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Sea surface temperature and southwest monsoon over India

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सार — भारत पर दक्षिणपश्चिम मानसून की संरचना और अनुरक्षण से सम्बन्धित अरब सागर, बंगाल की खाड़ी और उत्तरी हिन्द महासागर पर समुद्र सतह तापमान (एस.एस.टी.) के महत्व का अध्ययन किया गया है। केरल में मानसून के आरम्भ से पहले, भारत के पश्चिमी तट के निकट दक्षिणपूर्वी अरब सागर पर समुद्र सतह तापमान अधिकतम हो जाता है। दक्षिणी गोलार्द्ध ऊष्म जल द्वारा विषुवत रेखा को पार करना मानसून के शीघ्र या विलम्ब से आरम्भ होने से सम्बन्धित है। आरम्भ होने से पूर्व के सप्ताहों के दौरान समुद्र सतह तापमान और पवन तापमान के मध्य अन्तर की मात्रा शीघ्र/विलम्ब और अधिक/न्यून मानसून की ओर महत्वपूर्ण संकेत करता है। मानसून के आरम्भ से पूर्व 100 मीटर की गहराई तक की विशाल ऊष्मा जल संहति भारत के पश्चिमी तट की ओर बढ़ती है। 1979 में, इस जल संहति के पीछे और सामने की गति भारत पर मानसून की विभिन्न अवस्थाओं से सम्बन्धित है।

ABSTRACT. Importance of sea surface temperature (SST) over the Arabian Sea, Bay of Bengal and the north Indian Ocean is studied in relation with the formation and maintenance of the southwest monsoon over India. SST over southeast Arabian Sea close to the west coast of India becomes maximum before the onset of monsoon over Kerala. Crossing of the equator by southern hemispheric warm water seems to be related with the early or late onset of the monsoon. Magnitude of the difference between SST and air temperature during pre-onset weeks gives valuable hints for early/late and excess/deficient monsoon. A large warm water mass up to the depth of 100 metres shifts towards the west coast of India before the onset of the monsoon. In 1979, back and forth movement of this water mass seems to be related with the different phases of the monsoon over India.

Key Words — SST — Sea surface temperature, MONEX — Monsoon experiment, GFDL — Geophysical fluid dynamics laboratory, ISMEX—Indo-Soviet monsoon experiment.

1. Introduction

Large scale atmospheric circulations like the southwest monsoon over India are driven by the exchange of heat and moisture with the ocean surface. Based on data collected during Indo-Soviet monsoon experiment of 1973 (ISMEX), Ghosh *et al.* (1978) highlighted the importance of Arabian Sea in providing much needed heat and moisture for the southwest monsoon over India. Saha (1970) computed the zonal anomalies over the equatorial Indian Ocean and the Arabian Sea and offered plausible explanation for some monsoon features. Mohanti *et al.* (1983) studied the energetics of the monsoon circulation over the Arabian Sea and adjoining land areas. Earlier, Pisharoty (1965) suggested that the water vapour carried over India by monsoon winds was largely by evaporation over the Arabian Sea. Using the GFDL (Geophysical fluid dynamics laboratory) general circulation model Shukla (1975) demonstrated the effect of SST anomalies over the Somalia coast and the western Arabian Sea on the rainfall in India. It was also demonstrated that a colder SST anomaly results in an increase in surface pressure over the Arabian Sea.

Observations confirm that from the second-half of May to early August, SST over the western Arabian Sea decreases by about 3° C. This fall in temperature has been located up to a depth of 100 metres. Contrary to the observed northward flux of heat, cooling over the western Arabian Sea is a negative (southward) heat flux across a 'window' of 10° longitudinal extent. Three important mechanisms have been suggested : (a) eastward propagation of cold upwelled water from the coast of east Africa due to Ekman drifts, (b) anticyclonic gyre off east Africa coast as a result of the forcing by the curl of the wind stress and (c) cooling by evaporation.

In this paper an attempt is made to show by presenting observational data that a warm water mass crosses the equator in the pre-monsoon months and arrives the southeast Arabian Sea close to the west coast of India prior to the onset of the monsoon. This water

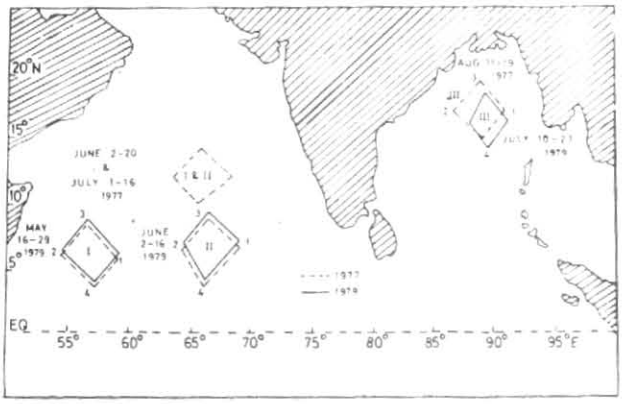


Fig. 1. Positions of the ships' polygons during 1977 and 1979 monsoon experiments

body was found warmer than the surroundings up to a depth of 100 metres.

2. Data and analysis

Data (SST) and air temperature collected during MONEX/FGGE period for the area 20° S-25°N & 40°-110° E have been used. Fortnightly mean data for 1979 have been analysed. In addition, monthly mean data for the years 1983 to 1988 (up to September) have been extensively used as the volume of data during these years was not enough for deriving fortnightly means. The area of analysis has been divided into 5-degree latitude-longitude squares and then analysed. For the years 1983, data for the area bounded by 5° S-25° N & 50°-105° E have been analysed. Normal values of SST were obtained from an atlas compiled by Hastenrath and Lamb (1979).

Data collected by five USSR research vessels in stationary polygon positions up to a depth of 800 metres during MONEX-1979 have been used. Positions of the ships' polygons are shown in Fig. 1.

3. Interpretation of the analysis

Analysis of SST over the study area has been done for (a) SST over Arabian Sea, Bay of Bengal and the north Indian Ocean, (b) Air-sea temperature difference, (c) SST anomaly over the area, and lastly (d) Water temperature up to a depth of 390 metres as available for Monex period.

3. 1. *Analysis based on monthly means*

3.1.1. *SST over south eastern Arabian Sea*

Seasonal (June-September) rainfall, normal rainfall and percentage departure of rainfall of India as a whole for seven years 1979 and 1983-1988 are given in Table 1. From this table it may be seen that 1983 and 1988 have excess monsoon rainfall (>110% of normal) while other years have either normal or deficient monsoon rainfall (<90% of normal). Fig. 2 presents mean monthly SST for southeastern Arabian Sea bounded by 65°-70°E longitude and 0°-10°N latitude, for the years 1979, 1983, 1986, 1987 and 1988. It is seen from the figure that from April and May, there is a sharp rise in SST over the central Arabian Sea. A peak was reached around the second and third week of May. Thereafter, a gradual fall in SST is seen until mid-August. A secondary maximum is, however, noticed in mid-October. On analysing Fig. 2 one notices that the SST in 1988 was highest from February to May and then again in July and August. Almost similar is the case during pre-monsoon months of 1983, which is an excess monsoon rainfall year. In 1979, one of the worst deficient rainfall year in the past decade, SST was the lowest. SST curves for 1987, another deficient monsoon year, was between the highest and lowest but mean May was just above 30° C which seems not adequate for a good monsoon. A similar situation is seen for 1986, another deficient monsoon year. However, SST curves for other normal years (not presented) also show patterns similar to that of 1986.

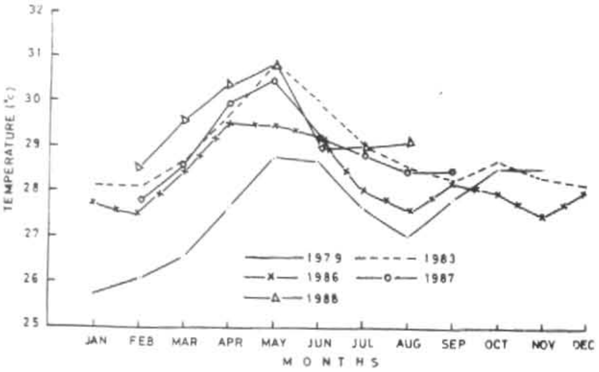


Fig. 2. Monthly mean SST over southeastern Arabian Sea

TABLE 1

Seasonal (Jun-Sep) rainfall (mm) over India

Year	Actual	Normal	Percentage departure from normal
1979	6611	8472	—22
1983	9778	8740	+12
1984	8355	8984	—07
1985	8623	9306	—07
1986	7521	8916	—16
1987	7251	9185	—21
1988	11072	9404	+18

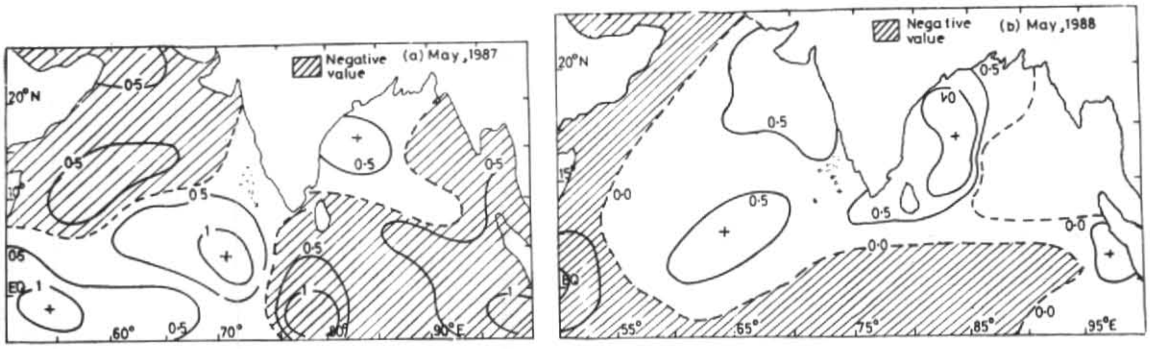
3.1.2. *Zonal SST anomaly*

We define a zonal SST anomaly($\triangle T_s$) by :

$$\triangle T_s = \overline{T}_s - T_s$$

where, T_s is the sea surface temperature at a 5-degree square of latitude and longitude, $\overline{T_s}$ is the zonal mean of SST along the latitude belt in which the 5-degree square falls. Zonal anomaly of SST, therefore, provides an indication of warm or cold sea over the same latitude belt.

Saha (1970) had computed the zonal anomalies over the equatorial Indian Ocean and the Arabian Sea. We wish to extend this to monsoon of 1979 and 1983 to 1988 by analysing the anomalies based on larger data sets.



Figs. 3 (a & b). SST anomaly during : (a) May 1987 and (b) May 1988

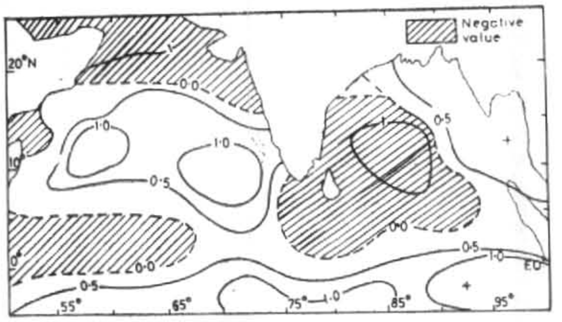


Fig. 4. Difference of SST and air temperature during May 1988 (shaded areas indicate negative values)

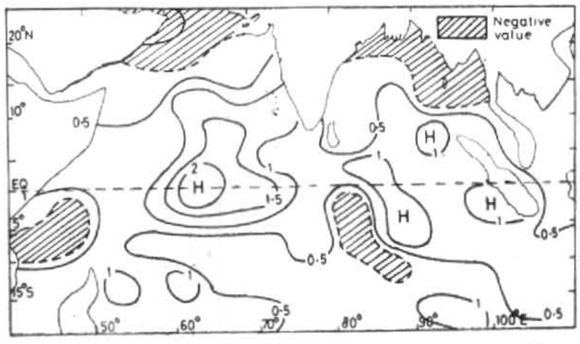


Fig. 5. Difference of SST and air temperature (°C) during onset (31 May-14 June 1979)

Positive anomaly indicates high SST values. These are also areas of high evaporation. Although water vapour divergence occurs in areas of high evaporation, latent heat is available to the atmosphere for heating in areas of condensation and evaporation only. Thus, diabatic heating of the atmosphere in areas of condensation and upward transport of sensible heat will lead to lowering of atmospheric pressure. The north-south gradient of sea level pressure may contribute to the process of strong cross-equatorial flow of air. This phenomenon of strengthening of SST anomaly was found to be related to the strength of the low level cross-equatorial jet before the onset of the monsoon. To demonstrate, two contrasting cases of a deficient monsoon (1987) and an excess monsoon (1988) rainfall *vis-a-vis* zonal SST anomaly, we present Figs. 3 (a & b). The shaded area indicates negative zonal anomaly while the remaining area remains positively anomalous. We note that while in May 1987 only a small portion of Arabian Sea was occupied by positive values, in May 1988 practically the whole of Arabian Sea was occupied by positive values resulting in strong north-south gradient of surface pressure.

3. 1. 3. *Difference of SST and air temperature*

The difference between SST and air temperature (SST — TT) determines the amount of evaporation from the sea surface. We note that an area of high temperature difference crosses the equator and approaches the west coast of India in the weeks preceding the onset. This difference may be of the order of 1°-2°C. In 1988, we note (Fig.4) that this area of high temperature difference crossed equator and lay centred around 10°N in the month of May. In this year, monsoon arrived over Kerala early. Exactly similar situation existed during May 1983, another excess monsoon year. However, in this year monsoon arrived late over Kerala. But in May 1983, unlike in May 1988, a large area of eastern and southern Bay of Bengal was covered with negative values of temperature difference. This situation probably did not favour an early onset of the monsoon over Kerala coast. The picture in 1979 was, however, different as most of the Arabian Sea and adjoining Indian Ocean area was covered with negative difference.

3. 2. *Analysis based on fortnightly means*

3. 2. 1. *SST over Arabian Sea*

An important feature observed during analysis of the various phases of the 1979 monsoon was the eastward propagation of a belt of high SST off the east coast of Africa from early May to mid-July. The fall in SST over the western sector was most marked during the period, because temperatures fell by nearly 4.5° C (from 30° C to 25.5° C) over this region. The onset phase of the monsoon was one of high SSTs over east central and eastern Arabian Sea off the coast of Africa. A similar high SST situation prevailed over the northern sector of the Bay of Bengal.

Prior to the break monsoon period, we noticed a fall in the SST by about 2°C at both the above locations.

3. 2. 2. *SST anomaly*

Analysis of fortnightly SST anomaly during 1979 present some interesting results. With the establishment of a cross-equatorial jet during pre-onset period, the SST anomaly strengthens in the next two weeks. During this period (1979) we found strong positive

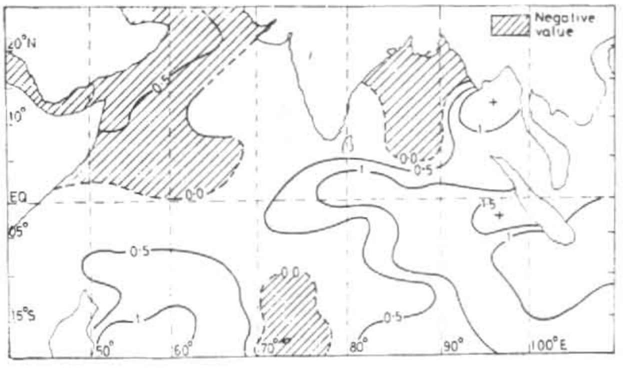


Fig. 6. Difference of SST and air temperature (°C) during a break monsoon (16-29 July 1979). Shaded areas indicate negative values

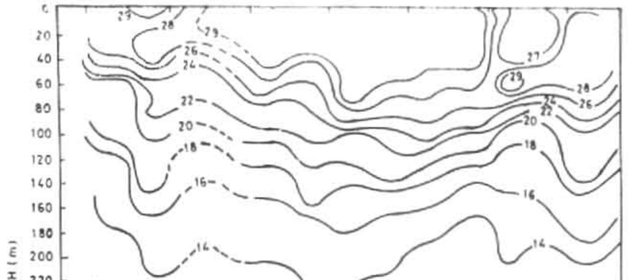


Fig. 7. Meridional variation of temperature structure of equatorial Indian Ocean during an active monsoon spell (15-29 June 1979)

anomaly over the central Arabian Sea and the Bay of Bengal while strong negative anomaly persisted over western Arabian Sea and the south Indian Ocean.

The first fortnight of July 1979, presents a different picture altogether. Here, one notes the strongest negative anomaly just over the coast of Somalia, while the strongest positive anomaly moved to the southern hemisphere off the coast of Sumatra. Even the north Bay of Bengal was covered by negative SST anomaly. This situation favours the formation of west-east oriented Walker circulation over the equatorial region inhibiting cross-equatorial monsoon flow. During the second fortnight of July 1979 the strongest negative anomaly moved northwards and the strongest positive anomaly moved southwards (10° S). A prolonged "break" in the monsoon prevailed over the Indian subcontinent during this period in 1979.

In early August 1979 when the monsoon revived partly, the strongest negative anomaly was seen near 10°N in the western Arabian Sea, while a strong positive anomaly was located over the north Bay of Bengal.

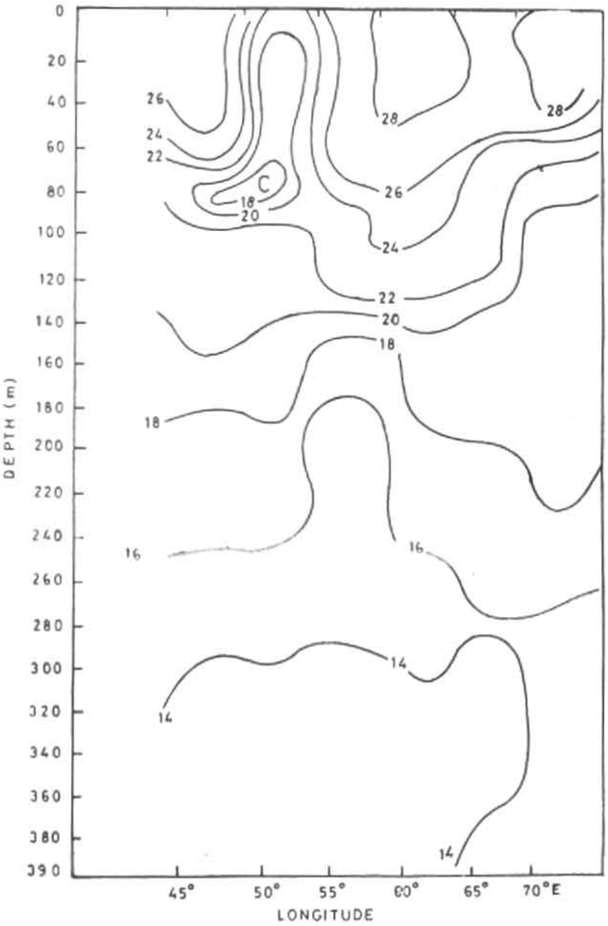


Fig. 8. Temperature structure of Arabian Sea (between 10° & 15° N) during active monsoon (21 June-5 July 1979)

3. 2. 3. *Difference of sea surface and air temperature*

Analysis of fortnightly temperature difference between sea surface and the adjoining air provided some hints on early or late and normal or deficient monsoon. We present the difference between two phases of the monsoon, namely (a) pre-onset and onset phase and (b) a "break" monsoon period (16-30 July 1979).

The main features are depicted in Figs. 5 & 6. (a) In Fig. 5 (31 May-14 June 1979) we note an area of high temperature difference crossing the equator between 60° and 70° E longitude. The difference of SST and air temperature in this area being 2°-3° C, the corresponding upward fluxes of sensible and latent heats were around 12 ly day^{-1} and 300 ly day^{-1} respectively. Early in the summer the difference was high in the southern hemisphere while the eastern coast of continents were covered by negative values. The belt of high difference started moving northwards with the approach of the monsoon.

(b) During the second-half of July 1979 a different picture emerged. We noted that most of the Arabian Sea and the north Indian Ocean was covered with negative difference, which implies that the air over the sea surface was warmer. This indicates that during this period, the Arabian Sea and the north Indian Ocean instead of being a heat source became a heat sink. Over the Bay of Bengal we note weak positive difference while

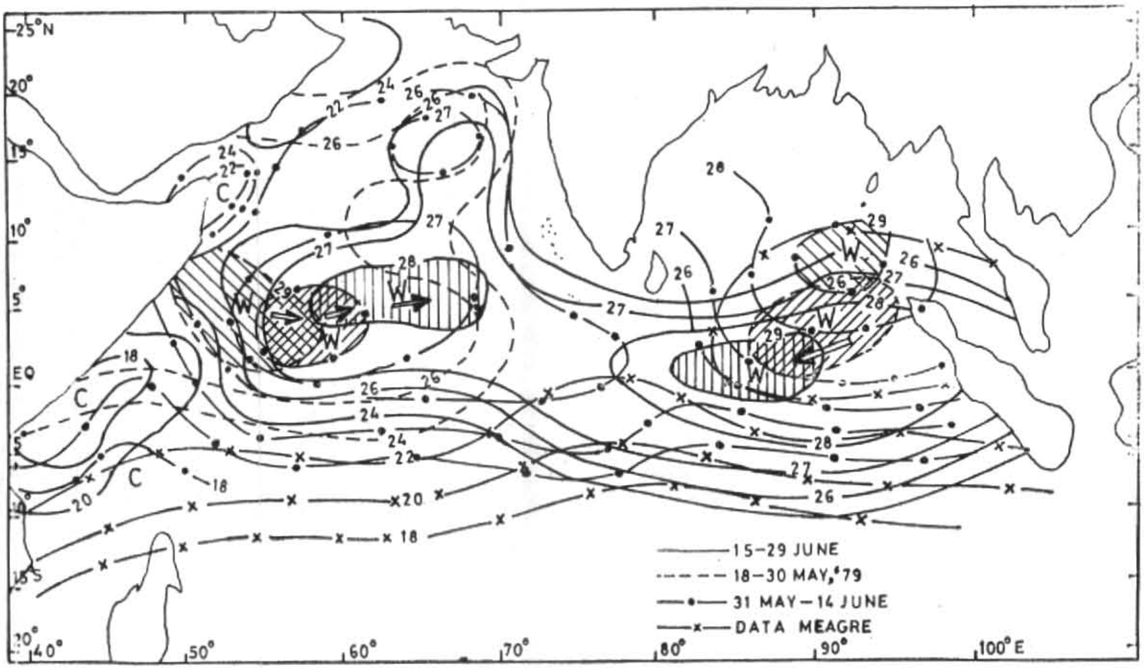


Fig. 9. Eastward movement of the mixed layer warm waters after the onset of the monsoon 1979 (Movement is shown by arrow heads)

over the south eastern Indian Ocean off Sumatra the difference was strongly positive. Thus, the strong positive difference over eastern Indian Ocean and strong negative difference over western Indian Ocean and the Arabian Sea strongly favours an east-west Walker circulation. The northern part of the Indian Ocean including the Arabian Sea was, thus, extracting heat from the atmosphere which is contrary to the seasonal behaviour in this part of the globe. This was the period of a prolonged "break" in monsoon in 1979.

3. 2. 4. *Temperature profile*

We present two diagrams (Figs. 7 and 8) representing vertical temperature structure of southern (5°-15°N) Arabian Sea and equatorial Indian Ocean (Fig. 7) as recorded by Monex research vessels for an active monsoon (21 June - 5 July) period in 1979. It is seen from Fig. 8 that a thick isothermal layer exists up to 50 m depth east of 55° E. Below this level a strong temperature gradient (of about 2° C/10 m) is seen up to 150 m indicating equatorial upwelling. It may be also noted that at every level up to a depth of about 130 m water is warmer east of 55° E. We present vertical structure of the temperature of the equatorial Indian Ocean waters in Fig. 7. We note from this diagram also that a huge water mass up to a depth of 70 m is warmer between 60°E and 95°E compared to its surroundings. The temperature structure of the equatorial Indian Ocean during pre-monsoon period of 1979 is presented in Fig. 7. We note that the warmest zone of water lies west of 55°E during the period. We also note that at every level up to about 130 m depth water west of 55°E is warmer than that to the east of it. The shifting of the warm water eastward is thus evident from these diagrams.

The shift of a zone of warm water upto the mixed layer depth is presented in a composite diagram (Fig.9). The positions of the warm waters are shown for different periods of the monsoon of 1979. We note that this warm water mass, which was close to the coast of east Africa during the pre-onset phase, reached southeastern Arabian Sea at the time of onset and was very close to the southwest coast of India after the onset period. Similarly, another zone of warm water was seen to move southwestwards in the Bay of Bengal. The movement of this warm water mass can be related to the activities of the monsoon over India. This warm water body transfers heat and moisture to the atmosphere which is so important for the maintenance of the southwest monsoon over India. Strong surface winds at the time of onset and during the active monsoon period bring about an increase in evaporation from the warm surface waters.

4. Concluding remarks

(*i*) Sea surface temperature over southeastern Arabian Sea close to the west coast of India becomes maximum before the onset of the monsoon over India. In excess monsoon rainfall years eastward propagation of a belt of high SST from east coast of Africa is noticed since early May. Crossing of the equator by warm southern hemispheric surface waters during early summer indicates an early or normal onset of the monsoon over India. Delay in this crossing seems to indicate late onset or subsequent weak monsoon situation.

(*ii*) *Difference of SST and air temperature (SST—TT)*— Early (late) crossing of the equator by an area of high temperature difference indicate an early (late) onset. The larger the area covered by the positive difference, higher is the chance of a subsequent monsoon to be good.

(*iii*) Extent and strength of the zonal SST anomaly over Arabian Sea and Bay of Bengal are found to be related with the strength of the low level cross-equatorial jet before the onset of the monsoon. Greater (smaller) anomaly area in pre-monsoon months seems to be associated with good (deficient) rainfall during subsequent monsoon.

(*iv*) *Warm water body close to Indian coast* — Waters up to a depth of 130 m are considerably warmer to the east of 55° E compared to those west of it during the onset and active phases of the monsoon. We found that a zone of warm water up to the mixed layer depth, crosses equator and moves eastward. This vast warm water body when close to the west coast of India supplies heat and moisture required for onset and maintenance of the southwest monsoon over India.

References

Ghosh, S.K., Pant, M.C. and Dewan, B.N., 1978, "Influence of the Arabian Sea on the Indian summer monsoon", *Tellus*, **3**, pp. 117-125.

Hastenrath, S. and Lamb, P.J., 1979, "*Heat Budget Atlas of Tropical and Eastern Pacific Oceans*", Wisconsin University Press.

Mohanti, U.C., Dube, S.K. and Singh, M.P., 1983, "A study of heat and moisture budget over the Arabian Sea and their role in the onset and maintenance of the summer monsoon", *J. Met. Soc. Japan*, **21**, 2, pp. 208-221.

Pisharoty, P.R., 1965, "Evaporation from Arabian Sea and the Indian southwest monsoon", *Proc. Symp. Met., Results of IIOE*, Bombay, pp. 22-26.

Saha, K.R., 1970, "Air and water vapour transport across the equator in the western Indian Ocean during northern summer", *Tellus*, **22**, pp. 681-687.

Shukla, J., 1975, "Effect of Arabian Sea SST anomaly on Indian summer monsoon : A numerical experiment with GFDL model", *J. atmos. Sci.*, **32**, pp. 503-511.