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The interannual variability of mid-latitude meridional circulation and its teleconnection with Indian monsoon activity

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Abstract. The statistical relationship between the summer monsoon rainfall over all India, northwest India and peninsular India, onset dates of monsoon and the index of mid latitude, (35° to 70°N) meridional circulation at 500 hPa level over different sectors and hemisphere based on 19 years (1971–1989) data, have been examined. The results indicate that (i) the summer monsoon rainfalls over all India, northwest India and peninsular India show a significant inverse relationship with the strength of meridional index during previous January over sector 45°W to 90°E. (ii) The summer monsoon rainfalls over all India and peninsular India show a significant inverse relationship with the strength of meridional index during previous December over sector 90°E to 160°E, (iii) The summer monsoon rainfall over northwest India shows a significant direct relationship with the meridional index during previous May over sector 160°E to 45°W.

Significant negative relationships are also observed between the meridional circulation indices of previous October (sector 3 and 4), previous December (sectors 1, 3 and 4), previous winter season (sector 3 and 4) and the onset dates of summer monsoon over India. The meridional circulation index thus can have some possible use for long range forecasting of monsoon rainfall over all India, northwest India and peninsular India, as well as the onset dates of monsoon.

Keywords. Meridional index; blocking ridges; circumpolar vortex.

1. Introduction

The search for new parameters for predicting seasonal Indian monsoon rainfall is an important aspect of long range prediction work in India. This is because of the immense importance the seasonal monsoon rainfall has on Indian economy mainly based on rainfed agriculture. In recent years, Indian monsoon rainfall has been found to have teleconnections with a large number of upper air circulation parameters. Ramaswamy (1962, 1975–76) qualitatively associated low index circulation in mid-latitudes with breaks in the Indian monsoon. Winstanley (1973) also observed increasing (decreasing) zonal circulation to be associated with increasing (decreasing) monsoon rainfall over Sahel and India. Raman and Rao (1981) associated prolonged breaks in Indian monsoon with upper tropospheric blocking ridges over East and West Asia. Joseph *et al* (1981) reported strong correlations between Indian monsoon rains and the monthly mean meridional wind over India during May at 200 hPa level. Banerjee *et al* (1978), Thapliyal (1982), Mooley *et al* (1986), Shukla and Mooley (1987) found a significant correlation between Indian monsoon rainfall and the latitudinal position of April 500 hPa subtropical ridge at 75°E. Kung and Sharif (1980, 1982) predicted the onset dates and monsoon rainfall using a variety of predictors which include the zonal and meridional components of the wind at 700 hPa and 100 hPa.

The search for new precursors of monsoon rainfall is a continuing process of research. The present work is an effort in this direction. The meridional exchange of air between higher latitudes and low latitudes occurs by occasional large outbreaks of polar air transporting heat and moisture to the higher latitudes. Such inter zonal exchanges in the mid troposphere is expressed in terms of index of meridional circulation over a particular geographical area. The meridional index characterises the intensity of transfer of air in the meridional direction over a geographical sector of the latitudinal zone 35°N to 70°N and is defined as the average from the sum of gradients of geopotential along the meridional direction per equatorial degree. Generally, meridional index may be said to periodically fluctuate between two extreme states. The one characterised by low meridional circulations with a contracted circumpolar vortex and the other marked by strong meridional circulations with meandering or cellular patterns and with an expanded circumpolar vortex.

In view of the fact that both meridional index in different months and seasons and monsoon rainfall show considerable interannual variability, it is felt that the fluctuations of Indian monsoon rainfall activity may be related to the meridional circulation features not only of the concurrent but premonsoon season also. This idea encouraged the present investigators to examine the teleconnections between the above two components of general circulation by analysing the time lead/lag relationship between them. It also explores the potential of mid latitudinal meridional index as a possible new predictor of monsoon rainfall activity over India.

In the present paper, we have attempted to examine the space time variability of two features of the monsoon activity in relation to the mid latitude meridional index. These are

- The onset of the monsoon.
- The total rainfall during the period June to September over the country as a whole and its two specific regions.

2. Details of data

In the current study, we could analyse the interrelationships for 19 years period (1971–1989), being the period for which the meridional index data is available. Mean monthly meridional (I_m) circulation index data were obtained from the Synoptic Bulletins for the northern hemisphere published by the Department of world weather, Hydrometeorological center of USSR. The indices refer to 500 hPa level for the latitudinal band 35°N-70°N, for three sectors between 45°W and 90°E (sector 1), 90°E to 160°E (sector 2), and 160°E to 45°W (sector 3). The meridional (I_m) index which is a measure of the strength of the meridional southerlies at 500 hPa over different sectors defined above, is taken here as the average of the 500 hPa contours (in decameters) intersecting the latitude circle per equatorial degree (i.e. per 111 km).

Sector 1 covers the whole of Europe and half of Asia including most of the Indian monsoon region while sectors 2 and 3 cover mainly the western Pacific and eastern Pacific Ocean respectively. A hemispheric meridional index (sector 4), has also been generated by taking the area weighted monthly mean values over sectors 1, 2 and 3, covering the whole earth. Figure 1 shows the partitioning of various sectors on the world map. Meridional index is expressed as percentage anomaly (ΔI_m) from their respective monthly means. Standard season means of anomaly of meridional index were formed from the monthly means as simple arithmetic averages.

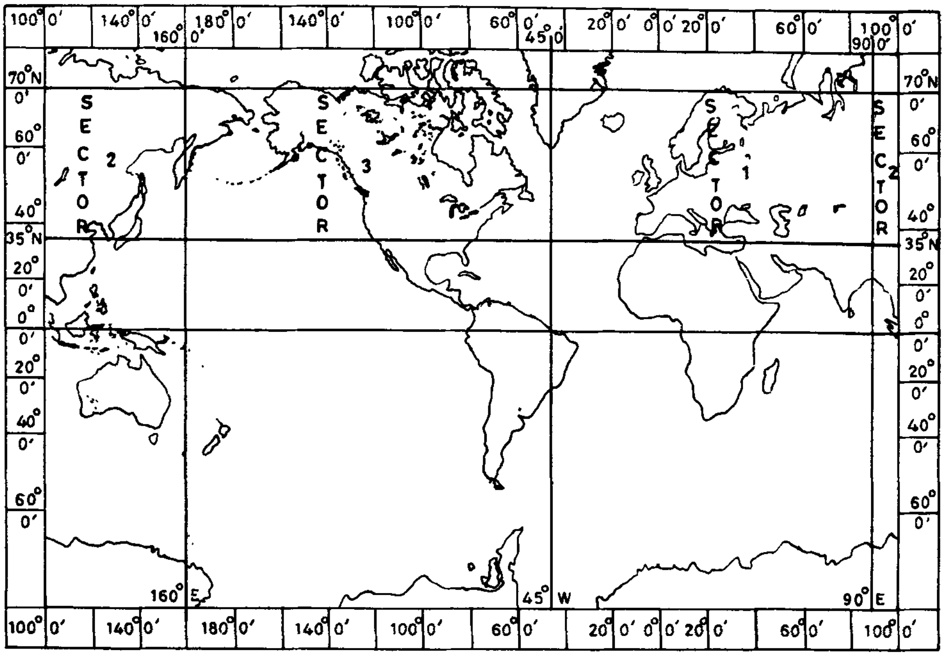

Figure 1. Schematic illustration of the three sectors over which circulation indices are defined.

The summer monsoon rainfall data sets over 31 meteorological subdivisions of India for the period 1971–1980 and over 33 meteorological subdivisions from 1981–83 were provided by the India Meteorological Department, Pune; while the data for the remaining period 1984–1989 were obtained from the journal *Mausam*. An area weighted average of rainfall for each of the 31 (1971–1980) and 33 (1981–1989) subdivisions of India, is taken as a measure of all India summer monsoon rainfall. Along with all India rainfall we have also examined relationships with area weighted rainfall for two specific rainfall regions over India which show considerable interannual variability. These two regions are northwest India comprising the meteorological subdivisions of Jammu and Kashmir, West Uttar Pradesh, Haryana, Punjab, Himachal Pradesh, Delhi, Chandigarh and Rajasthan. While the region peninsular India comprises of the meteorological subdivisions Maharashtra, Gujarat, Madhya Pradesh, Telengana, north interior Karnataka, coastal Karnataka and coastal Andhra Pradesh. Figure 2 shows the northwest and peninsular India and meteorological subdivisions of India. The means were found from 19 years data i.e. 1971–1989 as 84·8 cm, 53·8 cm, 87·8 cm, for all India, northwest India and peninsular India respectively. The rainfall values from 1971 to 1989 expressed as percentage departures from their respective means (ΔR) are used in this study.

The onset dates of summer monsoon over extreme tip of peninsular India each year were derived from Indian Daily Weather Reports. The normal date of onset of monsoon from 19 years data of 1971 to 1989 was found to be 2 June. Then onset dates were expressed as anomaly from the normal (ΔP). Negative departures indicate early onset of Indian summer monsoon while positive departures indicate late onset. The onset dates and its anomaly are presented in table 1.

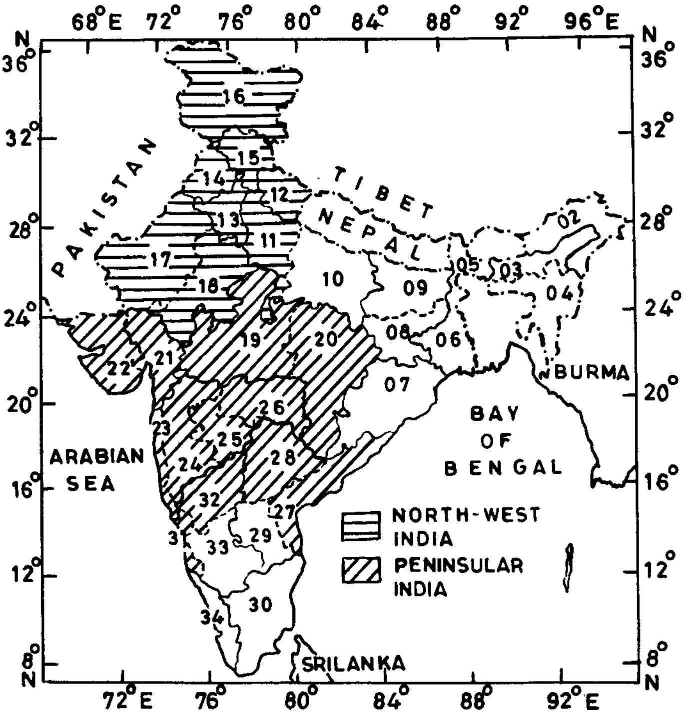

Figure 2. Location of different regions and 33 meteorological subdivisions over India.

Table 1. Onset dates of Indian summer monsoon and its anomaly.

Year	Onset dates over extreme south India	Departure of onset dates from mean (days)
1971	27 May	−6
1972	18 June	16
1973	4 June	2
1974	26 May	−7
1975	31 May	−2
1976	31 May	−2
1977	30 May	−3
1978	29 May	−4
1979	11 June	9
1980	1 June	−1
1981	30 May	−3
1982	28 May	−5
1983	13 June	11
1984	31 May	−2
1985	28 May	−5
1986	4 June	2
1987	2 June	0
1988	26 May	−7
1989	3 June	1

3. Procedure and results

It has long been recognised that a quantitative measure of the strength of the linear relationship between two variables which are supposed to be related in space and time can be studied by the absolute value of correlation coefficient. As such the simultaneous and lag correlation coefficients (c.c.) were computed between the monthly, and seasonal interannual fluctuations of the circulation indices over different sectors and the seasonal monsoon rainfall anomaly over all India, northwest India and peninsular India.

The correlation coefficients between the anomaly of all India rainfall, northwest India rainfall, peninsular India rainfall, anomaly of onset dates of monsoon and anomaly of meridional index for individual months from previous September to succeeding February were computed for all the sectors to see if there is any teleconnection between them. In addition to this the correlation coefficients for 3 seasons prior to monsoon season upto 2 seasons after the monsoon were also calculated. These are previous autumn season, three seasons prior to monsoon season, viz. September, October, November (SON-); previous winter season, two seasons prior to monsoon season, viz. December, January, February (DJF-); the previous spring season, one season prior to monsoon season, viz. March, April, May (MAM-); the summer season, concurrent with the monsoon season (JJA); the succeeding autumn season, one season after the monsoon season (SON +); and the succeeding winter season, two seasons after the monsoon season (DJF +).

Statistical tests of significance must be assessed in terms of the true statistical significance of the correlations. One has to consider the problem posed by the presence of autocorrelation (tendency of the climatic anomalies to persist over time). In the absence of any autocorrelation in the individual time series being related, the statistical significance of the correlation coefficients are ascertained according to the tabled critical values listed for conventional 1, 2 or 5 per cent significance levels. However, this method breaks down when the time series possess substantial autocorrelations, because its existence can lead to apparent relationships when none is actually present. In other words, it affects the reliability of the significance levels.

An autocorrelation analysis of a long all India rainfall series by Parthasarathy and Mooley (1978) indicated that only the 14th lag autocorrelation was significant at the 5% level. All others were insignificant. A similar auto correlation analysis by us for long Indian monsoon rainfall series for the period 1901 to 1989 also shows virtually no autocorrelation at various lags. Interestingly however, autocorrelation analysis of Indian monsoon series over a small period (1971–1989) as well as the meridional indices data over different sectors from 1971 to 1989, does show the presence of substantial autocorrelation. Consequently, failure to make adjustment for autocorrelation would result in too frequently erroneously concluding that teleconnections exist when, in fact, they do not. This adjustment is generally accomplished by estimating the reduction in the effective number of independent samples termed 'the effective number of degrees of freedom' that enter into the calculation of the 't' statistic, using methods described by Quenouille (1952), Bartlett (1955), and Davies (1976).

The technique of Davies which was employed by Chen (1982) has been adopted in this study. The effective number of degrees of freedom n of the data series N is estimated by

$$n = N\Delta T/\tau \tag{1}$$

The parameter τ, known as the integral time scale is given by

$$\tau = \sum_{i=-\infty}^{\infty} C_{xx}(i\Delta t)C_{yy}(i\Delta t)\Delta t \tag{2}$$

where C_{xx} and C_{yy} are the discrete autocorrelation coefficients of the two input time series $x(t)$ and $y(t)$ sample with time interval Δt, respectively. The integral time scale τ determines the time period required to find the new degree of freedom in the estimation of the correlation. Equation (2) and (1), following Davies method, were used to obtain τ and n for various correlations. The calculation has been continued upto lag 7 to find the final τ and n where the values of τ and n become stable. It was found that in 4 of the rainfall and meridional indices time series where significant c.cs were observed using conventional method, final τ is greater than 1 resulting in reduction of the effective number of degrees of freedom. The significance of the correlation coefficients was then estimated by using the new effective number of degrees of freedom 'n' computed from equation (1) and using the conventional students 't' test.

Most of the correlations are found to be generally small, however, it seems possible to link a few of them more closely with the monsoon rainfall. Table 2 shows the correlation coefficients (c.c.) between the anomaly of meridional index ΔI_m for different sectors and the monsoon rainfall anomaly (ΔR) over all India, northwest India and peninsular India respectively as well as with the onset dates of monsoon along with their level of significance. To simplify tables, only those correlations with ΔI_m have been presented which are significant at 5 per cent level or above in any month/season/sector. However, when ΔI_m in a sector shows significant correlations with any region, the correlations with the other regions also have been presented in that sector, even if it is not significant to study the relative contribution of ΔI_m to their degree of association. Negative sign in the table indicates premonsoon months/season respectively.

3.1 *Monsoon rainfall and meridional index*

It is found from table 2 that the monsoon rainfall does not show any correlation with the meridional index of the concurrent or succeeding months/seasons.

Looking for the existence of correlation coefficients during the previous months/seasons for prediction purposes, it is found from table 2 that circulation anomalies of previous December (sector 2), January (sector 1), and May (sector 3), have significant correlation with Indian monsoon rainfall anomalies. The interesting point to note is that the association is direct with the month of May (sector 3) while it is inverse with the month of December (sector 2) and January (sector 1). Following are the various regions over India, over which we find significant correlation coefficients.

- Strength of meridional index anomaly during previous January over sector 1 having c.c. of $-0{\cdot}59$ with all India and northwest Indian monsoon rainfall anomaly

Table 2. Correlation coefficient (c.c. × 100) between the anomaly of meridional index and the anomaly of Indian monsoon rainfall and onset dates for different months and seasons. Numbers in brackets indicate the sectors. Number 4 indicates hemisphere.

Months/ Seasons	All India rainfall	Northwest India rainfall	Peninsular India rainfall	Onset dates
October-				– 70**(3), – 68**(4)
December-	– 64**(2)	– 45(2)	– 66**(2)	– 55***(1), – 54***(3) – 58**(4)
January	– 59***(1)	– 59***(1)	– 57****(1)	
DJF-				– 61**(3), – 56***(4)
May	40(3)	63**(3), 53***(4)	33(3)	

*, **, ***, **** denote significance levels of ·1, 1, 2 and 5 per cent respectively.

at a level of significance of 2 per cent and a c.c. of – 0·57 with peninsular Indian rainfall at a level of significance of 5 per cent.

- Strength of meridional index anomaly during December over sector 2 having a c.c. of – 0·64 and – 0·66 with all India and peninsular India respectively at a level of significance of 1 per cent. However, its correlation with northwest Indian rainfall has a low absolute value and not significant.
- Strength of the meridional index anomaly during May over sector 3 and hemisphere with c.c.'s of 0·63 and 0·53 with northwest India rainfall only significant at 1 per cent and 2 per cent level respectively. Its correlations with all India and peninsular India rainfall are not significant.

The interannual variation of meridional index anomaly of previous December over sector 2 and the monsoon rainfall anomaly over all India, and peninsular India are shown graphically in figure 3a and 3b showing the remarkable inverse relationship between them. In other words, an above (below) normal intensity of meridional index during previous December is associated with below (above) normal all India and peninsular India monsoon rainfall. Since interannual variability of northwest Indian rainfall shows strongest direct relationship with the meridional index of May over sector 3, their variation has been presented in figure 3c. Here, an above (below) normal intensity of meridional index during previous May over sector 3 is associated with an excess (deficient) northwest Indian monsoon rainfall. From the point of view of long range forecasting, it may be concluded that the strength of meridional index during previous December over sector 2 and previous May over sector 3 can be used as predictors for monsoon rainfall explaining 41 per cent raiñfall variability (square of c.c. = – 0·64) over all India, 43 per cent over peninsular India and 40 per cent rainfall variability over northwest India respectively. The strong inverse association of December meridional circulation index with the subsequent monsoon rainfall shows that long range forecasting of monsoon prediction can be attempted as early as January, using the December index as a predictor.

3.2 *Monsoon onset date and meridional index*

Table 2 shows that meridional index of previous October over sectors 3 and hemisphere, previous December over sectors 1, 3 and hemisphere and previous winter

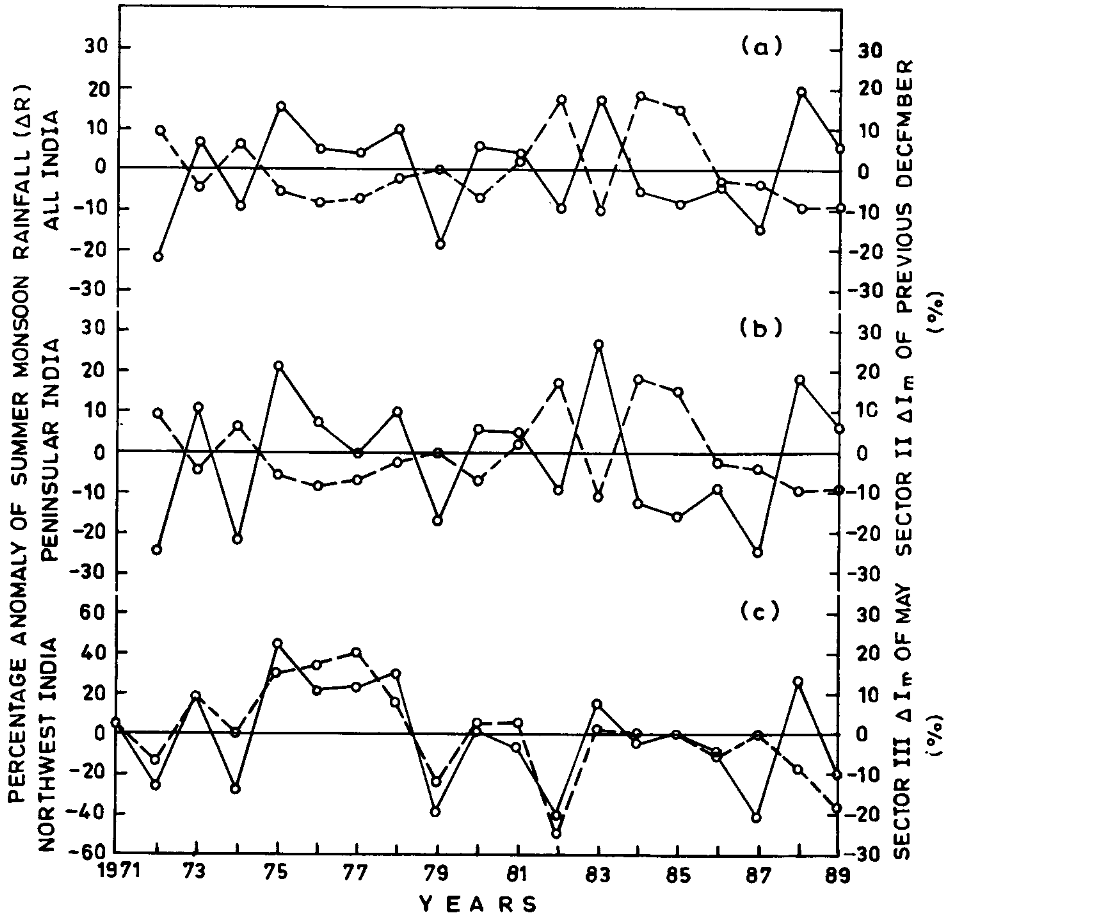

Figure 3. The year to year relationship between the percentage anomaly of (a) All India monsoon rainfall (ΔR) and meridional index over sector 2 during previous December (ΔI_m), (b) Peninsular India monsoon rainfall (ΔR) and meridional index over sector 2 during previous December (ΔI_m), (c) Northwest India monsoon rainfall (ΔR) and meridional index over sector 3 during May (ΔI_m). [ΔR – solid line, ΔI_m – dashed line].

(DJF) season over sectors 3 and hemisphere all have strong negative correlation coefficients with the onset dates of monsoon and significant at 1 per cent and 2 per cent levels. Out of all these parameters, the meridional indices of October over sector 3 and hemisphere have very high absolute magnitude of correlation coefficients of − 0·70 and − 0·68 at a significance level of 1 per cent with the onset dates of monsoon. Figure 4 shows the interannual variation of sector 3 previous October and previous winter (DJF) season meridional index anomaly and monsoon onset dates anomaly for the years 1971 to 1989. The remarkable inverse relationship is clearly visible in the figure. In other words, an above (below) normal strength of meridional index during previous October or winter season over sector 3 is associated with an early (late) onset of the succeeding monsoon rainfall. Thus, meridional index of previous October over sector 3 can be used as predictor of onset dates of monsoon over India explaining 49 per cent variability of onset dates of monsoon over India. The

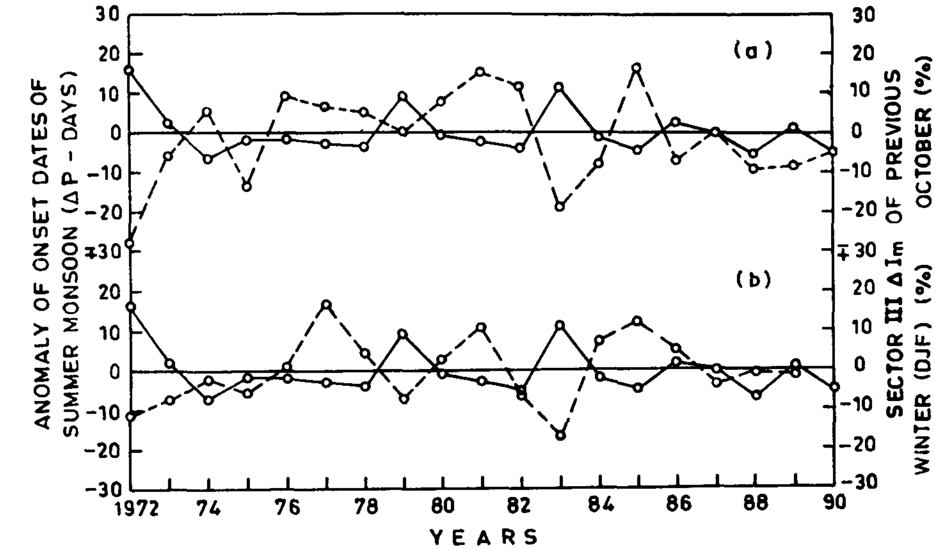

Figure 4. The year to year relationship between the anomaly of onset dates of monsoon (ΔP-days) and percentage anomaly of meridional index (ΔI_m) of (a) previous October over sector 3 (b) previous winter (DJF) over sector 3 (ΔP – solid line, ΔI_m – dashed line).

association in October may help the prediction of onset of Indian monsoon as early as in November.

The analysis presented here, shows a close teleconnection between the antecedent mid latitude meridional circulation and the succeeding Indian monsoon rainfall activity.

3.3 *Possible physical mechanism for the interaction between meridional indices and monsoon rainfall*

To understand the statistical relations discussed above, one must determine the physical processes at work and trace the steps between cause and effect even if the mechanism is purely an hypothesis. We propose here a mechanism to account for the mid-latitude/Indian monsoon effect.

Monsoon is essentially caused by the annual cycle of diabatic heating and cooling (Asnani and Mishra 1975). The summer heating causes an extensive low pressure area, frictional inflow and vertical motion which in the presence of moisture causes monsoon rainfall. This annual cycle of diabatic heating and cooling is accompanied by an annual cycle in all the elements of global circulation including semi permanent troughs and ridges lying in near north-south direction. Deviation in normal heating of the tropical atmosphere have a great effect not only on monsoon circulation patterns and rainfall during individual years but also on all the elements of global circulation from year to year and season to season. For example, anomalies in tropical heating create anomalies in different components of monsoon e.g. lagging/leading behind of the ITCZ/near equatorial trough over the Bay of Bengal and Arabian Sea away from their normal pattern, location and intensity of Tibetan High etc., which in turn cause anomalies in the rising branches of the Hadley and Walker circulation over the monsoon region. This is one of the major causes of interannual variation of monsoon rainfall and its onset dates. One important cause of the anomalous heating of the tropical atmosphere is the anomalies in the meridional transport of sensible heat from the tropical region to the extratropical region (Asnani and Awade 1978). Pisharoty (1981) proposed a hypothesis linking poleward transport of heat and the activity of monsoon. His hypothesis suggests that an active (subdued) monsoon over Southeast Asia is preceded by below (above) normal poleward transport of heat in the northern hemisphere during the preceding winter and spring months. In other words, Indian summer monsoon may be conceived of a delayed response to the inadequacy of the poleward transport of heat during the preceding winter and spring seasons.

Our study essentially corroborates Pisharoty's hypothesis although the physical link between meridional circulation and monsoon rainfall is likely to be complex and may arise through more than one physical effect. One effect seems to be the presence of deep troughs in mid troposphere over middle latitudes in winter and spring which have significant relations to the corresponding strength of meridional circulations. Significant meridional exchanges of sensible heat, momentum and moisture etc. between the tropical and extratropical regions are caused by these semipermanent troughs and ridges lying in near north south direction along with the migratory systems of each season (Asnani and Awade 1978). Anomalies in heat exchanges between tropics and extratropics cause anomalies in temperature gradient between tropics and extratropics. In association with excess heat going from tropics to middle latitudes, the temperature gradient between the tropical and extratropical region is reduced, zonal westerly flows in the middle latitudes become one of low zonal index while meridional flow becomes one of high meridional index. As proposed by Pisharoty, a high (low) meridional index situation during previous winter should therefore be followed by bad (good) monsoon, or in other words, a negative correlation should exist between monsoon rainfall and meridional indices during previous winter. Our analysis in fact shows significant negative correlation coefficients -0.64 and -0.59 respectively between all India monsoon rainfall and winter meridional index of December over sector 2 and that of January over sector 1.

It is interesting to note that both these sectors 1 and 2 lie north of the monsoon area where anomalies in winter meridional indices accompanied by long amplitude troughs and ridges, create anomalies in temperature difference between low latitude monsoon regions and higher latitudes. From our analysis, the indication emerges that variation in meridional circulation during winter maintains a certain type of influence even for several months and changes the atmosphere in such a way through this influence that it is forced to develop in a certain specific pattern. Thus, Indian monsoon region remains warmer (colder) even after several months following the lower (higher) meridional index over the sector 2 and 1 during December and January respectively. It is clear from the results mentioned above that Indian monsoon rainfall should be understood not as a local phenomenon but as an associated one affected by mid latitude meridional circulation over the eastern hemisphere (sector 1 and 2).

The question arises as to what makes December, January over these sectors so special. High zonal and low meridional circulation normally prevails over the extratropical latitudes during the winter period. However, as pointed out by Rossby (1937) and Smagorinsky (1953), there appears to be geographically preferred longitudinal zones where large scale forced perturbations are generated in the westerlies when ultra long waves amplify and extend to lower latitudes. According to Palmen and Newton (1969), the 500 hPa geopotential patterns in January show two strong large amplitude troughs one near the east coast of Asia near 140°E (sector 2) produced in part by diabatic heating of the cold Asiatic air masses moving over the Japanese current and by mountain effect or Tibetan Plateau. The second one occurs over the east coast of north America near 80°W (sector 3) in a mechanism similar to the Asiatic trough. The former corresponds to the Iceland low and the latter to the Aleutian low on sea level maps. Once established these troughs tend to set up high pressure ridges downstream at a wavelength determined by the strength of zonal westerlies (Rossby 1937). A third weaker trough of smaller wavelength extends from north Siberia to eastern Mediterranean at 10°E to 60°E (sector 1). In summer these major troughs are less marked. The January situation is more or less typical for the other months in the period November to April while the period June to September is typified by the July representing summer situation.

While the long term mean state described above is never observed during any month or season, interannual variations in position and amplitude of the long waves do occur which control the strength of the zonal and meridional indices. These are the anomalies that persist beyond the synoptic scale waves and are termed persistent anomalies which play important role in monsoon rainfall variability. Sometimes, one or the other index types dominate the flow around the hemisphere but equally likely, a high meridional index type situation may be found in one part of the hemisphere while a low meridional index may exist in the other. The strength of the trough over east coast of Asia controls the interannual variation of meridional index over sector 2 while the strength of the trough over east coast of north America and Siberia/eastern Mediterranean controls interannual variation of meridional index over sector 1 and sector 3 respectively. As already said, both the sectors 1 and 2 lie north of the monsoon area. Thus, some of the changes in the monsoon rainfall are associated with the influences of the meridional indices over sector 2 during December and sector 1 during January as explained by the above mechanism.

How does the relationship change from negative to positive with meridional index of May (spring season) over sector 3. It may be mentioned here that the basic circulation patterns in the middle of the troposphere expressed by 500 hPa remains more or less similar during the period November to April. However, the pattern changes appreciably during May. According to Wada (1971), at higher latitudes (50°N) a deep trough lies in the middle of the Pacific Ocean (sector 3) and persists during May to September. The patterns elsewhere are less marked. The meridional transport of heat ahead of the trough from the tropics to the extratropics would control the sea surface temperature (SST) over east Pacific during the subsequent season and through SST, the strength of ENSO (El Nino Southern Oscillation) and Walker circulation. A relatively stronger (weaker) trough associated with high (low) meridional index in sector 3 would thus result in negative (positive) SST anomaly over eastern Pacific during the subsequent monsoon season. Chattopadhyay and Bhatla (1993) established significant negative correlation coefficient between Indian monsoon rainfall and the simultaneous SST anomaly over eastern Pacific i.e. a simultaneous positive (negative) SST anomaly over eastern Pacific is associated with deficient (excess) monsoon rainfall over India. One might thus speculate that high (low) meridional index during May over sector 3 would be associated with excess (deficient) monsoon rainfall over India. In other words, a positive correlation should exist between meridional index during May over sector 3 and Indian monsoon rainfall, as found by the present authors.

Our analysis also establishes a significant negative correlation between onset dates of monsoon and previous October, December and DJF season meridional index over various sectors (1, 3 and hemisphere) other than sector 2 with which all India/peninsular India monsoon rainfall was related. This indicates that below (above) normal meridional indices over sector 1, 3 and hemisphere during previous October, December and DJF are associated with delayed (early) onset of monsoon over India. The mechanism is the same as explained earlier for monsoon rainfall. Apparently, it might be difficult to speculate how the same cause i.e. below normal meridional index or above normal temperature contrast between low and high latitudes which helps in above normal monsoon rainfall, is responsible for delayed onset of monsoon. However, a look at table 2 shows that although the relations are inverse for both monsoon rainfall and onset dates, the sectors are different. A correlation analysis between December meridional index over sector 2 on the one hand with December meridional indices over sectors 1, 3 and hemisphere respectively on the other hand shows virtually no correlations. This means that a below (above) normal December meridional index over sector 2 may be associated with either below (above) or above (below) normal meridional indices over sector 1, 3 or hemisphere with equal chances. A corollary of the above finding is that above or below normal all India/peninsular India monsoon rainfall does not depend on early or late onset of monsoon. This was also observed by Dhar *et al* (1980) who found that despite fluctuations in onset dates of monsoon by more than 30 days, the rainfall anomaly over three west coast subdivisions of India for the month of June or for the whole monsoon season is not related to the date of onset of monsoon.

4. Conclusion

The study of the Indian summer monsoon rainfall and mid latitude meridional index circulation for the period 1971 to 1989 has brought out the following important results.

- A significant inverse association exists between the meridional circulation index during previous January over sector 1 and the all India, northwest India and peninsular India monsoon rainfall. In other words, an above (below) normal meridional circulation anomaly in previous January over sector 1 is followed by below (above) normal monsoon rainfall over India.
- A significant inverse association is found between the strength of meridional index during previous December over sector 2 and the all India, and peninsular India monsoon rainfall. Thus, an above (below) normal meridional index during previous December over sector 2 can be used as a predictor of below (above) normal succeeding monsoon rainfall over India.
- A significant positive association between the strength of meridional index during previous May over sector 3 and 4 and monsoon rainfall over northwest India is also observed. In other words, the strength of meridional index over sector 3 and 4 in previous May can also be used as a predictor of monsoon rainfall over northwest India.
- Significant negative correlations are observed between the meridional circulation index during antecedent months and onset dates of monsoon over India viz. (a)

with previous October meridional circulation index over sector 3 and hemisphere (b) with strength of meridional index during previous December over sectors 1, 3 and 4 and during previous winter over sectors 3 and 4.

- The analysis of changes in the intensity of mid latitude meridional circulation over specific sectors and of associated shifts in trough and ridge position which are related to Indian monsoon at least confirms the geographic dependence between the processes under investigation and reflects the dynamic and climatological characteristics of different regions.

The above finding leads one to speculate that antecedent variations in the mid latitude meridional circulation of atmosphere can influence the interannual variation of the Indian monsoon rainfall activity, has some predictive value and it is not the other way round.

One of the limitations of this study is the relatively short time series of 19 years. Although this data length may be sufficient to generate a hypothesis, there is no additional data available to test the hypothesis and authors are fully aware of the potential danger of drawing definite conclusions from such statistical relationships, although, studies based on data of even lesser number of years have been reported elsewhere. Before one can use mid latitude meridional index for monsoon rainfall prediction, the results as observed in this study need to be further investigated with larger set of data to verify the relationship. In conclusion, it may be said that in view of the significant correlation observed in the study, the meridional circulation monsoon relationship is likely to be a profitable area for further investigation in future.

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