INTERNATIONAL JOURNAL OF CLIMATOLOGY, VOL. 16, 23–34 (1996)

EMPIRICAL STUDY ON NIMBUS-7 SNOW MASS AND INDIAN SUMMER MONSOON RAINFALL

R. H. KRIPALANI AND S. V. SINGH
Indian Institute of Tropical Meteorology, Pune-411008, India

A. D. VERNEKAR
University of Maryland, Washington, USA

AND

V. THAPLIYAL
India Meteorological Department, Pune 411005, India

Received 8 February 1994
Accepted 3 April 1995

ABSTRACT

In this study the relationship between Nimbus-7 snow mass and Indian summer monsoon rainfall (ISMR) for the period 1979–1987 is examined. Results reveal that the January snow mass over two regions of the former USSR—one located north-east of Moscow and the other lying between Mongolia and Siberia—shows a high inverse relationship with subsequent ISMR. However, the snow cover over Eurasia for the month of April shows a significant relation with ISMR. Implications of these connections in long-range forecasting of ISMR are also examined.

KEY WORDS: snow mass; Indian monsoon rainfall; Nimbus-7; correlation

1. INTRODUCTION

One of the most intriguing areas of research has been the study of the interaction between snow cover and various aspects of the atmospheric circulation. Snow cover is a critical component of the climate system because snow-covered land exhibits major differences from snow-free ground owing to the low heat conductivity, high thermal emissivity, low vapour pressure and high shortwave albedo of snow. Snow cover has been shown to exert a considerable local influence on weather variables.

More than 100 years ago, Blanford (1884) hypothesized that varying extent and thickness of the Himalayan snows exercise a great and prolonged influence on the climatic conditions and weather over the plains of north-west India. Blanford (1884) and Walker (1910) were apparently the first to correlate some measure of snow extent with Indian rainfall. The snow accumulation in the Himalayas during spring up to the end of May was in fact the first variable discovered and used for forecasting the summer monsoon rainfall in India. This variable was producing negative correlation with rainfall during the four decades ending 1920. In other words, high snow accumulation in the Himalayas during winter/spring was unfavourable for subsequent Indian rainfall. However, during the subsequent three decades the correlation was unsteady and even positive. After 1950, use of this variable for forecasting was abandoned. Further progress in predicting the monsoon by ground-based snow cover data was limited owing to difficulties in assessing snow coverage.

With the advent of satellite technology, estimates of snow cover have been available since 1966. Hahn and Shukla (1976) used a short-period record (1967–1975) of year-to-year variation of Indian summer monsoon rainfall and compared that with winter snow cover over Eurasia south of 52°N. The availability of more satellite data prompted Dey and Bhanu Kumar (1982, 1983), Dickson (1984), Bhanu Kumar (1986, 1987), Parthasarathy and Pant (1987) and Verma (1987, 1990) to examine Blanford's hypothesis. All these studies showed that the

CCC0899-8418/96/010023-12

correlation was negative, implying that extensive (little) Eurasian snow cover in winter/spring was followed by deficient (excess) summer monsoon rainfall, thus confirming Blanford's hypothesis. Based on the results of these studies, Gowarikar *et al.* (1989) have used the Eurasian snow cover during preceding December as one of the predictor variables in their long-range forecasting of monsoon rainfall.

All the above studies have concentrated on the areal coverage of the snow field, not on the mass field (i.e. snow depth). There are no empirical studies for snow mass–Indian monsoon rainfall connections. However, Barnett *et al.* (1989) investigated the long-standing hypothesis through simulation using a sophisticated atmospheric circulation model. They ran numerous integrations with snowfall rates over Eurasia, both doubled and half the normal. They found that increased (decreased) snow mass over Eurasia leads to a subsequent reduction (enhancement) in precipitation over south-east Asia. A. D. Vernekar, J. Zhou, and J. Shukla (pers. comm. 1991) and Yasunari *et al.* (1991) performed similar experiments with COLA GCM and MRI GCM respectively, and came to similar conclusions. The basic premise of these experiments was that the snow, soil, and atmospheric moisture all act to keep the land and overlying atmospheric column colder than normal during a heavy snow simulation thus reducing the land–ocean temperature contrast needed to initiate the monsoon.

As pointed out earlier, there are no empirical studies connecting the snow mass and Indian monsoon rainfall. Hence, in this study we examine the relationship between Northern Hemisphere snow mass, as derived from the Nimbus-7 satellite, with Indian monsoon rainfall and seek answers for the following questions.

(i) Are there specific regions over the Northern Hemisphere where the snow mass influences the interannual variability of the Indian monsoon rainfall?
(ii) If yes, what is its applicability in long-range forecasting of monsoon rainfall?
(iii) Out of the two snow measures—snow areal coverage and snow mass—which explains more interannual variability in rainfall?

The analysis method applied in this study is simple and straight forward. The data used in this study are described in section 2, and the results of the correlation analysis are detailed in section 3. Finally, in section 4, we discuss briefly the physical mechanism for the snow-mass–monsoon connections and enumerate the main findings of this study. A list of abbreviations used is provided at the end.

2. DATA

The satellite-derived Northern Hemisphere (NH) temporal and spatial snow-cover charts have been produced since November 1966, by the National Environmental Satellite Data and Information Services (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA). Unfortunately, most snow-depth observations were limited to point measurements and were poorly represented.

Since November 1978, the Scanning Multi-channel Microwave Radiometer (SMMR) on the Nimbus-7 satellite has been acquiring passive microwave data that can be used to measure snow extent and calculate snow depth on an areal basis (Chang *et al.*, 1987). Snow cover is a sensitive indicator of climate change, with the position of the southern boundary of snow cover in the NH of particular significance because it is likely to retreat northwards because of sustained climatic warming (Barry, 1984).

Microwave remote sensing can be accomplished either by measuring emitted radiation with a radiometer or by measuring the intensity of the return of a microwave signal with a radar (Hall and Martinee, 1985). Microwaves can penetrate the snow and respond to variations in subsurface properties. Working in the microwave region also permits remote observations of snow under nearly all weather and lighting conditions. The SMMR is a five-frequency, dual polarized microwave radiometer that measures the upwelling microwave radiation at 6·6, 10·7, 18·0, 21·0, and 37·0 GHz. In 1987, the SMMR showed signs of instrument failure. From August 1987 until it was turned off in July 1988, the SMMR operated in a non-scanning mode. For details of the SMMR instrument and the algorithm developed for snow-cover and snow-depth retrieval the reader may refer to Chang *et al.* (1992). The error in the SMMR-derived snow depths is more difficult to determine because there is no reliable data set with a spatially dense enough network with which to compare the SMMR-derived snow depths on a hemispheric basis. The only other data set available with which to derive global snow volume is the data set produced by the Rand

Corporation. Preliminary comparisons between the SMMR and Rand Corporation data sets for snow volume in the NH indicate that the data sets are comparable.

Monthly global snow-depths maps are available for 0·5° latitude by 0·5° longitude grid cells from 85°N to 85°S round the globe. Hence data are available for 720 by 340 grid cells for 106 months from November 1978 through to August 1987. Each map grid element has the values of snow depth in centimetres (3–250 cm). Regions of permanent ice, water, and no data have been identified by code numbers. The above data are available from the National Space Science Data Center (NSSDC), Goddard Space Flight Center, Greenbelt, Maryland.

Because 0.5° by 0.5° was too fine a mesh for the analysis we wished to do, we have prepared averages for a 5° by 5° coarse mesh. We have limited the area to snow over land north of 25°N because there is very little variation in snow cover on an annual basis in the Southern Hemisphere and over 99 per cent of it is confined to the continent of Antarctica. Also we have not included passive effects of the regions of permanent ice. Simple arithmetic averages for the 5° by 5° grids have been prepared depending upon the number of values available in each of the 100 0.5° by 0.5° cells. In 70 per cent of these 5° by 5° blocks the averages are based on more than 20 values (maximum 100). Thus we have snow depth data in centimetres for 72 by 12 (25°N to 85°N, 180°W to 0° to 180°E) blocks.

The Indian summer monsoon rainfall (ISMR) is taken from Parthasarathy *et al.* (1992). The snow-cover data for Eurasia–Northern Hemisphere–North America for the period 1973–1992 have been acquired from the Climate Analysis Center, USA. Some inconsistencies in snow-cover data are treated in section 3.4.

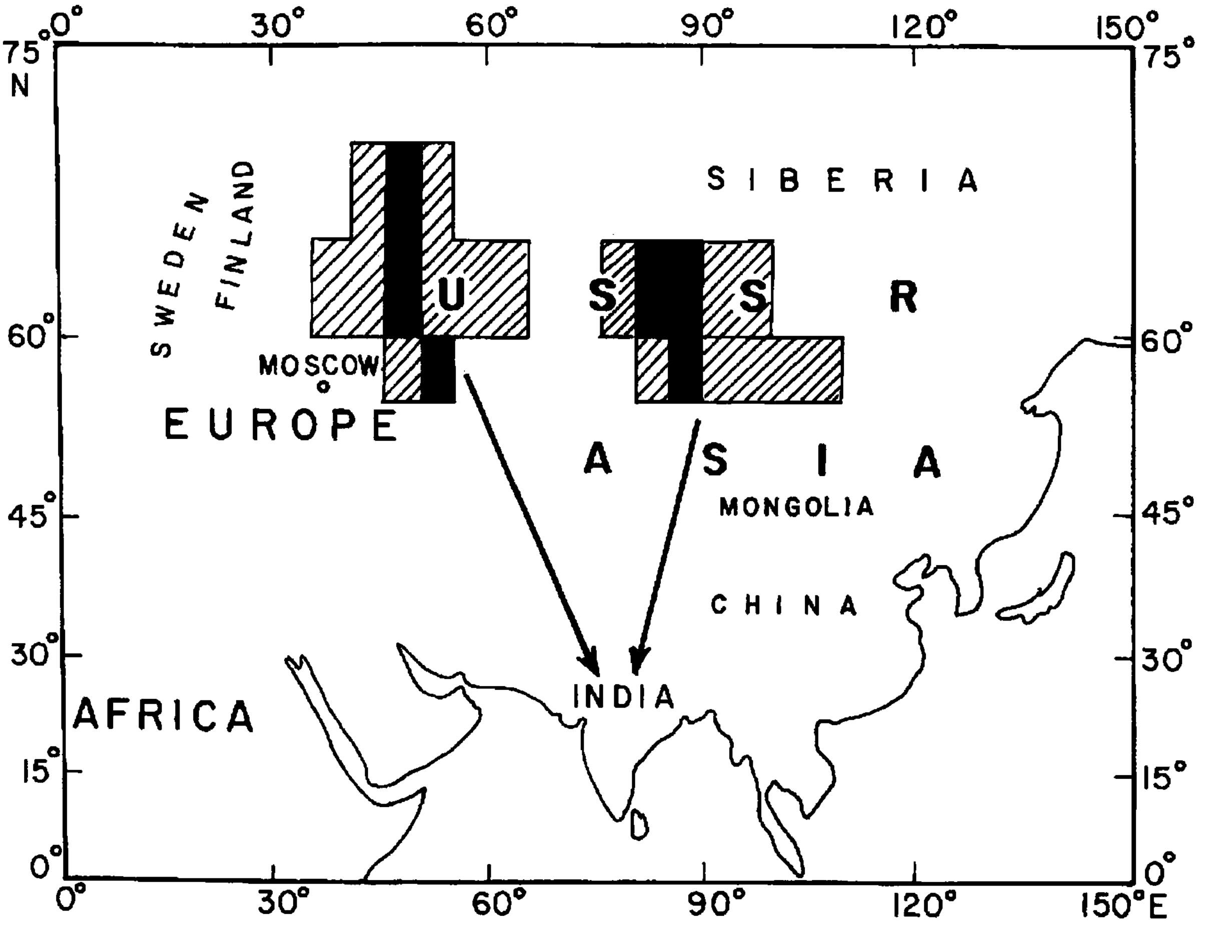

Figure 1. The hatched (dark) area shows the regions where the correlation coefficient of snow depth with the Indian summer monsoon rainfall is numerically greater than 0·7 (0·8)

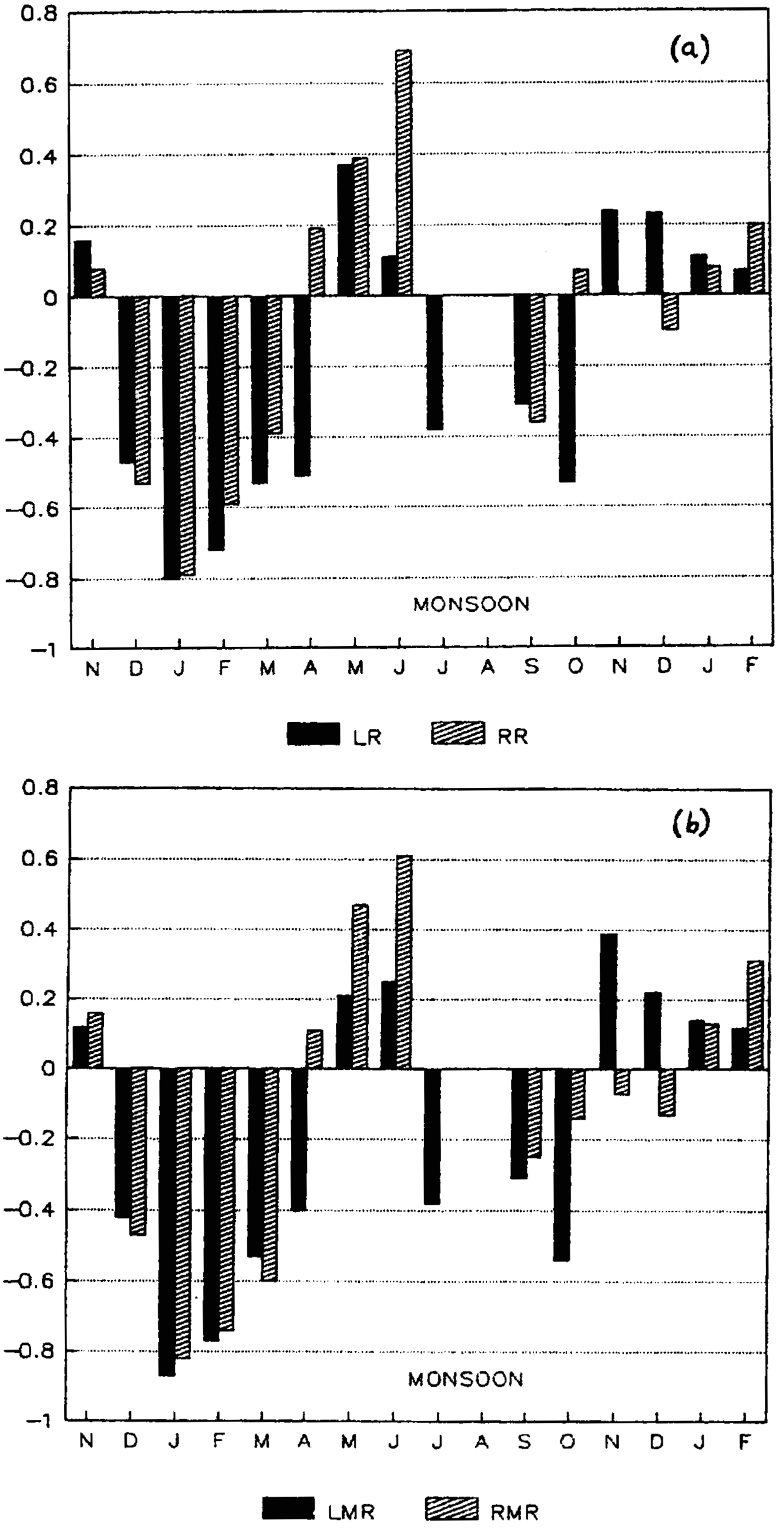

Figure 2. Lag-correlation between the Indian summer monsoon rainfall and the monthly snow depths. (a) For the left region (LR) and the right region (RR). (b) For the left middle region (LMR) and the right middle region (RMR) (See Fig. 1). The Indian summer monsoon period (June through to September) is also indicated (N = November, D = December, J = January, and so on)

In the following section of the paper we describe the results of our analysis. It will be shown that the snow mass (depth) appears to be the key climatological variable in affecting the interannual variability of the ISMR. Before we present the results, a word of caution—these results should be treated as tentative because they are based on limited data of 9 years (1979–1987) only.

3. RESULTS OF THE CORRELATION ANALYSIS

To search objectively for connections between the NH snow depth and monsoon rainfall over India, correlation coefficients (CCs) between the snow depth at each of the 72 by 12 blocks with rainfall of India have been computed for each month separately, starting from preceding November of the summer monsoon (June–September) until the following October. The significant CC for a sample of 10 is 0·71 (0·58) at the 1 per cent (5 per cent) level. The CCs in this analysis are based on a sample of nine values. Because rainfall is the key monsoon variable, the relationship with rainfall only is determined.

3.1. Relationship between snow mass (depth) and rainfall

Significant (at 5 per cent) negative CCs start appearing during December over the eastern hemisphere. The CCs are maximum for the month of January and significant at the 5 per cent level between 10°E to 105°E and 50°N to 70°N. In this large area there are two coherent regions where the CCs are significant at 1 per cent (Figure 1). In each of these coherent regions there are three blocks where the CCs are numerically $\geqslant 0.8$. The maximum

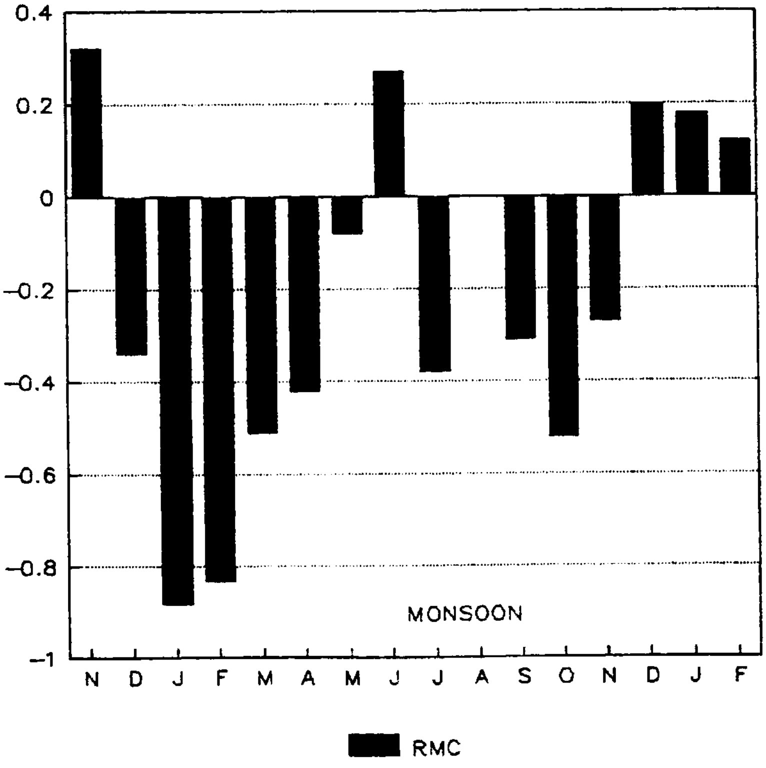

Figure 3. Lag-correlations between the Indian summer monsoon rainfall and the monthly snow depth for the region of maximum correlation (RMC). The Indian summer monsoon months (June through to September) are also indicated (N = November, D = December, J = January, and so on)

correlation is for the block 65°–70°N and 45°–50°E, where the correlation is −0·89. These coherent regions are shown hatched in Figure 1, whereas the blocks with correlation $\leqslant -0{\cdot}8$ have been shaded dark. Thus January snow depth over the former USSR shows significant CCs with Indian monsoon rainfall. The left region lies north-east of Moscow and the right region lies between Mongolia and Siberia. The negative CCs imply that light (heavy) snow mass over these regions in January is followed by a surplus (deficient) summer monsoon season (June through to September) over India.

The CCs still continue to be significant for the month of February but up to 65°E only. This area of significance goes on reducing for the month of March and April. For the month of May the CCs change their sign and become positive for the region lying between 55°E to 80°E and 60°N to 70°N. Thereafter, throughout the monsoon season until October, the CCs become insignificant. There are also some indications of negative correlations significant at the 5 per cent level over a small portion of the Himalayan region lying between 25°N to 35°N and 70°E to 85°E for the months of January and February.

As stated above there are two coherent regions where the CCs are significant at 1 per cent. Incidently each of these regions contain eleven 5° by 5° blocks. Monthly average snow depths for these two regions are computed based on 11 values for the entire data period, i.e. November 1978 through to August 1987. These two regions are designated as the left region (LR) and the right region (RR). Similarly averages for the three blocks for each of the above regions identified showing CC numerically $\geqslant 0{\cdot}8$ were determined. These are designated as LMR (left middle region) and RMR (right middle region). Hence we have four monthly time series of snow depths for the entire data period for LR, RR, LMR, and RMR.

Lag CCs between these time series and the ISMR are computed from the preceding November of the Indian monsoon period until the following February. These results are depicted in Figure 2. Figure 2(a) reveals that the winter time (December through March) snow depth is negatively correlated with rainfall. The maximum correlation is for the month of January (−0·8). The CCs continue to be negative until April for LR. For the months of May and June the CCs become positive and thereafter they appear to fluctuate randomly. Figure 2(b) shows similar features with maximum correlation of −0·87 (−0·82) for LMR (RMR) during January. A fifth time series is considered for the block, which shows maximum (−0·89) correlation, i.e. the block 65°–70°N, 45°–50°E. This region is designated as RMC (region with maximum correlation). Again similar results are seen, as depicted in Figure 3.

The above evidence strongly suggests that the variation in snow depth over these regions plays an important role in modifying the interannual behaviour of the ISMR. Thus the snow mass over these regions explains nearly 50–80 per cent variability in Indian monsoon rainfall.

It must be stressed that the above relationships should be considered as only tentative at this time. Further investigations incorporating longer period data are needed before more exact relationships may be put forth and the nature of these relationships defined.

In the following subsection the variations in snow depth over RMC are compared with variations of monsoon rainfall. Further a simple linear regression equation is developed between snow mass and rainfall.

3.2. *Snow mass over RMC—Monsoon rainfall*

Figure 4(a) shows the year-to-year variation of January snow-depth departures for the RMC series. The snow-depth departures for each year are obtained by subtracting the 9-year January mean from each year. The 9-year mean snow depth for this region is 24·0 cm. Along with these snow-depth departures, Indian summer time rainfall departures are also plotted as a function of year. An examination of this figure reveals that for all the 9 years, the year-to-year tendency in the snow depth over RMC is opposite to that of ISMR. Incidently the mean ISMR based on these 9 years is 798.9 mm, below the long-term normal (≈850 mm Parthasarathy *et al.*, 1992).

Because the January snow mass shows the maximum relationship, it gives sufficient lead time to foreshadow the subsequent June–September ISMR. Hence a simple linear regression equation is developed between snow depth over RMC and ISMR. The observed and estimated rainfall for the 9-year period are shown in Figure 4(b). This figure clearly indicates that the estimated values match very well with the observed values.

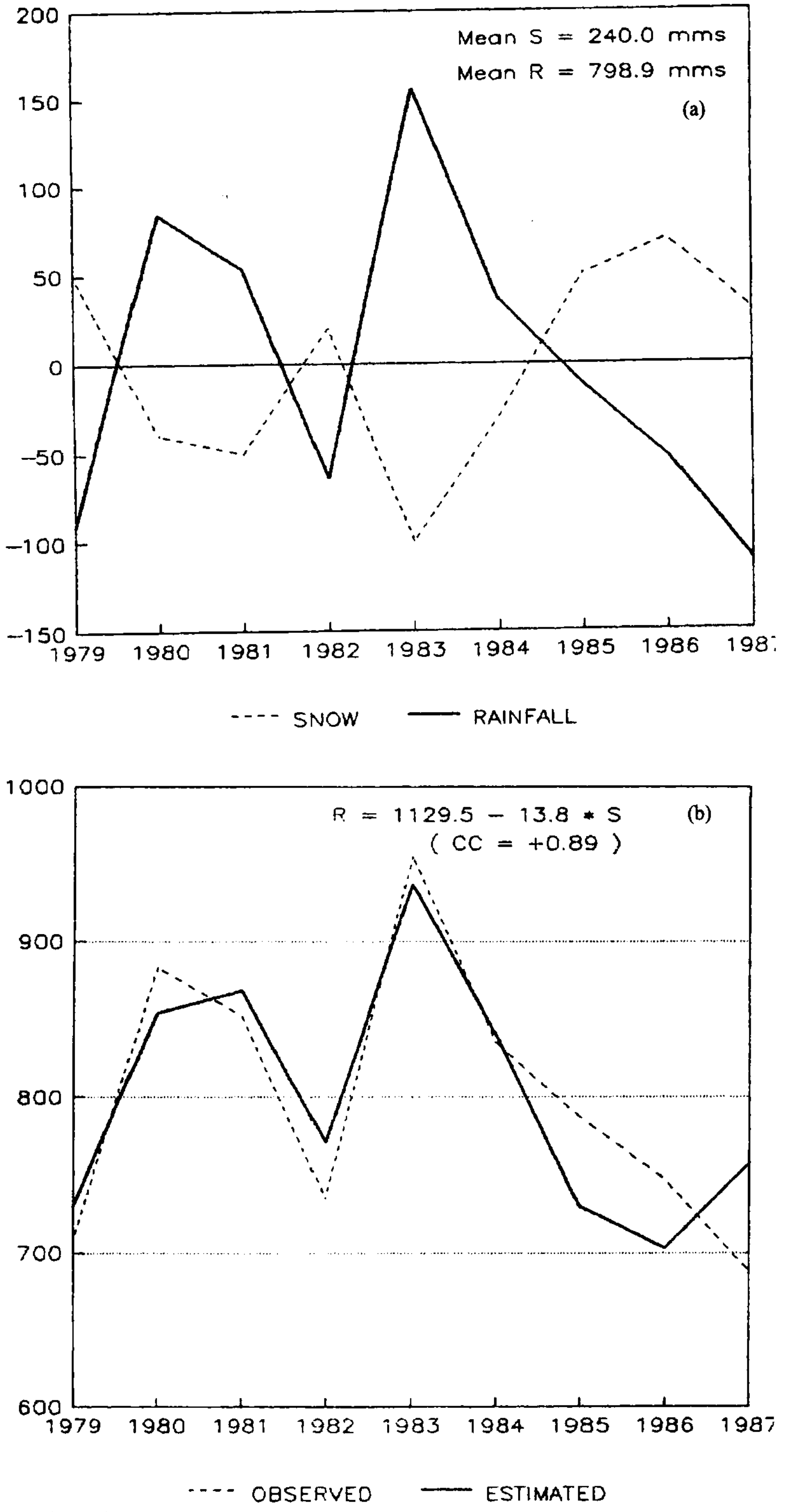

Figure 4. (a) Year-to-year variations of January snow depth departures over the region of maximum correlation (RMC) and the departures of the Indian summer monsoon rainfall. The dashed line is for the observed snow(S) and the solid line is for the estimated rainfall (R). The years are indicated along the *x*-axis and the departures in millimetres along the *y*-axis. (b) The observed (– – –) and the estimated (——) Indian monsoon rainfall. The simple linear regression between the rainfall (R) and the snow(S) is also shown. CC = correlation coefficient between observed and estimated rainfall. The years are indicated along the *x*-axis and the rainfall (mm) along the *y*-axis.

3.3. Relation between snow mass and rainfall over various regions of India

In this section, we attempt to investigate whether within the Indian monsoon region, the snow–monsoon relationship varies from one location to another. Hahn and Shukla (1976) also computed CCs between Eurasian winter snow cover and summertime rainfall anomaly of each meteorological subdivision. They found that values of the individual CC were mostly negative, and the largest negative CC for the 10 subdivisions lies between 13° and 22°N. Monsoon depression tracks and the monsoon trough tend to lie north of this region.

Here we have done a similar analysis and correlated snow depth over RMC with rainfall of the 52, 2·5° by 2·5° blocks. Daily rainfall data for these 52 blocks for June to September 1901–1990 were prepared for study of the intraseasonal and interannual low-frequency monsoonal oscillations (Singh *et al.*, 1992). From this data set monthly/seasonal data for the period 1979–1987 have been extracted for analysis in this study. The CCs for January snow depth over RMC and rainfall over each of these 52 blocks, separately for each month—June, July, August and September—and the season as a whole have been computed.

From Figure 5 it is apparent that the CCs for June are varied and insignificant. For July, except for north-east India, the CCs are negative throughout the country, and significant along the western parts of India, in particular over the region centred over 22°N, 72·5°E (CC = – 0·8). Surprisingly the CCs for August are less in magnitude. However, the CCs for September are spectacular with a maximum centred over 23°N, 73°E (CC = – 0.9). The seasonal rainfall also shows a similar pattern to September, with an additional centre located around 15°N, 79°E, and correlation is significant at the 5 per cent level. These relationships may provide useful information for monthly/seasonal interannual prediction of regional Indian monsoon rainfall, especially over western parts where the relations are strongest.

Having seen the importance of snow mass in influencing the interannual behaviour of monsoon rainfall, in the next subsection we investigate the relationship between areal extent of snow and the monsoon rainfall.

3.4. Relationship between areal snow cover and monsoon rainfall

Before we present the results of the relationships between Eurasian–Northern Hemisphere–North American snow cover and Indian monsoon rainfall, we give a brief history of the methods used to produce the snow-cover charts.

Northern Hemisphere snow charts have been produced by NOAA since 1966. Since 1967, the weekly maps have been based on photo-interpretation of visible imagery from the visible scanning radiometer of the NOAA Satellite system. However, it is recognized that in early years the snow extent was underestimated. Charting improved considerably in 1972 with the deployment of the very high resolution radiometer (VHRR) on board NOAA polar-orbiting satellites. Since 1972, charting accuracy is such that this product is considered suitable for continental-scale climate studies (Wiesnet *et al.*, 1987). Since 1990, a 1·6 μm channel has been introduced on the Advanced VHRR leading to the much improved detection of snow and ice cover. Thus the quality of the snow-cover data has varied since 1967.

A major inconsistency in NOAA monthly snow cover areas has been identified recently (Robinson *et al.*, 1990). Prior to 1981, continental areas were calculated from monthly summary charts, which consider a cell to be snow covered if snow is present on two or more weeks during a given month (Dewey and Heim, 1982). Since 1981, NOAA has produced monthly areas by averaging areas calculated from weekly charts. Tests comparing these two methods showed areas computed using monthly approach to be from several hundred thousand to over three million square kilometres greater than those calculated using weekly areas in all months except August. The offsets were not consistent. Unfortunately, to date, published time series of snow cover have used values supplied by NOAA, thus any publication with snow cover data covering both the pre- and post-1981 intervals contain inconsistencies (Robinson *et al.*, 1990).

In view of the above, we performed several experiments taking different periods of snow-cover data. Lag-correlation between Indian summer monsoon rainfall and the continental snow-cover over Eurasia, Northern Hemisphere and North America from the preceding November until the following December were computed. From the several experiments run, two important points emerged. (i) It was always the April snow cover over Eurasia and Northern Hemisphere that showed maximum correlation with ISMR. (ii) When we excluded the recent years data the correlations were insignificant and numerically less than 0·3. The results presented in Figure 6 are based on the

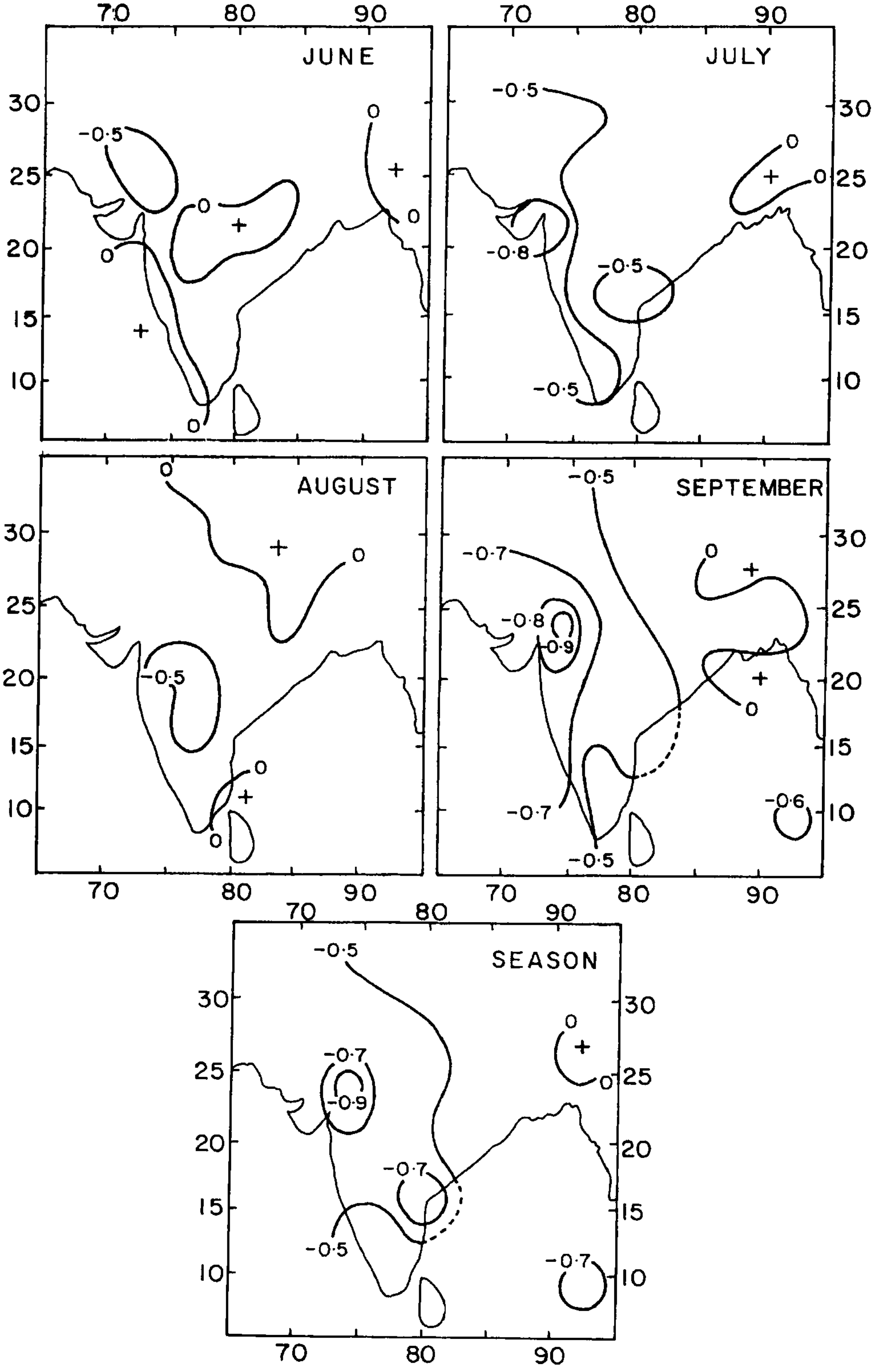

Figure 5. Spatial distribution of the correlation coefficients between January snow depth over the region of maximum correlation (RMC) and monthly rainfall over various locations of India (season = June through to September)

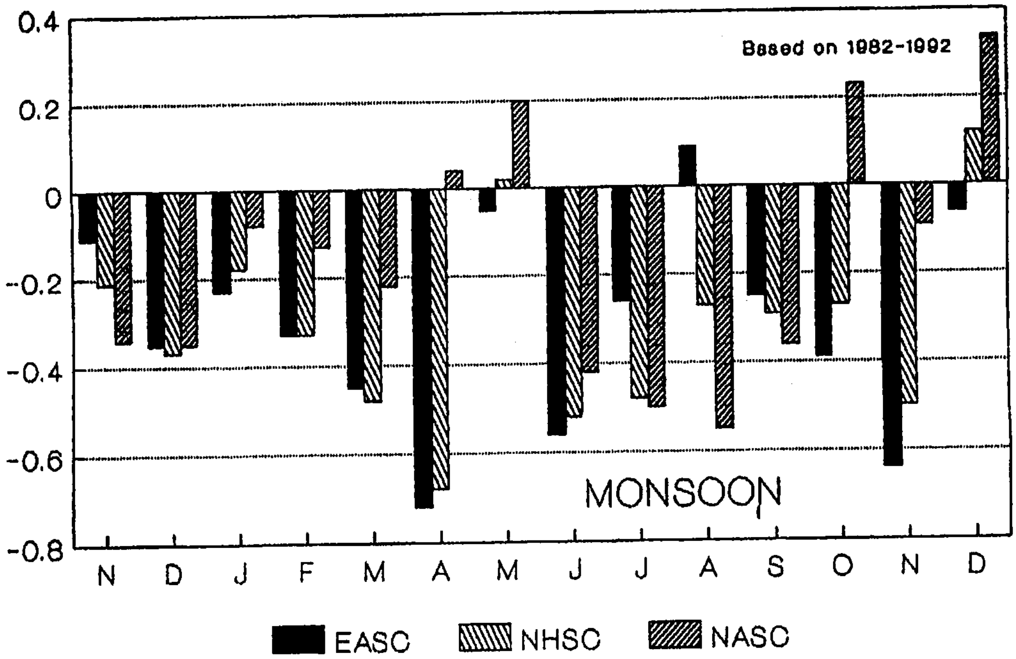

Figure 6. Lag-correlations between the Indian summer monsoon rainfall and the monthly Eurasian snow cover (EASC), Northern Hemisphere snow cover (NHSC) and North America snow cover (NASC). The Indian summer monsoon period (June through to September) is indicated (N = November, D = December, J = January and so on)

consistent data set (1982–1992). Except for the month of May the CCs are negative throughout. However, the maximum correlation is not during the winter period but at the beginning of spring. Significant correlation at the 1 per cent level is seen for the month of April with Eurasian (−0·72) and Northern Hemisphere (−0·68) snow cover. The inverse relationship signifies that extensive (little) Eurasian snow cover leads to deficient (excess) ISMR. Verma (1987, 1990) carried out a similar analysis using data for a 20-year period (1968–1987). He found that Eurasia snow cover (EASC) for December gave numerically the highest correlation (~ −0·44), but correlation for EASC during other individual months was numerically less than 0·3 and even less than 0·2.

In view of the inconsistencies noted in the snow cover data recently, we believe that the results presented in this paper should be treated as correct. However, we are unable to justify why the April snow cover over Eurasia should show maximum correlation, whereas the snow mass shows a maximum relationship during January. However, from the above it is clear that the surface forcings of Northern Hemisphere snow mass and Eurasian snow cover play an important role in the interannual variability of the Indian summer monsoon.

4. DISCUSSION AND CONCLUSIONS

In this study we have examined the linkage between NH snow mass and monsoon rainfall. The results described here in conjunction with those for the snow cover confirm the effects of snow on the interannual variability of the Indian summer monsoon. This finding is consistent with the model-simulated results. The results presented here are based on very short data series. It is quite possible that such high correlations will not be present in a much longer record. Nevertheless, the results are encouraging and monitoring of snow mass should be continued.

This study has not addressed the physical mechanism responsible for the pattern of interannual variability in ISMR. The mechanism responsible for the snow-monsoon linkage have been studied by others (e.g. Barnett *et al.*, 1989; Yasunari *et al.*, 1991). Barnett *et al.* (1989) tested the albedo-feedback hypothesis with realistic distribution of snow cover over Eurasia and the hydrological feedback hypothesis with varying snow depth and its subsequent melting, evaporation, and influence on soil hydrology. They concluded that the albedo effect associated with anomalous spatial distribution of snow cannot by itself have a sustained impact on subsequent monsoon development. They suggested that the hydrological feedback associated with Eurasian snow is mainly responsible for the snow–monsoon connection. Snow melting and evaporation processes influence the soil hydrology, change the meridional gradient of the temperature of the land and overlying atmosphere, and in turn affect the development of the following monsoon. They found that in general a heavier (lighter) than normal snow pack over Eurasia led to a weaker (stronger) than normal or poor (good) monsoon, thus verifying the hydrological feedback hypothesis.

There have been several studies recently on the linkages between Eurasian snow cover, Indian monsoon, and the El Niño-Southern Oscillation (ENSO) phenomenon. Khandekar (1991) has postulated that a lighter (heavier) than normal Eurasian snow cover followed by a surplus (deficient) monsoon season over India and vicinity could trigger an El Niño (inverse El Niño or La Niña) event in the eastern equatorial Pacific four to five seasons following the surplus (deficient) monsoon season. Song Yang (1993) on the other hand found that something unusual occurs to the Eurasian winter snow cover and ISMR connection during El Niño years. He postulates that the inverse snow–monsoon relationship is usually broken by El Niño events. Thus it appears that land surface processes over Eurasia play a vital role in the climate variations of that region and also may be important to global climate variations, e.g. ENSO events.

We have determined the relationship between the snow depth over RMC and other regional and global parameters influencing the variability of the Indian monsoon rainfall using 9 years of data. We found that the correlations between snow depth and subtropical ridge position over India, the Southern Oscillation Index and the Northern Hemisphere surface temperature to be −0·36, −0·35 and −0·79, respectively. The signs are consistent with known facts.

Finally, we conclude by enumerating our main findings of this study.

(i) January snow depth over two regions—one located north east of Moscow and the other lying between Mongolia and Siberia—shows high correlation with Indian monsoon rainfall, with values exceeding 0.8. The inverse relationship implies that heavier (lighter) than normal snow depth over these regions leads to deficient (excess) ISMR.
(ii) April Eurasian snow cover shows high correlation with ISMR, exceeding − 0·7. The inverse relationship implies that extensive spring snow cover over Eurasia is deterrent to monsoon rainfall and vice versa.
(iii) Our results, although preliminary may provide useful information for predicting seasonal and monthly rainfall over India nearly 4 months before the onset of the summer monsoon season.

Although the SMMR instrument on Nimbus-7 satellite has stopped functioning, the Special Sensor Microwave Instrument (SSM/I) on board the Defense Meteorological Satellite Platform (DMSP) launched in June 1987 is continuing the snow measurements begun in 1978 by SMMR. The results could be re-examined as more years of satellite-derived snow-depth data become available.

ACKNOWLEDGEMENTS

This work was supported under the Indo-US Sub-Commission on Science and Technology between NOAA, US Department of Commerce and DST, Government of India. The work was done at the Indian Institute of Tropical Meteorology, Pune, India. The authors express their thanks to Professor R. N. Keshavamurty, Director and Dr S. S. Singh, Deputy Director, for the facilities provided. Thanks are also due to Dr B. Parthasarathy and Mr R. K. Verma for reviewing the initial draft of the paper and to Mr V. R. Deshpande for help with the graphics.

Finally we thank NSSDC, Goddard Space Flight Center, Greenbelt and Climate Analysis Center, Maryland, USA for the snow-depth and snow-cover data respectively.

ABBREVIATIONS

COLA GCM	Center for Ocean Land Atmosphere General Circulation Model
DMSP	Defence Meteorological Satellite Platform
DST	Department of Science and Technology (Government of India)

EASC	Eurasian snow cover
ENSO	El Niño–Southern Oscillation
ISMR	Indian summer monsoon rainfall
MRI GCM	Meteorological Research Institute General Circulation Model
NESDIS	National Environmental Satellite Data and Information Services
NOAA	National Oceanic and Atmospheric Administration
NSSDC	National Space Science Data Center
NASC	Northern America snow cover
SMMR	Scanning multi-channel microwave radiometer
SSM/I	Special sensor microwave instrument
VHRR	Very high resolution radiometer

REFERENCES

Barnett, T. P., Dumenil, L., Schlese, U., Roeckner, E. and Latif, M. 1989. 'Effects of Eurasian snow cover on regional and global climate variations', *J. Atmos. Sci.*, **46**, 661–685.

Barry, R. G. 1984. 'Possible CO_2-induced warming effects on the cryosphere'. In Morner, N. A. and Karlen W. (eds), *Climate Changes on a yearly to Millennial Basis*, D. Reidel, pp. 571–604.

Bhanu Kumar, O. S. R. U. 1986. 'Eurasian winter snow cover and Indian summer monsoon rainfall', *Proceedings, International Seminar on Long Range Forecasting of Monsoon Rainfall*, New Delhi, 9–10 May.

Bhanu Kumar, O. S. R. U. 1987. 'Seasonal variation of Eurasian snow cover and its impact on the Indian summer monsoon. Large scale effects of seasonal snow cover', *Proceedings Vancouver Symposium*, Publication 166, International Association of Hydrological Sciences, pp. 51–60.

Blanford, H. F. 1884. 'On the connexion of Himalayan snowfall and seasons of drought in India'. *Proc. Roy. Soc. London*, **37**, 3–22.

Chang, A. T. C., Foster, J. L. and Hall, D. K. 1987. 'Nimbus-7 SMMR derived global snow cover parameter', *Ann. Glaciol.* **9**, 39–44.

Chang, A. T. C., Foster, J. L., Hall, D. K., Powell, H. W. and Chien, Y. L. 1992. 'Nimbus-7 SMMR derived global snow cover and snow depth data set—Documentation, Product, Description and Users Guide 4/90', *The Pilot Land Data System Publication*, 17 pp. + coloured photographs.

Dey, B. and Bhanu Kumar, O. S. R. U., 1982. 'An apparent relationship between Eurasian snow cover and the advanced period of the Indian summer monsoon', *J. Appl. Meteor.*, **21**, 1929–1932.

Dey, B. and Bhanu Kumar, O. S. R. U. 1983. 'Himalayan winter snow cover area and summer monsoon rainfall over India', *J. Geophy. Res.*, **88**, 5471–5474.

Dewey, K. F. and Heim, R. 1982. 'A digital archive of Northern Hemisphere snow cover, November 1966 through to December 1980', *Bull. Am. Meteorol. Soc.*, **63**, 1132–1141.

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.

Gowarikar, V., Thapliyal, V., Sarker, R. P., Mandal, G. S. and Sikka, D. R. 1989. 'Parametric and power regression models—new approach to long range forecasting of monsoon rainfall in India, *Mausam*, **40**, 115–122.

Hahn, D. G. and Shukla, J. 1976. 'An apparent relationship between Eurasian snow cover and Indian monsoon rainfall', *J. Atmos. Sci.*, **33**, 2461–2462.

Hall, D. K. and Martinee, J. 1985. *Remote Sensing of Ice and Snow*, Chapman and Hall, London, 189 pp.

Khandekar, M. L. 1991. 'Eurasian snow cover, Indian monsoon and ENSO—a synthesis'. *Atmos. Ocean*, **29**, 636–647.

Parthasarathy, B. and Pant, G. B. 1987. 'Indian summer monsoon and Eurasian snow cover', in *Western Himalayas*, Vol. I, Gyanodaya Prakash Publishers, New Delhi, pp. 61–71.

Parthasarathy, B., Rupa Kumar, K. and Kothawale, D. R. 1992. 'Indian summer monsoon rainfall indices', *Meteorol. Mag.*, **123**, 174–186.

Robinson, D. A. Keimig, F. T. and Dewey, K. F. 1990. 'Recent variations in Northern Hemisphere snow cover', NOAA preprints, *Proceedings, Fifteenth Annual Climate Diagnostics Workshop*, 29 October to 2 November, 1990, Asheville, North Carolina, pp. 219–224.

Singh, S. V., Kripalani, R. H. and Sikka, D. R. 1992. 'Interannual variability of the Madden–Julian Oscillations in Indian summer monsoon rainfall', *J. Climate*, **5**, 973–978.

Song Yang 1993. 'Enso–snow–monsoon associations and seasonal interannual prediction', *Proceedings, Seventeenth Annual Climate Diagnostics Workshop*, 18–23 October, 1992, Oklahoma, pp. 87–92.

Verma, R. K. 1987. 'Satellite monitoring of continental snow cover for climate studies', *Proceedings National Space Science Symposium*, 21–24 December 1987, PRL, Ahmedabad, 390 pp.

Verma, R. K. 1990. 'Recent monsoon variability in the global climate perspective', *Mausam*, **41**, 315–320.

Walker, G. R. 1910. 'Correlation in seasonal variation of weather', *Mem. India Meteorol. Dept.*, **21**, 22–45.

Wiesnet, D. R., Ropelewski, C. F., Kukla, G. J. and Robinson, D. A. 1987. 'A discussion of the accuracy of NOAA satellite-derived global seasonal snow cover measurements. Large scale effects of seasonal snow', *Proceedings, International Association of Hydrological Sciences, Vancouver Symposium*, Publication 166, pp. 291–304.

Yasunari, T., Kitoh, A. and Tokioka, T. 1991. 'Local and remote responses to excessive snow mass over Eurasian appearing in the northern spring and summer climate—a study with the MRI GCM', *J. Meteorol. Soc. Jpn.*, **69**, 473–487.