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Influence of Eurasian snow depth anomaly on the Indian summer monsoon circulation

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सार – यूरेशिया के तीन विभिन्न क्षेत्रों में शीत/वसंत ऋतु के दौरान पड़ी बर्फ की गहराई में अनियमिता और भारतीय ग्रीष्मकालीन मानसून वर्षा के बीच आनुभविक संबंध की जाँच करने के लिए ऐतिहासिक सोवियत दैनिक हिम गहराई (एच.एस.डी.एस.डी.) वर्जन II डाल सेटों का उपयोग किया गया है। ऐतिहासिक सोवियत दैनिक हिम की गहराई के आँकडों से यह पता चलता है कि चरम मौसम वाले विभिन्न दो वर्षों में, पश्चिमी यूरेशिया में अप्रैल के महीने में बर्फ की गहराई में विशेष अंतर है तथा वसंत ऋतु के दौरान पड़ी बर्फ की गहराई की असामान्यता के बीच प्रतिलोभ संबंध और 5% के महत्वपूर्ण स्तर पर –0.43 के गुणांक सहसंबंध के साथ भारतीय ग्रीष्मकालीन मानसून वर्षा अत्यंत संतुलित है। एन.सी.ई.पी./एन.सी.ए.आर. के पुनः विश्लेषित आँकडों का उपयोग करते हुए, मौसमी माध्य परिसंचरण पैटर्न की जाँच से पता चलता है कि पश्चिमी यूरेशिया में हिम की गहराई की अधिकता और न्यूनता वाले दो वर्षों के बीच निम्नस्तरीय वायुमंडलीय तापमान अंतर 10° से. तक अधिक हो सकता है जिससे कैस्पियन सागर में असामान्य चक्रवातीय परिसंचरण बढता है और यह भारत में मानसून परिसंचरण को प्रभावित करने का कारण हो सकता है एनसो परिघटनाओं अथवा यूरेशिया की भारी / हल्की हिमपात की विभिन्न अवस्थाओं की घटना के न्यून से अधिक भारतीय ग्रीष्मकालीन वर्षा से ऊपरी क्षोभमंडलीय वेग विभव अनियमितता के डीपोल संरचना की अवस्था पूर्णतया विपरीत है। तथापि एनसो की विपरीत अवस्थाओं के दौरान यूरेशिया की भारी वर्षा की अपेक्षा अपसरण केंद्र पूर्व–पश्चिम की और बढ़ता है जब आस्ट्रेलिया अपसरण केंद्र दक्षिण पूर्व की ओर बढ़ता है।

ABSTRACT. The Historical Soviet Daily Snow Depth (HSDSD) version II data set has been used to examine the empirical relationship between the winter/spring snow depth anomaly over three different regions of Eurasia and Indian Summer Monsoon Rainfall (ISMR). HSDSD data show that the difference in snow depth between two extreme years is most prominent over western Eurasia in the month of April and the inverse relationship between the spring snow depth anomaly and the following ISMR is very robust with correlation coefficient of –0.43 at 5% significant level. Examination of seasonal mean circulation pattern using NCEP/NCAR reanalysed data shows that low level atmospheric temperature difference between two extreme years of high and low western Eurasia snow depth in April can be as large as 10°C which gives rise to anomalous cyclonic circulation over the Caspian Sea and this may be responsible for affecting the monsoon circulation over India. Results also show that there is a complete phase reversal in the dipole structure of the upper tropospheric velocity potential anomaly from the deficient to excess ISMR irrespective of occurrence of different phases of ENSO events or high/low Eurasian snow. However, during opposite phases of ENSO, the divergence center has east-west shift as compared to the high Eurasian snow when the divergence center shifts to the southeast over Australia.

Key words – Indian summer monsoon rainfall, Historical soviet daily snow depth, El-Nino, Divergence centre, Correlation coefficients, Mid latitude circulation.

1. Introduction

An inverse relationship between the strength of the Indian summer monsoon and the extent of Eurasian snow cover in the preceding season has been documented by several authors (Hahn and Shukla 1976, Dickson 1984 and Sankar Rao *et al*. 1996). Sensitivity studies with general circulation models (GCMs) such as those of Barnett *et al*. (1989), Vernekar *et al*. (1995) have shown that when large, spatially coherent, positive snow anomalies are imposed over Eurasia in winter/spring, the monsoon circulation in the following summer is weaker than average. Bamzai & Shukla (1999) using snow fall frequency data have confirmed that only for the western Eurasian region, the correlation between the winter snow cover anomaly and subsequent monsoon rains is statistically significant. Kripalani *et al*. (1996) used snow depth from Nimbus-7 satellite and found two regions over Eurasia had negative correlation with the monsoon rainfall; one region to the north-east of Moscow and the other between Mongolia and Siberia. Kripalani & Kulkarni (1999) based on Historical Soviet Daily Snow Depth (HSDSD) version I data for the period 1881-1985 concluded that winter-time snow depth over western Eurasia surrounding Moscow shows significant negative relationship with subsequent monsoon rain whereas, that over eastern Eurasia in central Siberia has significant positive relationship with monsoon rainfall. They conjectured the existence of a mid-latitude long wave pattern with an anomalous ridge (trough) over Asia during the winter prior to a strong (weak) monsoon.

Meehl (1997) using a coupled Ocean-Atmosphere GCM demonstrated that land-surface conditions may create temperature contrast between land and ocean without any feed backs from snow cover. He further, inferred that snow cover anomaly may be an artifact of the mid-latitude circulation pattern associated with convective heating anomalies, rather than an independent forcing. Corti *et al.* (2000) based on their 12 ensemble runs of European Centre for Medium range Weather Forecasts (ECMWF) and previously established results (Palmer *et al*. 1992; Ju and Slingo 1995; Ferranti *et al*. 1997), concluded that the snow monsoon relationship is just an artifact of the influence of El Nino anomalies on both the winter time and the summer time circulations. However, they did not rule out an active role of the snow anomaly in causing the persistence of the Eurasian wind anomaly. They further, cited 1994 monsoon case (Soman and Slingo 1997) indicating that the snow related wind anomaly over Eurasia persisted from winter to summer independently from the Pacific SST anomaly. Using several simulations of ECMWF model, Ferranti and Molteni (1999) have concluded that the inter-annual variability of Eurasian snow-depth in early spring is influenced by the boundary forcing arising from SST anomalies over the tropical eastern Pacific during previous winter. Their results also indicate that Eurasian snow depth influences the seasonal mean monsoon independently of El-Nino Southern Oscillation (ENSO).

Almost all the observational studies of snow-monsoon connection are based on the relationship between the snow and monsoon rainfall only. How the antecedent snow is linked to the large scale monsoon circulation is not clear. Sankar Rao *et al*. (1996) using NOAA NESDIS data for the period 1967 to 1992 concluded that following the winters of more snow, stationary perturbations with higher pressures over central Asia north of India are produced in the lower atmosphere and the following Asian summer monsoon is weaker. Simultaneously, in the upper atmosphere, lower anomalous pressure occurs during summer which weakens the upper level monsoon high.

The purpose of the present study is to examine the evolution of seasonal mean monsoon circulation features from the midlatitude circulation in response to the Eurasian snow depth in April. A detailed analysis of the characteristics of atmospheric circulation during contrasting years of high(low) winter/spring snow depth followed by deficient(excess) monsoon rain over India has been done in order to identify the signal of excess or deficient monsoon rainfall two months in advance. In order to separate the effects of Eurasian snow from that of the Pacific SST, care has been taken so that the selected cases of high (low) snow years followed by deficient (excess) ISMR are not influenced by ENSO.

2. Data sources

The HSDSD version II data set provides a long-term climatological data (1881-1995) and updates and replaces the original HSDSD version 1 data set that was previously available from National Snow and Ice Data Center (NSIDC) on CDROM. The HSDSD data were extracted from the Soviet meteorological archive, which contains daily data from Russian\USSR World Meteorological Organisation (WMO) stations. The original data set was compilation of three meteorological archives such as (*i*) the TM1–Day archive, which contains daily meteorological observations for the USSR between 1874 and 1965, (*ii*) the Day–76 meteorological archive for the entire USSR between 1966 and 1984 and (*iii*) the Day–76 meteorological archive for the Taiga region between 1966 and 1984. The latest update from 1985 through 1995 comes from the Day–76 meteorological archives and includes 222 stations.

HSDSD includes daily snow depth and daily state of snow cover (percentage of surrounding area that is

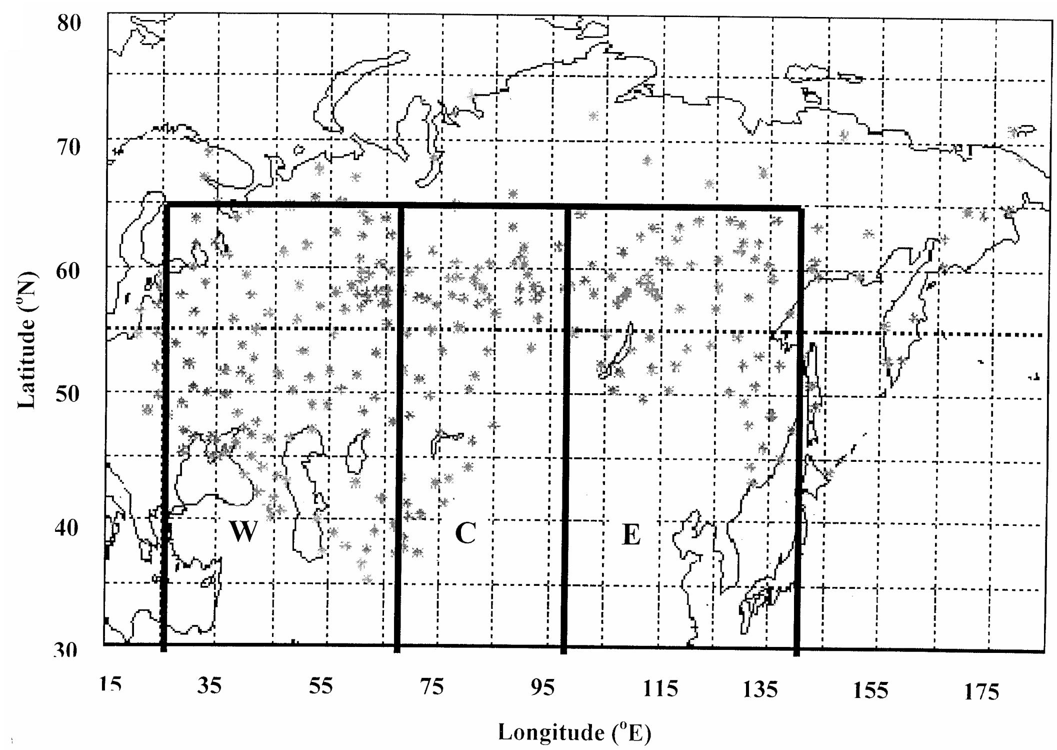


Fig. 1. Division of Eurasia into three zones *viz.* West (W), Central (C) and East (E). Stars (*) represent the locations of WMO defined stations where daily snow depth were observed in Historical Soviet Daily Snow Depth (HSDSD) version–II data set

covered by snow). Products derived at NSIDC and included on the CD-ROM are the daily, monthly, seasonal and climatological summaries. In this study daily data summaries are used to compute the monthly mean snow depth for all the 284 WMO defined stations. These stations are located in the mid-latitudes (Fig. 1) mostly inhabited area of Eurasia. The geographical distribution of the stations lie between 35° N and 72° N latitude lines and between 20° E and 180° E meridians, while the elevation of the stations varies from –15 meters to 2100 meters. Further the monthly mean snow depth data are categorised according to the number of days where snow depth was greater than 5cm, 10cm and 50cm. HSDSD product has been updated from 1881 (for the earliest operational stations) through 1995 using improved data quality control and sophisticated computer software. It may be noted that where slight differences in position between provided data and the WMO station position existed, the WMO station point was used.

ISMR data from June to September for the period 1881-1994 (Parthasarthy *et al.* 1995) have been used in classifying the excess, normal and deficient rain years. We have also used NCEP/NCAR reanalysed data for the period 1966-94 which include temperature, wind, velocity potential, stream function and geopotential fields at upper and lower atmospheres. These reanalyses were undertaken with fixed state-of-the-art data assimilation/analysis methods (Kalnay *et al.* 1996) to provide multi-year global data sets for a range of investigations of many aspects of climate, particularly inter-annual variability. Studies (WCRP 1998) indicate that the reanalysis has provided much improved consistent and more homogeneous global fields.

We have not used NCEP/NCAR reanalysed snow since this data set does not contain snow depth but the water equivalent of snow. Kripalani *et al.* (1998) analysed the data set and did not find its relationship with ISMR good. They explained that the difficulty in transferring the depth of newly fallen snow in to water equivalent is the major short coming in using NCEP/NCAR data for such studies.

3. Statistical relationship between Eurasian snow depth anomaly and ISMR

For better understanding of snow monsoon relationship and for easy comparison with all the previous

TABLE 1

Correlation coefficients between antecedent January and April snow depth anomalies over western, central and eastern Eurasia and Indian Summer Monsoon Rainfall (ISMR). Numbers in bracket show level of significance in %. Dashes indicate that the relationship is not statistically significant

Period	Months	Western Eurasia	Central Eurasia	Eastern Eurasia
1966–94	Jan	–0.50(1)	0.50(1)	0.42(5)
1975–94	Jan	–0.62(0.1)	0.57(0.1)	0.43(5)
1975–94	Apr	–0.43(5)	--	--

studies, Bamzai and Shukla (1999) correlated December, January, February and March (DJFM) mean snow cover anomalies for four regions with the following ISMR. Their four regions of study were (*i*) west Eurasia (40° N-60° N, 10° W-30° E), (*ii*) the whole of Eurasia (20° N-90° N, 0° -190° E), (*iii*) southern Eurasia (20° N-50° N, 0° -190° E) and (*iv*) the Himalayas (30° N-45° N, 60° E-105° E). They used satellite-derived snow cover data for 22 years spanning the period 1973 to 1994. Bamzai and Shukla (1999) found the largest correlation with the western Eurasia snow cover with correlation coefficient (CC) of –0.63 followed by the whole of Eurasia (–0.34). The winter and spring snow cover of southern Eurasia and the Himalayas have high interannual variability but are poorly correlated with the subsequent monsoon rainfall.

The HSDSD version II data set used by us does not contain uninterrupted data for all the stations. Hence clusters of stations are selected over which monthly mean snow depth data are available uninterrupted for a considerable length of time for statistical meaningful relationship. Based on this data set, three zones have been identified such as west (25° E-68° E, 35° N-65° N), central (68° E-98° E, 35° N-65° N) and east (98° E-140° E, 35° N-65° N) where consistent data are available. The Lag CCs between monthly snow depth anomaly for three regions namely western, central and eastern Eurasia and ISMR for the period 1966-94 are computed in this study. No attempt has been made to generate the missing data either by interpolation or by any other technique. We have used the actual data provided by HSDSD in the CD. However stations north of 65° N are not considered in this study because the number of stations are scarce and also the occurrence of missing data is high.

Table 1 presents the CCs along with their significant levels between monthly snow depth anomalies over western, central and eastern Eurasia over the latitudes 35° N to 65° N for the periods 1966-94 and 1975-94 with

TABLE 2

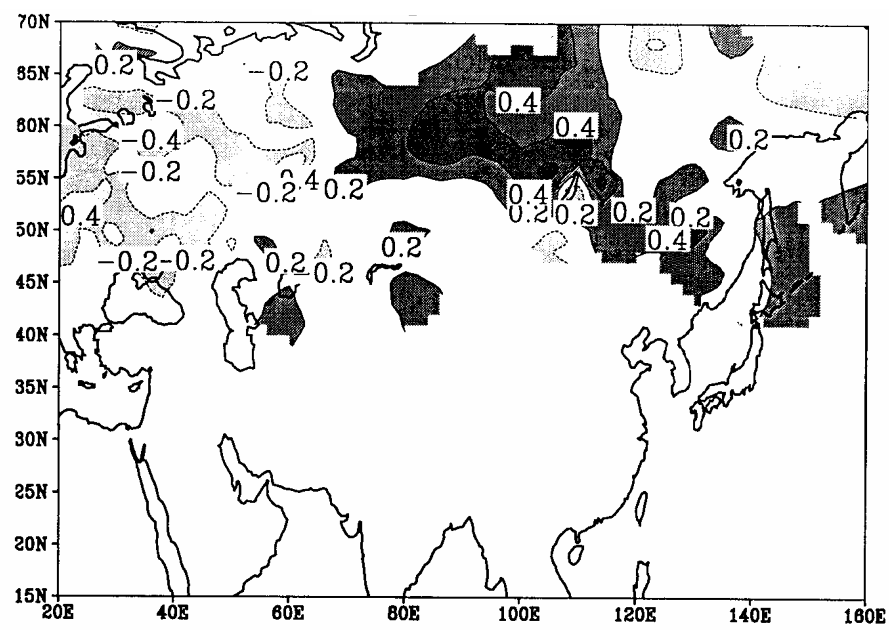
Same as in Table1 but for 19 years sliding correlation coefficients

Years	West (Jan) Eurasia	West (Apr) Eurasia	Central (Jan) Eurasia	East (Jan) Eurasia
1966–94	-0.50(1)	--	0.50(1)	0.42(5)
1966–84	-0.57(0.1)	--	0.57(0.1)	--
1967–85	-0.55(1)	--	0.52(1)	--
1968–86	-0.59(0.1)	--	0.52(1)	0.47(2)
1969–87	-0.61(0.1)		0.47(1)	0.53(1)
1970–88	-0.61(0.1)	-0.44(5)	0.54(1)	0.54(1)
1971–89	-0.51(1)	-0.41(5)	0.69(.1)	0.54(1)
1972–90	-0.50(1)	-0.44(5)	0.74(0.1)	0.57(0.1)
1973–91	-0.68(0.1)	-0.58(0.1)	0.59(0.1)	0.48(1)
1974–92	-0.64(0.1)	-0.57(0.1)	0.56(0.1)	0.50(1)
1975–93	-0.64(0.1)	-0.47(1)	0.55(1)	0.50(1)
1976–94	-0.57(0.1)	--	0.62(0.1)	0.46(2)

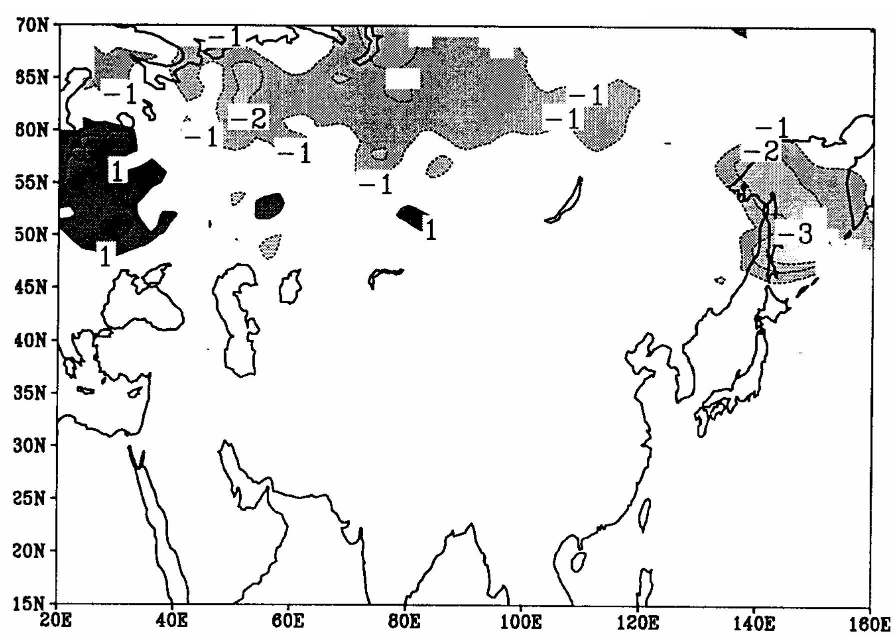
ISMR. Although HSDSD data set is for the period 1881 to 1994, there are a lot of missing data at many stations before 1966. In order to make a coherent time series, we have considered the period 1966 to 1994. Only those CCs which are significant at 5% level or above have been presented in the table. Table 1 shows that the January snow depth anomalies over western Eurasia have very good inverse relationship whereas the anomalies over the central and eastern Eurasia have positive relationship with the following ISMR. The April snow depth anomaly over western Eurasia has also strong negative relationship with the following ISMR for the period 1975-94. April snow depth anomalies over central and eastern Eurasia do not show any significant relationship with ISMR. To examine the consistency of above relationships, the CCs for overlapping 19 year periods have been recomputed during the period 1966-94 and are shown in Table 2. The highest magnitudes are obtained for the western Eurasia January snow depth during 1973-91, 1974-92 and 1975-93, all significant at 0.1% levels. The April snow depth anomaly over western Eurasia shows very strong relationship with the following ISMR for the period 1973-93.

Our analysis shows that January snow depth anomalies over western Eurasia lying between 25° E and 68° E depicts negative correlation while those over central and eastern Eurasia lying between 68° E and 140° E have

(a) **Correlation Coefficient**



(b) **Empirical Orthogonal Function-1**



Figs. 2(a&b). (a) Correlation coefficients (CCs) between January Eurasian snow depth anomalies at locations mentioned in Fig. 1 with the following ISMR during the period 1966-94. (b) EOF-1 of standardised snow depth anomalies in January corresponding to the stations and period considered in Fig. 2(a)

positive correlation with the subsequent ISMR [Fig 2(a)]. This result confirms the relationship of two coherent regions identified by Kripalani and Kulkarni (1999) with ISMR based on the earlier version of HSDSD data set. The new results of our study based on the version II HSDSD data set are the positive correlation of central

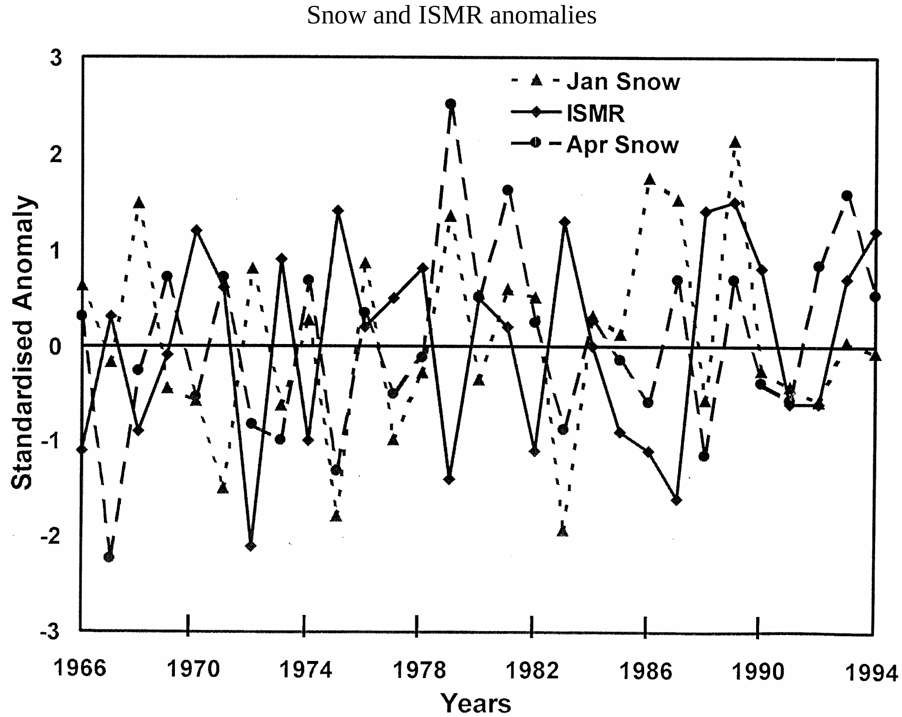


Fig. 3. Standardised snow depth anomaly over western Eurasia and ISMR for the period 1966-94

TABLE 3

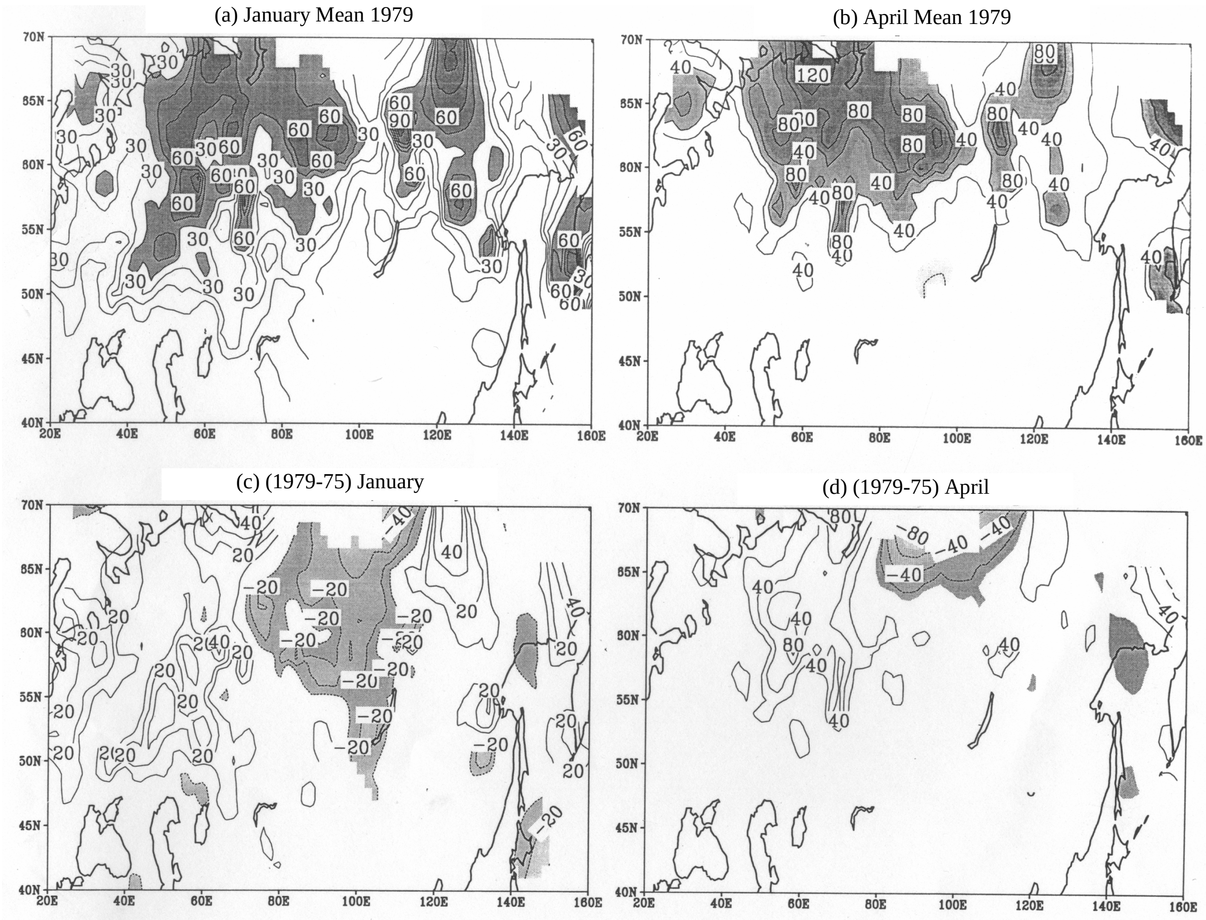
Seasonal Southern Oscillation Index (SOI) and Sea Surface Temperature (SST) anomaly for the years 1975, 1979, 1983 and 1987

Years	SOI				SST Anomaly(°C) (5° N-5° S, 150° W-90° W)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
1975	-0.1	0.8	1.9	1.8	-0.4	-0.5	-1.0	-1.3
1979	-0.1	-0.2	-0.3	-0.3	0.2	0.4	0.5	1.9
1983	-3.7	-1.7	-1.0	-0.4	3.3	3.2	1.6	0.4
1987	-1.2	-1.9	-1.6	-0.8	1.2	1.4	1.7	1.7

Eurasia snow depth in January with the following ISMR as shown in Tables 1 & 2.

Some notable CCs in the eastern Eurasia are, 0.55 (at 1% level), 0.55 (at 1% level) and 0.51 (at 1% level) at Cul'Man (56.9° N,124.9° E), Zigalovo (54.8°N, 105.2° E) and Kirensk (57.8° N, 108.1° E) respectively in the eastern side of Eurasia. CCs of –0.50, –0.47 and –0.47 are obtained at the stations Nizhnuj Tagil (57.9° N, 60.1° E) and Minsk (53.9° N, 27.5° E) and Vitegra (61.0° N, 36.5° E) respectively in western Eurasia.

Empirical Orthogonal Functions (EOF) of January snow depth anomaly for the period 1966-94 have also been computed for the whole of Eurasia and its three regions separately in the present study. January is selected because of its highest CC with ISMR. In our study EOF-1 over the whole of Eurasia, the western, central and eastern Eurasia explains about 19.5%, 27.2%, 31.1% and 26.5% of variability respectively. EOF-1 [Fig.2(b)] for the whole of Eurasia is compatible with the station wise CCs [Fig. 2(a)] especially in the western and central Eurasia. Our study based on the version II HSDSD gives stronger

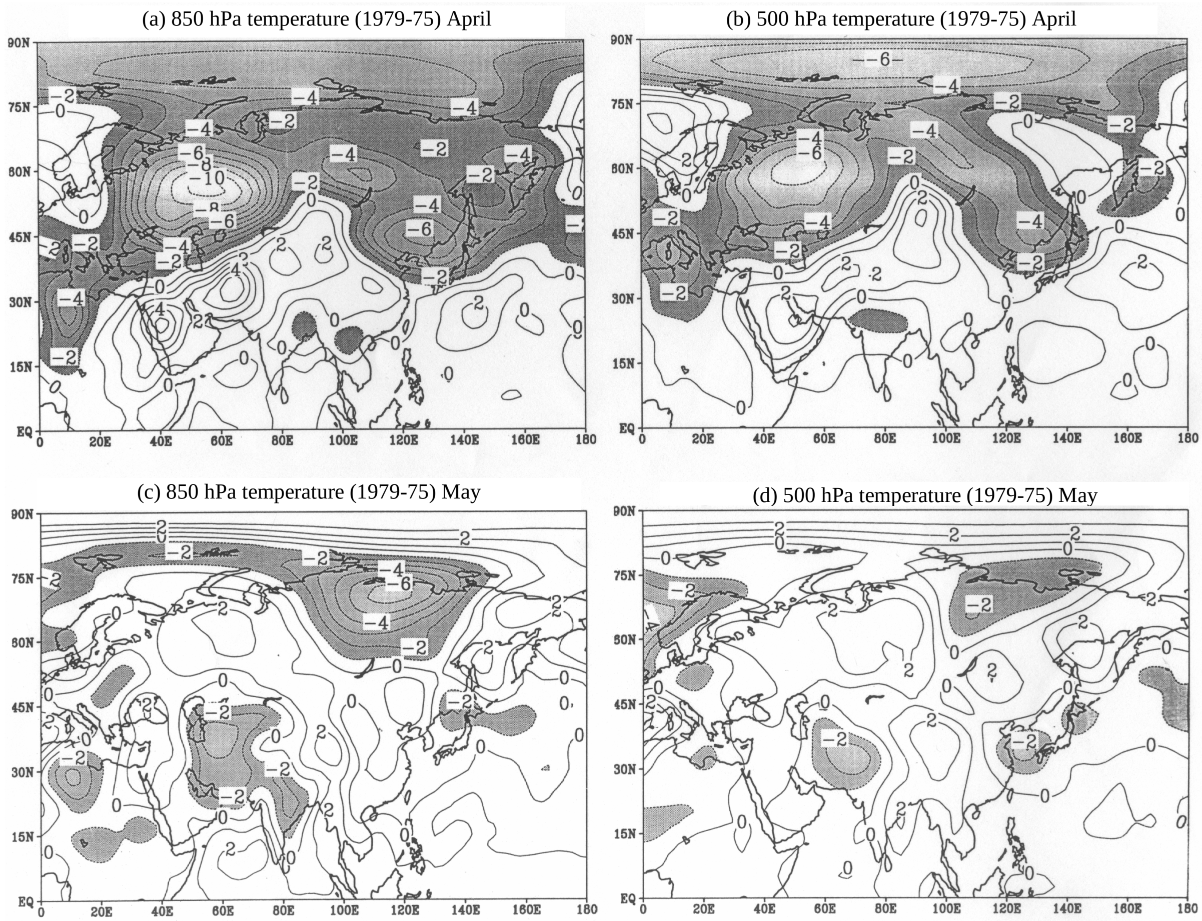


Figs. 4(a-d). Mean snow depth (cm) for 1979 (a) January and (b) April and snow depth (1979-75) difference (cm) in (c) January and (d) April

variability than the corresponding value obtained for the whole of Eurasia by Kripalani and Kulkarni (1999) based on version I data set. They found 15.8% and 15.5% variability in the first component during January and November over the whole of Eurasia. Better results obtained in the most dominant EOF-1 in our study as compared to those of Kripalani and Kulkarni (1999) may be ascribed to better quality of snow depth data in version II than in version I HSDSD.

4. Selection of high and low snow years

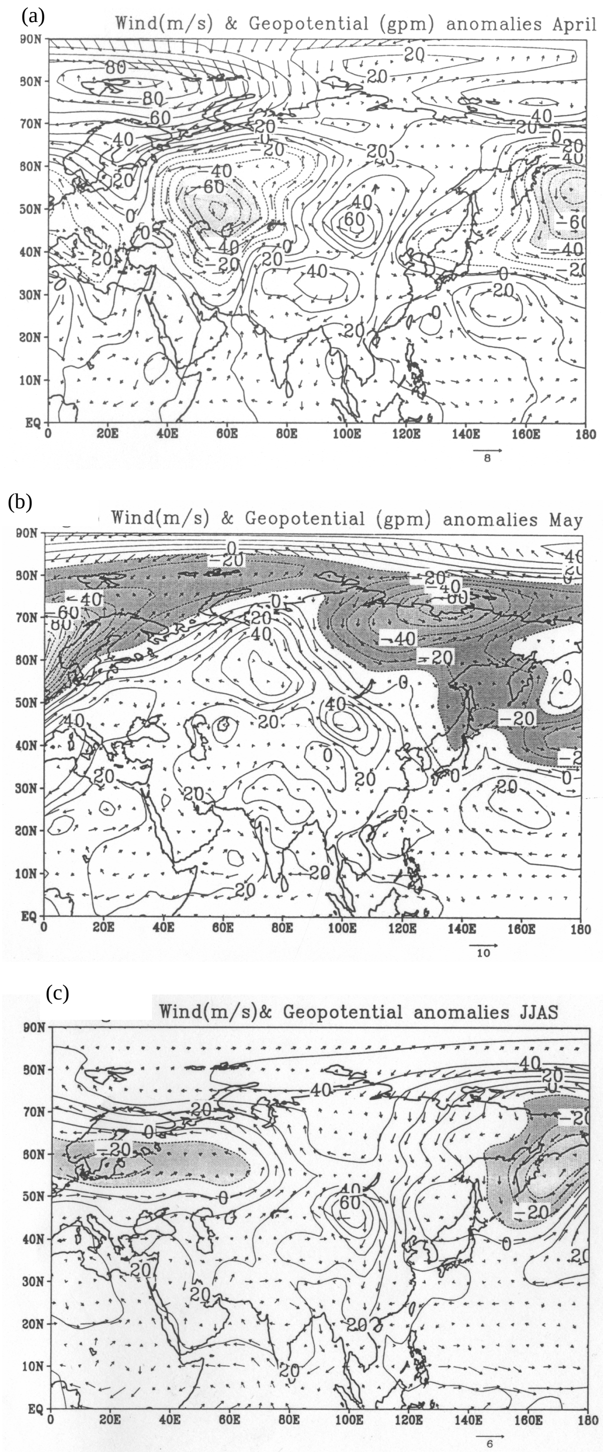
Using the monthly snow depth data for the year 1966–94, January and April mean values for each year over the western Eurasia are computed and the mean of the series and the standard deviations are also calculated. The snow depth of each year for the period 1966-94 is expressed as a standardised snow depth anomaly by dividing the departure of each year from normal by standard deviation. The standardised snow depth anomaly considered for the western Eurasia for the period 1966-94 is shown in Fig. 3. The years having snow depth anomaly between ±1 standard deviation are considered as normal snow years. Similarly the years having snow depth anomaly equal to or above +1 standard deviation are taken as high snow years and those having equal to or less than –1 standard deviation snow depth anomaly are identified as low snow years. Based on this criterion it is found that the years 1971, 1975 and 1983 are low snow years and 1968, 1979, 1986, 1987 and 1989 are high snow years. Rest of the years in the period 1966 to 1994 had normal snow depth anomaly. Similarly the ISMR rainfall anomaly for each year has been computed and plotted in Fig. 3. The years having ISMR anomaly more than or equal to +1 standard deviation are termed as excess monsoon years and those less than or equal to –1 standard deviation are considered as deficient monsoon years. The years having ISMR anomaly between –1 and +1 standard deviation are



Figs. 5(a-d). Temperature difference (°C) between 1979 and 1975 (a) 850 hPa April (b) 500 hPa April (c) 850 hPa May and (d) 500 hPa May

termed as normal monsoon years. Based on this criterion the years 1970, 1975, 1983, 1988 and 1994 are excess monsoon years and 1966, 1968, 1972, 1974, 1979, 1982, 1986 and 1987 are deficient monsoon years. Fig. 3 confirms the well established inverse relationship between the Eurasian snow depth anomaly and ISMR deviation. Out of all the years of high and low snow which are related to below normal and above normal monsoon years respectively, we have a case in 1975 where low winter snow is followed by excess monsoon rain and another case in 1979 where high snow is followed by deficient monsoon rain. These two years are considered to be free from the effect of ENSO phase on ISMR. It may be noted that in this study the effect of winter/spring snow on ISMR is being examined. In order to eliminate the effect of ENSO on ISMR, it will be consistent to consider the Pacific boundary conditions corresponding to winter/spring rather than that of JJA. The boundary conditions of JJA will only give a simultaneous relationship with ISMR. Normally ENSO events are classified by either the strength of the Southern Oscillation Index (SOI) or SST anomaly of different Pacific regions such as Nino-3, Nino-3.4 etc. In the present paper, both SOI and SST anomaly of winter/spring seasons are used in the identification of ENSO phases. SOI is the standardised anomaly of the mean sea level pressure difference between Tahiti and Darwin. For the years 1975 and 1979, SOI and SST anomaly are given in Table 3 based on the monthly SOI of the Climate Prediction Center (CPC). Considering JJA SST anomaly (–1.0° C), 1975 may be taken as La-Nina event. However, with a view to consider both the surface boundary conditions such as Eurasian snow and Pacific surface state corresponding to the same season, 1975 is taken equivalent to non-ENSO year in this study.

The relationship of April snow depth anomalies of western Eurasia with the following ISMR is also shown in Fig. 3. It is found that the high and low snow depth



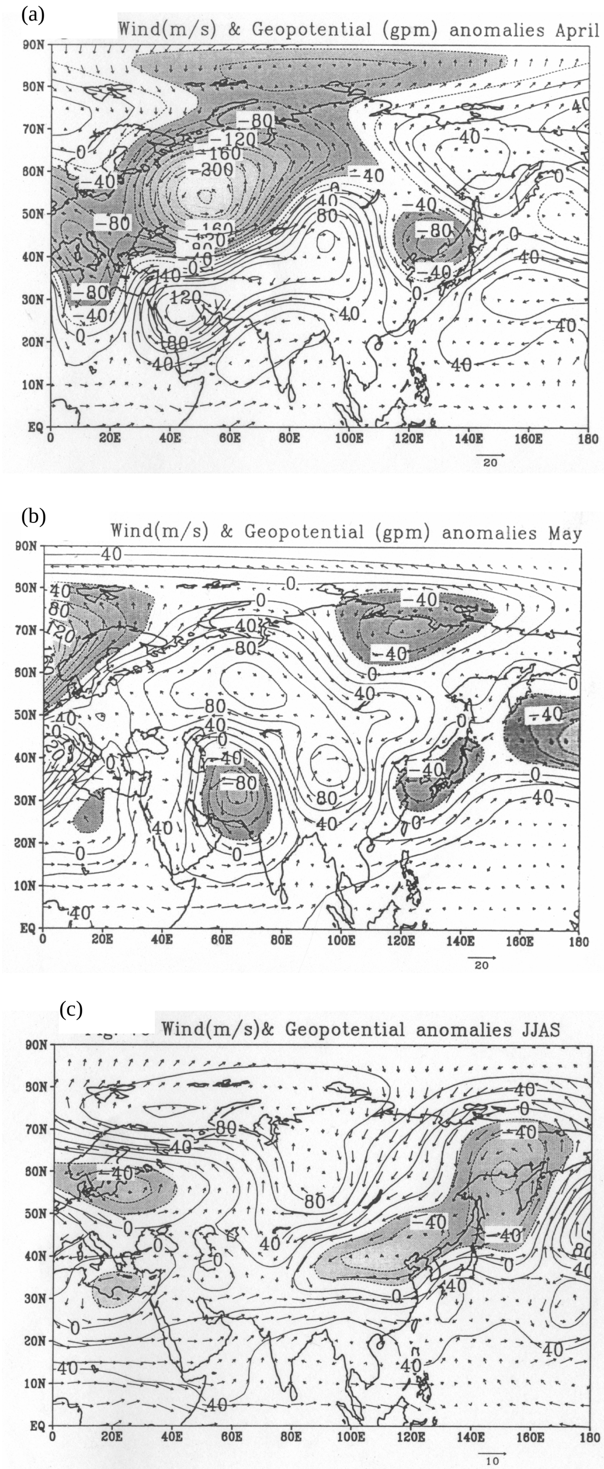
Figs. 6(a-c). Wind (1979-75) difference (m/s) and geopotential height (1979-75) difference (gpm) at 850 hPa for (a) April (b) May and (c) mean of June, July, August and September. The contours and arrows indicate the geopotential height differences and wind differences respectively

anomaly years classified using January snow depth anomaly over western Eurasia are not always the same as based on April snow depth anomaly. However the two cases of low snow depth anomaly followed by excess ISMR in 1975 and high snow depth anomaly followed by deficient ISMR in 1979 are common. In other words the characteristic of low/high snow depth anomalies in 1975 and 1979 remained the same in winter and spring.

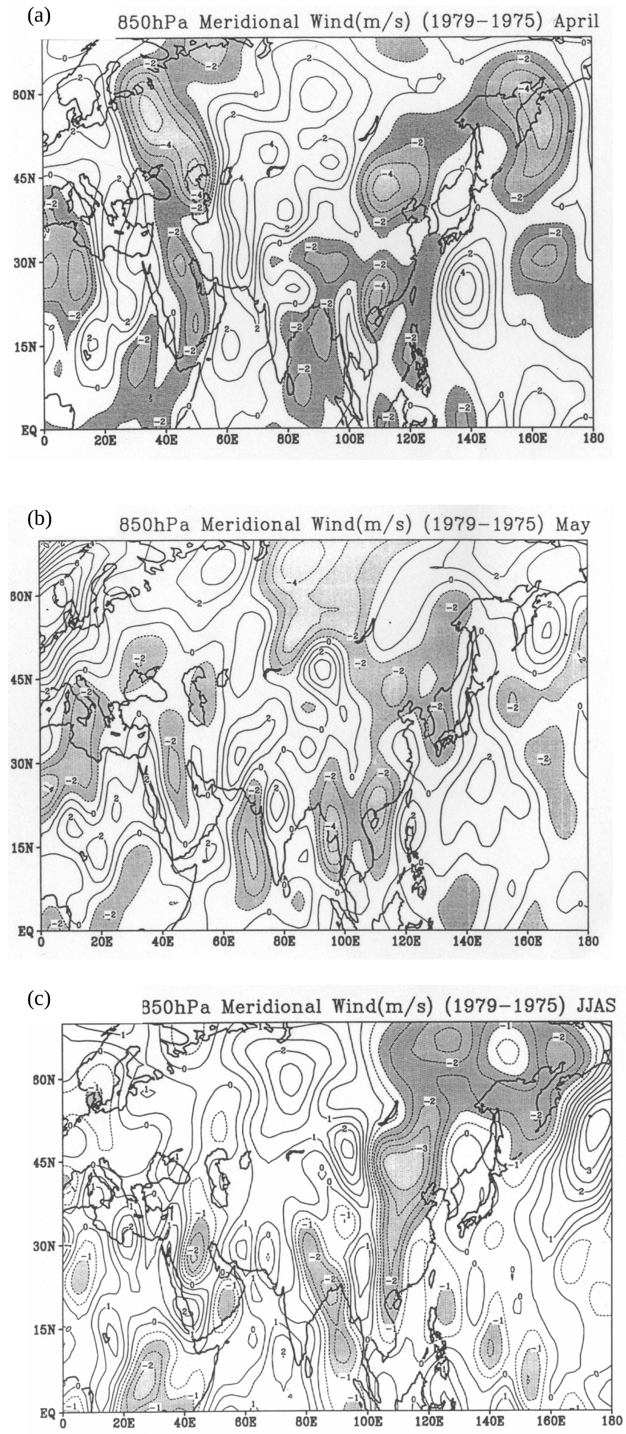
Figs. 4(a&b) show the January and April mean snow depths in 1979 respectively and Figs. 4(c&d) depict the high minus low snow depth anomaly (1979-75) in January and April respectively. Other cases of low/high snow followed by excess/deficient ISMR fall in 1983 and 1987 respectively. However, 1983 and 1987 were also La Nina and El Nino years respectively and hence are not considered for our analysis. This way we have eliminated the effect of SST which has been established as the most dominant slowly varying surface boundary condition and thus considered the effect of Eurasian snow on the monsoon circulation only. In order to compare the effect of high/low snow on the atmospheric circulation with that of El Nino/La Nina, we have chosen contrasting monsoon years 1972 and 1988 which had deficient and excess ISMR respectively under the spell of ENSO only (Table 3). Fig. 3 shows that both 1972 and 1988 had normal Eurasian snow depth anomaly.

5. Difference in circulation characteristics in high and low snow years

The difference in the circulation characteristics in 1979 and 1975 are studied in detail by analysing the difference in temperature, wind, geo-potential height, stream function and velocity potential in 1979 and 1975 from NCEP/NCAR monthly mean reanalysis at 850 hPa and 200 hPa. Bamzai and Shukla (1999) emphasised that the inverse snow-monsoon relationship holds specially in those years when snow is anomalously high or low for both the winter as well as the consecutive spring season. CCs given in Tables 1&2 and the snow depth difference in Figs. 4(c&d) indicate that the anomalous snow depths both in January and subsequent April are significant. Hence we have computed the circulation characteristics and plotted the difference fields in April and May individually and in June, July, August and September (JJAS) as the seasonal mean with a view to examine the evolution of the mean monsoon fields two months in advance in response to the Eurasian snow in April. It may be noted here that results of Kripalani *et al*. (1996) show the areal extent of snow cover over Eurasia having the strongest relationship during April. Also study by Bamzai and Shukla (1999) reveals



Figs. 7(a-c). Same as Figs. 6(a-c) except for 200 hPa

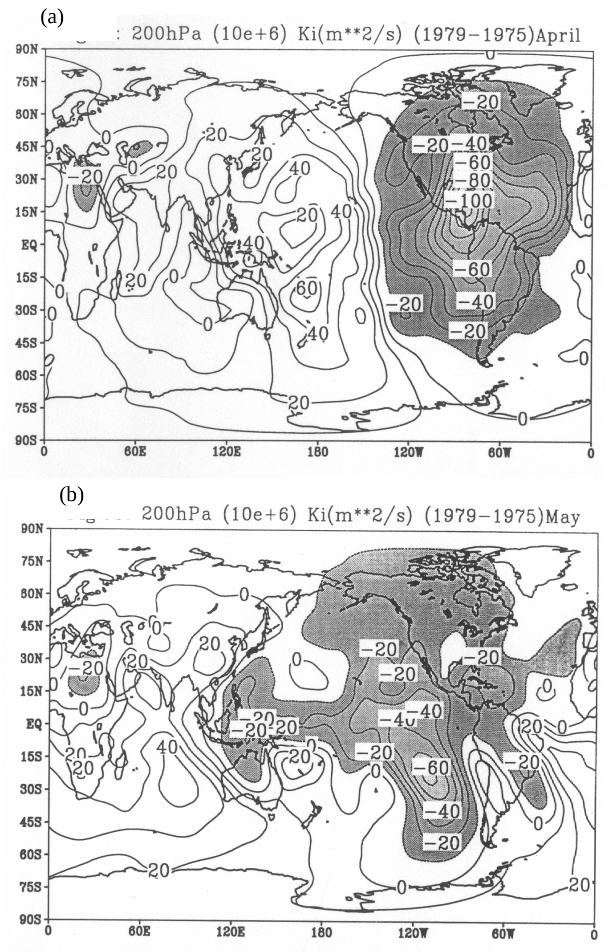


Figs. 8(a-c). Same as Figs. 6(a-c) but for meridional wind

that the inverse snow-monsoon relationship holds especially in those years when snow is anomalously high or low for both the winter as well as the consecutive spring season.

5.1. *Temperature anomaly*

Fig. 5(a) shows that the entire Eurasia is cooler in 1979 April compared to 1975 April. In 1979, the western region



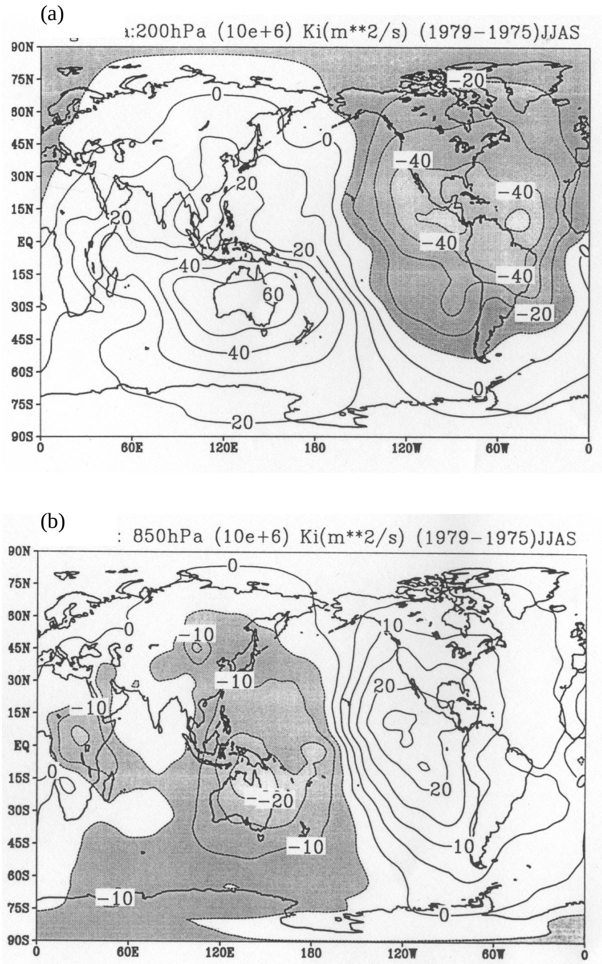
Figs. 9(a&b). Velocity potential difference (10^6 m^2/s) between 1979 and 1975 at 200 hPa (a) April and (b) May

was cooler maximum up to 10° C at 850 hPa whereas the eastern and central Eurasia were cooler maximum by 6° C and 4° C respectively. The cooling anomaly is observed up to 500 hPa level with 6° C in the west and 4° C in the central and eastern regions [Fig. 5(b)]. The cooling of the atmosphere can be ascribed to the snow depth anomaly shown in Fig. 4(c). In May 1979, the eastern Eurasia remains cooler by 6° C [Fig.5(c)] and the temperature difference is small at 500 hPa [Fig.5(d)]. The cooling over the western Eurasia in April [Fig. 5(a)] undergoes a southward shift as shown in Fig. 5(c). The cooling of the Afghanistan-Pakistan region up to mid-atmosphere [Fig. 5(d)] by about 2° C and some parts of north India at 850 hPa by about 3° C [Fig. 5(c)] might have played significant role in the weak monsoon circulation and deficient rain in 1979 compared with 1975. The atmospheric cooling of the eastern Eurasia and the monsoon heat low area has been persistent through the monsoon months as noticed (not shown in figure) in the difference (1979-75) field of JJAS means.

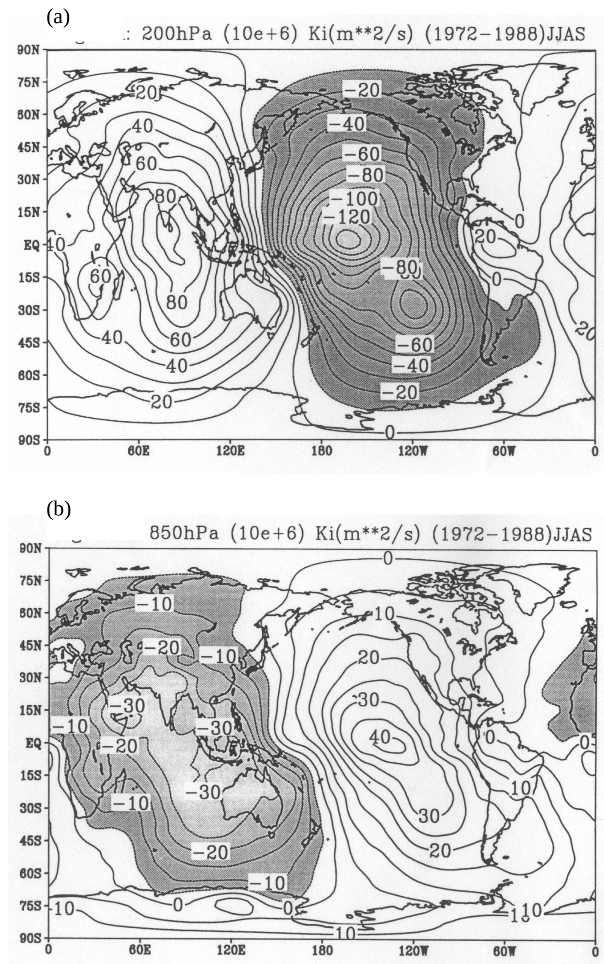
5.2. *Wind and geopotential height anomaly*

The lower level wind difference fields and geopotential height difference fields in April and May shown in Figs. 6(a&b) respectively are consistent with the corresponding temperature difference fields in Figs. 5(a&c). The anomalous cyclonic circulation over the Caspian Sea at 850 hPa in Fig. 6(a) can be attributed to the cooling due to the snow in April [Fig. 4(c)] almost at the same location. In May [Fig. 6(b)] the anomalous cyclonic circulation weakened and its remnants are visible over the west coast of India over Gujarat [Fig. 6(b)]. JJAS wind difference field at 850 hPa Fig. 6(c) clearly shows that the monsoon westerlies over the Arabian Sea were weaker in 1979 compared with 1975. The negative geopotential difference field over the western Eurasia can be attributed to the high snow Fig. 4(c) in 1979 compared to the low snow in 1975. From the geopotential difference fields in Figs. 6(a-c) it is seen that the monsoon heat low in May over central south Asia was weaker (positive values) in 1979 compared to 1975. This positive geopotential difference field indicates adverse pressure gradient anomaly for monsoon development.

The upper level wind difference fields and geopotential difference fields at 200 hPa in April, May and JJAS are depicted in Figs. 7(a-c). The upper level anomalous cyclonic circulation over the Caspian Sea shows a clear southward movement by about 20° latitudes from April to May, which gives rise to the anomalous westerly monsoon wind over Arabian Sea in 1979 May compared to 1975 May [Fig.7(b)]. Thus in 1979, the easterlies started weakening in April through May to give rise to weaker monsoon easterlies [Fig. 7(c)] during JJAS. Weak easterlies and westerlies at 200 hPa and 850 hPa respectively are the characteristics of weak monsoon circulation as it happened in 1979 compared to strong monsoon circulation in 1975. The geopotential difference field at 200 hPa in Figs. 7(a&b) indicates weaker upper level high (negative values) over east Asia in April and May 1979 which is prominent in JJAS [Fig. 7(c)]. Similar results were obtained by Sankar Rao *et al.* (1996). The corresponding upper level stream function difference fields (not given) indicates that weakening of the upper level circulation in 1979 over India and central Asia started in April and persisted through May up to JJAS. Rajeevan (1993) examined the composite mean circulation and thermal fields at 200 hPa from April to June and showed a cyclonic (anticyclonic) anomalous circulation with cold (warm) temperature observed over central Asia near Caspian Sea during April of drought (flood) years. The cold cyclonic anomalous circulation adversely affects the



Figs. 10(a&b). June, July, August and September velocity potential difference (m^2/s) between 1979 and 1975 (a) 200 hPa and (b) 850 hPa



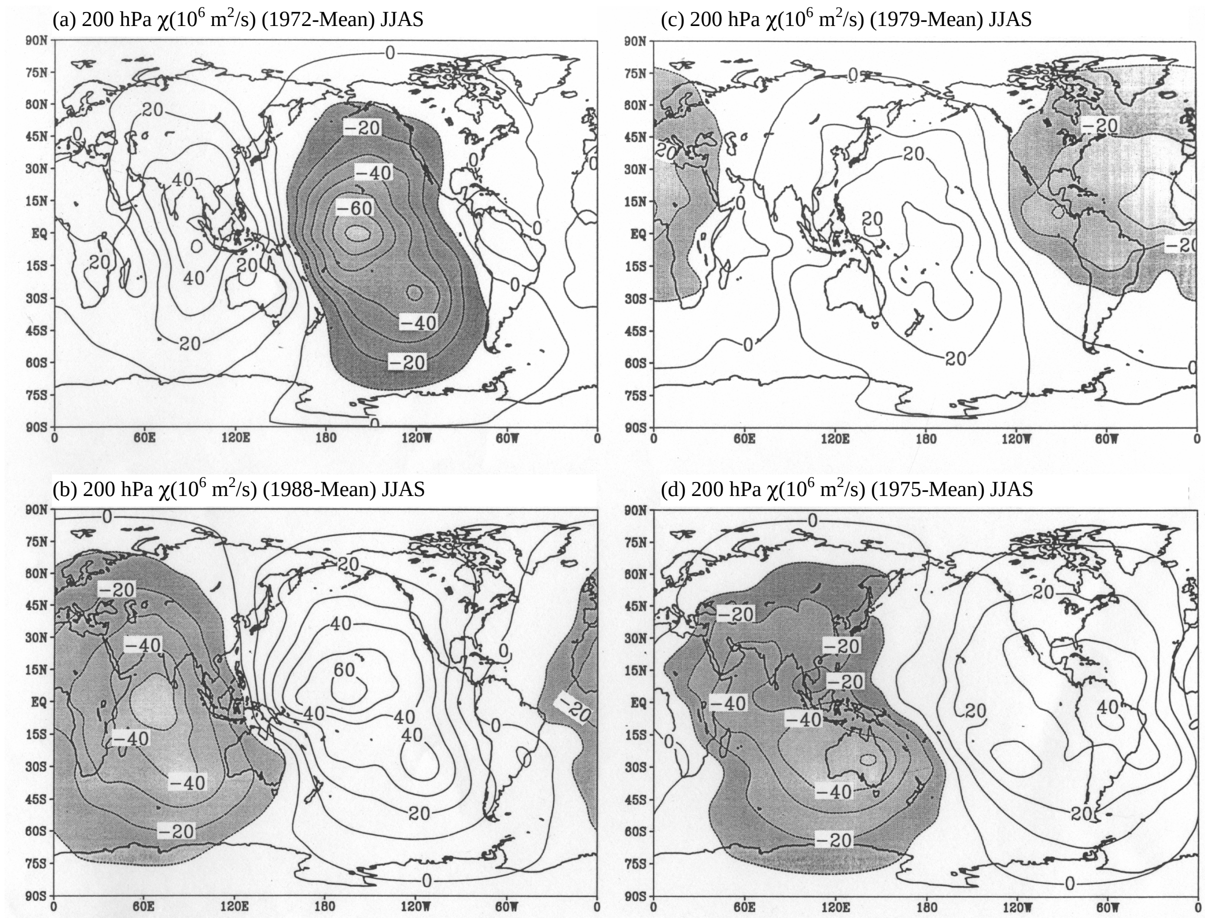
Figs. 11(a&b). Same as Figs. 10(a&b) but for 1972-88

monsoon activity due to excess Eurasian snow cover and the large scale intrusion of dry westerlies into Indian regions. Krishnan and Majumdar (1999) have shown the prominent southward incursion of midlatitude westerlies over northwest India during May at 200 hPa. Such an anomalous feature suppresses the development of upper tropospheric anticyclone and hence the monsoonal circulation over India. Earlier Joseph (1978) and Joseph *et al*. (1981) had also noted similar anomalous features which lead to weak monsoon over India.

Figs. 8(a-c) are in agreement with Figs. 6(a-c). Northerly wind anomaly in the entire belt of 15° N to 70° N over the Caspian Sea area in April in [Fig. 8(a)] indicates that the northerlies were stronger in 1979 compared with 1975 and hence there was advection of western Eurasian cold air up to Arabian sea. In May [Fig. 8(b)] the northerly anomaly over the Arabian Sea may be taken as the precursor to the weak southerly monsoon wind at the lower level in 1979. In JJAS, weaker southerlies Fig. 8(c) in 1979 are very prominent over most of the Indian region except over the Arabian Sea. This again supports the weak monsoon circulation in 1979 compared to 1975.

5.3. *Velocity potential anomaly*

The upper tropospheric velocity potential difference fields in April, May and JJAS are shown in Figs. 9 (a&b) and Fig. 10(a) respectively. It is well known that there is a strong upper level divergent centre (Krishnamurti *et al*. 1971) associated with the Asian monsoon. Normally the upstream side of TEJ is associated with the largest divergent centre and the downstream side, west of India is associated with convergence (Chen and Van Loon 1987). The positive



Figs 12(a-d). Difference of mean of June, July, August and September velocity potential (10^6 m^2 /s) at 200 hPa in (a) 1972, (b) 1988, (c) 1979 and (d) 1975. Difference field in each year is computed by deducting from 30 year mean value

difference field over the Indian subcontinent and the negative difference field to the east in Figs. 9(a&b) and Fig. 10(a) indicate that the upper level divergence centre was weaker over India in 1979 compared to 1975.

This divergent circulation changed in such a way that the intensity of TEJ over the monsoon regions of southern Asia and Africa was weak [Fig. 7(c)] in 1979. As shown by Chen and van Loon (1987), the anomalous divergent circulation during weak TEJ year reduces the generation of kinetic energy on the upstream side of the jet and the destruction of kinetic energy on the downstream side of the jet. The weak divergent circulation in 1979 [Fig. 9(a)] is thought to be due to the decrease of intensity of divergent circulations as well as their eastward shift. As a consequence the generation and destruction of kinetic energy on the upstream and downstream side of the jet respectively were also reduced during weak TEJ of 1979.

Comparing the dipole structures in Figs. 9(a&b) and Fig. 10(a), it is clear that the weakening of divergent center in the left and the convergence center in the right continued from April to May and then to JJAS. Figs. 9(a&b) and Fig. 10(a) are compatible with the wind difference fields in Figs. 7(a-c) respectively.

6. Difference in circulation characteristics in El Nino and La Nina years

El Nino and La Nina are the most important slowly varying boundary conditions which affect the monsoon circulation characteristics and associated rainfall. In this section, the differences in circulation characteristics between an El Nino year associated with deficient monsoon rain in 1972 and a La Nina year associated with excess monsoon rain in 1988 are examined and compared with the difference fields discussed in the previous section. As shown in Fig. 3, these two years had normal snow depth in winter over the western Eurasia. Fig. 3 also shows that in 1988, there was normal snow depth in April over the western Eurasia. JJAS wind difference fields of 1972 minus 1988 at 850hPa and 200hPa (figures not shown) over India are similar to those of 1979 minus 1975 [Figs. 6(c) and Fig. 7(c)] which confirms the fact that monsoon wind in 1972 were weaker than in 1988.

Velocity potential has been recognised as a very important field to examine the interannual variability of monsoon. Kanamitsu and Krishnamurti (1978) examined the upper level divergent circulation in normal rainfall year 1967 and during the drought year 1972 and found that the major center of the divergence circulation in the normal year was established near 20° N (close to Bay of Bengal) and in dry year it was located eastward and equatorward around 10° N. In order to compare the contrasting monsoon cases of 1979 *vs*. 1975 and 1972 *vs*. 1988, we have examined the lower and upper tropospheric velocity potential difference fields in both the cases. JJAS 1979 minus 1975 velocity potential differences at 200 hPa and 850 hPa are shown in Figs. 10(a&b) respectively. Similarly, JJAS 1972 minus 1988 velocity potential differences at 200 hPa and 850 hPa are shown in Figs. 11(a&b) respectively. Comparison of the two cases indicates dipole structures at the upper troposphere Figs. 10(a) and Fig. 11(a)] are similar and are in opposite phase to those at the lower troposphere [Fig. 10(b) and Fig. 11(b)]. However, the dipoles in 1972 *vs*. 1988 case are stronger in intensity than those in 1979 *vs*. 1975 case both at 200 hPa and 850 hPa. This shows that the contrast in divergence centers over India due to El Nino and La Nina is much more than that due to high and low Eurasian snow depth. Also in El Nino/La Nina case the centers of dipoles were in the equatorial belt. In case of high/low Eurasian snow depth, the anomalous velocity potential divergence center at 200 hPa and the corresponding convergence center at 850 hPa shift to the southern hemisphere over Australia. The centers at both the levels have southeast shift due to the snow anomaly over the western Eurasia [Fig. 4(c)]. The Indian Ocean SST anomaly also plays significant role in ISMR. However, in this study it is found that the Indian Ocean MAM SST anomaly in 1979 is very small *i.e*. –0.17° C compared to the mean value of 26.81° C during the period of study based on NCEP/NCAR reanalysis. Hence the effect of Indian Ocean MAM SST anomaly on 1979 ISMR is assumed to be small compared to that of Eurasian snow anomaly in the same year.

In order to study the shift of the dipole structures in deficient and excess monsoon years from the normal years, the velocity potential difference fields at 200 hPa in 1972, 1988, 1979 and 1975 are plotted in Figs. 12(a-d) respectively. The nature of dipole structure in the deficient monsoon year 1972 [Fig. 12(a)] is opposite to that in excess monsoon year 1988. There is a complete phase reversal in the upper tropospheric velocity potential anomaly from the deficient monsoon year to the excess year. One can attribute this to the east-west shift of the upper level divergence centre. The positive (weak) divergence anomaly over India in 1972 is replaced by negative (strong) divergence anomaly in 1988 giving rise to strong TEJ. 1972 and 1988 contrasting monsoon cases are due to El Nino and La Nina respectively. The above mentioned basic characteristics of the dipole structures in the velocity potential anomaly in 1979 [Fig. 12(c)] and 1975 [Fig. 12(d)] are also observed due to high and low Eurasian snow depth anomaly, but with certain differences. The centres of positive (weak) divergence anomaly in deficient monsoon year 1979 [Fig. 12(c)] and negative (strong) divergence anomaly in excess monsoon year 1975 [Fig. 12(d)] are shifted to the southeast over Australia.

7. Conclusions

Based on the results of this study the following conclusions can be made.

(*i*) Lag CCs indicate that antecedent January snow depth anomaly over western (25° E-68° E, 35° N-65° N), central (68° E-98° E, 35° N-65° N) and eastern (98° E-140° E, 35° N-65° N) Eurasia have significant CCs of –0.50, 0.50 and 0.42 respectively with the subsequent ISMR. February snow depth anomaly over eastern Eurasia has significant CC of 0.55 with the following ISMR. However, April snow depth anomaly over western Eurasia has correlation coefficient of –0.43 with the following ISMR at 5% significance level indicating that the inverse relationship between the spring snow depth anomaly and the following ISMR is very robust compared to winter snow depth anomaly.

(*ii*) Low level atmospheric temperature difference between two extreme years of high and low western Eurasia snow depth in April can be as large as 10^0C which gives rise to anomalous cyclonic circulation over the Caspian Sea. This anomalous circulation at the upper level migrates by about 20° latitudes to the south that may be responsible for weakening the monsoon circulation over India during the year having high snow depth anomaly over western Eurasia.

(*iii*) The upper level divergence center was weaker over India in 1979 compared to 1975. Comparison of the dipole structures in the velocity potential difference field at 200 hPa shows that in 1979 the weakening of divergence center over the Indian land mass and the convergence center to its right continued from April to May and then to JJAS.

(*iv*) There is a complete phase reversal in the dipole structure of the upper tropospheric velocity potential anomaly from the deficient to excess ISMR irrespective of the cause of excess/deficient ISMR *i.e*. El Nino/La Nina or high/low Eurasian snow. However, in case of El Nino, the divergence center has eastward shift as compared to La Nina whereas in case of high Eurasian snow the divergence center shifts to the southeast over Australia as compared to low Eurasian snow. This shift might be attributed to the excess west Eurasian snow depth in a high snow year. It is planned to model such observations with the help of a GCM.

(*v*) All the above conclusions are based on only one case of high west Eurasian snow followed by deficient ISMR and one case of low west Eurasian snow followed by excess ISMR during the period of study from 1966-94. No such other cases were available during the same period. The conclusions should be interpreted in the light of the statistical limitations of the data. These can be confirmed with the availability of more contrasting snow and monsoon years.

Acknowledgements

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References

Bamzai, A., and Shukla, J., 1999, "Relation between Eurasian snow cover, snow depth and the Indian summer monsoon: An observational study", *Jour. of Climate*, **12**, 3117-3132.

Barnett, T. P., Dumenil, L., Schlese, U., Roeckner, E. and Latif, M., 1989, "The effect of Eurasian snow cover on regional and global climate variations", *J. Atmos. Sci*., **46**, 661-685.

Chen, T. C., and Von Loon, H. 1987, "Interannual variation of the tropical easterly jet", *Month. Wea. Rev.*, **115**, 1739-1759.

Corti, S., Molteni, F. and Brankovic, C., 2000, "Predictability of snow depth anomalies over Eurasia and associated circulation patterns", *Q. J. R. Meteorol. Soc.*, **126**, 241-262.

Dickson, R. R., 1984, "Eurasian snow cover *versus* Indian monsoon rainfall – An extension of the Hahn-Shukla results", *J. Clim. Appl. Meteorol.*, **23**, 171-173.

Ferranti, L., Slingo, J. M., Palmer, T. N. and Hokins, B. J. 1997, "Relationship between interannual and intraseasonal monsoon variability as diagnosed from AMIP integration", *Q. J. R. Meteorol. Soc*., **123**, 1323-1357.

Ferranti, L. and Molteni, F., 1999, "Ensemble simulations of Eurasian snow-depth anomalies and their influence on the summer Asian monsoon", *J. R. Meteorol.*, **125**, 2597-2610.

Hahn, D. J. and Shukla, J., 1976, "An apparent relation between Eurasian snow cover and Indian monsoon rainfall", *J. Atmos. Sci.*, **33**, 2461-2462.

Joseph, P. V., 1978, "Sub-tropical westerlies in relation to large scale failure of Indian monsoon", *Indian J. Meteorol. Hydrol. & Geophys*., **29**, 412-418.

Joseph, P. V., Mukhopadhyaya, R. K., Dixit, N. V. and Vaidya, D. V., 1981, " Meridional wind index for long range forecasting of Indian summer monsoon rainfall", *Mausam*, **32**, 31-34.

Ju, J, and Slingo, J., 1995, "The Asian summer monsoon and ENSO", *Q. J. R. Meteorol. Soc.*, **121**, 1133-1168.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, J., Iredell, M., Saha, S., White, G., Wollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. 1996, "The NCEP/NCAR 40-year Reanalysis Project", *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Kanamitsu, M. and Krishnamurti, T. N., 1978, "Northern summer tropical circulations during drought and normal rainfall months", *Mon. Wea. Rev.,* **106**, 331-347.

Kripalani, R. H. Singh, S. V., Vernekar, A. D. and Thapliyal, V. 1996, "Empirical study on Numbus-7 snow mass and Indian summer monsoon rainfall," *Inter. J. Clim.*, **16**, 23-34.

Kripalani, R. H., Kulkarni, A. and Sabade, S. S., 1998, "Comparison of NCEP/NCAR Reanalysis, Nimbus-7 SMMR and historical Soviet snow depth data sets *vis-a-vis* Indian monsoon rainfall variability", Proc. *First WCRP Int. Conf. On Reanal.* (Silver spring, Maryland, USA, 27-31 October 1997), WCRP, 104, WMO/TD-876, 262-265.

Kripalani, R. H. and Kulkarni, A., 1999, "Climatology and variability of historical Soviet snow depth data: some new perspectives in snow – Indian monsoon Teleconnection", *Climate Dynamics*, **15**, 475-489.

Krishnamurti, T. N., 1971, "Tropical east-west circulations during the northern summer", *J. Atmos. Sci*., **28**, 1342-1347.

Krishnan, R. and Mujumdar, M., 1999, "Remotely and regionally forced pre-monsoon signals over northern India and neighborhood", *Q. J. R. Meteorol. Soc.*, **125**, 55-78.

Meehl, G. A., 1997, "The south Asian monsoon and the tropospheric biennial oscillation", *Jour. of Climate*, **10**, 1921-1943.

Palmer, T. N., Brankovic, C., Viterbo, P. and Miller, M. J. 1992, " Modelling interannual variation of summer monsoon", *J. Climate*, **5**, 399-417.

Parthasarathy, B., Munot, A. A. and Kothawale, D. R., 1995, “Monthly and seasonal rainfall series for All India”, *Report No.* RR-065, Indian Institute of Tropical Meteorology, Pune, p113.

Rajeevan, M., 1993, “ Upper tropospheric circulation and thermal anomalies over central Asia associated with major droughts and floods in India”, *Current Science*, **64**, 4, 244-247.

Sankar-Rao, M., Lau, M. K. and Yang, S., 1996, “On the relationship between Eurasian snow cover and the Asian summer monsoon”, *Int. J. Climatol*., **16**, 605-616.

Soman, J. K. and Slingo, J., 1997, “Sensitivity of Asian summer monsoon to aspects of sea surface temperature anomalies in the tropical Pacific Ocean”, *Q. J. R. Meteorol. Soc*., **123**, 309-336.

Vernekar, A. D., Zhou, J. and Shukla, J., 1995, “The effect of Eurasian snow cover on the Indian monsoon”, *J. Clim*., **8**, 248-266.

WCRP, 1998, “Proceedings of the first WCRP International Conference on Reanalysis”, WCRP-104, WMO/TD-No. 876, p461.