast of India. Relatively stronger haloclines are noticed probably produced by the presence of low saline Bay of Bengal/equatorial Indian Ocean waters in the surface layers (Levitus 1986, Cutler and Swallow 1984).

3.5. *Salinity variability along north-south direction*

The pre and post onset profiles collected along 65°E during 1973 are shown in Fig. 7. The meridional variation during the pre-onset regime is reflected in the location of the sub-surface maximum. In general, the strength of the maximum increased from the equator to 10°N

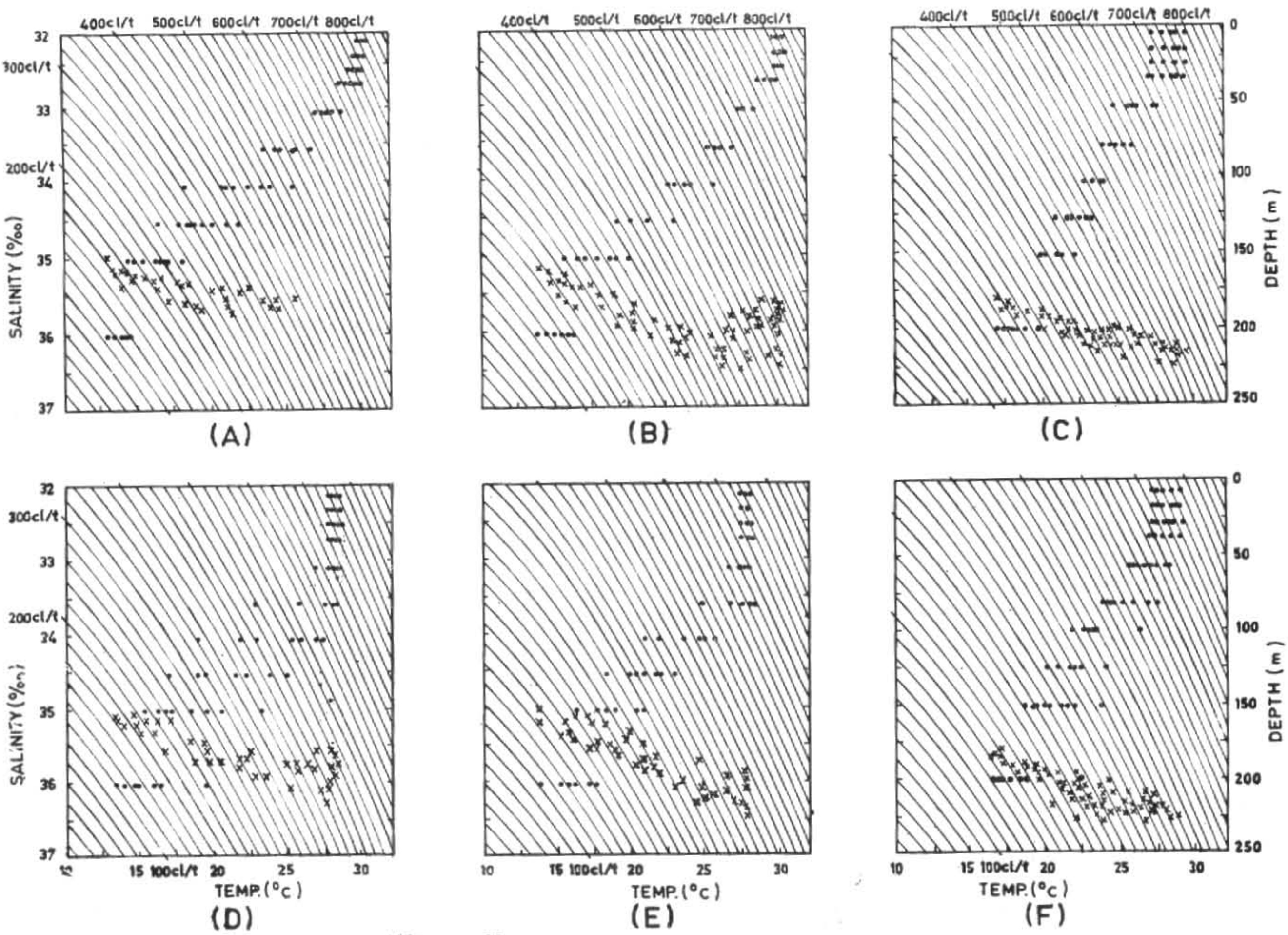

Fig. 10. Composites *T-S* (× × ×) and *T-D* (····) diagrams representing the pre and post onset regimes along 65° E during 1971 (a & b), 1972 (c & d) and 1973 (e & f)

with few exceptions. This sub-surface maximum disappeared during the post-onset regime. A general increase in the mean salinity of the water column is noticed with an increasing tendency towards north. Variations were minimum at the stations located in the vicinity of the equator and were maximum around 10°N. The observed halocline below the surface isohaline layer also showed a strengthening tendency towards north. The pre and post onset profiles collected along 65°E during 1971 and 1972 are presented in Fig. 8. Between the equator and 14°N the sub-surface maximum with an upsloping tendency towards north is evident during the pre-onset regime. Under the monsoonal forcing this maximum got mixed up producing deep isohaline layers. The thickness of the isohaline layer decreased from the equator towards north. The temporal changes in the near surface salinity regime were relatively large in a narrow latitudinal belt bounded by 8°-12°N and these changes decreased either side. Similarly the relative increase in the near surface salinity field between 8° & 12°N was also larger during 1972 compared to the corresponding increase in 1971.

3.6. *T-S analysis*

Composite *T-S* diagrams representing the pre and post onset regimes for each zonal and meridional transect are presented in Fig .9. Along 8° 30′N the *T-S* plot shows large scatter during the pre-onset regime especially in the salinity field suggesting that the upper waters are more heterogeneous before the monsoonal onset (Figs. 9 a & b). There is a significant increase in the density of the upper 50-60 m water column from pre to post onset regime. The sub-surface high salinity maxima corresponding to the Arabian Sea high salinity watermass is observed around 400-440 cl/t surface during the pre-onset regime. The whole upper layer lies around 400-440 cl/t after the monsoonal onset following an increase in salinity and decrease in temperature. Similar features can also be observed along 11° 30′N section (Figs. 9 c & d). However, during the pre-onset regime the *T-S* scatter is larger along this section compared to that along 8° 30′ N indicating a stronger zonal asymmetry in the upper ocean water characteristics at this latitude. The differences in the *T-S* field show smaller variations along 16° N (Figs. 9e & f) mainly due to short repeat interval between the samplings (*i.e.*, about two weeks).

The *T-S* plots along 65° E section during 1971, 1972 and 1973 also show the presence of the Arabian Sea high salinity watermass around 400-440 cl/t especially during the pre-onset regime (Figs. 10 a & b). The scatter in the salinity field is also large during pre-onset regime. A closer examination indicates that the upper layer salinity during the pre-onset regime was lowest in 1971 compared to 1972 or 1973, while the post-onset salinity was highest in 1972. The overall salinlty change from pre to post onset regime was minimum in 1973. Supplementary data sets are not available to explain the observed year to year differences.

3.7. *Short-term variability*

From the above analysis it is amply clear that the thermohaline response is of variable nature in the Arabian Sea. To demonstrate this type of differences further within the basin, two time series stations were chosen from the data availability point of view, one on the equator (TS1) and the other in the northeastern Arabian Sea (TS2), where short time series measurements were made during pre and post onset regimes. These data sets provide an excellent opportunity for comparison purposes. The relevant surface marine meteorological data were available only for the equatorial station.

The mean vertical temperature and salinity profiles corresponding to pre and post onset regimes at TS1 and TS2 are shown in Fig. 11. Although the mixed layer cooling was of the same order at both the stations considerable differences are evident in the deepening of the layer. The layer did not show any marked deepening at TS1 whereas at TS2 it deepened by about 50 m. The deepening of the layer at TS2 was mostly attributed to Ekman type of convergence in the upper layers in the wake of a translating onset vortex traversed in the vicinity of the observational station (Rao 1986 b). This type of convergence depresses the stratified waters leading to an increase in the mixed layer depth. Strong similarity in the thermal gradients beneath the mixed layer of both the regimes provides adequate support for this inference. At TS1 the thermocline diffused from pre to post onset regime. The salinity variations at TS1 were very small with a mild change of around 0.1 ppt in the upper 100 m water column.

The surface meteorological forcing is found to be an important agency which produces variations in the upper ocean. In order to gain a better description on the variability of the thermal structure, the observed surface meteorological and derived heat budget estimates are analysed only for TS1 (Fig. 12) as no meteorological data are available for TS2. With the northward propagation of ITCZ the surface pressure (PR) at TS1 registered an increase. Winds (FF) fluctuated between 3 to 8m/s. A marginal increase in the cloud cover (CL) from pre to post onset regime is evident. Growing saturation of the surface air with the progress of monsoon is also clear with the progressive reduction in the wet bulb depression (DB-WB). The sea minus air temperature (SMA) was mostly positive suggesting weak unstable regime. The SST fluctuated between 30° and 30.5° C during the pre-onset regime. A drop of over 1° C in SST during the intervening period is also evident. Moderate cooling continued during the post-onset regime.

As no direct measurements of solar radiation (Q_I) are available, an attempt was made to derive Q_I with the aid of Hastenrath and Lamb's (1979) values calibrated to the daily observed cloud cover at this station. During the pre-onset regime the initial and ending days were relatively disturbed as evident from strong wind speed and as the derived Q_I values were also lower. Depending upon the cloud cover, the Q_I mostly fluctuated between 180 and 280 W/m. The other heat loss terms such as net longwave rediation (Q_L), sensible heat flux (Q_S) and latent heat flux (Q_E) were derived following Rao *et al.* (1985). The Q mostly fluctuated around

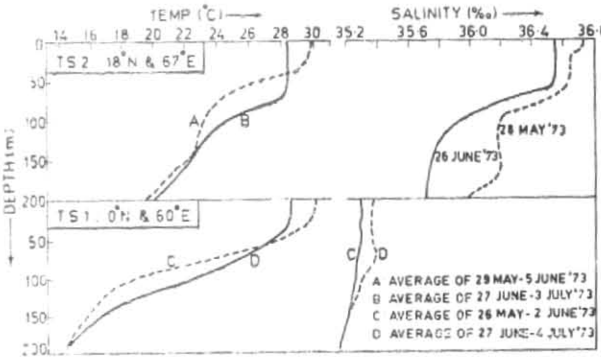

Fig. 11. Phase averaged vertical profiles of temperature and salinity for the pre (dotted line) and post onset (continuous lines)regimes at TS1 and TS2

— 40 W/m². The magnitude of Q_S was comparatively lower which fluctuated around the zero line. The Q_E was large during the disturbed days when winds were stronger. The surface heat budget term Q was positive throughout during both the regimes leading to net accumulation of heat of 0.8×10^8 J/m² and 0.7×10^8 J/m² during the pre and post onset regimes respectively. However, during the pre-onset regime SST showed practically no variation from 29 May to 5 June, and during the post onset regime the SST dropped by about 0.4°C from 27 June to 3 July 1973. These observations suggest the importance of other processes which control SST. In the present study the colder waters upwelled off Somalia coast advected eastward might have offset the surface heat gain producing equilibrium during the pre-onset regime and cooling during the post-onset regime. Lack of corresponding measurements on the horizontal gradients around TS1 disabled the estimation of advective and other process.

4. Conclusions

With the onset and sway of the summer monsoon the watermass modification in the upper layers of the Arabian Sea varied in the spatial domain. The mixed layer temperature increased in association with deepening from pre to post onset regime only in the northeastern Arabian Sea (*i.e.*, along 20° N).

Cooling and deepening of the mixed layer are evident over most of the Arabian Sea from pre to post onset regime. The cooling and deepening of the layers are maximum in the 8°-12° N belt. However, weak deepening is noticed in the eastern Arabian Sea (east of 70° E) and northern Arabian Sea (north of 20° N) as the seasonal upwelling off the southwest coast of India inhibits deepening of the layer in the former region.

At the equator, the mixed layer depth did not show much variation from pre to post onset regime except a cooling of about 2°C during 1973 whereas moderate deepening was noticed in 1971 and 1972.

In the southern and central Arabian Sea the pre-onset profiles showed a well defined sub-surface salinity maxima. Under the monsoonal forcing, this sub-surface maxima was eroded and the advection from north enhanced the surface layer salinity. However, in the northern Arabian Sea the changes in the salinity profile were minimum. The *T-S* analysis showed the presence of

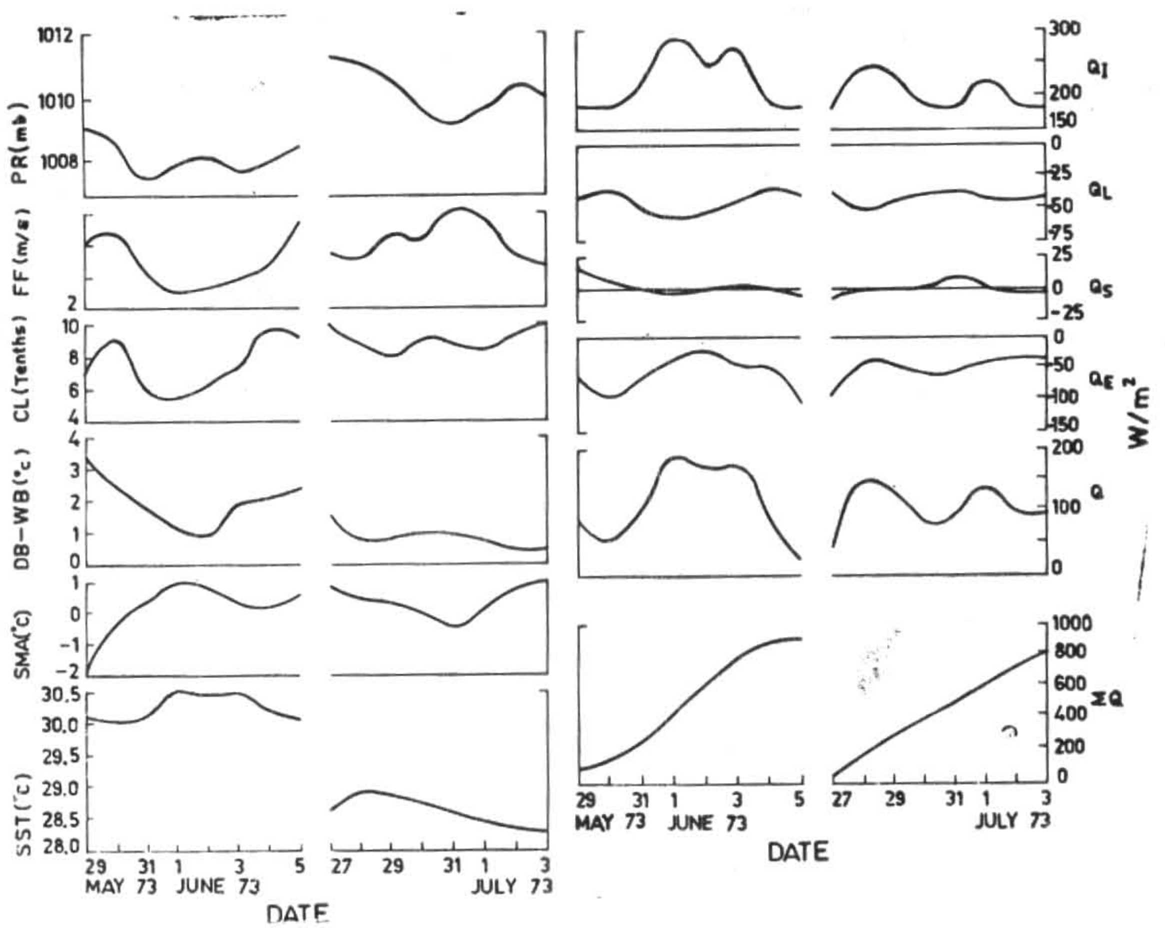

Fig. 12. Daily march of surface meteorological elements and derived heat budget estimates at TS1

Arabian Sea high salinity watermass around 400-440 cl/t during the pre-onset regime. The salinity field showed larger scatter during pre-onset regime compared to that of post-onset regime with some interannual variability.

At TS1 a cooling of about 2° C is noticed between the pre and post onset regimes, although the layers deepening was less than 10 m. During both the regimes the short time series data showed undisturbed conditions resulting heat gain to the sea. However, the observed cooling suggests the importance of lateral advections of cold waters from west to this site. At TS2 a cooling of about 2° C and deepening of the layer by about 50 m from pre to post onset regime is noticed in the wake of onset vortex.

The analysis revealed considerable variations in the watermass characteristics in the topmost 100 m water column.

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