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# Indian Monsoon Variability in a Global Warming Scenario

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**Abstract.** The Intergovernmental Panel on Climate Change (IPCC) constituted by the World Meteorological Organisation provides expert guidance regarding scientific and technical aspects of the climate problem. Since 1990 IPCC has, at five-yearly intervals, assessed and reported on the current state of knowledge and understanding of the climate issue. These reports have projected the behaviour of the Asian monsoon in the warming world. While the IPCC Second Assessment Report (IPCC, 1996) on climate model projections of Asian/Indian monsoon stated "Most climate models produce more rainfall over South Asia in a warmer climate with increasing $CO_2$", the recent IPCC (2001) Third Assessment Report states "It is likely that the warming associated with increasing greenhouse gas concentrations will cause an increase in Asian summer monsoon variability and changes in monsoon strength."

Climate model projections (IPCC, 2001) also suggest more El Niño – like events in the tropical Pacific, increase in surface temperatures and decrease in the northern hemisphere snow cover. The Indian Monsoon is an important component of the Asian monsoon and its links with the El Niño Southern Oscillation (ENSO) phenomenon, northern hemisphere surface temperature and Eurasian snow are well documented.

In the light of the IPCC global warming projections on the Asian monsoon, the interannual and decadal variability in summer monsoon rainfall over India and its teleconnections have been examined by using observed data for the 131-year (1871–2001) period. While the interannual variations show year-to-year random fluctuations, the decadal variations reveal distinct alternate epochs of above and below normal rainfall. The epochs tend to last for about three decades. There is no clear evidence to suggest that the strength and variability of the Indian Monsoon Rainfall (IMR) nor the epochal changes are affected by the global warming. Though the 1990s have been the warmest decade of the millennium (IPCC, 2001), the IMR variability has decreased drastically.

Connections between the ENSO phenomenon, Northern Hemisphere surface temperature and the Eurasian snow with IMR reveal that the correlations are not only weak but have changed signs in the early 1990s suggesting that the IMR has delinked not only with the Pacific but with the Northern Hemisphere/Eurasian continent also. The fact that temperature/snow relationships with IMR are weak further suggests that global warming need not be a cause for the recent ENSO-Monsoon weakening.

Observed snow depth over the Eurasian continent has been increasing, which could be a result of enhanced precipitation due to the global warming.

## 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 India occurs during the summer monsoon period June to September. The year-to-year variability in monsoon rainfall occasionally leads to extreme hydrological events (large scale droughts and floods) resulting in serious reduction in agricultural output and affecting the vast population (in excess of one billion) and the national economy. A normal monsoon with an evenly distributed rainfall throughout the country is a bonanza, while an extreme event of flood or drought over the entire country or a smaller region constitutes a natural hazard. Hence the variation in seasonal monsoon rainfall may be considered a measure to examine climate variability/change over the Indian monsoon domain in the context of global warming.

Two of the external factors which cause the extreme events are the El Niño Southern Oscillation (ENSO) phenomenon and the Himalayan/Eurasian snow. The link between the Indian monsoon rainfall (IMR) and ENSO, was first suggested by Sir Gilbert Walker nearly 100 years ago. During the last two decades several studies have shown that the warm phase (El Niño) is associated with weakening of the Indian monsoon with overall reduction in rainfall while the cold phase (La Nina) is associated with the strengthening of the Indian monsoon with enhancement of rainfall. However during recent times it has been observed that the ENSO – IMR relationship has been weakening (Kripalani and Kulkarni, 1997a; Krishna Kumar *et al.*, 1999; Ashok *et al.*, 2001). Several factors have been attributed to this weakening: modulation by the decadal variability of monsoon rainfall (Kripalani and Kulkarni, 1997a, b); chaotic nature of the monsoon (Webster and Palmer, 1997); linkages with the Indian Ocean Dipole mode (Saji *et al.*, 1999; Behera *et al.*, 1999; Webster *et al.*, 1999; Ashok *et al.*, 2001); Atlantic Oscillation (Chang *et al.*, 2001) and global warming (Krishna Kumar *et al.*, 1999; Ashrit *et al.*, 2001)

The snow-IMR connections were also suggested more than 100 years ago by Blanford (1884). With the availability of satellite snow cover estimates, the negative snow-monsoon relationships have been confirmed. Excessive (deficient) snow during the preceeding winter is unfavourable (favourable) for the subsequent summer monsoon. (e.g., Hahn and Shukla, 1976; Khandekar, 1991; Kripalani *et al.*, 1996; Bamzai and Shukla, 1999). The observed snow-monsoon connections have also been reproduced through models (e.g., Barnett *et al.*, 1989; Vernekar *et al.*, 1995; Bamzai and Marx, 2000).

The analysis of more than 150 years of observed Northern Hemisphere Surface Temperature data (Jones, 1994) have shown an increasing trend inferring the recent global warming issue (IPCC, 2001). The main future climate projections through coupled models (IPCC, 2001) relevant to the present study are

- Global averaged temperatures are projected to rise under all scenarios
- It is likely that warming associated with increasing greenhouse gas concentrations will cause an increase of the Asian summer monsoon precipitation

variability. Changes in monsoon mean duration and strength depend on the details of the emission scenario. The confidence in such projections is also limited by how well the climate models simulate the detailed seasonal evolution of the monsoon.

- Global warming is likely to lead to greater extremes of drying and heavy rainfall and increase the risk of droughts and floods that occur with El Niño events in many regions.
- In contrast with the simulations of extreme temperature by climate models, extreme precipitation is difficult to reproduce
- Recent trends for surface temperature to become more El Niño-like in the tropical Pacific, with the eastern tropical Pacific warming more than the western tropical Pacific, with a corresponding eastward shift of precipitation are projected to continue in many models
- Northern hemisphere snow cover is projected to decrease further.

The monsoon precipitation simulated by atmospheric General Circulation Models has been evaluated in the AMIP (Atmospheric Model Intercomparison Project) runs (e.g., Gadgil and Sajani, 1998). The precipitation variation is less well simulated. However the models show better skill in reproducing the interannual variability of circulation indices over the Indian Summer Monsoon region, indicating that the models exhibit greater fidelity in capturing the large-scale dynamic fluctuations than the regional scale rainfall variations. Thus climate model projections of "increased variability and strength of the Asian monsoon" requires a detailed analysis, since monsoon rainfall is an important socio-economic feature of India.

Given the importance of the IPCC reports as a global consensus on our understanding of the climate issue, the purpose of this study is to examine

(i) The interannual and decadal scale IMR variability in the present global warming scenario
(ii) Whether the recent ENSO- Monsoon weakening is related with the global warming
(iii) The impact of global warming on snow-monsoon links and make an assessment of the above projections related with ENSO-Snow-Monsoon interactions. Simple statistical tools and long historical data sets are used.

## 2. Data

(i) The time series of IMR (June through September) has been downloaded from the website (www.tropmet.res.in) of the Indian Institute of Tropical Meteorology for the period 1871–2001. This time series has been generated by area-weighting the rainfall at 306 stations well distributed raingauges across the country. The station rainfall data were obtained from the Indian Meteorological Department. The quality of this data set is very good and it is one of the most reliable long series of data going back to 1871. The mean IMR is

851.4 mm with a standard deviation of 82.4 mm. The variation of this series has been widely studied and can be considered as a measure of the intensity of monsoon over the Indian region.

(ii) The Darwin Pressure Tendency (DPT) – the mean sea level pressure (MSL) difference (April minus January) for Darwin in Northern Australia representing the state of the Southern Oscillation (Shukla and Mooley, 1987). The data period (1871–2001) is updated from the Climate Diagnostic Bulletins, NOAA, USA. This parameter is the most effective in explaining IMR variability compared to other indices of the ENSO phenomenon. The relationship between IMR and DPT is negative. Less DPT value signifies strengthening of the zonal Walker circulation over the Pacific, inducing good monsoon activity over India.

(iii) Northern Hemisphere Surface Temperature (NHST) anomalies – average for January and February (Jones, 1994). The data series (1871–2001) is also updated from Climate Diagnostic Bulletins, NOAA, USA. This data set is the best as an indicator of global warming. The relationship between IMR and NHST is positive. Increase in temperature may intensify the land-ocean temperature contrast and the meridional Hadley circulation and favour monsoon activity over India.

(iv) Observed historical Soviet snow depth data for the 1881–1995 period. This data product has been developed at the National Snow and Ice Data Center (NSIDC), Boulder, Colorado, USA under the bilateral data exchange agreement with the former USSR (details in Kripalani and Kulkarni, 1999). This data set has undergone through quality control checks at NSIDC.

The above data sets are highly reliable.

## 3. Interannual and Decadal Variability

The IMR series has been subjected to simple statistical techniques to investigate the variations and teleconnections on interannual and decadal time scales. The lag-1 autocorrelation is not significant suggesting that the rainfall series is free from Markovian type of persistence. Also Mann-Kendall test (WMO, 1966) for trend depicts no significant trend.

Figure 1(a) shows the standardized rainfall time series depicting interannual variability. While there appear to be year-to-year random fluctuations, on the seasonal to century scale, the most prominent variations on the interannual scale are between the so-called good monsoon seasons with above average rainfall and the poor monsoon seasons with deficient rainfall. These can be inferred from the figure. A careful examination of these extreme events (floods and droughts) provides useful information. Here we define a flood (drought) when the standardized IMR is greater (less) than or equal to $+1.0$ ($-1.0$). These years along with the standardized IMR are tabulated in Table 1.

To examine whether global warming has had any impact on the frequency of these events, we divide the entire data period (1871–2001) into two equal halves

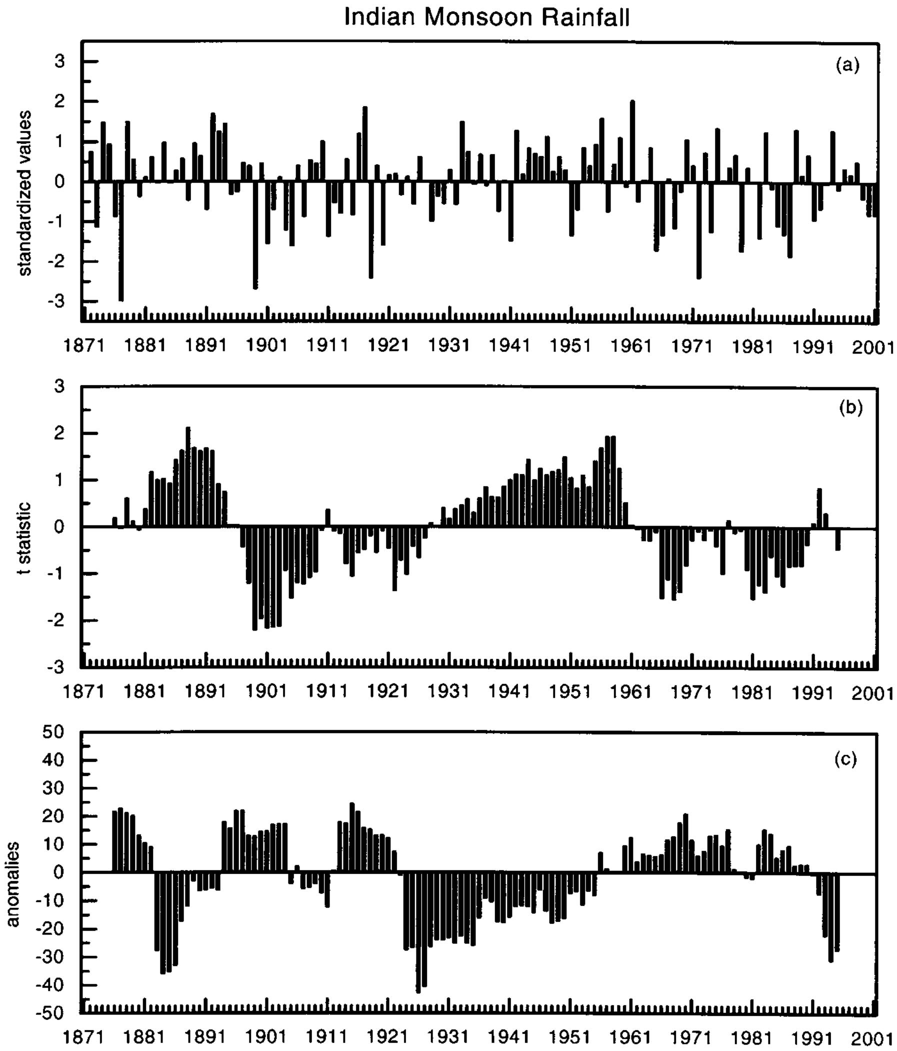


*Figure 1.* Variability of the Indian summer monsoon rainfall (a) Year-to-year standardized IMR depicting interannual variability; (b) Values of Cramer's $t$-statistic for the 11-year running means depicting decadal variability and the epochs of above and below normal rainfall. Values are plotted at the center of the 11-year period (c) Anomalies in mms of the standard deviations for the running 11-year period (i.e., standard deviation for the 11-year period minus the standard deviation of the entire period) depicting how the variability has changed with time. Values are plotted at the center of the 11-year period.

*Table I.* Extreme events of floods (IMR >= +1.0) and Droughts (IMR < = −1.0) over India Figures in brackets indicate the standardized rainfall values.

| Sr. No. | Years IMR > = +1.0 | Years IMR < = −1.0 |
|---|---|---|
| 1 | 1874 (1.5) | 1873 (−1.2) |
| 2 | 1878 (1.5) | 1877 (−3.0) |
| 3 | 1884 (1.0) | 1899 (−2.7) |
| 4 | 1889 (1.0) | 1901 (−1.6) |
| 5 | 1892 (1.7) | 1904 (−1.2) |
| 6 | 1893 (1.3) | 1905 (−1.6) |
| 7 | 1894 (1.5) | 1911 (−1.4) |
| 8 | 1910 (1.0) | 1918 (−2.4) |
| 9 | 1916 (1.2) | 1920 (−1.6) |
| 10 | 1917 (1.9) | 1928 (−1.0) |
| 11 | 1933 (1.5) | 1941 (−1.5) |
| 12 | 1942 (1.3) | 1951 (−1.4) |
| 13 | 1947 (1.2) | 1965 (−1.7) |
| 14 | 1956 (1.6) | 1966 (−1.4) |
| 15 | 1959 (1.1) | 1968 (−1.2) |
| 16 | 1961 (2.1) | 1972 (−2.4) |
| 17 | 1970 (1.1) | 1974 (−1.3) |
| 18 | 1975 (1.4) | 1979 (−1.7) |
| 19 | 1983 (1.3) | 1982 (−1.4) |
| 20 | 1988 (1.3) | 1985 (−1.1) |
| 21 | 1994 (1.1) | 1986 (−1.3) |
| 22 | – | 1987 (−1.9) |

1871- 1935 (65 years) and 1936–2001 (66 years). During the first (second) half of the period there are 11 (10) events of floods and 10 (12) events of droughts, suggesting that the frequency of these events is practically same during the two periods.

The mean standardized IMR for floods during the first (second) half is 1.37 (1.35). The difference between the means has been tested by the Student's t-test (WMO, 1966) and found to be insignificant ($t = 0.17$, $t$-value at 5 per cent significance level is ~2.0). Similarly the mean standardized IMR for droughts during the first (second) period is −1.77 (−1.52) ($t = 1.08$, insignificant). The mean IMR for the first (second) 65 (66) years is 849.4 (853.3) mms ($t = 0.18$, insignificant)

As per IPCC (2001) report most of the global surface temperatures increase has occurred in two periods viz. 1910–1945 and since 1976. Hence we now divide the entire data period again is two parts, first the global warming period (1910–1945, 1976–2001: 62 years) and the non-global warming period (1871–1909, 1946–1975: 69 years)

A similar analysis as above shows that the mean standardized IMR for floods during the global warming (non-global warming) period is 1.32 (1.38) ($t$ = 0.44, insignificant). The mean standardized IMR for droughts is −1.52 and −1.72 respectively ($t$ = 0.85; insignificant). Finally the mean IMR for the global warming period (62 years) is 845.6 mms, while for the non-global warming period (69 years) is 856.5 ($t$ = 0.75, insignificant). Thus the frequency and intensity of extreme events has not changed nor the mean IMR has changed due to the global warming.

The short-term decadal climate fluctuations have been studied by applying Cramer's test for 11-year running means (WMO, 1966). The computational procedure is explained in the Appendix. This statistic, which compares the 11-year means with the overall mean, has been used to isolate periods (if any) of above and below average rainfall and not to test their significance. The 11-year Cramer's t statistic are presented in Figure 1(b). The most striking feature are the epochs of above and below normal rainfall. The IMR shows major turning points around 1895, 1930, 1962 and 1992. These results are consistent with the earlier results (Joseph 1976; Pant *et al.*, 1988; Kripalani and Kulkarni, 1997a). From the data analysis it appears that the IMR has probably entered into an above normal epoch in the 1990s, the warmest decade in the last century (IPCC, 2001). Such entry into an above normal epoch have also been noted earlier (mid 1870s and around 1930). Though the entry into an above normal epoch around 1930 falls in the first warming period (1910–1945), it is unlikely that the decadal variability is due to global warming. An interesting point is that at the start of both the warming periods (1910 and 1976) the IMR shows an impression of entering into an above normal epoch (Figure 1(b)). But it actually enters the above normal epoch about two decades later. More data is needed to re-examine this issue.

Though the reasons for this epochal behaviour have not been examined here, Webster *et al.* (1998) attribute the inter decadal variability of the Pacific Ocean to be the primary factor for decadal scale variation of monsoon activity. However Kripalani *et al.* (1997) and Kripalani and Kulkarni (1999) attribute this variability with events in the Northern Hemisphere mid-latitudes. A recent study by Kulkarni *et al.* (2001) suggests changes in solar irradiance as one of the probable sources of this variability.

Finally to examine how the variations of IMR have varied with time, anomalies for the running 11-year standard deviations (11-year standard deviation minus the standard deviation for the entire period) are shown in Figure 1(c). In general the variability is below (above) the normal during the epochs of above (below) normal rainfall, suggesting that the variability may be more associated with the epochal changes than global warming. Since the 1990s have been the warmest decade of the millennium, as per the climate model projections the variability should increase. However the variability has reduced during the past recent decade (Figure 1c). Using a dynamic wind index over the Indian region Wang *et al.* (2001) have also noted the suppressed variability in recent times.

In summary there is no clear evidence to suggest that the mean monsoon rainfall, frequency and intensity of extreme events, decadal variability are affected by the global warming. Thus the global warming like forcing appears to be very small and does not produce any significant impact which can be identified outside the natural climate variability.

## 4. Global Warming and ENSO – Monsoon Association

The Indian monsoon is primarily driven by the land-sea temperature contrast and large scale global features like ENSO, Eurasian snow, stratospheric Quasi-Biennial Oscillation and some other regional features such as the mid-tropospheric ridge location (details available in Krishna Kumar *et al.*, 1995; Khandekar, 1996; Thapliyal and Kulshrestha, 1992; Thapliyal, 2001). Most of these features are directly or indirectly related to ENSO, NHST/Eurasian snow. Hence we focus our attention on these issues only.

To examine the relationship of IMR on decadal basis with DPT (an index of ENSO phenomenon) and NHST (index of global warming), 11-year sliding correlation coefficients (CCs) are computed.

Figure 2(a) depicts the 11-year sliding correlation coefficients of DPT with IMR. The relationship appears to be weak up to 1930, however during 1930–1970 the relationship amplifies in magnitude and thereafter starts weakening with CCs nearly zero in 1990s, even changing sign after 1995. This clearly depicts the recent ENSO – IMR weakening. Such weak relationships have been observed earlier in the late 1890s and mid 1920s. However the relationship appears to be weakest (CC = +0.6) during the current decade. Whether the cause for this weakening is global warming can be answered by the decadal scale relationship of IMR with NHST.

Figure 2(b) shows 11-year sliding CCs of IMR with NHST. During the period 1960–1980 the relationship of IMR with NHST was strong, after 1980 it is weakening, around 1990 it becomes zero and changing sign after that. If global warming is really the cause of the recent ENSO-monsoon weakening then the relationship between NHST and IMR should strengthen in recent times. However the drastic fall in CCs between IMR and NHST do not support global warming as a cause of the ENSO-monsoon weakening. Khandekar (2000) also suggested that the IMR variability does not appear to be influenced by global warming.

Such secular variations between IMR and several of its predictors have been noted earlier (e.g., Pant *et al.*, 1988; Parthasarathy *et al.*, 1991; Rajeevan 2001). However the interesting point is that the IMR not only shows weak relationship with DPT after 1990s but also with NHST around the same time. Hence the IMR variability appears to have delinked not only with the Pacific but also with the

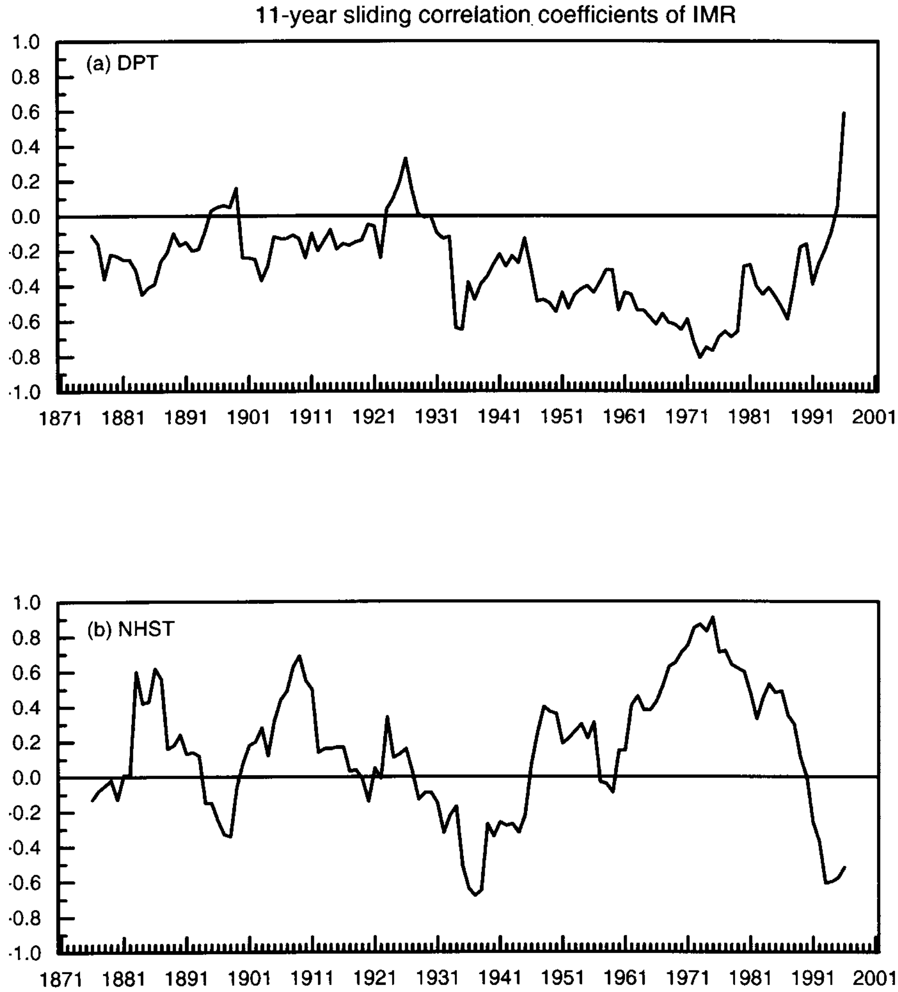


*Figure 2.* 11-year sliding correlation coefficients of IMR with DPT (index of ENSO : top panel) and NHST (index of global warming : bottom panel) showing how the relationships have varied with time. Values are plotted at the center of the 11-year period.

Northern hemisphere. In a recent study Kripalani and Kulkarni (2001) have shown that monsoon related events (rainfall over South Asia, rainfall over East Asia, Pacific circulation, Northern Hemisphere circulation) over geographically separated regions seem to get linked or delinked around the same time.

Kripalani and Kulkarni (1997a) were probably the first to point out the recent ENSO-IMR weakening. Their results showed that that impact of El Niño (La Nina) is more severe during the below (above) normal epochs. Thus the impact of ENSO events on IMR is modulated by the decadal variability in monsoon rainfall and depends on the prevailing epoch. This may be a possible reason that none of the El Niños after 1990 (prolonged 1991–1994 and severe 1997) have had any adverse impact on IMR since IMR appears to have entered into an above normal epoch (Figure 1(b)). More details can be found in Kripalani *et al.* (2001).

## 5. Observed Snow Variability

Satellite-derived snow estimates are available since mid 1960s only – a period too short to examine snow variations on decadal basis and draw inferences on the climate change issues. Modelling studies (e.g., Barnett *et al.*, 1989) and observational studies (e.g., Kripalani *et al.*, 1996) have shown the snow mass is better related with IMR than snow cover extent. Further studies have also shown that there are localized regions over Eurasia is particular Western Eurasia where snow variations are better related with IMR (Kripalani *et al.*, 1995; Kripalani and Kulkarni, 1999; Bamzai and Shukla, 1999). Recently the observed Soviet snow depth data product has been developed for the 1881–1995 period (details in Kripalani and Kulkarni, 1999; Kripalani *et al.*, 2002a). Using this observed snow depth data Kripalani and Kulkarni (1999) identified two coherent regions – one over Western Eurasia (WE) where IMR depicts negative relationship and the other over Eastern Eurasia (EE) where the relationship is positive. This dipole correlation configuration is strongest during the month of January. The physical significance of this dipole structure in relation to monsoon variability over India can be found in Kripalani and Kulkarni (1999).

To examine the interannual and decadal variability in snow, time series of Soviet snow depth is prepared by averaging snow depth over WE region (55°–65° N; 30°–60° E) and EE region (55°–65° N; 80°–110° E). For the west region a long time series is available for the period 1891–1995 while for the east region the data period is 1930–1995. Since January snow depth shows maximum relationship with IMR (Kripalani and Kulkarni, 1999), the series are constructed for the month of January only. Figure 3 shows standardized series (top panel) and the values of Cramer's t for 11-year period (bottom panel) for the snow depth over WE. The values for the Cramer's $t$-statistic are computed in a similar way as done for IMR (Section 3) and explained in the Appendix. As noted in Figure 1(b) epochal variability of IMR shows below normal rainfall in the period 1895–1930 and above normal rainfall in 1930–1962 period. Interestingly the epochs of Soviet snow depth over WE show a remarkable out-of-phase resemblance to the epochal variability of IMR, with 1896–1925 showing above normal and 1925-1975 below normal snow depth. A careful comparison of Figure 1(b) and Figure 3(b) shows that the turning points for snow precede those of IMR. Thus the epochal variability of IMR may have some links with the Eurasian continent. After 1980, snow depth over western Eurasia has entered into an above normal epoch.

Figure 4 shows similar statistic for the snow depth over EE. Though the data length is not very large, the decadal variability (bottom panel) gives interesting results. Over the eastern region also, snow depth shows an above normal trend after 1970s. Thus both the regions show increase in snow depth in recent times. This is

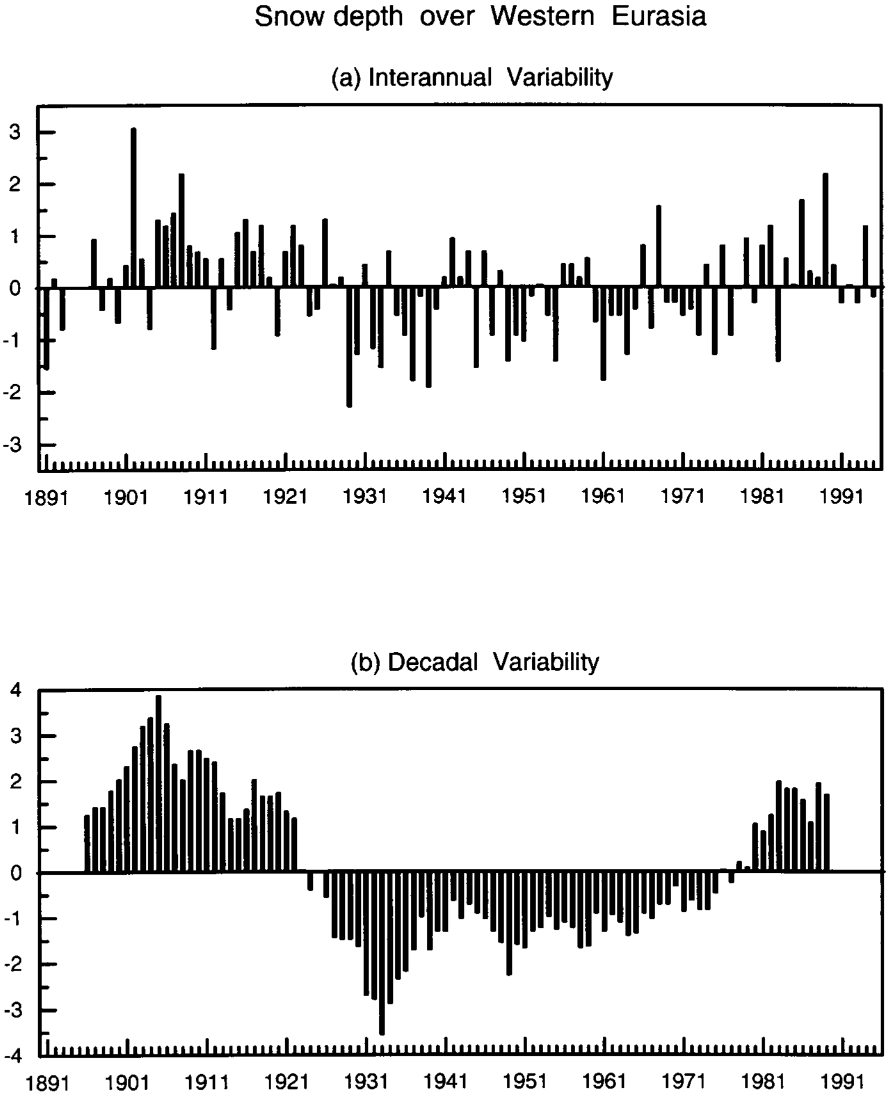


*Figure 3.* Variability of snow depth over Western Eurasia (a) Year-to-year standardized values of snow depth depicting interannual variability. (b) Values of Cramer's $t$-statistic for the 11-year running means of snow depth showing the decadal variability and the epochs of above and below normal snow depth over Western Eurasia. Values are plotted at the center of the 11-year period.

supported by the fact that the most dominant empirical orthogonal function of the Soviet snow depth shows significant increasing trend (Ye, 2000). The increase in snow depth is likely to be associated with increasing precipitation related to the warming in surface air temperature (IPCC, 1996, 2001; Ye and Mather, 1997). This increasing trend is attributed to sea surface temperature trends over north and

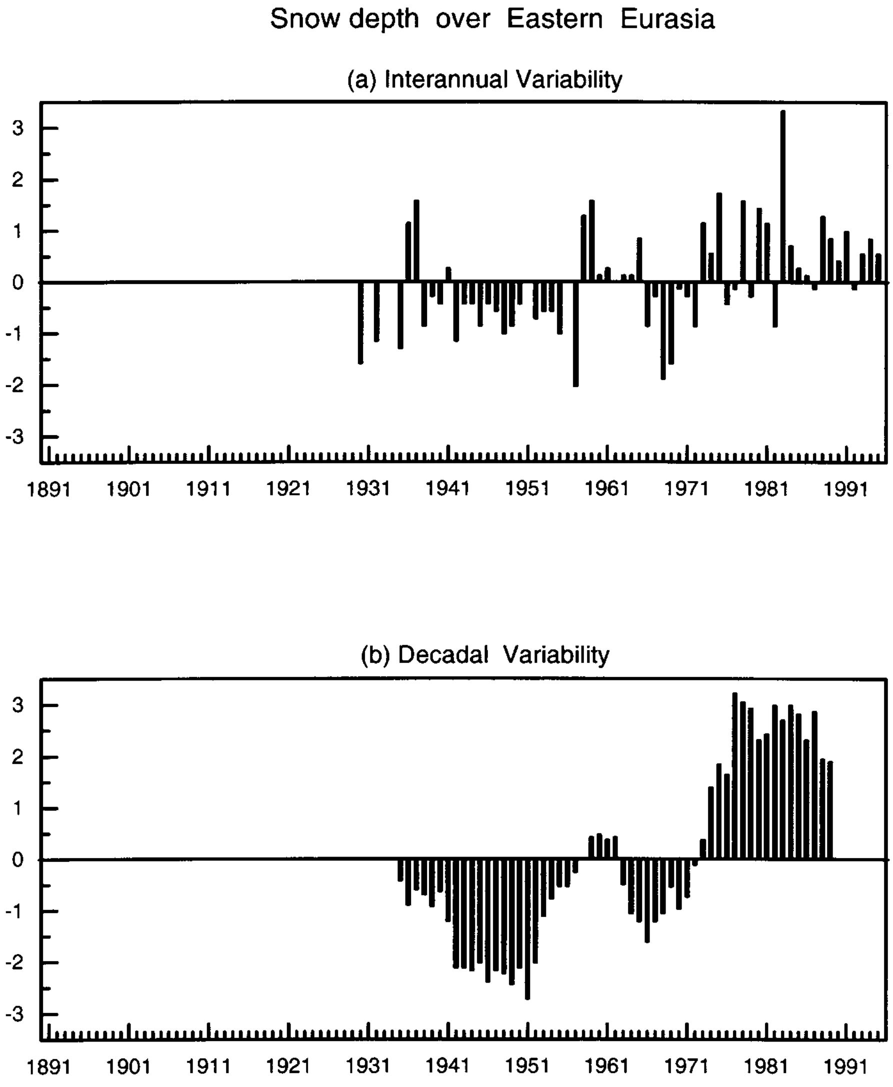


*Figure 4.* Same as Figure 3 but for snow depth over Eastern Eurasia.

tropical south Atlantic (Ye, 2000). These may be the possible reasons that in spite of the increase in surface air temperature, snow depth over Eurasia is increasing.

### 5.1. DECADAL SNOW – MONSOON ASSOCIATIONS

To examine the variations of snow-monsoon links, 11-year sliding CCs are computed. Figure 5 depicts 11-year sliding CCs of WE snow depth (top panel), and EE snow depth (bottom panel) with IMR. The relationship of WE snow with IMR, strengthens during the period 1950–1980, it weakens thereafter. Thus the weaken-

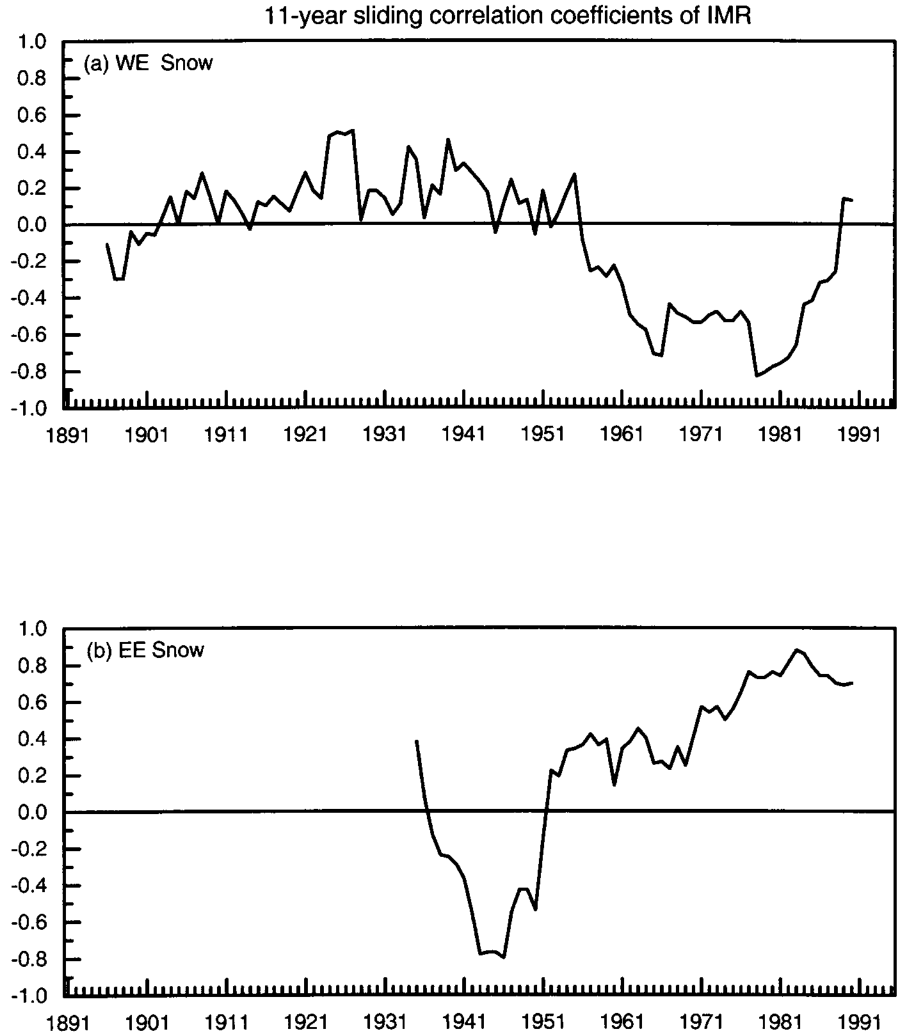


*Figure 5.* 11-year sliding correlation coefficients of IMR with snow depth over Western Eurasia (top panel) and Eastern Eurasia (bottom panel) showing how the relationships have varied with time. Values are plotted at the center of the 11-year period.

ing relationship of IMR with NHST, DPT and snow appears to have commenced around the same time i.e., 1970, with CCs near zero and changing signs around 1990s. Whether these are related with the changed properties of El Niño after 1970s (Wang and An, 2001) needs a separate investigation. The relationship of EE snow (Figure 5(b)) with IMR amplifies after 1950s and it shows continuous increasing relationship.

The above analysis suggests that the IMR variability has de-linked not only with the Pacific but also with the Northern Hemisphere/Eurasian continent. This could be a part of natural climate variability.

## 6. Discussion and Conclusions

A study of the Indian monsoon rainfall variability and its teleconnections on interannual and decadal time scales has been carried out by using data for 130 years. This study has shown that with the analysis of historical data sets, some valuable scientific insight can be gained. The interannual variability shows random year-to-year fluctuations, while the decadal variability shows distinct alternate epochs (lasting approximately 3 decades) of above and below normal rainfall. This interannual and decadal variability appear to have no relationship with global warming.

The relationship of IMR with DPT (index of ENSO) shows that the relationship has changed sign around 1990 and shows maximum positive relationship (as against the well documented negative relationship) during the last decade, confirming the recent ENSO-Monsoon weakening. However the relationship of IMR with NHST and snow over western Eurasia has also weakened in recent times, suggesting that the global warming need not be a cause for the ENSO-Monsoon weakening. Thus the IMR variability seems to have no teleconnections with the Pacific nor the Northern Hemisphere/Eurasia in recent times. Even the well established negative relationship between IMR and winter Himalayan snow cover has broken in recent times (Kripalani et al 2002b)

The observed snow depth variations over western and eastern Eurasia show an increasing tendency, which may be related with increased precipitation due to global warming (Ye and Mather, 1997).

Studies by several authors in India have shown that there is no statistically significant trend in IMR for country as a whole (e.g., Thapliyal and Kulshrestha, 1991; more references in Pant and Rupa Kumar, 1997). Rupa Kumar *et al*. (1992) using observed data have shown that there are areas over India with decreasing trends of rainfall and there are also areas with increasing trends. Using a climate model Pal *et al*. (2001) suggest that the total rainfall may not change significantly but the temporal and spatial distribution over India are likely to change. However classification of seasonal rainfall patterns over India to identify dominant modes of spatio-temporal variability for the period 1871–1994 showed no change in the spatial patterns. In fact time variation of some clusters showed that there are epochs where particular cluster dominates (Kulkarni *et al*., 1992; Kulkarni and Kripalani, 1998) and these clusters have no relationship to the global warming.

Several studies caution the direct use of these model scenarios on regional scale for studying the impacts since GCMs do not capture the finer details of the spatial variations and the results are not free from uncertainties (eg Rupa Kumar and Ashrit, 2001; De, 2001)

Stephenson *et al*. (2001) investigated possible trends in several large-scale indices that describe the Asian summer monsoon using results from recent atmospheric general circulation experiments. They found a weakening of the monsoon circulation. Singh (2001) investigated the long term trends in the frequency of cyclonic disturbances (depressions and cyclonic storms) over Bay of Bengal and the Arabian Sea using 100-year (1890–1999) data and found significant decreasing trends. Thus there seem to be no support for the intensification of the monsoon nor any support for the increased hydrological cycle as hypothesized by greenhouse warming scenario in model simulations nor the long historical observed data analysed here.

In conclusion the analysis of observed data for the 131-year period (1871–2001) suggests no clear role of global warming in the variability of monsoon rainfall over India.

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## Appendix

### Cramer's test for comparison of means of subperiods with the mean of the whole period (WMO, 1966)

One of the standard tests of significance recommended by WMO in the routine analysis of climatic fluctuations is the Cramer's $t$-test. Some times one may prefer to examine the stability of a long record in terms of a comparison between the overall mean of an entire record and the means of certain parts of the record. A test due to Cramer can be applied to determine whether the difference of the means are no larger than would be compatible with a "null hypothesis" of randomness.

$\bar{\bar{x}}$ = mean

$s$ = standard deviation of all $N$ values

i.e.,

$$\bar{\bar{x}} = \frac{1}{N}\sum_{i=1}^{N} x_i, \quad s = \left[\frac{1}{N}\sum_{i=1}^{N} x_i^2 - \bar{\bar{x}}^2\right]^{1/2}$$

$\overline{x_k}$ is the mean of the subperiod of $n$ values, to be compared with $\bar{\bar{x}}$ namely

$$\overline{x_k} = \sum_{i=k+1}^{k+n} \frac{x_i}{n}; \quad \text{defining} \quad r_k = \frac{\overline{x_k} - \bar{\bar{x}}}{s}.$$

We compute

$$t_k = \left[\frac{n(N-2)}{N-n(1+r_k^2)}\right]^{1/2} r_k.$$

The statistic $t_k$ is distributed as 'Student's $t$' with $N$-2 degrees of freedom. This test may be repeated for any desired number and choice of sub-periods (here we have used the subperiod as 11 years since decadal) in the whole record. The time plot of the t-values (plotted at the center of the subperiod) gives a pictorial representation of the variability.

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