INTERNATIONAL JOURNAL OF CLIMATOLOGY, VOL. 17, 1055–1067 (1997)

ASSOCIATION OF THE INDIAN SUMMER MONSOON WITH THE NORTHERN HEMISPHERE MID–LATITUDE CIRCULATION

R. H. KRIPALANI*, ASHWINI KULKARNI AND S. V. SINGH
Indian Institute of Tropical Meteorology, Pune–411 008, India

Received 14 March 1996
Revised 27 January 1997
Accepted 31 January 1997

ABSTRACT

The association between the mid–latitude circulation and rainfall over the Indian region on an intraseasonal time–scale is investigated by considering 11 years (1974–1984) of Northern Hemisphere 500 hPa geopotential heights and rainfall data for the Indian summer monsoon months June through to September. On the basis of extensive correlation analysis between the geopotential heights and rainfall, it is seen that three regions over the mid–latitudes, the Manchurian region, the Algerian region and the Caspian sea region show positive correlation with rainfall over India, with higher values north of 20°N latitude. Lead and lag correlations between the heights at the locations identified above and rainfall over India reveals that some common element of low–frequency variability is influencing the mid–latitude circulation and Indian rainfall.

On the interannual scale the connections between the winter–time low–frequency patterns (the Pacific/North Atlantic, the West Pacific Oscillation, the North Atlantic Oscillation and the Eurasian) and Indian summer monsoon rainfall (ISMR) are investigated. Only the West Pacific Oscillation pattern shows a significant relationship with the ISMR. Further, the interannual and the decadal variability is examined by using the Northern Hemisphere zonal index data for the period 1900–1993. Results reveal that the decadal–scale variability of the ISMR and the circulation features of the Northern Hemisphere are connected. © 1997 by the Royal Meteorological Society. *Int. J. Climatol*., 17: 1055–1067 (1997)

(No. of Figures: 8 No. of Tables: 0 No. of References: 35)

KEY WORDS: Indian monsoon variability; teleconnections; 500 hPa heights; zonal index.

1. INTRODUCTION

The easterlies of the tropics are separated by the westerlies of the extratropics roughly along the 30°N parallel. However, there is no rigid wall between the tropics and the extratropics. As such these two weather regimes interact significantly to create abnormal weather conditions through teleconnections. A large number of studies have been done to examine the influence of the mid–latitude circulation on the Indian monsoon rainfall on intraseasonal and interannual scales. A review of work done in this regard is given in Keshavamurty and Shankar Rao (1992) and Asnani (1993). The basic premise of all these studies has been that the monsoon is a system thermally driven by land–ocean contrasts, and any element that takes away the heating from the monsoon region or mixes cold air into it will weaken the monsoon.

The basic flow in the mid–latitudes is from the west, hence most investigators have examined the circulation features upstream (central Asia) on intraseasonal time–scales. On this time scale, the mid–latitude atmosphere shows a semi–regular alternation between high index periods of predominantly zonal flow and low index periods when large amplitude waves or blocking regimes are dominant. According to Ramaswamy (1962), during these periods of low index the troughs in the westerlies penetrate deeper over India, causing monsoon breaks. These troughs may suppress the monsoonal thermal contrast by cold air advection and change the local meridional circulation. Prior to these large–scale breaks, formation of large–scale blocking, first over the Caspian region and later over eastern Siberia, has been noted by Raman and Rao (1981).

*Correspondence to: R. H. Kripalani, Indian Institute of Tropical Meteorology, Pune-411 008, India. Email: rhksup@tropmet.ernet.in

CCC 0899-8418/97/101055–13 $17.50

Most of the work on an intraseasonal scale is based on individual case studies, hence the purpose of this study is to consider data as a whole and to determine whether there are preferred window regions over the northern mid-latitudes for the southward propagation of these waves. In order to investigate this we objectively determine the relationship between mid–latitude circulation and rainfall over India on a subseasonal time–scale during the summer period (section 3). To remove high–frequency variability, 5–day average values have been considered. Earlier, such studies generally were confined to the winter season (e.g. Liebmann and Hartmann, 1984). Studies for the summer season used either outgoing longwave radiation (OLR) (Kurihara, 1989) or geopotential heights (Yasunari, 1986) as a proxy for tropical convection. We use the actual rainfall data to represent convection. The mid–latitude flow is characterized by the 500 hPa geopotential heights.

On an interannual scale, Blanford (1884) had recognized the adverse effects of Himalayan snow on the performance of the monsoon variability. Besides the Himalayan and Eurasian snow accumulation during the preceding winter (Hahn and Shukla, 1976), signifying the radiative influence through boundary forcing, other parameters having links with the Northern Hemisphere (NH) mid–latitude circulation features have been associated with the monsoon performance. Notable being the NH winter temperature anomaly (Verma *et al*., 1985), signifying the sensible heat build–up of the thermal forcing of the monsoon, and the latitudinal position of the 500 hPa subtropical ridge along 75°E during April (Banerjee *et al*., 1978), signifying the strength of the mid–latitude zonal flow during the spring season. A recent study by Kripalani *et al*. (1996) has shown that the snow depth during January over the former USSR is highly related with subsequent Indian summer monsoon rainfall (ISMR). Most of these relationships will tend to suggest that the excessive baroclinic activity of the extratropical latitudes is unfavourable for a well–developed monsoon.

The atmospheric circulation exhibits substantial low–frequency variability, which often strongly influences the precipitation patterns. Recurrent patterns of low–frequency variability are often referred to as ‘teleconnections’. The primary teleconnection patterns over the NH are the Pacific/North American (PNA) pattern, the West Pacific Oscillation (WPO) pattern, the North Atlantic Oscillation (NAO) and the Eurasian (EU) teleconnection pattern (Wallace and Gutzler, 1981; Barnston and Livezey, 1987). Besides these patterns the strength of the north–south pressure gradients over the NH can be estimated from the differences in zonally averaged sea–level pressure between two latitudes (say 35°N and 65°N), normally termed as the zonal index (ZI). Hence the relationship between the interannual behaviour of the ISMR and the winter–time circulation indices of the above four patterns and the ZI are also investigated (section 4). The Indian monsoon has shown variability on a decadal scale, with distinct epochs of above and below normal rainfall. Whether the decadal behaviour of the ISMR is connected with events in the NH is also investigated in the same section.

2. DATA

(i) Five–day 500 hPa contour heights, characterizing mid–latitude flow patterns for the region 30°–60°N and 0°–180°E at 5° latitude by 10° longitude, were extracted from global data received from Takashi Nakayama of Japan Meteorological Agency (JMA). Data are produced from the daily (1200 UTC) operational global objective analysis scheme at the Numerical Prediction Division, JMA. We have considered mid–latitude flow patterns north of 30°N because it is not only the northern limit of monsoon circulation but is also very nearly the boundary between global easterlies and westerlies during the monsoon season (Shankar Rao *et al*., 1991). The longitudinal domain is restricted to the eastern hemisphere, focusing attention only on the Asian monsoon region. This region consists of 133 grid–points (Figure 1). Data for June to September for an 11–year period, 1974–1884, giving a total of 264 (24×11) 5–day charts, are used.

(ii) Five–day rainfall amounts for the same period for 52 blocks over India (Figure 1) are used. Details of the Indian rainfall are given in Singh *et al*. (1992).

(iii) Standardized time series (prepared by NOAA/NWS/NMC/CAC, Washington, DC) of the seasonal PNA/WPO/NAO/EU patterns have been picked from the Climate System Monitoring publication (WMO and UNEP, 1995). These patterns and time series are determined by performing an orthogonally rotated principal component analysis of NH monthly mean 700 hPa heights for the December through to February period between 1964 and 1994 (Barnston and Livezey, 1987).

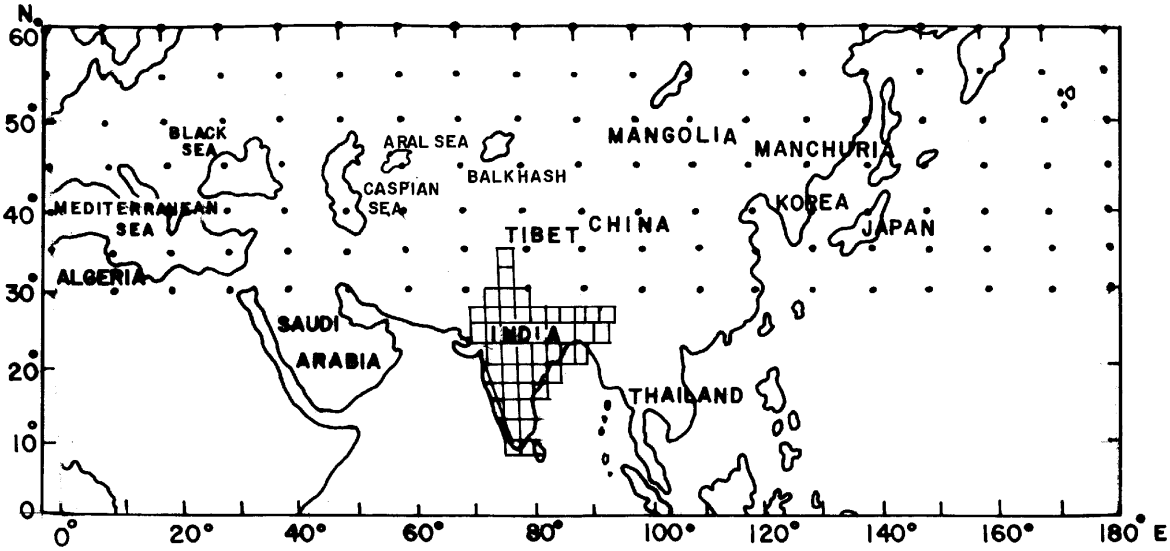

Figure 1. Location of gridpoints for mid-latitude flow pattern data

(iv) Values of the standardized anomalies of the NHZI (prepared by Deutscher Wetterdienst, Seewetteramt, Hamburg computed over the band from 35°N to 65°N for the winter season (November through to March) for the period 1900–1993 have also been picked from the Climate System Monitoring publication (WMO and UNEP, 1995).

(v) The seasonal (June through to September) Indian monsoon rainfall for the period 1900–1993 has been taken from Parthasarathy *et al*. (1994).

(vi) Northern Hemisphere surface temperature (NHST) average for January and February for the period 1900–1993 (Jones *et al*., 1982).

(vii) Darwin pressure tendency (DPT)—mean sea–level (MSL) pressure difference between January and April for Darwin in northern Australia representing the state of the Southern Oscillation for the period 1900–1993 (Shukla and Paolino, 1983).

(viii) The 500 hPa subtropical ridge position (latitude) along 75°E during April (Ridge) for the period 1939–1993 (Banerjee *et al*., 1978).

3. INTRASEASONAL ASSOCIATIONS

Before the intraseasonal connections are investigated, the mean and the variability of the geopotential heights are computed. A picture of the 500 hPa mean and variability (standard deviation, SD) of the geopotential heights during the period of study is shown in Figure 2. From the figure it is apparent that the mean geopotential height decreases from 30°N to 60°N, whereas the SD increases. Thus from the tropics to the poles the standard deviation keeps on increasing, being at a minimum near the tropics and maximum near the poles. The maps reflect the increasing baroclinicity towards the poles. The SD is least just north of India. This figure will provide a basis for interpreting the observed differences on the intraseasonal time–scale. Before the computations are performed the interannual variability is removed by subtracting from each individual 5–day period, the seasonal mean for that particular year.

To search objectively for connections between the mid–latitude flow patterns and precipitation over the Indian region, correlation coefficients between the 500 hPa height at each grid–point with rainfall of the 52 blocks over India are computed. The largest of the positive correlations between a 500 hPa grid–point and all precipitation points is plotted at the corresponding 500 hPa grid–point. Similarly, the largest positive correlation between a

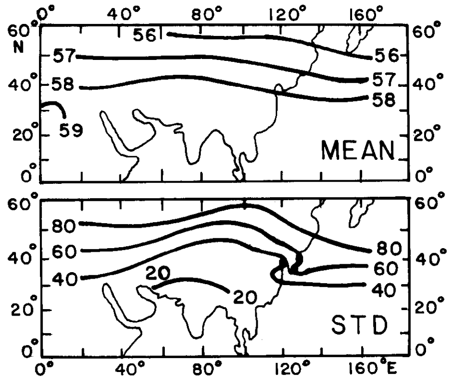

Figure 2. The 500 hPa mean and variability (standard deviation) of geopotential heights during period of study

precipitation block and entire 500 hPa field is plotted at the corresponding precipitation block. This approach is similar to the one followed by Liebmann and Hartmann (1984).

3.1. Map of maximum correlation

Figure 3 shows the spatial distribution of the maximum correlations obtained through the above procedure for concurrent periods. Almost all geophysical time series involve some degree of dependence between consecutive values. Hence the effective sample size (264) has to be adjusted. With the tests suggested by Sciremammano (1979), the actual number of degrees of freedom is about half the present value. The significant correlation for a sample of 100 at 1 per cent is $\sim 0{\cdot}3$. Keeping this in view, Figure 3 reveals three distinct geographical centres for a strong relationship between the mid–latitude geopotentials and precipitation. The centres are connected by double headed arrows. The convergence of these arrow heads over northern India suggests that the northern parts experience maximum influence due to the extratropical circulation.

The first region of strong correlation lies over the Manchurian region north of Korea, near 45°N, 130°E. These correlations are in agreement with those obtained by Yasunari (1986) with 700 hPa geopotential heights over central India. This relationship shows high correlation (>0·4) with rainfall over large parts of the country north of 20°N. The highest correlation is 0·46, which is comparable to those obtained by Liebmann and Hartmann (1984)

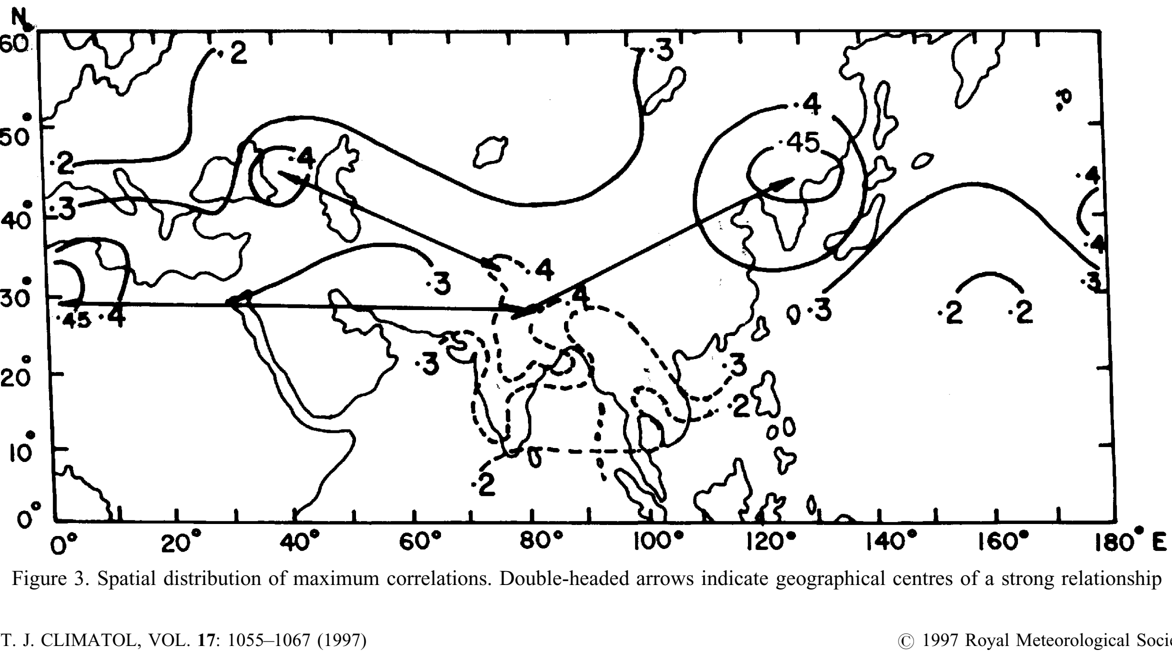

Figure 3. Spatial distribution of maximum correlations. Double-headed arrows indicate geographical centres of a strong relationship

using OLR as a measure of convection. Their correlations declined significantly when they used precipitation as a measure of convection. Considering this, the correlations obtained here are satisfactory. The second centre lies over northern Africa, near the Mediterranean sea at around 30°N, 0°E. This region has the maximum value of correlation (0·48), and correlates with rainfall of a block lying near 30°N over India. The third region lies near the Caspian Sea around 45°N, 40°E. This region shows maximum correlation of 0·41 with the northernmost block over India. The positive correlations over the above three centres indicate that a ridge around these areas would be associated with enhanced convective activity over the Indian region, whereas a trough would be associated with deficient rainfall. It may be remarked that the spatial structure of correlations seen in Figure 3 does not necessarily prove that tropical precipitation is caused or influenced by the extratropical circulation, although fortuitously this can be true.

Based on previous studies, the region near the Caspian Sea is an important region, the blocking over which is associated with breaks in the monsoon, signifying low rainfall over central India. According to this hypothesis we should obtain a high negative correlation over this region. When the minimum negative correlation values were plotted, all the correlations over the Caspian region were insignificant, with absolute values less than 0·15. The association of the breaks with the blockings is reported only through case studies. The correlations reported here use all the data. Even if the blocking over the Caspian region is associated with breaks over India, the frequency of occurrence of such cases is small, such that it is not reflected in the overall relationship.

In the following subsection we examine the lead and lag correlations between geopotential heights at these three locations and the rainfall distribution over the Indian region.

3.2. Maps of rainfall correlation with geopotential height as key regions

Contour heights at each of the above three points, namely (i) 45°N, 130°E, (iii) 30°N, 0°E, and (iii) 45°N, 40°E, are correlated with rainfall of each of the 52 blocks over India. In order to assess their importance in medium range forecasting and the evolution process of these linkages, the lag correlations with a lag of plus or minus three pentads are also computed in addition to the concurrent correlations.

Figure 4 shows the spatial distribution of the correlation between geopotential at point 45°N, 130°E and rainfall over the Indian region for lags of −3, −2, −1, 0, 1, 2, 3 pentads. Negative (positive) lag implies that height (rainfall) leads rainfall (height). From the preceding to the simultaneous period the positive correlation centre over India increases in strength, expands in area and drifts southward. When the lag increases from 1 to 3, the correlations go on reducing and drifting northwards. The near symmetry in results between the positive and negative lags suggests that what has been captured primarily is a low–frequency contemporaneous relationship.

The spatial distribution of the correlation coefficients for the point 30°N, 0°E shows similar features. However, the distribution of correlations for the point 45°N, 40°E shows a significant relationship only for lag 0 and is confined to the block north of 30°N (figures not presented).

The lag correlations between rainfall over India and the reference geopotential height indirectly indicate the phase relationship among the rainfall oscillation at different locations through the direct phase relationship between rainfall and the geopotential height.

3.3. Maps of geopotential correlation with rainfall over key regions

It is worthwhile to examine the correlations of rainfall at a particular point with geopotential height distribution over the mid–latitude region. For this we have considered the average rainfall of four blocks that showed maximum correlation (> 0·45) in Figure 3. The four blocks have been shown shaded in Figure 5 in the simultaneous (lag = 0) panel. Because rainfall is highly variable in space, it is desirable to consider spatial averaging.

Figure 5 shows the spatial distribution of the correlations of geopotential over the mid–latitude region with the rainfall over the north Indian region. Here also the lag varies from −3 to +3 pentads with similar convention. From the preceding to the simultaneous period the area of maximum correlation increases in strength and drifts southwards from 55°N, 120°E to 45°N, 125°E. From the simultaneous to the succeeding period, the area of maximum correlation in this region shifts further eastwards. An interesting feature noted is that the maximum correlation (lag = 0) here is 0·55 against 0·45 in Figure 4.

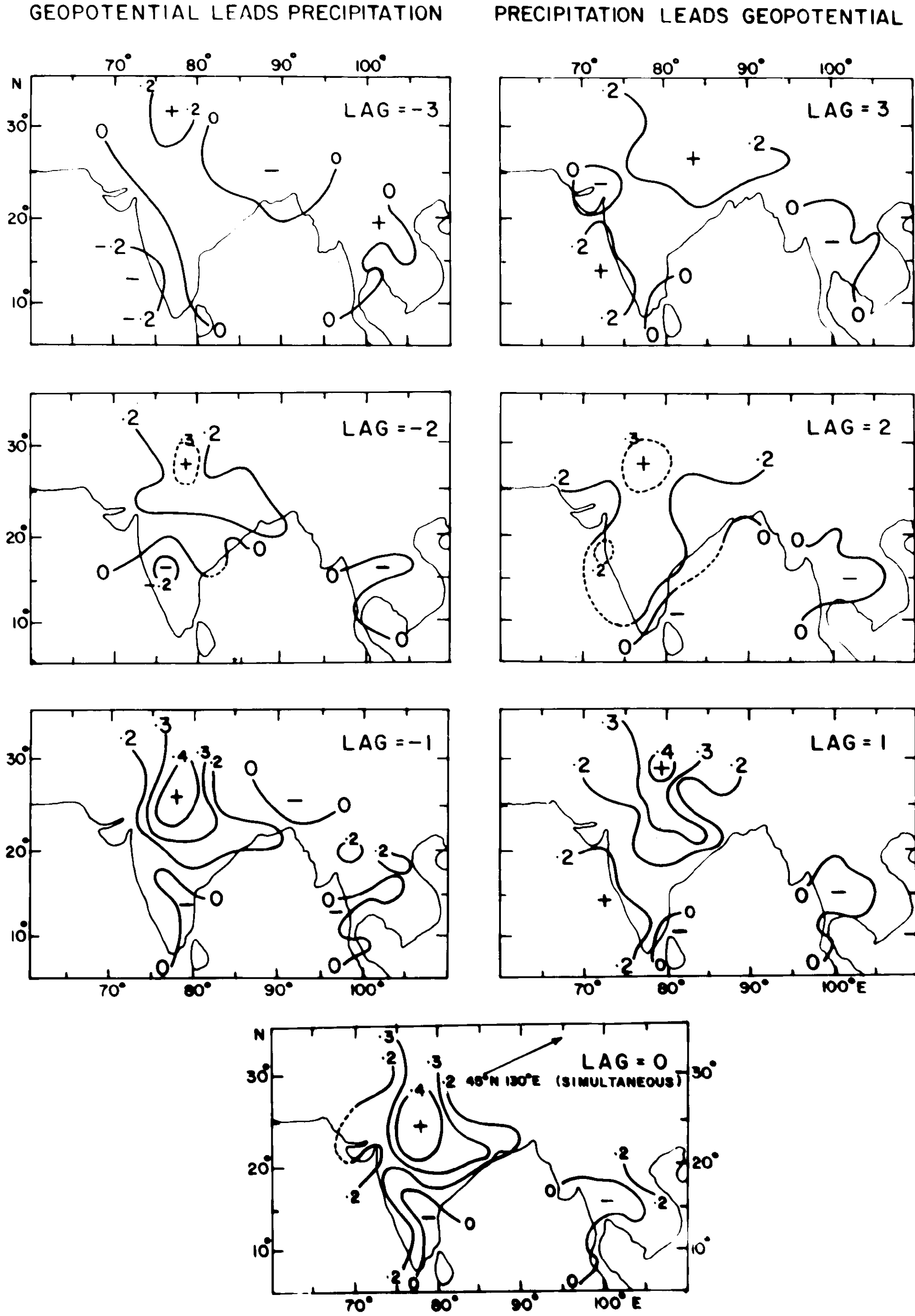

Figure 4. Spatial distribution of correlation between geopotential at 45°N, 130°E and rainfall over the Indian region with lags based on pentads

Figures 3–5 seem to indicate that large–scale ridging in the mid–latitude and the implied easterly flow on its southern flank near 30°N favours enhanced precipitation over northern India and vice versa. Figure 3 implies that all three centres are important in determining the rainfall anomalies over northern India. The similar sign of correlation at all centres is consistent with a broad zonally extensive geopotential of the same sign. This is further substantiated by Figures 4 and 5. Figure 4 suggests that a single location only has a simultaneous correlation with

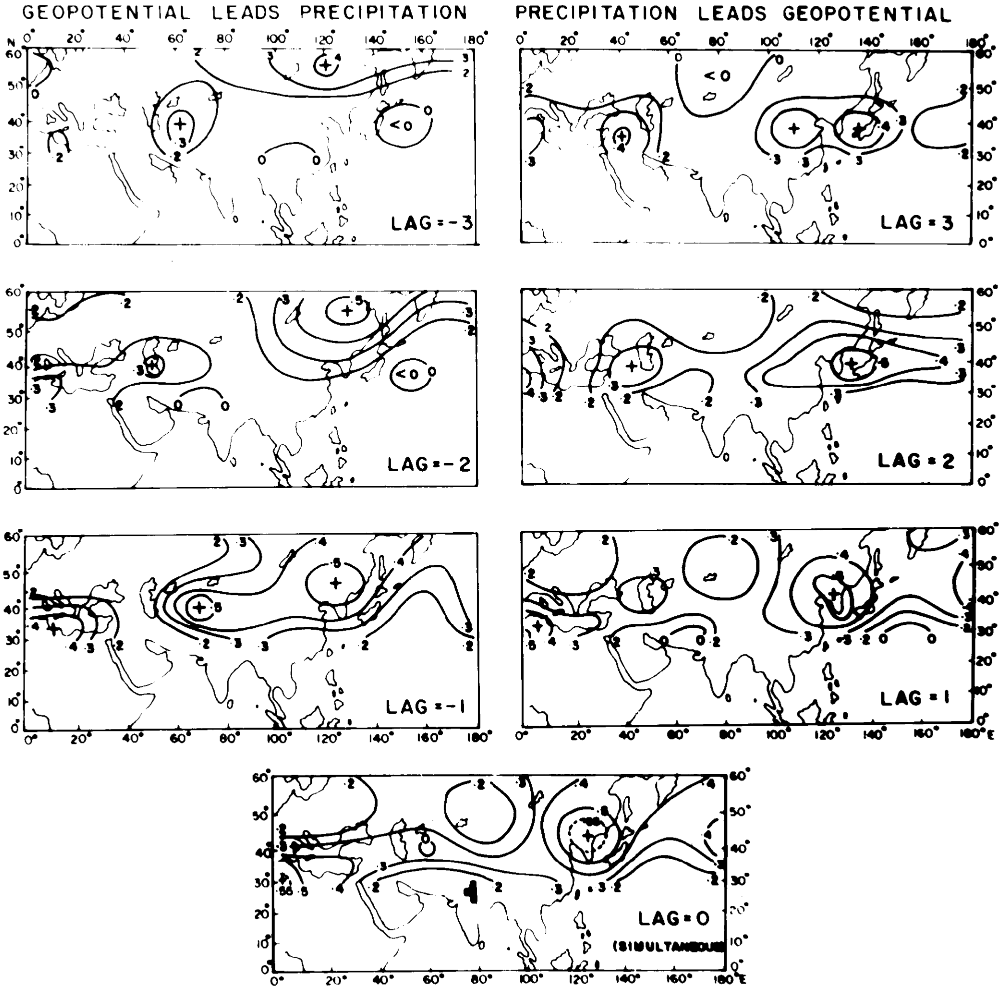

Figure 5. Spatial distribution of correlations between geopotential in the mid-latitude region and rainfall in northern India, with lags based on pentads

Indian rainfall with little evidence of an asymmetry in lead/lag correlations. On the other hand, Figure 5 shows some evidence for the large–scale mid–latitude flow leading rainfall anomalies over northern India. The nature of the evolution is again of very large scale and includes the three centres seen in Figure 3. The contrast with Figure 4 indicates that the large–scale evolution is more important than the geopotential at any one location.

Synoptically, Figure 5 implies increasing easterly flow to the north of India prior to a positive rainfall anomaly. Alternatively, westerlies become more defined prior to and during negative rainfall anomalies. The small change in the pattern for the positive lags suggests that this is a large–scale, low–frequency evolution, the zonal coherence of which is interrupted eventually by geopotential anomalies of the opposite sign (e.g. lag 3, Figure 5).

Again the lag correlations between the extratropical geopotential heights and the reference rainfall indirectly indicates the phase relationship among the geopotential height oscillations at different locations through the direct phase relationship between the geopotential height and the rainfall.

4. INTERANNUAL AND DECADAL ASSOCIATIONS

The connections between the interannual behaviour of the ISMR and the indices of the large–scale teleconnection patterns (PNA, WPO, NAO and EU) have also been investigated through the correlation analysis approach. Lead and lag correlations between the indices of these patterns and the ISMR are computed for the data period 1964–

1994. For a sample of 30, the significant correlation coefficient at the 5 (1) per cent level is 0·35 (0·45). Out of the four patterns, only the WPO pattern shows some significant relationship with the ISMR. The correlation coefficient between the winter WPO index and the subsequent ISMR is $-0{\cdot}35$. However, the correlation coefficient between the ISMR and the subsequent winter WPO index is $+0{\cdot}45$. This suggests that the weakening of the winter WPO pattern enhances the subsequent ISMR, which in turn strengthens the following winter WPO pattern. Thus the teleconnections act both ways, the tropical heat sources affecting the extratropical circulation as well as the extratropical wave motion influencing the tropical convection. From the above analysis it is apparent that the intraseasonal and interannual Indian monsoon variability depends more on the events to the east of India than to the west. A study to investigate the connections between India and China rainfall (Kripalani and Singh, 1993) has also shown that the interannual rainfall variations over India are in phase with rainfall variations over northern China.

The winter NHZI, which signifies the strength of the north–south pressure gradient, influences the climatic conditions over the Northern Hemisphere. This index has been unprecedented during the last 5 years. This index has exceeded two standard deviations in 3 of the 5 years. This also is consistent with the large increase in the observed intense extratropical cyclones in the North Atlantic since the winter of 1988–1989 (WMO and UNEP, 1995).

As in the case of the above four patterns, lead/lag correlations between the winter NHZI and the ISMR for the data period 1900–1993 are computed. The significant correlation coefficient for a sample of 90 is $\sim 0{\cdot}20$ (0·25) at the 5 (1) per cent level. The winter NHZI shows no significant relationship with the subsequent ISMR. However, the ISMR shows some relationship with the following winter NHZI (correlation $= -0{\cdot}22$). Further, the ISMR also shows a significant relationship with the following winter NHZI for lags from 7 through to 10 years (correlation $= -0{\cdot}3$, $-0{\cdot}2$, $-0{\cdot}2$ and $-0{\cdot}2$). Although the magnitude of the correlations are too small to draw any firm conclusions, the persistent significant correlations at later lags prompted us to look into the decadal–scale variability.

The ISMR has shown variability on the decadal scale, with distinct epochs of above and below normal rainfall (Joseph, 1976). Recent investigations of 125 years (1871–1995) of ISMR by Kripalani and Kulkarni (1997) have shown that the period 1880–1895 and 1930–1963 are characterised by above normal ISMR with very few droughts. However, the periods 1895–1930 and 1963–1990 have witnessed below normal ISMR with a high frequency of droughts. Very little data are available to link the decadal scale behaviour with other circulation regimes. Kripalani and Kulkarni (1997) subjected the 125 years ISMR to Cramer's *t*–test (WMO, 1966) to determine the epochal behaviour. This test is utilized to examine the stability of a long record consisting of a series of observations in terms of a comparison between the overall mean of an entire record and the means of certain parts of the record. The time series of the computed *t*–values visually shows the subperiods (or epochs) that are above or below the overall mean. The computational procedure is available in WMO (1966). As the data for NHZI was available for the period 1900–1993, the ISMR is subjected to Cramer's *t*–test for the same period in order to facilitate comparison.

Figure 6 (top panel) shows the values of the Cramer's *t*–statistic for the 11–year running means of the ISMR. This figure is consistent with the results of the previous studies, and clearly shows the epochal behaviour of the ISMR, with the period roughly between 1930 and 1960 showing an epoch of above normal rainfall. Similar computations are done for the NHZI and are depicted in the bottom panel of Figure 6. The epochs of NHZI show remarkable out–of–phase resemblance to the epochs of the ISMR. The turning points for ISMR are around 1927 and 1963, whereas for NHZI they are around 1934 and 1970. It appears that the decadal–scale monsoon variability is influencing the decadal–scale variability of the Northern Hemisphere circulation.

To examine whether other important variables related to the performance of the ISMR show the epochal behaviour as shown in Figure 6, the Cramer's *t*–test was applied to the 11–year running means of the Ridge, NHST and the DPT. The Ridge represents the most important regional circulation parameter. The NHST represents the global climatic variability and includes to a large extent the large–scale trends in the global climate system as well as the surface heating, particularly along the mid–latitudes. The DPT represents the Southern Oscillation, the most important cause of the short–term fluctuations of the tropical climate system. Hence these three variables encompass the regional, extratropical and the tropical forcings on the ISMR. Figure 7 shows the Cramer's *t*–static for the NHST and DPT. Although the pattern of NHST and DPT (Figure 7) does not coincide

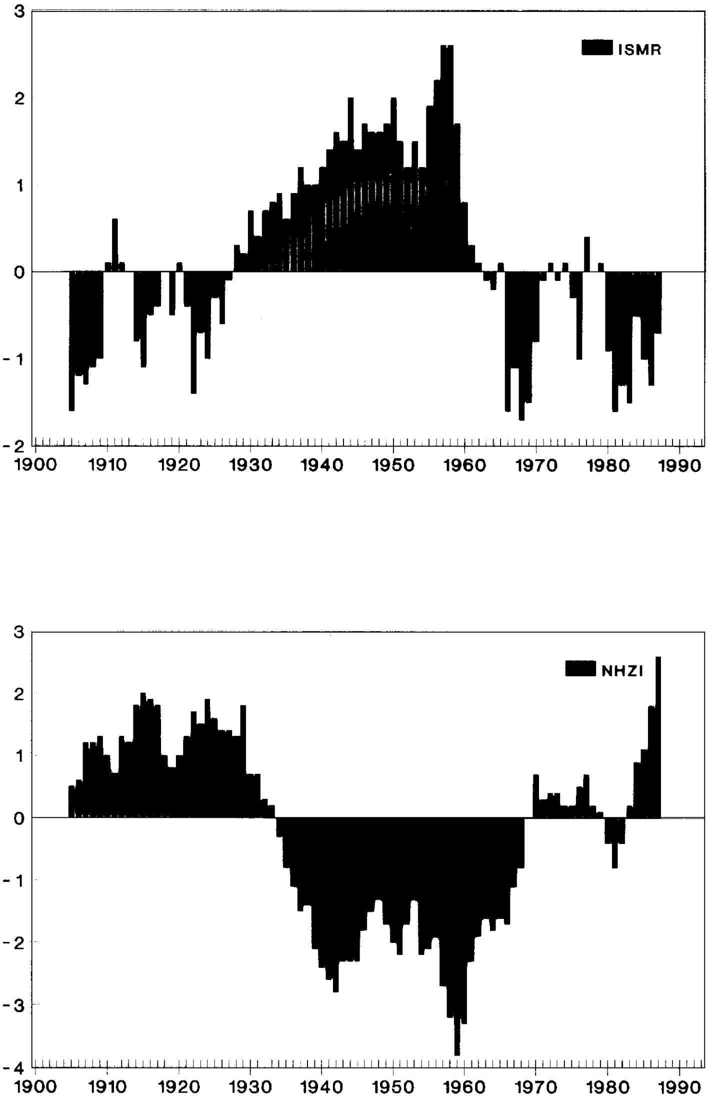

Figure 6. Cramer's t-statistic for ISMR and NHZI

with the pattern of the ISMR in Figure 6, the epochal behaviour of DPT has some similarities with the ISMR. The downward trend of t_k for DPT begins at about 1933 and ends at about 1958. This period is in the range of the above normal epoch of the ISMR. These results are consistent with earlier studies (e.g. Elliott and Angell, 1987).

The Cramer's t–statistic for the Ridge is shown in Figure 8. Although the data available for the Ridge is for a short period (1939–1993), they do show some resemblance with the epochal behaviour of the ISMR. The turning point for the Ridge is around 1965. The subtropical ridge in the tropospheric levels is a permanent feature of the general circulation. The Indian monsoon is also a part of the general atmospheric circulation. Hence the progress of the movement of this ridge is bound to affect the meridional propagation of the monsoon circulation. Banerjee *et al.* (1978) have shown that when the subtropical ridge at the 500 hPa level is poleward of the normal position (14·5°N along 75°E), the ISMR tends to be above normal, while years when the ridge is equatorward of the normal position are followed by below normal ISMR.

Attempts have been made to link the decadal/epochal behaviour of the ISMR with other circulation regimes and to examine the possible cause of these long–term changes. Joseph (1976) pointed out that the greater

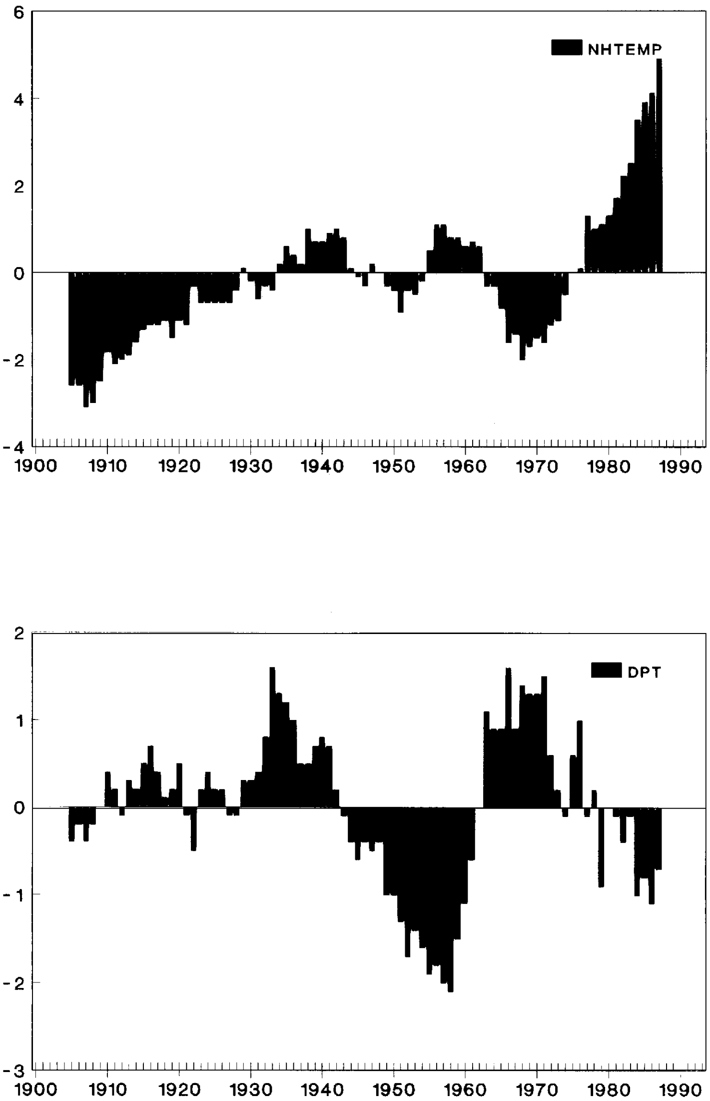

Figure 7. Cramer's *t*-statistic for the NHST and DPT

equatorward penetration of the upper tropospheric westerlies over India leads to conditions favourable for the occurrence of large–scale monsoon failures over India. Epochs of below/above normal rainfall are associated with long–term changes in the upper tropospheric westerlies over India. He also suggested that the epochs of large–scale failures of the ISMR were the epochs of low sun–spot activity and the epochs of generally above normal monsoons were epochs of high sun–spot activity. Further the epochs of monsoon failures are associated with high frequencies of volcanic eruptions whereas the epochs of above normal monsoon activity were free from volcanic eruptions. Sikka (1980) suggested a possible link with the global surface temperature such that the decades in which the global warming trend was significant showed better performance of the monsoon rainfall over India. Sikka (1980) further attributed the epochal behaviour of the ISMR to the frequencies of the occurrence of El Niño events. A recent study by Kripalani and Kulkarni (1997) has shown that these epochs are not forced by the frequencies of El Niño or La Niña events.

Such secular changes, i.e. the epochal behaviour, have also been noted between the relationship of the Indian monsoon rainfall with different circulation regimes, such as sea–surface temperature over the tropical Pacific Ocean (Angell, 1981), annual sun–spot numbers (Ananthakrishnan and Parthasarathy, 1984), NHST (Verma *et*

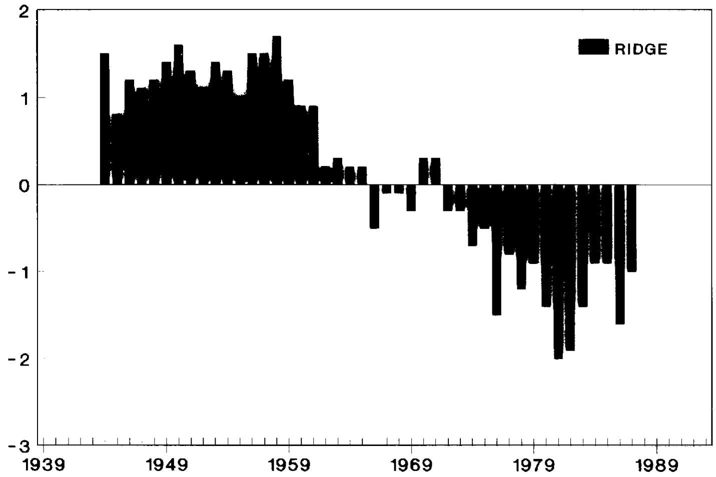

Figure 8. Cramer's *t*-statistic for the Ridge

al., 1985), the Southern Oscillation (Elliott and Angell, 1988), Bombay and Darwin pressure (Parthasarathy *et al*., 1991), Ridge, DPT and sea–surface temperature over the Arabian sea (Hastenrath and Greischar, 1993). Most of the above studies show major turning points in these relationships around 1900 and 1940.

Fu and Fletcher (1988) examined the zonal and meridional components of the surface winds over the Indian Ocean region and concluded that the relative dominance of the two wind components had been undergoing significant decadal–scale variability. They identified distinct climatic regimes in wind components and classified the period 1875–1900 as the meridional monsoonal period and the period 1900–1940 as the zonal monsoonal period over the Indian region, which are also somewhat synchronous with the high and low epochs of the ISMR.

In this study it is seen that NHZI and Ridge both show better resemblance with the epochal behaviour of the ISMR than NHST and DPT. Incidently both these variables are circulation features of the Northern Hemisphere extratropics. This would seem to suggest that the epochal behaviour of the ISMR and the events in the NH mid-latitudes are linked. From this analysis it appears that the ISMR is forcing the epochal behaviour in the Northern Hemisphere, because the turning points of the NHZI follow those of the ISMR after about 7 years. It is also likely that some other factor is forcing the epochal behaviour of ISMR and the circulation features in the northern extratropics. A recent general circulation model sensitivity study by Kulkarni and Mandke (1996) showed the sensitivity of the ISMR to solar forcing. Their study revealed that the 76–year solar forcing cycle may be one of the prominent underlying mechanisms for the decadal variability of the ISMR.

5. SUMMARY AND DISCUSSION

Using 5–day average anomalies of mid–latitude 500 hPa heights and precipitation over India, a search is made for lag–lead relationships between tropical rainfall and mid–latitude circulation patterns using correlation techniques. The mid–latitude heights over the Manchurian and the Algerian regions reveal the strongest relationship. The region around the Caspian Sea shows slightly lower correlations. These connections apparently work through the intensification of the mid–latitude ridge system, either through the intensification and the northward shift of the subtropical high in the Pacific sector or through the weakening of the zonal flow in the west Asian sector. The significant correlations could be noted even when the contour heights lead or lag the rainfall by two pentads. This would suggest that some common element of low frequency variability is affecting both the mid–latitude circulation and the tropical rainfall.

Although the correlation pattern may be meaningful physically, the total variance explained by even the largest correlation is small (less than 25 per cent), and therefore the potential value of the mid–latitude geopotential anomaly only, as a predictor of tropical precipitation on an intraseasonal time–scale, through linear empirical relationships, is limited. However, the correlations obtained are comparable to the lag correlations obtained by the Madden Julian Oscillations (MJOs) (Singh and Kripalani, 1990), which are recognized as the most important features of tropical circulation on a low–frequency scale. Therefore, the relationships examined here in mid–latitude circulation are important for the northern parts of the country in the manner MJOs are considered important for prediction over central and southern India.

This study has succeeded in describing the contemporaneous relationship between monsoon rainfall and the NH circulation. However, the physical hypothesis that would explain these observations needs to be examined. It is likely that the simultaneous relationship between rainfall and the geopotential heights could result from the subsidence in the descending branch (Algerian and the Manchurian regions) of the thermally direct circulation, the upward branch of which is driven by the condensation heating associated with the monsoon rainfall. These intraseasonal relationships are based on the data period 1974–1984. However, there have been secular variations in the relationship between ISMR and the large–scale variables (section 4). Hence, it is likely that the intraseasonal relationships may be different during other epochs.

On an interannual scale the connections between the winter–time large–scale patterns, the PNA, WPO, NAO and EU and the ISMR were investigated. Excepting the WPO pattern, none of the above patterns show any significant relationship. However, the NHZI and the ISMR show some relationship on a decadal scale, suggesting that the epochal behaviour of the ISMR and the circulation features of the NH are connected in some way. Further work is required to examine this aspect and to elucidate the mechanism of these connections.

ACKNOWLEDGEMENTS

The authors are thankful to Professor R. N. Keshavamurty, Director and Dr S. S. Singh, Deputy Director, Indian Institute of Tropical Meteorology for encouragement and facilities provided. The daily rainfall data of India were obtained from the India Meteorological Department. The geopotential data were kindly supplied by Dr Takashi Nakayama of Japan Meteorological Agency.

REFERENCES

Ananthakrishnan, R. and Parthasarathy, B. 1984. ‘Indian rainfall in relation to the sunspot cycle, 1871–1978’, *J. Climatol.*, **4**, 149–169.

Angell, J. K. 1981. ‘Comparison of variations in atmospheric quantities with sea surface temperature variation in the equatorial Pacific’, *Mon. Wea. Rev.*, **109**, 230–243.

Asnani, G. C. 1993. *Tropical Meteorology*, Published by Professor G. C. Asnani, Indian Institute of Tropical Meteorology, Pune, 1202 pp.

Banerjee, A. K., Sen, P. N. and Raman, C. R. V. 1978. ‘On foreshadowing southwest monsoon rainfall over India with mid–tropospheric circulation anomaly of April’, *Ind. J. Meteorol., Hydrol., Geophys.*, **29**, 425–431.

Barnston, A. G. and Livezey, R. E. 1987. ‘Classification, seasonality and persistence of low frequency atmospheric circulation patterns’, *Mon. Wea. Rev.*, **115**, 1083–1126.

Blanford, H. F. 1884. ‘On the connexion of Himalayan snowfall and seasons of droughts in India’, *Proc. Roy. Soc. London*, **37**, 3–22.

Elliott, W. P. and Angell, J. K. 1987. ‘The relation between Indian monsoon rainfall, the Southern Oscillation and hemispheric air and sea temperature: 1884–1984’, *J. Clim. Appl. Meteorol.*, **26**, 943–948.

Elliott, W. P. and Angell, J. K. 1988. ‘Evidence for changes in Southern Oscillation relationships during the last 100 years’, *J. Climate*, **1**, 729–737.

Fu, C. and Fletcher J. 1988. ‘Large signals of climatic variations over the ocean in the Asian monsoon region’, *Adv. Atmos. Sci.*, **5**, 389–404.

Hahn, D. G. and Shukla, J. 1976. ‘An apparent relationship between Eurasian snow cover and Indian monsoon rainfall’, *J. Atmos. Sci.*, **33**, 2461–2462.

Hastenrath, S. and Greichar, L. 1993. ‘Changing predictability of Indian monsoon rainfall anomalies?’, *Proc. Ind. Acad. Sci (Earth Planet. Sci.)*, **102**, 35–48.

Jones, P. D., Wigley, T. M. L. and Kelly P. M. 1982. ‘Variations in surface air temperature, Part I: Northern Hemisphere’, *Mon. Wea. Rev.*, **110**, 59.

Joseph, P. V. 1976. ‘Climatic change in monsoon and cyclones 1891–1974’, *Proceedings, Symposium on Tropical Monsoons*, Indian Institute of Tropical Meteorology, Pune, pp. 378–387.

Keshavamurty, R. N. and Shankar Rao, M. 1992. ‘Middle latitudinal effects on the monsoon’, in *The Physics of Monsoons*, Allied Publishers, New Delhi, pp. 125–143.

Kripalani, R. H. and Kulkarni, A. 1997. ‘Climatic impact of El Niño/La Niña on Indian monsoon: a new perspective’, *Weather*, **52**, 39–46

Kripalani, R. H. and Singh, S. V. 1993. ‘Large scale aspects of India–China summer monsoon rainfall’, *Adv. Atmos. Sci.*, **10**, 71–84.

Kripalani, R. H., Singh, S. V., Vernekar, A. D. and Thapliyal, V. 1996. ‘Empirical study on Numbus–7 snow mass and Indian summer monsoon rainfall’, *Int. J. Climatol.*, **16**, 23–34.

Kulkarni, J. R. and Mandke, S. K. 1996. 'A possible mechanism of decadal variability of Indian Summer Monsoon Rainfall', *Theor. Appl. Climatol*, submitted.
Kurihara K. 1989. 'A climatological study on the relationship between the Japanese summer weather and the subtropical high in the western north Pacific', *Geophys. Mag.*, **43**, 45–104.
Liebmann, B. and Hartmann, D. L. 1984. 'An observational study of tropical–midlatitude interaction on intraseasonal time scales during winter', *J. Atmos. Sci.*, **41**, 3333–3350.
Parthasarathy, B., Munot, A. A. and Kothawale, D. R. 1994. 'All–India monthly and seasonal rainfall series 1871–1993', *Theor. Appl. Climatol.*, **49**, 217–224.
Parthasarathy, B., Rupakumar, K. and Munot, A. A. 1991. 'Evidence of secular variations in Indian monsoon rainfall–circulation relationships', *J. Climate*, **4**, 927–938.
Raman, C. R. V. and Rao, Y. P. 1981. 'Blocking highs over Asia and monsoon droughts over India', *Nature*, **289**, 271–273.
Ramaswamy, C. 1962. 'Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and the subtropical westerly jet streams', *Tellus*, **14A**, 337–349.
Sciremammano, F. 1979. 'A suggestion for the presentation of correlations and their significance levels', *J. Phys. Oceanogr.*, **9**, 1273–1276.
Shankar Rao, M., Lykossov, V. N., Volodin, E. M., Nikitin, A. E., Degtiarev, A. I. And Rao, K. G. 1991. 'Relationships between the global general circulation and the Indian summer monsoon', *Adv. Atmos. Sci.*, **8**, 137–148.
Shukla, J. and Paolino, D. A. 1983. 'The Southern Oscillation and long range forecasting of the summer monsoon rainfall over India', *Mon. Wea. Rev.*, **111**, 1830–1837.
Sikka, D. R. 1980. 'Some aspects of the large–scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters', *Proc. Ind. Acad. Sci. (Earth Planet. Sci.)*, **89**, 179–195.
Singh, S. V. and Kripalani, R. H. 1990. 'Low frequency intra–seasonal oscillations in Indian rainfall and outgoing longwave radiation', *Mausam*, **41**, 217–222.
Singh, S. V., Kripalani, R. H. and Sikka, D. R. 1992. 'Interannual variability of the Madden–Julian oscillations in Indian summer monsoon rainfall', *J. Climate*, **5**, 973–978.
Verma, R. K., Subramanian, K. and Dugam, S. S. 1985. 'Interannual and long–term variability of the summer monsoon and its possible link with Northern Hemisphere surface air temperature', *Proc. Ind. Acad. Sci (Earth Planet. Sci.)*, **94**, 187–198.
Wallace, J. N. and Gutzler, D. S. 1981. 'Teleconnections in the geopotential height field during the northern hemisphere winter', *Mon. Wea. Rev.*, **109**, 784–812.
WMO 1966. *Climatic Change*, Technical Note No. 79, WMO No. 195–TP–100, World Meteorological Organisation, Geneva, 53 pp.
WMO and UNEP 1995. 'The Global Climate System Review June 1991–November 1993', *Climate System Monitoring. World Climate Data and Monitoring Programme*. World Meteorological Organization and United Nations Environmental Programme, Geneva, 150 pp.
Yasunari, T. 1986. 'Low–frequency interactions between the summer monsoon and the northern hemisphere westerlies', *J. Meteorol. Soc. Jn.*, **64**, 693–708.

