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Characterizing the long-term variability of snow-cover extent over the interior of North America

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ABSTRACT. Historical and reconstructed snow-cover data show evidence of a gradual increase in snow cover over the continental interior of North America (NA) during much of the 20th century, primarily in response to increasing snowfall. A rapid decrease in Canadian-prairies snow cover after 1970 is not observed over the Great Plains. Analysis of snow-cover–climate relationships revealed systematic increases in the sensitivity of snow cover to Northern Hemisphere (NH) temperatures over the 1940–65 period. This change is mainly due to an increase in snowfall-temperature sensitivity during this period. Seasonal analysis revealed that the observed increase in snow-cover and snowfall temperature sensitivity is primarily a spring phenomenon. A marked increase in the importance of the spring period is observed around 1960, which coincides with a well-documented change in atmospheric circulation over NA. The post-1960 period is characterized by a significant inverse relationship between snow cover and hemispheric air temperature over the Canadian prairies and northern Great Plains regions.

INTRODUCTION

A number of studies have reported trends of earlier disappearance of spring snow cover over several regions of North America (NA) during the last 20–30 years, in conjunction with enhanced warming of spring temperatures (e.g. Foster, 1989; Stuart and others, 1991; Brown and Goodison, 1993). Evidence for a close link between snow-cover extent and temperature at the hemispheric scale was provided by Robinson and others (1991) who documented a strikingly close inverse relationship between satellite-derived snow-covered area (SCA) and temperature over the Northern Hemisphere (NH) during the last two decades. Using the same data, Karl and others (1993) obtained a statistically significant negative relationship between NA snow cover and NH temperature ($\Delta S/(\Delta T_{\mathrm{NH}})$. Groisman and others (1994) provided a physical explanation for the earlier spring disappearance of snow cover by demonstrating an enhanced positive feed-back between snow cover and the radiative balance in the spring period.

While the last-named three studies shed important light on the role of snow cover in the global climate system, they are all based on the same post-1972 period of satellite data. This 20 year period is insufficient to determine snow-cover–climate relationships with any degree of confidence, particularly in light of the decadal and longer-term variability known to affect the climate system (e.g. Schlesinger and Ramankutty, 1994). Karl and others (1993) recognized this by noting that snow cover in the 1980s (the warmest decade this century) may not have been typical. In light of this uncertainty, the aim of this paper is to apply the results of independent snow-cover reconstruction efforts being carried out at Rutgers University and the Canadian Atmospheric Environment Service, to gain greater understanding of long-term variability in snow cover, and snow-cover–climate relationships across the Great Plains/prairies region of North America. Snow cover in this area is closely linked to boundary-level climate variables (e.g. Karl and others, 1993; Robinson and Leathers, 1993). In addition, $2 \times CO_2$ GCM climate simulations (e.g. Boer and others, 1992) suggest this area will experience a large northward retreat in seasonal snow cover.

SNOW-COVER RECONSTRUCTION

Assessment of natural variability in snow-cover extent requires reliable data covering ~100+ years in length. Daily snow-depth observations extend over many decades, but there is potential for considerable noise in the data from the measurement process. Fortunately, much of the noise is reduced when point snow-depth measurements are integrated over time and space to derive regional snow-cover information. Robinson (1991) demonstrated that regionally averaged snow-cover duration (SCD) anomalies from station data agree quite closely with corresponding satellite-derived SCA anomalies in non-mountainous terrain.

Lengthy records of daily snow depth are available in digital format for over 1100 cooperative climate stations throughout the U.S.A. These data were found to be of high quality over the Great Plains region where almost half of the available stations reported data prior to 1910 (Hughes and Robinson, 1993b). Nevertheless, an average 18% of data were missing, which required the development of a reliable method to reconstruct missing values. The first step in this process was the development and application of quality-control procedures for daily climatological data (Robinson, 1993) to create a high-quality daily climate data set for the Great Plains. These data were subsequently used to develop regionally and seasonally dependent snow-depth-change/temperature-regression relationships, which were employed to reconstruct daily snow depth from daily temperature and snowfall data (the DC method; Hughes and Robinson, 1993a). Gridded values (1° lat. × 1° long.) of snow cover over a region extending from approximately 37° to 49° N and 90° to 110° W were used in this study. Details of the gridding method and location of stations are provided by Hughes and Robinson (1993a).

In Canada, daily snow-depth observations are only available in digital format from 1955 onward. A preliminary analysis of the DC method at several Canadian stations revealed large amounts of noise in snow-depth-change–temperature relationships. To reduce the noise from day-to-day variability in snow depth measurements, daily snow-depth data were converted to seasonal SCD values. These data were then used to calibrate a simple snow-cover mass-balance model using daily snowfall and maximum temperature as input. The resulting seasonal calibration factors were interpolated to a grid, which allowed SCD to be reconstructed at any site with long time series of daily snowfall and temperature data. The method was able to account for over 70% of the variance in annual snow-cover variability over southern Canada. Details of the method (subsequently referred to as BG) and verification results are provided by Brown and Goodison (1993).

Recent work reveals that the DC and BG methods yield similar results when reconstructed SCD data are converted to anomalies and spatially averaged. Over the Canadian prairies, for example, the difference in annual SCD between the two methods is typically less than ±10% of the corresponding mean observed SCD. On the basis of these results, historical and reconstructed snow-cover data from the USA and Canada were assembled to analyze long-term variability in snow-cover extent over a large part of the continental interior of North America.

REGIONAL ANALYSIS OF SNOW-COVER VARIABILITY

Three types of data were used in the analysis: (1) annual SCD (number of days with snow depth ≥2.54 cm), (2) total snowfall, and (3) maximum air temperature averaged over the snow-cover season. These data were available on a 1° lat./long. grid over the Great Plains for the period 1909–87, and at individual stations over the Canadian prairies for the period 1900–92. Annual statistics were defined with respect to the start of the snow-cover year, i.e., 1909 refers to the 1909/10 snow-cover season. Reconstructed SCD data were used exclusively over Canada because the spatial density is about twice that of the post-1955 network of observed SCD data. Maximum air temperature was used as it exhibits the strongest relationship to snow cover (Brown and Goodison, 1993; Karl and others, 1993). The Great Plains maximum temperature data used a September–May snow-cover averaging period, while the prairies data used October–May. The one-month difference should not create any inconsistency.

The data were converted to anomalies with respect to a 1961–80 reference period, then spatially averaged over three 5° lat. × 10° long. boxes located east of the Rockies: the western prairies (WPRA), the northwest Great Plains (NWGP) and southwest Great Plains (SWGP) (see Fig. 1). The data were also summarized for the larger Canadian-prairies (CP) and Great Plains (GP) regions for analysis of snow-cover sensitivity to NA and NH temperatures. The three sub-regions were selected to provide a north–south transect across the area where future snow-cover changes are expected to be large. The size of the areas was based on the results of a principal-component analysis of Great Plains snow cover carried out by Hughes and Robinson (1993b). Summary snow-cover statistics and mean inter-station spatial correlation coefficients are shown in Table 1 for each region. Snow cover in the WPRA and NWGP regions exhibits higher spatial coherence and less temporal variability than the SWGP region due to less variable snow cover at higher latitudes (viz. the increase in the coefficient of variation (COV) moving to lower latitudes).

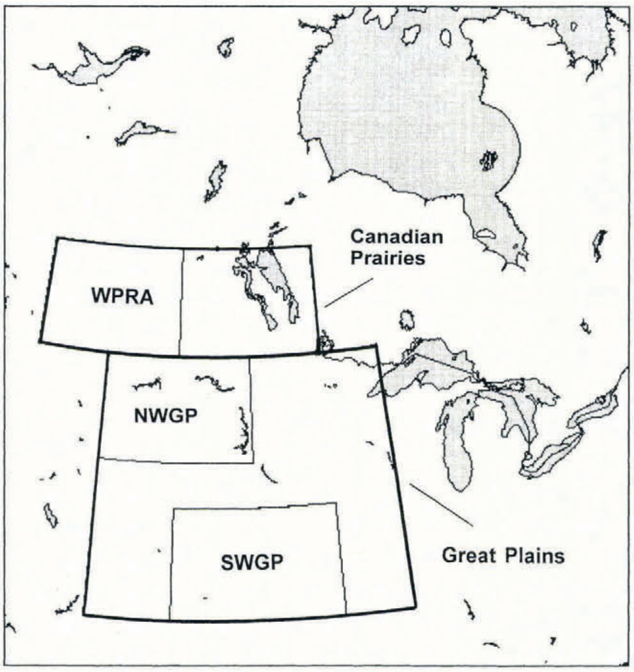

Fig. 1. Location map showing areas selected for regional analysis of snow cover.

Table 1. Location of regions, mean inter-station correlation (r), and 1961–80 snow-cover-duration (SCD) statistics

Region	*Lat.*	*Long.*	*No. of Stations*	*r*	*SCD*	
					Mean d	*COV*
WPRA	49–54° N	105–115° W	27	0.66	115.4	0.225
NWGP	44–49° N	100–110° W	28	0.62	88.0	0.293
SWGP	37–42° N	95–105° W	70	0.52	34.1	0.361
CP	49–54° N	95–115° W	45	0.62	121.8	0.208
GP	37–49° N	90–110° W	219	0.35	69.2	0.227

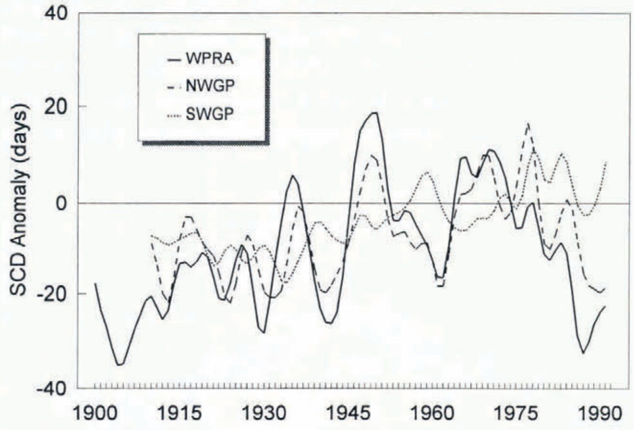

Fig. 2. Historical variability in annual snow cover for the WPRA, NWGP and SWGP regions. Values have been smoothed with a nine-term binomial filter. Values for the NWGP and SWGP regions after 1987 were estimated from satellite data.

Table 2. Linear regression results for change in annual snow cover, total snowfall and mean maximum temperature over the entire period of data. Significant (95% level) changes shown in bold

Region	*Period*	*Snow cover* d year^{-1}	*Snowfall* cm year^{-1}	*Max. temp.* °C year^{-1}
WPRA	1900–92	0.180	**0.341**	0.0046
NWGP	1909–87	0.197	**0.422**	0.0092
SWGP	1909–87	**0.236**	**0.210**	0.0021
CP	1900–92	0.137	**0.253**	0.0054
GP	1909–87	**0.248**	**0.277**	0.0040

Historical variability in snow cover for the three sub-regions is presented in Figure 2. Data for the 1988–92 period for the NWGP and SWGP regions were obtained from satellite-derived estimates of SCD which agree closely ($r^2 > 0.9$) with station-derived SCD values over the Great Plains. The data are characterized by large inter-annual variability, which is smoothed with a nine-term binomial low-pass filter to facilitate the regional comparison. All three regions show evidence of a gradual increase in snow cover during the 20th century, which reached maximum levels in the early 1970s over the Canadian prairies, and the mid- to late 1970s over the Great Plains. The increase is statistically significant over the southern Great Plains and for the Great Plains as a whole. Linear regression analysis of trends in snow cover, snowfall and maximum temperature (Table 2) revealed that the increased snow cover is linked to statistically significant increases in snowfall across all regions. Significant long-term increases in snowfall across the Great Plains and southern Canada have been previously documented by Hughes and Robinson (1993b) and Groisman and Easterling (1994). In contrast, there are no significant long-term trends in maximum temperature. A rapid decrease in snow cover since 1970 is a noticeable feature of the Canadian prairies, although the change does not appear to be outside the range of natural variability exhibited during the 20th century. Since the late 1970s, snow cover over the northern Great Plains has also decreased. However, the southern Great Plains show no evidence of any systematic decrease in snow cover over the last two decades.

SNOW-COVER–CLIMATE RELATIONSHIPS

Understanding snow-cover–climate relationships is important for a number of reasons including verification of GCMs and construction of scenarios of future snow-cover conditions. For example, an evaluation of 17 GCMs by Cess and others (1991) revealed no consensus as to the sign of the snow-cover–climate feed-back. Recently, however, Groisman and others (1994) provided evidence of a significant positive feed-back between snow cover and the radiative balance from 20 years of satellite data (1973–92).

Snow-cover sensitivity to temperature ($\Delta S/\Delta T_{\max}$) and snowfall ($\Delta S/\Delta S_{\text{fall}}$) may be examined within a much longer context using the historical SCD data. $\Delta S/\Delta T_{\max}$ and $\Delta S/\Delta S_{\text{fall}}$ were computed over the entire period of record using the method of least-squares (Table 3). Significant negative temperature and positive snowfall relationships were found in all regions. The results reveal that inter-annual variability of snow cover in the southern Great Plains is more closely linked to inter-annual variability in snowfall, while snow-cover inter-annual variability in the northern Great Plains and prairies

Table 3. Summary of annual snow-cover–climate relationships by region. All values are significant at the 95% level (r^2 values shown in parentheses)

Region	*Period*	$\Delta S/\Delta T_{\max}$ d °C^{-1}	$\Delta S/\Delta S_{\text{fall}}$ d cm^{-1}	$\Delta S_{\text{fall}}/\Delta T_{\max}$ cm °C^{-1}
WPRA	1900–92	−12.4 (0.71)	0.58 (0.59)	−11.8 (0.37)
NWGP	1909–87	−12.8 (0.60)	0.74 (0.64)	−11.2 (0.39)
SWGP	1909–87	−3.5 (0.16)	0.47 (0.67)	−7.1 (0.22)
CP	1900–92	−12.1 (0.72)	0.64 (0.64)	−12.1 (0.47)
GP	1909–87	−8.6 (0.41)	0.77 (0.76)	−9.9 (0.42)

regions is more closely linked to inter-annual variability in maximum air temperature. Significant negative values of $\Delta S_{\text{fall}}/\Delta T_{\max}$ were found over all regions. Karl and others (1993) explain this relationship through a change in the fraction of frozen to total precipitation. However, Isaac and Stuart (1992) show that total precipitation amount and temperature are negatively correlated over a large area east of the Rockies. This regional response is related to the Pacific–North America (PNA) teleconnection pattern which exerts a strong influence on the precipitation and temperature regime of western North America (Leathers and others, 1991). Changes in precipitation amount enhance a positive feed-back, in that warmer (colder) temperatures are associated with less (more) snowfall a thinner (deeper) snowpack, and a lower (higher) albedo, contributing to earlier (later) snowmelt and warmer (cooler) local air temperatures.

Using 19 years (1973–91) of satellite data, Karl and others (1993) obtained a significant negative relationship between NA annual mean snow cover and NH annual surface temperature ($\Delta S/\Delta T_{\text{NH}}$) of -1.5×10^6 km^2 °C^{-1}. This relationship suggests a ~20% reduction in mean annual NA snow cover for a 1.0°C warming of NH air temperature. However, Karl and others (1993) noted this relationship may not be representative because of the short period of data used and because of the anomalously warm global temperatures experienced during the 1980s.

To address this concern, $\Delta S/\Delta T_{\text{NA}}$ and $\Delta S/\Delta T_{\text{NH}}$ were computed over much longer periods with the historical annual SCD data for the two larger CP and GP regions shown in Figure 1. In addition, the data were split into two approximately equal periods (1900–45 and 1946–89) to examine the null hypothesis that snow-cover temperature sensitivity has not changed during this century. T_{NH} and T_{NA} were calculated from the gridded mean monthly surface temperature data set of Jones and others (1991) for a latitudinal range of 35–85° N and a longitudinal range of 70–130° W for NA. The temperature data were averaged over the October–May snow-cover season, and $\Delta S/\Delta T$ computed from least-squares linear regression analysis using regionally averaged annual SCD anomalies. The results (Table 4) show that $\Delta S/\Delta T_{\text{NA}}$ has increased significantly over the Canadian prairies and the Great Plains, and that $\Delta S/\Delta T_{\text{NH}}$ has also increased over the Canadian prairies. The same analysis for the three sub-regions revealed that the significant increase over the GP region is mainly due to increased sensitivity over the northern Great Plains.

To determine whether the observed increases in sensitivity were systematic in nature or the result of a climatic jump, $\Delta S/\Delta T_{\text{NH}}$ was computed for the CP and GP regions using a running 21 year block, with regression coefficients plotted at year 11. The results (Fig. 3) show evidence of a systematic increase in $\Delta S/\Delta T_{\text{NH}}$ over both regions from 1940 to 1965, after which sensitivity remains more-or-less constant. In order to determine the role that the temperature–snowfall relationship might play in the

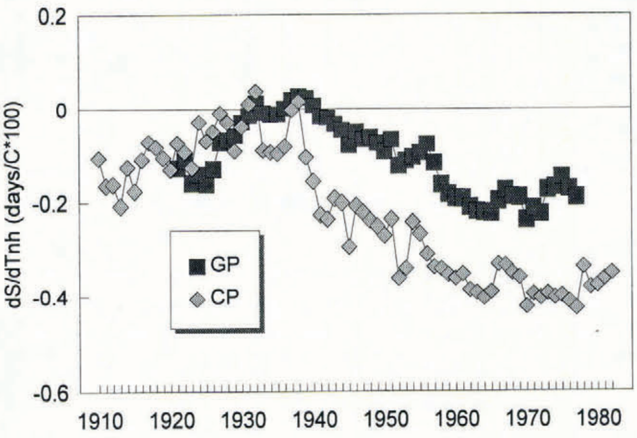

Fig. 3. Secular variability in $\Delta S/\Delta T_{\text{NH}}$ for the CP and GP regions as derived from linear regression analysis for consecutive 21 year blocks of data. Values for each block are plotted at year 11.

Table 4. Summary of linear relationships between annual SCD and annual T_{NA} and T_{NH} for 1900–45 and 1946–89. Relationships statistically significant from zero are shown in bold. Correlations are shown in parentheses

	$\Delta S/\Delta T_{\text{NA}}$		$\Delta S/\Delta T_{\text{NH}}$	
	1900–45 d °C^{-1}	*1946–89* d °C^{-1}	*1900–45* d °C^{-1}	*1946–89* d °C^{-1}
CP	**−16.0** (−0.48)	**−32.4*** (−0.74)	−3.8 (−0.07)	**−34.0*** (−0.52)
GP	**−8.2** (−0.46)	**−13.7*** (−0.56)	−5.2 (−0.16)	**−14.3** (−0.33)

* Significant (95%) difference between periods.

observed response (remember that snowfall and temperature are negatively correlated), the above analysis was repeated using multiple regression analysis of SCD versus T_{NH} and total snowfall. The results revealed that most of the 1940-65 increase in $\Delta S/\Delta T_{\mathrm{NH}}$ in both regions is related to an increase in the snowfall–temperature relationship. This was confirmed by comparing scatter plots of snowfall and temperature anomalies for the 1900–45 and 1946–89 periods. The latter period was characterized by noticeably larger positive snowfall anomalies for negative temperature anomalies.

Analysis of sensitivities on an annual basis may not give a completely clear picture of temporal change in snow-cover sensitivity. This is because different atmospheric conditions and physical processes are involved in the accumulation and ablation of snow cover. Analysis of temporal variability in seasonal values of $\Delta S/\Delta T_{\mathrm{NH}}$ was therefore carried out for the CP region by splitting the SCD data into fall and spring periods on either side of 1 February. Fall and spring temperatures were averaged over the October–December and March–May periods, respectively (the variability in SCD occurs during these periods)[*]. The results (Fig. 4) reveal large differences in seasonal sensitivities, and it is apparent that the increase in annual snow-cover temperature sensitivity seen after 1940 (Fig. 3) is primarily attributable to the spring season. An interesting feature is the marked cross-over of the fall and spring sensitivities which occurred after 1960. This shift may reflect a significant change in NA circulation to more positive values of the PNA teleconnection pattern in the late 1950s (Leathers and Palecki, 1992), and highlights the importance of looking at seasonal variability in snow-cover–climate relationships. Seasonal analysis of $\Delta S_{\mathrm{fall}}/\Delta T_{\mathrm{NA}}$ revealed a similar shift to increased spring-snowfall temperature sensitivity around 1960, which is also consistent with a change in atmospheric circulation around this time.

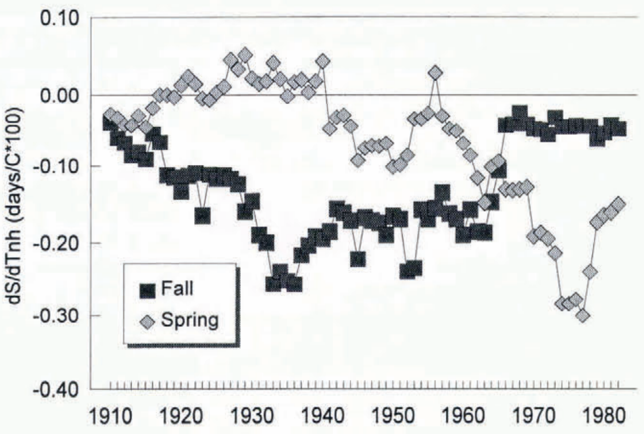

Fig. 4. Secular variability in seasonal values of $\Delta S/\Delta T_{\mathrm{NH}}$ for the CP region. Analysis method and plotting as described in Figure 3.

REGIONAL SNOW-COVER RESPONSE TO GLOBAL WARMING

Regional snow-cover climate-sensitivity analyses are useful for a number of purposes such as validating the control climates of GCMs, and estimating regional snow-cover response to global warming. For the Canadian prairies and Great Plains, the regional sensitivity of annual snow-cover duration to maximum air temperature and snowfall for the post-1960 period is able to be well described through multiple linear expressions of the form:

$$\begin{aligned} CP(1961\text{–}92)\quad & \Delta\mathrm{SCD} = 0.29(\pm 0.09)\Delta S_{\mathrm{fall}}(\mathrm{cm}) \\ & \quad - 8.98(\pm 1.44)\Delta T_{\max}(^{\circ}\mathrm{C}) \quad r^2 = 0.90 \\ GP(1961\text{–}87)\quad & \Delta\mathrm{SCD} = 0.40(\pm 0.11)\Delta S_{\mathrm{fall}}(\mathrm{cm}) \\ & \quad - 7.18(\pm 2.00)\Delta T_{\max}(^{\circ}\mathrm{C}) \quad r^2 = 0.86. \end{aligned}$$

Assuming a $2\times\mathrm{CO}_2$ warming scenario of a 4°C increase in mean air temperature over the interior of NA (Boer and others, 1992), that $T_{\max}$ increases by an equivalent amount (this may not necessarily be the case), and no change in snowfall, the above relationships suggest reductions in snow cover of ~30 d in both regions. However, the significant negative snowfall–temperature relationships observed in both regions suggest reductions in total snowfall of 15.1(±2.0) cm $^{\circ}\mathrm{C}^{-1}$ over the Great Plains, and 12.9(±1.8) cm $^{\circ}\mathrm{C}^{-1}$ over the prairies based on the 1961–92 period. If these snowfall changes are used in the above snow-cover–climate relationships, the assumed 4°C warming in $T_{\max}$ results in a larger ~50 d reduction in snow-cover duration over both regions. This translates into a ~40% decrease in mean SCD over the prairies, and a ~70% decrease in mean SCD over the Great Plains. The latter reduction would completely eliminate snow cover south of 40° N based on the 1961–80 snow-cover climatology. This is not as large a decrease as that shown by Boer and others (1992), where the $2\times\mathrm{CO}_2$ simulated winter snow line for NA retreats to about 50° N. However, it should be noted that the above regional sensitivity-based estimates do not account for the climate feed-backs arising from a large reduction in snow-covered area. There is also no guarantee that the current atmospheric circulation pattern over NA (which plays a major role in the observed regional sensitivities) will be the same in a warmer world. To highlight the uncertainty involved in the above scenario, computing ΔSCD with ±95% confidence intervals for all change coefficients yields a range in ΔSCD of –22 to –94 d over the GP, and –28 to –80 d over the CP. Reductions in snow cover in the order of 80–90 d would completely eliminate Great Plains seasonal snow cover south of about 45° N.

SUMMARY AND CONCLUSIONS

Observed and reconstructed snow-cover duration data over the continental interior of North America exhibit a gradual increase in snow cover over much of the 20th century, primarily in response to increasing snowfall. The most noticeable regional difference is a rapid decline in snow cover over the Canadian prairies after 1970, which is not observed over the Great Plains. This decrease in

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[*] A comparable seasonal analysis was unable to be carried out with the Great Plains SCD data set because it used different definitions for the spring and fall periods.

SCD is found to be within the range of natural variability exhibited during the 20th century.

An investigation of the response of regional snow cover to larger-scale temperature changes revealed systematic increases in the sensitivity of snow cover to NH temperatures in the 1940–65 period over the Great Plains and Canadian prairies. This change is mainly due to an increase in snowfall temperature sensitivity during this period, which produced larger positive snowfall anomalies for a given negative temperature anomaly. A marked increase in spring snow-cover and snowfall temperature sensitivity was observed over the interior of NA after 1960. This is consistent with a change to more positive values of the PNA circulation index at the end of the 1950s.

These results highlight the importance of atmospheric circulation patterns, such as the PNA teleconnection, in the snow-cover climate sensitivity over the interior of North America. Under the post-1960 circulation regime, snow cover over the Canadian prairies and northern Great Plains is characterized by a strong positive feedback, i.e., warmer (colder) temperatures are associated with less (more) snowfall, a thinner (deeper) snowpack, and a lower (higher) albedo, contributing to earlier (later) snowmelt and warmer (cooler) local air temperatures. Under this regime, snow cover exhibits a close inverse relationship with hemispheric air temperature, not observed during the first half of the 20th century.

Assuming a $2 \times CO_2$ warming scenario of a 4°C increase in winter maximum air temperature over the interior of NA, regional snow-cover/snowfall temperature sensitivities for the post-1960 period suggest reductions in mean SCD of $\sim 40\%$ and $\sim 70\%$ over the Canadian prairies and Great Plains, respectively. This would eliminate Great Plains seasonal snow cover south of about 40°N based on the 1961–80 mean.

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