Mausam, (1984), 35, 3, 323-330

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Air-sea interaction on a seasonal scale over north Indian Ocean—Part I : Inter-annual variations of sea surface temperature and Indian summer monsoon rainfall

P. V. JOSEPH and P. V. PILLAI
Meteorological Office, Pune

सार — 1961 से 1973 तक 13 वर्षो की अवधि में अरबसागर के दो और बंगाल की खाड़ी के एक, चुने हुए प्रतिनिधि में जलयानों से किए गए प्रेक्षणों से समुद्री पृष्ठ तापमान के मासिक माध्यों का अध्ययन किया गया है । प्रत्येक चयन किया हुआ प्रतिनिधि क्षेत्र 3° अक्षांश × 2° देशान्तर का है । इनमें से "ए" 11° 00′ उ०, 59° 30′ पू०, "बी" 14° 00′ उ०, 71° 30′ पू० एवं "सी" 11° 00′ उ०, 83° 30′ पू० में केन्द्रित है । संपूर्ण अवधि के दौरान प्रत्येक चयनित प्रतिनिधि क्षेत्र के समुद्री पृष्ठ तापमानों के मासिक माध्यों के 12 माह के गतिमान माध्य स्पष्टतः तीन वर्षीय उतार-चढ़ाव को इंगित करते हैं । ए, बी और सी स्थानों के समुद्री पृष्ठ तापमानों की मासिक विसंगतियों की श्रेणियों का हरात्मक एवं शक्ति स्पेक्ट्रम विश्लेषण किया गया जो वार्षिक विचरण के अतिरिक्त यह भी दर्शाता है कि केवल 3 वर्षीय आवर्तितता का विचरण ही सर्वप्रमुख है । 15° द० के उत्तर की ओर के हिन्द महासागर क्षेत्र के लिए 1965 से 1973 तक 9 वर्षों की अवधि के समुद्री पृष्ठ तापमानों के मासिक माध्यों के पंचघाती वर्ग औसतों को ज्ञात किया गया है । यह देखा गया है कि समुद्री पृष्ठ तापमानों का 3 वर्षीय उतार-चढ़ाव उत्तरी हिन्दमहासागर के उस विस्तृत क्षेत्र को प्रभावित करता है, जहां उतार-चढ़ाव के लिए शक्ति स्पेक्ट्रम विश्वास्थता स्तर 95 प्रतिशत है ।

1961 से 1973 के आंकड़ों का उपयोग करके ए, बी और सी स्थानों के समुद्री पृष्ठ तापमानों की विसंगतियों एवं भारत में मानसूनी वर्षा के सहसंबंधों को ज्ञात किया गया है । देखा गया है कि मानसूनपूर्व के महीनों का समुद्री पृष्ठतापमान मानसून वर्षा के बाद के समुद्री पृष्ठ तापमान से धनात्मक रूप से सहसंबंधित है, लेकिन यहां सहसंबंध अल्प है और सांख्यिकीय दृष्टि से सार्थक नहीं है । तथापि ए, बी और सी में मानसूनी वर्षा और मानसून के बाद के समुद्री पृष्ठ तापमानों का सहसंबंध ऋणात्मक रूप से सार्थक है ।

ABSTRACT. Monthly mean sea surface temperature (SST) obtained from ship observations have been studied for two 'selected representative areas' (SRA) in the Arabian Sea and one in the Bay of Bengal for the 13-year period 1961 to 1973. Each SRA is 3 degrees longitude × 2 degrees latitude. They are centred, A at 11 deg. 00′N, 59 deg. 30′E, B at 14 deg. 00′N, 71 deg. 30′E and C at 11 deg. 00′N, 83 deg. 30′E. 12 monthly running means of the monthly mean SST of each SRA shows a pronounced three-year oscillation during the whole period. The series of monthly anomalies of SST for A, B and C were subjected to harmonic and power spectrum analyses, which also show that apart from the annual variation, the only prominent periodicity is the 3-year variation. For the 9-year period 1965 to 1973, five-degree square averages of monthly mean SST have been worked out for the Indian Ocean area north to 15 deg. S. It is found that the 3-year oscillation in SST covers a large area of north Indian Ocean, where power spectrum analysis of SST monthly anomalies shows significant peaks at confidence level 95% for this oscillation.

Correlations between monsoon rainfall of India and the SST anomalies at A, B and C have been worked out using data of 1961 to 1973. It is found that the SST of pre-monsoon months is positively correlated with the following monsoon rainfall, but the correlation is low and not statistically significant. However, the monsoon rainfall is significantly negatively correlated with the post-monsoon SST of areas A, B and C.

1. Introduction

1.1. During some epochs, Indian summer monsoon rainfall has shown large inter-annual variations, with large scale monsoon failures occurring in some years. Joseph (1976) has shown that Indian summer monsoon rainfall, the upper tropospheric winds over south Asia and the tracks of post-monsoon cyclonic storms of Bay of Bengal have undergone a 3-year oscillation during the period 1964 to 1973. The oscillation in rainfall is seen right from 1961, with good monsoons occurring in 1961, 1964, 1967, 1970 and 1973 and monsoon failures occurring in between. From a preliminary study by Joseph (1981) it is seen that the ocean-atmosphere interaction on a seasonal scale is the possible mechanism for this oscillation. Large scale monsoon failures over India during 1965 and 1966 caused increase in sea surface temperature (SST) in the Arabian Sea and Bay of Bengal. The warm sea was taken as responsible for the good monsoon of

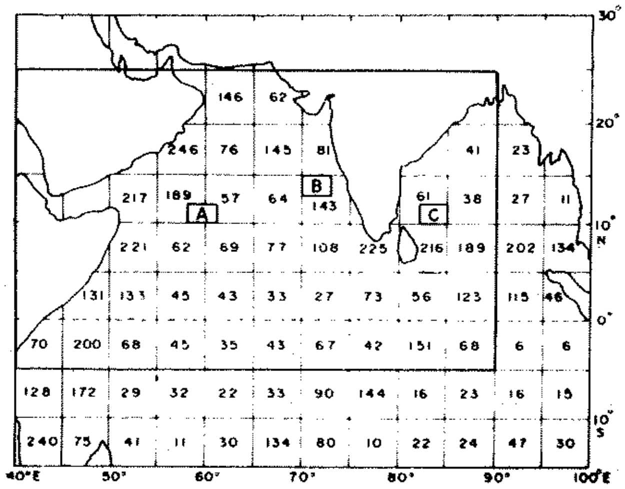

Fig. 1. Average monthly frequency of SST observations (1965-1973)

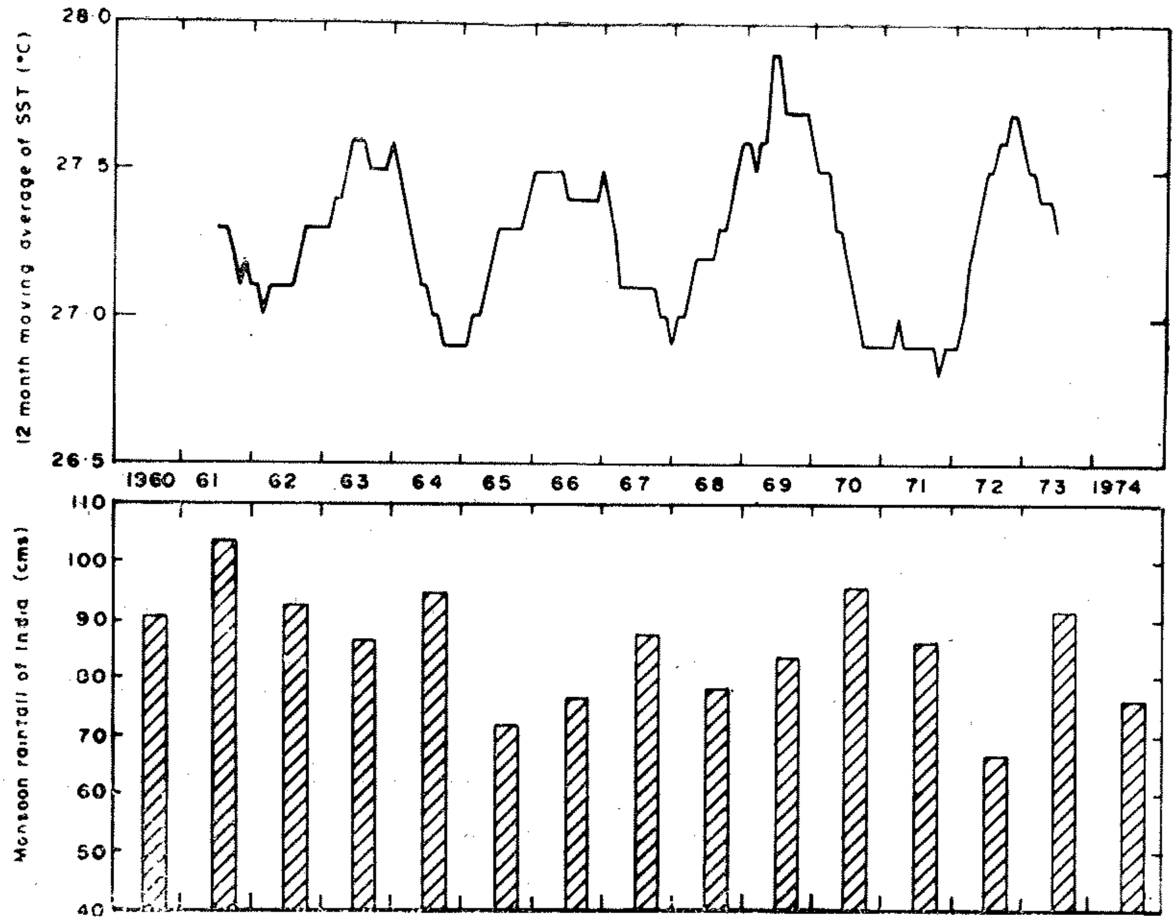

Fig. 2. Top figure gives the twelve months moving average of SST observation A. Bottom figure gives the monsoon rainfall of India as derived by Parthasarathy and Mooley (1978). The 3-year oscillation is clearly seen in both figures

TABLE 1

Number of SST observations in A, B and C during 1964

SRA	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A	107	105	105	118	100	133	81	89	93	84	101	95
B	25	50	44	38	45	28	38	45	33	34	23	40
C	28	23	36	31	22	26	21	27	14	20	12	21

1967 through changes introduced in the upper troposphere from the post-monsoon months of 1966. The good monsoon of 1967 cooled the sea areas and the cycle repeated.

1.2. In this paper the inter-annual variation of SST during the period 1961 to 1973 and its relation with the Indian summer monsoon rainfall have been studied. As per decisions of WMO Congress-IV in 1964, India gets meteorological observations from the ships of the Voluntary Observing Fleet of about 40 maritime nations, checked by the meteorological services of those countries, for the Indian Ocean area north of latitude 15 deg. S as shown in Fig. 1. Out of the 17 'selected representative areas' (SRA), three areas A, B and C were chosen for study, as marked in Fig. 1. Each of these SRA is 3 degrees longitude × 2 degrees latitude. They are centred at 11.0 deg. N, 59.5 deg. E, 14.0 deg. N, 71.5 deg. E and 11.0 deg. N, 83.5 deg. E. Monthly mean SST for A, B and C prepared by India Meteorological Department for inclusion in the publication *'Marine Climatological Summaries'* for 1961 to 1967 were provided to the authors by India Meteorological Department. Similar monthly means for the years 1968 to 1973 were derived from the data stored in magnetic-tapes at the National Data Centre of Meteorological Office, Pune. Details regarding these data are desribed by Korkhao and Nene (1972). Table 1 gives the number of SST observations available in each month of a typical year 1964 for A, B and C.

1.3. For the period 1965 to 1973, five-degree latitude-longitude square averages of monthly mean SST were also worked out for the Indian Ocean, north of 15 deg. S. Fig. 1 shows the average number of SST observations per month available for each five-degree square during this period. Total number of SST observations available for the whole area monthwise is given in Table 2. It may be seen that the number of SST observations available is somewhat less in 1973.

2. Analysis of SST data of A, B and C, 1961 to 1973

2.1. Twelve month moving average of the monthly mean SST of A, B and C shows a pronounced 3-year oscillation. Fig. 2 shows this for the area A. Even after applying a 12-month moving average, the double amplitude is considerable-about 0.7 deg. C for the first two cycles and about 1 deg. C for the third and fourth cycles. The figure also shows the monsoon rainfall index June-September for the whole of India as derived by Parthasarathy and Mooley (1978). The 3-year cycle is seen in the rainfall also but with the opposite phase.

2.2. To see the real double amplitude for the 3-year cycles in SST at A, the normal SST for each month was calculated as an average of 13 years and monthly anomalies were obtained as departures from the monthly normals. Monthly normal is calculated giving equal weights to all the individual observations of a month during the 13-year period. Thus the normal or the 13-year average SST of a month $\bar{T}$ is given by :

$$\bar{T} = \frac{\sum_{i=1961}^{i=1973} N_i T_i}{\sum_{i=1961}^{i=1973} N_i}$$

The index i denotes the year and T is an individual monthly mean value obtained from N observations of SST. To have some smoothing the four 36-month cycles beginning January 1962, January 1965, January 1968 and January 1971 were averaged and the mean cycle thus obtained for A is shown in Fig. 3. The thick line marked is the 5-month moving average of those values. It is seen that the double amplitude of the 3-year oscillation in SST at A (with the annual cycle removed) is about 1.5°C (Maximum SST—Minimum SST). The thick line shows that SST increased during two consecutive years and decreassed during the third year, thus giving a saw-tooth type of wave. Detailed examination of the data showed that the increase and decrease of SST occurred across the monsoon months June to September and that the anomaly generated by a monsoon persisted till the next monsoon. It may be noted that a 3-year periodicity in the heat storage in the top 100 metre layer of the north Indian Ocean during the period 1964 to 1974 has been reported by Golvastov (1980).

2.3. To study the amplitude and phase of the 3-year wave in SST, the 144 monthly anomaly values of each area A, B and C from January 1962 to December 1973 were subjected to harmonic analysis. The series was expressed as :

$$x = \bar{x} + \sum_{i=1}^{i=N/2} \left(A_i \sin \frac{2\pi i t}{p} + B_i \cos \frac{2\pi i t}{p} \right)$$

where, p is the total period (144 months) and N is the number of observations (144). The amplitude of the i^{th} harmonic is :

$$C_i = (A_i^2 + B_i^2)^{1/2}$$

and the time at which i^{th} harmonic reaches maximum (phase) is :

$$t_i = \frac{p}{2\pi i} \text{ arc tan } (A_i/B_i)$$

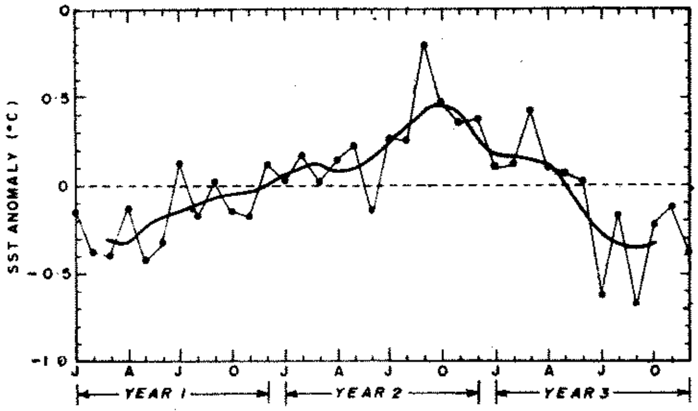

Fig. 3. Average SST anomaly in a 3-year cycle at location A (average of 4 cycles during 1962 to 1973)

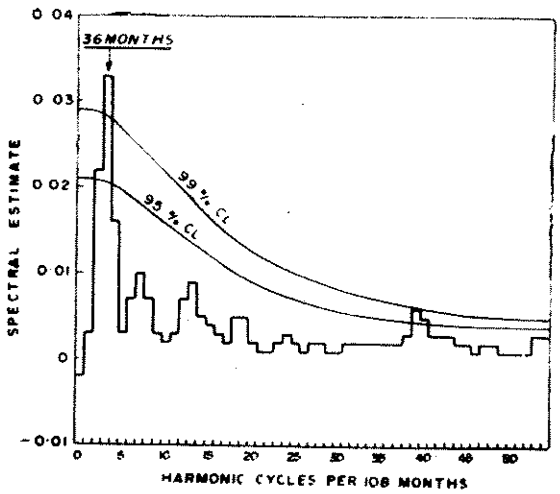

Fig. 4. Spectral analysis of monthly mean SST series, 1961 to 1973 for location A

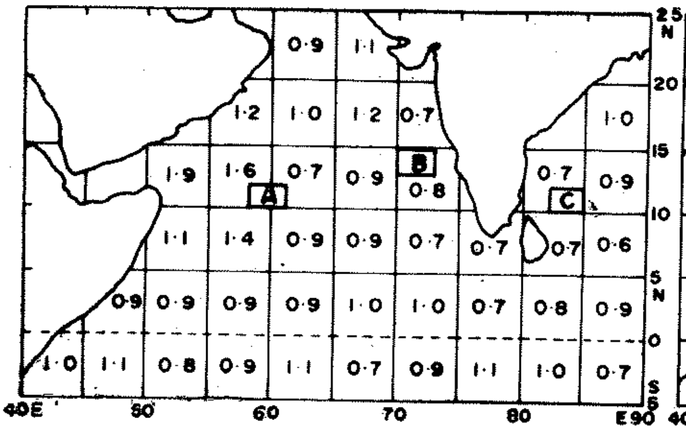

Fig. 5. Double amplitude of 3-year cycle of SST anomalies (1965 to 1973)

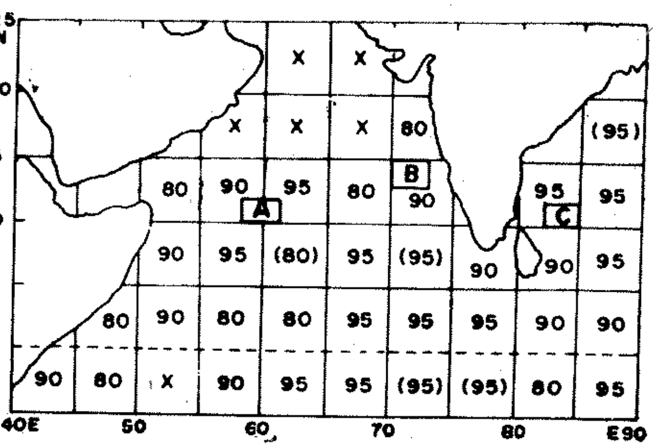

Fig. 6. Significance (confidence level in %) of the 3-year oscillation (1965 to 1973)

TABLE 2

Number of SST observations in each month over Indian Ocean north of 15°S during 1965 to 1973

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1965	7507	7564	8217	7441	7887	7322	8314	8637	7234	8615	8101	7791
1966	5648	8055	9308	8274	8149	8095	7521	8181	7069	7629	8484	8115
1967	8037	8076	8340	8055	8286	6748	6586	6261	6034	6123	5225	6007
1968	6698	6757	8247	8617	8653	7986	7506	7963	7615	7098	7489	7742
1969	8241	7278	7623	7509	6442	7708	8391	7746	7452	8307	7686	7611
1970	7382	6623	6943	6290	7497	6965	7481	7346	6941	7026	6560	7361
1971	7075	6481	7744	6789	7173	6458	6697	7365	6740	7217	7883	7315
1972	7011	6504	7390	6508	6966	6845	7057	7433	6863	7264	6698	6593
1973	4945	4810	4946	4566	4218	4199	4513	4659	4384	4491	4451	1145

The variance accounted for by the i^{th} harmonic is $C_i^2/2s^2$, where s is the standard deviation (*See* Panofsky and Brier 1968). Data in respect of the first 12 harmonics are given in Table 3. At all the 3 areas, the fourth harmonic (36 months wave) has the maximum amplitude and it accounts for the highest per cent of variance. For all other harmonics the variance is very low. This shows that the only prominent oscillation is the 3-year oscillation. The phase of maximum SST at A is 20 (August of second year), at B is 21 (September of second year) and at C is 26 (February of third year).

2.4. Power spectrum analysis of the series of 156 monthly anomaly values for A, B and C for the years 1961 to 1973 with lag of 54 months was also carried out as per the method outlined in WMO technical note No. 79 (1966) on *'Climatic change'*. Fig. 4 shows the spectrum for area A. The 3-year cycle is significant at confidence level 99%. Areas B and C also show the 3-year cycle, but it is significant at confidence level 95% at C and only at 90% confidence level at B.

3. SST and Indian monsoon rainfall (1961 to 1973)

3.1. It is of interest to examine whether the SST at A, B and C is correlated with the monsoon rainfall. For this, seasonal averages of SST anomaly for the four seasons, winter (January and February), pre-monsoon (March, April and May), monsoon (June, July, August and September) and post-monsoon (October, November and December) were calculated for A, B and C. These were correlated to the anomalies of monsoon rainfall 1 June to 30 September of the whole of India for the same year using the rainfall series as derived by Parthasarathy and Mooley (1978). The correlation coefficients between the monsoon rainfall anomaly and the SST anomaly are given in Table 4. The significance at confidence level '*s*' of the correlation coefficient '*r*' is also given in the table. The correlation between monsoon rainfall and SST of previous winter and pre-monsoon seasons is positive but not significant. The correlation changes sign during the monsoon season (concurrent correlation) but is not significant except at A. However, the monsoon rainfall is significantly (at 97% confidence level) negatively correlated with the SST of the following post-monsoon season at A, B and C, which shows that a poor monsoon warms significantly the Arabian Sea and the Bay of Bengal. In this connection reference is invited to Weare (1979) who performed an Empirical Orthogonal Function analysis of Indian Ocean SST data of 1949-1972 and found that a warmer Arabian Sea or Indian Ocean is weakly associated with decreased rainfall over much of the Indian sub-continent, in agreement with the concurrent negative correlation (significant only at A) described in this para.

4. Area affected by the 3-year oscillation (1965 to 1973)

4.1. As described in section 1.3, for each 5-degree square a series of 108 monthly values of SST was obtained. With a condition of at least 5 observations of SST for a monthly average, the data series of most of the squares outside the thick line boundary of Fig. 1 were not complete and so could not be used. The average 3-year cycle of SST anomalies were worked out using data of the 3-cycles beginning January 1965, January 1968 and January 1971. The double amplitude (maximum *minus* minimum SST) of the mean 3-year cycle for each 5-degree square is given in Fig. 5. The 3-year oscillation is found to have double amplitude of about 1 deg. C over a large area of the north Indian Ocean; over western Arabian Sea it is around 1.5 deg. C as at A.

4.2. The 108 SST monthly anomaly value series of each 5-degree square was subjected to power spectrum analysis with lag of 36. Practically all the squares show a 3-year wave. The 3-year wave is significant at confidence levels 80%, 90% and 95% as shown in Fig. 6. The 'X' mark shows that confidence level is less than 80%. It is seen that a large area of the Indian Ocean

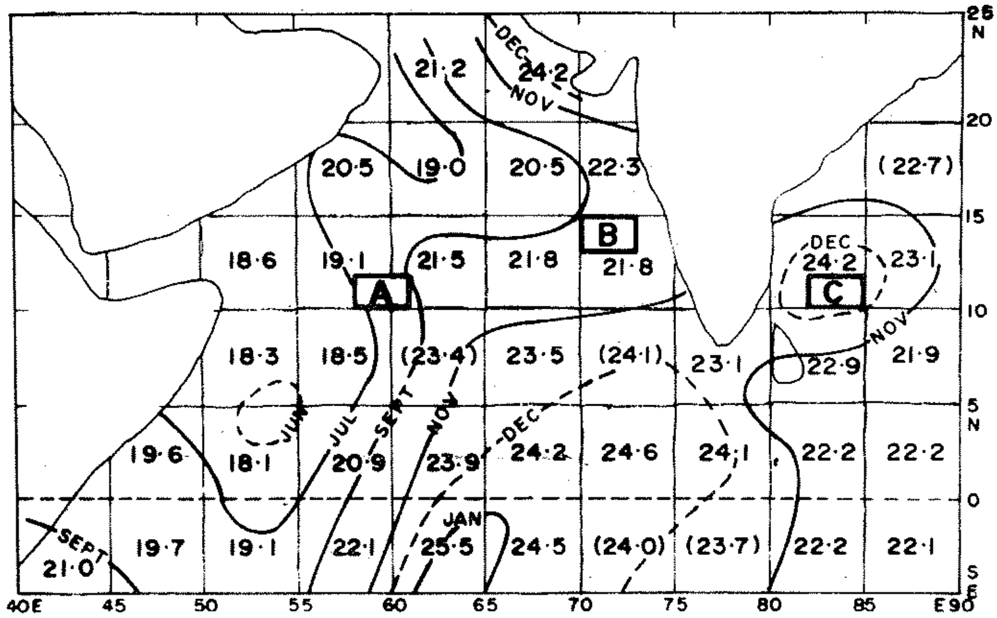

Fig. 7. Phase of maximum SST of the 3-year harmonic (1965 to 1973)

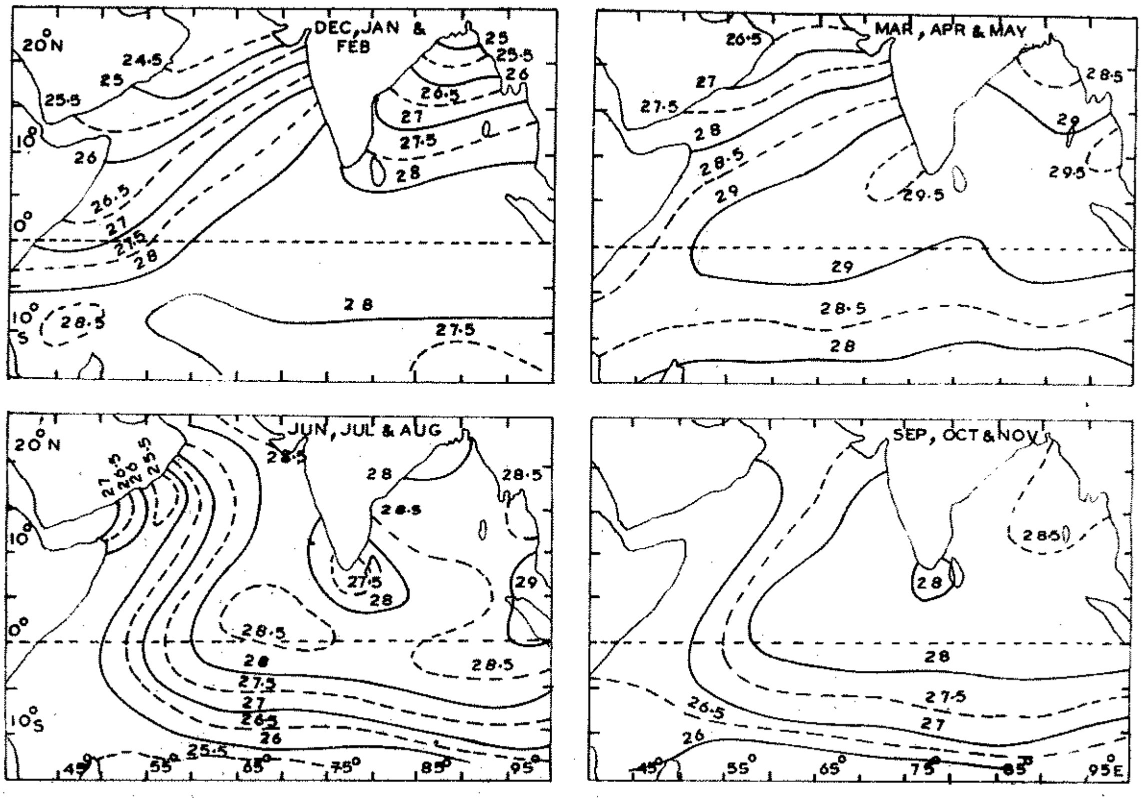

Fig. 8. Isopleths of seasonal mean sea surface temperature in °C

TABLE 3

Amplitude and phase of and variance accounted by the first 12 harmonics of the monthly SST series 1962 to 1973

Harmonic	Area A Amp (°C)	Area A Phase (month)	Area A Var (%)	Area B Amp (°C)	Area B Phase (month)	Area B Var (%)	Area C Amp (°C)	Area C Phase (month)	Area C Var (%)
1	0.03	50	0	0.18	58	11	0.07	105	1
2	0.10	11	2	0.13	8	5	0.06	49	1
3	0.14	40	4	0.07	0	2	0.21	43	10
4	0.35	20	25	0.25	21	20	0.26	26	15
5	0.11	19	2	0.05	16	1	0.02	24	0
6	0.02	23	0	0.05	7	1	0.07	16	1
7	0.06	10	1	0.12	8	5	0.14	7	5
8	0.11	8	3	0.08	8	2	0.10	6	2
9	0.08	0	1	0.05	0	1	0.09	14	2
10	0.16	13	5	0.09	2	2	0.04	11	0
11	0.11	9	2	0.08	3	2	0.06	9	1
12	0.03	9	0	0.03	8	0	0.03	10	0

TABLE 4

Correlation between Indian monsoon rainfall anomaly and seasonal mean SST anomaly at A, B and C of the same year for the period 1961 to 1973

Season	Area A r	Area A s (%)	Area B r	Area B s (%)	Area C r	Area C s (%)
January & February	0.29	80	0.45	90	0.35	80
March to May	0.35	80	0.43	90	0.28	80
June to September	—0.54	95	—0.33	80	—0.25	80
October to December	—0.62	97	—0.59	97	—0.57	97

Serial or lag correlation were calculated for each of the time series of SST and rainfall. As no significant persistence was found, the actual length of the series was used for estimating the level of significance.

north of 5 deg. S has a 3-year oscillation in SST significant at confidence level 95% (The values given in brackets in Figs. 6 and 7 show that in these squares one value of the 108 values in the series is an average with less than 5 observations).

4.3. Harmonic analysis was done of the 108-month SST series of each 5-degree square. In all the squares the 36 months wave (third harmonic) is the only prominent wave. The phase of maximum SST of the 36-month wave is shown in Fig. 7, with isolines marked in months, July of second year (phase 19) to January of third year (phase 25). The progression of phase from west to east is interesting. The phase propagation is fast along central Arabian Sea and slow over south Arabian Sea and the equatorial regions. Ocean currents may have a role in this.

5. Seasonal mean SST over north Indian Ocean 1965-1973

5.1. Using monthly mean data of 5-degree squares of 9-year 1965-1973, seasonal mean SST was calculated for each 5-degree square for the four three-month periods December to February, March to May, June to August and September to November. Using these values seasonal mean SST charts were prepared. These are given in Fig. 8. Isopleths of SST have been drawn at intervals of 0.5 deg. C. The axis of warmest temperature lies close to the equator during December-February. Along with increase of SST, this axis shifts northwards by March-May. SST of June-August shows the effect of monsoon cooling all over the north Indian Ocean. The effect of upwelling and the spreading of the cold water generated thereby are seen over western Arabian Sea and to the south of Peninsular India; these areas warm up by September-November. The three-year oscillation in SST is superimposed on this normal annual cycle.

5.2. The normal SST over southeast Arabian Sea is around 28 deg. C during September-November. In this season the entire north Indian Ocean has warmed considerably once in 3-year with southeast Arabian Sea as the centre of the anomalous warming as may be seen from Fig. 7. This may be responsible for the change in upper tropospheric circulation described in Joseph (1981).

6. Conclusions

6.1. The following conclusions may be drawn from the study :

(*a*) Sea surface temperature (SST) over the north Indian Ocean is found to have undergone a significant three-year oscillation during the period 1961 to 1973.

(*b*) Indian monsoon rainfall June to September is found to be significantly negatively correlated with the mean SST over north Indian Ocean during the post-monsoon season October - December.

(*c*) It is found that during the period 1965-1973 two consecutive monsoon failures have warmed the entire north Indian Ocean. Since the mixed layer deepens during the summer monsoon season as may be seen from Rao *et al.* (1976), the net result of two consecutive monsoon failures is the production of anomalously warm water in the north Indian Ocean to a depth of about 80 metres from the surface. This vast reservoir of heat should be important in relation to changes in the upper tropospheric flow patterns over south Asia as reported by Joseph (1981).

6.2. In Part II of this paper a detailed study of SST and related atmospheric parameters over the north Indian Ocean during the two contrasting years 1972 and 1973 will be presented. 1972 was a major drought year in India and in 1973 India had excess rainfall during the monsoon season June to September. In Part III of the paper the effect of the increase in SST over the north Indian Ocean caused by failure of monsoon rains over India on the post-monsoon tropical cyclones will be discussed.

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References

Golovastov, V. A., 1980, Peculiarities of ocean thermodynamics in the tropical Indian Ocean during the southwest monsoon 1979, Results of Summer MONEX field phase research (Part-B), FGGE Operations Report, Vol. 9, WMO, p. 186.

Joseph, P. V., 1976, Monsoon rainfall and cyclone tracks in relation to 500 mb altitudes 1955 to 1974—Proceedings of Symposium on '*Tropical Monsoon*', Indian Institute of Tropical Meteorology, Pune, p. 494.

Joseph, P. V., 1981, Ocean-atmosphere interaction on a seasonal scale over north Indian Ocean and Indian monsoon rainfall and cyclone tracks—A preliminary study, *Mausam*, **32**, p. 237.

Korkhao, J. M. and Nene, Y.R., 1972, Marine climatological summaries, *Vayu Mandal*, **2**, p. 225.

Panofsky, H. A. and Brier, G. W., 1968, *Some applications of statistics to Meteorology*, Pensylvania State University Publication.

Parthasarathy, B. and Mooley, D. A., 1978, Some features of long homogeneous series of Indian Summer Monsoon rainfall, *Mon. Weath. Rev.*, **106**, p. 771.

Rao, D. P., Sarma, R. V. N., Sastry, J. S. and Premchand, K., 1976, On the lowering of the surface temperatures in the Arabian Sea with the advance of the south-west monsoon season, Proceedings of the Symposium on '*Tropical monsoons*', Indian Institute of Tropical Meteorology, Pune, India, p. 106.

Weare, R. C., 1979, A statistical study of the relationships between ocean surface temperatures and the Indian monsoon, *J. atmos. Sci.*, **36**, p. 2279.