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Spatial and Temporal Relationships Between Global Land Surface Air Temperature Anomalies and Indian Summer Monsoon Rainfall

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With 12 Figures

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Summary

Using the 60 year period (1931–1990) gridded land surface air temperature anomalies data, the spatial and temporal relationships between Indian summer monsoon rainfall and temperature anomalies were examined. Composite temperature anomalies were prepared in respect of 11 deficient monsoon years and 9 excess monsoon years. Statistical tests were carried out to examine the significance of the composites. In addition, correlation coefficients between the temperature anomalies and Indian summer monsoon rainfall were also calculated to examine the teleconnection patterns.

There were statistically significant differences in the composite of temperature anomaly patterns between excess and deficient monsoon years over north Europe, central Asia and north America during January and May, over NW India during May, over central parts of Africa during May and July and over Indian sub-continent and eastern parts of Asia during July. It has been also found that temperature anomalies over NW Europe, central parts of Africa and NW India during January and May were positively correlated with Indian summer monsoon rainfall. Similarly temperature anomalies over central Asia during January and temperature anomalies over central Africa and Indian region during July were negatively correlated. There were secular variations in the strength of relationships between temperature anomalies and Indian summer monsoon rainfall. In general, temperature anomalies over NW Europe and NW India showed stronger correlations during the recent years. It has been also found that during excess (deficient) monsoon years temperature gradient over Eurasian land mass from sub-tropics to higher latitudes was directed equatowards (polewards) indicating strong (weak) zonal flow. This temperature anomaly gradient index was found to be a useful predictor for long range forecasting of Indian summer monsoon rainfall.

1. Introduction

The Indian summer monsoon from June to September contributes about 75–90% of the annual rainfall of India. Therefore summer monsoon rainfall is important for agricultural economy and power generation in the country. The summer monsoon rainfall averaged over the whole of India is found to be stable over the past 125 years with no long term trend. But it is dominated by large interannual variability. The interannual variability of Indian monsoon rainfall occasionally leads to droughts and floods over different parts of the country. Droughts may even result in serious reduction in agricultural output (Parthasarathy et al., 1992). The observational facts and physical plausibility support the hypothesis that the interannual variability of Indian monsoon is significantly influenced by slowly variying boundary conditions like snow cover, Sea Surface Temperature (SST) soil moisture (Shukla, 1987). In addition, past studies (Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987) confirmed a link between the E1-Niño/Southern Oscillation phenomenon and Indian monsoon rainfall. In view of the critical influence of interannual variability of summer monsoon rainfall on agricultural and industrial production, long-range forecasting of Indian summer monsoon rainfall assumes profound importance for policy making and mitigating efforts. To develop a reliable long-range forecasting scheme it becomes necessary to understand the physical forcings and associated anomalies causing the interannual variability of monsoon rainfall. For that purpose diagnostic studies on examining global circulation anomalies also become important. Such studies are also useful in identifying useful predictors for long-range forecasts.

Since monsoon is basically a thermally driven large scale circulation, it is logical to expect that any large scale thermal anomaly may have its influence on the monsoon. Sikka (1980) examined the All-India summer monsoon rainfall and NH surface air temperatures during the period 1875 to 1975 and observed that the high rainfall epoch (1921–1950) was associated with higher temperatures and the low rainfall epoch (1951–1970) with lower temperatures. Verma et al. (1985) examined the relationships between Indian monsoon rainfall and northern hemispheric surface air temperatures. Their results suggest a statistically significant positive relationship with a time lag of about six months exists between monsoon rainfall and northern hemispheric surface air temperature. A cooler Northern Hemisphere during January/February leads to a poor monsoon. Recently Mooley and Paolino (1988) studied the mean monthly surface thermal field over India during the pre-monsoon months and its association with the Indian monsoon rainfall during the period 1901–1975. They found that the mean May minimum temperatures over North West India showed highly significant positive correlation with the subsequent monsoon rainfall. Recently Krishnakumar et al. (1997) examined the relationship between premonsoon thermal field over India and following summer monsoon rainfall, using maximum and minimum temperature data of 121 stations. However these studies addressed only the aspects of the relationships with regional or hemispherically averaged temperatures only. No detailed study is available on examining the spatial and temporal relationships between global land surface air temperature anomalies and Indian monsoon rainfall. It may be quiet possible to identify few critical geographical areas where these relationships are more dominant. This study is therefore designed to examine some aspects of these relationships making use of a long-time series of global gridded land surface air temperature data.

In section 2 data used and methods of study are described. In section 3 results are discussed and in section 4 the results are summarized.

2. Data and Methods of Study

We have used all India monsoon (June to Sept) rainfall which have been prepared by area weighting sub-divisional rainfall of all 35 meteorological subdivisions in India. The mean (R) standard deviation (S) and coefficient of variation for all-India summer monsoon rainfall for the period 1901–1970 are 88 cm, 9 cm and 10% respectively. The sub-divisional monsoon rainfall for the 35 subdivisions of India were taken from the records of India Meteorological Department (IMD). The monsoon rainfall of an individual year is classified as deficient when it is less than R−S and as excess when it is more than R+S (Ananthakrishnan and Parthasarathy 1984). Figure 1 shows the all-India summer monsoon rainfall series during 1901–1997 showing the deficient and excess years.

Global monthly gridded land surface air temperature anomaly data (Jones et al., 1986; Jones and Briffa, 1992) were taken from the Greenhouse Effect Detection Experiment (GEDEX) CD-ROM. The anomalies were calculated from the base period of 1951–1970. This data set of Dr. P. D. Jones is widely used for studies on climate variability and climate prediction. The compilation of monthly mean surface air temperature is based on land-based meteorological data and fixed position weather ship data. Only reliable or corrected station data have been used in calculating area averages. This monthly data set on GEDEX CD-ROM is available on a monthly basis with a resolution of 5° lat × 10° long and the data is available from 1851. We have however used the latest 60 years of data of the period 1931–1990 for this study.

During the 60 year period of 1931–1990 there were 9 excess monsoon years (1933, 1942, 1956,

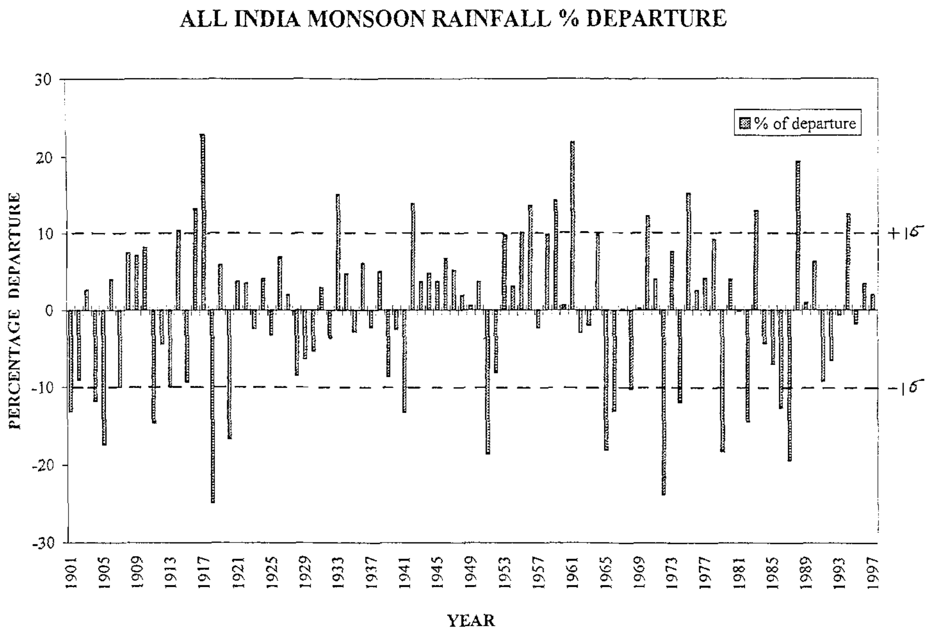

Fig. 1. All India area weighted monsoon rainfall departures from 1901 to 1997 as percentage departure from normal

1959, 1961, 1970, 1975, 1983 and 1988) and 11 deficient monsoon years (1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1986 and 1987). Composite temperature anomalies were prepared monthwise for these excess and deficient monsoon years and the differences in the anomaly patterns were examined. The Student's t-test (WMO 1966) has been used to test the significance of the differences in the anomaly patterns between the excess and deficient years. In addition, correlation coefficients between the temperature anomalies and Indian monsoon rainfall were computed monthwise and the results were analyzed. Spatial as well as the secular variations of the relationships were examined in detail.

3. Results and Discussions

3.1 Composite Spatial Anomaly Patterns

We have examined composite temperature anomaly charts of 9 excess and 11 deficient monsoon years for all the 12 months. We were interested to examine the thermal anomalies during the winter and premonsoon seasons with the ultimate aim of identifying some predictors for long range forecasts of monsoon rainfall. Therefore for want of space, we discuss here only the results of four alternate months starting from January. The composite anomalies during the month of March do not show any significant relationship with monsoon rainfall, and these anomalies are therefore not discussed further. Similarly, the anomalies in the Southern Hemisphere (data from south American continent were sparse) were also not significant and are excluded from further discussions.

Figure 2a, b and c show the differences in composite temperature anomalies between the excess and the deficient years over Eurasia and north Africa, during January, May and July. Figure 3a, b and c show the same but for the north American continent.

During January, over north Europe and north Asia, north of 60° N, temperature anomalies were significantly warmer during the excess years than during the deficient years. The maximum difference over these areas exceeded even 5 °C. Over central Asia, centred around 40° N, temperature anomalies were significantly cooler (exceeding 2 °C) during the excess years. Eventhough over most of north American continent, temperature anomalies were warmer during the excess years, only over a small area centred 50° N and 100° W, composite temperature differences were significant.

During May, significant differences were noticed over NW India and adjoining Pakistan, central Asia centred around 50° N, African region centered around 10° N and NW Europe. Excess monsoon years were associated with

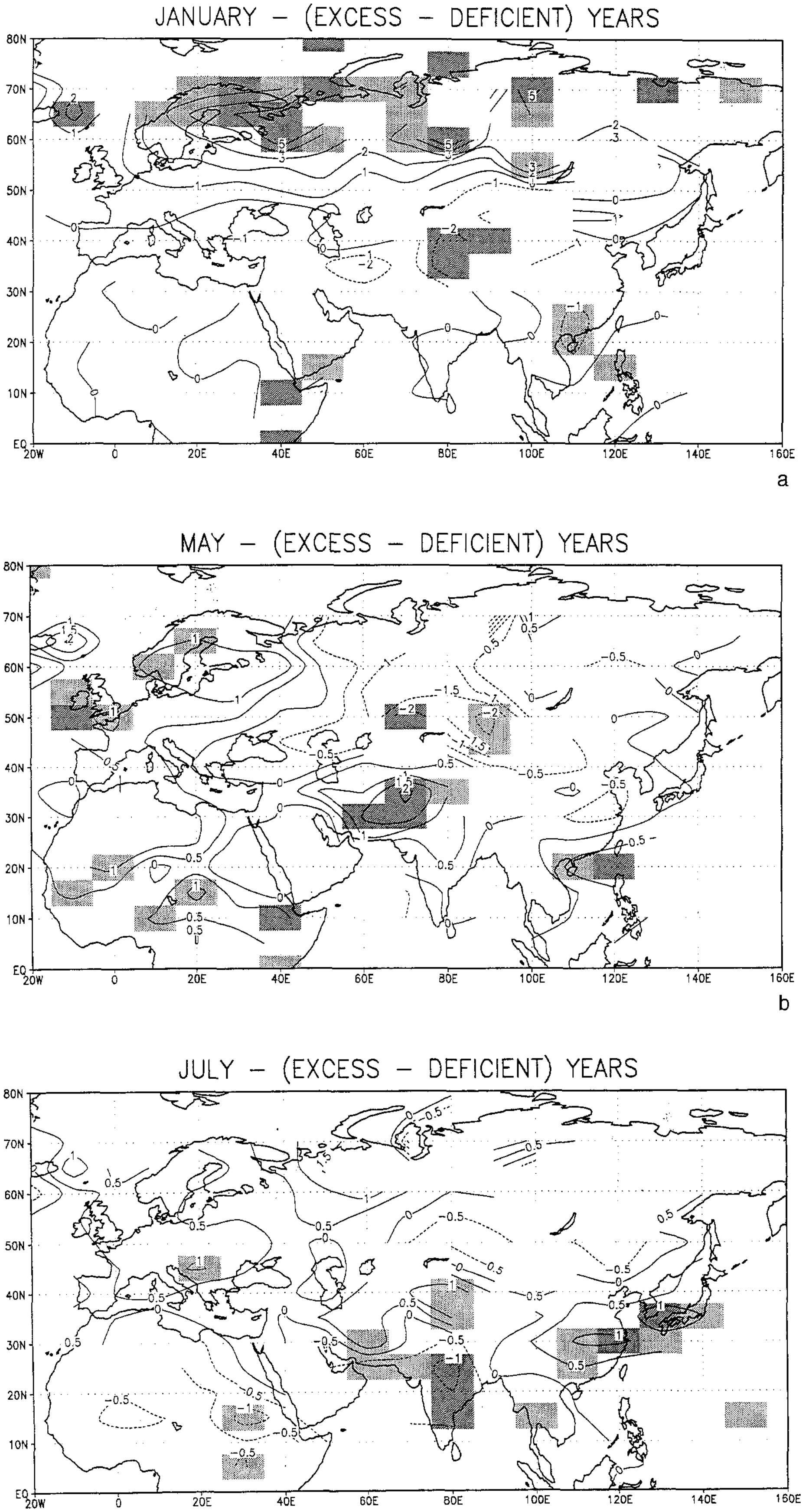

Fig. 2. Composite temperature anomaly differences between excess and the deficient monsoon years during a) January b) May and c) July over Eurasia and north Africa. Contour interval for January is 1 °C for all other months 0.5 °C. Light (dark) shading represents statistically significant areas with significance of 5% (1%) level

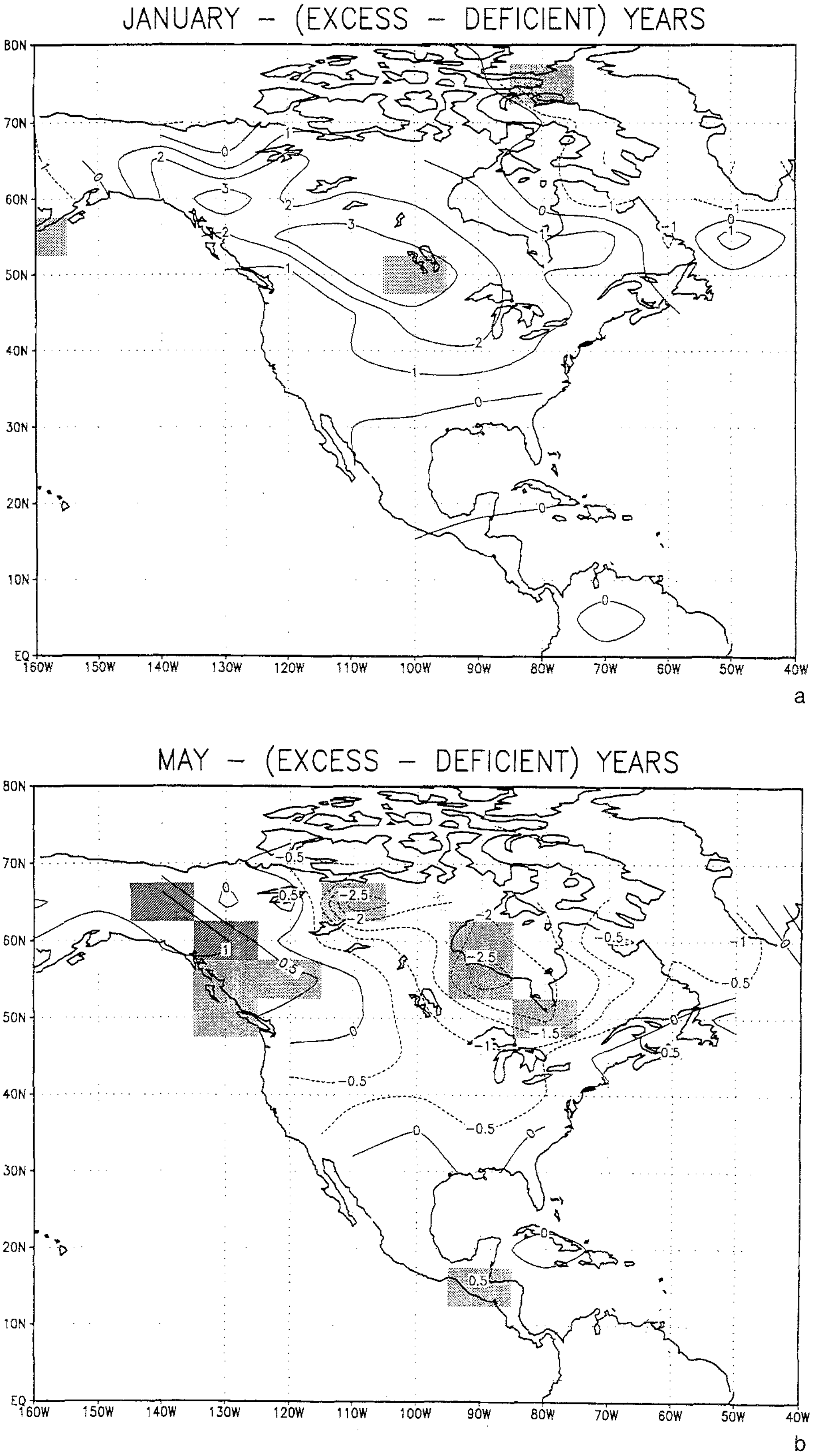

Fig. 3. Same as Fig. 2 but for the north American continent

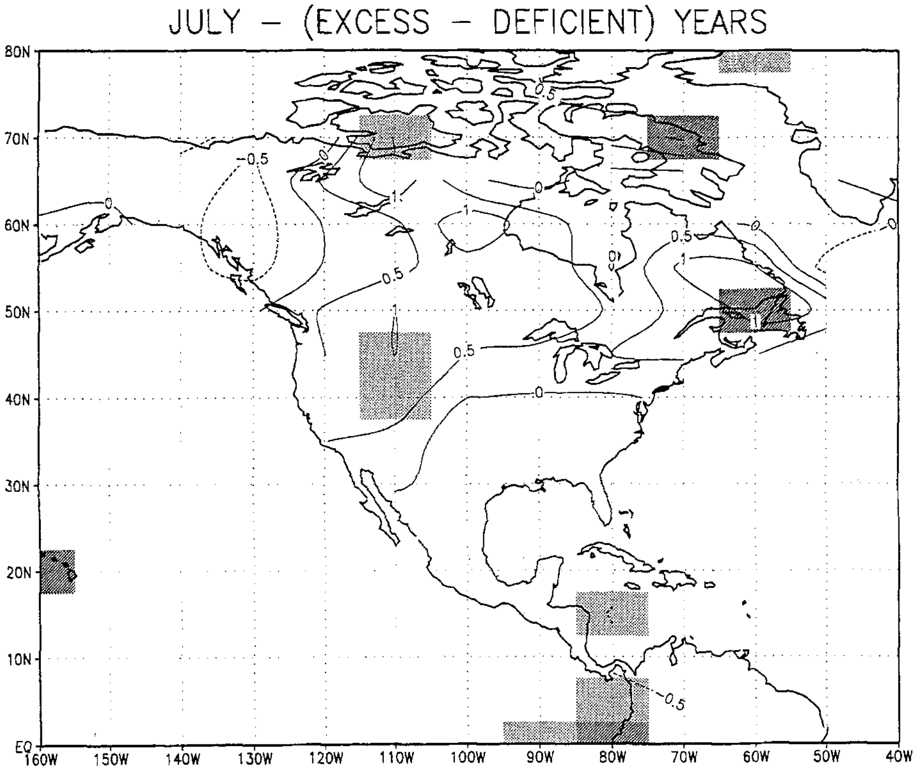

Fig. 3. (*Continued*)

warmer temperature anomalies over NW India, African region and NW Europe, and colder temperature anomalies over central Asia. Over north American continent, significant differences were observed over central Canada and over Alaska. Excess monsoon years were associated with colder (warmer) temperature anomalies over central Canada (Alaska). It is interesting to note that the temperature anomaly pattern over the north American region changed its phase from winter to summer season.

In July, significant differences were observed over Indian subcontinent, east Asia, NE parts of Africa centred around 15° N. An excess (deficient) monsoon was associated with cold (warm) anomalies over the Indian region. These anomalies were out of phase with the anomalies observed over east Asia. This may be due to the observed out of phase relationship between Indian summer monsoon and east Asian summer monsoon rainfall (Kripalani and Singh, 1993; Lau et al., 1988).

It has been found that the signals during January persisted during February but with weaker magnitudes. Anomalies similar to May anomalies were observed during April also, but again with weaker magnitudes.

The warm (cold) temperature anomalies over Europe and North America during January of excess (deficient) monsoon years may be associated with the strength and phase of North Atlantic Oscillation (NAO). Walker and Bliss (1932), van Loon and Rogers (1978) and Wallace and Gutzler (1981) addressed various aspects of NAO and associated temperature anomalies observed over Europe, Greenland and America. The positive phase of NAO indicates a strong Icelandic low, high pressure along 40° N, below normal temperatures in the Greenland-Labrador area and in the middle east and above normal temperatures in the NW Europe and eastern north America south of 60° N. The negative phase indicates above normal temperatures in the Greenland area and below normal temperatures over NW Europe and eastern north America. In this study, we have observed above (below) normal temperature over NW Europe, central America during excess (deficient) years. The anomalies over Greenland and adjoining Canadian region were out of phase with the anomalies observed over NW Europe. These observations therefore suggest that excess (deficient) monsoon rainfall over India may be associated with the positive (negative) phase of NAO with deep (shallow) Icelandic low and above (below) normal temperatures over Europe in Winter. Dugam et al. (1997) who analysed the NAO index suggested that the NAO index during winter has a statistically significant inverse relationship with rainfall over India on climatological time scales.

The negative (positive) anomalies over NW India during May of deficient (excess) monsoon years suggest intense (weak) monsoon heat low over this region. The relationship between surface heating over heat low region and Indian monsoon rainfall activity are well documented by Mooley and Paolino (1988), Rajeevan and Dubey (1994), Parthasarathy et al. (1990), Li and Yanai (1996) and Krishnakumar et al. (1997). The negative (positive) temperature anomalies over the Indian region and African monsoon region during July months of excess (deficient) monsoon years may be associated with more (less) spatial distribution of convective clouds.

3.2 Correlation Patterns

3.2.1 Spatial Patterns

We have calculated the correlation coefficients between Indian summer monsoon rainfall and temperature anomalies at each grid point for the period 1931–1990. Figure 4a, b and c show spatial patterns of the correlation coefficients for January, May and July months respectively.

During the month of January, significant positive correlations (significance level more than 5%) were observed over NW Europe and significant negative correlations were observed over central parts of Asia just north east of India. Over Eurasian land mass, region north of around 45° N was positively correlated with Indian monsoon rainfall whereas the region between 30° N to 45° N was negatively correlated. Over north American continent however no statistically significant correlations were observed (not shown), even though significant temperature differences were observed between deficient and excess monsoon years over a smaller area.

During the month of May, the temperature anomalies over west Europe, NW parts of India were positively and significantly (more than 5% level) correlated with Indian monsoon rainfall. Again, over the American continent no statistically significant correlations were observed. Also temperature anomalies over a small region over Africa centred around to 10° N were positively correlated with Indian monsoon rainfall.

During the month of July, temperature anomalies over broad areas over central Africa and Indian region showed significant negative correlations with Indian monsoon rainfall indicating negative (positive) temperature anomalies during excess (deficient) monsoon years. Temperature anomalies over eastern parts of Asia however showed out of phase relationship; i.e. significant positive correlations with Indian monsoon rainfall.

3.2.2 Secular Variations

The presence of secular variations in the strength of correlations between Indian monsoon rainfall and circulation parameters has been realised since Sir Gilbert Walker's time. This problem was addressed in detail by Gowarikar et al. (1991), Parthasarathy et al. (1991), Hastenrath and Greischer (1993) and Annamalai (1995). For example, Parthasarathy et al. (1991) have examined the relationship between Bombay Mean Sea Level pressure tendency and Indian monsoon rainfall and found turning points in the correlation coefficients around the years 1870, 1900, and 1940. They attributed these turning points to delineation between two alternating regimes in the monsoon circulation identified as "meridional" and "zonal" types of Fu and Fletcher (1988). They concluded that the Indian summer monsoon had passed through two meridional (1871–1990, 1941–90) and two zonal (1847–70, 1901–40) circulation regimes during the past 150 years.

To examine the secular variations in the relationship between Indian monsoon rainfall and temperature anomalies, we have calculated correlation coefficients for two 30 year periods, 1931–1960 and 1961–1990. The correlation coefficients for these two 30 year periods during the months of January and May over Eurasia and north Africa are shown in Figs. 5 and 6 respectively. There were appreciable differences between correlations during the two periods in January. Over Europe positive correlations were stronger during the second half than the first half. In fact, during the first half, temperature

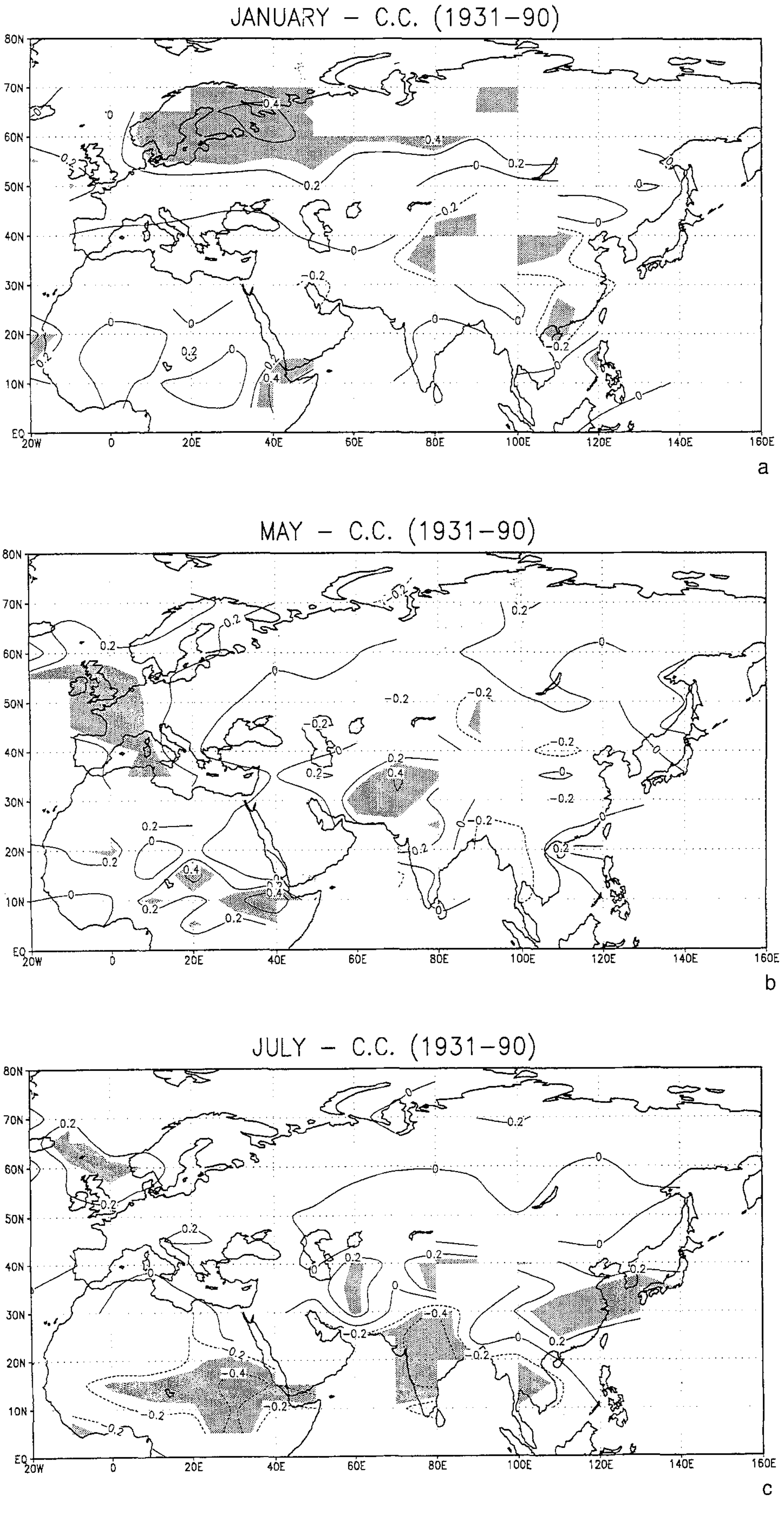

Fig. 4. Correlation coefficients between Indian monsoon rainfall and temperature anomalies during a) January b) May and c) July. Contour interval is 0.2. CCs which are significant at ≥5% level are shaded. Contours of positive (negative) CCs are represented by continous (broken) lines

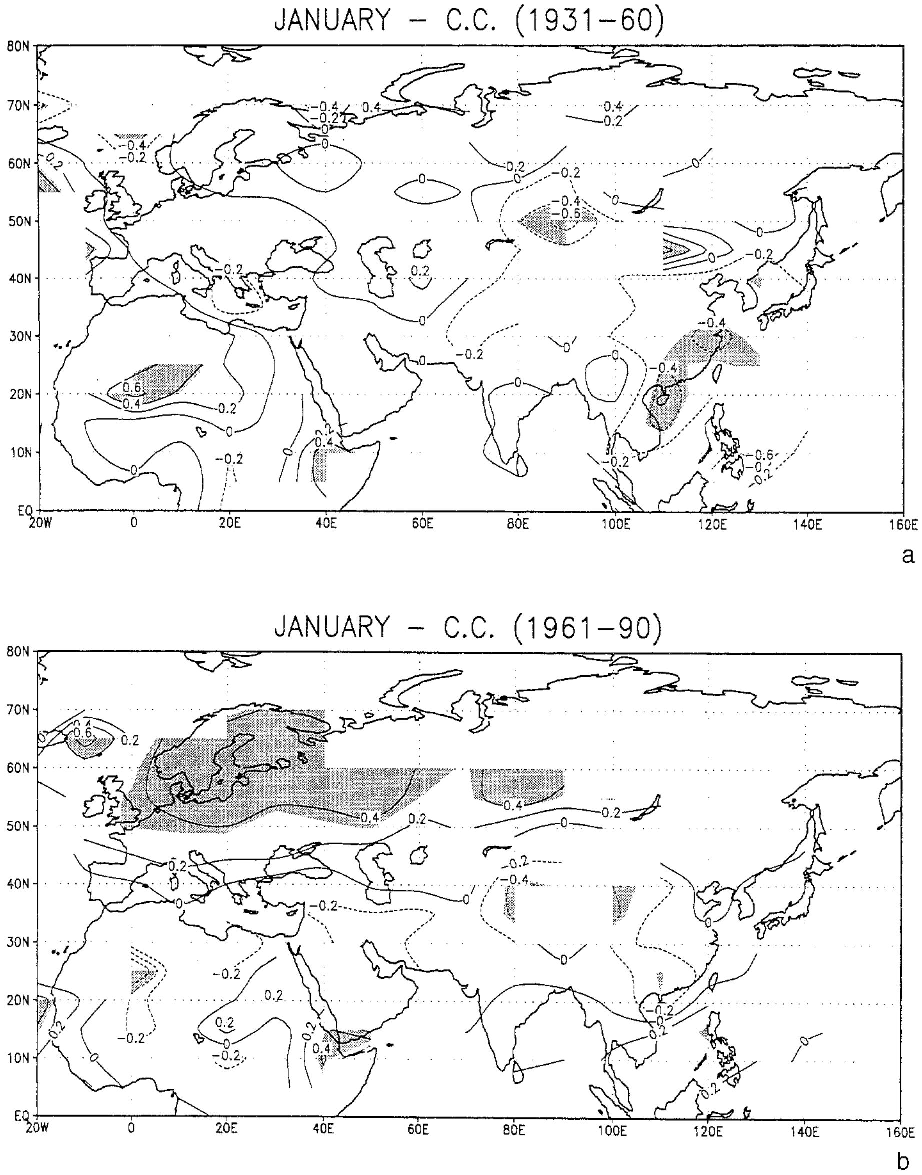

Fig. 5. Correlation coefficients between Indian monsoon rainfall and temperature anomalies during January for the period a) 1931–1960 b) 1961–1990. Contour interval is 0.2. CCs which are significant at ≥5% level are shaded. Contours of positive (negative) CCs are represented by continous (broken) lines

anomalies over some of parts of Europe showed small negative correlations with monsoon rainfall. During the period 1961–90, maximum correlations exceeded 0.45 over Europe which is significant even at 1% level. Another appreciable difference was noticed over eastern parts of Asia. During the first 30 year period of 1931–1960, negative correlations exceeding 0.37 (which is significant at 5% level) were noticed. However, during the period 1961–90 these negative correlations decreased in strength. Over North American continent there were no secular variations.

During the month of May also, there were appreciable differences in the correlations between the two periods. Positive correlations over NW India, and central Africa were stronger during the later 30 year period of 1961–1990 than the first 30 year period of 1931–1960. In the first half, temperature anomalies over a small region of north Africa showed significant positive correlations. The correlations over NW Europe and central Africa during the period 1961–90 were more than 0.37 which is significant at 5% level. Over Europe, area of significant correlations shifted from south during the first half to the north during the second half. However correlations over North America during the first 30 year period of 1931–60 were significant at 1% level (Fig. 7). During the second half, these correlations decreased in strength and became statistically insignificant.

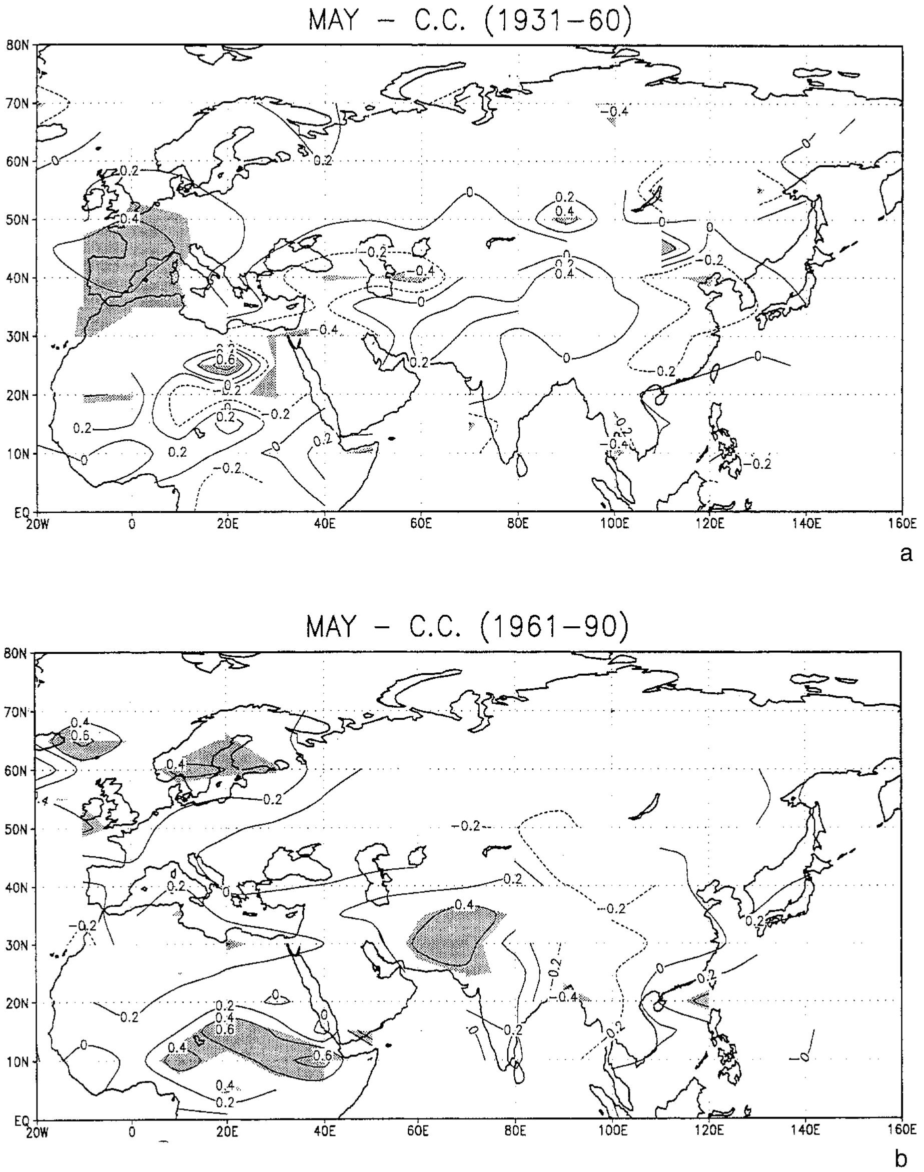

Fig. 6. Same as Fig. 5 but for the month of May

The secular variations of correlation coefficients over different parts of the globe were further examined by calculating 30 year moving correlations between Indian monsoon rainfall and average temperature anomalies over i) NW Europe ii) NW India. The results are shown in Fig. 8. During January, correlations over NW India generally varied little between −0.20 and −0.3 and were not significant. But during May, strength of the positive correlations steadily increased from 1965 and reached a plateau of about 0.4 in 1973. Afterwards C.Cs more or less remained close to 0.4 and further a steep increase was noticed from 1987. Thus the C.C for the 30 year period increased from 0.2 which is statistically insignificant during 1931–1960 to 0.50 during 1961–1990. The C.C. of January temperature over NW Europe increased form 0.04 during 1931–1960 to 0.58 during the period of 1961–90. During May, CCs exhibited an increasing strength from the year 1982.

3.2.3 North-South Temperature Gradient over Eurasian Land-mass

In section 3.2.1 we have discussed that during January temperature anomalies over Eurasian land mass, north (south) of 45° N is positively (negatively) correlated with Indian monsoon rainfall. In other words, excess Indian monsoon is associated with decreased south to north winter temperature gradient form sub-tropics to higher latitudes. This is because of the lower (higher)

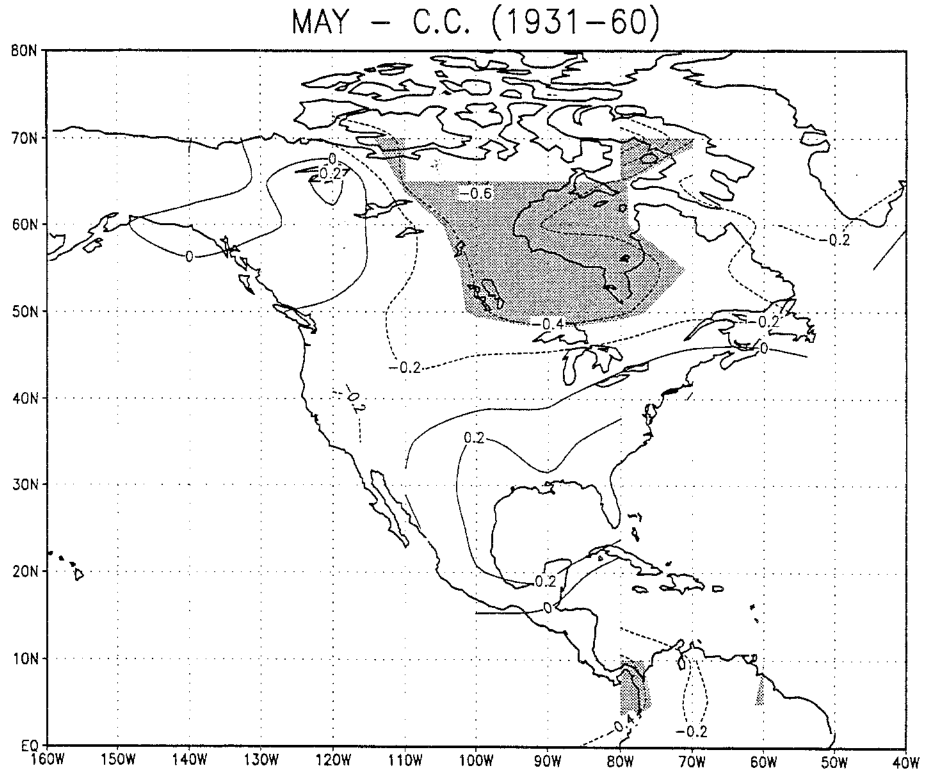

Fig. 7. CCs between Indian monsoon rainfall and temperature anomalies over north American continent during May for the period 1931–1960

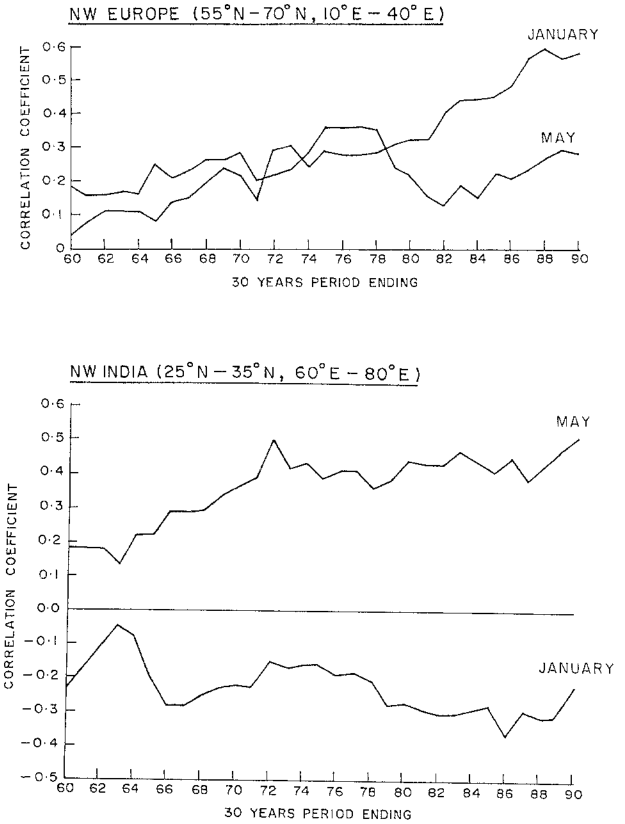

Fig. 8. 30 year period moving correlations between Indian monsoon rainfall and temperature anomalies over a) NW Europe (55° N–70° N, 10° E–40° E) b) NW India (25° N–35° N, 60° E–80° E) for the months of January and May

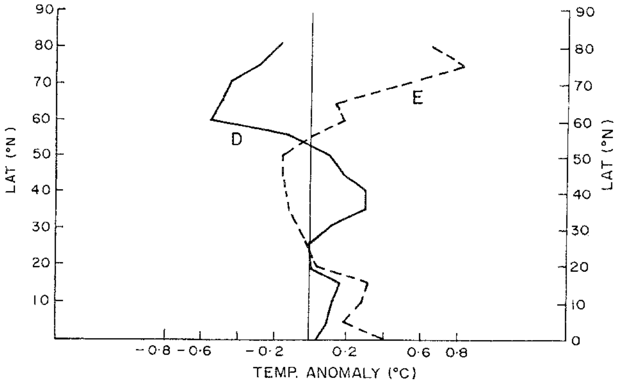

Fig. 9. Composite zonal averages of temperature anomalies over Eurasian land mass (0 to 150 °E) in respect of deficient (D) and excess (E) monsoon years

than normal temperatures over subtropics (higher latitudes). To examine this aspect in detail, we have made composite zonal averages (averaged between longitudes 0 to 150° E) of temperature anomalies during January in respect of 9 excess and 11 deficient monsoon years (Section 2). The resultant composite zonal averages are shown in Fig. 9. There were little differences in the tropical region. Appreciable differences were noticed north of 25° N. During excess (deficient) monsoon years the gradient of temperature anomaly from the subtropics to higher latitudes is equatowards (polewards). This implies that during excess (deficient) monsoon years, sub-tropical region was colder (warmer) than normal and higher latitude region was warmer (colder) than normal.

Raman and Maliekal (1985) analysed northern hemispheric pressure anomalies in relation to Indian summer monsoon and found similar (hydrostatically) meridional structure of zonally averaged pressure anomalies. They found that during the winters of excess monsoon years, there exists a steep, poleward directed pressure anomaly gradient from the sub tropics to higher latitudes. In the deficient monsoon years, they found that the pressure anomaly gradient is directed equatoward. Thus equatoward directed temperature anomaly gradient over mid-latitudes of Eurasia seems to be the precursor of below normal Indian summer monsoon activity. The steep poleward pressure anomaly gradient observed during excess monsoon years may indicate a strong zonal flow in the circumpolar westerlies. On the other hand when this pressure gradient reverses, zonality is disturbed and the circum polar flow becomes persistently meridional and leads to persistently above normal blocking activity over Eurasia. Blocking over high latitudes of Eurasia was associated with monsoon droughts-over India (Raman and Rao, 1981; Shukla, 1987).

We have further examined the usefulness of this gradient as a predictor in long range forecasting of Indian summer monsoon rainfall. We have calculated a meridional temperature anomaly gradient index as the difference between longitudinally (0 to 150° E) averaged temperature anomalies in the latitude zones 30–50° N and 50–70° N. The calculated temperature anomaly gradient index for the period 1931–1990 are shown in Fig. 9 along with all India monsoon rainfall for the same period. The correlation coefficient between the two time series is −0.47 which is significant at 1% level. The 30 year moving correlations are shown in Fig. 10 which show that the strength of correlations has increased in magnitude with time. For example, the C.C. for the period 1931–1960 is −0.23 whereas C.C for the latest 30 year period of 1961–1990 is −0.65, almost a three fold increase. This temperature anomaly gradient index is also found to be better correlated with Indian monsoon rainfall than the NH temperature anomaly which is one of the predictors widely used in long-range forecast models (Gowariker et al., 1991; Hastenrath and Greischer, 1993; Krishnakumar et al., 1995). The correlation of NH temperature anomaly with all India monsoon rainfall for the period 1931–1990 is 0.30 which is appreciably smaller than the correlation of temperature anomaly gradient index (−0.47) for the same period. Even for the latest 30 year period 1961–1990, the CC with temperature anomaly gradient index (−0.65) is appreciably larger than the CC with NH temperature anomaly (0.42). It has been also found that this temperature anomaly gradi-

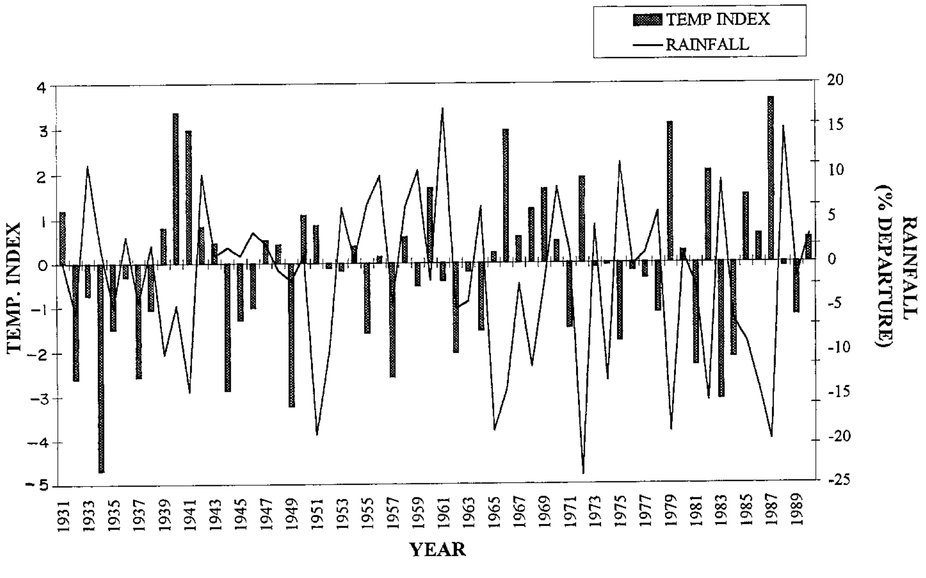

Fig. 10. Time series of temperature anomaly gradient index and Indian monsoon rainfall for the period 1931–1990

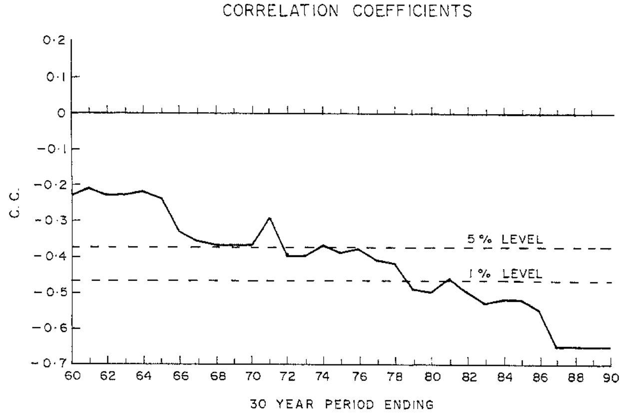

Fig. 11. 30 year period moving correlations between temperature anomaly gradient Index and all Indian monsoon rainfall

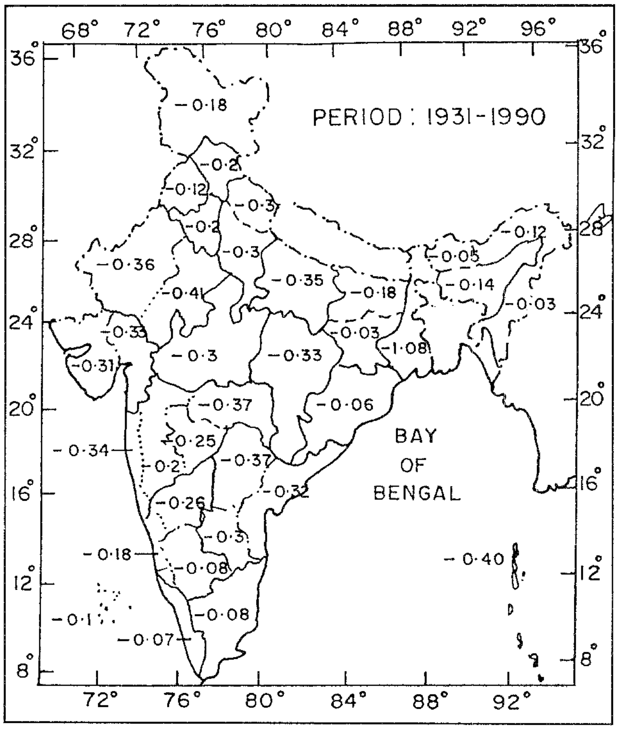

Fig. 12. Correlation coefficients between temperature anomaly gradient index and subdivisional monsoon rainfall for the period 1931–1990

ent index is significantly correlated with monsoon rainfall on sub-divisional scale also. Figure 11 shows the CCs between this index and sub-divisional monsoon rainfall for the period 1931–1990. The rainfall over sub-divisions of north-eastern parts of India were negatively (but not significantly) correlated with the temperature anomaly gradient index. But rainfall over 16 sub-divisions were positively and significantly (at 5% level) correlated with the temperature anomaly gradient index. The usefulness of this index for hindcasting Indian Monsoon rainfall has been further examined by analysing its relationship with deficient, normal and excess monsoon categories using contingency table as shown in Table 1. The contingency table is statistically significant even at 0.1% level. There is very high probability (86%) for deficient monsoon rainfall, when this index is more than one standard deviation (standard deviation for the period 1931–1990 is 1.7). On such occasions, probability to receive excess rainfall is zero. Similarly, where the temperature index is less than one standard deviation, probability to receive deficient rainfall is zero. The mean values of this index for the 11 deficient monsoon years and the 9 excess monsoon years are 1.7 and −0.46 respectively. Using the Student's t test (WMO) 1966), it has been found that the difference between these two means is statistically significant at 0.5% level.

Table 1. *Contigency Table of Frequency of Occurrence of Deficient (D), Excess (E) and Normal Rainfall (N) over India during Monsoon (June-Sept.) Season vs January Temperature Anomaly Gradient Index when it is Normal (within one Standard Deviation ($\sigma = 1.7$), (TI_N), more than 1σ (TI(+) and less than 1σ (TI(−).). Period: 1931–1990.*

	D	N	E	TOTAL
TI(+)	6	1	0	7
TI	5	29	7	41
TI(−)	0	10	2	12
Total	11	40	9	60

$\chi^2 = 25.057$, significant at 0.1 percent level. Probabilites estimated from contingency table are,

1) Neglecting temperature anomaly index, $P_r(D) = 0.183$, $P_r(E) = 0.150$

2) In years with TI_+, $P_r(D) = 0.857$, $P_r(E) = 0.0$

3) In years with TI_-, $P_r(D) = 0$, $P_r(E) = 0.166$

Thus this temperature anomaly gradient index seems to be a useful predictor since it is statistically and physically significant. We strongly recommend to use it in long range prediction models.

4. Summary and Conclusions

Using the 60 year period (1931–1990) gridded land surface air temperature anomalies data, we have examined the spatial and temporal relationships between Indian summer monsoon rainfall and temperature anomalies. The following main conclusions can be drawn from this study.

i) There were statistically significant differences in the composites temperature anomaly patterns between excess and deficient monsoon years over a) NW Europe, North America and central Asia during January and May b) over NW India and adjoining areas during May, c) over central Africa during May and July and d) over Indian sub-continent and eastern parts of Asia during July. The significant temperature differences found over NW Europe and North America during January may be linked with phase and strength of North Atlantic Oscillation. The significant differences noticed over NW India and adjoining areas during May were associated with the interannual variation in summer solar heating.

ii) Temperature anomalies over NW Europe and NW India during January and May were positively correlated with Indian summer monsoon rainfall. Similarly temperature anomalies over central parts of Asia during January were negatively correlated. During the month of July, temperature anomalies over central African region and Indian region were negatively correlated whereas temperature anomalies over eastern parts of Asia were positively correlated with Indian summer monsoon rainfall.

iii) There were secular variations of CCs between temperature anomalies and Indian summer monsoon rainfall. Temperature anomalies over NW Europe and NW India showed stronger correlations during the recent 30 years.

iv) There were appreciable differences in the zonally averaged January temperature anomalies profiles over Eurasian land mass between the excess and deficient monsoon years. During excess (deficient) monsoon years, temperature anomaly gradient from sub-tropics to higher latitudes was directed equatowards (polewards) indicating strong (weak) zonal index. This temperature anomaly gradient index is found to be a useful predictor for long range forecasting of Indian summer monsoon rainfall.

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