Relation between Eurasian Snow Cover, Snow Depth, and the Indian Summer Monsoon: An Observational Study

A. S. Bamzai* and J. Shukla

Institute for Computational Sciences and Informatics, George Mason University, Fairfax, Virginia, and
Center for Ocean–Land–Atmosphere Studies, Institute of Global Environment and Society, Calverton, Maryland

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ABSTRACT

Satellite-derived snow cover data for 22 yr and snow depth data for 9 yr over Eurasia have been analyzed to reexamine the possible relation of snow with the Indian summer monsoon. In contrast to the previous studies that use snow cover averaged over all of Eurasia as a single number, the frequency of occurrence of snow at each grid point over Eurasia is correlated with the Indian summer monsoon rainfall. Thus specific geographical regions over Eurasia that are responsible for the well-known inverse relationship between Eurasian snow cover and Indian monsoon rainfall are delineated.

It is found, somewhat surprisingly, that western Eurasia is the only geographical region for which a significant inverse correlation exists between winter snow cover and subsequent summer monsoon rainfall. However, composites for high and low snow cover over Eurasia show spatially homogeneous large-scale patterns of snow cover and surface temperature anomalies. Winters of high and low snow cover for Eurasia are found to be associated with colder and warmer than normal temperatures, respectively, for large regions of the Eurasian continent. 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. Contrary to previous findings, no significant relation is found between the Himalayan seasonal snow cover and subsequent monsoon rainfall.

1. Introduction

The Asian summer monsoon, of which the Indian summer monsoon is a significant part, is a major phenomenon affecting the lives of a large number of people who live in the Tropics. The year-to-year variations of monsoon rainfall affect agriculture, drinking water, energy, and the overall economy of many tropical countries. It is no surprise, therefore, that the understanding and prediction of monsoon variations have been a topic of intense scientific research for more than 100 yr. Charney and Shukla (1981) hypothesized that the slowly varying boundary conditions at the earth's surface can provide the required memory in the climate system to make it possible to predict space–time averaged monsoon circulation and rainfall. Because of the inadequacies of dynamical models (Sperber and Palmer 1996) and the inherent unpredictability of the intraseasonal fluctuations during the monsoon season, it has not been possible to make useful predictions of summer monsoon rainfall using dynamical models. On the other hand, several countries in the monsoon region (notably, China and India) routinely issue long-range forecasts of monsoon rainfall using empirical–statistical techniques. The Asian summer monsoon is a coupled atmosphere–land–ocean phenomenon in which both the largest water mass on earth, the Indian and Pacific Oceans, and the largest landmass on earth, the Eurasian continent, play significant roles. The interannual variations of the Asian summer monsoon rainfall and especially the variations in rainfall over India are significantly correlated with the tropical sea surface temperature and the Eurasian snow cover anomalies. Of all the varying surface conditions, snow cover experiences the largest spatiotemporal fluctuations, thus it has the potential to influence the radiation and energy budget of the lower atmosphere through the effect of heating of the land surface and the diabatic heating of the atmosphere. The combination of land–sea temperature contrast and latent heat release that drives the monsoon system suggests that a diminution or delay of the normal warming of the Asian landmass would possibly give rise to a delayed or weakened monsoon circulation.

More than a century ago, Blanford (1884) suggested that the varying extent and thickness of the Himalayan

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* Current affiliation: Department of Geography, Rutgers—The State University, Piscataway, New Jersey.

Corresonding author address: A. S. Bamzai, % Center for Ocean–Land–Atmosphere Studies, Institute of Global Environment and Society, Inc., 4041 Powder Mill Road, Suite 302, Calverton, MD 20705.
E-mail: abamzai@cola.iges.org

snow cover can exert some influence on the climatic conditions and weather over the plains of India. He associated the increased winter snow cover in the northwest Himalayas with decreased rainfall over the plains of western India. Walker (1910) extended these results and found a negative correlation between the amount of total accumulated snow depth at the end of May and the amount of summer monsoon rainfall over India during the period 1876–1908, and he used Himalayan snow as one of the predictors of monsoon rainfall. However, during the 1960s, the India Meteorological Department removed snow accumulation from the list of predictors routinely used for the long-range forecasting of summer monsoon rainfall. Interest in the snow–monsoon relation was revived after an inverse relationship between satellite-derived Eurasian winter snow cover and subsequent Indian summer monsoon rainfall was reported (Hahn and Shukla 1976).

The physical basis for a Eurasian snow–monsoon relation was presented by Shukla (1984) and Shukla and Mooley (1987). The memory of anomalous winter snow in the climate system resides in the wetness of the underlying soil as snow melts during the spring and summer seasons. Excessive snow anomalies in winter and spring give rise to colder ground temperature in the subsequent summer because a substantial fraction of the available solar energy during spring and early summer goes toward melting the snow and evaporating water from the wet soil rather than toward heating the ground. Excessive snowfall in the early part of winter also tends to reduce solar radiation in winter by increasing the surface albedo, thus resulting in persistence of colder temperatures. It is the colder ground temperature over Eurasia during summer that is considered to be responsible for weaker monsoons.

Numerous research papers have been published investigating the snow–monsoon relationship (Dey and Bhanukumar 1982, 1983; Dickson 1983, 1984; Ropelewski et al. 1984; Dey et al. 1985; Khandekar 1991; Yang and Lau 1995, 1996; Yang 1996; Parthasarathy and Yang 1995; Sankar-Rao et al. 1996). The relationship between Eurasian–Himalayan snow cover and the large-scale Chinese rainfall has also been a topic for a few research papers (Chen and Yan 1981; Zhao 1984; Yang and Xu 1994). Possible influence of the Eurasian snow on the general circulation of the atmosphere has been suggested by several researchers (Fu and Fletcher 1985; Morinaga and Yasunari 1987; Kodera and Chiba 1989; Yasunari 1990, 1991; Yasunari and Seki 1992; Wang and Yasunari 1994; Li 1994; Yanai and Li 1994; Li and Yanai 1996). The purpose of this paper is to reexamine the Eurasian snow–monsoon relationship. Many of the previous observational studies (Hahn and Shukla 1976; Dickson 1984; Sankar-Rao et al. 1996) have used the Eurasian snow cover as a single number representing average snow cover over the entire Eurasian continent. In this paper, satellite-derived snow cover and snow depth data are analyzed at each grid point over Eurasia to delineate the specific geographic regions for which snow cover fluctuations might be related to the Indian monsoon rainfall.

2. Analysis of snow and monsoon data

a. Datasets

The National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data and Information Service (NESDIS) dataset used in this study is the weekly gridded dataset spanning the period January 1973–September 1994. Each grid cell contains one bit of information for each week: 0 (for the absence of snow) or 1 (for the presence of snow). The digitized snow cover data is on a 2° × 2° Northern Hemisphere grid from 20° to 90°N. The grid cell area ranges from 16 000 km^2 at high latitudes to 42 000 km^2 at low latitudes. Weekly snow cover derived from the NOAA/NESDIS satellites consists of digitized maps prepared from visible imagery from NOAA polar-orbiting satellites supplemented by the Geostationary Operational Environmental Satellite and Meteosat. Since the snow cover data for a grid point is in binary form (snow or no snow on a weekly basis), the interannual variability of snow cover at a point is a measure of the interannual variability of the frequency of occurrence of snow at that point.

For snow depth, the fine resolution, albeit shorter time series, of monthly means of the *Nimbus-7* National Aeronautics and Space Administration scanning multichannel microwave radiometer data for the entire globe for the period November 1978–August 1987 has been utilized (Chang et al. 1987, 1990, 1992). The brightness temperatures at 37 and 18 GHz were used to estimate the snow depth using the following equation (Chang et al. 1987): $\mathrm{SD} = 1.59(T_{18} - T_{37})$, where SD is the uniform snow depth (in 10^{-2} m), and T_{18} and T_{37} are the brightness temperatures at 18 and 37 GHz, respectively. The snow density is assumed to be 300 kg m^{-3} and the average snow grain size is assumed to be 0.35×10^{-3} m. The constant 1.59 is derived by using the linear portions of the 37- and 18-GHz responses to obtain a linear fit to the difference between these two channels. The total snow-covered area derived from snow depth data is typically about 10% less than the snow cover data (Foster et al. 1994, 1996) because passive microwave sensors cannot detect shallow dry snow less than 5×10^{-2} m in depth.

The monsoon dataset used for this study is the all-India summer monsoon rainfall, which is an index based on the observed area-weighted average June–September (JJAS) rainfall from 306 rain gauge stations distributed over the entire Indian subcontinent (Mooley and Parthasarathy 1984; Parthasarathy et al. 1994). The surface air temperature dataset used here is the 1946–98 Climate Anomaly Monitoring System data (Ropelewski et al. 1985). The station data have been interpolated to an

R40 Gaussian grid corresponding to an approximate resolution of 1.76° latitude × 2.81° longitude.

b. Method of analysis

The seasonal climatology of snow cover frequency for the period 1973–94 was constructed using the NOAA/NESDIS snow cover data. The mean snow cover frequency for a given grid cell (i, j; the indices i and j denote longitude and latitude) and season is calculated by summing the number of weeks in that season for which snow cover was present for a cell and expressing this number as a fraction of the total number of weeks possible in that season for the period of the entire dataset. If w_{ij} is the total number of weeks that had a value of 1 (presence of snow) during the winter season, and if w is the total number of weeks during the winter seasons, then the winter climatology for snow cover frequency, W_{ij}, is given by $W_{ij} = w_{ij}/w$.

The seasonal climatologies were constructed separately for the boreal winter [December–March (DJFM)] and spring [April–May (AM)]. The fractional value of the climatology at any location is thus a measure of the frequency of snow being present in a given season. For example, a value of 0.9 for W_{ij} implies that for 90% of the time that grid box was covered with snow.

The seasonal anomaly of snow cover frequency at each grid point was calculated as the difference of the seasonal snow cover frequency from its climatological value. The standard deviation of winter and spring snow cover was computed from the these seasonal anomalies. The units are in percentage snow cover (snow cover frequency × 100). The spatial average weekly snow cover for a geographical region was calculated by summing the area of all grid cells that had snow on the ground for that week. Monthly snow cover was calculated by averaging the contribution from the snow cover for the weeks that fell within a specified month.

3. Results

a. Snow cover, snow depth, and Indian summer monsoon rainfall anomalies

Figure 1 shows the winter (DJFM) climatology and standard deviation for the Northern Hemisphere for the period 1973–94. A large region of Eurasia is covered with snow for more than 90% of winter and the interannual variability of snow cover is nearly zero for the northern areas of Eurasia and very low (between 5% and 10%) for a large area. Since snow cover by itself gives no information on snow mass, the examination of the snow–monsoon hypothesis is greatly restricted, because the regions of high snow cover and low interannual variability of snow cover contribute minimally to the correlation with monsoon rainfall when, in fact, it is likely that the actual role of snow over these areas may be greater.

Figure 1b shows the interannual variability of winter snow cover. There is a region of high interannual variability around 40°N surrounded on either side by regions of lower variability. Regions of maximum interannual variability for winter months are the interior of the North American continent, the Rocky Mountains, eastern Eurasia, the Himalayan region, and western Eurasia. The northernmost regions of both continents are largely snow covered during winter and thus exhibit very little interannual variability. The decrease in snow cover from winter to spring is apparent in Fig. 2. The only regions with greater than a 75% likelihood of snow cover on the ground are the mountainous regions of both continents and the extreme high latitudes. The lower panel of Fig. 2 shows that during northern spring, regions of highest snow cover variability are the Himalayas and the eastern Eurasian region (above 55°N). Figure 3a shows maps of correlation between winter snow cover and winter surface temperatures and Fig. 3b between winter snow cover and spring surface temperatures. Significant correlation between snow cover and subsequent surface temperature is evident over the interior of the Eurasian continent at mid- and high latitudes, and this supports the basic premise of the snow–temperature–monsoon relationship.

Trends in the snow cover data were examined for all seasons and the largest (decreasing) trend was found in spring months in agreement with previous results (Robinson et al. 1993; Groisman et al. 1994). In calculating the correlation with monsoon rainfall anomalies, the linear trend in snow cover and Indian monsoon rainfall was removed. Using these detrended data, correlation coefficients were computed between the monsoon rainfall anomalies and the seasonal snow cover frequency anomalies for each grid area over Eurasia.

Maps of correlation coefficients for DJFM and AM seasons are shown in Fig. 4. A nine-point spatial smoothing was applied before plotting the results. Correlation values of 0.37 and 0.43 are significant at the 90% and 95% levels, respectively. There is an inverse correlation for a large coherent region of western Eurasia (40°–60°N, 10°W–30°E) during DJFM that persists through the AM season. There are no regions of significant positive correlation. The snow cover in the Himalayan region appears to be correlated positively with the Indian monsoon rainfall.

Correlation between snow depth and JJAS Indian rainfall was also examined; however, the results are not presented because the snow depth data are available only for 9 yr. The correlation is high in a contiguous large region of central Eurasia, which is in agreement with the results of Kripalani et al. (1996), who used snow depth data at a coarse resolution of 5° × 5°.

b. Regional snow cover and Indian summer monsoon rainfall

Correlation between regional snow cover and monsoon rainfall anomalies was computed after removing a linear

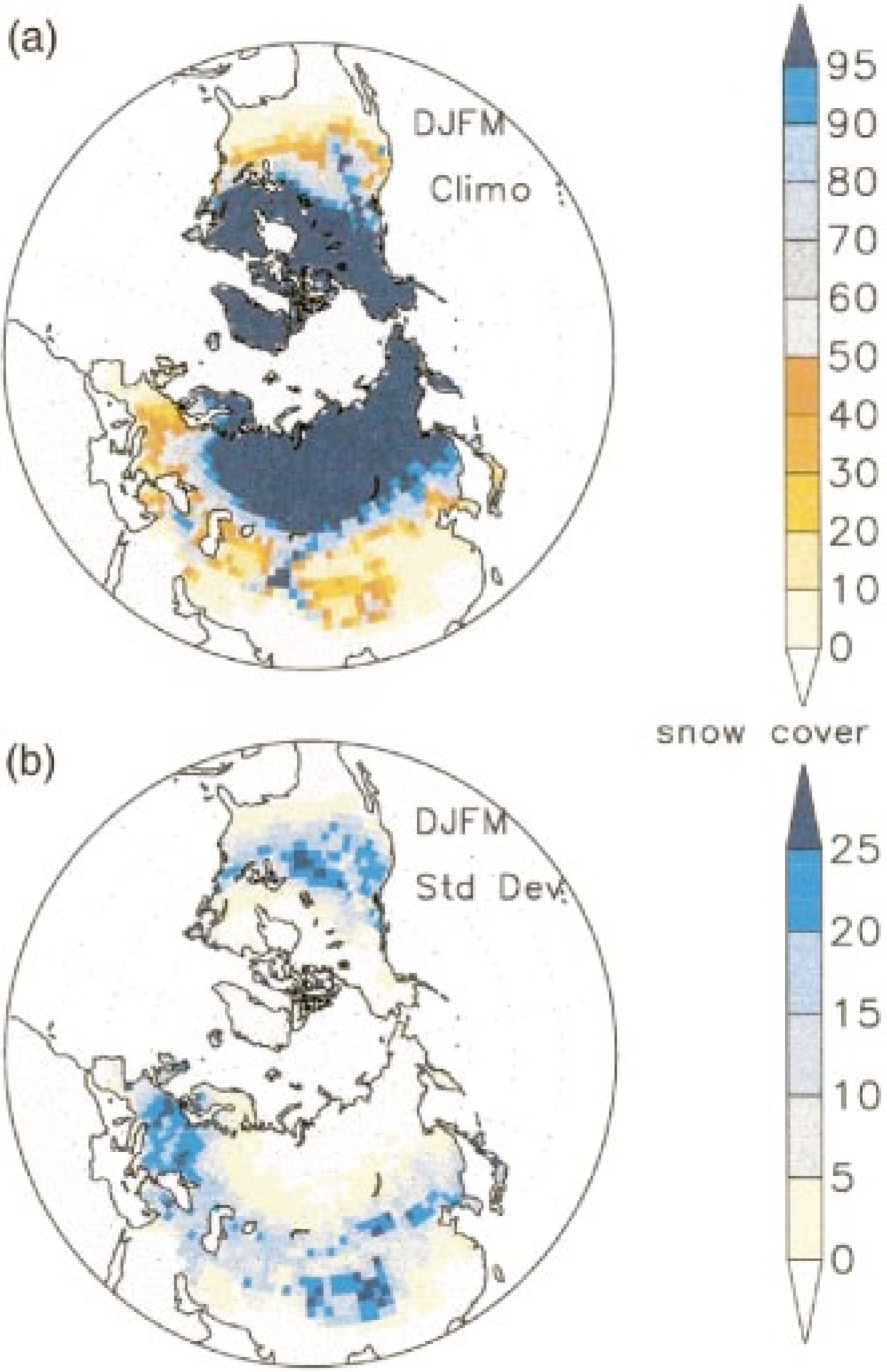


FIG. 1. Northern Hemisphere DJFM (a) snow cover climatology and (b) standard deviation. Results are based on data for the period 1973–94. Unit for snow cover is the % of snow cover on ground (snow cover frequency × 100).

trend from both datasets. To facilitate a comparison with previous studies, the DJFM snow cover anomalies for four regions were correlated with subsequent JJAS India summer rainfall anomalies. The results for western Eurasia, all of Eurasia, southern Eurasia, and the Himalayas are shown in Fig. 5. In these calculations, the region selected for western Eurasia is defined by 40°–60°N, 10°W–30°E; southern Eurasia is the region of Eurasia south of 50°N, similar to the area used by Hahn and Shukla (1976). The largest correlation is found with the western Eurasian snow cover (−0.63), followed by Eurasia (−0.34). The correlation coefficients between Eurasian snow cover anomalies and the Indian monsoon rainfall anomalies averaged for DJFMAM, DJFM, and AM

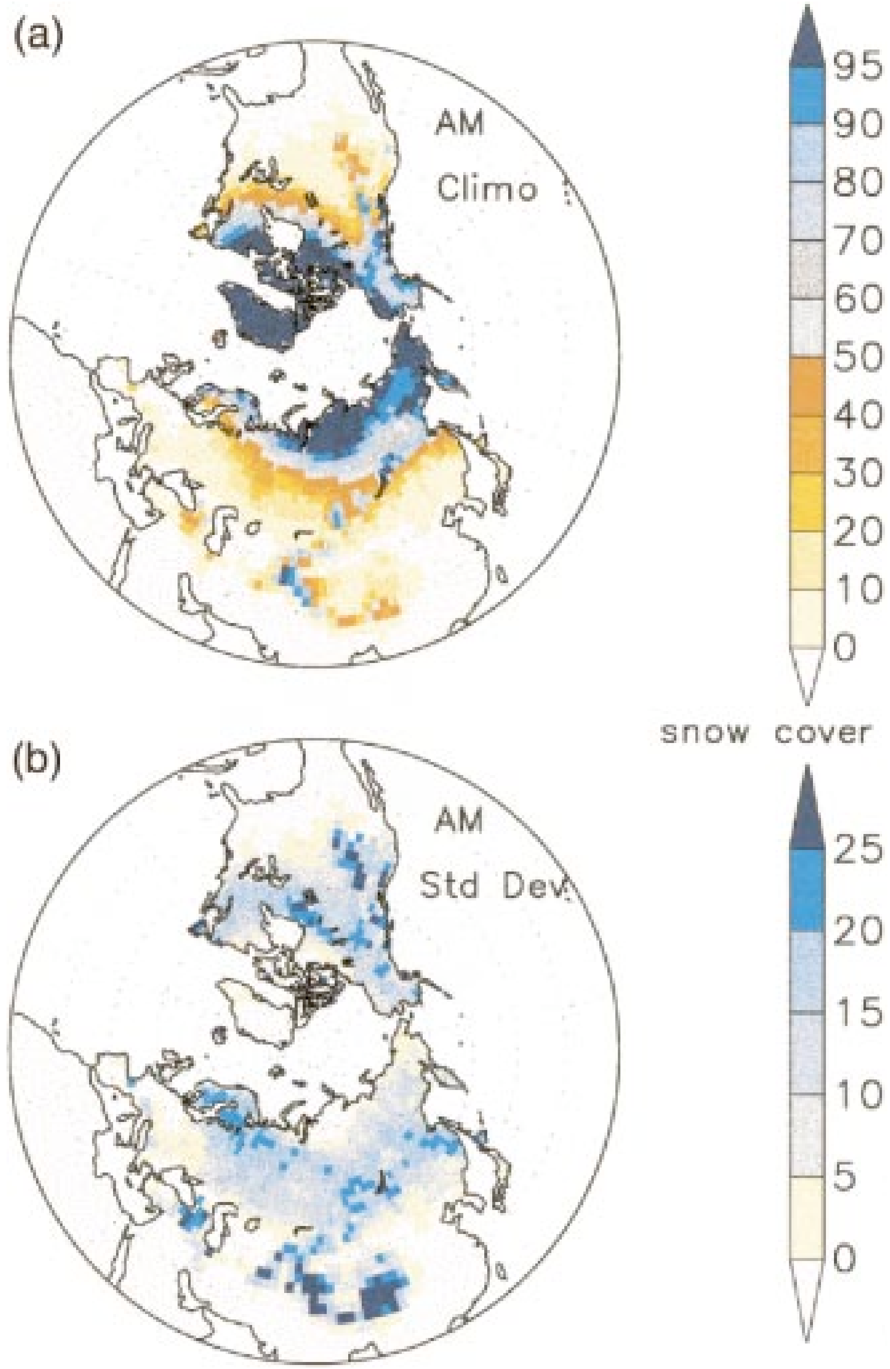


FIG. 2. Northern Hemisphere AM (a) snow cover climatology and (b) standard deviation. Results are based on data for the period 1973–94. Unit for snow cover is the % of snow cover on ground (snow cover frequency × 100).

for the 1973–94 period are −0.39, −0.34, and −0.28, respectively. A correlation coefficient of 0.43 is significant at the 95% level. The regions of southern Eurasia and the Himalayas have high interannual variability for winter and spring snow cover but are poorly correlated with the subsequent monsoon rainfall. There were only a few years for which winter snow cover anomalies persisted through the spring season. DJFM as well as AM Eurasian snow cover was high only for one year, 1985, and low for three years, 1975, 1989, and 1990. In all such years, the inverse snow–monsoon relationship was found to be valid.

c. Composite analysis for high and low snow cover over Eurasia

Composite maps of snow cover and surface temperature were constructed by averaging for the years with high and low snow cover over Eurasia (Fig. 5b). Years for which snow cover was greater than or less than one standard deviation were included in the composites. The years of high snow cover for which surface temperature data is available are winters corresponding to January 1978, 1979, 1985, and 1987; years of low snow cover are winters corresponding to January 1975, 1981, 1989, and 1990. The DJFM and AM results are shown in Figs. 6 and 7, respectively. The top panel shows the composite difference (high − low) snow cover, and the bottom panel shows the composite difference (high − low) surface temperature. For both the lower panels of these figures, temperature values for grid boxes with missing data have been calculated by interpolation from neighboring grid cells.

As expected from the correlation results, the largest snow cover differences for DJFM are found in the western Eurasian region. However, snow cover and surface temperature anomalies occur over the entire Eurasian region. The occurrence of large-scale snow cover and surface temperature anomalies support the basic premise of the reverse snow–monsoon relationship. The upper panels of Figs. 6 and 7 show that the snow cover anomaly over the Himalayan region is of the opposite sign to that over the northern Eurasia. This observed feature needs to be investigated further.

d. Composite analysis for above- and below-normal Indian summer monsoon rainfall

In the present dataset, years of above-normal monsoon rainfall are 1975, 1983, 1988, and 1994; and years of below-normal monsoon rainfall are 1974, 1979, 1982, 1985, 1986, and 1987. The composite snow cover anomalies for the two sets of years were constructed for DJFM (Fig. 8) and AM (Fig. 9). Figure 8 shows that years of above-normal India summer rainfall are characterized by negative snow anomalies in winter over the western Eurasia region, and vice versa. Above-normal monsoon rainfall years are associated with negative AM snow anomalies (Fig. 9) for central Eurasia (55°–65°N, 10°–40°E). Figures 8 and 9 both suggest an inverse relationship between snow cover over Eurasia and the Himalayan region. These results need to be further examined with longer time series of snow.

During the limited period of the snow depth data (1978–87), there is only 1 yr with above-normal Indian monsoon rainfall (1983) and there are 4 yr of below-normal Indian monsoon rainfall (1979, 1982, 1985, 1986, and 1987). Composite DJFM snow depth anomalies for the two sets of years are shown in Fig. 10. The upper panel for the excess Indian monsoon rainfall shows large-scale winter snow depth anomalies in the central Eurasian region. For years of deficient Indian monsoon rainfall, large-scale positive snow depth anomalies are present in central Eurasia. For the spring season (not shown), no spatially coherent snow depth anomalies were found in the present dataset. Occurrence of snow depth anomalies in the northern parts of Eurasia where snow cover anomalies are quite small reiterates the necessity of studying snow–monsoon relation with snow depth data. However, these results are based on a short time series, and there is a clear need to reexamine these results using a longer time series, possibly including ground station observations.

4. Summary and discussion of results

A detailed analysis of snow cover and snow depth anomalies over Eurasia reconfirms the well-known inverse relationship between the winter season Eurasian snow cover and the Indian monsoon rainfall. However, for the 22-yr period considered here, it is only the western Eurasian region for which the correlation between the winter snow cover anomaly and the Indian monsoon rainfall is found to be statistically significant. This is not surprising because for the eastern Eurasian region snow cover is near 100% for the entire season, and the interannual variability of snow cover is quite small. With the exception of the Himalayan region, interannual variability of the winter season snow cover is the largest for the western Eurasian region.

It is somewhat difficult to put forward a physical mechanism that would explain the influence of the western Eurasian snow cover on the Indian monsoon rainfall. There are two possible explanations for the observed correlation between the western Eurasian snow cover and the Indian monsoon rainfall. One possibility is that both the western Eurasian snow cover and the monsoon rainfall anomalies are the results of low-frequency changes in the planetary scale circulation. We do not know of such a low-frequency phenomena, and therefore we cannot propose this as an explanation for the snow–monsoon relationship. The other possibility is that larger snow cover anomalies over western Eurasia are just a regional manifestation of large-scale snow anomalies over all of Eurasia, and it is the limitation of the binary (snow/no snow) nature of snow cover data that does not allow a quantitative estimate of snow depth anomalies in an otherwise snow covered region. Composite maps of snow cover anomaly indeed show that although the largest winter season snow cover anomalies occur over the western Eurasia, the snow cover anomalies have a very large spatial scale covering the entire Eurasian region. The underlying mechanism for the snow–monsoon relationship is also supported by the observed winter and spring surface temperature anomalies, which have large spatial scales covering nearly the entire Eurasian region.

The snow–monsoon relation is found to hold in all years when the winter snow cover anomalies persist

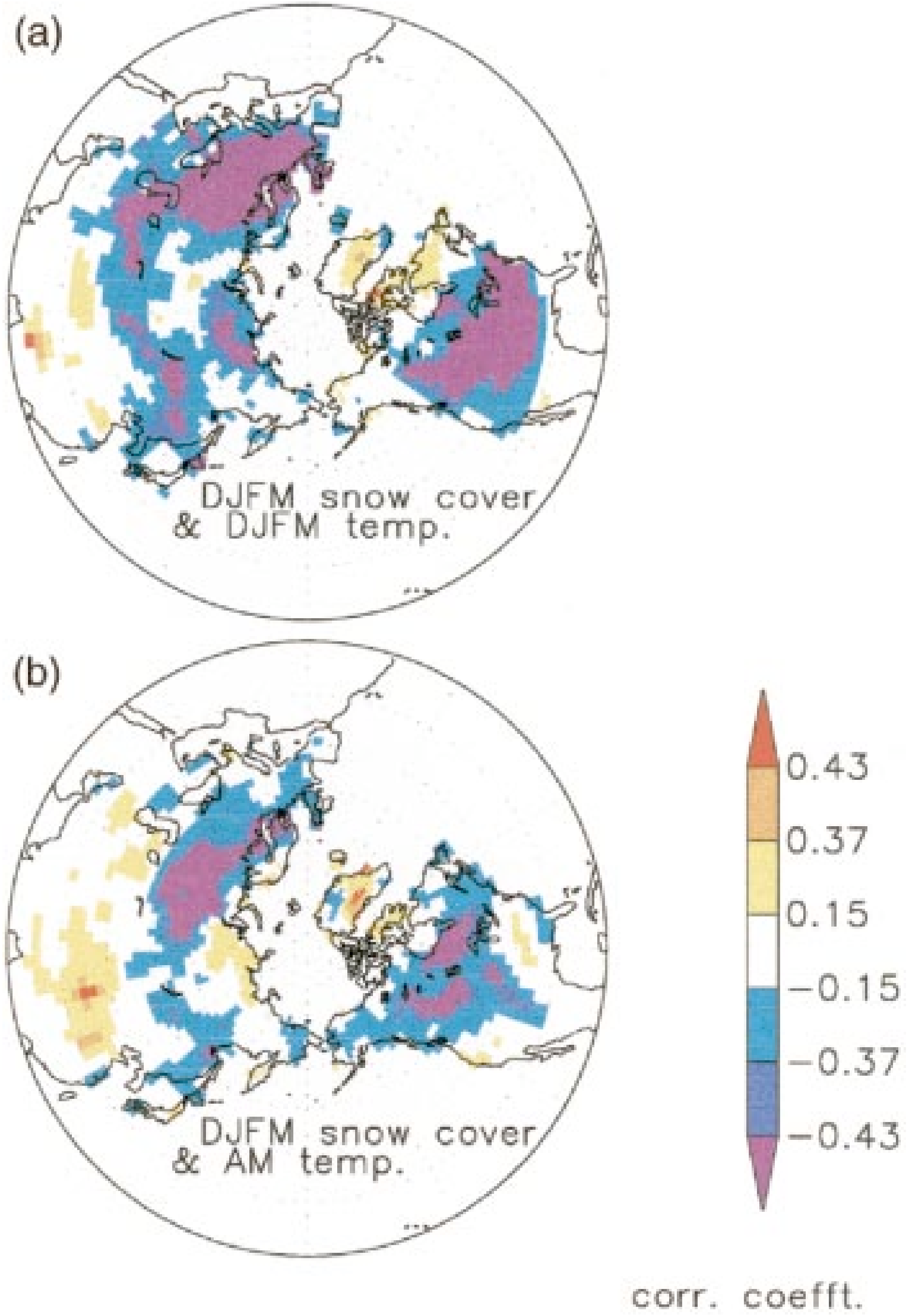


FIG. 3. Correlation coefficient between (a) DJFM snow cover and DJFM surface temperature, and (b) DJFM snow cover and AM surface temperature. Results are based on data for the period 1973–94.

through the spring season. The surface temperature composite analysis also shows, as expected, higher temperatures for years of low snow cover in Eurasia, and vice versa, and that surface temperature anomalies persist from winter to premonsoon months. The results of composite analysis for low and high JJAS India rainfall years also indicate that years of high JJAS rainfall are preceded by years of low winter snow cover over Eurasia, with the largest anomalies over the western Eurasian region. These years of high JJAS rainfall are also associated with low spring season snow over the central Eurasian region. In contrast, years of low JJAS rainfall are preceded by years of high winter snow cover in the western Eurasian region and high spring snow cover in the central Eurasian region. The composite analysis of high and low snow cover over Eurasia shows that these

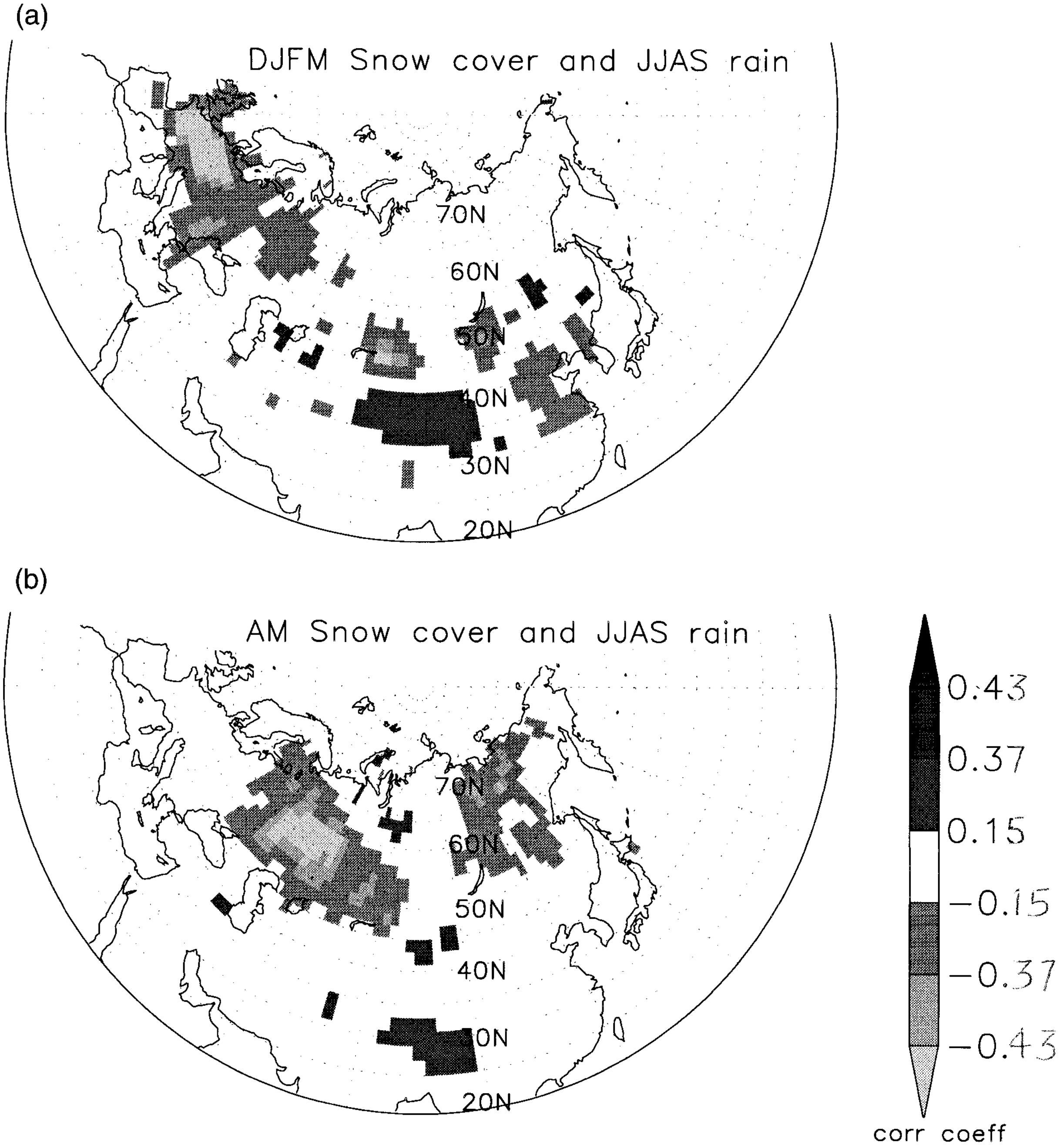


FIG. 4. Correlation coefficient between (a) DJFM snow cover and JJAS Indian monsoon rainfall and (b) AM snow cover and JJAS Indian monsoon rainfall. Results are based on data for the period 1973–94. Correlations of magnitudes 0.37 and 0.43 are significant at 90% and 95% confidence levels, respectively.

years are characterized by fairly large-scale snow cover and snow depth anomalies.

A comparison of the results of this paper with previously published papers shows that the correlation coefficient (cc) between the Eurasian snow cover and the monsoon rainfall is lowest (cc = −0.34) in the present study. Hahn and Shukla (1976) used 1967–76 data (cc = −0.54), Dickson (1983, 1984) used 1967–80 data (cc = −0.59), and Sankar-Rao et al. (1996) used 1973–90 data (cc = −0.41). Previous papers by Hahn and Shukla, and Dickson used subjectively analyzed monthly data (see appendix), whereas Sankar-Rao et al. and the present work use weekly data to construct monthly and seasonal means by accurately binning the weekly data. The low cc values for the present work compared to Hahn and Shukla, and to Dickson are mainly because of not in-

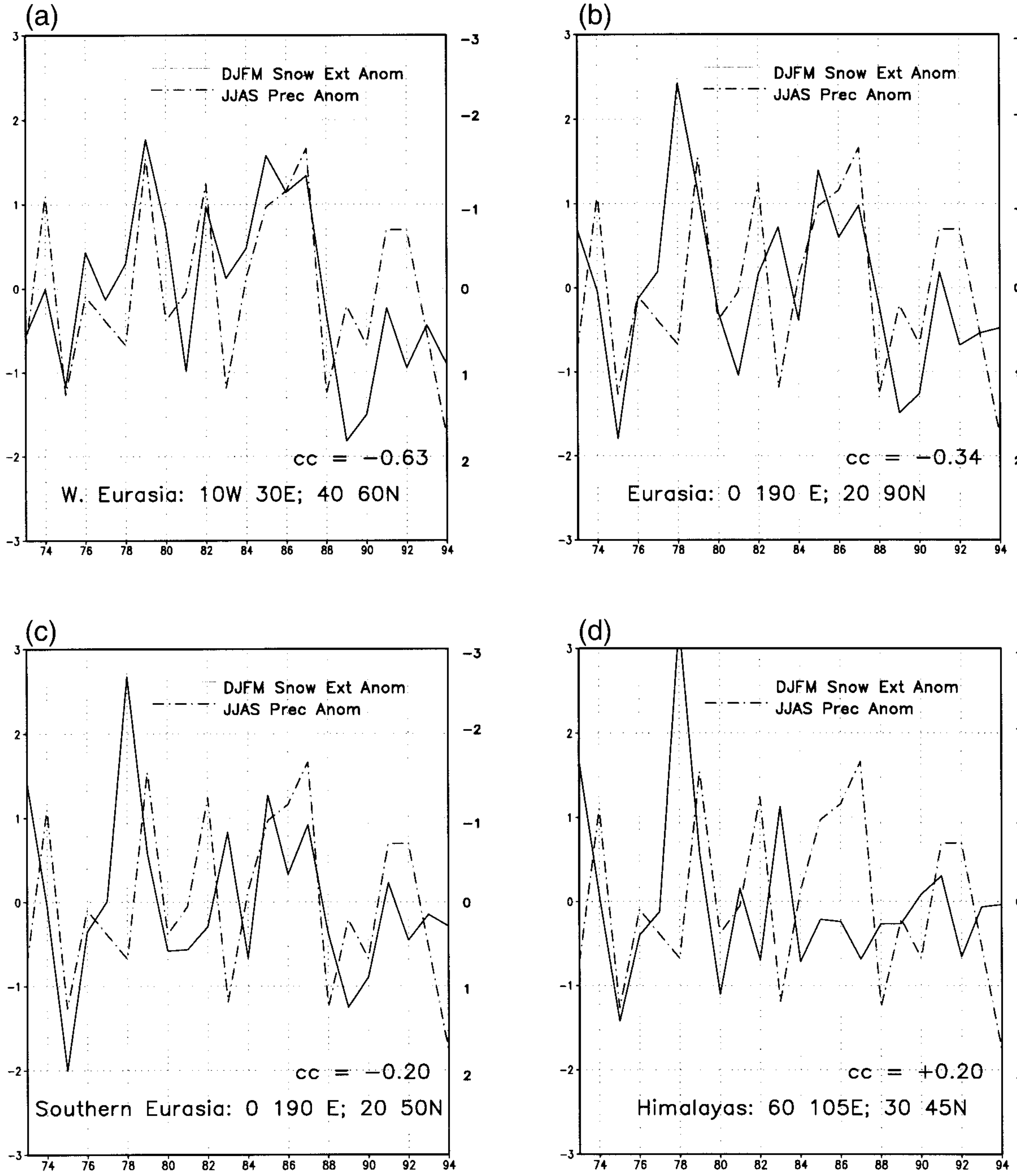


FIG. 5. Interannual variability of standardized winter snow cover anomalies and JJAS Indian monsoon rainfall anomalies. Correlation coefficient (cc) obtained for the time period 1973–94 is indicated on the lower right of each panel. Axis for the rainfall values is reversed. Correlation coefficient of 0.43 is significant at 95% confidence level.

cluding the 1967–72 data. Eurasian snow cover anomalies in the present work are similar to those in Sankar-Rao et al.; however, cc values are different because the present study includes four additional years (1991–94).

Based on the correlation analysis and composite anomaly maps alone, it cannot be asserted that the snow anomaly and the associated surface temperature anomaly directly influence the Asian monsoon or the monsoon rainfall over India. Controlled numerical experiments with realistic models of the climate system using realistic snow cover and snow depth are essential to understand the mechanism through which extensive snow anomalies would produce deficient or excess Indian monsoon rainfall.

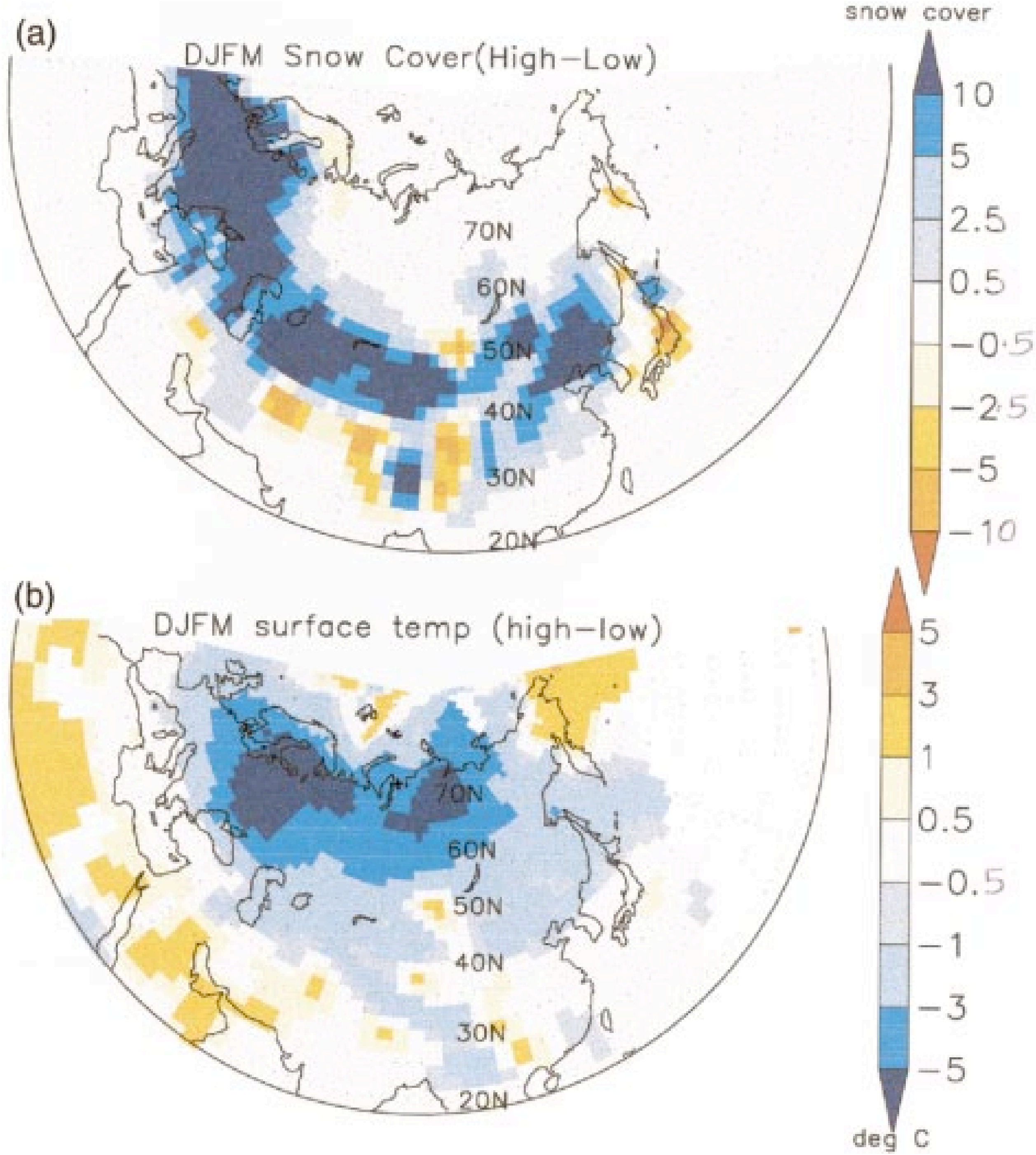


FIG. 6. Composite DJFM snow cover and temperature anomalies for years of high and low Eurasia snow cover. Results for snow cover are based on data for the period 1973–94. Unit for snow cover is the % of snow cover on ground (snow cover frequency × 100). Unit for temperature is K.

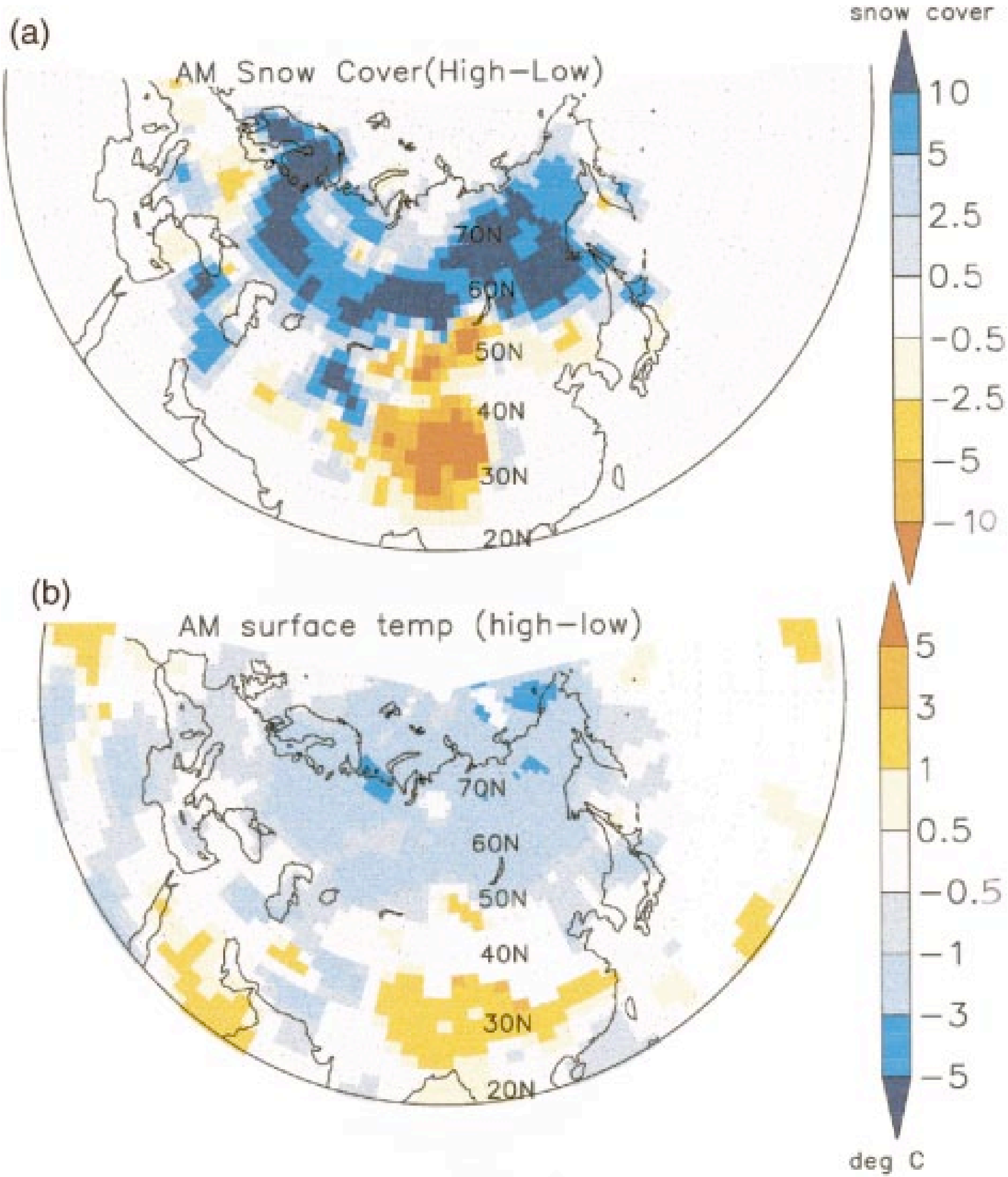
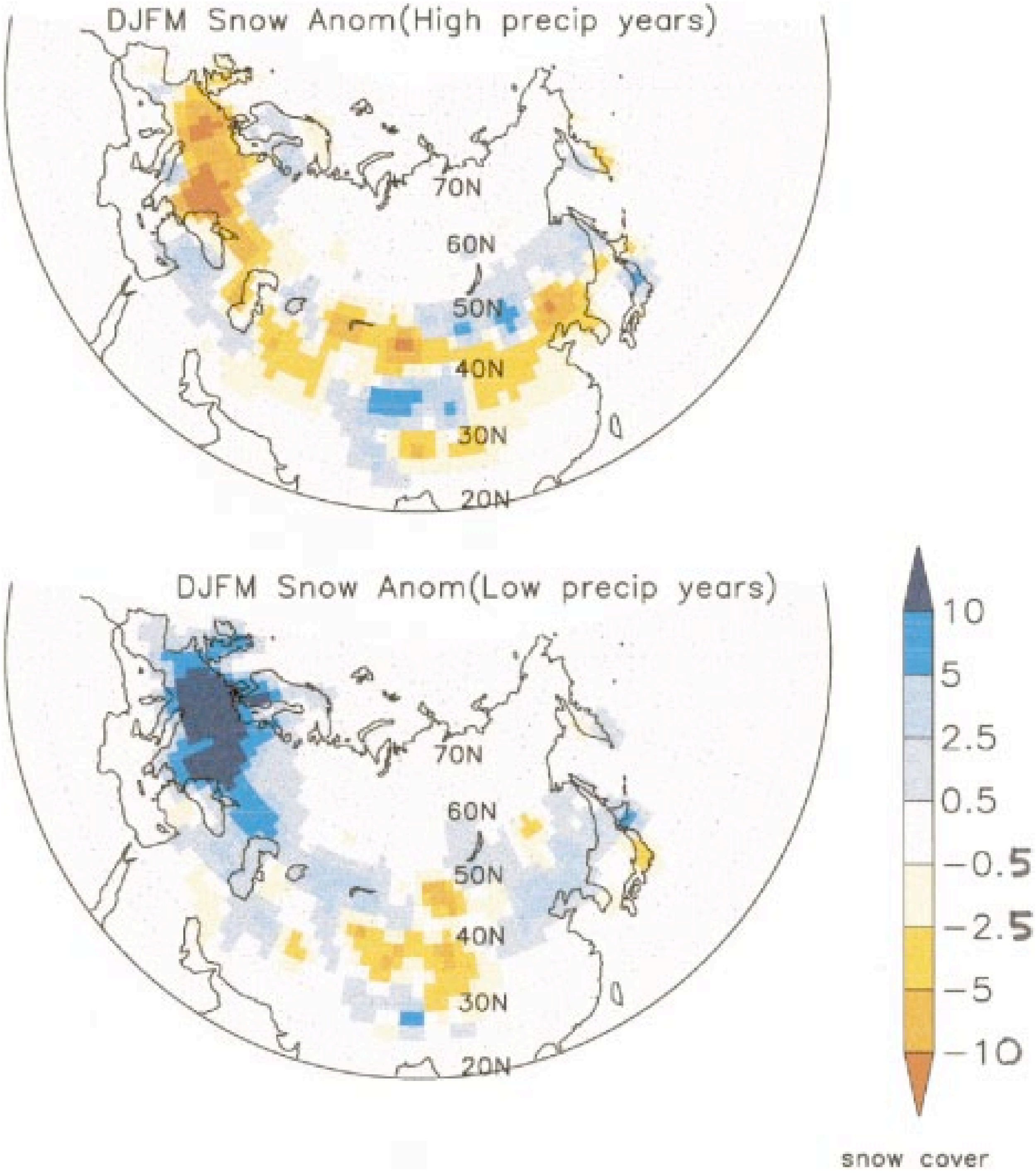


FIG. 7. Composite AM snow cover and temperature anomalies for high and low Eurasian snow cover. Results for snow cover are based on data for the period 1973–94. Unit for snow cover is the % of snow cover on ground (snow cover frequency × 100). Unit for temperature is K.


DJFM Snow Anom(High precip years)

DJFM Snow Anom(Low precip years)

FIG. 8. Composite DJFM snow cover anomalies for years of high and low JJAS Indian monsoon rainfall are shown in the top and bottom panels, respectively. Results are based on data for the period 1973–94. Unit for snow cover is the % of snow cover on ground (snow cover frequency × 100).

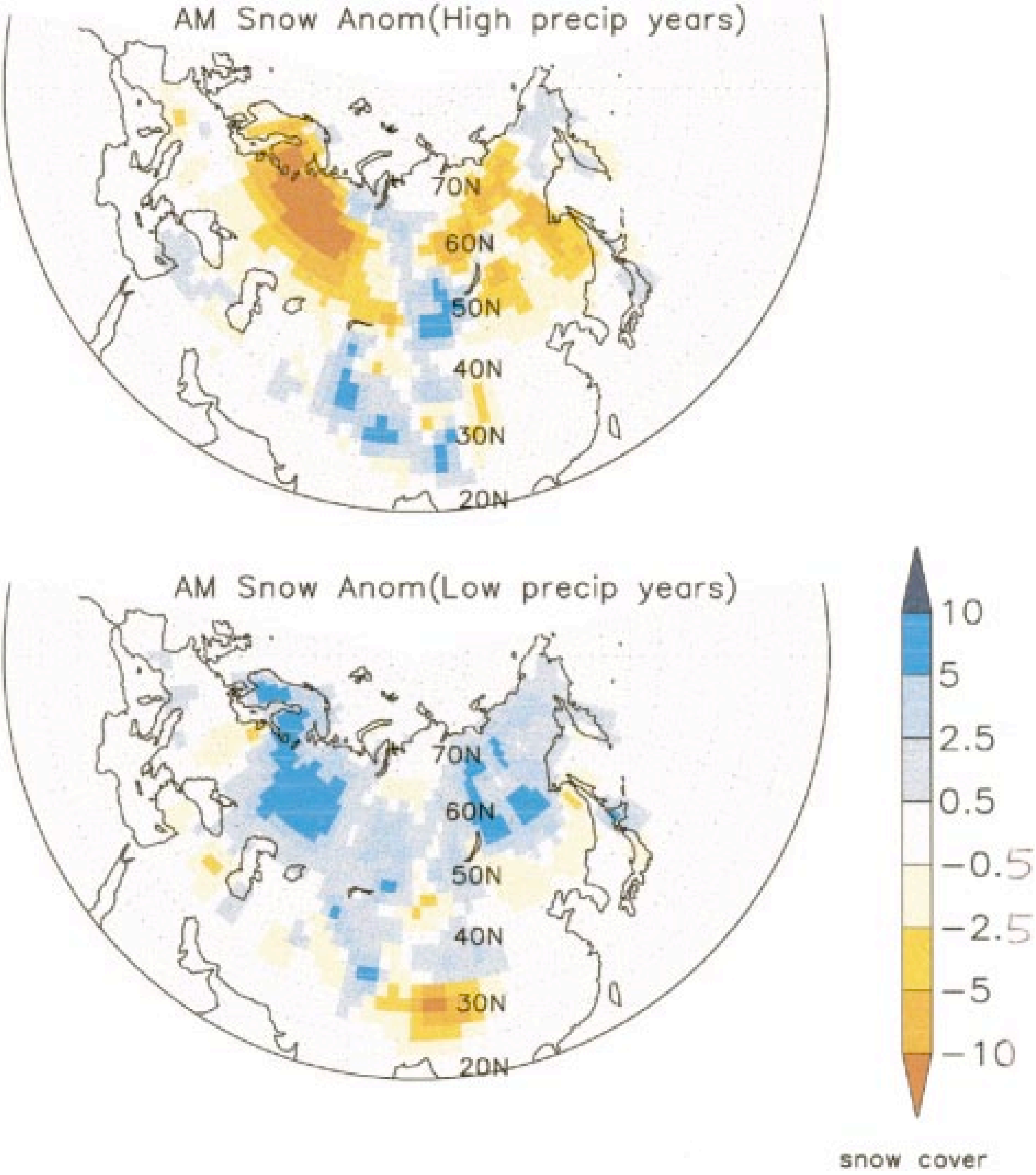


FIG. 9. Composite AM snow cover anomalies for years of (a) high JJAS Indian monsoon rainfall and (b) low JJAS Indian monsoon rainfall. Results are based on data for the period 1973–94. Unit for snow cover is the % of snow cover on ground (snow cover frequency × 100).

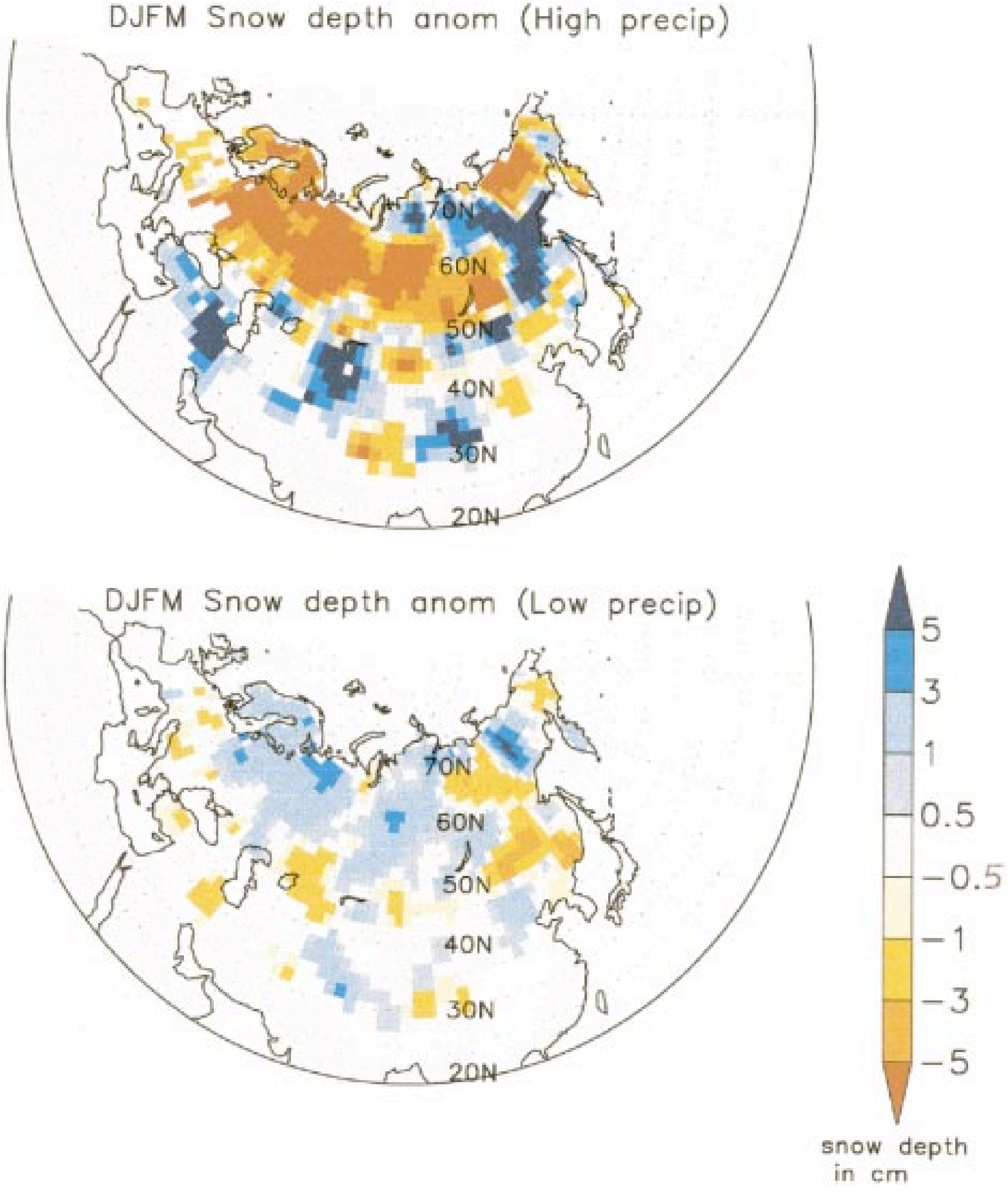


FIG. 10. Composite DJFM snow depth anomalies for years of (a) high JJAS Indian monsoon rainfall and (b) low JJAS Indian monsoon rainfall. Results are based on snow depth data for the period 1979–87. Unit for snow depth is 10^{-2} m.

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APPENDIX

Uncertainty in Snow Cover Data and Previous Snow–Monsoon Results

Prior to 1972, snow cover was underestimated especially during fall (Kukla and Robinson 1981; Ropelewski et al. 1984; Robinson et al. 1991). In 1972, the deployment of advanced very high resolution radiometer with a resolution of 1 km onboard NOAA satellites enhanced the accuracy of snow cover estimates, making them suitable for continental-scale studies. Visible sensors are unable to penetrate dense forest cover and monitor underlying snow. There are ambiguities in the recognition and demarcation of patchy snow areas and uniform lightly vegetated areas. There is some analyst error in interpreting snow-free versus snow-covered terrain.

Robinson et al. (1991, 1993) identified some inconsistencies in the earlier NOAA data. The NOAA monthly snow cover areas were calculated from monthly summary charts that considered a cell to be snow covered if snow is present on two or more weeks during a given month. Since 1981, NOAA produced monthly areas from weekly charts by deriving a subjective average of the weekly chart boundaries for each month. Testing the two methodologies, Robinson et al. (1991) found areas computed by the monthly approach to be from several hundred thousand to over three million square kilometers greater than those calculated using weekly areas in all months except August. In the present study, monthly and seasonal fractional snow coverage was computed by accurately binning weekly data. The weekly data were considered representative of snow cover three days before and three days after the midweek date, and an appropriate weight was assigned to the number of days of each week that fell in a given month.

An examination of snow cover anomalies for individual years used by previous authors shows that there is a large disagreement for years 1968 (Dickson snow cover is large positive, whereas Hahn–Shukla anomaly is very small and positive) and 1977 (Dickson snow cover is small and negative, whereas Hahn–Shukla anomaly is large and positive). For the years 1967, 1969, 1972, 1973, 1974, and 1976, there is a difference in magnitude of over 0.5×10^6 km^2. Standardized snow cover anomalies as computed by Sankar-Rao et al. (1996) and the present study are in good agreement. The values of correlation between Eurasian snow cover anomalies and JJAS Indian rainfall show that studies that have included the 1967–71 data report higher correlation. Dickson (1983, 1984) observed a larger correlation between winter Eurasian snow cover and Indian monsoon rainfall when the period 1967–72 was excluded. He adjusted the data to account for the biases in the data over the Himalayan region.

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