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EL NINO SOUTHERN OSCILLATION, EURASIAN SNOW COVER AND THE INDIAN MONSOON RAINFALL

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This study investigates the El Nino Southern Oscillation (ENSO)-Monsoon and snow-monsoon teleconnections using long data series for more than one hundred years. Analysis of short-term climate variability over India reveals distinct epochs of above and below normal summer monsoon rainfall over India. The epochs tend to last for about 3 decades. It is seen that the impact of El Nino (La Nina) is more severe during the below (above) normal epochs. Thus the impact of ENSO events on Indian monsoon rainfall (IMR) is modulated by the decadal variability of rainfall.

The snow-monsoon relationship reveals that the winter-time snow depth over western (eastern) Eurasia is negatively (positively) related with the subsequent summer monsoon rainfall over India. The dipole correlation configuration is indicative of a mid-latitude long-wave pattern with an anomalous ridge (trough) over north Asia prior to strong (weak) Indian monsoon. The decadal scale IMR variations seem to be more associated with mid-latitude snow depth variations rather than the tropical ENSO variability.

Key Words: ENSO; Eurasian Snow; Indian Monsoon; Teleconnections

1 Introduction

Seasonal variation of rainfall is the most distinguishing feature of the monsoonal regions of the world. About 80% of the annual rainfall over a large part of India occurs during the summer monsoon period (June to September). The year-to-year variability in the Indian Monsoon Rainfall (IMR) occasionally leads to extreme hydrological events (large scale droughts and floods) over different parts of the country, resulting in serious reduction in the agricultural output and affecting the national economy. Two of the external factors which cause these extreme hydrological events are the El Nino Southern Oscillation (ENSO) phenomenon and the Eurasian Snow cover. The prime objective here is to re-examine the ENSO-IMR and Snow-IMR relationships using data for more than 100 years in view of the recent changes observed in these teleconnections.

2 Data

i) The time series of IMR (June to September) has been downloaded from the website (www.tropmet.res.in) of the Indian Institute of Tropical Meteorology for the period 1871-1999.

ii) Darwin Pressure Tendency (DPT) Mean sea level pressure difference between January and April for Darwin in northern Australia repesenting the state of the Southern Oscillation[1] for the same period as IMR updated from Climate Diagnostics Bulletins (CDB) Climate Prediction Center, USA.

iii) The Historical Soviet Snow Depth data product developed at the National Snow and Ice Data Center, Boulder, Colorado, USA under the bilateral data exchange agreement with the State Hydrometeorological Service Obninsk Russia the monthly average snow depth values (cms) are for 284 stations with data period varying from 1881 to 1984. More details on this data product are available in ref. [2].

3 ENSO-Monsoon

It is now well recognized that the ENSO phenomenon is an important mode of the earth's year-to-year climate variability. The link between the Indian monsoon and the ENSO was first suggested by Sir Gilbert Walker nearly a century ago. In general studies have shown that the warm phase (i.e. El

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Nino) of the ENSO Phenomenon is associated with the weakening of the Indian monsoon with overall reduction in rainfall, while the cold phase (i. e. La Nina) is associated with strengthening of the Indian monsoon with possible enhancement of rainfall[3]. Further, studies have also shown that the IMR exhibits decadal variability with distinct epochs of above and below normal rainfall[4]. During the recent decade it has been observed that the impact of the prolonged 1991-94 EI Nino and the severe 1997 EI Nino on IMR was negligible.

Based on the above observations, we seek to investigate the following:

(i) Whether the impact of ENSO events on IMR is modulated by the decadal variability in monsoon rainfall

(ii) Why the ENSO-Monsoon relationships have weakened after 1990s?

3.1 Decadal IMR Variability and Impact of ENSO

The time series of IMR for the period 1871-1999 has been subjected to statistical tests. The mean (M) IMR is 84.3 cms with a standard deviation (SD) of 8.4 cms. The IMR is defined as excess (deficient) when its value is greater than M[1]+ISD (less than M[1]-ISD), otherwise it is normal. To illustrate the significant long-term changes, the Mann-Kendall rank test (World Meteorological Organization 1966)[5] was applied to IMR. No long-term trends were detected. The short-term climate variations were studied by applying Cramer's t-test for the 11-year (since decadal) running means (World Meteorological Organization 1966)[5]. The values of the Cramer's t-statistic for the 11-year running means are depicted in Fig. 1. The most striking features are the epochs of above and below normal rainfall. There appears to be an inherent epochal variability in the rainfall series. The periods 1880-1895 and 1930-1962 (1895-1930 and 1962-1992) are characterized by above (below) normal rainfall with very few (frequent) droughts. The turning points are noted around 1880, 1895, 1962 and 1992.

To examine the impact of ENSO events on IMR during the below and above normal epochs simple statistical procedure is applied. During the period 1871-1990 there were 27 occurrences of EI Nino events[6] (updated from CDB) and 23 occurrences of La Nina events[7] (updated from CDB).

Over the 120 year period (1871-1990) there have been 11 occurrences of very strong EI Nino episodes (1877, 1884, 1891, 1899, 1911, 1918, 1925, 1941, 1957, 1972, 1982)[8]. The worst drought situations over India were recorded during 1877, 1899, 1918 and 1972. Interestingly, all these years fall during the below normal phase of the epochal variability. However, the strong EI Ninos of 1884, 1891, 1941 and 1957 did not result in extreme drought situations over India, probably because these episodes are during the above normal phase of the epochal variability. The impact of the 1911 and 1982 EI Ninos during the below normal

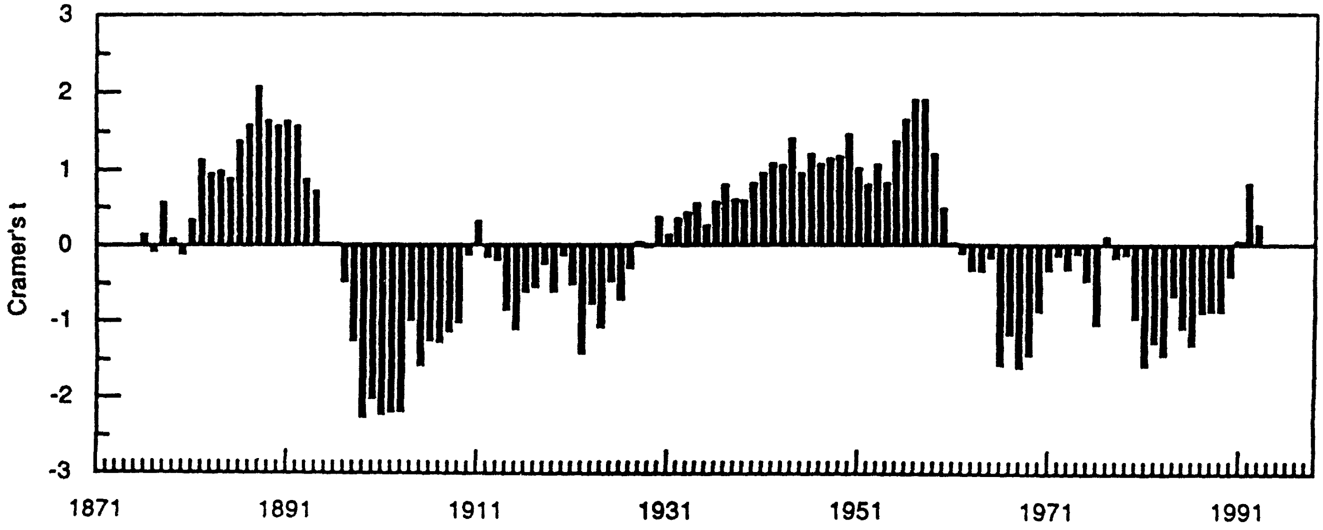


Fig. 1 Values of the Cramer's t-statistic for 11-year running means of the IMR, depicting decadal monsoon variability. The values are plotted at the centre of the 11-year period.

rainfall epochs was substantial, while that of the 1925 El Nino was not.

The analysis for the period 1871-1990 shows that the standardized IMR for the 14 El Nino cases in the below normal epochs is - 1.5 while for the 9 cases during the above normal epoch is -0.4 (cases around the turning points have been omitted). The difference between these means are significant at 1 per cent confidence level, suggesting that the impact of El Nino on IMR is much more severe during the below epochs than the above epochs. A similar analysis for the La Nina cases shows that the standardized IMR for 8 La Nina cases in the above epochs is +0.8, while for the 15 cases during the below epochs is +0.5. The differences between the means for the La Nina cases are not significant at the 1 nor 5 per cent level, however the results suggest that the impact of La Nina on IMR is more substantial during the above epochs.

Hence the major extreme events of rainfall (severe droughts/floods)in particular droughts are due to the phase locking between the internal epochal variability and the external forcing of El Nino. Thus the impact of ENSO events on Indian monsoon rainfall is modulated by the decadal behaviour of monsoon rainfall and depends on the prevailing epoch. This idea was suggested in our earlier work[9]. Such phase-locking between the ENSO events and decadal rainfall variability is also observed over the Southeast Asian monsoon domain[10].

3.2 El Ninos After 1990s

Fig. 2 shows the equatorial sea surface temperature anomalies over the Nino 3.4 region (5^0 N - 5^0S, 170^0W - 120^0W) indicating a moderate El Nino during the 1991 -94 period, and a severe El Nino during 1997 and a La Nina during 1998.

During the 1991-94 period there was a prolonged El Nino. While the Indo-Australian and the African regions experienced drought conditions, central Pacific, Ecuador and Peru experienced very heavy rainfall[11]. However, India did not experience a severe drought. Although during the monsoons of 1991 (standardized IMR = –0.8) and 1992 (–0.8) the IMR was on the negative side, the monsoon of 1993 (+0.3) and 1994 (+1.0) were on the positive side. During the 1997 El Nino (1998 La Nina) most of the Australian region was under drought (flood) conditions[11,12]. Inspite of the severe 1997 El Nino, the IMR was on the positive side (+0.2). During the 1998 La Nina also the IMR was on the positive side (+0.6)[13]. A close examination of Fig. 1 reveals that IMR has entered into an above normal epoch around 1990. As seen above the impact of El Nino on IMR is not substantial during the above normal epochs. This may be a possible reason that none of the El Ninos after 1990s have had any adverse impact on IMR.

4 Snow-Monsoon

Another important factor which has considerable impact on IMR is the Eurasian Snow cover. Snow plays an important role in the climate fluctuations. Many studies have demonstrated the relevance of snow to climate system[14]. Snow depth could be indicative of large-scale changes in temperature advection. The cold dense air generated above a snow surface may be propagated to regions far away by atmospheric teleconnections. This could

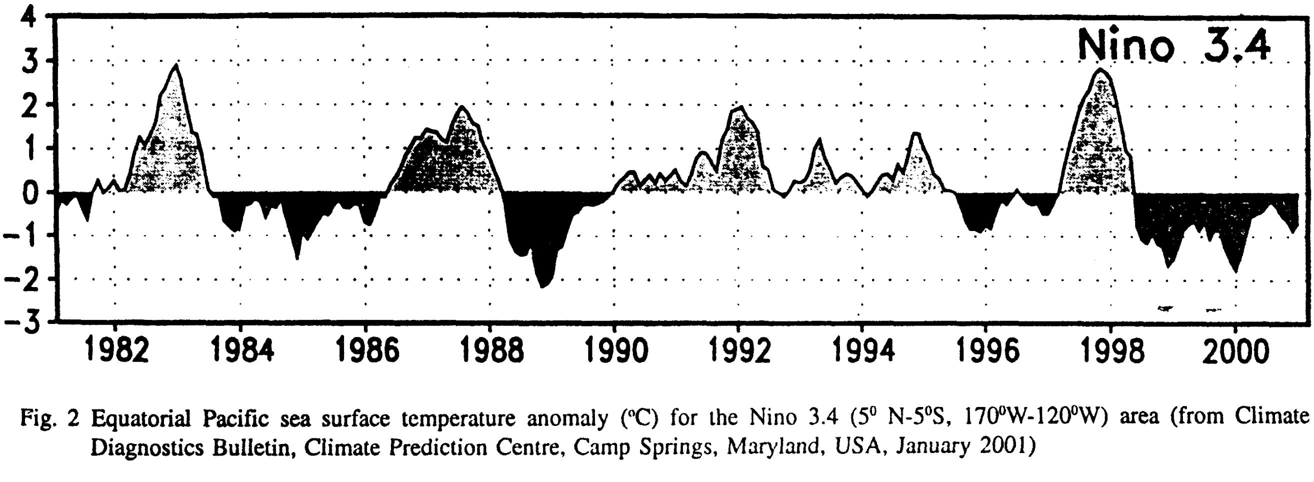


Fig. 2 Equatorial Pacific sea surface temperature anomaly (^{0}C) for the Nino 3.4 (5^0 N-5^0S, 170^0W-120^0W) area (from Climate Diagnostics Bulletin, Climate Prediction Centre, Camp Springs, Maryland, USA, January 2001)

induce delayed effects on climate system. The impact of Eurasian snow pack on the summer monsoon over India is probably the best known example of such a interaction. More than 100 years ago Blanford[15] was apparently the first to correlate some measure of snow with Indian rainfall. With the advent of satellite technology, estimates of snow cover have been available since 1966. Several studies[16-19] using satellite derived snow cover data showed that the correlation between Eurasian snow cover and IMR was negative implying that extensive (little) Eurasian snow cover in winter/spring was followed by deficient (excess) IMR, thus confirming Blanford's hypothesis. All these studies have concentrated on the areal coverage of snow field and not on depth. Recent studies have also shown that snow variations over localized regions of Eurasia, in particular Western Eurasia have substantial impact on the subsequent summer monsoon rainfall[18-20]. Some modelling studies have concluded that the albedo effect associated with the spatial distribution of snow cannot by itself have a sustained impact on the subsequent monsoon development, but the hydrological feedback mechanism associated with the Eurasian snow depth is mainly responsible for the snow-monsoon connections[21]. The lack of sufficient coverage of ground truth snow depth data has made it difficult to assess this aspect empirically. However, recently the Historical Soviet snow depth data product has been developed[2].

In the light of this discussion we try to examine the interaction of Soviet snow depth data with IMR by applying simple statistical techniques.

4.1 Soviet Snow Depth and IMR

To search objectively for the connections between the snow depth and IMR correlation coefficients (CCs) between the snow depth in each location over the Soviet region and rainfall of India have been computed for each month separately. To examine the interaction between snow-IMR-snow, spatial patterns of lag and lead relationships have been examined. Hence CCs of IMR are computed with snow depth for the months November through April preceding as well as following the Indian monsoon period. All the monthly spatial patterns reveal a dipole correlation configuration, hence Fig. 3 shows the patterns for the month of January only, which reveals maximum relationship. The correlation are based on the 1966-1984 period[2]. The value of significant correlation for a sample of this size at 5 per cent significance level is ~0.4.

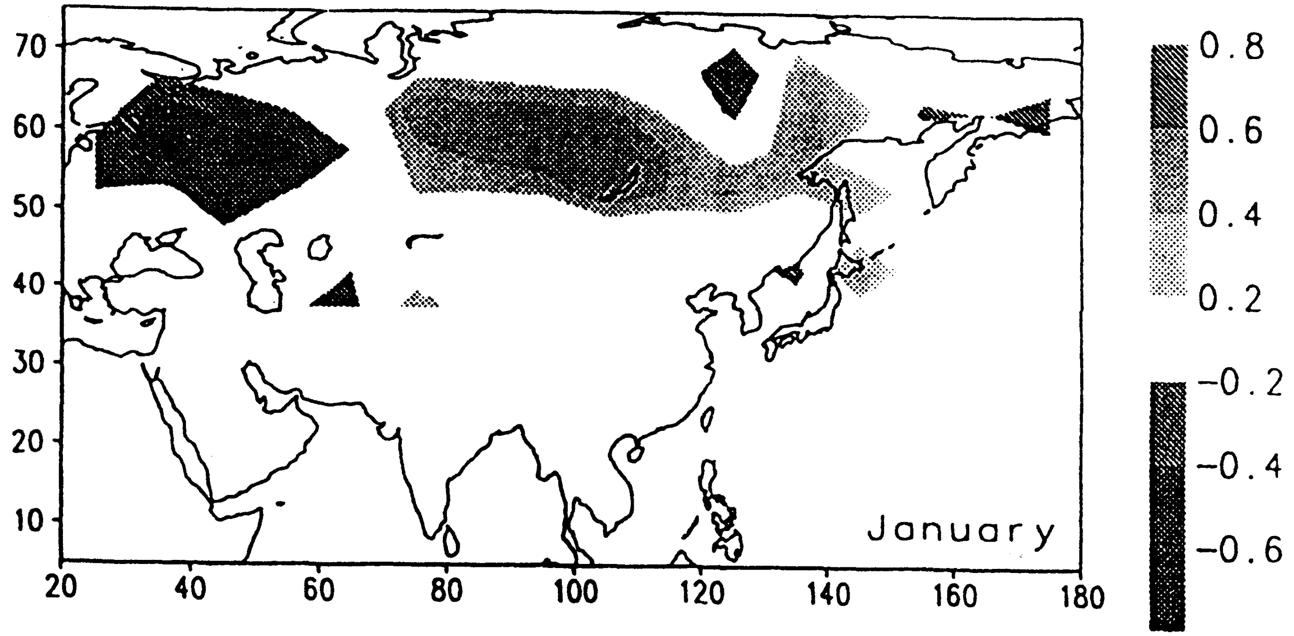
There are two coherent regions of significant relationships. Prior to monsoon significant negative relationship is observed between 20°-70°E. In contrast significant positive relationship is observed between 70°-140°E. This is the most striking feature of the analysis. Both the regions lie north of 50°N. Klassen *et al.*[22] also found IMR to be related to the temperature fields of the extratropics north of 55°N. The left region lies over western Eurasia surrounding Moscow, while the right region lies over eastern Eurasia north of Mongolia in central Siberia. After the monsoon although similar patterns are maintained, the signs reverse. This probably indicates that there is a two way interaction between the snow and monsoon, supporting the hypothesis put forth by Meehl[23] that monsoon plays an active part in the tropospheric biennial oscillation.

4.2 Physical and dynamic basis for snow-monsoon links

The land-sea temperature contrast is the basic forcing of the Indian monsoon. Excessive snowfall during the previous winter and spring seasons can delay the build up of the monsoonal temperature gradient because part of the solar energy will be reflected and part will be utilized for melting the snow or for evaporating the soil moisture. A relatively small amount of energy will be left for warming the surface and hence the atmosphere. Thus the lingering of deep snow and greater aerial extent of snow cover in winter/spring could be an important factor for the slower and smaller build-up of the summer season continental heat sources. On the other hand, light snow and a smaller aerial extent would be conducive to good monsoon activity. In view of this hypothesis and observational evidence the relation between snow and monsoon rainfall should be negative.

In our analysis, the west region surrounding Moscow shows significant negative relationship, while the east region over central Siberia shows significant positive relationship. Some studies have shown a well-organized large-scale pattern at the mid-troposhpheric level during the winter prior to

Correlations – Before Monsoon



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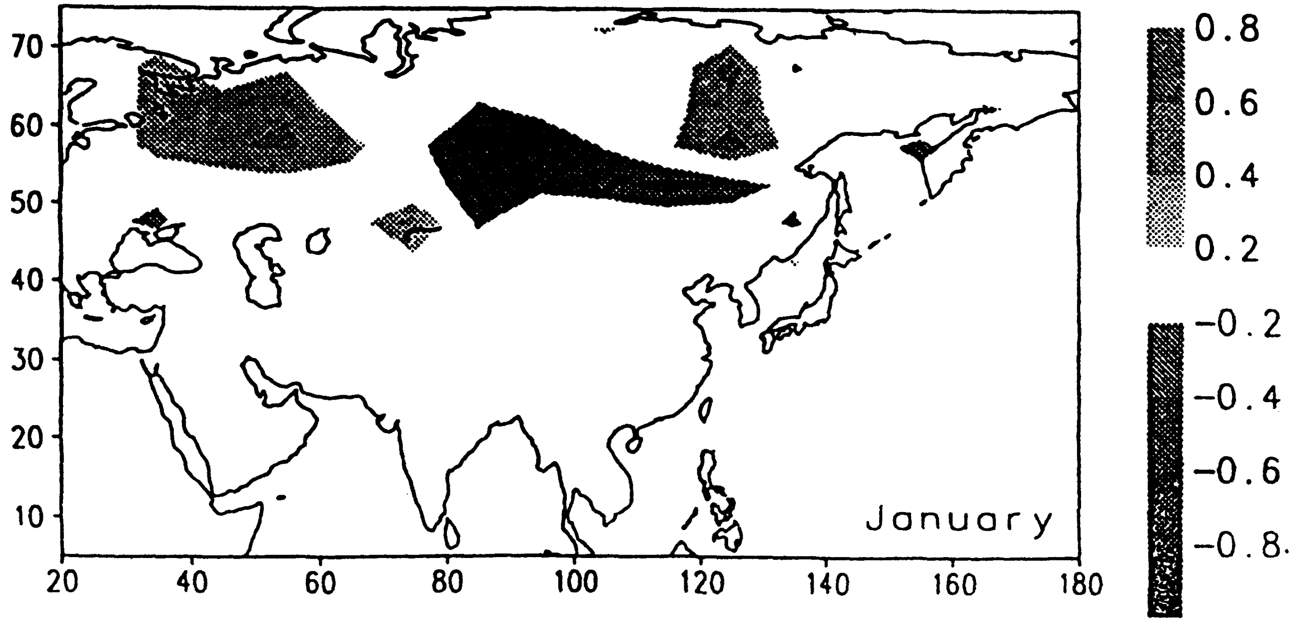

Fig. 3 The spatial distribution of the correlations of Soviet snow depth for the month of January with IMR prior and following the monsoon, showing dipole configuration.

a strong monsoon over the northern hemisphere. This mid-latitude long-wave pattern is indicative of an anomalous ridge (trough) prior to a strong (weak monsoon[23,24]. The mid-latitude patterns reverse after monsoon[23,24].

It is interesting to note that the patterns of snow depth variation during the pre-monsoon and post-monsoon imply changes in mid-latitude circulation similar to those described above. That is the negative correlations to the west and positive to the east indicate low snow depth to the west and high snow depth to the east before a strong monsoon, and *vice versa* the winter after a strong monsoon. This implies an anomalous anticyclonic circulation or a strong ridge over Asia before a strong monsoon with warm air advected from south on the west side of the high to reduce snow depth, and cold air from the north on the east side of the high to preserve deep snow and *vice versa* after a strong monsoon, with an anomalous trough over Asia and cold southward flow on the west side of the trough associated with deep snow (positive correlation), and warm southerly flow on the east side of the trough and thinner snow cover (negative correlations). A schematic representation of these processes is shown in Fig. 4. Thus the snow depth changes may be more indicative of changes in the large-scale mid-latitude circulation that affects land temperature, land-sea temperature contrast and subsequent monsoon strength.

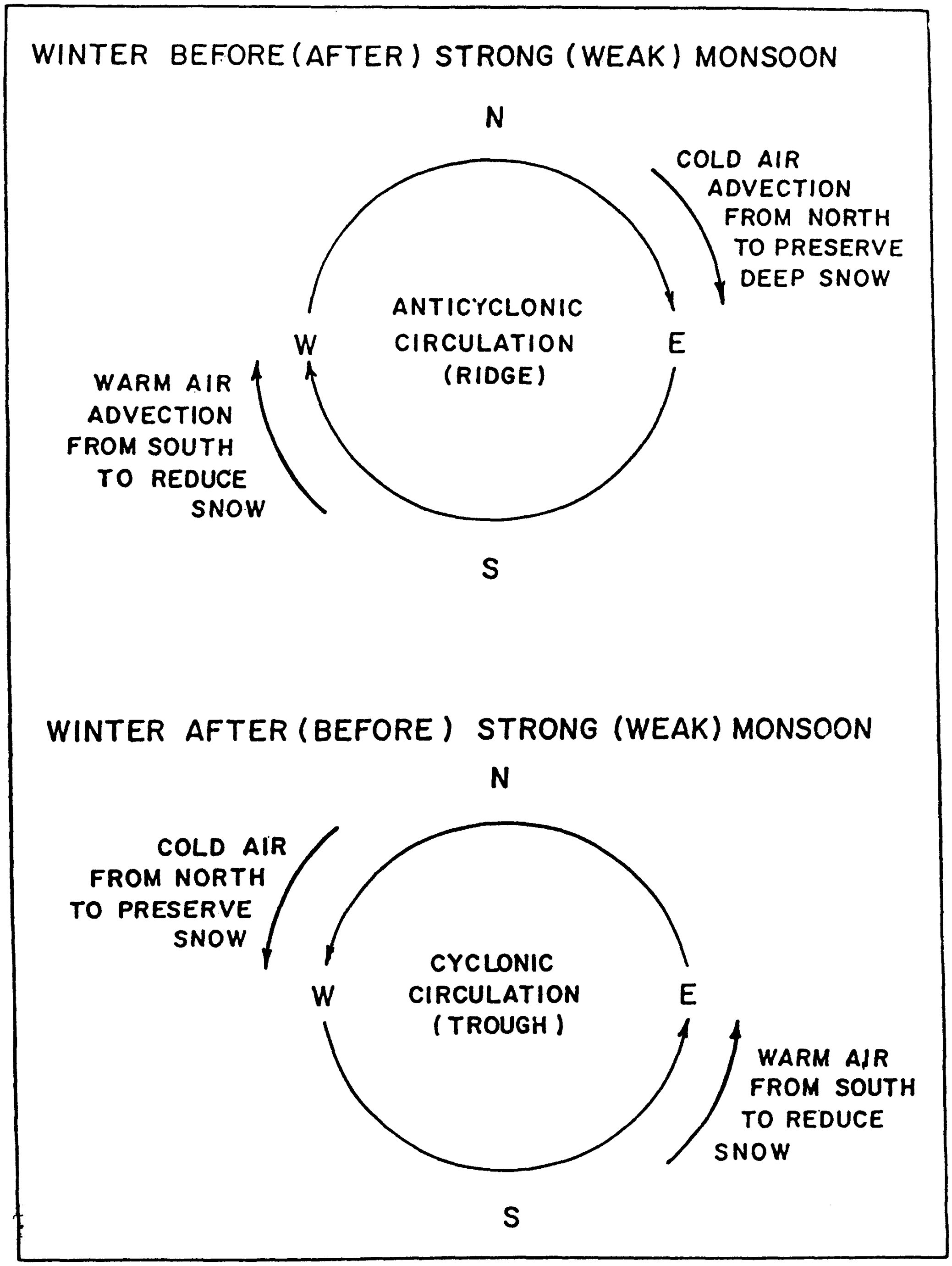

Fig. 4 Schematic representation depicting a ridge (trough) over the Russian region during winter prior to a strong (weak) monsoon and a reversal of the processes during the winter following the monsoon (N-north; S-south; W-west; E-east).

4.3 Decadal Snow-Rainfall Associations

The IMR has shown variability on the decadal scale, with distinct epochs of above and below normal rainfall. To examine the decadal variability in snow, time series of soviet snow depth (SSD) is prepared by averaging snow depth over the west region (western Eurasia - this is a region where long series of snow depth data are available). As seen above the interannual variability of IMR is related with ENSO phenomenon also-an index of this phenomenon is the Darwin Pressure Tendency (DPT; April minus January). Hence the time series of SSD, IMR and DPT for the common period 1898-1985 have been subjected to Cramer's t-test for the 21-year running means. Here the 21-year means are compared with the overall mean. Fig. 5 depicts these results. This figure clearly shows the epochal behaviour of the IMR, with the period roughly between 1930 and 1960 showing an epoch of above normal rainfall. The epochs of SSD show a remarkable out-of-phase resemblance to the epochs of IMR, with the period 1930 to 1960 depicting below normal snow depth. However, an examination of this statistic for DPT shows cyclic variations during the period 1930-1960. This suggests that the epochal behaviour of IMR is linked more with Northen Hemisphere mid-latitude snow variations rather than the tropical oceanic ENSO variability. This is consistent with our earlier results given in ref. [25].

5 Discussion and Conclusions

Through the analysis of short-term fluctuations of seasonal rainfall time series, it was found that there are epochs of above and below normal rainfall. The major extreme events of rainfall (severe floods/ droughts) are due to the phase locking between the epochal variability and the external forcing i.e. the impact of El Nino (La Nina) on the IMR is more severe during the below (above) normal epochs. Thus impact of ENSO events is modulated by the decadal variability of monsoon rainfall and depends on the prevailing epoch. Similar epochal variability is also noticed for rainfall regimes over East Asia, with epochs tending to last for about three decades over China as over India and five decades over Japan[26]. The turning points for China follow that of India about a decade later.

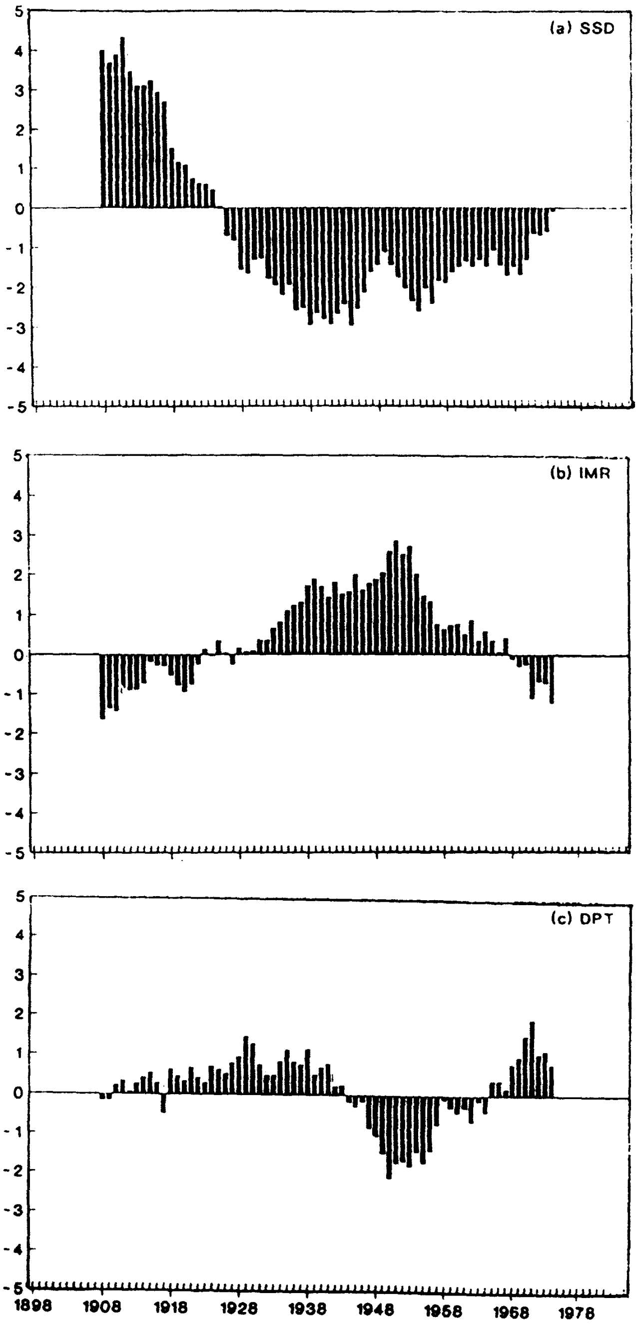

Fig. 5 Values of the Cramer's t-statistic for 21-year running means for- **a)** Soviet snow depth; **b)** IMR; **c)** DPT. The values are plotted at the centre of the 21-year period.

The lagged correlation results of snow depth with IMR show a significant negative relationship with snow depth over western Eurasia surrounding Moscow. The principal result is a strong positive correlation of IMR with snow depth over eastern Eurasia in central Siberia, which has not been reported earlier. This dipole-type correlation pattern implies an anomalous anticyclonic (cyclonic) circulation or a strong ridge (trough) over north Asia before a strong (weak) monsoon. An important result is the reversal of the correlation signs after the monsoon over both the regions suggesting the role of IMR in the tropospheric biennial oscillation.

The decadal- scale IMR variability seems to be linked with events over Northern Hemisphere mid-latitudes than over tropical oceanic regions[25]. This study has also shown that the decadal-scale variations of IMR are associated with the decadal-scale snow variations. The annual snow cover has been declining after 1980s[27] in particular below normal anomalies have been observed[28] after 1988. The reduced extent of snow during the 1980s has occurred during one of the warmest decades of the past century[27]. Thus the recent snow variations further support that the IMR is tending towards an epoch of above normal rainfall with a turning point around 1990.

Thus with the analysis of available instrumental historical data, some new scientific insight has been gained in the ENSO-Monsoon and Snow-Monsoon teleconnections.

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