# Interannual Variations of Sea Surface Temperature over the Arabian Sea and the Indian Monsoon: A New Perspective

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## ABSTRACT

The interannual variation of surface fields over the Arabian Sea and Bay of Bengal are studied using data between 1900 and 1979. It is emphasized that the monthly mean sea surface temperature (SST) over the north Indian Ocean and monsoon rainfall are significantly affected by synoptic systems and other intraseasonal variations. To highlight the interannual signals it is important to remove the large-amplitude high-frequency noise and very low frequency long-term trends, if any. By suitable spatial and temporal averaging of the SST and the rainfall data and by removing the long-term trend from the SST data, we have been able to show that there exists a homogeneous region in the southeastern Arabian Sea over which the March–April (MA) SST anomalies are significantly correlated with the seasonal (June–September) rainfall over India. A potential of this premonsoon signal for predicting the seasonal rainfall over India is indicated. It is shown that the correlation between the SST and the seasonal monsoon rainfall goes through a change of sign from significantly positive with premonsoon SST to very small values with SST during the monsoon season and to significantly negative with SST during the post-monsoon months. For the first time, we have demonstrated that heavy or deficient rainfall years are associated with large-scale coherent changes in the SST (although perhaps of small amplitude) over the north Indian Ocean. We also indicate possible reasons for the apparent lack of persistence of the premonsoon SST anomalies.

## 1. Introduction

Recent numerical simulations on the predictability of monthly and seasonal means in the tropics (Charney and Shukla, 1981; Shukla 1981), and the ability of climate models to simulate low-frequency atmospheric variability as a response to slowly varying boundary conditions (Lau and Oort, 1985) have raised some hope that there may be a physical basis for dynamical prediction of monthly and seasonal means. However, a considerable amount of research is still needed before the operational feasibility of this method is demonstrated. Until then we have to depend on statistical and empirical techniques for long-range forecasting of monthly and seasonal scales. It is, therefore, highly desirable to document significant empirical relationships among various components of the ocean–atmosphere–land system. Such studies are essential for identifying the proper parameters to be used in the statistical and empirical techniques of long-range prediction. Moreover, careful empirical studies can also provide important insight into the underlying physical processes responsible for these relationships. It is with such an objective that we have undertaken the present empirical study.

The role of the sea surface temperature (SST) over the Arabian Sea on the southwest monsoon over India has been a controversial subject for a long time (Pisharoty, 1965; Saha, 1974; Saha and Bhavadekar, 1973; Ghosh et al., 1978). Two different possibilities exist. First, the variations of SST over this region can influence monsoon rainfall through variations of available moisture supply. On the other hand, variations of the monsoon circulation itself can produce variations in SST over this region through changes in the evaporative cooling and changes in cloud cover. In this article we present evidence that significant relationships between SST and seasonal monsoon rainfall can be identified only with premonsoon and post monsoon SSTs. While the premonsoon (March–April or March–April–May, i.e. MA or MAM) SST anomalies over the southeastern Arabian Sea seem to influence the monsoon rainfall during the subsequent months (June–September, JJAS), the monsoon itself seems to affect the north and southwestern Arabian Sea during the post-monsoon months (September–November, SON). It appears that during the monsoon season (JJAS), the monthly mean SSTs are corrupted by sampling errors resulting in the loss of any significant relationship between the SST and monsoon rainfall.

Earlier attempts to discover significant correlations between SST anomalies over the Arabian Sea during the premonsoon months (MAM) and monsoon rainfall (Shukla and Misra, 1977; Weare, 1979; Cadet and

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Diehl, 1985) have met with little success. This may be due to the fact that, while seasonal variations of the SST over this region are very large, interannual variations are very weak. The standard deviation of these anomalies for any month is of the order of 0.5°C. Thus, if there exists a climatic signal on interannual time scales, it must have a small amplitude. The problem is, therefore, to decipher this small-amplitude, low-frequency signal from a background of high-frequency noise of comparable or larger amplitude. Therefore, judicious temporal and spatial filtering is necessary to bring out this weak low-frequency signal. Our choice is based on the following considerations.

In recent years it has been clearly documented (Sikka and Gadgil, 1980; Yasunari, 1980; Krishnamurti and Subramaniyam, 1982) that the monsoon region has a dominant intraseasonal fluctuation with periodicity of 30–50 days. This mode is basically associated with the fluctuations of the ITCZ (Sikka and Gadgil, 1980; Yasunari, 1980). Prior to the beginning of May, the ITCZ, and hence the maximum amplitude of this mode, is confined to south of 5°N. During May, it fluctuates between 5° and 15°N. After the onset of the monsoon (roughly between the last week of May and the first week of June), this mode starts propagating to the north over the Indian region and affects all the meteorological variables over this region (Sikka and Gadgil, 1980; Murakami et al., 1984, 1986; Murakami and Nakazawa, 1985). This mode influences not only the rainfall over India, but also surface parameters over the Arabian Sea through changes in cloudiness and wind strength associated with it (Mysak and Mertz, 1984; Mertz and Mysak, 1984). Mysak and Mertz (1984) have shown that the amplitude of the sea surface temperature fluctuations with a period ranging from 30–50 days may be of the order of 1°C in the Somali current region (4°S). We believe that similar changes in the SST may occur even in the north Arabian Sea due to the same phenomenon. Since there are considerable interannual variations in the onset date of monsoon (or the initiation of the northward migration of the 30–50 day mode) and the speed of the northward migration itself, the phase of this mode in a given month during the monsoon season will be different from one year to another. As a result, we expect that the correlation between monthly mean SST and monthly mean rainfall over India will be significantly affected by this mode. In most of the previous studies (Shukla and Misra, 1977; Cadet and Diehl, 1984), correlations between monthly mean SST anomalies and monthly mean rainfall were examined. We believe that the interannual signal was mixed with the intraseasonal signal in these studies, which may explain some of the contradictory results.

To remove the effect of the 30–50 day mode, we decided to use only seasonally averaged (June–September, JJAS) monsoon rainfall. Since continental India falls under the influence of this mode only from the beginning of June, this averaging is expected to effectively remove this intraseasonal fluctuation from the monsoon rainfall data. Because we believe that this oscillation of the ITCZ occurs due to a dynamical feedback in the atmosphere (Goswami and Shukla, 1984), there may be a lag in the response of the oceanic mixed layer to this atmospheric oscillation. Therefore, a similar averaging may not be effective in removing this oscillation from the SST data. With the monthly mean SST data that is available, it is not possible to establish this conjecture. In any case, the SST anomalies will also be averaged over two or three months. Similarly, to remove small-scale spatial fluctuations, we decided to take either the area-weighted whole India rainfall or area-weighted rainfall averaged for each of 31 meteorological subdivisions of India. The SST data are averaged over 5° lat × 5° long boxes.

The aim of this study is to reexamine the question of an association (or lack thereof) between the Arabian Sea SST and monsoon rainfall with the new perspective about intraseasonal fluctuations in view. In the next section we describe the basic data used in the study and the method of analysis used. In section 3 we present correlations between seasonally averaged whole India rainfall and the SST averaged over different 5° × 5° boxes. This has been done to identify the region(s) of the Arabian Sea that is (are) significantly related to monsoon rainfall and vice versa. Having identified such regions, we examined the spatial variations of these correlations over various meteorological subdivisions of India. These results are presented in section 4. Keeping in mind the importance of any premonsoon predictor for monsoon rainfall, the relationship between the premonsoon SST and monsoon rainfall is examined in some detail in section 5. A summary of the results and some speculations regarding physical processes responsible for these correlations are presented in section 6.

## 2. Data and analysis

The seasonal mean (JJAS) rainfall spatially averaged over each of the 31 meteorological subdivisions of India, given as percentage departures from long-term means, is obtained from Shukla (1987). We have also taken the seasonally averaged whole India rainfall from the same source. The whole India rainfall is obtained as the area-weighted mean of the 31 subdivisional rainfalls. We have selected the period from 1900 to 1979 for the rainfall time series, because this is the period for which SST data were available to us.

The basic marine dataset used in this study has been derived from the TDF-11 marine deck of the National Climate Data Center at Asheville, North Carolina (NCDC, 1968). This dataset has been described in many studies (e.g. Rasmusson and Carpenter, 1982; Barnett, 1984). From the individual ship reports, monthly mean data averaged over individual 5° lat

× 5° long boxes for SST, air temperature (ART) and surface winds ($u$ and $v$ components) for the period 1900 to 1979 were compiled over the region shown in Fig. 1 (equator to 30°N, 40° to 100°E). This figure also shows the average number of observations per month for each 5° × 5° box. Keeping in view the climatologies derived by earlier authors (e.g., Hastenrath and Lamb, 1979), we carried out a gross check to reject spurious data. We rejected wind data if $|u|$, $|v| > 25$ m s$^{-1}$ and rejected SST or ART if (SST, ART) $\leqslant$ 15°C or $\geqslant$ 40°C. We found that such cases were rare. Next we obtained the climatological mean for each calendar month and the anomalies for individual months over all the boxes by subtracting from individual monthly means the climatology for that month. This removed the seasonal cycle, as well. An additional check was done by calculating the standard deviation of these anomalies and rejecting the data if the absolute value of an anomaly was larger than four times its standard deviation. The climatological means and corrected anomalies were then recalculated. We examined the time series of the SST anomalies over many boxes and noted that observations are missing for nearly five years during 1941 to 1945.

### *a. Seasonal cycle vs interannual fluctuations*

In this section we point out the differences between the amplitudes of the seasonal variations and those of interannual variations. The seasonal variations of the climatological mean SST over a number of boxes were examined (not shown here) and found to be similar to the ones obtained in earlier studies (e.g., Shukla, 1987). The seasonal variation of the SST over the Arabian Sea has a typical double peak structure with one major maximum around April–May, a minimum around July–August and a secondary maximum around October–November. The amplitude of the seasonal variation is largest (about 5°C) near the western coast and decreases towards the east. In contrast to these large seasonal variations, the interannual variations are much smaller. Figure 2a shows the standard deviation (SD) of the interannual variations of the SST anomalies for a typical month (June). It is seen that almost everywhere the SD is of the order of 0.5° C. The seasonal variations of the interannual SD over four selected boxes are shown in Fig. 2b. It is seen from this figure that the standard deviations remain nearly constant throughout the year.

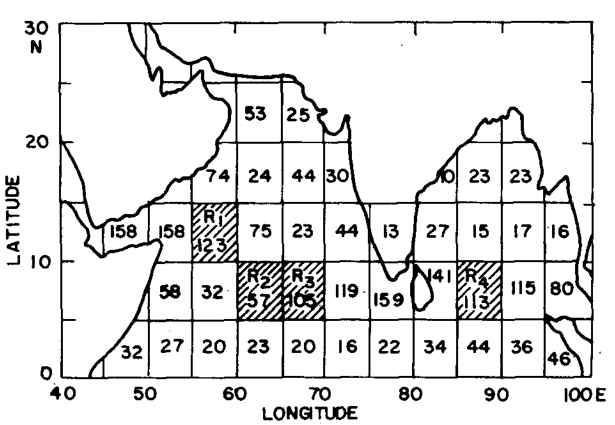

FIG. 1. The oceanic region over which surface data is examined. The numbers within each box represent mean number of observations per month.

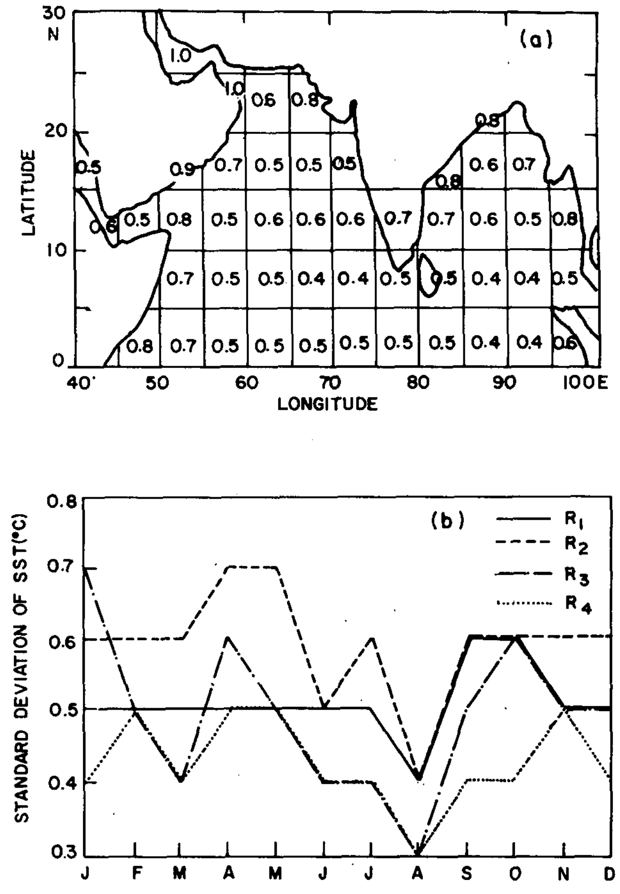

FIG. 2. (a) The standard deviation of the SST anomalies (°C) for a typical month (June) (b) The seasonal variations of the standard deviations (°C) of the SST anomalies for the four boxes marked in Fig. 1.

### *b. Long-term trend of SST and air temperature*

An examination of the time series of the SST anomalies over all the boxes revealed that the temperatures were consistently colder before the 1940s while they were consistently warmer after the 1940s. Figure 3 shows examples of the raw anomaly time series over one box ($R_2$) marked on Fig. 1. A nearly linear long-term trend is seen in these time series. Qualitatively, the picture is the same over all the boxes. In Fig. 4 we show ten-year running means of SST and air temper-

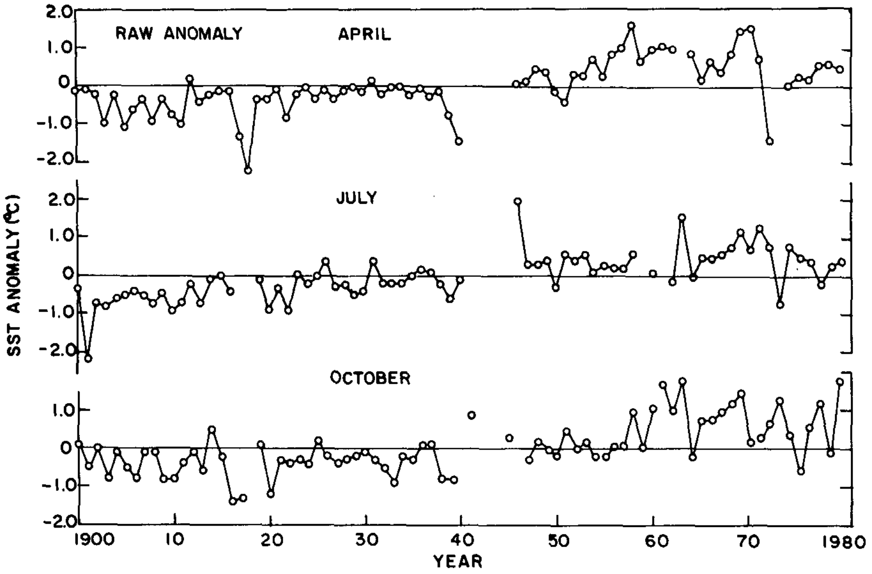

FIG. 3. The time series of raw anomaly for three months over a representative box, $R_2$, shown in Fig. 1.

ature anomalies over a few selected boxes. The same trend is seen in all the boxes. Such long-term trends in SST are also seen in the Pacific and North Atlantic (Wright and Wallace, 1983; Barnett, 1984). As discussed by Barnett (1984), a part of the trend in the SST may be due to the systematic conversion from bucket to injection measurements. Since the air temperature also shows a similar trend, however, part of the warming trend may be real. Nevertheless, for the correlation studies to be presented in this article, we have removed this long-term trend from the SST and ART anomalies by simply subtracting the ten-year

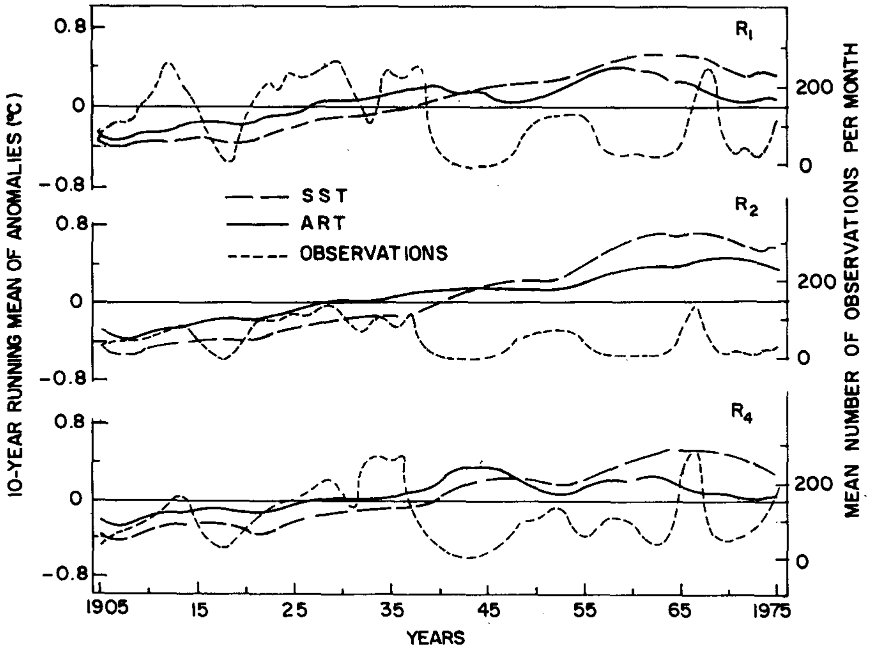

FIG. 4. Ten-year running mean of the SST and ART anomalies over three boxes shown in Fig. 1. Also shown are the average number of observations per month for the 70 years.

running mean from the raw time series. As a result, the length of the time series has been reduced to 69. We did not see any such trend in the wind fields.

It is interesting to note that the difference between the SST and ART changes sign between 1940 and 1950. This is the period when the gradual conversion from bucket to injection methods of measuring SST took place. Since no instrumental bias is expected for the ART data, this change in the sign of SST-ART may be mainly due to the bias in the SST data. This may also provide us with an estimate of the bias in the SST data. In Fig. 4, we have also plotted the average number of observations per month over these boxes. The number of observations indicates that the analysis based on our historical data should be viewed with caution for two periods, 1941–45 and 1957–63, when the number of observations available was very small.

## 3. Correlation between whole India rainfall and SST

To identify regions of the Arabian Sea, if any, that correlate with monsoon rainfall, we chose the seasonal rainfall averaged over the whole of India as given by Shukla (1987) as an indication of large-scale monsoon activity, and we correlated this quantity with the SST anomalies over all the oceanic boxes. Figure 5 gives four sets of such correlations, where the SST time series is created by averaging SST anomalies over four different sets of months. It is clear from this figure that during MA or MAM the SST over most of the north Indian Ocean correlates positively with monsoon rainfall with a certain degree of spatial coherence. It also shows that the SST over two boxes in the southeastern Arabian Sea ($R_2$ and $R_3$) during the premonsoon months correlates most strongly and significantly with the monsoon rainfall. Figure 5c shows that except for one box over the Bay of Bengal (between 10° and 15°N, 90°–95°E), the JJA SST over most of the ocean does not significantly correlate with monsoon rainfall. The spatial homogeneity of the correlation field is also poor during the JJA season. On the other hand, the SON SST correlates negatively over most of the oceanic region. The spatial homogeneity of the correlation field is high, and the highest significant correlations occur in the western and northern Arabian Sea. Thus, we have been able to identify roughly the region over which

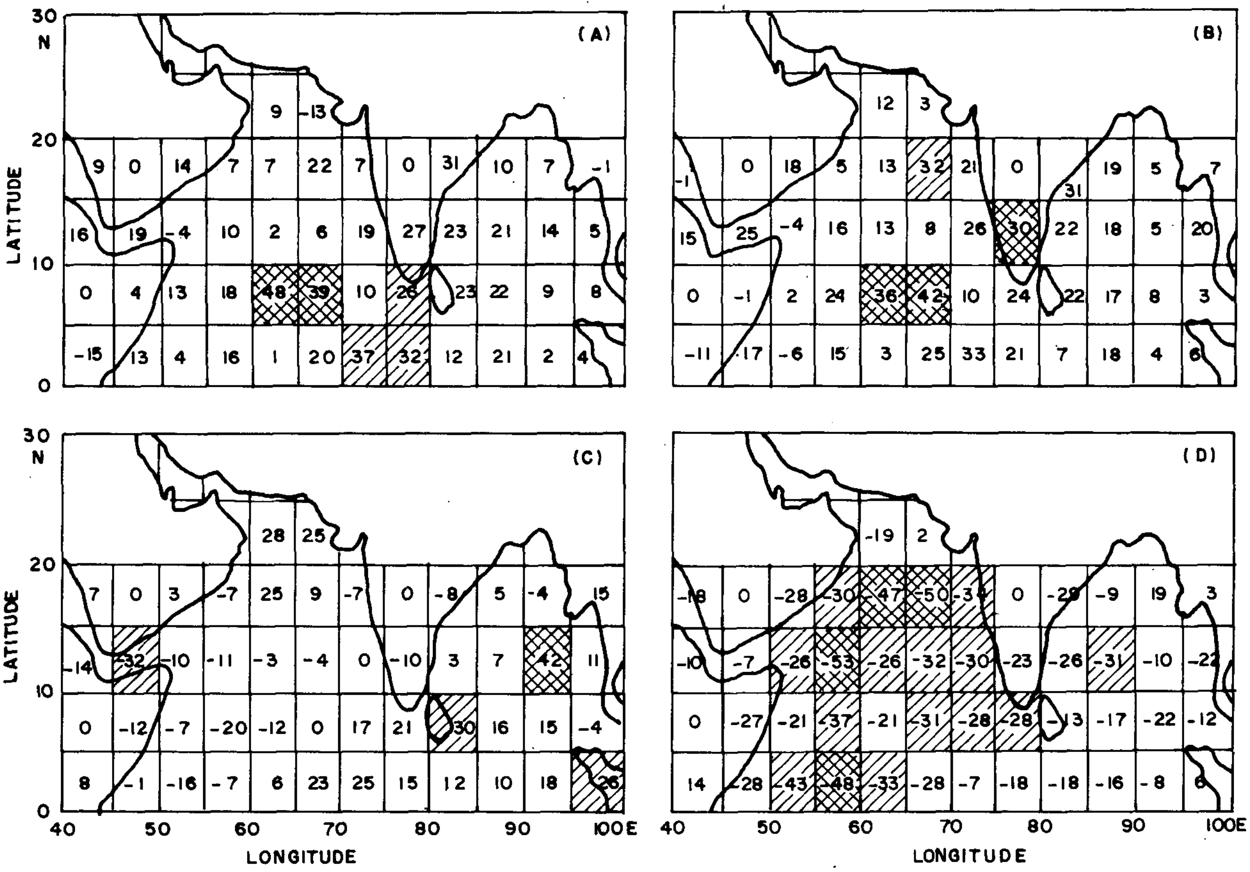

FIG. 5. Correlation coefficients (×100) between whole India seasonal rainfall and SST over different boxes averaged for (a) MA (b) MAM, (c) JJA, (d) SON. Number of years for which data is available varies from box to box. Hatching denotes significance at 95% level while crosshatching denotes significance at 99% level.

the premonsoon SST significantly affects monsoon rainfall during the subsequent months, and we have also been able to identify regions that become significantly affected by the monsoon during the post-monsoon months.

## 4. Spatial variation of the correlations over India

In the previous section we selected boxes $R_2$ and $R_3$ to represent the region over which the premonsoon SST seems to affect the monsoon rainfall of the following season. Similarly, we selected box $R_1$ to represent the oceanic region that is significantly affected by the monsoon. With the hope of finding some clue regarding the physical mechanisms responsible for these correlations, we examine in this section the spatial distribution and homogeneity of the correlations over various meteorological subdivisions of India. Figure 6 shows the correlations between SST anomalies averaged over $R_2$ and $R_3$ and seasonal monsoon rainfall over different meteorological subdivisions of India. It is interesting to note that the correlations between MA and MAM SST and seasonal rainfall change sign from significantly negative over a few eastern Indian subdivisions to significantly positive over most of northwestern and peninsular India. This is consistent with findings of Shukla (1987) and others that eastern Indian rainfall does correlate weakly negatively with the homogeneous northwest and homogeneous peninsular (as defined by Shukla, 1987) rainfall. The spatial homogeneity of the correlation field is noteworthy. This spatial homogeneity is absent for the correlation between

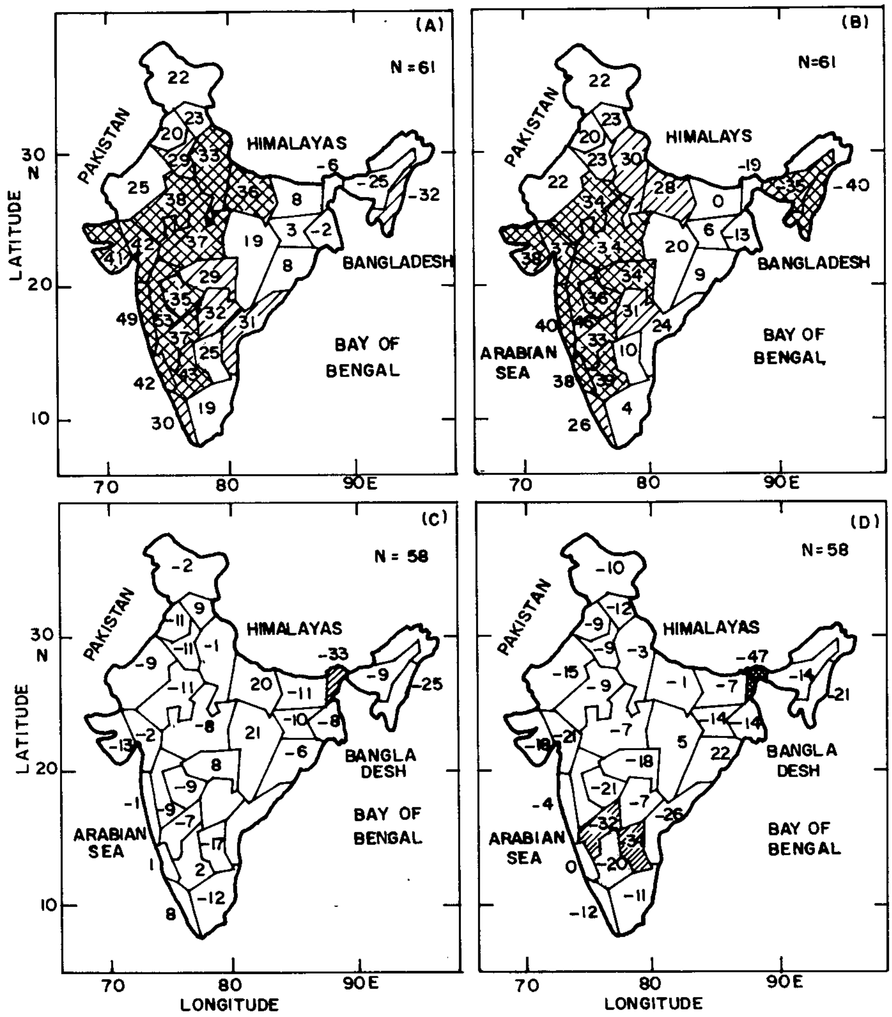

FIG. 6. Correlation coefficient (×100) between seasonal rainfall over different meteorological subdivisions of India and SST averaged over $R_2$ and $R_3$ for (a) MA, (b) MAM, (c) JJA and (d) SON. *N* in each figure represents the number of years for which data is available. The hatching convention is the same as in Fig. 5.

JJA SST and seasonal monsoon rainfall. This spatial homogeneity is again found, however, for the correlation between SON SST and seasonal rainfall. Almost everywhere over India the sign of this correlation is negative. We contrast Fig. 6 with Fig. 7 where we present correlations between SST over $R_1$ and seasonal rainfall over different subdivisions. We note that the correlations with the premonsoon SST over this region are positive but insignificant. On the other hand, the correlation between SON SST over this region and monsoon rainfall is negative and highly significant over most of the meteorological subdivisions. Again, the correlation between JJA SST and monsoon rainfall is weak and has no spatial coherence.

## 5. The SST over $R_2$ and $R_3$: a premonsoon predictor for monsoon rainfall?

In this section we explore the prospect of using the MA SST anomaly averaged over $R_2$ and $R_3$ as a premonsoon predictor for the seasonal monsoon rainfall. In Fig. 8, we show time series between 1901 and 1979 of all India rainfall and the MA SST anomaly averaged over $R_2$ and $R_3$ with and without the long-term trend. The long-term trend is clearly seen in the raw time series as revealed by the ten-year running mean (dotted curve). The SST data available to us were from 1900 to 1979. Since the corrected anomalies were obtained by subtracting the ten-year running mean, two periods of five years, each at the beginning and end of the series were lost. The existence of the long-term trend is also evident from Table 1, where we present serial correlations up to a lag of five years for all three time series shown in Fig. 8. The very large serial correlations even up to a lag of five years for the raw SST time series show the high degree of persistence in this series. On the other hand, both the rainfall and the corrected SST time series have very small serial correlations, indicating the overall lack of persistence in these series.

Figure 9 shows a scatter diagram between normalized whole India rainfall and normalized MA corrected SST

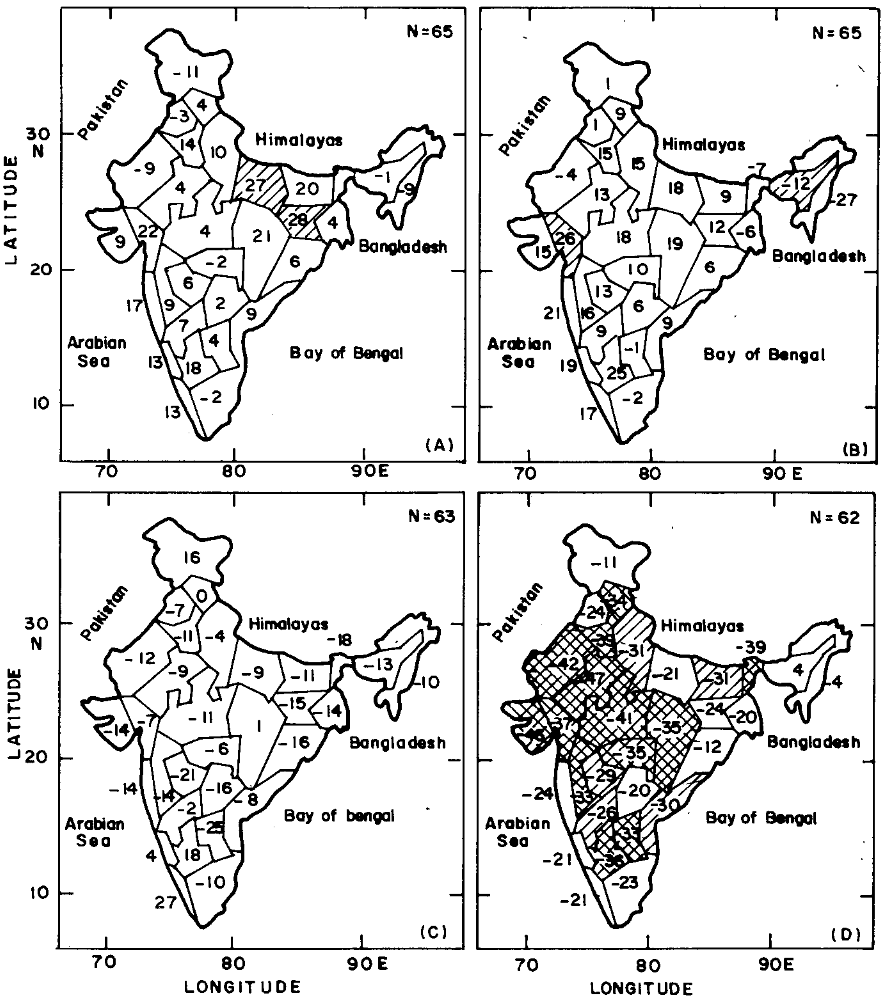

FIG. 7. As in Fig. 6 but with SST anomalies averaged over $R_1$.

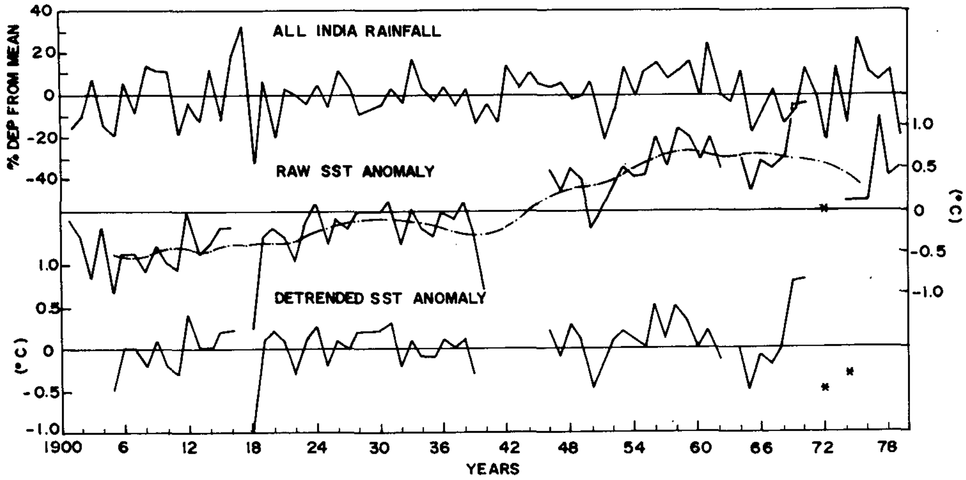

FIG. 8. Time series of all India rainfall and MA SST anomaly averaged over $R_2$ and $R_3$ with and without the long-term trend. The dotted curve is the ten-year running mean which was subtracted from the raw time series to get the detrended one.

anomaly averaged over $R_2$ and $R_3$. It is seen that most of the heavy rainfall years are in the upper right-hand quadrant and most of the severe drought years are in the lower-left quadrant. In the sample of 61 years for which SST data are available there is only one year (1908) for which the normalized rainfall anomaly is greater than +1 but has a negative SST anomaly. Similarly, there are only two years (1915, 1920) for which the normalized rainfall anomaly is less than or equal to −1 but which have a positive SST anomaly. In particular, no point falls in either the upper-left quadrant (with normalized SST anomaly greater than +1 and normalized rainfall anomaly less than −1) or lower-right quadrant (with normalized SST anomaly less than −1 and normalized rainfall anomaly greater than +1). The correlation coefficient between the two time series is +0.48. Since the serial correlations for both the rainfall and the corrected SST time series are extremely small, the correlation is highly significant. Except for the Darwin pressure trend discussed by Shukla and Paolino (1983), we are not aware of any other antecedent parameter that correlates so strongly with the monsoon rainfall of the following season using such a long record. Another antecedent parameter appears to be the April position of the 500 mb ridge over India along 75°E, which strongly correlates with the seasonal rainfall, but this parameter has a much shorter record (Mooley et al., 1986). The correlation coefficient between monsoon rainfall and the raw SST anomaly is 0.33. However if we take into account the large serial correlation in the latter series (Table 1), the reduction in degrees of freedom due to persistence (Quenouille, 1952) makes this correlation statistically insignificant. This further illustrates the importance of removing the long-term trend from the SST data.

TABLE 1. The serial correlations up to a lag of five years using data between 1905 and 1974. The number within the parentheses represents the number of years used to compute the correlation coefficient.

| Correlation coefficient | Lag in years | Whole India rainfall | Raw SST anomaly | SST anomaly after removing the trend |
|---|---|---|---|---|
| $r_1$ | 1 | −0.15 (69) | 0.72 (55) | 0.09 (55) |
| $r_2$ | 2 | 0.12 (68) | 0.63 (55) | −0.09 (55) |
| $r_3$ | 3 | 0.05 (67) | 0.67 (52) | −0.05 (52) |
| $r_4$ | 4 | −0.19 (66) | 0.60 (51) | −0.09 (51) |
| $r_5$ | 5 | −0.06 (65) | 0.63 (49) | −0.08 (49) |

Thus, the MA SST averaged over $R_2$ and $R_3$ appears to be a potentially useful predictor for the seasonal rainfall over India. We are currently in the process of constructing a regression equation for predicting seasonal monsoon rainfall using this parameter in conjunction with several other parameters. The results of this study will be reported elsewhere.

## 6. Discussion and summary

For the first time, we have been able to identify a region in the Arabian Sea over which the premonsoon (MA or MAM) SST is strongly correlated with monsoon rainfall during the subsequent months (JJAS). Also noteworthy is the spatial homogeneity of this correlation field. Our success in finding these statistically significant correlation patterns and the lack of such success by earlier authors may be attributed to our removal of relatively high-frequency noise by judicious spatial and temporal averaging and to the removal of the long-term trend in the SST data. It appears that the filtering of the intraseasonal noise from the monsoon rainfall by averaging over the whole season is very

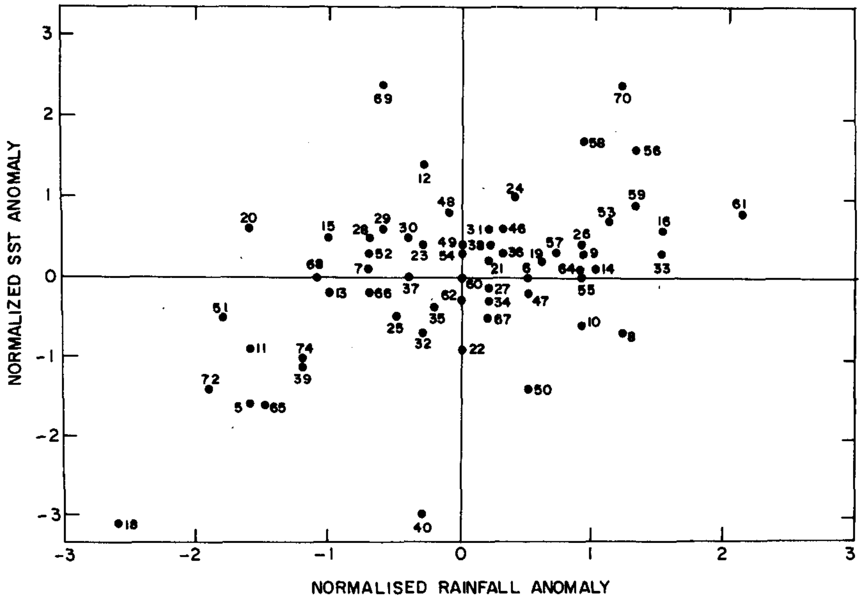

FIG. 9. The scatter diagram between normalized MA SST anomaly averaged over $R_2$ and $R_3$ and normalized whole India rainfall anomaly. The numbers denote years (minus 1900).

important. The intraseasonal 30–50 day mode starts influencing the Arabian Sea north of 10°N only from the month of May. It is therefore interesting to note that it is only the April SST or March–April SST that correlates most strongly with the monsoon rainfall of the following season. As the SST for the monsoon months starting with the month of May is included, the correlation with the monsoon rainfall deteriorates. It appears that conventional seasonal averaging of the monthly mean SST is not adequate to remove intraseasonal noise from the SST data.

Wu (1984) obtained weak positive correlations between MAM SST averaged over a large region (equator–15°N, 50°–75°E) of the Arabian Sea and the monsoon rainfall (also see Hastenrath, 1985). This is now understandable in the light of our results. It can be argued from Fig. 5a that if the SST is averaged over a larger region of the Arabian Sea, the sign of the correlation with seasonal monsoon rainfall will remain the same but the magnitude will be smaller. Joseph and Pillai (1984) also found positive correlations between the MAM SST over a region in the southeastern Arabian Sea and monsoon rainfall. However, they had data only for 13 years, and the correlation was not statistically significant. This region over the southeastern Arabian Sea indeed seems to be somewhat special. Joseph and Pillai (1986) found that the SST during April 1973 (a heavy rainfall year) was much warmer over this region as compared to the SST during April 1972 (a drought year).

The physical process through which the southeastern Arabian Sea influences the monsoon is not clear to us at this time. To shed some light on this point, we calculated the composite of MA SST anomalies for eight heavy rainfall years for which the normalized rainfall anomalies were 1.2, 1.5, 1.5, 1.1, 1.3, 1.3, 1.1 and 1.1, respectively, and for ten deficient rainfall years for which the normalized rainfall anomalies were −1.6, −1.6, −2.6, −1.6, −1.2, −1.8, −1.5, −1.1, −1.9 and −1.2, respectively. These composites are shown in Fig. 10. The years for the composites were selected on the basis of the criterion that the absolute value of the normalized rainfall anomaly must be greater than one and there must be more than 15 observations per month over the region. It is also to be noted that in selecting these years we have not been biased by Fig. 9. For example, the heavy rainfall year 1908 for which the SST anomaly is negative and the deficient rainfall year 1920 for which the SST anomaly is positive are also included in the composites. Even with these constraints, Fig. 10 shows that the SST anomaly has remarkable spatial homogeneity although the absolute magnitude of the SST anomalies is rather small. While during MA of heavy rainfall years, most of the north Indian Ocean is covered with positive SST anomalies, during deficient rainfall years, it is covered with negative SST anomalies.

We showed earlier (Fig. 7) that the correlation between monsoon rainfall and SST of May to August is very poor. This seems to indicate that the above or below normal SST seen during MA does not persist into the monsoon season. This is supported by Fig. 11, where we have plotted the bimonthly SST anomalies averaged over $R_2$ and $R_3$ composited for the same heavy and deficient rainfall years mentioned above. The difference in SST anomaly between heavy and deficient rainfall years during MA is large and significant, as the

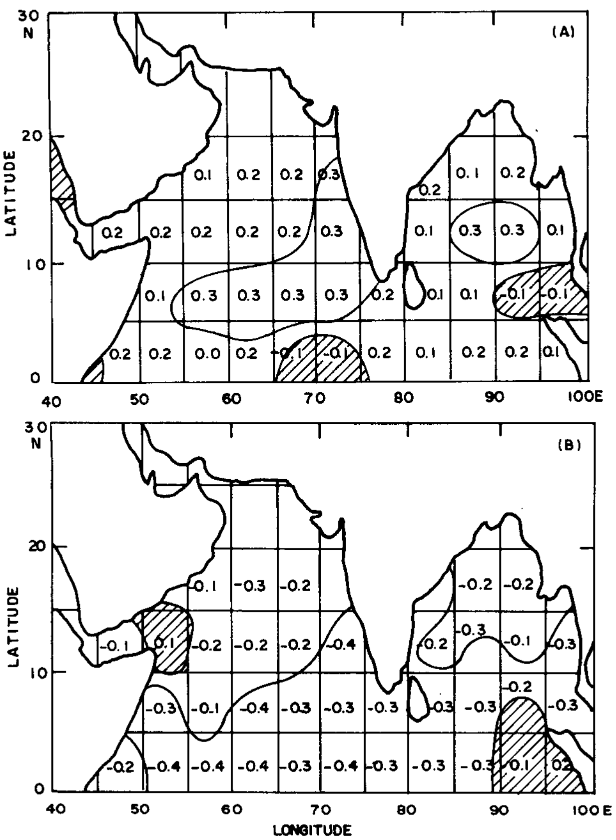

FIG. 10. MA SST anomalies (°C) averaged for (a) eight heavy-rainfall years 1908, 1916, 1933, 1953, 1956, 1959, 1961 and 1970 (0.3°C contour is marked and negative regions shaded), and (b) ten deficient rainfall years 1905, 1911, 1918, 1920, 1939, 1951, 1965, 1968, 1972 and 1974 (−0.3°C contour is marked and positive region shaded).

standard deviation of the anomaly itself is of the order of 0.3°C. However, this anomaly does not seem to persist into MJ.

Thus, we are faced with the following difficulty. Figure 10 clearly indicates that it is the large-scale boundary forcing associated with above normal (or below normal) SST through which the seasonal monsoon rainfall is being affected. However, it is difficult to conceive of any physical mechanism through which such boundary forcing seen during MA would influence June–July–August–September rainfall unless it persists for the next few months. We propose the following explanation for this apparent contradiction.

The above normal (or below normal) large-scale SST anomaly may indeed persist well into the monsoon season, but we may be missing it in our monthly mean SST data due to a sampling problem. This sampling problem arises because of two factors which influence the monthly mean SST for the months of May to September. First, the onset of the monsoon is followed by a rapid cooling of about 1°C within a short period of about a week or so over most of the Arabian Sea (Seetaramayya and Master, 1984). Because the onset of the monsoon takes place in the month of May during some years and in the month of June in other years, the monthly mean SSTs for May and June are significantly affected by the interannual variations of the onset date. Second, synoptic-scale systems also affect the SST through cloud radiation feedback and wind-induced cooling. Since the number of depressions and lows is different from one year to another, this introduces another sampling error into the monthly mean SST. Moreover, the number of observations going into constructing the monthly mean of a given month is different from one year to another. As a result, most of the days going into the monthly mean in one year could be "disturbance" days while in another year most of them could be "clear" days. This sampling problem may result in a significant difference in the monthly means of the given month for the two years. This process will be more important between June and September. This, we believe, is why the correlation with SST weakens when we include months starting with June. A way this problem may be resolved is to have observations averaged over smaller periods so that the high-frequency component may be filtered more effectively.

In using the MA SST anomaly over $R_2$ and $R_3$ as a premonsoon rainfall predictor, it should be noted that year-to-year fluctuations of the SST anomalies are quite weak (Fig. 8). It may be argued that these fluctuations are within the limit of observational errors. However, if a large number of observations are available over a homogeneous region of the size 5° lat × 10° long, reliable measurements of such fluctuations may be possible. Therefore, it may still be possible to use this signal for the prediction of monsoon rainfall.

To summarize, in this empirical study we have demonstrated the importance of removing the long-term trend from the SST data and removing intraseasonal noise from the rainfall data. For the first time, we have found coherent spatial patterns of the correlation field between the monsoon rainfall and the Arabian Sea SST. This we attribute to our separation of

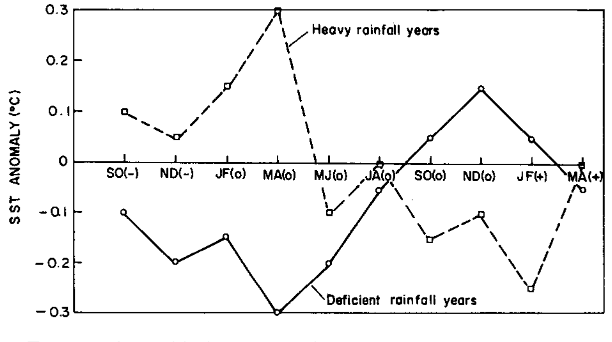

FIG. 11. Bimonthly SST anomalies averaged over $R_2$ and $R_3$ composited for the eight heavy rainfall years and ten deficient rainfall years noted in Fig. 10.

interannual climate signal from the background noise. We have also been able to identify a homogeneous region in the southeastern Arabian Sea over which the premonsoon SST is significantly correlated with the monsoon rainfall of the following season. This finding may be of considerable value for long-range prediction of the monsoon rainfall. On the basis of the spatial pattern of composited SST anomalies, we show that during heavy or deficient rainfall years, there are large-scale changes of the SST over the Indian Ocean. We also speculated about why the SST signal seen during MA does not persist into the monsoon season.

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