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Interannual and long-term variability of the summer monsoon and its possible link with northern hemispheric surface air temperature

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Abstract. Some statistical properties of the summer monsoon seasonal rainfall for India during the last 100 years (1881–1980) are presented. The most recent decade of 1971–1980 shows the lowest value of standard-decadal average monsoon rainfall (86·40 cm) and is also characterised by the second highest value of coefficient of variation in monsoon rainfall (12·4 %). The combined last two standard-decadal period of 1961–1980 was the period of the largest coefficient of variation and the lowest average monsoon rainfall for India.

The possible influence of global climatic variability on the performance of the monsoon is also examined. Analyses of correlation coefficient show that 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.

All the major drought years during the last 3 decades had much cooler January/February periods over the northern hemisphere—1972 having the coldest January/February with a temperature departure of −0·94°C and the most disastrous monsoon failure.

Keywords. Variability of the summer monsoon; northern hemispheric surface air temperature; decadal averages; global climatic variability; monsoon failure; coefficients of variability; long range prediction.

1. Introduction

The Indian summer monsoon from June to September contributes about 75 % of the annual rainfall of the country and is, therefore, vital for the agricultural economy and prosperity of India. Although the definitive characteristic of the monsoon is a seasonal pattern, variations are observed on time-scales ranging from days to decades. Over larger time-scales, there are interannual variations in the seasonal precipitation leading to years of drought and flood. Variations on larger time-scales for periods upto or exceeding decades, have been revealed by more than hundred years of recorded data. The reasons for the variability on longer time-scales are not well understood and more study is required to gain insight into the physical factors responsible for such variations.

The period since 1960 has been characterised by large year-to-year variations in the summer monsoon activity over India. Increased variability has also been noticed in other climatic parameters all over the globe. Variability of monsoon on these longer time-scales has thus entered a new age of study in the context of the World Climatic Research Programme.

Monsoon is basically a thermally-driven large-scale circulation. It is, therefore, logical to expect that any global-scale thermal anomaly may have its influence on the monsoon. The present study deals with interannual and longer time-scale variability of the monsoon and its possible relationship with northern hemispheric (NH) surface temperature anomalies. For this purpose, summer monsoon seasonal rainfall for India has been taken as an index of the large-scale performance of the monsoon.

2. Data and analysis procedure

The data of summer monsoon seasonal rainfall for India were obtained from Parthasarathy and Mooley (1978) and updated to provide the recent 100-year series—from 1881 to 1980. The monsoon rainfall, in this series, has been computed by weighting the areas of the different meteorological sub-divisions. The time-series thus provides a long homogeneous series of monsoon rainfall.

The northern-hemispheric surface air temperature anomaly data for the same 100-year period of 1881 to 1980 have been obtained from the recent study of Jones *et al* (1982), which provides one of the most comprehensive, homogeneous and reliable temperature series of the northern-hemisphere. Using objective techniques, they have computed the monthly mean station data gridded on a 5° latitude by 10° longitude grid. The anomalies are computed with reference to optimum grid period of 1946–60 which has the best data coverage.

In the present study, we have analysed separately the two series to examine their year-to-year and long-term variability and have attempted to investigate a possible linkage between them.

3. Variability of the monsoon

Some aspects of long-term variability of monsoon rainfall were described earlier by Parthasarathy and Mooley (1976) and Banerjee and Raman (1976). Interannual variations in summer monsoon (June–September) rainfall of India for the period 1881–1980 are shown in figure 1. Monsoon performance is depicted in terms of percentage departure of rainfall from its long-term average. Taking the rainfall departure range of $\pm 10\%$ as the normal monsoon activity, extreme monsoon years are delineated by the values in excess of 10% and 20% departures. These departure values are almost equal to 1σ and 2σ respectively. There were fifteen major monsoon failures of which four (1899, 1918, 1972 and 1979) were the worst years when the rainfall departures were $\leqslant -20\%$ of the average, during the last 100 years. There were nine years of good monsoon in this period. Monsoon rainfall departures during the 1960s and 1970s showed a remarkable "Sawtooth" pattern (see figure 1) which is unique in the record and marks the last two decades as a period of unusual year-to-year variability.

Long-term variability of the summer monsoon during the past 100 years is analysed in terms of decadal statistics of rainfall and occurrence of extremes. Decadal variability is shown in table 1 (adapted from Parthasarathy and Mooley 1978, and updated). The following points are noteworthy: (a) The first two decades of the twentieth century were characterised by a low value of average rainfall (~ 87 cm). The decadal average thereafter increased progressively reaching a peak during 1941–1950 (~ 93 cm). It has, since then, been decreasing, reaching the lowest value (~ 86 cm) during 1971–1980 (b) Monsoon variability was high in the first two decades of the century, peaking at 13·6 % during 1911–1920. The variability was considerably low during the subsequent four-decades (1921–1960). The monsoon activity, since then, has shown increasingly large variability reaching a 12·4 % coefficient of variation in 1971–1980, the second highest value during the 100-year record. (c) Frequency of occurrence of extreme monsoons during different decades of the twentieth century is also shown in table 1 in the last two columns. In the first two decades of 1901–1920 there were as many as six major

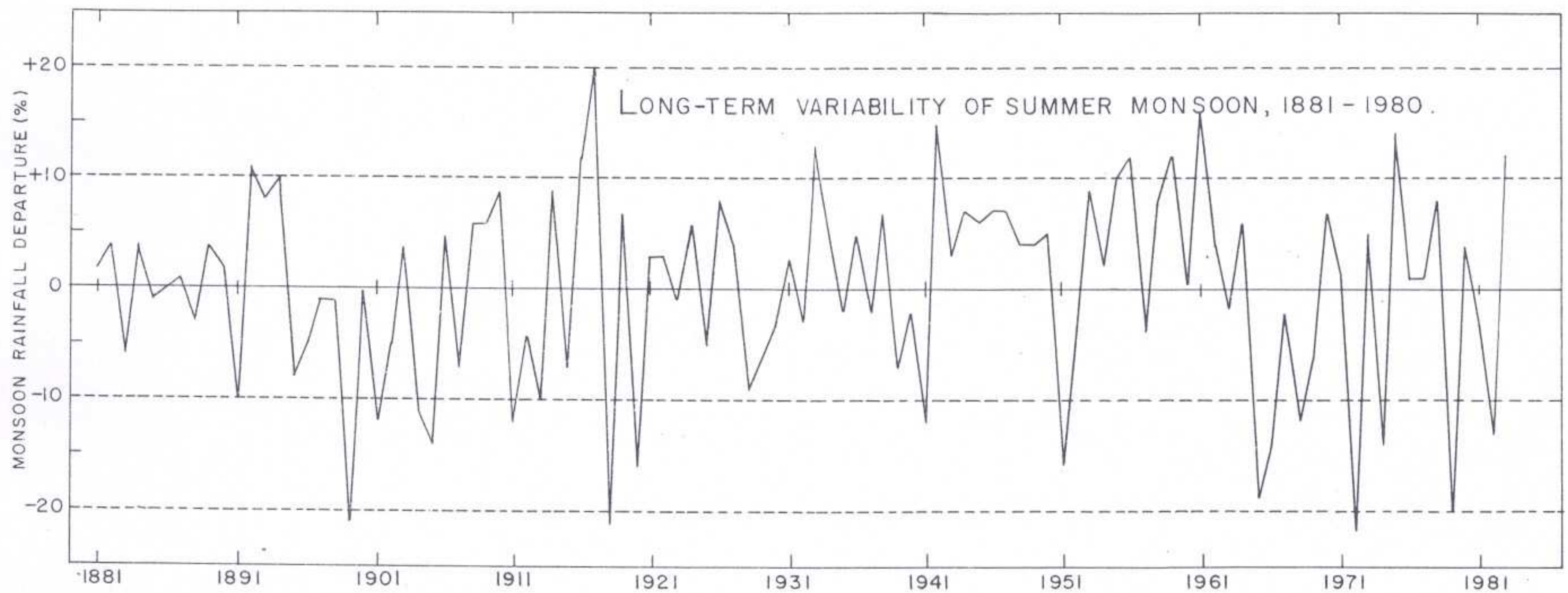


Figure 1. Summer monsoon (June–September) rainfall departure of India (%) for the 100 year period 1881–1980. Dotted lines of ±10% and ±20% are drawn to delineate years of extreme monsoon.

Table 1. Decadal variability of the summer monsoon: some statistics of the summer-monsoon rainfall of India (1881–1980) (after Parthasarathy and Mooley 1978, updated)

Decade	Average (cm)	Difference from long-term average of 88·75 (cm)	Standard deviation (cm)	Coefficient of variation (%)	Years of extreme monsoon: Bad (< −10% departure)	Years of extreme monsoon: Good (> +10% departure)
1881–1890	89·61	+0·86	2·94	3·3	Nil	
1891–1900	87·01	−1·74	8·51	9·8	1899	1892
1901–1910	86·83	−1·92	7·95	9·2	1901, 1904, 1905	
1911–1920	86·89	−1·86	12·01	13·8	1911, 1918, 1920	1916, 1917
1921–1930	88·90	+0·15	4·76	5·4		
1931–1940	90·87	+2·12	5·23	5·8	Nil	1933
1941–1950	93·17	+4·42	5·90	6·3	1941	1942
1951–1960	91·40	+2·65	8·36	9·1	1951	1956, 1959
1961–1970	86·99	−1·76	−9·79	11·3	1965, 1966, 1968	1961
1971–1980	86·40	−2·35	10·74	12·4	1972, 1974, 1979	1975

monsoon failures. These decades were also characterised by low average rainfall and high coefficient of variation. This was followed by an epoch of a four-decadal period during which there were only two major monsoon failures (none during the decades of 1921–1930 and 1931–1940 and one each during the decades of 1941–1950 and 1951–1960). This epoch was also characterised by high average rainfall and low coefficient of variation. The two subsequent decades, 1961–1970 and 1971–1980, again witnessed a high frequency of monsoon failures numbering six, and was also characterised by low average rainfall and high coefficient of variation. Frequent occurrences of poor monsoons during epochs, broadly coinciding with the above mentioned epochs, were also reported by Joseph (1976) in his study of climate changes in monsoon and cyclones during 1891–1974.

4. Variability of northern-hemispheric surface air temperature

During the recent two decades there has been considerable interest in the long-term variability of global/hemispheric surface temperature because of its impact on climatic change. Some of the recent studies, which have estimated the interannual and long-term variability of surface temperature are by Lamb (1975), Mitchell (1975), Budyko (1977), Angell and Korshover (1978), Barnett (1978), and Yamamoto and Hoshiai (1979). Jones *et al* (1982) recently analysed the northern hemispheric surface temperature over the period 1881–1980. Within statistical uncertainties, their series appears to be homogeneous and representative of changes over the northern hemisphere.

In figure 2, we reproduce the figure of Jones *et al* depicting the time variation of northern hemispheric annual mean surface temperature anomalies from the 1946–60 mean. We have drawn two vertical dotted lines to delineate the three distinct epochs: (a) 1881–1920: A 40-year epoch of cooler northern hemisphere during late nineteenth and early twentieth century. (b) 1921–1960: A 40-year epoch of warmer northern hemisphere during mid-twentieth century (peaked in 1938). (c) 1961–1980: A current epoch of cooler northern hemisphere.

Table 2 shows decadal variability of annual and seasonal means of northern hemispheric surface air temperature anomaly in terms of mean and standard deviations. The annual mean shows an abrupt increase in the decadal mean from the

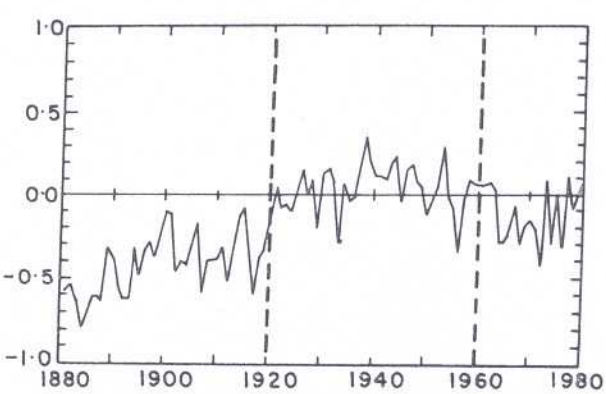


Figure 2. Northern hemisphere annual mean surface temperature anomalies from the 1946–1960 mean (°C) after Jones *et al* (1982). Vertical dotted lines are drawn to delineate three distinct climatic epochs.

Table 2. Decadal variability of annual and seasonal mean northern-hemispheric surface air temperature anomaly (1881–1980). Reference period 1946–60 (data source: Jones *et al* 1982)

Decade	Annual		Winter (Dec., Jan., Feb.)		Spring (Mar., Apr., May)		Summer (Jun., Jul., Aug.)		Autumn (Sep., Oct., Nov.)	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
1881–1890	−0·57	0·15	−0·79	0·41	−0·46	0·29	−0·44	0·18	−0·61	0·17
1891–1900	−0·39	0·18	−0·76	0·54	−0·36	0·29	−0·21	0·13	−0·26	0·28
1901–1910	−0·36	0·14	−0·41	0·24	−0·30	0·26	−0·36	0·20	−0·35	0·22
1911–1920	−0·31	0·17	−0·44	0·43	−0·31	0·25	−0·23	0·18	−0·29	0·22
1921–1930	+0·00	0·12	−0·11	0·31	−0·03	0·18	+0·02	0·11	+0·09	0·15
1931–1940	+0·08	0·17	+0·03	0·28	+0·03	0·21	+0·12	0·12	+0·14	0·24
1941–1950	+0·09	0·12	+0·03	0·32	+0·14	0·10	+0·03	0·08	+0·16	0·15
1951–1960	+0·01	0·17	+0·11	0·28	−0·01	0·25	+0·03	0·15	−0·01	0·20
1961–1970	−0·13	0·15	−0·17	0·36	−0·08	0·21	−0·13	0·13	−0·10	0·20
1971–1980	−0·10	0·20	−0·18	0·31	+0·05	0·26	−0·10	0·19	−0·16	0·20
Total period 1881–1980	−0·17	0·26	−0·28	0·45	−0·13	0·30	−0·13	0·23	−0·13	0·32

first four decades of 1881–1920 compared to the subsequent decades 1921–1960. This is again followed by a relatively lesser but substantial decline during the decades 1961–1980. Decadal standard-deviations of annual mean anomaly remain of the same order throughout ten decades but is highest in the last decade 1971–1980.

Decadal variabilities of different seasons, more or less, follow the annual variability pattern. Winter, however, seems to be different, particularly during the cooler epochs. During these epochs the decadal mean anomaly and the decadal standard-deviation are maximum during winter.

5. Relationship between summer monsoon and NH surface air temperature

Figure 3 shows correlation coefficients between northern hemispheric monthly means of surface air temperature anomalies and summer monsoon rainfall departure of India

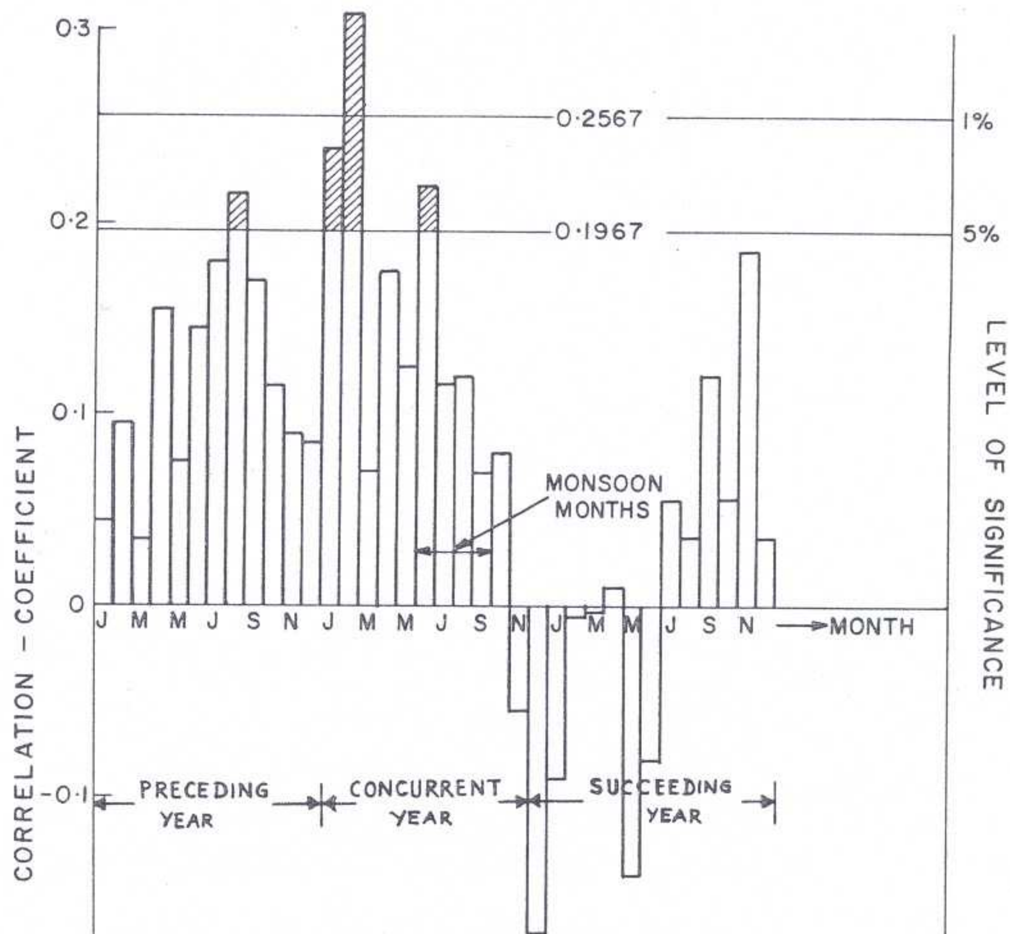


Figure 3. Correlation between summer monsoon rainfall departure of India and northern hemispheric monthly means of surface air temperature anomalies for 1881–1980. Monsoon rainfall is correlated successively with mean monthly temperature anomalies starting from January of the preceding year through December of the succeeding year.

for the 100-year data series of 1881–1980. For this purpose, monsoon rainfall departures of 100 years are correlated successively with (a) 100 values of monthly mean temperature anomalies of all the 12 months of the preceding year, (b) all the 12 months of the concurrent year and (c) all the 12 months of the succeeding year. Correlation coefficients are shown as ordinates along with lines of 5 % and 1 % levels of significance drawn to delineate significant correlations. There are only four months showing correlations higher than 5 % significant level. All these correlations are positive. These are: (a) August of the preceding year (5 % significant level) (b) January of the concurrent year (5 % significant level), (c) February of the concurrent year (1 % significant level) and (d) June of the concurrent year (5 % significant level). Correlation with combined January–February temperature anomaly is also very significant (at 1 % level).

To test the stability of the relationship, we have split the 100-year series into two equal series and computed the correlations similarly. Figure 4 depicts the correlations in the two split-up series. The second half period (1931–1980) more or less shows the same pattern of correlation as the 100-year series. The first half period (1881–1930), however, does not show any significant correlation. The time variation of relationship as shown in figure 5e seems to have some order and is not random. The physical mechanism responsible for this variation must be very complex and needs further investigation. It

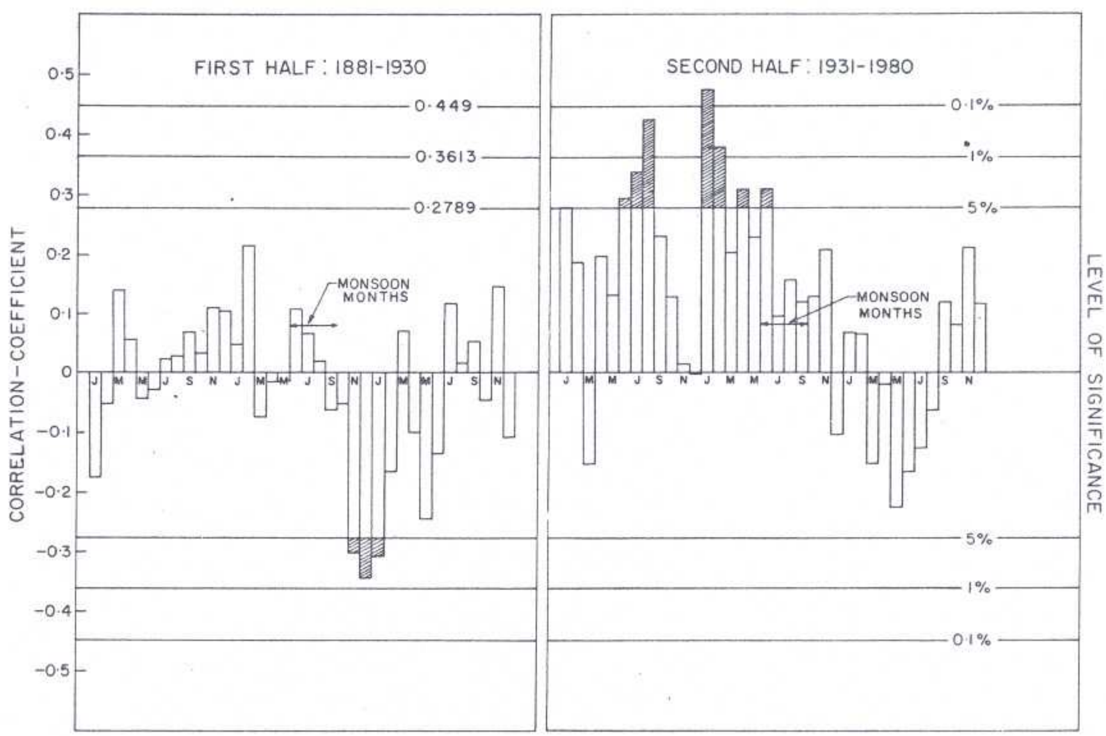
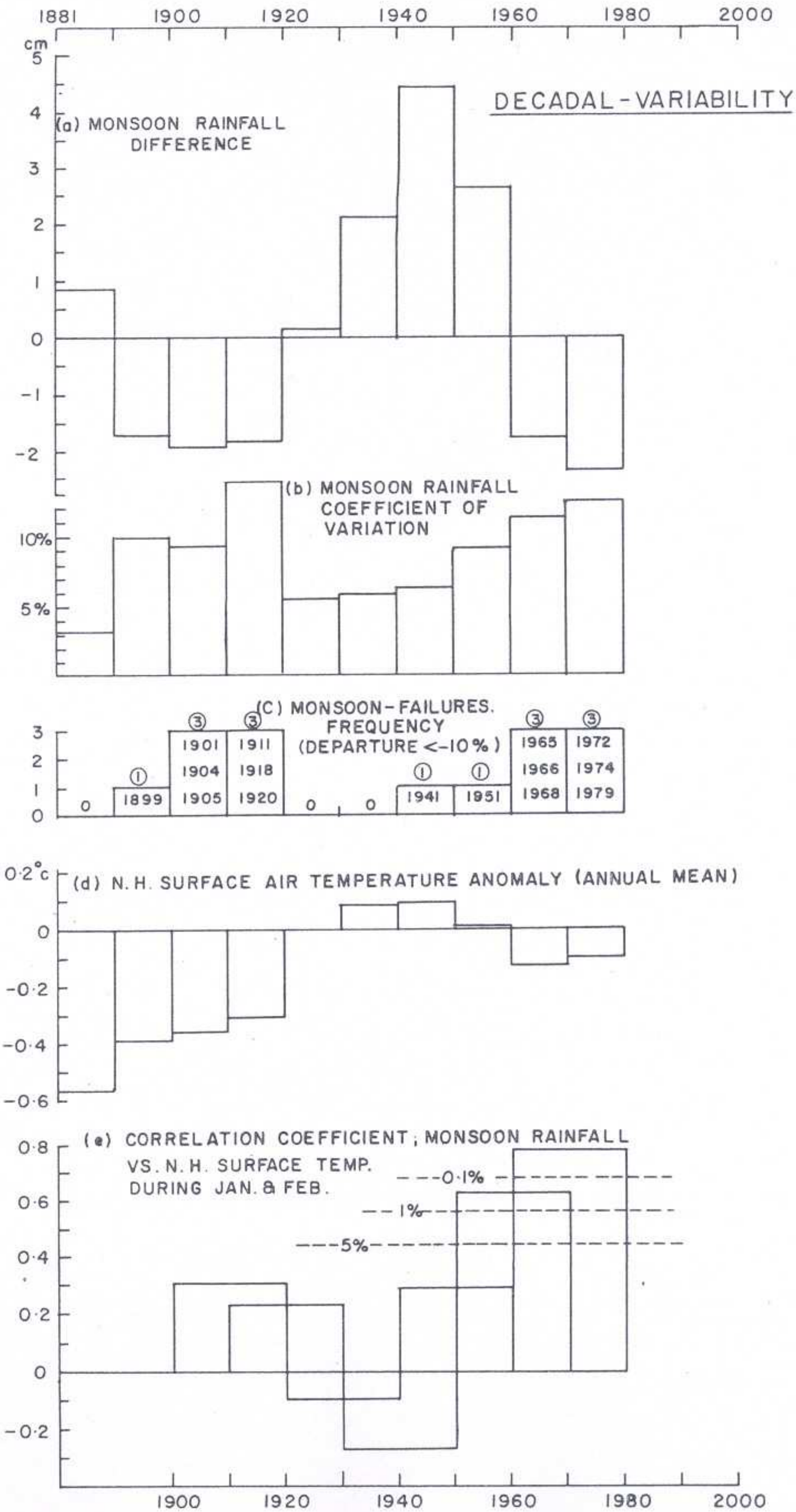


Figure 4. As in figure 3, except that the 100-year series is split into two equal series of 50 years.

Figure 5. Decadal variability of: (**a**) monsoon rainfall difference, (**b**) coefficient of variation of monsoon rainfall, (**c**) frequency of monsoon failures, (**d**) northern hemispheric surface air temperature anomaly (annual mean), and (**e**) correlation coefficient between monsoon rainfall and NH surface temperature during January–February: 1881–1980.



1881
1900
1920
1940
1960
1980
2000
cm
DECADAL-VARIABILITY
(a) MONSOON RAINFALL DIFFERENCE
(b) MONSOON RAINFALL COEFFICIENT OF VARIATION
10%
5%
(C) MONSOON-FAILURES. FREQUENCY (DEPARTURE <-10%)
1899
1901 1904 1905
1911 1918 1920
1941
1951
1965 1966 1968
1972 1974 1979
0·2°c
(d) N.H. SURFACE AIR TEMPERATURE ANOMALY (ANNUAL MEAN)
(e) CORRELATION COEFFICIENT; MONSOON RAINFALL VS. N.H. SURFACE TEMP. DURING JAN. & FEB.
0·1%
1%
5%

may be noted here that many meteorological predictors have shown similar types of variation in their relationship with the monsoon rainfall. Consistent high correlation (CC varying from 0·5 to 0·8) for the past three decades, as shown in figure 5e, suggest that during the current epoch the relationship can be treated as sound.

6. Predictive potential of the relationship: long-range forecast of monsoon failure over India

The statistical relationship between monsoon and NH surface air temperature, as discussed in §5 indicates that an appreciably cooler northern-hemisphere during: (a) the preceding August (b) just past January and February and (c) concurrent June, may lead to deficient summer monsoon rainfall over India. Of these, the most important for prediction purposes are February and combined January–February, both showing positive correlation, significant at 1 % level. It is relevant to refer here to the pioneering work of Blanford (1884) who found that the excessive winter and spring snowfall in the Himalayas was prejudicial to the subsequent monsoon rainfall of India. Blanford used this as one of the important factors for long-range forecasting of monsoon seasonal rainfall.

Considering the highly significant positive relationship between monsoon activity and the winter surface temperature anomaly over the northern-hemisphere, the most logical questions for long-range forecasting would obviously be what critical value of temperature anomaly should be considered as 'appreciably cooler' leading to possible failure of monsoon and also, how well the criterion performs when tested against an independent data-set. An attempt is made to answer these questions in the following paragraphs. The results are depicted in table 3.

Based on results discussed so far, the stable climate period of 1921–1950 is taken as the reference period. One standard deviation (σ) of winter time NH surface temperature anomaly for this reference period is taken as the critical value of anomaly. A period is defined as extreme warm or extreme cold if the temperature anomaly is $\geqslant +1\sigma$ or $\leqslant -1\sigma$ respectively. This criterion is applied to years of period independent of and after reference period (i.e. 1951–1980); and extreme years are delineated.

In table 3 standard-deviation values for January, February, January–February combined and winter (December, January, February), along with delineated extreme years are shown. Amongst these extreme thermally anomalous years, extreme monsoon years are also marked. Apparently there is no skill in forecasting good monsoon years as there is hardly any correspondence between a good monsoon year and an extreme warm year. But there is an extremely good correspondence between a bad monsoon year and a year of extreme cold winter during the past 3 decades.

All the bad monsoons of the last 3 decades (1951–1980) are accounted for when the criterion is applied with the January–February and winter temperature anomalies. The best result is obtained with the January–February temperature anomaly, i.e. when January–February surface temperature anomaly over the northern-hemisphere is that of "appreciably-cooler" category ($\leqslant -0{\cdot}4$°C); the ensuing monsoon is likely to be bad. However, there were also two such years, when the temperature anomalies were less than the critical values but the years were not bad monsoon years. Nevertheless, the relationship may be used for guidance in long-range forecasting of monsoon failure leading to drought over India.

Table 3. Standard deviation of winter NH surface air temperatures during the stable climate period of 1921–1950; and years of extreme temperature anomalies during the period independent of and after the sample period. Temperature anomaly in °C, shown in brackets.

		January	February	Jan. and Feb.	Winter (Dec., Jan., Feb.)
Standard Deviation σ(°C)		0·47	0·50	0·40	0·30
Extreme years		1955 (+0·65)	1953 (+0·54),		
			1963 (+0·65)	1958 (+0·54)	●1956 (+0·39)
	Warm		1960 (+0·61),		1958 (+0·39)
	$\geq +1\sigma$	1958 (+0·74)	1973 (+0·59)		1980 (+0·37)
		*1951 (−0·79)	*1951 (−0·79)	*1951 (−0·79)	*1951 (−0·51)
		1954 (−0·67)	*1965 (−0·54)	*1965 (−0·43)	*1965 (−0·46)
	Cool	*1966 (−0·72)	1967 (−0·55)	*1966 (−0·40)	*1966 (−0·31)
	$\leq -1\sigma$	1967 (−0·47)	1969 (−0·86)	1967 (−0·51)	1967 (−0·44)
		*1968 (−0·89)	*1972 (−0·71)	*1968 (−0·59)	*1968 (−0·32)
		1969 (−0·72)	*1979 (−0·88)	1969 (−0·79)	1969 (−0·81)
		*1972 (−1·16)		*1972 (−0·94)	1971 (−0·45)
		*1974 (−0·67)		*1974 (−0·57)	*1972 (−0·70)
				*1979 (−0·48)	*1974 (−0·44)
					*1979 (−0·39)

●Good monsoon (rainfall departures > 10%); *bad monsoon (rainfall departure < −10%).

7. Conclusions

The conclusions drawn in the present study are summarised in the following paragraphs as depicted through histograms (a)–(e) in figure 5 on the basis of the decadal variability in monsoon activity on one side and NH surface temperature on the other. Their relationship and variability in different epochs have special significance.

(a) The difference of the summer monsoon rainfall in India from its long-term average is an index of the large-scale performance of the monsoon. Its decadal variability is shown in figure 5a. Monsoon rainfall on a decadal average, was relatively less during the early part of this century (1891–1920), appreciably more during the mid-part (1931–1960) and decreased substantially during the last two decades (1961–1980).

(b) The coefficient of variation is an index of the variability of the monsoon rainfall. Its decadal variation is shown in figure 5b. Monsoon activity, on a decadal average, had large variability during the early part of this century, comparatively less variability in the middle and has been increasing since then. The combined last two decadal periods of 1961–1980 witnessed the largest variability during the last one hundred years.

(c) Decadal frequency of the large scale failure of monsoon rainfall leading to droughts over India is shown in figure 5c. There were frequent monsoon failures during the early part of the century (six years during 1901–1920), they were very much less frequent during the mid-century (only two years during 1921–1960) and have again become more frequent during the last two decades (six years during 1961–1980).

(d) Decadal variation of annual mean surface air temperature over the northern hemisphere is representative of global climatic changes and trends. This is shown in figure 5d. The northern hemisphere as a whole, had been relatively cooler during the early part of this century, became warmer during the mid-century (reaching a peak around 1940), and has been cooler again during the last two decades. Winter is characterised by the largest mean anomaly as well as the largest variability in temperature.

(e) A direct relationship seems to exist between monsoon and northern hemispheric winter surface temperature, the latter probably acting as one of the dominant forcings for the monsoon. The relationship is statistically very significant (at 5% level with January temperature anomaly and at 1% level with February and January–February combined temperature anomalies).

The relationship has been more significant during the last two decades of 1961–1980 (at 0·1% level with various combinations of winter months). The highest correlation coefficient of 0·77 is obtained with the temperature anomaly of the January–February period. In figure 5e, the two-decadal variation in correlation coefficient with the January–February temperature anomaly is shown. There appears to be some order in the variations of the relationship in different climatic epochs reaching a positive peak during the current cooler epoch.

The relationship assumes special significance because of the 6-months difference between the monsoon peak activity (July–August) and the NH surface temperature anomaly (January–February) that is significantly related with it in the present epoch. The relationship, thus, may provide guidance in long range forecasting of the monsoon, particularly of its failure about 3 to 4 months before its onset in June.

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