Historical Analysis of North American Snow Cover Extent
Merging Satellite and Station Derived Snow Cover Observations

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ABSTRACT

Visible satellite and station-derived snow cover observations over the continental United States are integrated to examine variations in North American snow cover between November and March from 1910 through 1996. Winter (DJF) snow extent was low during the 1920s and 1930s, and peaked during the 1970s and 1980s; however, linear trends are not an important component of winter variability. During March, however, a significant linear increase in snow extent of approximately 0.5% per year between 1910 and 1971 is found. March snow cover extent peaked during the 1950s through 1970s, and has since decreased. During the 1990s, December (March) snow extent has been at its maximum (minimum) dating back to the 1910s. These seasonal changes are associated with surface temperature and changes in tropospheric circulation. The results of this analysis permit future evaluations of regional and continental scale snow extent within the context of century-long variations and improve our ability to detect climate change.

Key words: climate variability, snow, North America

INTRODUCTION

Characterizing the distribution and natural variability of snow cover is important for climate change detection, understanding snow and climate associations, as well as for improving models that predict snow cover. Across much of North America, snow lying on the ground greatly influences hydrologic, biologic, chemical and geologic processes at or near the surface of the earth. The high albedo of a snow cover as well as other radiative and thermodynamic characteristics may directly affect differences in surface air temperature between snow covered and snow free terrain (Walsh et al. 1985; Namias 1985; Robinson and Dewey 1990; Leathers and Robinson 1993; Karl et al. 1993; Groisman et al. 1994; Leathers et al. 1995), making snow cover both a passive and active variable in the climate system.

Satellite-derived snow cover maps have been available since the early 1970s. These records show that in the late 1980s and the first half of the 1990s snow cover was less extensive over North America than during the 1970s through the mid-1980s (Robinson 1993a). Despite the broad spatial coverage that satellites provide, this short interval of record is insufficient for characterizing the uniqueness of the recent snow cover fluctuations. A longer period of record is necessary to place the changes recently noted into an historic perspective. Historical station observations lack the spatial extent of the satellite observations, but provide the temporal component that satellites lack for long-term climate analysis. This study utilizes digital daily climate data from the Historical Daily Climate Dataset (HDCD) compiled by Robinson (1988, 1993b) in conjunction with visible wavelength satellite data from the National Oceanic and Atmospheric Administration (NOAA) to assess historical snow cover and climate variability. Based on a series of correlation analyses between satellite and station data over the continental United States, we extend the record of regional and continental scale snow cover extent back to 1910. In this way, long-term station observations can be used along with the recent satellite data to assess historical climate variability in snow extent, and to place fluctuations observed in the satellite data into a long-term perspective.

DATA

Satellite

Weekly snow charts produced by image interpretation of NOAA visible wavelength satellite data are used in this study (Robinson 1993a). The

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charts are digitized to an 89 X 89 grid, with cell resolutions of 16,000 to 42,000 km^2 depending on latitude. The satellite data are geographically complete: all land areas of the Northern Hemisphere that have seasonal snow cover are included. If more than half of a grid cell is snow-covered, the entire cell is flagged as snow; otherwise, it is considered snow-free. Limitations of visible imagery for snow cover detection include problems with cloudiness, as well as with solar illumination, dense forest cover, and steep terrain. However, on a monthly time scale these data are suitable for climatic studies (Kukla and Robinson 1981). Corrections for inconsistencies in the demarcation of land versus ocean grid cells used in chart digitization, and an improved routine to calculate monthly average snow frequencies from weekly charts are applied to the NOAA dataset (Robinson 1993a). In this study we use monthly average snow cover frequencies for each grid cell from 1972 through 1996.

Station

Station observations of snow cover over the continental United States are obtained from the Historical Daily Climate Dataset (HDCD). This dataset contains long-term digitized records of daily snow depth, snowfall, precipitation, maximum and minimum temperatures for over 1100 cooperative climate stations distributed throughout the United States (Robinson 1989, 1993b). Observed snow cover records pre-date 1920 for approximately 45% of the stations. All stations report snow measurements by 1948. In addition, observations from 22 stations located in the Canadian Prairies were obtained from the Climate Research Branch of the Canadian Atmospheric Environmental Service (Brown 1995, Canadian Atmos. Env. Serv., pers. comm.). Snow depth observations in the Prairies are available prior to 1955 for 60% of the stations, with all stations reporting snow depth by 1966. Previous studies using the HDCD revealed that the quality and quantity of snowfall and snow depth measurements are more likely to be suspect or missing than any other variable observed (Robinson 1989; Robinson and Hughes 1991). Other researchers confirmed similar problems working with snow data (Karl et al. 1989). We therefore established a series of primary quality control procedures to identify and flag questionable observations. All data are quality controlled and checked for inconsistencies, errors, and missing values (Robinson 1993b). Station observations of snow depth are reported in whole inches, with a depth less than 0.5 inches reported as a trace, and not recorded in the HDCD digital files. The locations of the NOAA grid cells and the HDCD stations are shown in Figure 1.

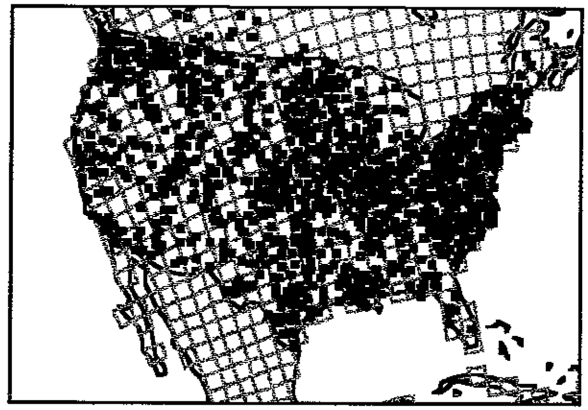

Figure 1. Location of NOAA digitized grid cells, HDCD cooperative stations, and Canadian Prairies stations

METHODOLOGY

Defining snow cover regions

Principal components analysis (PCA) is used on the satellite snow maps from November through March to identify areas that exhibit spatially and temporally coherent snow cover. For each month, grid cells that are consistently either snow-covered or snow-free are eliminated from this study. The remaining grid cells therefore comprise an "active area" where snow cover is variable. These active areas are seen from November through March (fig. 2). Regions within which snow cover fluctuates coherently (i.e. their interannual fluctuations are correlated) as defined by the PCA, are shown in bold in Figure 2.

Data processing

For each coherent region shown in Figure 2, a station-based record of snow cover duration is calculated. For each station, monthly time series of the number of snow covered days ≥ 1 inch (2.54 cm) are computed. Stations are required to have non-missing values for at least two thirds (i.e. 15 years) of the 22 years from 1972-1993, the period of overlap between the satellite and station data. The 1972-1993 mean is removed from each station time series resulting in monthly anomalies of snow cover duration. Regional time series are created by averaging all anomaly time series within the defined region.

Modeling regional snow extent

A simple regression model is used to estimate the extent of snow cover from the station data. Regional snow extent anomalies derived from satellite observations are the dependent variables, and snow

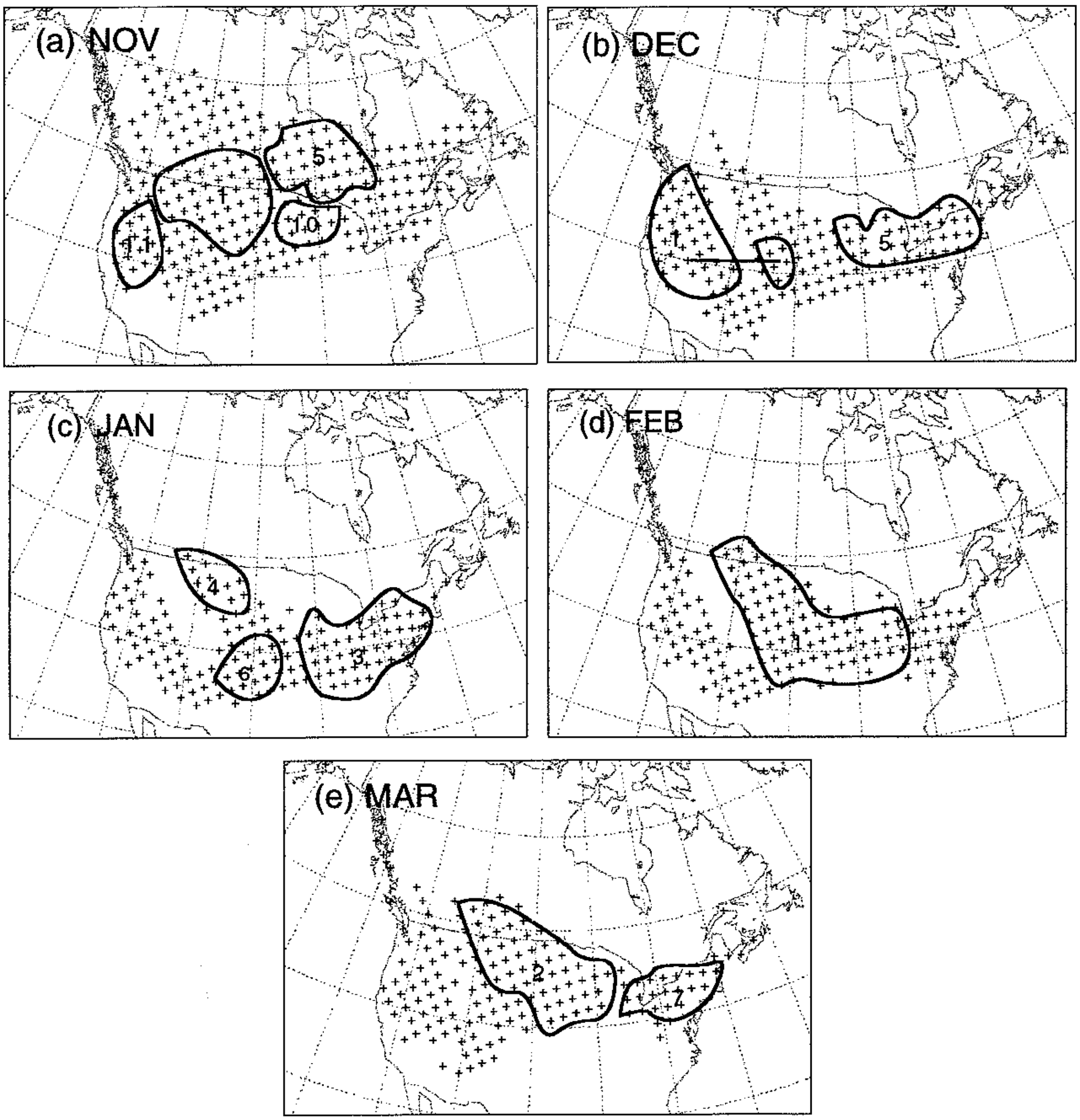

Figure 2. Areas of "active" snow cover for each month from (a) November through (e) March are identified with crosses. Thick lines indicate regions of coherent snow cover fluctuation (0.71 PCA loading contours). Numbers identify the component associated with each region (see Frei et al. this volume for further explanation).

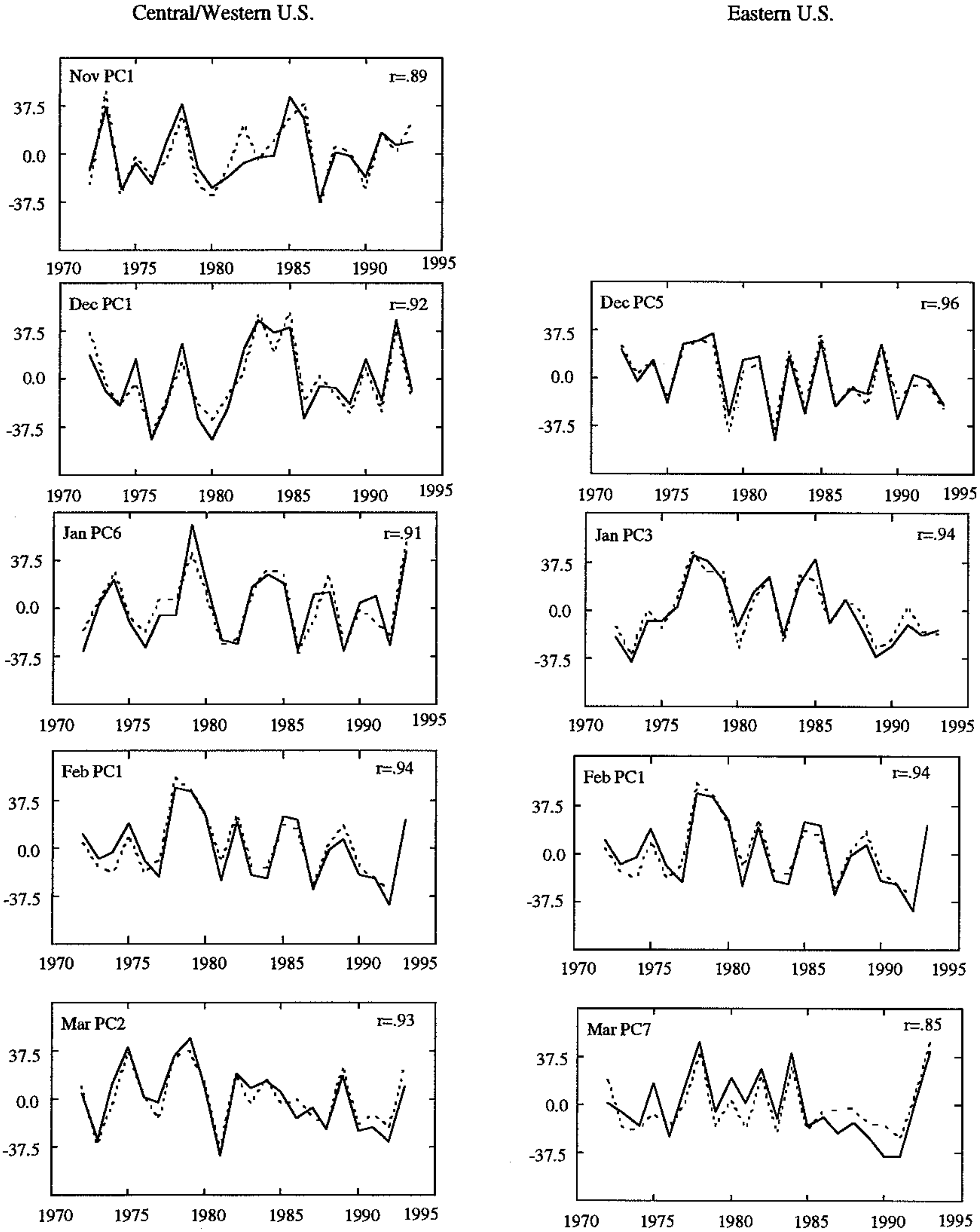

Figure 3. Comparison between observed and modeled regional snow cover extent anomalies (%), 1972-1993. Eastern active region in November is north of the United States border. Solid line=observed extent; dotted line=modeled extent.

cover duration anomalies from the station observations are the independent predictors. The regression model is expressed as:

$$Y_i(t,x) = b_i\, x_i(t) \pm SE_i \quad (1)$$

where Y = remotely-sensed regional snow cover extent (% snow cover extent per month)
x = station-based regional snow cover duration (#days cover ≥ 1" per month)
t = year (1972, 1973, ... 1993)
b = regression coefficient
i = PC region
SE = standard error of prediction

Correlation between the two data sources for the period of overlap (1972-1993) is high for all of the active regions (fig. 3). Pearson correlation coefficients range from a low of 0.85 in March PC7 to a high of 0.96 in December PC5. All values are significant at the 0.01 level (n=22, p=.01, 1-tailed). Residuals (not shown here) from the regressions have no patterns that indicate non-linearities or other problems, and standard errors range from 9%-14% percent of the regional areas. Although the regression model tends to underestimate the dispersion in values and in some cases misses extreme values, in no case does the model estimate a value to be high when it should be low or vice versa.

Before estimating snow extent in the pre-satellite era (1910-1971), two questions are addressed: 1) Have the principal component regions remained constant in time? and 2) How do changes in the number of stations and their distribution affect our estimates? The assumption that the geographic centers of orthogonal snow cover signals have remained approximately constant over time is examined for all active regions. A group of 204 well distributed, high quality HDCD stations are selected. A correlation analysis using all 204 stations reveals that the snow cover regions remain constant back to 1910. The problem of station distribution over time is illustrated for December where the number of stations increases from less than 10 in 1900 to over 50 in 1970 (fig. 4). As the number of stations does vary over time for all regions, neither regression coefficients nor standard errors remain constant. To estimate the coefficients and standard errors for data from the pre-satellite era, we compute regional snow cover duration anomalies for each decade using only the stations that report during that time. The resulting time series are used in the regression analysis with satellite data from the recent period. The regression model of equation (1) is therefore expanded to compute a decadally-specific regression coefficient and error term:

$$Y_i(t,x) = b_{ij}\, x_{ij}(t) \pm SE_{ij} \quad (2)$$

where i = PC region
j = 1, 2, ..., 6 (decadally specific station distributions prior to the satellite era)
$b_{ij} = b_{i1}$ (1910-1919) $SE_{ij} = SE_{i1}$ (1910-1919)
: :
b_{i6} (1960-1971) SE_{i6} (1960-1971)

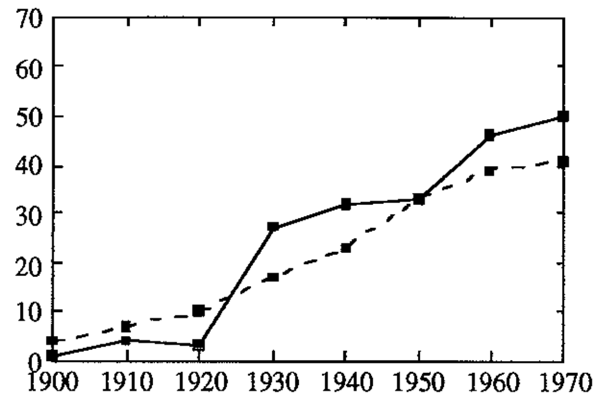

Figure 4. Number of stations reporting snow depth for December PC1 (solid line) and December PC5 (dotted line), 1900-1970.

Data from the stations used in the regression equation must have non-missing values for seven of the ten years in the decade. As an example, in December, 50 stations are included in the regional average for PC1 during 1972-1993. During the 1910s however, only 4 stations have non-missing values for at least seven years in the decade (fig. 5). The coefficients and error terms from each decade are then applied to all the station data that are available during that decade.

Modeling North American snow extent

We extend this analysis and use the regional variations in snow cover duration to estimate historical changes in snow extent on a continental-scale. Time series for the coherent regions within the United States were found to explain between 63%-88% of the variance in the North American snow cover mapped by satellite (1972-1994) (table 1) (see Frei et al., this volume). This suggests that station observations from these small geographic regions may be used to model snow extent over larger geographic areas. We are able to reconstruct snow extent for December through March only, as these are the months for which we have station observations.

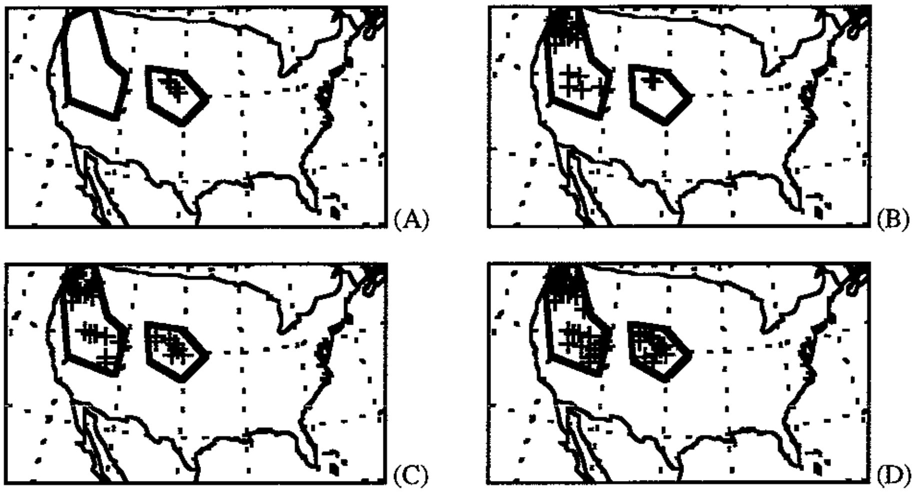

Figure 5. Station locations used in the regression analysis. Here, for Dec. PC1 (A) 1910, (B) 1930, (C) 1950 and (D) Current

Table 1. Variance explained by snow cover fluctuations within coherent regions as a % the total variance explained by continental signal.

Month	*# regions in North America*	*total explained variance (%)*
November	4	82
December	2	73
January	3	63
February	1	88
March	2	81

To model monthly North American snow extent, we use a multiple regression analysis, with remotely-sensed snow extent as the dependent variable and the station-derived regional snow cover duration from all of the PC regions as predictors. The Pearson correlation coefficients between modeled and observed snow cover extent over North America for the satellite-era, December through March, range from 0.77-0.92 (fig. 6). To estimate extent from 1910-1971, decadally-specific station distributions are used to determine regression coefficients, constants, and standard errors. Monthly North American snow cover extent (1910-1971) may be modeled using the following equation:

$$NA_{(t,x)}=a_j+\mathop{S}_{i=1}^{n}[b_{ij}\,x_{ij}(t)]\pm SE_j \qquad (3)$$

where i = PC region
j = 0, 2, ..., 6 decadally specific station distributions prior to satellite era.
n = number of PC regions used in multiple regression

Regional snow cover extent (1910-1971): November-March

Estimates of historical (1910-1971) regional snow extent are discussed in terms of departures from the 1972-1993 (satellite-era) mean values. Yearly anomalies, shown in Figure 7, are considered to be different than zero only for magnitudes greater than ±1 standard error. The average standard errors for the historical time period range from approximately 9% of the regional areas (December PC5 and January PC3) to 14% (December PC1). Standard errors generally decrease between 1910 and 1971, reflecting the increasing number of station observations.

Model results from November through February indicate that late-autumn and winter (DJF) snow extent in the historical period was generally below the 1972-1993 mean. For each of these months, there were approximately two to four times as many low snow cover years as high years during that period (table 2). For example, November PC1 had 31 below-average years, and only 11 above-average years, with no extended periods of extremely low or high snow extent (fig. 7a). In some regions, however, certain times stand out as having particularly low snow extent. For example, February PC1 (fig. 7b) had persistently low snow extent between 1920 and 1935.

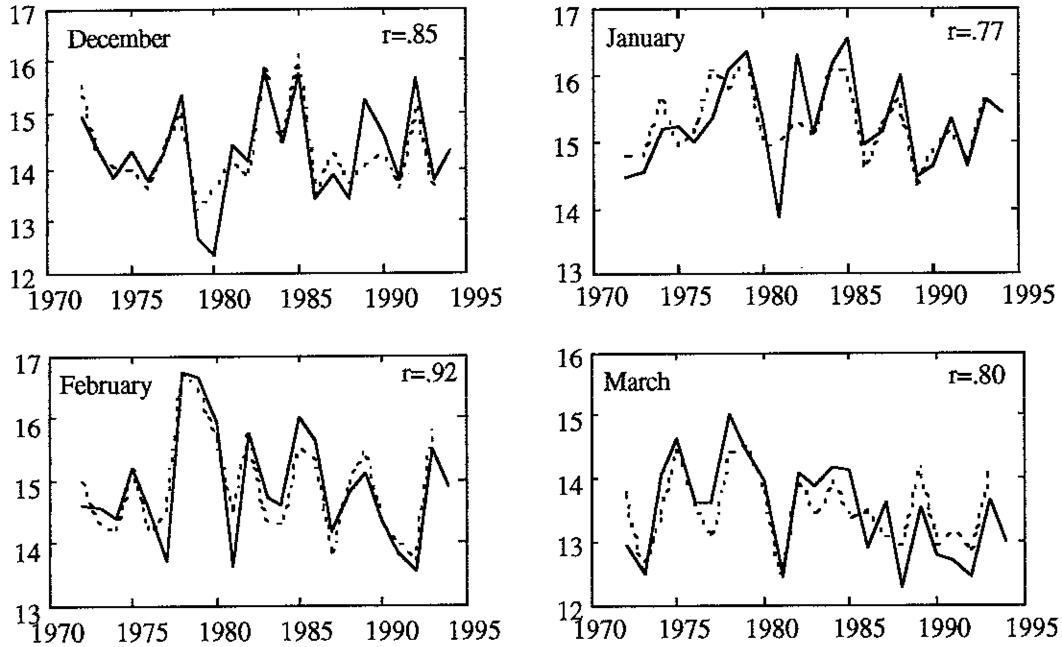

Figure 6. Comparison between observed and modeled North American snow cover extent (millions of square kilometers), 1972-1993. Solid line=observed extent; dotted line=modeled extent.

Trend analyses of regional historical (1910-1971) snow extent anomalies from November through February reveal no linear trends at ≥95% significance. In addition, low frequency fluctuations are isolated by passing the time series through a nine-point binomial filter. Analyses of the filtered time series reveal linear trends only for January PC6 and February PC1: over both regions an increase of about 0.31% per year is found to be significant at the 99% level. These trends explain 36% (January PC6) and 33% (February PC1) of the variability. With these exceptions, linear trends are not an important component of late fall and winter snow over the last century.

Historical records for March show variations that are different from those of winter over both the central and eastern portions of the continent. Between 1910-1971, the model indicates that March had approximately an equal number of low and high years (table 2). In addition, a trend of increasing snow cover extent is found. Over central North America (March PC2) snow extent increased at a rate of 0.47% per year (significant at the 99% level). Smoothed values show a significant trend of 0.54% per year. These trends are due to an abrupt shift in snow extent in the mid-1940s. From 1910-1947, 18 years had low extent and only 5 years had high extent. From 1948-1971, only two years were low while 12 were high.

Over the eastern United States, snow cover in March also increased. Trend analysis using the unsmoothed (smoothed) time series of March snow cover data from 1910-1971 reveals a trend of 0.57% (0.52%) per year (fig. 7c). This time series can be divided into three periods. During the early part of the record, from 1910-1927, there were 11 low years, and only 2 high years. During the middle years (1928-1954) snow extent was approximately equal to the 1972-1993 mean, with 6 high and 5 low years. During the later period, from 1955-1971, 8 years were high, and none were low. Thus, across the continent, snow extent in early spring tended to increase at approximately 0.5% per year between 1910 and 1971.

Table 2. Number of years 1910 and 1971 of below/above average snow extent in each region (±1 standard error from the 1972-1993 observed mean).

	#Low Years	*#High Years*
Nov PC1	31	11
Dec PC1	27	7
Dec PC5	26	15
Jan PC3	32	13
Jan PC4	36	13
Feb PC1	31	7
Mar PC2	20	17
Mar PC7	16	16

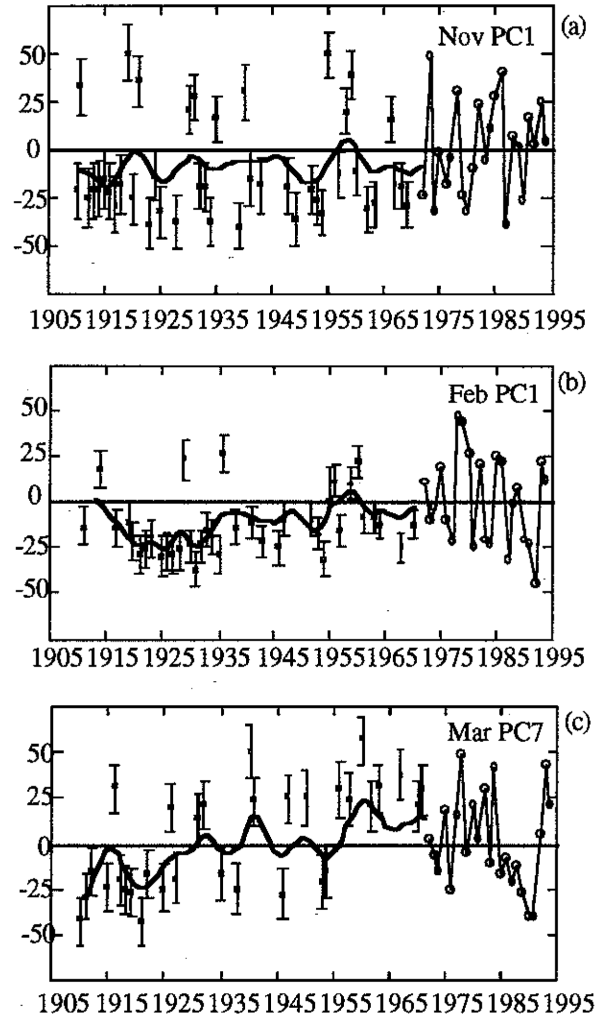

Figure 7. Estimated regional snow cover extent anomalies (%) from 1910-1971. High and low anomalies are the estimate ± 1 standard error as computed from the regression analysis. A nine-point binomial filter is used to smooth the time series to illustrate longer term fluctuations. From 1972-1994, the observed snow cover extent anomalies are shown.

Continental snow cover (1910-1971): December - March

Decadal fluctuations in North American snow extent are examined from the 1910s through the 1960s. Estimates of model error for the historical period are based on differences between modeled and observed snow extent using station *observations* after 1972 and station *distributions* before 1972. Estimates of decadally averaged errors range from 0.03 x 10^6 km^2 (February, 1960s) to 0.30 x 10^6 km^2 (January, 1910s).

Winter (DJF) snow extent varied considerably from the 1910s through the 1960s (fig. 8). Snow extent was low in the 1920s and the 1930s, and high in the 1910s and the 1960s. The largest changes are found in February, where snow coverage decreased by 570,000 km^2 between the 1910s and 1920s, and increased by 510,000 km^2 between the 1920s and the 1960s. For each month, the snow extent found in the 1960s is approximately equal to that of the 1910s.

In contrast, March snow cover extent reached its peak values in the 1950s and remained high through the 1960s. The increase in March snow cover extent between the lowest decade (1920s) and the 1950s was *720,000 km^2, constituting a larger range than seen in any of the winter months. Also March had significantly more snow cover in the 1950s and 1960s than during the 1910s.

DISCUSSION

Since the early 1970s, when snow cover began to be monitored accurately using satellites, considerable variation in snow cover has been observed. Over North America, December snow extent increased from the 1970s through the 1990s by 210,000 km^2. January extent peaked in the 1980s and decreased by 260,000 km^2 in the 1990s. February and March extent peaked in the 1970s and decreased by 640,000 km^2 and 800,000 km^2, respectively, in the 1990s.

By extending the snow cover record back to 1910, we are able to define the variability of snow cover extent over North America for the past century (table 3). Decadal means of monthly snow extent vary from 15.06 x 10^6 km^2 in January to 13.49 x 10^6 km^2 in March; ranges (maximum - minimum) vary between 0.64 x 10^6 km^2 and 0.92 x 10^6 km^2. Since the 1970s, snow extent in January and February is within the range observed during the historic period. However, recent variations in December and March are outside the historic range. During the first half of the 1990s, the December snow extent was at a century-long maximum, while March extent was at a century-long minimum. For the decades between the 1910s and the 1990s, we find that snow cover for December peaks in the 1990s, that for January and February peaks in the 1970s and 1980s, and that for March peaks in the 1950s-1970s.

These results may indicate a recent (post-1970) shift in the onset of the winter and spring seasons. Since the early 1970s, North American snow extent has been increasing in November and December, and decreasing in March, April, and May (November, April, and May not shown in figure). Furthermore, monthly averaged snow extent within each coherent region is correlated with surface temperature and

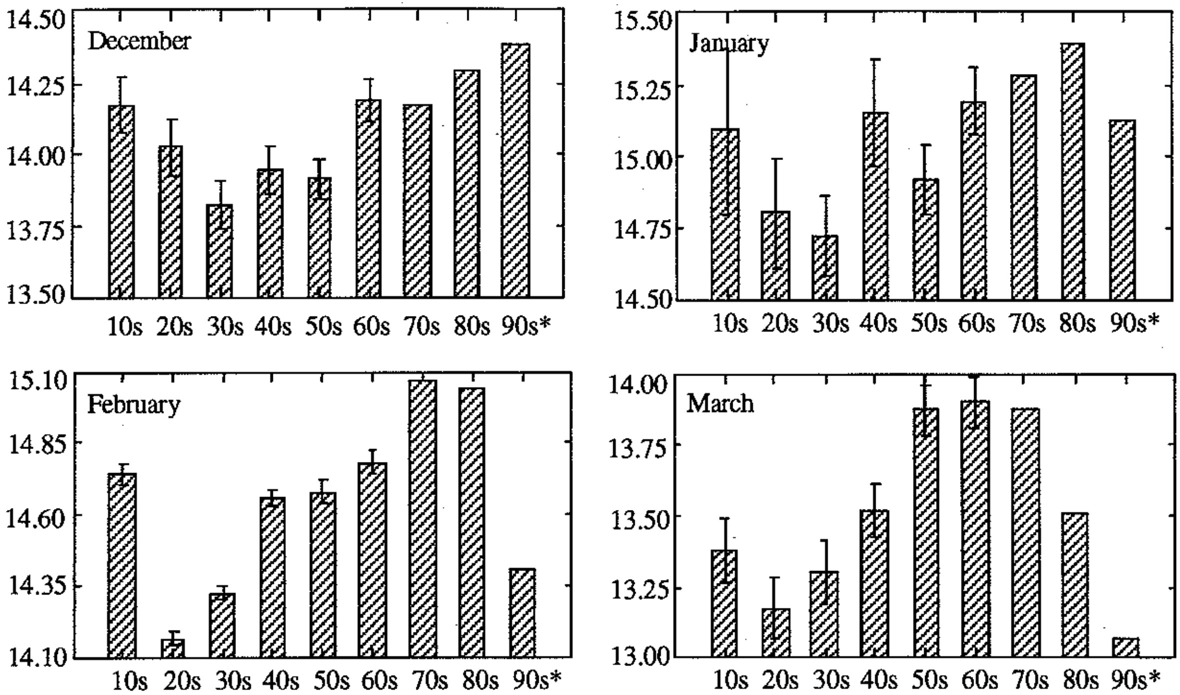

*Figure 8. Decadal fluctuations of North American snow cover extent (millions of square kilometers) since the 1910s. The error term for the estimates 1910-1970 are based on differences between station-derived and satellite snow cover within the satellite era, using station distributions from earlier decades. *1990-1996 Jan., Feb., Mar.; 1990-1995 Dec.*

snowfall; in recent years, November and December have been snowier and colder, while spring has been warmer with less snowfall. Frei et. al. (1996) find that high snow extent is associated with the increased persistence of synoptic patterns that are conducive to snowfall and the maintenance of snow cover. For example, increased meridionality, low 500-mb heights over the continent, and a westward shift of the climatological west-North American ridge are associated with extensive snow cover over western and central North America. Such synoptic associations to surface snow cover are maintained throughout the snow season, albeit weakened during spring. Thus, in terms of atmospheric dynamics, recent changes may be associated with earlier winter and spring seasons: the shift from the typical autumn to the typical winter pattern of mid-tropospheric geopotential heights is happening earlier in November; the shift from typical winter to spring patterns is happening earlier in March. These dynamic associations will be investigated in more detail.

Table 3. Statistics for decadally averaged snow extent between 1910 and 1996. The 1990s include months up to March, 1996. All values in 10^6 km^2.

Month	*Mean*	*Maximum*	*Minimum*	*Range*
Dec	14.10	14.38	13.82±0.08	0.64
Jan	15.06	15.39	14.72±0.14	0.81
Feb	14.62	15.07	14.17±0.02	0.92
Mar	13.49	13.90±0.09	13.07	0.92

CONCLUSIONS

Satellite observations of snow cover extent between 1972-1993 are integrated with near century-long station observations of snow duration for the months of November through March. Station-based and remotely-sensed observations are highly correlated. Thus we can use regression models based on the two sets of observations, between 1972-1993, to estimate regional and continental scale monthly snow extent prior to the satellite era (1910-1971). Snow cover from 1910-1971 was generally less extensive than in recent decades. During late fall and winter, we find that linear trends are not an important component of snow fluctuations. In contrast, during early spring we find a significant linear increase in snow cover across the continental United States between 1910 and 1970 of approximately 0.5% per year.

North American winter (DJF) snow extent was low in the 1920s and 1930s, high in the 1910s, and reached its peak values in the 1970s and 1980s. For March however, snow extent peaked earlier, reaching its highest values in the 1950s and 1960s. The variability of decadally averaged snow extent during the satellite era is of the same magnitude as during the previous six decades. During January and February, mean snow extent since the 1970s has been within the range observed during the historical period.

However, during the 1990s, snow extent during December and March are outside of the ranges observed from the 1910s to the 1980s. Decadally averaged December snow extent is now at a century-long maximum, while March snow extent is at a minimum. Since the 1970s, surface temperature and snowfall, in addition to snow extent in the coherent regions, have been changing during the fall and spring seasons. These changes are characterized by an earlier transition from fall to winter, as well as from winter to spring, conditions. Since snow extent is highly correlated to mid-tropospheric height patterns, these changes may be accompanied by earlier shifts into the typical winter and spring synoptic regimes. During spring, due to the higher solar insolation, the contribution of snow-albedo to the surface energy budget is more important than it is during the late fall and winter. It therefore becomes an important component of these seasonal changes. Synoptic and radiative changes that have occurred in recent years are currently being investigated in more detail.

Observations of snow extent may now be viewed within the context of longer-term variations. On the regional and continental scales, we have documented the interannual and inter-decadal variability of snow extent since 1910, extending our record by over 60 years. Using this information, it will be possible to determine if future changes in snow cover represent a climatological shift outside of the variability of the last nine decades. Future work will integrate satellite and station snow cover observations from Canada, the former Soviet Union, and China, to document changes in snow cover from October through May over all of North America and Eurasia.

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