Spatial and Temporal Variability of Canadian Monthly Snow Depths, 1946-1995

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ABSTRACT

In 1995 the Canadian Atmospheric Environment Service (AES) made a major effort to digitize paper records of daily and weekly snow depth which were not in the Canadian Digital Archive of Climate Data. This resulted in the extension of the snow depth record at many stations back to the late 1940s, and the filling of missing data from a number of stations, particularly in the Arctic. This paper describes the database and the methods used to quality control and reconstruct missing data, and presents an analysis of the spatial and temporal characteristics of the data over the 1946-1995 period. Principal component analysis of monthly snow depths revealed that snow depths varied coherently over relatively large regions of Canada with dominant centres of action located over the West Coast, Prairie, Yukon-Mackenzie, southern Ontario, northern Québec and Maritime regions. In many cases, nodes of coherent snow depth variations were associated with corresponding nodes of coherent snow cover duration fluctuations, with the two times series exhibiting significant positive correlations. Winter and early spring snow depths were observed to have decreased significantly over much of Canada in the 1946-1995 period, with the greatest decreases occurring in February and March. The snow depth changes were characterized by a rather abrupt transition to lower snow depths in the mid-1970s which coincided with a well-documented shift in atmospheric circulation in the Pacific-North America sector of the Northern Hemisphere.

INTRODUCTION

Snow comprises an integral component of the global climate system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric circulation. Snow cover is also considered to be a useful indicator of climate change because of its sensitivity to temperature (Karl *et al.* 1993; Groisman *et al.* 1994), and because of predictions that anthropogenic global warming should be greatest in northern snow-covered areas (IPCC, 1995). The importance of snow cover as an indicator of change was highlighted in a recent paper by Myeni *et al.* (1997) who documented an increase in the active growing season across much of the Northern Hemisphere high latitudes from 1981-1992. This change was attributed to earlier disappearance of spring snow cover which appears to be part of a recent trend toward earlier disappearance of spring snow and ice cover over much of North America in conjunction with enhanced warming of spring temperatures (Foster, 1989; Stuart *et al.*, 1991, Robinson *et al.* 1991; Hanson *et al.*, 1992; Karl *et al.*, 1993; Skinner, 1993; Brown and Goodison, 1996).

The ability to document large-scale variations in snow cover is greatly constrained by the nature of the available data sets. NOAA satellite-derived weekly snow cover observations provide a consistent record of Northern Hemisphere snow covered area (SCA), but this is temporally constrained to the post-1971 period. Studies using this dataset have documented a 10% decrease in Northern Hemisphere annual SCA (Groisman *et al.* 1994), and large scale systematic decreases in North American annual SCA (Karl *et al.* 1993; Robinson *et al.* 1993) over the 1972-91 period. The satellite data record, however, is too short to reach any conclusions about possible climate warming-induced trends in snow cover, and the more recent NOAA SCA data suggest that hemispheric snow cover may be returning to pre-1980s levels. *In-situ* snow depth data provide greater temporal information, but these data are typically biased toward populated areas and to lower elevations, and tend to be regional in character. In North America, a considerable effort has been made to understand snowpack variations over the western United Sates (Aguado *et al.*, 1992; Changnon *et al.*, 1993; Dettinger and Cayan, 1995; Cayan, 1996) because of the importance of snow to the water supply of the region. However, the authors are unaware of any studies which have looked at snow depth variations over North America at a continental-scale. This paper uses a newly-expanded and updated station-based daily snow depth database for Canada (Braaten, 1996) to investigate the spatial and temporal characteristics of monthly snow depth over a 50-year period between 1946 and 1995.

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CANADIAN SNOW DEPTH DATABASE

Daily measurements of Canadian snow depths began in 1941 at principal observing stations and in 1981 at most climate observing stations. Observers were instructed to record the average of a series of measurements, avoid snow drifts and ensure that the total depth, including any layers of ice, was measured. Snow depth measurements were recorded in whole inches prior to 1975 and to the nearest centimetre after that date (Potter 1965). Until recently, regular snow depth measurements taken before 1955 did not appear in the Digital Archive of Canadian Climate Data. In 1995 a project was initiated under the CRYSYS program (Goodison and Brown, 1997) to rescue paper and micro-film records of daily and weekly snow depth measurements in storage at AES. These data, representing measurements for about 400 stations with varying lengths of record in the period 1900 to 1990, were combined with daily snow depth observations in the Canadian Digital Climate Archive to form a separate Canadian snow depth database. Few snow depth observations were found before 1946, so the main impact of the additional data was to extend the snow depth record back to the late 1940s, and to increase the spatial distribution of stations with 30 years or more of snow data, particularly in the Arctic region.

The observing network is biased to low latitudes and to low elevations, and the snow depth observations are made, for the most part, in open areas. The snow depth measurements are also essentially point observations, and local-scale variations in snow accumulation are not taken into account such as in snow course measurements. For these reasons, the station observations are unlikely to be representative of the surrounding terrain and vegetation cover. Nevertheless, these observation should still represent an internally consistent measure of temporal variations in snow cover which one would expect to be well-correlated over relatively large areas. This argument is supported by Brown and Goodison (1996) who found significant correlations between station- and satellite-derived estimates of seasonal snow cover duration over four different climatic regions of Canada (Maritimes, S. Ontario, Prairies, West Coast).

Quality Control

The snow depth data were subject to internal consistency checks following Robinson (1989). Daily snow depth changes were compared with corresponding temperature, rainfall and snowfall conditions and unexpected results flagged. The data were found to be of very high quality throughout the country (internal consistency ranging from 98.5% in the Maritimes to 99.1% in Saskatchewan and Manitoba) and most inconsistencies were determined to be most likely related to the timing of the snow depth observation (a PM as opposed to an AM snow depth reading) rather than the quality. To identify typographical errors, spike-checking software was developed to detect and flag sudden snow depth fluctuations of 20 cm or greater which reversed themselves within a three-day period. This identified approximately 600 spikes of which about 400 turned out to be obvious typographical errors.

The potential effects of station shifts and urban warming on snow depths were investigated by visually examining station difference series following the approach of Jones *et al.* (1986). The investigation was carried out for stations with large identifiable shifts in location or elevation, and for stations in major urban centres. None of the shifted stations showed any detectable inhomogeneity, which is most likely related to the higher noise levels associated with daily snow depth observations. Only two urban stations, McGill (7025280) and Toronto (6158350), showed evidence of an urban warming effect in their snow depth records. These two stations were subsequently eliminated from further analysis.

Data-Filling

Temporal analyses of station data are often confounded by gaps in the observational record. In order to avoid this problem, missing values in the Canadian daily snow depth database were reconstructed using a combination of an empirical temperature-index model and linear interpolation. The reconstruction method is based on the water balance of Johnstone and Louie (1983) where snow is accumulated using the observed daily snowfall, and melted from a calibrated temperature-index method following the U.S. Corps of Engineers (1956):

$$M = \boldsymbol{k}\,[(1.88 + 0.007\,R)(9/5T) + 1.27],\ T > 0°C \quad (1)$$

where M = snowmelt water (mm day^{-1})
$\boldsymbol{k}$ = locally-calibrated snowmelt factor
T = mean daily air temperature (°C)
R = mean daily rainfall (mm).

A fixed mean density of 300 $kg.m^{-3}$ was assumed for snow on the ground. This approach was found to give the best overall results in an evaluation of methods for reconstructing snow depth information from climatological data (Brown, 1996). However, Brown (1996) concluded that none of the methods evaluated performed reliably over a range of different snow cover climates. For this reason, the reconstruction method was combined with observed snow depth information whenever this was available. At the end of each data-gap, the error between the predicted and observed snow depth was calculated and distributed linearly over the entire missing section of record. This reduced the cumulative error by 'forcing' the model to agree with available snow depth observations. A QC flag was created for each reconstructed depth based on the number of days to the nearest observation. Thus users of the database can set different threshold levels to screen out reconstructed data, or accept only reconstructed data where the model was regularly updated as in the case of weekly snow depth observations.

The robustness of the data-filling method was examined at four stations from different climatic regions of Canada which had complete data in the 1955-1994 period (Edmonton, Gander, Whitehorse and Windsor). The method was successively run with decreasing amounts of observed data (equally spaced) to construct root-mean-squared (RMS) error curves for snow depth and snow cover duration (SCD) defined as the number of days with snow depths ≥ 2 cm. Sample plots for Gander and Whitehorse are shown in Figure 1. At these two stations, error remained low until the proportion of the reconstructed data reached 85%-90%. This appears to be the threshold level for capturing synoptic-scale variations in snow depth. Figure 1b for the 86% reconstruction level (corresponding to the filling of weekly snow depth observations) shows that the error is not concentrated in any particular season or period (e.g. accumulation or ablation), and broadly follows the temporal evolution of the snowpack.

Tables 1 and 2 summarize error results for snow depth and SCD from all four stations for reconstruction levels of 50%, 75%, 86% and 97% (one observation per month). Two main points are evident. First, errors in SCD are considerably lower than snow depth because there is less variability during the snow year and because temperature-index methods are very successful at capturing interannual variability in snow cover (Brown, 1996). Second, the % error in reconstructed snow depth is strongly related to the duration of the snow cover season. At stations with well-defined snow cover seasons such as Whitehorse, the % error is less than 10% at the 86% reconstruction level. At Windsor, however, where snow cover is more ephemeral in nature, the corresponding snow depth reconstruction error exceeds 75%. This difference in reconstruction performance was taken into account in the following analyses by setting a 50% reconstruction limit for stations with a mean annual SCD of less than 90 days, and the 86% limit (weekly) for all other stations. This allowed the inclusion of a considerable amount of newly digitized weekly data in the analyses.

Table 1. RMS error (cm) in reconstructed snow depth for four stations at various levels of reconstruction. Values in parentheses are RMS errors expressed as a percentage of mean winter snow depth.

	Percentage Reconstructed Data			
Station	**50%**	**75%**	**86%**	**97%**
Edmonton, AB	1.3 (6.7%)	1.5 (7.7%)	2.0 (10.2%)	4.9 (25.1%)
Gander, NF	3.4 (10.4%)	3.9 (11.9%)	5.2 (15.9%)	10.8 (33.0%)
Whitehorse, YT	1.3 (4.0%)	1.4 (4.3%)	2.0 (6.2%)	4.5 (13.9%)
Windsor, ON	2.1 (52.5%)	2.6 (65.0%)	3.1 (77.5%)	4.8 (120.0%)

Table 2. RMS error (days) in reconstructed snow cover duration for four stations at various levels of reconstruction. Values in parentheses are RMS errors expressed as a percentage of mean annual snow cover duration.

	Percentage Reconstructed Data			
Station	**50%**	**75%**	**86%**	**97%**
Edmonton, AB	2.7 (1.9%)	4.0 (2.9%)	5.7 (4.2%)	11.4 (8.4%)
Gander, NF	4.0 (2.7%)	4.7 (3.2%)	7.1 (4.9%)	15.3 (10.6%)
Whitehorse, YT	2.0 (1.1%)	2.6 (1.5%)	5.3 (3.0%)	13.9 (7.9%)
Windsor, ON	2.7 (5.4%)	5.7 (11.4%)	6.8 (13.6%)	14.9 (29.8%)

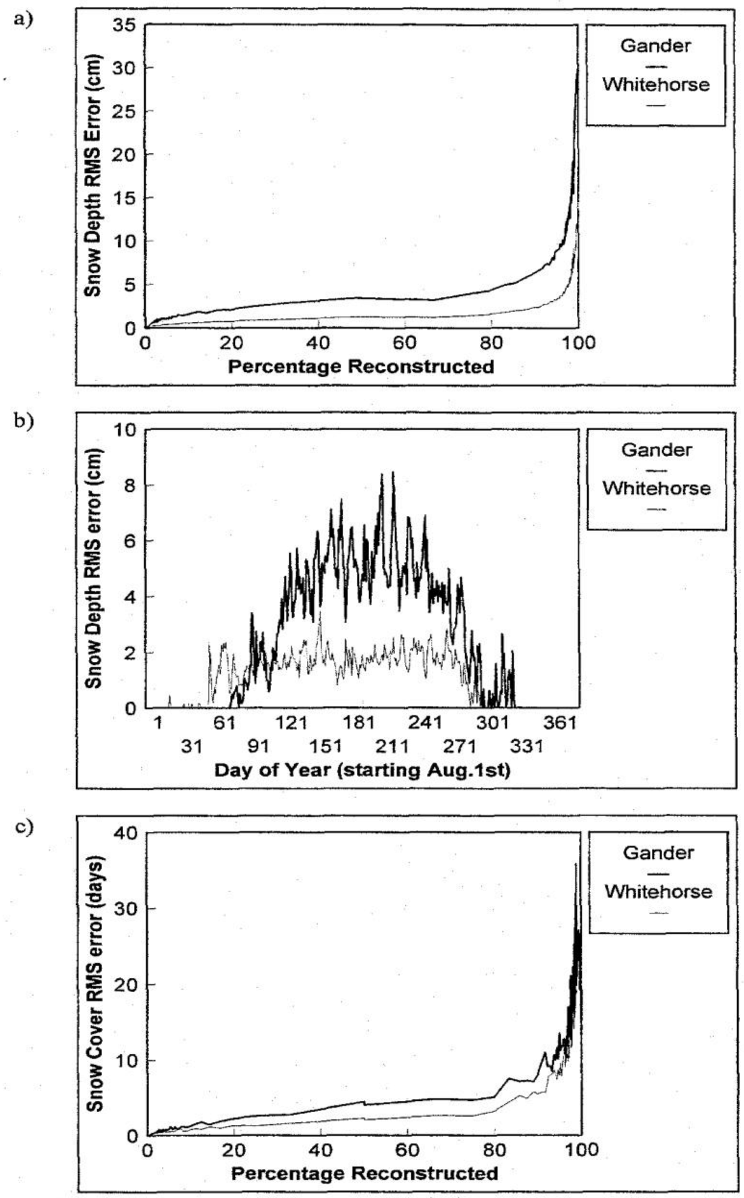

Figure 1: Snow depth reconstruction statistics for Gander and Whitehorse: a) total annual RMS error in snow depth reconstructions by proportion of data that is reconstructed; b) daily RMS error at the 86% reconstruction level (weekly observations); c) RMS error in snow cover duration reconstruction by proportion reconstructed.

TRENDS IN CANADIAN SNOW COVER AND SNOW DEPTH

Linear regression analysis was used to look at first order changes in Canadian snow depth and SCD between 1946 and 1995. Stations with at least 40 years of data within the 1946-1995 period were included in the analysis. This resulted in 122 stations spread over the entire country, but with a noticeable decrease in station density in northern latitudes (Fig. 2). At each station, mean monthly snow depth and seasonal SCD were calculated for each year of record. To ensure that data approximated a normal distribution, only stations with more than 50% non-zero or non-maxima data values were included in the analysis. Slopes and corresponding Student t-statistics were computed from least-squares regression analysis and interpolated to a 200 km grid using the Shepard interpolation routine (Figs. 2 and 3). The interpolated slope t-statistics are shown as shaded zones of marginally-significant ($0.05 < p < 0.1$) and significant ($p < 0.05$) local change. These shaded areas should not be taken to represent the actual areal extent of significant change because the effect of auto-spatial-correlation is not taken into account. They are useful, however, in showing which stations exhibited significant local change.

Snow Depth

The monthly snow depth change results are shown in Figure 2. The main feature is the dominance of snow depth decreases in nearly all months. Statistically significant local decreases in snow depth are widespread in January, and these increase in magnitude and spatial extent in February and March when most stations in Canada exhibit statistically-significant reductions in snow depth. The monthly development of the snow depth decreases occurs in three nodes; one located in the Mackenzie Basin area, one in the lower St. Lawrence River region, and a broad band stretching across northern Ontario and the Prairie provinces. Maximum snow depth changes of 1.0 to 1.5 $cm.yr^{-1}$ were observed in these areas. The east coast region was the only area which exhibited an increase in snow depth over the study period. This coincides with a long-term trend toward greater winter and spring snowfall over the east coast of Canada (Brown and Goodison, 1996). Stations exhibiting monthly snow depth decreases in excess of 1.0 $cm.yr^{-1}$ were manually verified against surrounding stations and with available snow course information. Only 2 stations failed these checks; Norman Wells, N.W.T. and Sept-Isles, Québec. In both cases, winter snow depths showed evidence of a sudden drop in the early 1980s which were inconsistent with snowfall totals and adjacent snow course data.

Snow Cover Duration

The snow cover duration change results are shown in Figure 3. The dominant feature is the large area of locally significant decrease in spring snow cover which extends across almost the entire western half of Canada. Locally significant decreases in snow cover duration are also observed over much of the Arctic in the summer. These results are consistent with recent trends toward earlier disappearance of snow and ice cover over much of North America in conjunction with enhanced spring warming. Figure 3 also shows that a number of areas in southern Canada have experienced significant decreases in snow cover during the fall season. Most areas west of Québec show decreased winter snow cover although few stations exhibited locally significant decreases. The only area experiencing an increase in snow cover was the Maritimes in winter. These results confirm the conclusion of Brown and Goodison (1996) that the largest decreases in snow cover have occurred over western Canada. However they also show that the change is still significant when looked at over a longer 50 year period (Brown and Goodison used a much shorter 1961-90 period) and highlight the importance of snow cover changes in the spring and summer seasons. These results are consistent with a recent trend toward an earlier active growing season across much of the northern and western portions of North America (Myeni *et al.*, 1997).

PRINCIPAL COMPONENT (PC) ANALYSIS

The objective of the PC analysis was to determine whether there were regions in Canada were monthly snow depths varied coherently in space and time. This information can be used to investigate the mechanisms responsible for interannual variations in snow depths (e.g. Cayan, 1996) although this is not attempted in this paper. The analysis was also extended to seasonal values of SCD to provide comparison information from the same stations and time period. To carry out the analysis, station values of monthly mean snow depth and seasonal totals of snow cover

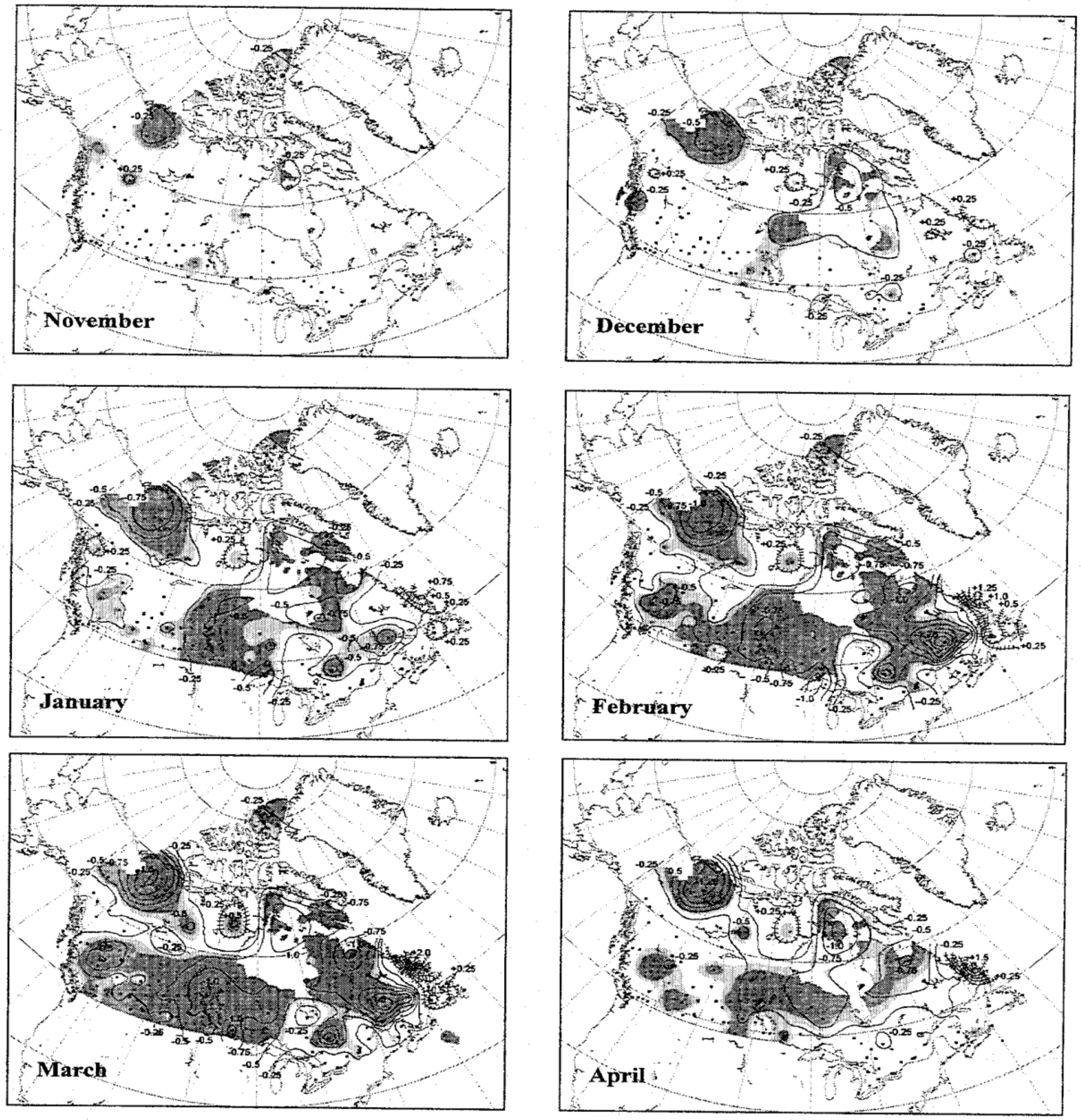

Figure 2: Average change in mean monthly snow depth over the 1946-95 period ($cm.yr^{-1}$). Increases are shown as cross-hatched contour lines and decreases as regular lines. The filled squares show the locations of the stations included in the analysis (were required to have at least 40 years of data in the period). Dark shading is used to highlight areas where changes in snow depth were locally significant ($p < 0.05$). Light shading is used to highlight areas where station exhibited marginally significant ($0.05 < p < 0.10$) snow depth changes.

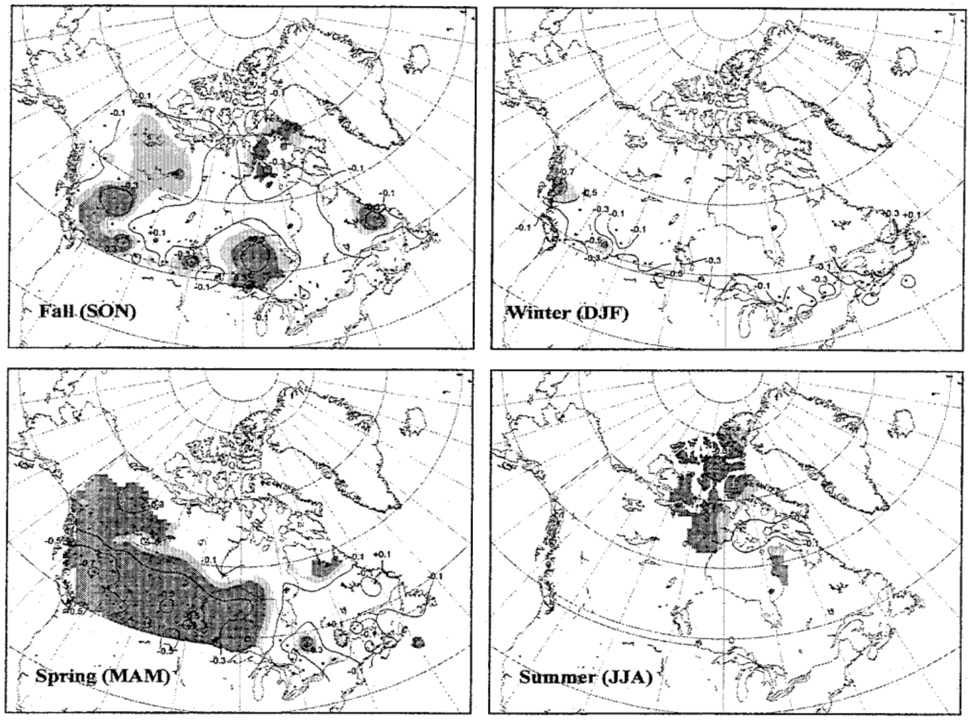

Figure 3: Average change in seasonal snow cover duration over the 1946-95 period (days.yr^{-1}). See Figure 2 for explanation of shading.

duration were first interpolated to a 190.5 km polar-stereographic grid using an inverse distance weighting scheme. Gridding was carried out to avoid unduly biasing the results to the denser network of stations in populated regions of southern Canada. This problem is not overcome entirely since large areas of northern Canada are poorly represented by the available station network. The PC analysis was confined to the 1955-1995 period to ensure an even distribution of gridpoints over all months (much of the pre-1995 period data is concentrated in the winter months). To be included in the PC analysis, gridpoints had to have a minimum of 36 years of data in the 41-year period, and at least 18 years which were non-zero or less than the maximum possible snow cover duration for SCD. Inspection of the number of valid gridpoints for monthly snow depth revealed these remained relatively stable (~400) over the entire period. An "S-mode" PC analysis was applied following Brown (1995) where the matrix columns are the gridpoints, and the matrix rows are the values for each year from 1955 to 1995. In "S-mode" analysis, a plot of the PC loadings provides information on the spatial structure of the field (e.g. areas of coherent interannual changes in monthly snow depth), while a plot of the PC scores provides information on the temporal variability of snow depths within the defined coherent regions. An orthogonal varimax rotation was applied to the identified principal components (PCs) to avoid many of the problems of unrotated PCs discussed by Richman (1986).

Results

A total of 12 PCs were computed for each month and PCs explaining >5% of the variance were visually inspected to determine whether they formed a coherent region. Typically 5-6 important PCs were observed per month which collectively explained about 40% of the total variance. A summary of the main snow depth response regions is provided in Figure 4. These results agree with Cayan (1996) and Aguado (1990) who found that snowpack accumulations were coherent over scales of a least a few hundred kilometres. The same response regions were observed to occur across multiple months which indicated that there was some consistency in the results. A summary of regions where monthly snow depths varied coherently in three or more months is provided in Table 3:

Table 3: Regions and months when monthly mean snow depths were observed to vary coherently over time.

Region	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
West Coast		x	x	x				
Western Prairies	x	x	x	x	x	x	x	
Yukon-Mackenzie	x	x	x	x	x	x	x	x
S. Manitoba-N. Ontario	x	x					x	x
S. Ontario-Québec			x	x	x	x	x	
N. Québec	x	x						x
Maritimes		x	x	x	x	x	x	

The fact that coherent snow depth regions were found confirms the argument stated earlier that snow depth measurements made at AES stations do indeed contain regionally-consistent snow depth information. This would not be the case if the snow depth measurements were severely contaminated by random errors. The reason snow depths do vary coherently is related to several factors. Firstly, in shoulder seasons and in regions experiencing ephemeral winter snow cover, the initiation and melting of the snowpack are strong regional signals which affect snow depths over relatively large areas. This explains why there are many similarities between the snow depth and snow cover duration response regions (Fig. 5). During periods of continuous snow cover, interannual variations in snow depth would arise from interannual variations in precipitation and temperature which are controlled by large-scale variations in atmospheric circulation patterns e.g. the Pacific-North America (PNA) teleconnection pattern was shown by Gutzler and Rosen (1992) and Brown and Goodison (1996) to have a major impact on show cover over the western half of North America.

The PC results presented in Figure 4 for October, December, February and April give an indication of the size and the seasonal transition of the coherent snow depth regions. In October, snow cover expands rapidly over North America which results in a relatively even distribution of regions across Canada. Alberta and northern Québec were the two most important regions explaining 11.7 and 10.3% of the variance respectively. The snow depth results show a number of similarities to the fall SCD results in Figure 5. In December, the patterns move southward reflecting the southward migration of the snow line and the main winter storm tracks. The Prairie region (PC3) explained the largest fraction of the variance which agrees with Brown (1995) who found that the dominant region of North American winter snow cover variability was centred over the Prairies and Great Plains. In February, the Prairie region was again the main node explaining 13.2% of the total variance. PCs located over the Prairie region were observed to explain the largest portion of the variance from December through to March. One of the main reasons for this is that snowfall and temperature over the continental interior of NA are strongly modulated by the PNA teleconnection pattern. In April, the centres of action move north over western Canada into N. Alberta/B.C. and the Mackenzie Basin/Yukon area as the snowline retreats northward. The April snow depth response areas show a number of similarities to the spring SCD response patterns in Figure 5.

To investigate the similarities in the two sets of PC results presented in Figures 4 and 5, PC score time series from co-located response regions were compared for all three seasons. In all cases, snow depth and SCD time series exhibited significant positive correlations which is not surprising since a thinner (deeper) snowpack will ablate more rapidly (slowly). This result has potentially useful practical applications because snow cover information is more readily available than snow depth information e.g. Brown and Goodison (1996) were able to successfully reconstruct SCD information over much of Canada back to 1915, and NOAA weekly snow cover data are available over the Northern Hemisphere from the early 1970s. The results of this study suggest it should be possible to infer snow depth information from snow cover in areas and seasons where these are highly correlated. An example is shown in Figure 6 for the Prairie region. The results of the regression analysis in Figures 2 and 3 suggested that this area had experienced a significant decrease in snow depth and snow cover over the spring period. However, Figure 6 shows that this change was not gradual, but occurred as more of a shift to shallower snow depths and a shorter spring snow cover season in the late 1970s.

To obtain a more detailed look at the temporal characteristics of the widespread winter changes in snow depths suggested by Figure 2, winter (JFM) snow depths were averaged over three of the main response regions identified from the PC analysis which had experienced the largest decreases in winter snow depths: Prairies, Yukon-Mackenzie

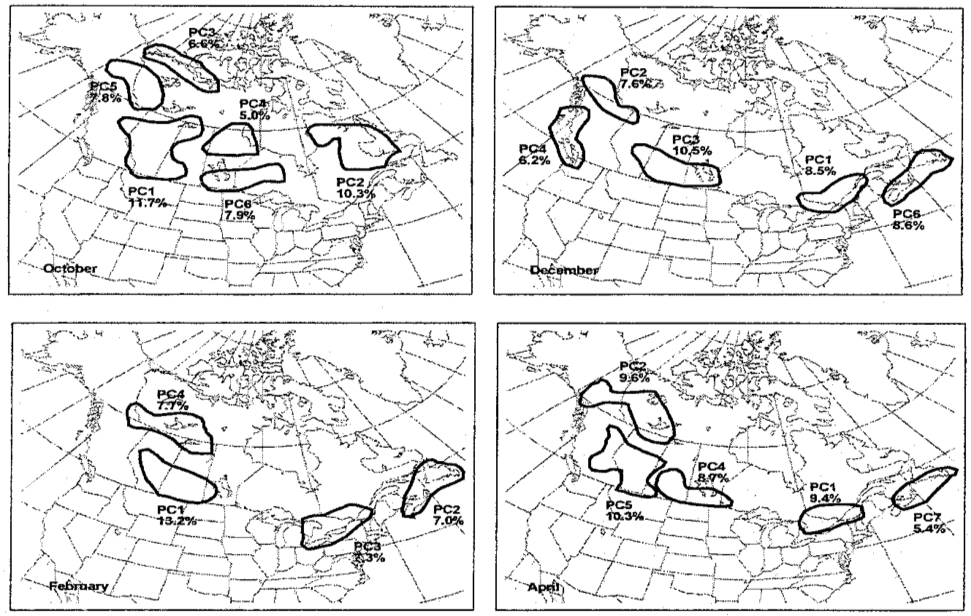

Figure 4: Location of PCs explaining more than 5% of the variance in monthly mean snow depth over the 1955-1995 period. Lines approximate the 0.7 contour of rotated PC loadings.

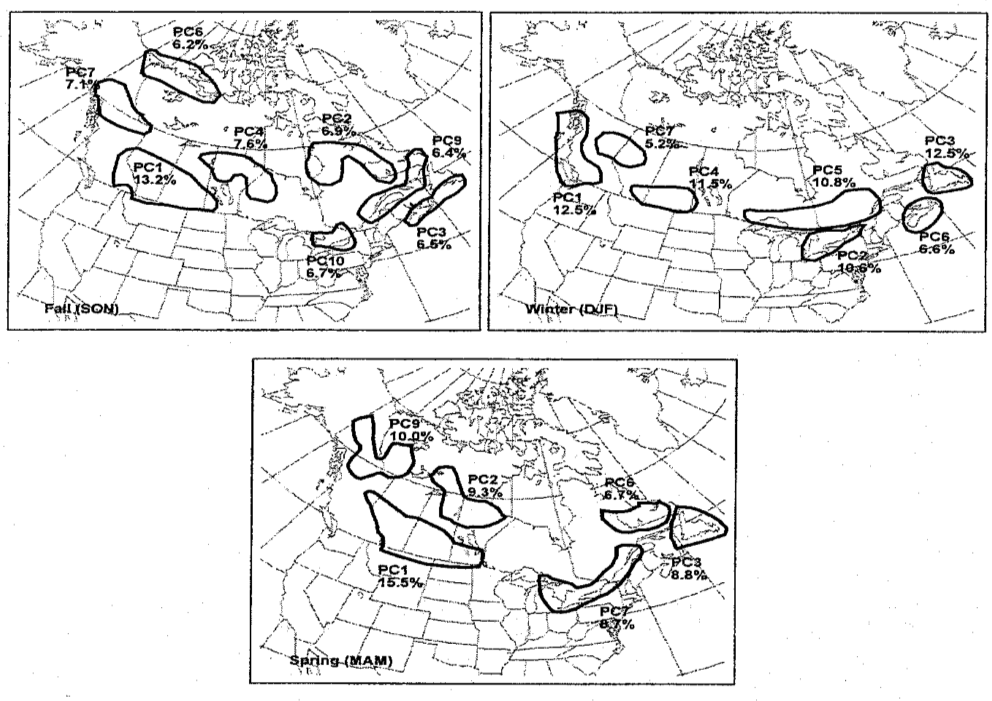

Figure 5: Location of PCs explaining more than 5% of the variance in seasonal snow cover duration over the 1955-1995 period. Lines approximate the 0.7 contour of rotated PC loadings. Results for the Summer (JJA) period are not shown as there were insufficient gridpoints to generate spatially consistent response regions.

and the lower St. Lawrence Valley. These areas were found to have a good distribution of winter snow depth information back to 1946. The results (Fig. 7) show the same pattern as Figure 6 which suggests that a shift to lower winter snow depths in late-1970s is a widespread feature. This change coincides with a well-documented (Trenberth, 1990) shift in the atmospheric circulation over the North Pacific in 1976 which was associated with widespread abrupt environmental changes (Ebbesmeyer *et al.*, 1991). Trenberth (1990) noted that the sudden 2 mb decrease in mean North Pacific sea-level pressures was also an index of change in the PNA pattern which has been shown in several studies to be closely linked to temperature, precipitation and snow cover variability over North America, particularly in the western half of the continent (Gutzler and Rosen 1992; Brown, 1995; Brown and Goodison, 1996).

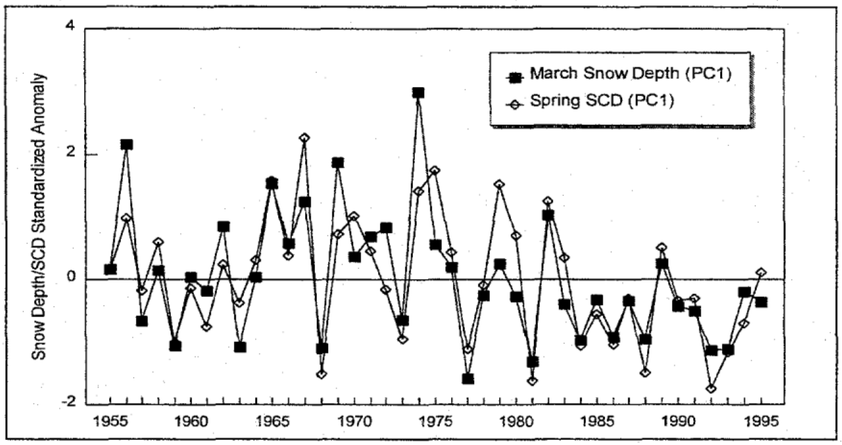

Figure 6: Comparison of March snow depth and spring snow cover fluctuations over the Prairie region. The correlation coefficient for both series is 0.8.

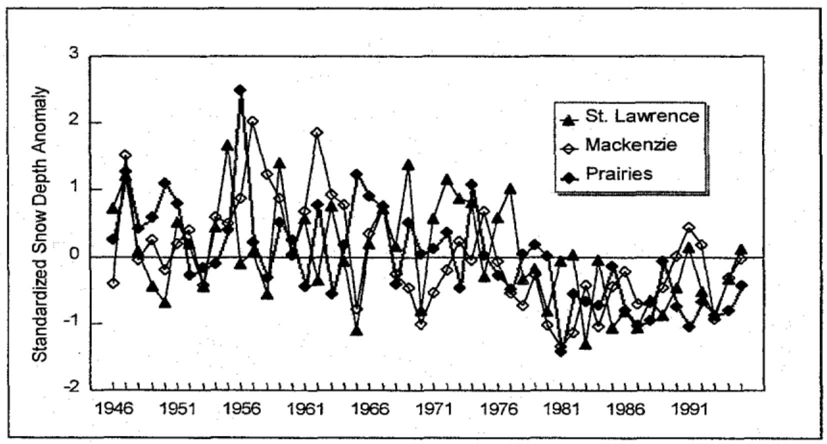

Figure 7: Temporal variation in mean winter (JFM) snow depth over three important snow depth response regions identified in the PC analysis. Snow depths are expressed as standardized anomalies.

CONCLUSIONS

The development of a quality-controlled, expanded daily snow depth data base for Canada (Braaten, 1996) has allowed an investigation to be made of the spatial and temporal characteristics of snow depth variability over Canada during the last 40-50 years. Both snow depth and snow cover were observed to have experienced important decreases over many regions of Canada since 1946. Widespread snow depth decreases were observed in the three month period from January to March, with the largest decreases occurring in March. The largest snow depth decreases were observed in three nodes centred over the Prairies, the Mackenzie Basin and the lower St. Lawrence Valley. The decrease in March snow depths was associated with significant reductions in spring snow cover over western Canada. Principal component analysis revealed that monthly snow depths varied coherently over relatively large areas. The most important regions of snow depth variability were the West Coast, Prairie, Yukon-Mackenzie, southern Ontario, northern Québec and Maritime regions. In most of these regions, snow depth and snow cover variability were found to be closely related. Analysis of the temporal characteristics of snow depth decreases revealed that the change was not gradual, but had occurred as a rather rapid transition in the late 1970s to a new regime with shallower winter snowpacks and a shorter spring snow cover season. This change is likely related to a major shift in atmospheric circulation over the North Pacific and North America in 1976 (Trenberth, 1990) which is considered to be linked to a 20-year oscillation involving unstable atmosphere-ocean interactions over the North Pacific (Latif and Barnett, 1996). This rapid transition highlights the importance of natural climate variability in snow cover variations over North America.

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REFERENCES

Aguado, E., D. Cayan, L. Riddle and M. Roos, 1992: Climatic fluctuations and the timing of West Coast streamflow. *J. Climate*, **5**:1468-1483.

Braaten, R.O., 1996: An updated Canadian snow depth database. Contract report prepared for Atmospheric Environment Service, September, 1996, 24 pp.

Brown, R.D. and B.E. Goodison, 1996: Interannual variability in reconstructed Canadian snow cover, 1915-1992. *J. Climate*, **9**:1299-1318.

Brown, R.D., 1996: Evaluation of methods for climatological reconstruction of snow depth and snow cover duration at Canadian meteorological stations. *Proc. 53rd East. Snow Conf.*, May 1-3 1996, Williamsburgh, Virginia, 55-65.

Brown, R.D., 1995: Spatial and temporal variability of North American snow cover, 1971-1992. *Proc. 52nd East. Snow Conf.*, 6-8 June 1995, Toronto, Ontario, 69-78.

Brown, R.D., M.G. Hughes and D.A. Robinson, 1995: Characterizing the long-term variability of snow-cover extent over the interior of North America. *Annals of Glaciology*, **21**:45-50.

Cayan, D.R., 1996: Interannual climate variability and snowpack in the western United States. *J. Climate*, **9**:928-948.

Changnon, D., T.B. McKee, and N.J. Doesken: 1993: Annual snowpack patterns across the Rockies: long-term trends and associated 500-mb synoptic patterns. *Mon. Weather Review*, **121**:633-647.

Dettinger, M.D. and D.R. Cayan, 1995: Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *J. Climate*, **8**:606-623.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McLain, F.H. Nichols, D.H. Peterson and K.T. Redmond, 1991: 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. *Proc. Seventh Annual Pacific Climate (PACLIM) Workshop*, Pacific Grove, CA, 115-126.

Foster, J.L., 1989: The significance of the date of snow disappearance on the Arctic tundra as a possible indicator of climate change. *Arctic and Alpine Research*, **21**:60-70.

Goodison, B.E. and R.D. Brown, 1997: CRYSYS - Use of the Cryospheric System to Monitor Global Change in Canada. *Proc. GER'97 (International Symposium: Geomatics in the Era of Radarsat)*, May 24-30, 1997, Ottawa, Ontario.

Groisman, P.Ya, T.R. Karl, and R.W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science*, **263**:198-200.

Gutzler, D.S., and R.D. Rosen, 1992: Interannual variability of wintertime snow cover across the Northern Hemisphere. *J. Climate*, **5**:1441-1447.

Hanson, H. P., C.S. Hanson, and B.H. Yoo, 1992: Recent Great Lakes ice trends. *Bull. Amer. Met. Soc.*, **73**:577-584.

IPPC, 1995: *Climate Change 1995 - The Science of Climate Change*. J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.), Cambridge University Press, 572 pp.

Johnstone, K., and P.Y.T. Louie, 1983: *Water balance for Canadian climate stations*. Report DS#8-83, Canadian Climate Centre, Downsview Ontario, 16 pp.

Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelly and T.M.L. Wigley, 1986: Northern Hemisphere surface air temperature variations: 1851-1984. *J. Clim. and Appl. Meteorol.*, **25**:161-179.

Karl, T. R., P. Ya. Groisman, R. W. Knight, and R. R. Heim Jr., 1993: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Climate*, **6**:1327-1344.

Latif, M. and T.P. Barnett, 1996: Decadal climate variability over the North Pacific and North America: dynamics and predictability. *J. Climate*, **9**:2407-2423.

Myeni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar and R.R. Neuman, 1997: Increased plant growth in northern high latitudes from 1981-1991. *Nature*, **386**(6626):698-701.

Potter, J.G., 1965: *Snow cover*. Climatol. Studies Number 3, Dept. of Transport, Meteorological Branch, Canada, 57 pp.

Richman, M. B., 1986: Rotation of principal components. *J. Climatol.*, **6**:293-335.

Robinson, D.A., K.F. Dewey, and R.R. Heim, 1993: Global snow cover monitoring: an update. *Bull. Amer. Met. Soc.*,**74**:1689-1696.

Robinson, D.A., 1989: Evaluation of the collection, archiving and publication of daily snow data in the United States. *Physical Geog.*, **10**:120-130.

Robinson, D.A., F.T. Keimig, and K.F. Dewey, 1991: Recent variations in Northern Hemisphere snow cover. *Proc. 15th Ann. Climate Diagnostics Workshop*, Asheville, NC, 219-224.

Skinner, W.R., 1993: Lake ice conditions as a cryospheric indicator for detecting climate variability in Canada. *Proc. "Snow Watch '92"*, R.G. Barry, B.E. Goodison, and E.F. LeDrew (eds.), World Data Center A for Glaciology, Glaciological Data Report GD-25, 204-240.

Stuart, R.A., D.A. Etkin, and A.S. Judge, 1991: *Recent observations of air temperature and snow depth in the Mackenzie Valley area and their implications on the stability of permafrost layers*. Canadian Climate Centre Report 91-2, Atmospheric Environment Service, Downsview, Ontario, 178 pp.

Trenberth, K.E., 1990: Recent observed interdecadal climate changes. *Proc. Symp. on Global Change Systems - Special Sessions on Climate Variations and Hydrology*, American Meteorological Society, 91-95.

United States Army Corps of Engineers, 1956: *Snow hydrology: summary report of the snow investigations*. Portland, Oregon, North Pacific Division, U.S. Army Corps of Engineers.