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MONITORING SNOW COVER ON THE TIBETAN PLATEAU USING PASSIVE MICROWAVE SATELLITE DATA

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ABSTRACT

Output from satellite-borne passive microwave sensors has increasingly been recognized as an important means of monitoring snow cover. However, employing a single global algorithm to extract a snow signal from multichannel microwave data does not accurately monitor snow across all landscapes. One such region where difficulties occur is the Tibetan Plateau, where global algorithms overestimate the extent of cover. Here, adjustments we have made to the Chang et al. [1] global algorithm are discussed. Given the linear fit between snow depth and brightness temperature in the algorithm, estimated snow depths for individual 1° x 1° cells are reduced in 10 mm increments. This continues until the number of regional cells estimated to be snowfree agree with a detailed analysis of snow cover using shortwave satellite imagery. In 15 Plateau test cases, an average of 80 mm of snow is subtracted from original microwave estimates of cell snow depth over the more level portions of the Plateau and 60 mm over more mountainous areas to reach agreement with shortwave values. Possible reasons for the original overestimation are discussed. The microwave offsets are applied to over 500 snow charts derived from Scanning Multichannel Microwave Radiometer data using the Chang et al. algorithm between 1979-87. These data show that the average annual (Sep-Aug) percent coverage of snow on the Plateau is 35%, with the most snow observed in the 1982/83 season (39%) and the least in 1982/83 (26%). The mean is 10% larger than less accurate estimates obtained from lower resolution hemispheric snow charts that are derived from shortwave satellite data.

1. INTRODUCTION

The Tibetan Plateau, with an average elevation of approximately 5000 meters, covers an area of about two million square kilometers in western China. The combination of altitude and area makes this a unique climatologic region, and influences atmospheric dynamics in locations adjacent to as well as farther from the Plateau [2-5]. Given its high elevation and lower middle latitude location, large quantities of solar radiation reach the surface of the Plateau throughout the year. The major variable influencing the distribution of this radiation once it reaches the surface is snow cover. A fresh snow cover as shallow as 0.1 m may increase the albedo of the essentially treeless landscape to 0.80, this being about 0.60 higher than when the surface is snowfree. The melt of snow increases soil moisture, resulting in large quantities of absorbed solar energy leaving the surface and atmospheric boundary layer as latent heat. Thus, between the reflective and latent losses of energy, sensible heating on the Plateau is greatly reduced by the presence of snow.

Despite the importance empirical and modeling investigations ascribe to Plateau snow cover, knowledge of the kinematics of Plateau snow remains less than adequate. Ground station observations of snow are virtually absent in the western half of the Plateau. The limited number of stations in the eastern half tend to be in inhabited locations where the climate is likely to be most tolerable, thus may not be representative of regional conditions [6]. Satellite observations of surface conditions on the Plateau have been made using shortwave imagery since the 1960s. However, NOAA weekly snow charts [7], the only shortwave product to continuously report the extent of snow cover over the Northern Hemisphere during this period, did not monitor snow on the Plateau in a consistent manner until the late 1970s [8-9]. Even since then, cloudiness frequently obscures portions of the region for a week or more at a time, limiting the timeliness of these reports. Furthermore, no information on snow water equivalent or depth is directly attainable from shortwave analyses.

Plateau snow conditions may also be monitored by measuring microwave radiation emitted from the surface. Sensors on-board polar orbiting satellites measure this radiation in several wavelengths, and empirical or theoretical algorithms are applied to microwave brightness temperatures to estimate snow extent and mass (expressed as water equivalent or depth). A microwave approach provides information on snow extent and mass regardless of sky conditions, making for a potentially invaluable means of monitoring regional and global snow conditions. However, to date, only generic algorithms derived for the global study of snow have been used to estimate Plateau snow, and these overestimate the extent of cover [10]. Most of the cover estimated from microwave data is quite shallow. This is verified by available station observations, and suggests that global microwave algorithms might be successfully adjusted to better estimate Plateau snow cover. This manuscript describes such an effort. The global algorithm of Chang et al. [1] is adjusted to better represent Plateau snow extent by comparing microwave estimates with detailed shortwave satellite analyses of regional cover. Concentration is on snow extent, as the absence of ground truth over most of the Plateau makes estimates of depth difficult to evaluate. Finally, Plateau snow cover will be examined from 1978 to 1987 using the adjusted microwave charts and the results compared with estimates of Plateau cover from NOAA snow charts that are derived from shortwave satellite data.

2. DATA

a) Microwave

Microwave data used in this investigation were measured by the Scanning Multichannel Microwave Radiometer (SMMR) on-board the Nimbus-7 satellite. This instrument flew from November 1978 to August 1987. Data were collected on a one day on one day off basis, requiring five days (or three days on) to obtain global coverage. Chang et al. [1] developed a theoretical algorithm that uses the difference in brightness temperatures of 18 and 37 GHz SMMR night time returns to derive a snow depth/brightness temperature relationship for a uniform snow field (eq. 1):

$$SD = 15.9 \times (T_{18H} - T_{37H}) \text{ mm} \qquad (1)$$

where SD is snow depth (mm), and T_{18H} and T_{37H} are the horizontally polarized brightness temperatures for the SMMR 18 GHz and 37 GHz radiometers. Resolutions at these freqencies are 55 and 27 km, respectively. This algorithm is based on a regression relationship derived from theoretically calculated brightness temperatures for a layer of snow of varying depth (up to 1.0 m) and density above frozen soil. This generic algorithm assumes a snow density of 300 kg m^{-3} and a mean snow-grain radius of 0.3 mm. It was tuned for a uniform snow field with moderate snow depth over low elevation regions.

Algorithm results for the five-day periods closest to the middle of the months of November 1978-79, 1984-86 and January and March 1979-80, 1985-87 are used in the case studies discussed in sections 3 and 4. Data are mapped to a 0.5° x 0.5° grid, with snow of ≥30 mm reported in 10 mm increments. The original grid is averaged to a 1° x 1° grid to conform with the shortwave data discussed in the next section.

b) Shortwave

Detailed charts of snow cover over western China are constructed using shortwave Defense Meteorological Satellite Program (DMSP) imagery. Image resolution is 2.8 km and the spectral range of the DMSP sensor is 0.4-1.1 μm. Snow is identified on shortwave imagery by recognizing characteristic textured surface features and brightness.

Images from five consecutive days are used to document mid-month cover for the intervals listed in the previous section. The five days permit most of the surface to be observed, although clouds occasionally persist over a portion of the region for the full observation period. Charted cover is digitized for 1° x 1° grid cells. Where snow is present, a cell is determined to have a brightness value ranging from 1 to 3, depending on the spatial coverage and depth of the snow cover. In this lightly vegetated region, the brightness increases as the cover becomes more spatially complete and deep. For comparison with microwave values, all cells charted as class 1 (low brightness), 2, or 3 (high brightness) cover are classified as snow cells, even though less than half of the surface is snow covered for all class 1 cells and even some class 2 cells. At least two trained observers charted Plateau surface conditions for each of the 15 study cases. A close agreement between the analysts occurred in every case, and for this study, the shortwave charts are considered accurate for mapping the extent of snow cover.

3. METHODOLOGY

The microwave and shortwave products are analyzed using GRASS (Geographic Resources Analysis Support System), a raster-based geographic information system developed by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory. This permits rapid, consistent and repeatable analyses of the two spatially referenced data sets. Analyses include data filtering, map overlaying and map algebra.

Digital terrain analysis is also performed using GRASS to objectively define the high altitude study region. National Geophysical Data Center digital elevation model data with a grid cell resolution of 0.08° x 0.08° are averaged for one degree cells throughout western China. All one degree cells having an average elevation exceeding 3500 meters are used in the study. These high elevation cells are divided into two subregions to determine whether relief has any impact on the microwave values. The division is based on an analysis of the diversity of elevation within a grid cell. The low diversity cells will be referred to as the Plateau plains and the high diversity cells as the mountainous Plateau. The shaded cells in Figure 1a represent the entire study region. The plains dominate the Plateau west of 90°E, occupying 101 of the 119 cells. The mountainous cells in the west include portions of the Himalayan, Kunlun Shan and Tian Shan ranges. East of 90°, 65 of the 83 cells are mountainous, but with less well defined ranges than in the west.

An initial comparison of the original microwave snow output with the shortwave charts indicates a significant microwave overestimation of the extent of snow cover over the Plateau subregions. This is exemplified in Figure 1, where the shortwave chart (1a) reports snow cover in 74% of the cells, while the generic Chang microwave analysis (1b) finds a 97% coverage of snow, with only six of the 202 cells snowfree.

The linear fit between snow depth and brightness temperature in the Chang algorithm, and the shallow snow depths (<100 mm) reported by the microwave analysis in most cells shown to be snowfree in the shortwave charts suggests that by applying an offset to equation 1, microwave estimates of snow coverage over the Plateau can be adjusted to better match detailed shortwave observations. In the case shown in Figure 1, offsets of -80 mm over the Plateau plain and -60 mm over the mountainous Plateau result in the best match between the adjusted microwave (72% cover) (Fig. 1c) and shortwave estimates. Results of this analysis for the 15 study cases are reported in the next section.

4. ALGORITHM ADJUSTMENTS

The microwave offset needed to achieve the closest spatial agreement with a shortwave chart, ranges between -40 mm and -160 mm over the Plateau plain (Table 1). Offsets range from 0 to -160 mm over the mountainous Plateau (Table 2). The mean offset for the 15 cases is -80 mm over the Plateau plain and -60 mm over the mountainous Plateau. There is no apparent relationship between the size of the offset and the study month. However, larger offsets are generally required when shortwave charts indicate a low extent of snow. In all cases, not only is a close agreement achieved with respect to percent snow coverage, but the spatial distribution of the cover agrees well between the shortwave and adjusted microwave analyses.

5. PLATEAU SNOW COVER: 1978-1987

The mean offsets for the two Plateau subregions have been applied to all microwave charts generated between December 1978 and August 1987. On average, the Plateau is 31% snow covered in fall, 59% in winter, 40% in spring, and 9% in summer (Table 3). The annual average cover is 35%. The average coverages over the two subregions are within a few percent of each other in all but the winter, when the mountainous Plateau has 8% more cover than the Plateau plain. Coverage estimates are biased towards the high side, as many cells on the Plateau that are categorized as snow covered according to the shortwave or the adjusted microwave analyses are not fully covered. This situation is not balanced by partial cover in those cells reported to be snowfree.

A year-to-year survey of snow extent indicates annual (Sep-Aug) cover varying from 39% in 1982/83 to 26% in 1984/85. Fall cover was at a maximum in 1985, winter cover in 1985/86 and spring cover in 1983. Minima for these three seasons were set in the 1984/85 snow season. Figures 2 and 3 show the annual and seasonal departures from normal for the Plateau plain and mountainous Plateau subregions. They further illustrate the year-to-year variations in snow extent, and suggest that there is a somewhat greater persistence of anomalies from one season to another over the mountainous subregion than on the Plateau plain. This is observed best in 1982/83.

Seasonal microwave estimates are larger than ones obtained from the NOAA shortwave charts. The annual NOAA value of 25% snow coverage is 10% lower than the microwave average, and fall (25%), winter (38%) and spring (25%) NOAA estimates are from 6 to 21% below microwave averages. Summer values differ by 1% (NOAA 10%). Comparisons of NOAA and microwave estimates with DMSP derived values for the 15 test cases show an absolute error of 23% for NOAA and 17% for microwave estimates (microwave values are computed using mean offsets). In 12 of the 15 cases NOAA areas are lower than DMSP values, while only 9 microwave cases are lower. When taking into account the sign of the difference, the microwave mean of the 15 cases is only 1% above the DMSP value while the NOAA mean is 23% below the DMSP value. The higher spatial and temporal resolution of the microwave analysis makes it more accurate than the NOAA product. The temporal factor is primarily a result of the frequent cloud cover over the Plateau preventing shortwave analyses, yet not interfering with microwave evaluations.

6. DISCUSSION

The overestimation of snow cover over the Tibetan Plateau when applying global snow algorithms to passive microwave data is probably due to the fact that (1) the assumed snow density and mean snow-grain radius in the algorithm are different from those in western China, and (2) the algorithm was tuned for a uniform snow field with moderate snow depth in low elevation regions. Elsewhere around the Northern Hemisphere microwave analyses tend to underestimate snow extent. A comparison of mean monthly snow extent over the entire Northern Hemisphere finds values derived using the Chang microwave algorithm to be between 80 and 90% of areas calculated from NOAA shortwave charts in winter and spring, 20 to 40% of the NOAA estimates in summer, and 40 to 70% of NOAA areas in fall [11]. At this scale the NOAA values are considered to be more accurate than the microwave estimates due to wet and shallow snow along the periphery of low elevation continental snowpacks remaining undetected in the standard microwave analyses.

A number of other efforts are underway to better understand the microwave problems that lead to errors in snow monitoring. These include regional investigations of snow extent and volume oriented towards the development of additional region-specific algorithms. Landscapes of interest include mountains [12-13], forest [14-15], tundra [16] and prairie [17]. Some studies include data from the 85 GHz channel on the Special Sensor Microwave Imager currently on-board DMSP satellites. Results indicate that adding this channel improves the recognition of shallow snow cover [18].

7. CONCLUSIONS

With snow cover having an important role in the energy and hydrologic budgets both locally and beyond, it is critical that accurate information on the extent and mass of the Tibetan snowpack be available. In this investigation, we modified the generic microwave algorithm of Chang et al. [1] in order to improve the monitoring of snow extent on the Plateau. A lack of ground truth prevents an adequate assessment of snow mass estimates. Analyses of over 500 microwave snow charts covering the 1979-87 period found that on average the Plateau is 31% snow covered in fall, 59% in winter, 40% in spring, and 9% in summer. The annual (Sep-Aug) average cover is 35%, with the most snow observed in the 1982/83 season (39%) and the least in 1982/83 (26%). These values are from 6% to 21% higher in the fall, winter and spring than values derived from shortwave-derived NOAA snow charts. The microwave estimates are more accurate, having a higher spatial and temporal resolution than the NOAA analyses. The temporal factor is primarily a result of the frequent cloud cover over the Plateau preventing shortwave analyses, yet not interfering with microwave evaluations.

The improvements demonstrated in this study suggest that region-specific algorithms can lead to a more accurate assessment of snow kinematics. Additional work is needed, and in some cases in progress, to develop algorithms for different snow conditions and physiographic regions.

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Table 1. Results of the 15 case studies of snow extent on the Plateau plain. Included is the percent coverage of snow as determined from the shortwave (SW), unadjusted microwave (uaMW) and best-fit adjusted microwave (aMW) analyses. The offset (mm) that resulted in the best fit is also listed.

month/year	SW	uaMW	offset	aMW
Jan 79	20.9	84.9	-160	20.1
Jan 80	36.8	89.5	-120	40.5
Jan 85	68.0	87.8	-40	71.0
Jan 86	83.2	93.7	-50	83.5
Jan 87	71.8	99.1	-80	70.6
Mar 79	53.5	83.9	-80	50.0
Mar 80	25.0	81.5	-110	29.3
Mar 85	45.1	71.3	-50	46.0
Mar 86	65.1	87.0	-60	71.1
Mar 87	68.1	92.1	-70	67.6
Nov 78	59.1	79.6	-60	56.0
Nov 79	17.6	81.6	-150	15.0
Nov 84	60.6	85.5	-50	63.5
Nov 85	79.5	91.9	-60	80.0
Nov 86	72.7	92.2	-60	75.4
mean	55.1	86.8	-80	56.0

Table 2. Same as Table 1, except for the mountainous Plateau.

	SW	uaMW	offset	aMW
Jan 79	39.8	86.4	-160	40.7
Jan 80	51.8	93.5	-120	50.7
Jan 85	66.0	81.3	-40	67.5
Jan 86	95.2	92.4	0	92.4
Jan 87	78.3	94.0	-50	78.3
Mar 79	56.6	91.5	-70	54.9
Mar 80	47.0	81.7	-100	45.1
Mar 85	37.0	70.0	-50	43.8
Mar 86	78.0	78.1	0	78.1
Mar 87	78.0	80.5	0	80.5
Nov 78	70.3	81.1	-40	71.6
Nov 79	30.0	89.7	-130	33.3
Nov 84	69.0	76.0	-40	67.1
Nov 85	92.8	89.0	0	89.0
Nov 86	72.0	82.3	-40	73.4
mean	64.1	84.5	-60	64.4

Table 3. Seasonal and annual percent snow cover over the Plateau. Winter (Dec-Feb), spring (Mar-May), summer (Jun-Aug), fall (Sep-Nov), annual (Sep-Aug)

	Fall	Winter	Spring	Summer	Annual
1978/79	-	63	40	11	-
1979/80	35	59	39	7	36
1980/81	29	55	40	7	33
1981/82	25	59	43	10	35
1982/83	30	63	50	11	39
1983/84	36	61	34	9	35
1984/85	24	44	30	8	26
1985/86	36	72	38	7	38
1986/87	34	56	44	9	37
mean	31	59	40	9	35

Figure 1. Shortwave (DMSP) and microwave charts of snow cover for mid January 1987 over the Plateau study region. Latitude (°N) and longitude (°E) are shown on the left and top edges of the charts, respectively. The shortwave chart (a) shows the distribution of snow cover brightness classes 1-3 and those cells observed to be snowfree (4). Chart (b) is the unadjusted microwave depiction of snow cover. Snow depth categories include (1) 30-100 mm, (2) 110-200 mm, and (3) >200 mm. Category 253 represents snowfree cells. The empty cells in this chart and chart (c) that are shaded in (1) are missing microwave data. Chart (c) depicts the distribution of snow cover after the mean offset of -80 mm is applied to the Plateau plain cells and the -60 mm offset is applied to the mountainous Plateau cells. The cell categories may be interpreted as in chart (b).

Figure 2. Departures of snow cover on the Plateau plain expressed as the percentage of the seasonal or annual mean.

Figure 3. Same as Fig. 2, except for the mountainous Plateau.

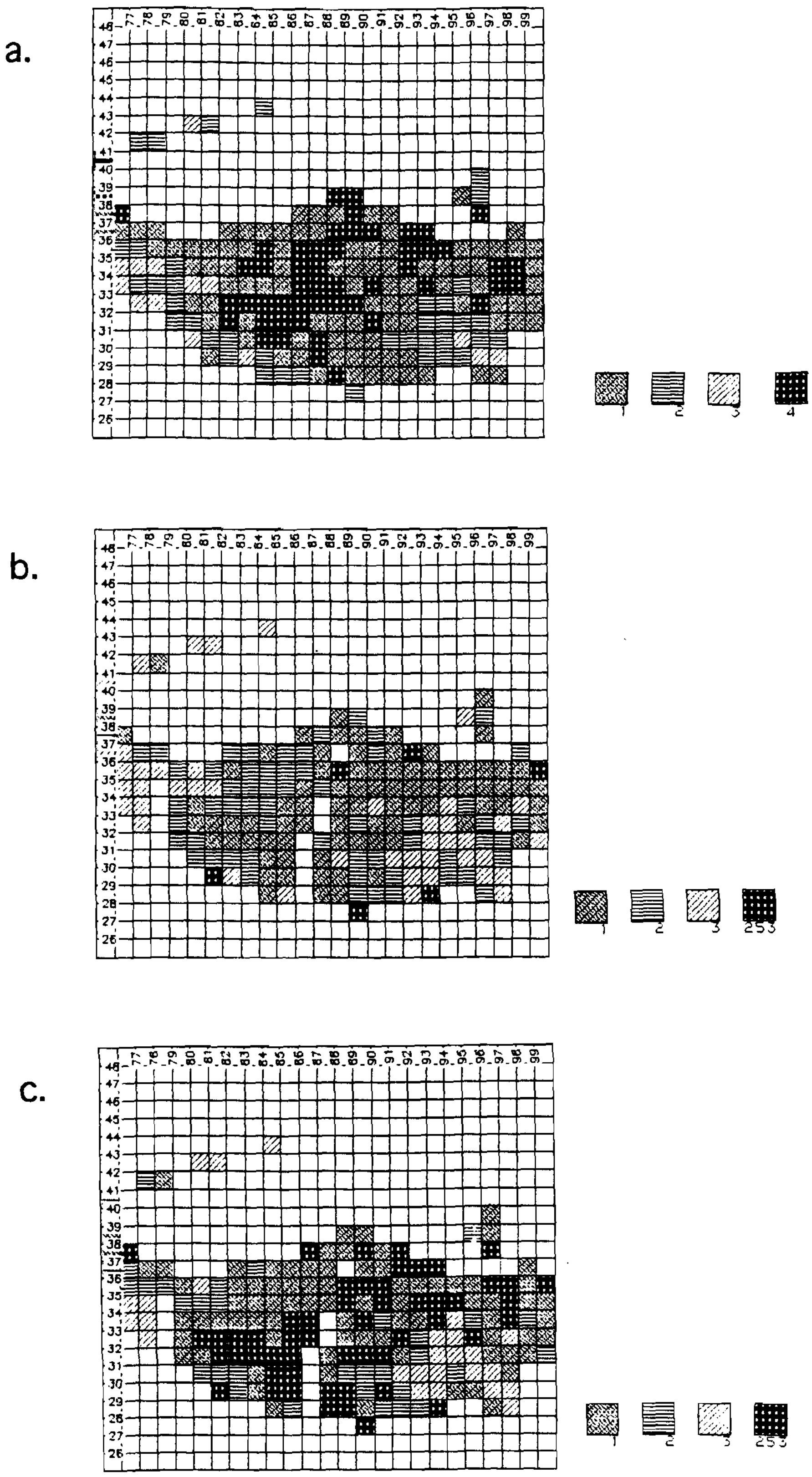
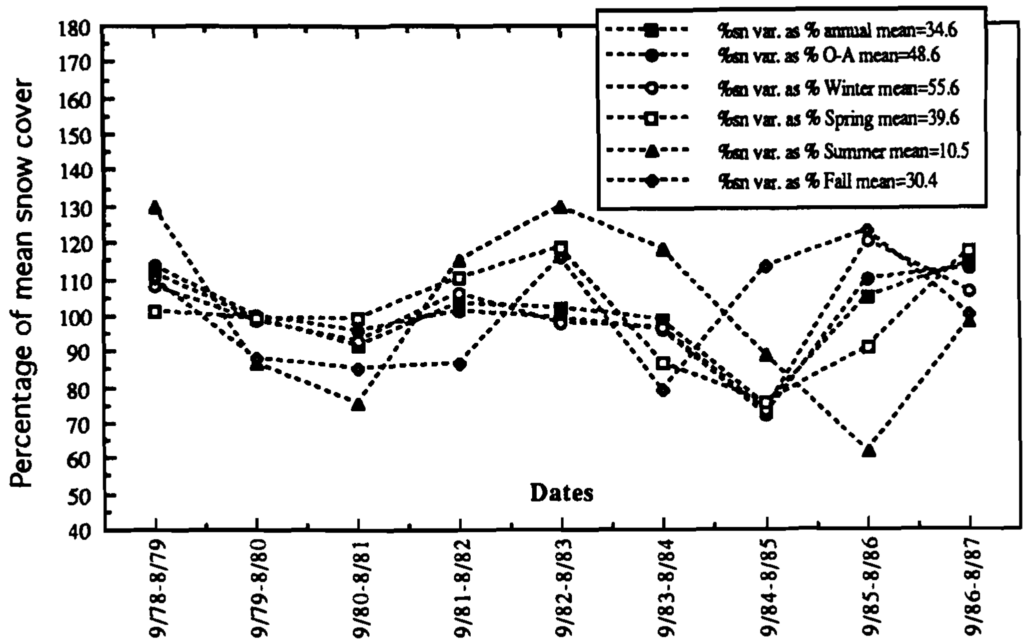


fig 1

fig2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Percentage of mean snow cover
Dates
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170
160
150
140
130
120
110
100
90
80
70
60
50
40
9/78-8/79
9/79-8/80
9/80-8/81
9/81-8/82
9/82-8/83
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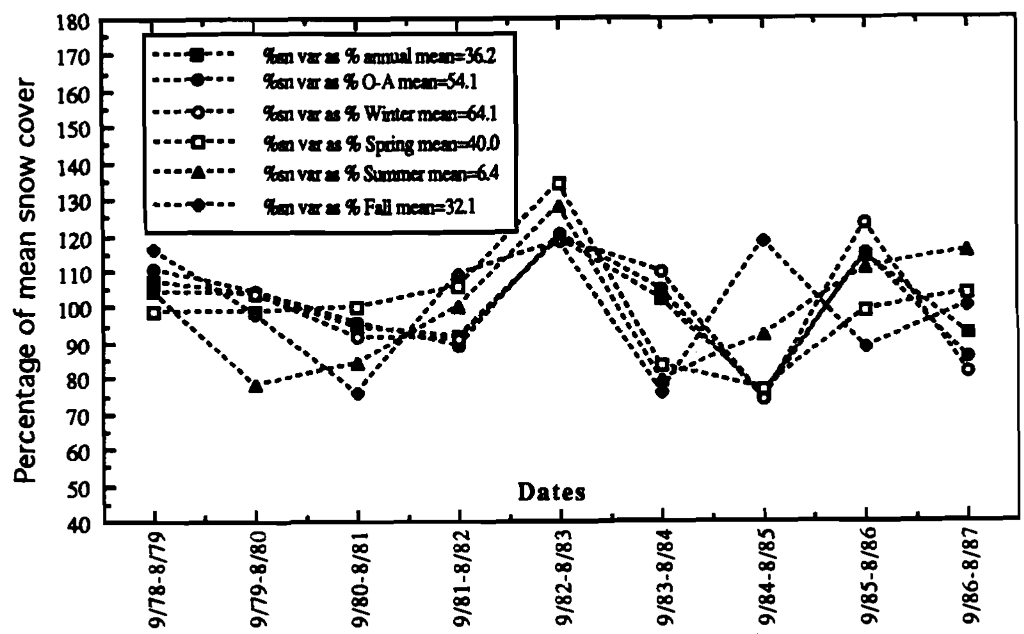
9/84-8/85
9/85-8/86
9/86-8/87

fig3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Percentage of mean snow cover
Dates
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
9/78-8/79
9/79-8/80
9/80-8/81
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