

## Air-sea interaction on a seasonal scale over north Indian Ocean — Part II : Monthly mean atmospheric and oceanic parameters during 1972 and 1973

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सार — मानसून-हिन्द महासागर अन्तर्क्रिया पर विस्तार से विचार विमर्श किया गया है। इसके लिए विपरीत मानसूनी वर्षा वाले दो लगातार वर्षों, 1972 तथा 1973 का महासागर तथा वायुमण्डल का 5 डिग्री वर्ग मासिक माध्य आंकड़ों का उपयोग किया गया है। 1972 में मानसून मुख्यतः असफल रहा और सूखा पड़ा तथा 1973 में मानसून के समय भारत में सामान्य से अधिक वर्षा हुई।

ऐसा पाया गया कि 1972 के मानसून के पहले के महीनों में उत्तरी हिन्द महासागर सामान्य से अधिक ठण्डा था (ऋणात्मक स. स. तापमान असंगति)। इस अवधि में उपरि क्षोभमण्डलीय उप-ऊष्णकटिबन्धीय पछुआ पवनें (मासिक माध्य) दक्षिण एशिया के ऊपर भूमध्य रेखा क्षेत्र की ओर, अरब सागर देशान्तरों के ऊपर सुदूर दक्षिण में अतिक्रमण कर जाती हैं। जून से सितम्बर 1972 के कमजोर मानसून ने ऊष्णकटिबन्धीय हिन्द महासागर के ऊपर एक गर्म स. स. तापमान विसंगति पैदा कर दी। यह विसंगति कम उत्थवण, विशेषकर सोमालिया तथा अरब के तटों के, कम पवन मिश्रण, कम वाष्पन तथा कम मेघ निर्माण के कारण मानसून ऋतु में महासागर की सतह के कम ठण्डा होने की वजह से पैदा हुई। इस प्रकार बनी विस्तृत स्थानिक विस्तार वाली धनात्मक स. स. तापमान विसंगति अक्टूबर 1972 से मई 1973 तक बनी रही। इस अवधि में दक्षिण एशिया के ऊपर उपरि क्षोभमण्डलीय परिभ्रमण में ऊष्णकटिबन्धीय पूर्वी पवनें (पछुआ पवनों के बजाय) और उत्तरी भारत में उप-ऊष्णकटिबन्धीय पछुआ पवनों के जेट-प्रवाह की बड़ी हुई गति थी। ये परिणाम प्रेक्षकों तथा प्रशांत महासागर के ऊपर गर्म स. स. तापमान वाली विसंगति वाले सामान्य परिसंचरण मॉडल अनुसंधानों से सहमत होते हैं। 1973 का मानसून अच्छा था तथा अक्टूबर 1973 से ठण्डी विसंगतियां एक बार फिर उत्तरी हिन्द महासागर के ऊपर दिखाई पड़ीं।

**ABSTRACT.** Monsoon-Indian Ocean interaction is examined in detail using 5-degree square monthly mean data of ocean and atmosphere of two consecutive years of contrasting monsoon rainfall, 1972 and 1973. There was a major monsoon failure (drought) in 1972; in 1973 India had excess rainfall during the monsoon season.

It is found that north Indian Ocean is colder than normal (negative SST anomaly) during the months prior to monsoon of 1972. During this period upper tropospheric sub-tropical westerlies (monthly mean) intruded equatorwards over south Asia, farthest south over the Arabian Sea longitudes. The weak monsoon of June to September 1972 produced a warm SST anomaly over tropical Indian Ocean on account of decreased cooling of the ocean surface layer during the monsoon season due to decreased upwelling, particularly off the coasts of Somalia and Arabia, decreased wind mixing, decreased evaporation, and decreased clouding. The positive SST anomaly of large spatial extent thus created persisted from October 1972 to May 1973. The upper tropospheric circulation over south Asia during this period had equatorial easterlies (instead of westerlies) and increased strength of the sub-tropical westerly jet stream over north India. These results agree with observations and GCM simulations over Pacific Ocean with warm SST anomalies. Monsoon of 1973 was good and cold SST anomalies again appeared over north Indian Ocean from October 1973.

### 1. Introduction

1.1. In Part I of the paper, Joseph and Pillai (1984) studied inter-annual variations of Sea Surface Temperature (SST) over north Indian Ocean during the period 1961 to 1973 and the relationship between the intensity of the monsoon as shown by the area weighted monsoon rainfall of India derived by Parthasarathy and Moolley (1978) and the SST field. It was found that SST over

north Indian Ocean had undergone a triennial oscillation during this period, similar to the triennial oscillation in the atmospheric parameters over south Asia observed by Joseph (1975, 1976). Indian monsoon rainfall (June to September) was also found to be significantly negatively correlated with the SST over north Indian Ocean of the post-monsoon season (October to December). To understand the physical mechanisms responsible for these, the authors have studied in this

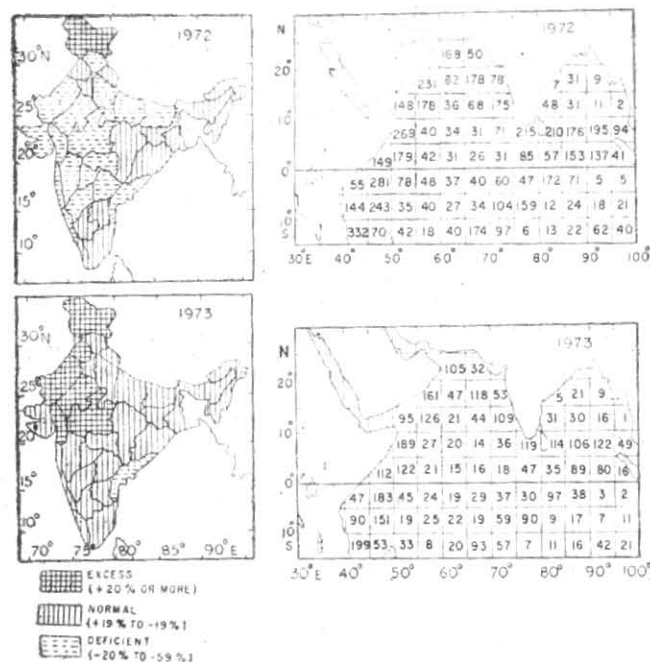


Fig. 1. Departures from normal of monsoon rainfall 1 June to 30 September of sub-divisions of India for 1972 and 1973

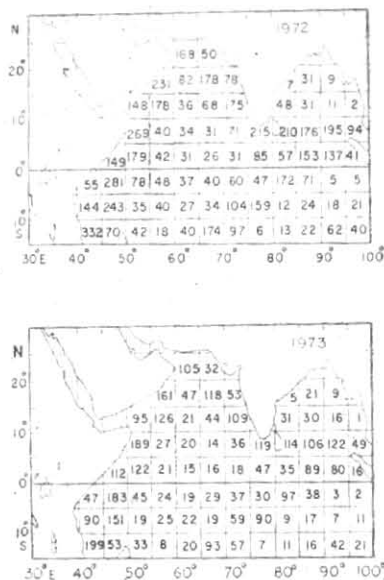


Fig. 2. Average number of SST observations per month over 5-degree latitude-longitude squares during 1972 and 1973

paper the parameters of the ocean and the atmosphere over north Indian Ocean during two consecutive years of contrasting monsoon seasonal rainfall.

1.2. The years 1972 and 1973 were chosen for this detailed study of the oceanic and atmospheric parameters and their mutual interactions. 1972 was a major drought year in India; in 1973 India had more than normal rainfall during the monsoon season June to September. The area weighted monsoon rainfall for the whole of India for the period 1 June to 30 September as derived by Parthasarathy and Mooley (1978) is 66.29 cm for 1972 and 91.59 cm for 1973; the long term normal rainfall as derived by them using data for 105 years (1866 to 1970) is 88.75 cm. Fig. 1 gives departures from normal of monsoon rainfall of sub-divisions of India for the years 1972 and 1973 (Here the normal used to obtain rainfall departures is the 1901-1950 normal). Fig. 1 shows the area affected by large rainfall deficiencies in 1972. Central and northwest India had large rainfall deficiencies. In contrast, in 1973, practically the whole of India had either normal or excess rainfall.

1.3. Monsoons of 1972 and 1973 had other differences as well, as per accounts given in *Indian Journal of Meteorology & Geophysics*, 1973 and 1974. In 1972 the monsoon arrived in Kerala, at the southern tip of India, as late as 18 June (normal date for onset here is 1 June). The advance of monsoon over south Peninsula and northeast India was delayed by a fortnight, over north Peninsula by about 10 days and over the central parts of India by about a week. However, its advance to northwest India was near the normal date.

Another major anomaly of 1972 monsoon was the long 'Break Monsoon' spell which lasted from 17 July to 4 August. The monsoon withdrew from northwest India about a week earlier than normal. In 1973 monsoon advanced into Kerala on 23 May, a week before the normal date. The advance of monsoon over Peninsular India was normal. However, its advance into Assam was delayed by a week, into Uttar Pradesh by 10 to 15 days and to most parts of northwest India by about 5 days. Monsoon withdrew from north India about a week to 10 days later than normal. There was a short 'Break Monsoon' during the last week of July.

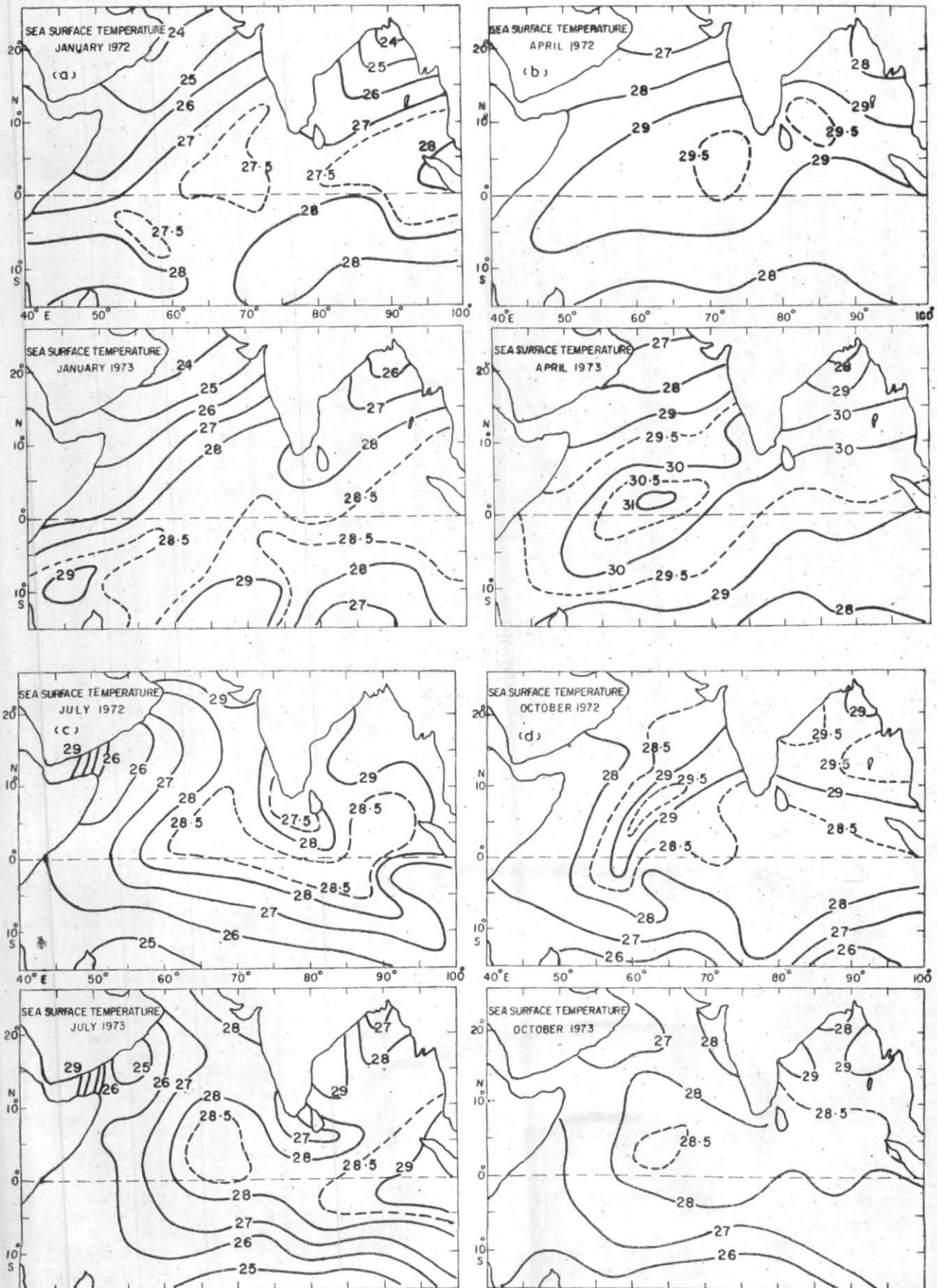
## 2. Data used

2.1. The data used in the study have been described in Part I. About 7000 ship observations giving SST measurements are available for each month of 1972 and about 4500 for each month of 1973 for the Indian Ocean area north of 15° S as given in Table 2 of Part I. Observations in surface wind, cloudiness etc are more in number. The average number of SST observations per month in each 5-degree latitude-longitude square during 1972 and 1973 are shown in Fig. 2. This study uses monthly mean data for 5-degree squares of sea surface temperature, total cloudiness (in oktas), wind speed (scalar and vector mean), and dew point temperature. In drawing isopleths of various fields, data of 5-degree squares which have less than 5-observations in a month have not been used. Such 5-degree squares have been very few in number.

## 3. Sea Surface Temperature (SST) during 1972 and 1973

3.1. Fig. 3 gives the monthly mean SST over north Indian Ocean during January, April, July and October of 1972 and 1973. The isotherms of SST have been drawn using the monthly mean 5-degree square values. Fig. 3(a) gives SST of January. Practically all over the area SST is about 0.5 deg. C to 1 deg. C colder in January 1972 than in January 1973. Maximum SST in January 1973 is 28.5 deg. C to 29.0 deg. C while in January 1972 it is 27.5 deg. C to 28.0 deg. C. The axis of maximum SST in both the cases is south of the equator. By April sea has warmed considerably as may be seen from Fig. 3(b). The axis of maximum SST is now in the northern hemisphere, near the equator over western Arabian Sea and at 5 deg. N to 10 deg. N over Bay of Bengal. April 1973 is generally warmer than April 1972 by 1 deg. C and at some areas by 1.5 deg. C. During monsoon as seen from Fig. 3(c) — the July SST charts, reversal of SST (1972 warmer and 1973 colder) is seen over a small area off the coasts of Somalia and Arabia. After the monsoon season the pattern is reversed over a large area as may be seen from Fig. 3(d). October 1972 is warmer in SST than October 1973, particularly over Arabian Sea. One factor comes out clearly from this analysis, that the SST anomaly changes across the monsoon (June to September) season. A poor monsoon season warms the sea (SST) and a good monsoon cools the sea. This was also seen in Part I; the SST anomaly is changed mainly by the monsoon season and the SST anomaly created by one monsoon does not change appreciably till the next monsoon.

3.2. From an examination of the annual variation of the monthly mean SST values of each 5-degree square for 1972 and 1973, it is seen



Figs. 3(a-d). Monthly mean sea surface temperature isotherms for January, April, July and October of 1972 and 1973. Full lines are for whole °C and broken lines are for half °C



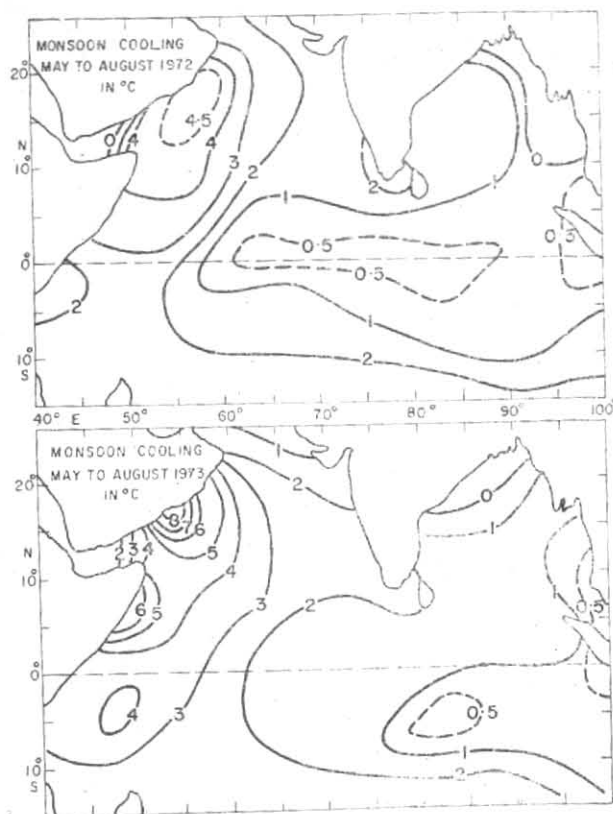


Fig. 4. Isolines of monsoon cooling of SST (May minus August) in °C

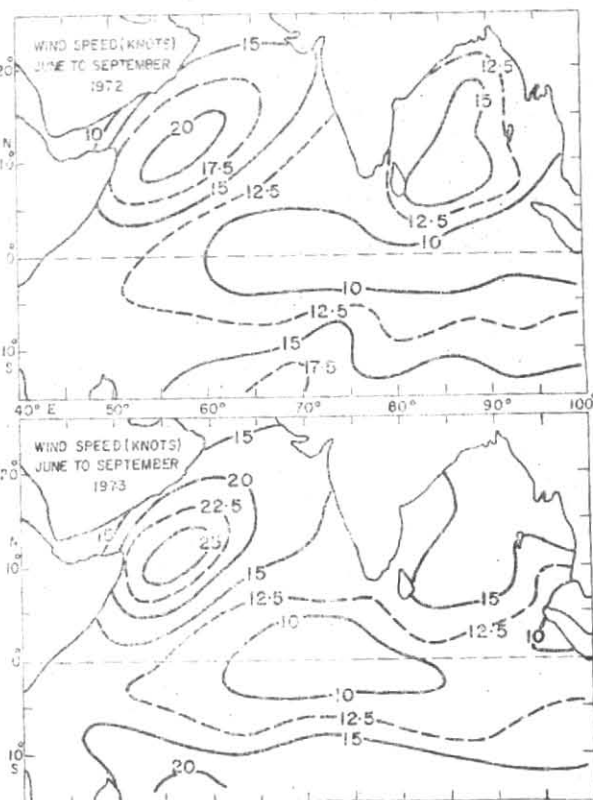


Fig. 5. Isotachs (in kt) of the scalar mean wind speed of the 4 monsoon months June to September for 1972 and 1973

that SST anomalies are created by the differences in the extent of monsoon cooling from May to August. If this cooling is large, a negative SST anomaly is created and if this is small, a positive SST anomaly is created. Fig. 4 gives the isolines of the monsoon cooling in SST (May minus August) in 1972 and 1973. The isolines have been drawn using the values of monsoon cooling at each of the oceanic 5-degree squares. In both the years the monsoon cooling is largest over western Arabian Sea and decreases eastwards. In 1972, over the upwelling areas off the coasts of Somalia and Arabia the monsoon cooling is about 4 deg. C only whereas in 1973 the cooling is through 6 deg. C to 8 deg. C. In the rest of the areas also monsoon cooling is more in 1973 than in 1972, by about 1 deg. C in a large part of the area. A similar result has been obtained by Anjaneyulu (1980) comparing SST of two good monsoon years 1963 and 1964 with that of two poor monsoon years 1965 and 1966 at a few locations over Arabian Sea.

3.3. In section 4 the factors responsible for the monsoon cooling of the north Indian Ocean in general and the Arabian Sea in particular are examined to find the difference between 1972 and 1973, years of poor and good monsoon respectively.

#### 4. Other atmospheric and oceanic parameters of 1972 and 1973

4.1. *Surface wind speed* — Fig. 5 gives the isotachs of the scalar mean wind speed of the monsoon season June to September of 1972 and 1973, drawn using

the 5-degree square mean wind speeds. Both in 1972 and 1973 the speed maximum of western Arabian Sea is very prominent. There are lesser speed maxima in central Bay of Bengal and in the Indian Ocean south of the equator. Western Arabian Sea shows great contrast, where wind speed is about 25% more in 1973 than in 1972. This would have effect on the upwelling off the coasts Somalia and Arabia. Stronger winds also induce stronger mixing in the surface layer of the ocean and greater evaporation, both conducive to larger cooling in SST. Therefore, the overall effect of the wind speed difference between the monsoons of 1972 and 1973 is greater cooling of north Indian Ocean during the monsoon season in 1973 than in 1972, particularly over the western Arabian Sea.

4.2. *Evaporation* — From the monthly mean 5-degree square averages of wind speed (scalar mean), SST and dew point temperature reported in ship synoptic observations, the total evaporation during the four monsoon months June to September in grams per square centimetre of the ocean surface has been calculated. The bulk aerodynamic formula for evaporation 'E' in gram per square centimetre from sea surface per second is taken as

$$E = K \rho_a (q_s - q_a) V_a$$

where  $q_s$  is the saturation specific humidity at the SST with reference to a salinity of 35 per mille,  $q_a$  is the specific humidity at the level of ships deck (obtained from dew point temperature),  $V_a$  is the wind speed at ship's deck level and  $\rho_a$  is the density of air. The constant  $K$  has been taken as  $1.4 \times 10^{-3}$ . Fig. 6

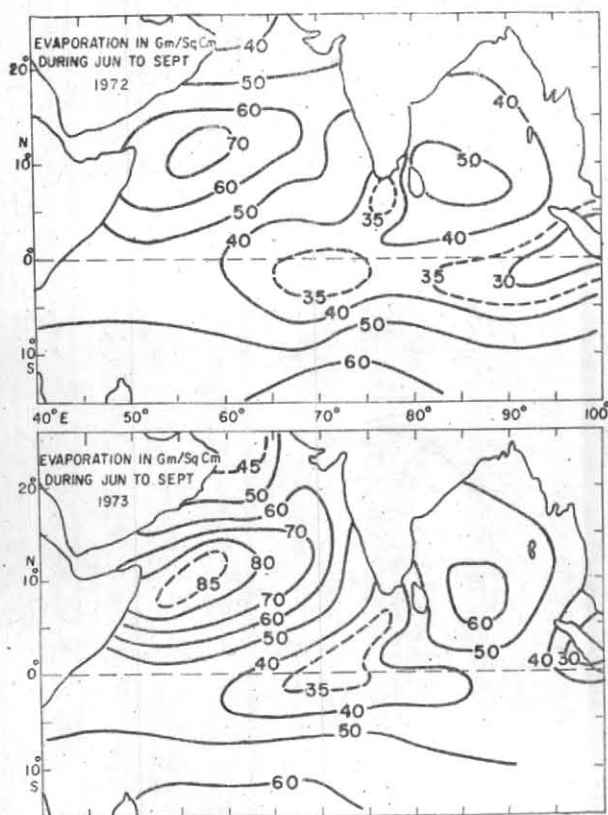


Fig. 6. Isolines of total evaporation during the 4 monsoon months June to September for 1972 and 1973

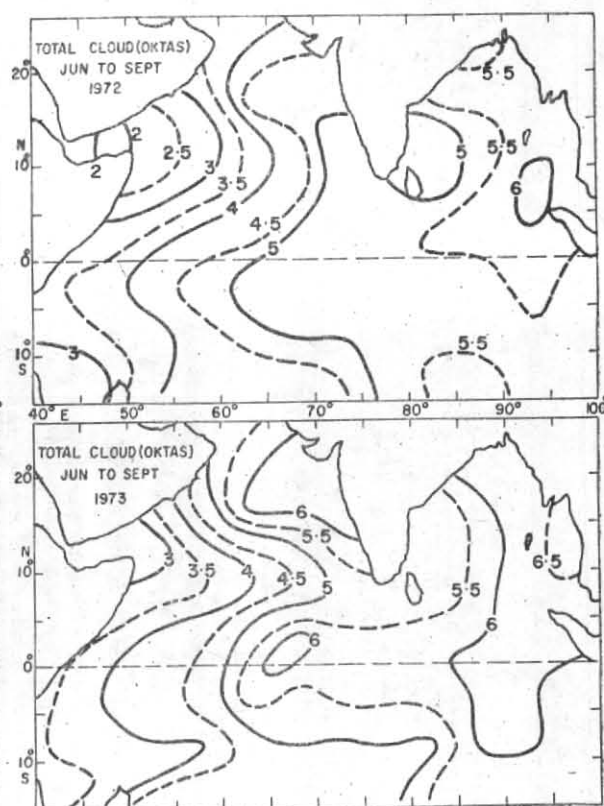


Fig. 7. Isolines of total cloud cover (in oktas) as a mean of the 4 monsoon months June to September for 1972 and 1973

gives the isolines of the evaporation during the monsoon seasons of 1972 and 1973. These isolines are almost parallel to the isotachs of the scalar mean wind speed (Fig. 5), showing the dominant control by the wind speed of the evaporation process. Evaporation is more in 1973 by about 20% compared to 1972 over Arabian Sea and Bay of Bengal. There is not much difference in evaporation between 1972 and 1973 south of the equator. Evaporation causes cooling of the sea and thus has a control on SST.

4.3. *Cloud cover* — Fig. 7 gives the isolines of mean cloud cover (all clouds) in oktas during the monsoon season June to September of 1972 and 1973. All over the area, clouding is more in 1973 than in 1972. The effect of cloud cover on SST is complicated, as the amount of cloud cover controls both the solar radiation and the cloud radiation falling over the sea, but the overall effect of a larger cloud cover may be decreased warming of the sea surface.

4.4. All the above factors are favourable for greater cooling of the north Indian Ocean during the monsoon season of 1973 than during the monsoon season of

1972, agreeing qualitatively with the SST variation observed during 1972 and 1973.

#### 5. Formation of a deep mixed layer over Arabian Sea

5.1. Rao *et al.* (1976), using all the available bathy-thermograph data have constructed mean bathy-thermograms for the months of May, June and July for each 5-degree square in the zonal belt 10 deg. N to 15 deg. N over the Arabian Sea. These mean bathy-thermograms are given in *Mausam*, 31, p. 556. West of 55 deg. E to a depth of 250 metres the July temperatures at any depth are lower by about 2 deg. C than those of May. SST falls from 28.8 deg. C in May to 26.3 deg. C in July. In the square 55 deg. E to 60 deg. E the mean bathy-thermograms are similar in the top 100 metres and SST falls from 29.4 deg. C in May to 24.8 deg. C in July. The area west of 60 deg. E is indicative of upwelling. In the square 60 deg. E-65 deg. E, the July bathy-thermogram is seen to have an isothermal layer from surface to about 80 metres below and steep temperature gradient is observed below 80 metres. SST has fallen from 30 deg. C in May to 27.6 deg. C in July. Below 60 metres the July temperature is higher by 3 deg. to 4 deg. C than corresponding temperatures in May. A similar change is seen in the

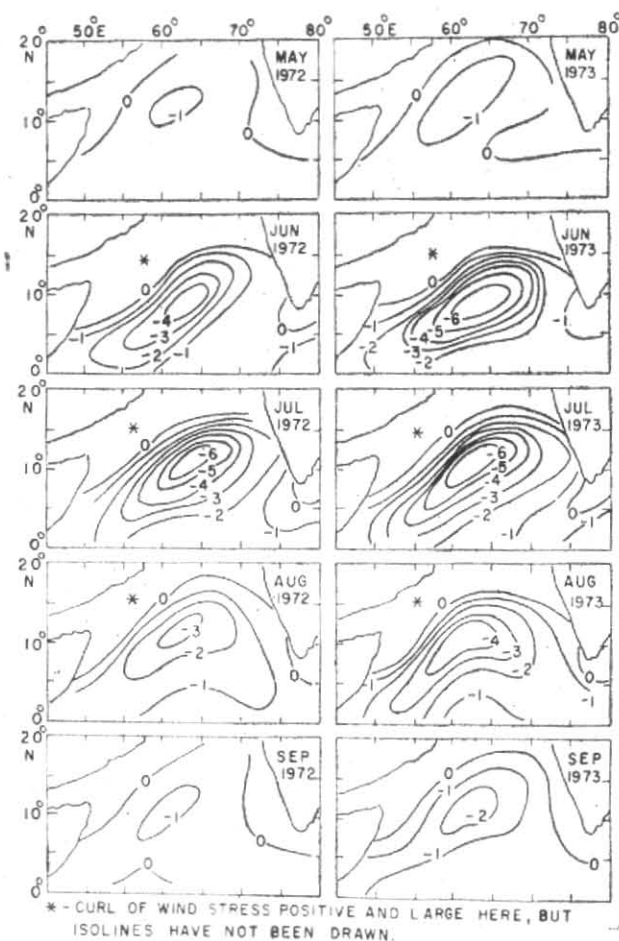


Fig. 8. Curl of the wind stress (in  $10^{-8}$  dynes  $\text{cm}^{-2}$ ) over Arabian Sea for each month of the period May to September for 1972 and 1973

square 65 deg. E-70 deg. E. The pattern has changed again east of 70 deg. E.

5.2. The deep mixed (isothermal) layer that has formed over central portions of Arabian Sea is indicative of strong downwelling. In the open ocean, curl of surface wind stress on the ocean, is a measure of the upwelling/downwelling. Surface wind stress ' $T$ ' was computed from the vector monthly mean wind ' $V$ ' for each 5-degree square using the relation

$$T = \rho_a C_D V^2$$

where,  $\rho_a$  is the air density. The drag coefficient ' $C_D$ ' is taken as  $2.8 \times 10^{-3}$ .  $T$  was assumed to have the direction of the vector mean wind. As suggested by Roden (1974) and used by Hastenrath and Lamb (1979), a relatively large value of  $2.8 \times 10^{-3}$  was used for  $C_D$  to compensate for the underestimation involved in taking the mean of  $V^2$  as the square of the vector mean wind speed. From the components of the wind stress  $T_x$  and  $T_y$  at the centre of each 5-degree square, the vertical component of the wind stress curl was computed by the centred difference

scheme. The poleward convergence of the meridians has been accounted for. Near the edges of the Arabian Sea, as the 5-degree square oceanic areas are not complete, the calculated curl values assuming that 5-degree squares are complete are not reliable.

5.3. The isolines of wind stress curl, computed as explained in para 5.2 are given in Fig. 8 for each of the months May to September of 1972 and 1973. The July chart compares well with similar computation done using 1 degree square mean data (climatic averages for 60 years) by Hastenrath and Lamb (1979). Hantel (1972) has related the curl of wind stress and the vertical motion ' $w$ ' at the bottom of the oceanic mixed layer as

$$w = \frac{1}{\rho f} \left( \frac{\partial T_y}{\partial x} - \frac{\partial T_x}{\partial y} \right)$$

where  $\rho$  is the density of sea water and  $f$  is the coriolis parameter. Negative wind stress curl is conducive to upwelling in the southern hemisphere and downwelling in the northern hemisphere. Thus, there is a large area of downwelling in the Arabian Sea. Downwelling is particularly strong over central Arabian Sea.

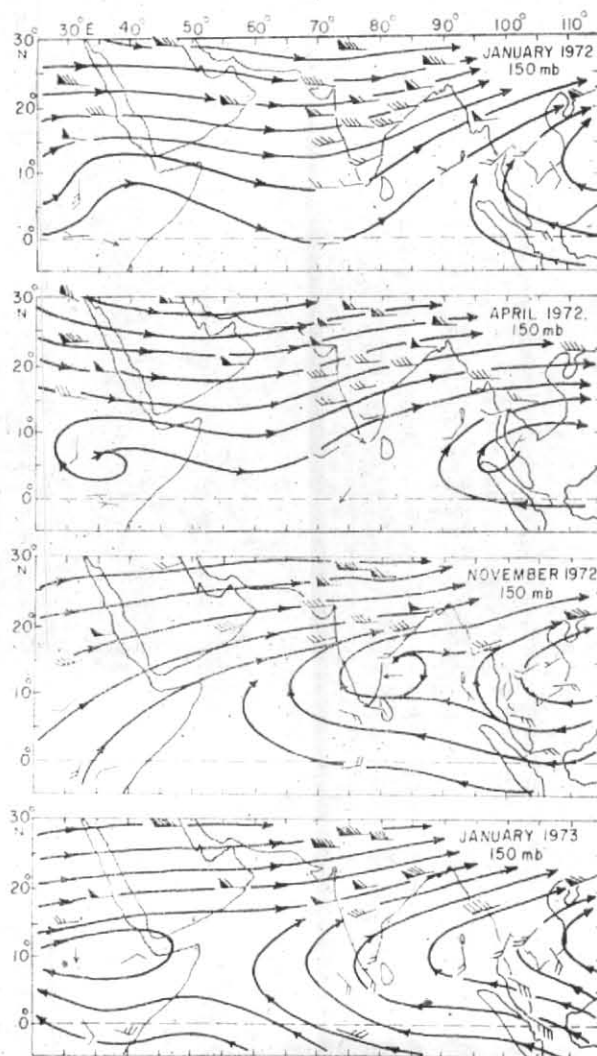


Fig. 9. Monthly mean wind at 150 mb level and their stream lines (The change from April 1972 to November 1972 may be noted)

5.4. The following emerge from the analysis :

- (i) The large downwelling in central Arabian Sea may be mainly responsible for the deep isothermal layer that develops during the monsoon season.
- (ii) Downwelling is more in 1973 than in 1972 in all the months May to September except July.
- (iii) Therefore, the isothermal layer over central Arabian Sea should be thicker in 1973 than in 1972.

#### 6. Upper wind and temperature changes (1973 minus 1972)

6.1. The upper tropospheric monthly mean wind flow over north Indian Ocean (at 150 mb) is shown in Fig. 9. In January 1972 northern hemisphere sub-

tropical westerlies are seen over Arabian Sea upto the equator. The sub-tropical anticyclone is over the extreme southeast of the map area. The same flow pattern persists, upto the monsoon as may be seen from the April circulation in the figure. As seen from section 3, pre-monsoon SST was colder than normal in 1972. The SST anomaly changed sign during the monsoon season of 1972 and this warm anomaly persisted till the monsoon of 1973. From Fig. 9 it may be seen that the circulation features at 150 mb also changed across the monsoon of 1972. In November 1972 and January 1973 as shown in the figure, a strong easterly belt is seen over the equatorial area. The sub-tropical anticyclone is seen prominently over the Bay of Bengal, Peninsular India and east Arabian Sea. This change in circulation features is discussed in detail by Joseph (1981). Perhaps the changes in SST anomaly and the changes in circulation features are inter-related.



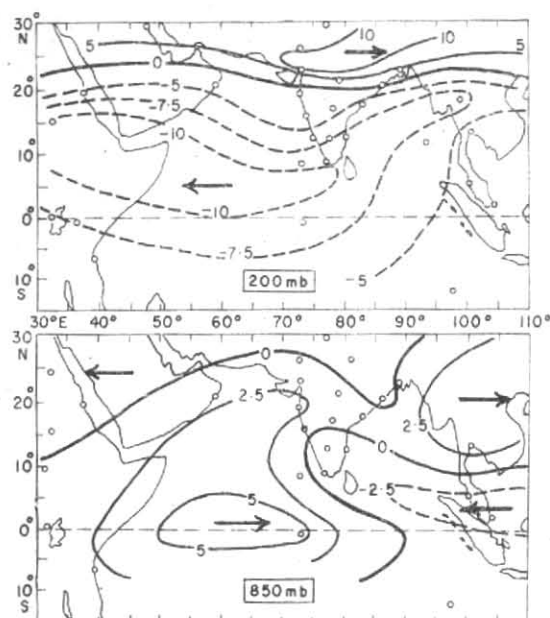


Fig. 10. The difference in monthly mean 'u' at 850 mb and 200 mb for January 1973 minus January 1972. Open circles mark stations whose data have been used. Isolines have been drawn at 2.5 metre per second intervals, continuous lines for westerly anomaly and broken lines for easterly anomaly

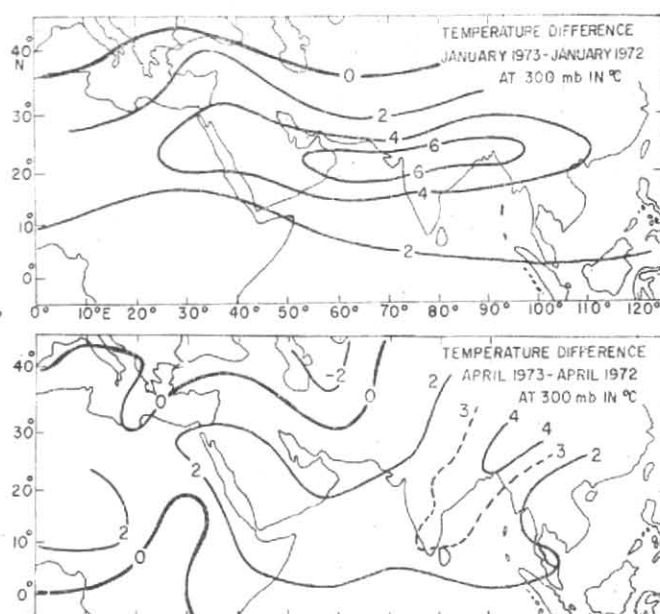


Fig. 11. Temperature difference at 300 mb, 1973 minus 1972, for January and April, in °C

6.2. Fig. 10 gives the difference between the monthly zonal component of wind ( $u$ ) at 850 mb and 200 mb between the two years, 1973 minus 1972, for January. During this month the SST difference, 1973 minus 1972, is positive over a large area of tropical Indian Ocean. The difference 1973 minus 1972 is taken as 'anomaly' in this paper. As may be seen from Fig. 10, over a positive SST anomaly there is a westerly anomaly at 850 mb and an easterly anomaly at 200 mb. The sub-tropical westerlies at 200 mb of the latitude belt 20 deg. N to 30 deg. N show a positive (westerly) anomaly. This result is significant. It agrees with the observational studies of Bjerknes (1969) with SST anomalies over the tropical East Pacific. Therefore, there is reason to believe that the upper wind changes over India that occurred across the monsoon of 1972 were caused by the change in SST anomalies. A similar result is obtained for April.

6.3. Support for this SST circulation relation has also been obtained from the available sensitivity studies using General Circulation Models (GCM) conducted for the Pacific Ocean, where the GCM generated circulation features with climatological SST as the bottom boundary condition and that with an imposed SST anomaly were compared. Such a study for the Pacific Ocean was done by Julian and Chervin (1978) using the NCAR GCM, where they imposed a warm SST anomaly over the tropical eastern Pacific, similar to the anomalies in El-Nino situations. They obtained, in the upper troposphere (near 200 mb) stronger easterlies over the warm SST anomalies and also stronger sub-tropical westerlies (and STJ) to the north and south, in fact anomalous anticyclones to the north

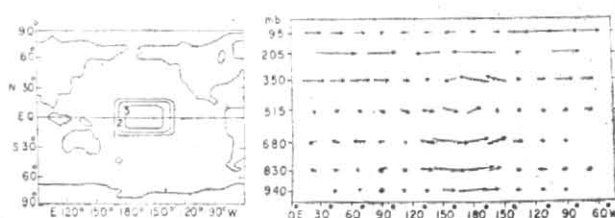


Fig. 12. Left figure gives the SST anomaly used by Keshavamurthy (1982) in his GCM study using GFDL model. Right figure gives the mean anomaly for June to August in 'u' in the equatorial-height plane (Average for 10°S-10°N)

and south of the SST anomaly. Sadler (1980) criticised this GCM simulation on the ground that in real nature, although similar circulation anomalies were created, they were displaced somewhat westwards. The actual circulation anomaly at 200 mb (1973 minus 1972) for January has been documented by him in the paper.

6.4. Keshavamurthy (1982) performed a study similar to that by Julian and Chervin (1978) (*Loc. cit.*). He imposed a 3 deg. C warm SST anomaly of spatial scale about 60 degrees in longitude by 40 degrees in latitude over the tropical Pacific Ocean, symmetric around the equator and performed sensitivity studies using the GCM of the Geophysical Fluid Dynamics Laboratory, Princeton. He performed three experiments, first with the SST anomaly over East Pacific and second and third with SST anomalies over Central



Pacific and West Pacific. Fig. 12 gives the location of the Central Pacific SST anomaly and the circulation anomaly obtained in the zonal wind component ( $u$ ) as a mean over the equatorial belt 10 deg. S-10 deg. N. Over the warm SST anomaly (but somewhat displaced to the west, in better agreement with what actually happens in the atmosphere) there is a westerly anomaly around 850 mb and an easterly anomaly around 200 mb. He also got stronger subtropical westerlies around 200 mb to the north and south.

6.5. If the results of the GCM studies done with Pacific SST anomalies are applied over the Indian Ocean (although the climatology and geography are different over these two areas), then the observed circulation change 1973 minus 1972 find a satisfactory explanation. It would, however, be better to conduct a GCM simulation for the Indian Ocean area imposing an SST anomaly of intensity and spatial scale as observed, say, 1973 minus 1972. The available GCM simulations for this ocean area, e.g., Shukla (1975) and Washington *et al.* (1977) have used SST anomalies of very small spatial scales. The latter study clearly shows that global scale changes to circulation can be caused only by an anomaly of large spatial scale; small scale (spatial) anomalies of SST are able to generate only local effects.

6.6. It is interesting to examine the temperature changes in the upper troposphere. A warm sea is likely to create increased deep moist convective activity. Deep convection heats the upper troposphere and the warm anomaly created by this cause is known to be strongest around 300 mb. Fig. 11 gives the temperature difference between the two years (1973 minus 1972) at the 300 mb level for January and April. The temperature differences are 4 deg. C to 6 deg. C over and to the north of the warm SST anomaly.

## 7. Conclusion

The following conclusions may be drawn from the study :

(i) A good monsoon produces a negative SST anomaly over north Indian Ocean and a poor monsoon produces a positive SST anomaly.

(ii) The SST anomaly generated by a monsoon persists till the next monsoon.

(iii) A poor monsoon produces a warm SST anomaly over north Indian Ocean on account of decreased monsoon cooling due to the following :

- (a) Weaker upwelling off the coasts of Somalia and Arabia.
- (b) Reduced wind mixing due to weaker surface winds.
- (c) Reduced evaporation which is largely controlled by surface winds.
- (d) Reduced cloud cover.

(iv) The positive SST anomaly over the tropical Indian Ocean of large spatial extent generated by the poor monsoon of 1972 changed the atmospheric circulation in the lower and upper troposphere over a large area over north Indian Ocean and South Asia. This circulation anomaly and also the warm SST anomaly lasted from October 1972 to May 1973. The circulation returned to the pre-1972 monsoon conditions soon after the good monsoon of 1973 which cooled the north Indian Ocean and destroyed a major part of the positive SST anomaly.

(v) The observed changes of tropospheric circulation over north Indian Ocean find satisfactory explanation from the results of GCM simulations with imposed SST anomalies over the Pacific Ocean.

(vi) Better verification may become possible when a GCM experiment is performed with imposed SST anomalies over tropical Indian Ocean of intensity and spatial scale as documented in this paper.

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