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Long-term Variability of Summer Monsoon and Climatic Change

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Abstract

Long-term variability of summer monsoon (June-September) rainfall for India during the last 100-year period (1881-1980) are discussed. The basic data are obtained from the study of Parthasarathy and Mooley (1978) and updated. Taking departure value of $< -10\%$ of the average as major failure of monsoon rainfall, there have been fifteen such years, out of which four years (1899, 1918, 1972 and 1979) were the worst years when the departures were $\leq -20\%$ of the average. The long term variability is described in terms of some statistical properties of monsoon rainfall taking standard decadal periods as unit. The recent two-decads of 1961-1980 witnessed very large variability in the rainfall activity of monsoon over India in the last one hundred years. This period is characterised by the highest coefficient of variability (11.5 %), the lowest average rainfall (87.07 cm) and the maximum frequency of major monsoon failures (6).

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Possible relationship between the climatic variability and the large-scale performance of monsoon is examined. For this purpose, monthly mean variations in surface air temperature over Northern Hemisphere for the same hundred year period of 1881-1980, from the recent study of Jones et al (1982) have been used. Analyses of correlation coefficients show an interesting result that statistically very significant positive relationship with a time-lag of about six months exists between monsoon rainfall and Northern Hemispheric surface air temperature. Significantly cooler (anomaly of $\leq$ -0.4°C relative to reference period of 1946-60) Northern Hemisphere during January-February may, most likely, lead to a poor monsoon. This relationship seems to hold more, particularly during the current epoch of last 2-decades when the Northern Hemisphere has been comparatively cooler.

All the major drought years of the last 3-decades were preceded by significantly cooler January-February period over Northern Hemisphere. 1972, the most disastrous monsoon failure year of the twentieth century was also preceded by the coldest January-February period over Northern Hemisphere. The relationship, thus, may find useful application in long-range forecasting of monsoon, particularly of large-scale monsoon failure leading to drought.

1. Introduction

The summer monsoon of Southeast Asia is the largest regional anomaly of general circulation of the atmosphere. Although monsoon is a seasonal phenomenon , fluctuations in monsoon are observed on time scales ranging from days to decades. For India, monsoon rainfall, whose period is taken from June to September, accounts for over 75 percent of the annual rainfall. Monsoon rainfall, therefore, plays an important role in the economy of the country. Occurrences of extreme monsoon rainfall can lead to years of drought and flood.

Monsoon is basically a thermally driven large-scale circulation which cannot be isolated from the planetary-scale circulation. It is, therefore, scientifically logical to expect that any global-scale thermal anomaly may have its influence on monsoon. The present study deals with inter-annual and longer time-scale variability of monsoon and its possible relationship with Northern Hemispheric surface temperature anomalies. For this purpose, summer monsoon seasonal rainfall for India has been taken as an index of the large-scale performance of monsoon.

2. Data and analysis procedure

The data of summer monsoon seasonal rainfall for India are obtained from the study of 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, Wigley and Kelly (1982). The study provides one of the most comprehensive, homogeneous and reliable temperature series of Northern-Hemisphere. Using objective techniques, they have computed the monthly mean temperature anomalies based on 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.

In the present study, we have first analysed separately the two series with a view to examine their year-to-year and long-term variability and then attempted to investigate if the two climatic phenomena provide any possible linkage between them.

3. Variability of monsoon

3.1 Inter-annual variability

Interannual variations in summer monsoon (June-September) rainfall of India for the period 1881-1980 are shown in Fig.1. Monsoon performance is depicted in terms of percentage departure rainfall from its long-term average of 89 cm. (Since we are interested in large-scale activity of the monsoon, the rainfall statistics are rounded to whole numbers). The standard deviation (σ) comes out to be 8 cm. Taking rainfall departure range between $\pm$ 10% as normal monsoon activity, extreme monsoon years are delineated by the values in excess of 10% and 20% departures (shown by dotted lines in the figure). These departure values are very nearly equal to 1σ and 2σ respectively. These extreme monsoons, with

their percentage departures are given in Table 1. There were fifteen major failures of monsoon out of which four years (1899, 1918, 1972 and 1979) were the worst years when the rainfall departures were $\leqslant$ -20% of the average, during the history of last one hundred years. There were nine years of good monsoon in this period. Monsoon rainfall departures during 1960s and 1970s showed a remarkable "saw-tooth" pattern (see Figure 1) which is unique in the record and which marks the last two decades as a period of unusual year-to-year variability.

3.2 Long-term variability

Long-term variability of summer monsoon during past one hundred years is analysed in terms of decadal and two-decadal statistics of rainfall and occurrence of extremes. Decadal variability is shown in Table 2 (adapted from the study of Parthasarathy and Mooley, 1978, and updated). The following points are noteworthy :

a) The first two decades of the twentieth century were characterised by low value of average rainfall ($\sim$ 87 cm.).

b) The decadal average then increased progressively to a peak in the decade 1941-1950 ($\sim$ 93 cm.).

c) It has, since then, been decreasing, reaching the lowest value ($\sim$ 86 cm.) in the just passed decade of 1971-1980 during the last 100-years of record.

d) Standard deviation and coefficient of variation are the measure of variability of any variable. Monsoon variability was, thus, high in the first two decades of the century, peaking at 13.8% during 1911-1920.

e) The variability was considerably low during the subsequent four-decades (1921-1960).

f) The monsoon activity, since then, had shown increasingly large variability reaching 12.4% coefficient of variation in the just passed decade of 1971-80, second highest value during the 100-year record.

g) It is interesting to examine the frequency of occurrence of extreme monsoons during different decades of twentieth century. Extreme monsoons are defined as 'Bad' when departures are $<-10\%$ and as 'Good' when departures are $> +10\%$. Such years are shown in last two columns. Frequency of 'Bad' monsoons seems to have more relevance when correspondences are drawn with the decadal rainfall averages and its coefficient of variations.

In the first two decades of 1901-1910 and 1911-1920, there were as many as six major monsoon failures (1901, 1904, 1905, 1911, 1918 and 1920). These decades were also characterised by low average rainfall and high coefficient of variation.

These decades were followed by an epoch of four-decadal period during which there were only two major monsoon failures (None during the decades of 1921-1930 and 1931-1940. 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 subsequent two decades of 1961-1970 and 1971-1980 again witnessed a very high frequency of monsoon failures numbering six (1965, 1966, 1968, 1972, 1974 and 1979). The period was also characterised by low average rainfall and high coefficient of variation.

Frequent occurrences of years of poor monsoon during epochs, broadly coinciding with above mentioned first and third epochs, were earlier reported by Joseph (1976) in his study of climate changes in monsoon and cyclones, 1891-1974.

From the above mentioned points it may appear that one of the time-scales of long-term variability of monsoon may be of the order of two to four decades. Keeping this in view, rainfall statistics for two-decadal periods were also computed (Table 3). From this it is clearly revealed that the just-ended epoch of two-decades (1961-1980) was the most abnormal period during last one hundred years, as far as the long-term variability of monsoon activity over India is concerned. It was characterised by the lowest average rainfall and the highest coefficient of variability (including highest frequency of occurrence of major monsoon failures). Whether the coming one or two decades would have the same abnormal characteristics in monsoon variability, is a most challenging prediction problem, climatologists and meteorologists would

like to answer ? An insight into the problem is probably provided in Tables 2 and 3. It appears that the high frequency of monsoon failures is the main cause for low values of average monsoon rainfall, in absence of sufficient compensation from good monsoons. It also seems that, mainly, the high frequency of monsoon failure contributes to its high variability. If it is so, then the problem reduces to finding out why there are more number of major monsoon failures in some epochs compared to others? Possible influence of the short-term climatic change or changes in the mean-state of the forcings which play vital role in establishing such large-scale circulations like monsoons and their subsequent maintenance, seem very important. This aspect is investigated in the latter sections.

4. Variability of northern-hemispheric surface air temperature

During the recent two decades there have been considerable interest amongst scientists, 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 the long-term variability of surface temperature are by Angell and Korshover (1978), Barnett (1978), Budyko (1977) Yamamoto and Hoshiai (1980), Lamb (1975) and Mitchell (1975). Results of these and other investigations may not have one-to-one-correspondence because different authors have used different data sources, different techniques of analysis and different reference periods; but by-and-large they agree on broad aspects of large-scale temperature changes. Some aspects of climatic-change that is going on, thus emerge quite clearly.

In one of the most recent publications Jones, Wigley and Kelly (1982) have analysed in detail the northern hemispheric surface temperature over the period 1881-1980. They have produced, using objective techniques, a long-term series of monthly mean northern-hemispheric temperature anomalies based on monthly mean station data gridded on a 5° latitude by 10° longitude grid. The anomalies have been computed with reference to optimum grid period of 1946-60. Within the statistical uncertainties, their series appears to be both homogeneous and representative of changes over the northern hemisphere. In Fig. 2, we have reproduced their figure which depicts 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 three distinct epochs, which become clearly apparent. These are :

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.

c) 1961-1980 : A current epoch of cooler northern hemisphere.

So far as trends in temperature changes are concerned, there seems little doubt that northern hemisphere had warming trend between about 1881 and 1940, and cooling trend after 1940. However, in recent years, since about 1972, there has been an apparent warming but with considerable year-to-year variability. Whether this is a short-term upward fluctuation superimposed on a longer-term cooling trend, remains a point of discussion.

Data of the recent three years became available after this paper was written. To emphasise the particularly pronounced year-to-year variability of Northern-Hemispheric surface temperature in recent years, it may be mentioned that 1972 was the coldest year (anomaly of -0.42°C) after 1917 and that 1981 as the warmest year (anomaly of +0.48°C) on record.

Table 4 shows decadal variability of annual and seasonal means of northern-hemispheric surface air temperature anomaly in terms of means and standard deviations.

In the annual mean picture, there is abrupt increase in the decadal mean from the first four decades of 1881-1920 (decadal anomalies of the order of -0.4°C) to subsequent four decades of 1921-1960 (decadal anomalies of the order of +0.05°C) which is again followed by relatively lesser but substantial decline during the last two decades of 1961-1980 (decadal anomalies of the order of -0.1°C). Decadal standard-deviations of annual mean anomaly remain of the same order throughout ten decades but is highest in the last decade of 1971-1980.

Decadal variabilities of different seasons, more or less, follow the annual variability pattern. Winter, however, seems to play major influential role, particularly during the cooler epochs, so far as the short-term climatic variability is concerned. During these epochs the decadal mean anomaly and the decadal standard-deviation are maximum during winter. Even, average of the whole hundred year period of 1881-1980, shows largest temperature anomaly and largest standard-deviation during winter season. Summer shows the lowest variability. Many aspects of year-to-year and decadal variability are extensively discussed by Jones et al (1982). We have emphasised here only some of these, relevant to the present study.

The winter role, as pointed out by Van Loon and Williams (1976a, 1976b), for deciding the average temperature trend over the northern-hemisphere, is connected with circulation changes on the scales of long-waves in high latitudes. In contrast, during summer, according to them, the combination of weaker temperature contrasts, larger role played by the shorter waves and the smaller amplitude of the longer waves in middle and high latitudes, diminishes the summer variability and its influence on hemispheric average variability.

5. Relationship between summer monsoon and N.H. surface air temperature.

Fig. 3 shows correlation coefficients between northern hemispheric monthly means of surface air temperature anomalies and summer monsoon rainfall departure of India for the 100-year data series of 1881-1980. For this purpose, monsoon rainfall departures of 100 years are correlated successively with 100

values of monthly mean temperature anomalies of all the 12-months of the preceding year, with all the 12-months of the concurrent year and with all the 12-months of the succeeding year.

Correlation coefficients are shown in the ordinate along with the 5% and 1% level of significance lines drawn to delineate significant correlations. There are only four months showing significant correlations higher than at 5% level of significance. All these correlations are positive. These are :

a) August of preceding year (5% significant level)
b) January of the concurrent year (5% significant level)
c) February of the concurrent year (1% significant level)
d) June of the concurrent year (5% significant level)

Correlation with combined January-February temperature anomaly is also very significant (at 1% level).

These relationships assume special importance because of their predictive potential for long-range forecast of monsoon, as these temperature anomalies correspond to months before the monsoon. This aspect of the relationship is discussed latter in Section 5.2. We have examined the auto-correlations of the two series. Since both the series have very small auto-correlations, the correction in computing the exact values of significant levels will be insignificantly small and is therefore ignored.

5.1 Stability of the relationship

To test the stability of the relationship, we have split the 100-year series into two equal series and computed the correlations. Fig. 4 depicts the correlations in the two split-up series. The second half period (1931-1980) more or less shows the same pattern of correlations as the 100-year series. The first half period (1881-1930), however, does not show any significant correlation. This may indicate that probably the relationship holds more during the period when northern-hemisphere has a cooling trend, as during the last three to four decades.

From the discussions in the earlier sections it seems quite reasonable to take a two-decadal period as unit of time-scale for short-term climatic fluctuations. Jones et al (1982) also showed that all seasons have time-scale trends of $\gtrsim 20$ year. It would also be desirable to take overlapping two-decadal periods to mark approximately the time of reversal in climate change. Also, ten-year series may be too short to illustrate any relationship between two climatic events with some degree of confidence. With these points in mind, to look further into stability of the relationship to finer resolution (viz. two-decadal period), correlation coefficients between monsoon rainfall and N.H. surface temperature anomalies are computed for overlapping two-decadal periods and shown in Table 5. Temperature anomalies correspond to annual mean and to more relevant combinations of winter months. "Stars" show different levels of significance.

Correlation with the annual mean temperature anomaly show positive correlation during last three-decades - significant at 5% level in the last two-decades. Earlier decades show negative correlation but not at significant level.

Correlations with the winter-time combinations show more or less same pattern of variation, viz.

a) Positive correlation during the first three decades of the present century (1901-1930) but not at significant level.

b) Negative correlation during mid-century (1931-1950). (5% significance with winter temperature anomaly).

c) Positive correlation at high to very high level of significance during last three decades (1951-1980).

Lower values of correlation coefficient with annual mean temperature anomaly during the last three decades, as compared to correlations with winter time anomalies, may be explained through Figs.3 and 4. Reversal of sign of correlation in general - from positive during the months preceding the monsoon to negative during the months following the monsoon, would tend to lessen the otherwise strong influence of the pre-monsoon months, when anomalies during both the periods are averaged in a calendar year.

The relationship has not been stable through the last 100-year period, analysed in the present study. What could be the probable cause of such variations in the relationship between the two climatic events ? It is remarkable that the correlations did not change randomly. The relationship had one sign (positive) during one type of climate (cooler epochs of late nineteenth to early twentieth centuries and last three

decades). The relationship had opposite sign (negative) during the opposite type of climate (warmer epoch of mid-twentieth century). Jones et al (1982) also noted in their N.H. surface air temperature analyses that on the year-to-year time scales, there are periods when the seasons are correlated and others for which there is no statistically significant correlation. According to them, the reasons may be related to the more slowly varying components of the climate system.

There are observational and modelling evidences which suggest that interannual and long term variability of atmospheric circulations can be greatly influenced by slowly varying global surface boundary conditions of sea surface temperature, sea ice, snow cover and soil moisture. The physical mechanisms responsible for such influences, though quite complex, may ultimately result in net surface air temperature anomaly on global or hemispheric scale.

In the present study, winter-time surface temperature anomaly stands out as a significant factor influencing the following summer monsoon. We have, therefore, now to seek which of the boundary forcings may influence the winter temperatures most ? Snow cover seems to be the probable answer as discussed in the following paragraph.

A number of studies have shown strong inverse relationship between snow-cover over Eurasia and large-scale performance of monsoon since the first studies by Blanford (1884) and Walker (1910). Some of the recent studies amongst them are that of Hahn and Shukla (1976) and of Dey and

Bhanukumar (1982). Another important aspect of the snow-cover on the hemispheric-scale is brought out in a study by Wiesnet and Matson (1976), who have shown that there is a very strong persistency in snow cover over the northern-hemisphere from December through March. The direct relationship between winter-time surface temperature of Northern Hemisphere and Indian monsoon obtained in this study therefore, shows the possible influence of the winter-snow cover anomaly over the Northern Hemisphere (or even over Eurasia) on the Northern Hemispheric surface temperature anomaly; that excessive and persistent winter snow-cover over Eurasia/Northern Hemisphere is synonymous to lowering of the winter time Northern Hemispheric surface air temperature. This seems quite plausible because excessive, persistent and increased snow cover would result in increased albedo and utilisation of more solar energy in melting the snow-both processes leading to decrease of surface air temperature. This can delay and weaken the spring and summer heating of the Asian land mass which is the basic driving force of the large-scale monsoon circulation.

In our earlier studies (Verma, 1980a, 1980b and 1982) we have shown that the upper tropospheric thermal field anomalies tend to persist from pre-monsoon months of April-May to monsoon period and also that negative (positive) anomalies

are associated with negative (positive) anomalies of Indian summer monsoon rainfall. It is quite likely that this long persistence of anomaly and its relation with the monsoon may be related to the slowly varying boundary forcings of snow cover over Eurasia or SST anomalies over Tropical oceans.

Dewey and Heim (1981) have studied variations in N.H. seasonal snow cover based on satellite observations and have found that there was an overall increase in snow-cover area from 1966 to 1980. They also noted that there has been a trend toward earlier, more extensive snow cover in the fall and slower ablation in the spring. Their observations are supported by the results of a model study conducted by Choudhary and Kukla (1979) where-in they noted that the addition of more CO_2 to the atmosphere could significantly reduce the shortwave energy absorbed at snow and ice surfaces and thus delay the recrystallisation of snow and dissipation of pack-ice, resulting in a cooling rather than a warming effect. They additionally noted that this process may contribute to an extension of snow and ice seasons marked by delayed snowmelt in spring, and early snow deposition in autumn.

Thus, during the last three decades, larger winter cooling anomalies, supported by observations and model studies, have greatly influenced the climate pattern - made it cooler and unstable. This changed climatic state seems to be favourable for the relationship between monsoon and surface temperature anomaly over northern hemisphere during winter time.

5.2 Predictive potential of the relationship : Long-range forecast of monsoon failure over India

The relationship between monsoon and NH surface air temperature as discussed in Section 5 may be applied for long-range forecasting of summer monsoon over India, particularly its failure or large deficiency in rainfall leading to drought, because of its significant correlation with the winter-time temperature anomalies, about 3 to 4 months ahead of the onset of monsoon. The relationship, in a statistical sense, indicates that appreciably cooler northern-hemisphere during;

August of preceding year
January and February of the year and
June of the year

may lead to deficient summer monsoon rainfall over India during the year. Out of these months the most important for prediction purpose are February and combined January-February temperature

anomalies both showing positive correlation, significant at 1% level during the last 30 years.

Bearing in mind the highly significant positive relationship between monsoon activity and the winter-time surface temperature anomaly over northern-hemisphere, most logical question for long-range forecasting would be obviously as to what critical value of temperature anomaly be considered as "appreciably cooler" leading to possible failure of monsoon ? Also, how well the criteria 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 6 and Fig.5.

Based on discussions in the previous sections, stable climate period of 1921-50 is taken as reference period. One standard-deviation (σ) of winter time N.H. surface temperature anomaly for this reference period is taken as the critical value of anomaly. A period is defined as an extreme warm or an extreme cold period if the temperature anomaly is $\geq +1\sigma$ or $\leq -1\sigma$ respectively. This criteria is applied to years of period independent of - and after the reference period (i.e. 1951-1980); and extreme years are delineated.

In Table 6, 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 for forecasting of good monsoon years as there is hardly any correspondence between good monsoon year and extreme warm year. But there is an extremely good correspondence between bad monsoon year and year of extreme cold winter-months.

All the bad-monsoons of the last 3-decades (1951-80) are accounted for when the criteria 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 Northern-Hemisphere is that of "appreciably-cooler" category ($\leq -0.4°C$); the ensuing monsoon is likely to be bad. There is very high skill for forecasting of occurrence of bad monsoon or monsoon failure with January-February hemispheric winter temperature anomalies (7 out of 9 or 78% probability of success and 7 out of 10 or 70% probability of success respectively). However, there were two such years when though the temperature anomalies were less than the critical values but the years were not bad-monsoons.

Nevertheless, the relationship may be used in long-range forecasting of monsoon failure leading to drought over India.

Choosing January-February temperature anomaly, which reveals the most significant relationship, we have plotted, in Fig.5, a scatter diagram of years during 1951-80, with relation to its rainfall departure and January-February temperature anomaly. The year is denoted by its last two-digits near the circle. To delineate extreme years in respect of both variables, $\pm \sigma$ lines are also drawn (dotted). Clustering of all the years of monsoon failure ($\leqslant$ - 10% departure) in the sector characterised by $\leqslant -1\sigma$ January-February temperature anomaly, clearly brings out the high potentiality of January-February surface air temperature anomaly over Northern-Hemisphere for foreshadowing large-scale failure of summer monsoon over India. There is no such correspondence for good monsoon years.

The year of 1972 stands out remarkably as the most disastrous monsoon failure, as well witnessing the coldest January-February over Northern-Hemisphere not only during the last 3 decadal period but since beginning of the present century.

6. Conclusions

Results discussed in Sections 3, 4 and 5 amply demonstrate that during the last 100 years the two climatic events, namely, the summer monsoon of SE Asia and the surface temperature of Northern-Hemisphere, have shown some striking similarities in their long-term variabilities with decade as unit. Sikka (1980), while discussing 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, also observed that anomalous epochs in the monsoon rainfall coincide with the epochs having anomalous patterns of temperature distribution in the Northern-Hemisphere.

The conclusions drawn in the present study are summarised in the following paragraphs as depicted through histograms (a) - (e) in Fig.6 on the basis of the decadal variability in monsoon activity on one side and N.H. surface temperature on the other. Their relationship and its variability in different epochs has special significance.

(a) Summer monsoon rainfall difference of India from its long-term average is an index of large-scale performance of monsoon. Its decadal variability is shown in Fig.6 (a).

Monsoon rainfalls on decadal average, were relatively less during early part of this century (1891-1920), appreciably more during mid-century (1931-1960) and decreased substantially during the last two decades (1961-1980).

(b) Variability of monsoon rainfall denoted by its coefficient of variation is an index of stability of the phenomenon. Its decadal variation is shown in Fig.6(b). Monsoon activity, on decadal average, had large variability during the early part of this century, comparatively less variability during the mid-century and has been increasing since then. The combined last two decadal period of 1961-1980 witnessed the largest variability during last one-hundred years.

(c) Decadal frequency of large-scale failure of monsoon rainfall leading to droughts over India are shown in Fig.6(c). There were frequent monsoon failures during early part of the century (six numbers during 1901-1920), they were very much less frequent during mid-century (only two numbers during 1921-1960) and have again become more frequent during last two decades (six numbers during 1961-1980).

(d) Decadal variation of annual mean surface air temperature over Northern Hemisphere is representative of global climatic change and trends in it. This is shown in

Fig.6(d). The Northern-Hemisphere, as a whole, had been relatively cooler during the early part of this century, became warmer during the mid-century, (reaching peak around 1940), and had been cooler again during the last two-decades.

Winter is characterised by largest mean anomaly as well as largest variability, in temperature.

(e) A direct relationship seems to exist between monsoon and Northern-Hemispheric winter-time surface temperature later one 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).

The relationship has been still more significant during the last two-decade of 1961-1980 (at 0.1% level with various combinations of winter months). Highest correlation coefficient of 0.7747 is obtained with the temperature anomaly of January-February period. In Fig.6(e), the two-decadal variation in correlation coefficient with January-February temperature anomaly is shown. There appears some order in the variations of the relationship in different climatic epochs reaching positive peak during the current cooler epoch.

The relationship assumes special significance because of 6-months lag between the monsoon peak activity (July-August) and the N.H. surface temperature anomaly (January-February). The relationship, enables long-range forecasting of monsoon (particularly of its failure) about 3 to 4 months before its onset in June.

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Legend of Figures

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Fig. 4 : As in Fig. 3, except that 100-year series is split-up into two equal series of 50-years.

Fig. 5 : Monsoon rainfall departure of India and Northern Hemispheric January-February surface temperature anomaly in years during last three decades (1951-1980). Year is denoted by its last two-digits, near the circle. $\pm\sigma$ lines (dotted) are drawn to delineate extreme years in respect of both variables.

Fig. 6 : 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 N.H. surface temperature during January-February : 1881-1980.

Legend of Tables

Table 1 : Extreme years of summer monsoon rainfall (1881 - 1980)

BAD YEARS			GOOD YEARS		
S.No.	Year	Departure (%)	S.No.	Year	Departure (%)
1	1899*	-21	1	1892	+11
2	1901	-12	2	1916	+13
3	1904	-11	3	1917@	+20
4	1905	-14	4	1933	+13
5	1911	-12	5	1942	+15
6	1918*	-21	6	1956	+12
7	1920	-16	7	1959	+12
8	1941	-12	8	1961	+17
9	1951	-16	9	1975	+14
10	1965	-19			
11	1966	-14			
12	1968	-12			
13	1972*	-22			
14	1974	-14			
15	1979*	-20			

* Very Bad Year @ Very Good Year

Table 2 : Decadal variability of summer monsoon : Some statistics of summer-monsoon rainfall of India (after Parthasarathy and Mooley, 1978; and updated). 1881-1980.

Decade	Average	Difference from long-term Average of 88.75 cm. (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	NIL	
1931-1940	90.87	+2.12	5.23	5.8		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

Table 3 : Rainfall statistics for 2-decadal periods

Period	Average (cm)	Difference from Long-term Av. ~89 cm.	S.D.(cm)	Coefficient of variation (%)
1881-1900	88.31	-0.69	6.50	7.3
1901-1920	86.86	-2.14	9.95	11.4
1921-1940	89.89	+0.89	4.95	5.5
1941-1960	92.29	+3.29	7.00	7.6
1961-1980	86.69	-2.31	10.00	11.5

Table 4 : 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., July, Aug.)		AUTUMN (Sep., Oct., Nov.)	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
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

Table 5 : Correlation coefficients between summer monsoon rainfall departure of India and N.H. surface air temperature anomaly, 1881-1980. Correlations computed for overlapping two-decadal periods.

Period	Northern-Hemispheric surface air temperature anomaly				
	Annual mean	Winter mean (Dec., Jan., Feb.)	Jan.Feb. mean	Jan. mean	Feb. mean
1881-1900	-0.2349	-0.0235	-0.0260	-0.2719	+0.3267
1891-1910	-0.2106	-0.1002	+0.0015	-0.2493	+0.2942
1901-1920	-0.2124	+0.2076	+0.3120	+0.3835	+0.1662
1911-1930	-0.0523	+0.3270	+0.2331	+0.3713	+0.0494
1921-1940	-0.1705	-0.1170	-0.0883	-0.1024	-0.0424
1931-1950	-0.2238	-0.4482*	-0.2694	+0.0261	-0.4092
1941-1960	-0.0030	+0.2801	+0.2897	+0.4319	+0.0360
1951-1970	+0.3620	+0.7233***	+0.6274**	+0.6375**	+0.4983*
1961-1980	+0.5405*	+0.7064***	+0.7747***	+0.6830***	+0.7239*

* Significant At 5% level

** " 1% level

*** " 0.1% level

Table 6 : Standard Deviation of winter-time N.H. surface air temperature during stable climate period of 1921-50; and years of extreme temperature anomalies during the period independant of and after the sample-period. Temperature anomaly in °C, shown in brackets.

		January	February	Jan. & Feb.	Winter (Dec., Jan., Feb.)
Standard Deviation (°C)		0.47	0.50	0.40	0.30
EXTREME YEARS	WARM	1955 (+0.65) 1958 (+0.74)	1953(+0.54), 1963(+0.65) 1960(+0.61), 1973(+0.59)	1958(+0.54)	**1956(+0.39) 1958(+0.39) 1980(+0.37)
	COOL	*1951 (-0.79) 1954 (-0.67) *1966 (-0.72) 1967 (-0.47) *1968 (-0.89) 1969 (-0.72) *1972 (-1.16) *1974 (-0.67)	*1951 (-0.79) *1965 (-0.54) 1967 (-0.55) 1969 (-0.86) *1972 (-0.71) *1979 (-0.88)	*1951 (-0.79) *1965 (-0.43) *1966 (-0.40) 1967 (-0.51) *1968 (-0.59) 1969 (-0.79) *1972 (-0.94) *1974 (-0.57)	*1951 (-0.51) *1965 (-0.46) *1966 (-0.31) 1967 (-0.44) *1968 (-0.32) 1969 (-0.81) 1971 (-0.45) *1972 (-0.70)
Independent of and after the stable period				*1979 (-0.48)	*1974 (-0.44) *1979 (-0.39)

**Good Monsoon (Rainfall Departure > 10%); *Bad monsoon (Rainfall Departure < -10%)

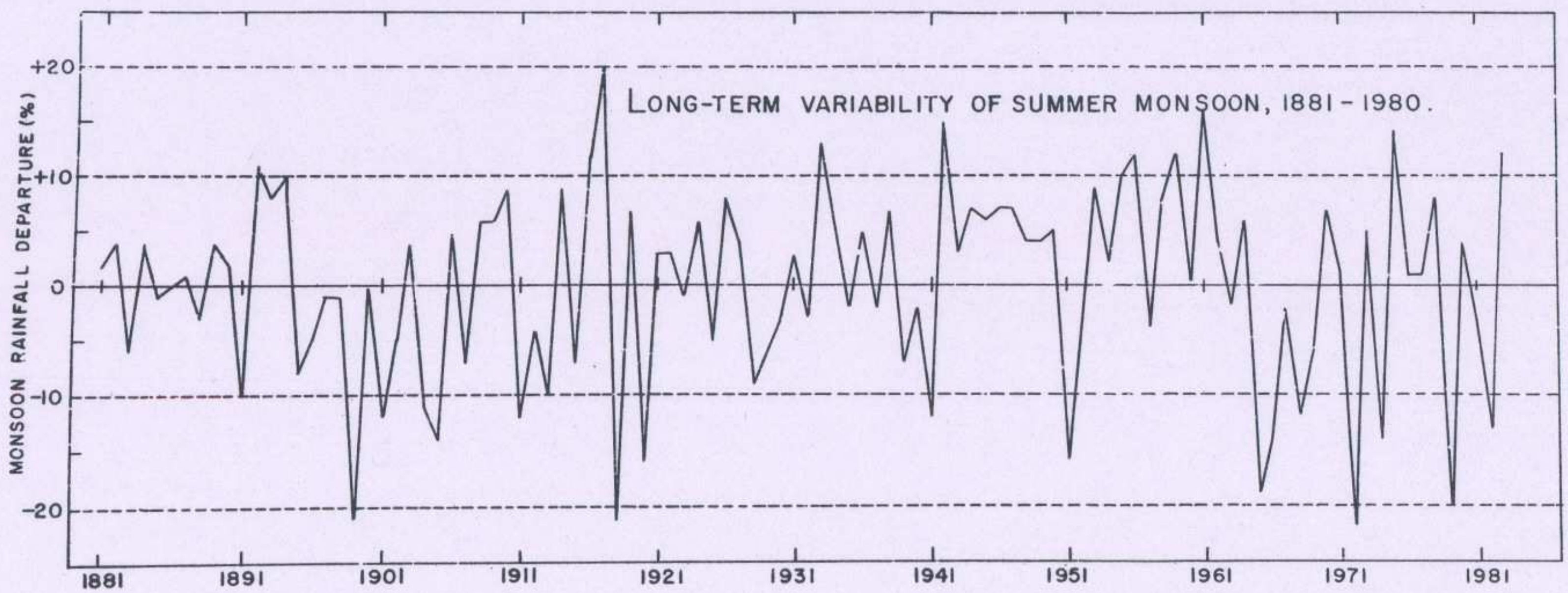


Fig.1: Summer monsoon (June-September) rainfall departure of India (%) for 100 year period of 1881-1980
Dotted lines of ± 10% and ± 20% are drawn to delineate years of extreme monsoon

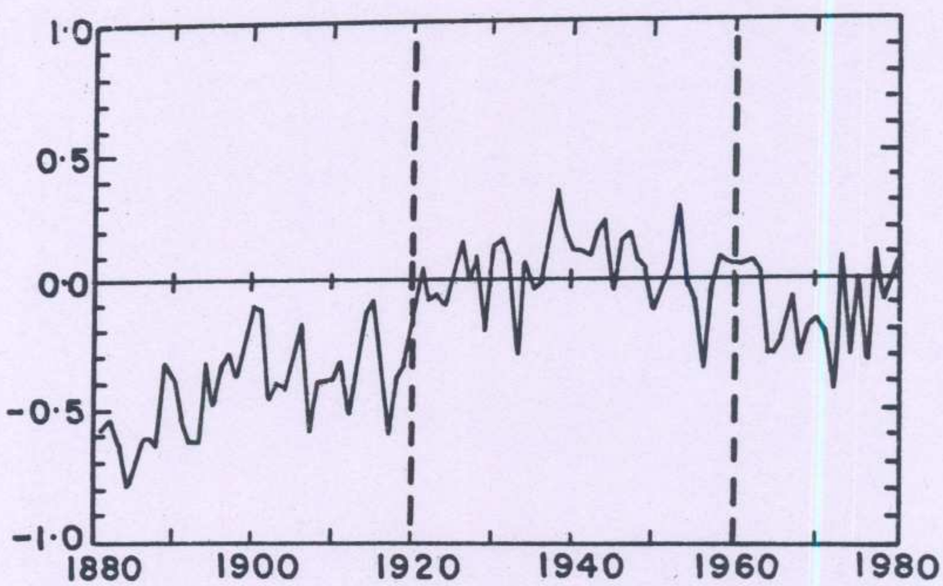
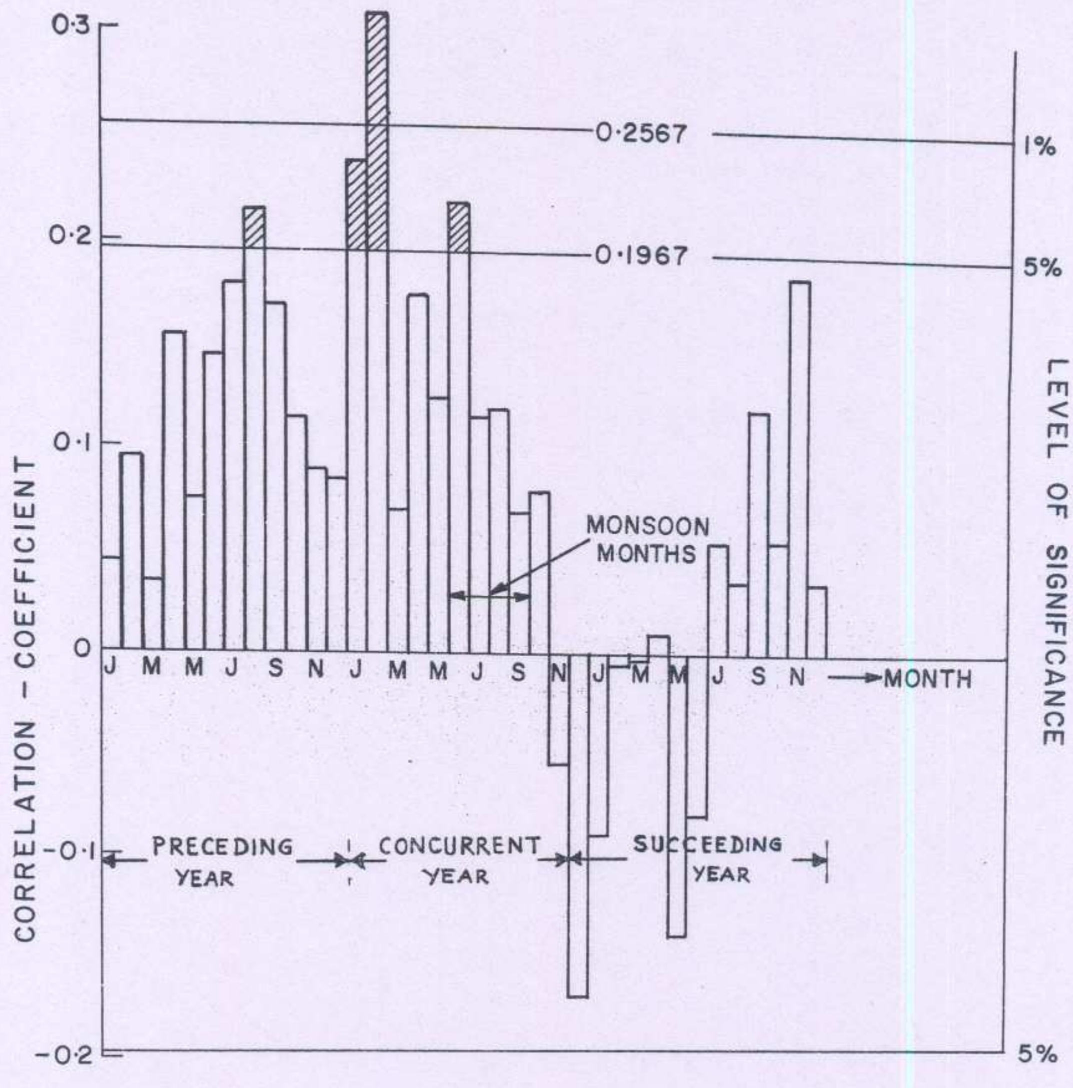


FIG. 2 Northern Hemisphere annual mean surface temperature anomalies from the 1946-60 mean (°C). (after Jones et al, 1982). Vertical dotted lines are drawn to delineate three distinct climatic epochs.



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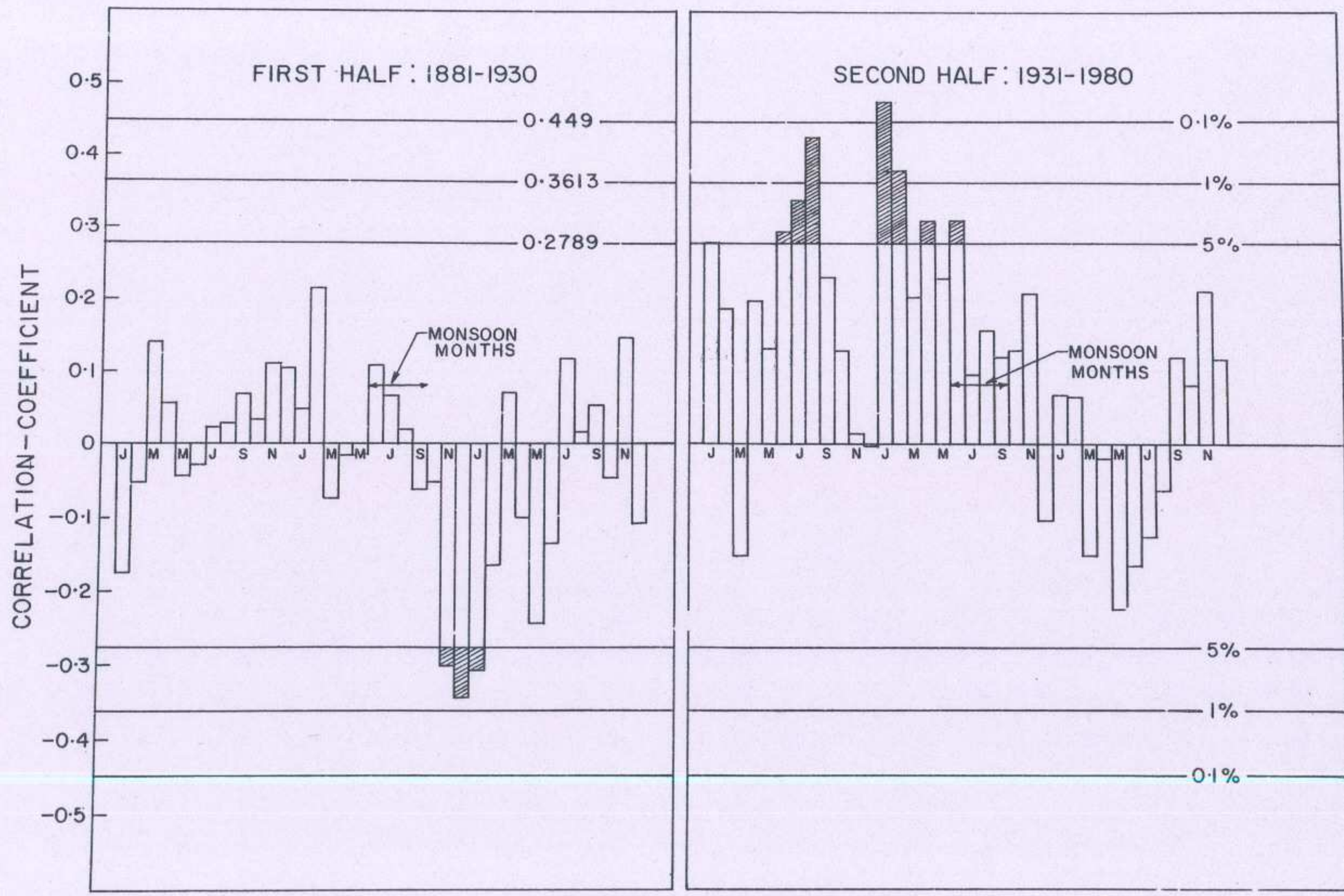

FIG. 4. As in Fig. 3, except that 100-year series is split-up into two equal series of 50-years.

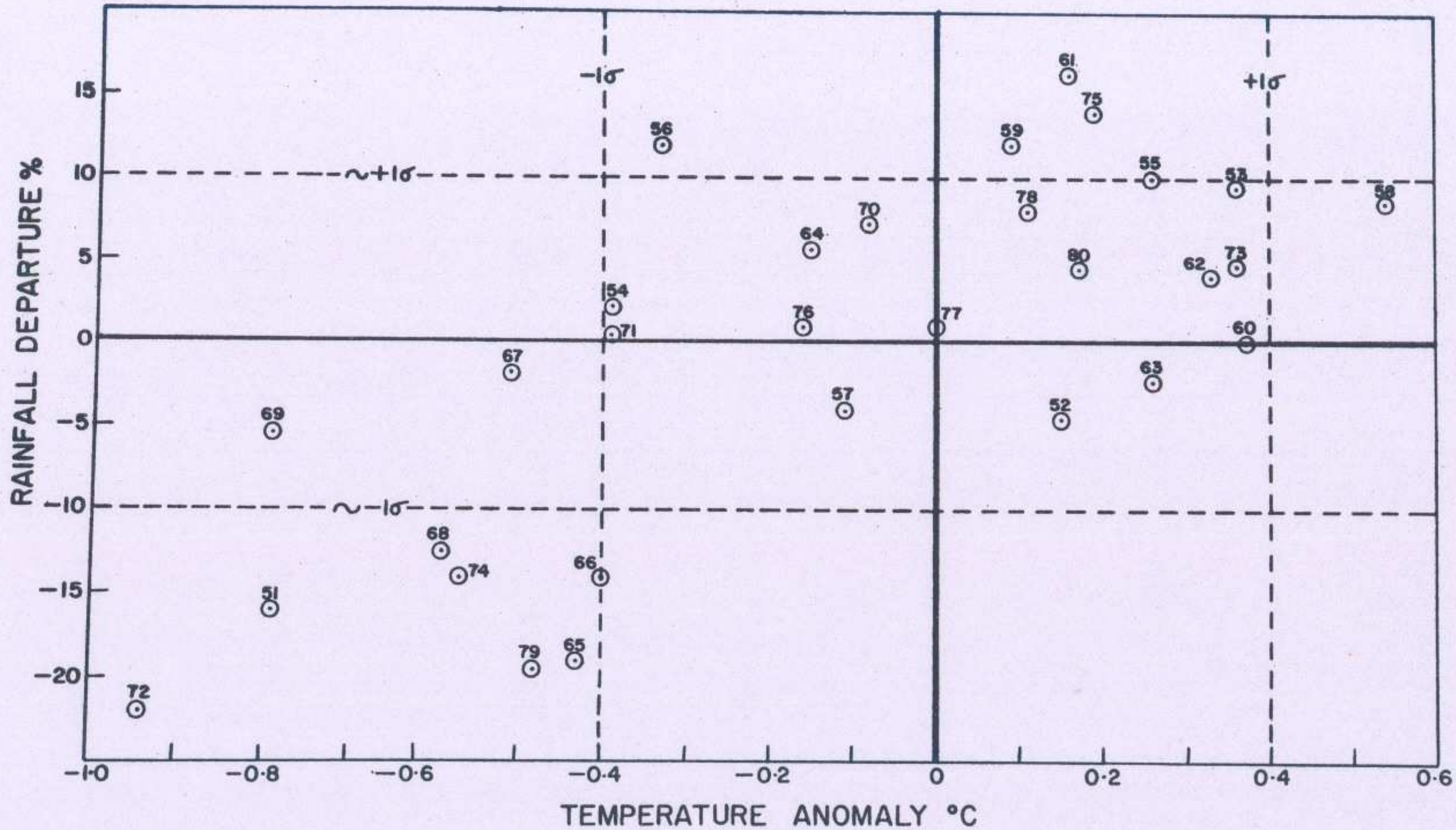

FIG.5 MONSOON RAINFALL DEPARTURE OF INDIA AND NORTHERN HEHISPHERIC JANUARY-FEBRUARY SURFACE AIR TEMPERATURE ANOMALY IN INDIVIDUAL YEARS DURING THE LAST THREE DECADES (1951-1980). YEAR IS DENOTED BY IT'S LAST TWO DIGITS NEAR THE CIRCLE. $\pm 1\sigma$ LINES (DOTTED) ARE DRAWN TO DELINEATE EXTREME YEARS IN RESPECT OF BOTH THE VARIABLES.

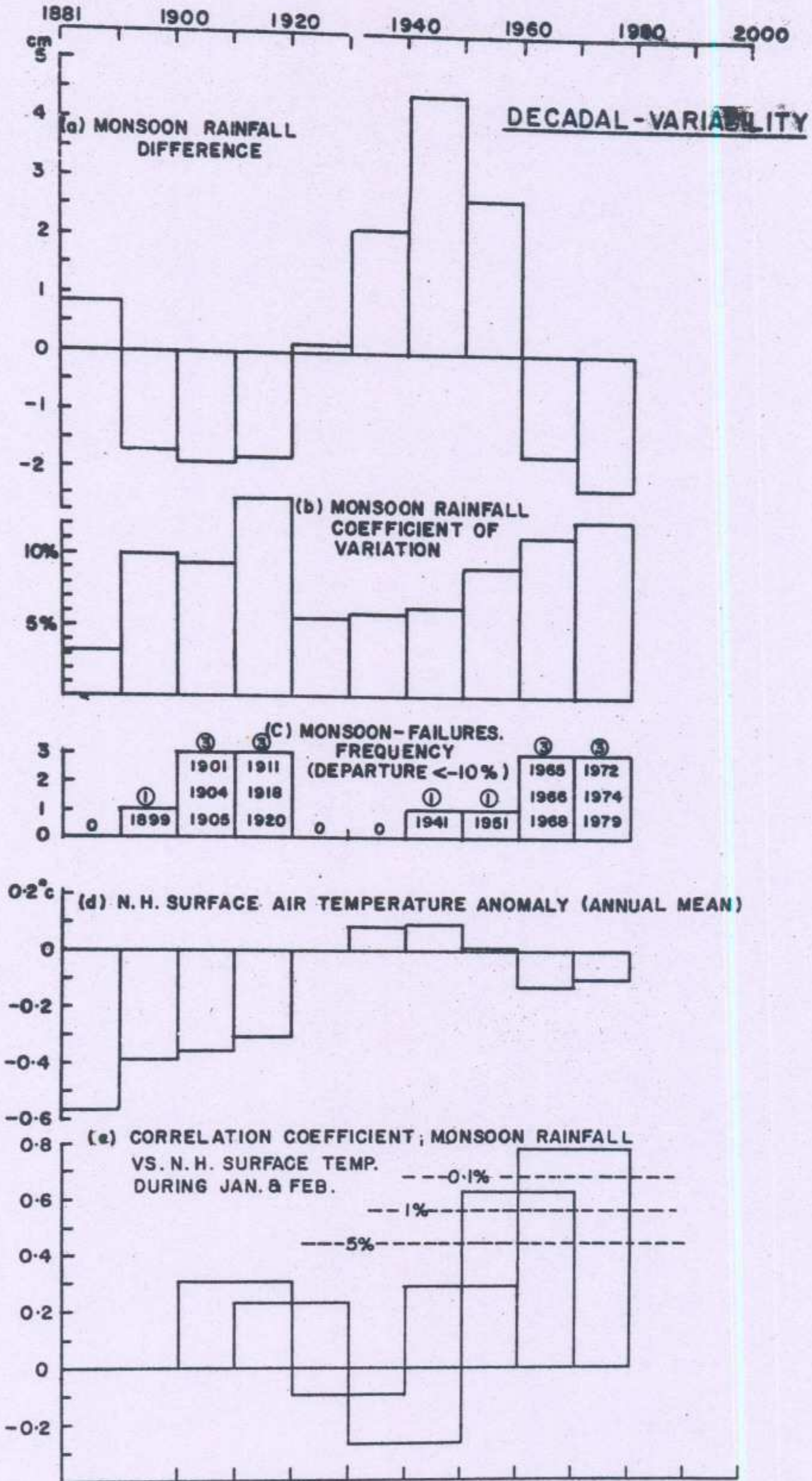

FIG.6 Decadal variability of: (a) monsoon rainfall difference, (b) Coefficient of variation of monsoon rainfall, (c) frequency of monsoon failures, (d) Northern Hemispheric surface air temperature anomaly (annual mean); and (e) correlation coefficient between monsoon rainfall and N.H. surface temperature during January-February: 1881-1981.