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Recent Observed Trends and Modelled Interannual Variability in Canadian Snow Cover

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ABSTRACT

Analysis of Canadian daily snow depth data revealed a consistent reduction in the duration of snow cover over the period of record (1955-89). This was most marked in southern regions of the Prairies and western Canada where the annual duration of snow cover has decreased an average of 1.0 to 1.5 days/yr over the 35 year period. Most of this decrease occurred in the spring in association with significantly warmer spring temperatures. Analysis of reconstructed snow cover duration data from 1900 in three regions (W. Prairies, S. Ontario and Maritimes) revealed quite different responses and scales of variability. However, a characteristic feature of the data was a trend toward increasing snow cover duration from the late-1920s to the late-1960s, followed by a rapid decrease during the 1970s and 1980s. The lack of a consistent relationship between snow cover and air temperature highlighted the complex nature of snow-climate interactions in Canada.

INTRODUCTION

Cryospheric components of the climate system, such as snow cover and sea-ice extent, are considered to be sensitive integrators of basic climate elements, and as such, to be potentially effective indicators of regional and global climate change. For example, Robinson et al. (1991) provide evidence of a marked decrease in Northern Hemisphere snow covered area from 1973 to 1990. They show that this decrease is consistent with observed increases in hemispheric temperatures over the same period and argue that it may be due in part to a snow-albedo feedback. This observation is consistent with GCM doubled-CO_2 simulations which typically show a reduction in snow covered area and a substantial northward retreat of the snow-line in the Northern Hemisphere.

While satellite data provide the most reliable estimates of snow covered area, the period of record is too short to say anything about long-term variability in snow cover. Station data provide longer time series, but spatial coverage is frequently less than optimal, and there can be numerous problems with data quality (e.g. see Robinson, 1989). However, when care is made in quality control and selection of a station network, station-derived snow cover data in non-mountainous terrain have been found to agree well with satellite-derived snow products at a seasonal time scale (Robinson, 1991).

Daily snow depth data for Canadian principal and synoptic stations are currently only available in digital format from the mid-1950s. Analysis of longer-term variability in snow cover therefore requires reconstructing the annual evolution of the snow pack. A review of snow cover reconstruction methods is provided in Hughes and Robinson (1992). Energy balance methods, while preferred from a physical standpoint, are inappropriate because much of the required input data is only available for short periods. Temperature index methods, based on empirical relationships between snow-melt and melting degree-days, use a "bulk" melt factor term to account for a host of local parameters such as latitude, exposure, and cloudiness. Hughes and Robinson (1992) found this method difficult to apply on a regional basis because of large variability in derived melt factors and base temperatures. They preferred using a depth change (DC) method based on the empirical relationship between observed reduction in snow depth, and the corresponding mean air temperature. They used this approach to develop regional and seasonal snow depth change-temperature relationships, which when used with daily snowfall data, allowed them to reconstruct daily snow depths at individual stations with a high degree of confidence.

A preliminary analysis of the DC method at several Canadian stations revealed large amounts of noise in the snow depth change-temperature results which made it difficult to develop clear relationships. Part of this noise is probably due to data quality. However, wind erosion of the snow pack is considered to be a contributing factor in many exposed areas of Canada. To get around the problem of noise in daily snow depth data, it was decided to look at the feasibility of directly reconstructing snow cover duration, the assumption being that this was a more "robust" index of regional snow cover.

In light of the above discussion, the aims of this paper are therefore: (1) to document and investigate recent spatial and temporal trends in observed snow data from Canadian stations for evidence of the warming signals noted by Robinson et al. (1991); and (2) to examine longer-term (1900-1990) variability in snow cover reconstructed from daily snowfall and temperature data.

CANADIAN SNOW COVER, 1955-89

Snow depth data

Potter (1965) reported that daily snow depth measurements began in 1941 at principal observing stations. However, regular measurements do not appear in the Digital Archive of Canadian Climate Data until about 1954. The measurement procedure requires the observer to determine the "average" depth of snow on the ground. There is potential for considerable noise to be introduced into the data from the measurement process (e.g inadequate sampling of variable snow cover, observer bias, and changes in measurement location). There is also the question of how representative the data are of the surrounding area: based on measurement guidelines, the data should be mainly representative of exposed sites.

Snow cover duration

It is difficult to derive consistent information on snow covered area from daily snow depth values because of the largely inadequate and variable spatial distribution of measuring sites. However, some of these problems can be overcome by integrating snow depth information over time. For example, the annual duration of snow depth greater than a certain threshold should be a reasonable, internally-consistent proxy of annual variability in snow cover in the area around an observing site (provided the measurement method does not vary greatly between observers or over time, and there are no significant changes in the observing site).

In this study, snow cover was defined by a 3 cm depth threshold. The snow year was defined as August to July, and the snow cover duration was obtained by totalling the number of days where the daily snow depth was ≥3 cm. To provide some insight into the relative importance of changes at the beginning and end of the snow cover season, the snow year was split into fall (August to January) and spring (February to July) half-year periods.

Trend analysis

To investigate the presence of significant temporal and spatial trends in snow cover, a linear regression analysis was performed on the annual series of snow cover duration for all stations with at least 25 years of data in the period 1955-89 (approximately 150 stations). Computed slope values were spatially filtered by interpolating to a 200 km grid, and contoured to analyze regional patterns (Figure 1). The most notable feature was a consistent reduction in snow cover duration across all regions of Canada: only 5 of the 150 stations exhibited a positive slope. The reduction in snow cover duration was greatest over the southern Prairies and B.C. interior where it exceeded 1 day/yr. This represents a 40-50% reduction in annual snow cover duration.

The seasonal nature of the observed trend was investigated by computing Student t-values for the spring and fall slopes. These t-values were interpolated to a 200 km grid and contoured to give some idea of the relative seasonal strengths of the observed trends. The effect of serial correlation in residuals and the possibility of "statistically significant" slopes arising due to chance was not taken into account (see Zwiers, 1990). However, large areas with consistent t-values >2.0 do provide a qualitative indication of important regional change.

The t-test results (not shown) indicated that the pattern observed in Figure 1 was largely a result of earlier melt in the spring period. This observation is consistent with other North American snow cover studies (e.g. Foster, 1989; Stuart et al., 1991; and Robinson et al., 1991). It is also consistent with other cryospheric variables. For example, Skinner (1992) noted a recent trend toward earlier spring ice break-up at many Canadian lakes, while Hanson et al. (1992) recently documented statistically significant earlier spring break-up in the Great Lakes.

Link to air temperature trends

An identical statistical analysis was performed using the gridded air temperature data set of Jones at al. (1991) to look at possible linkages with air temperature trends. The results (not shown) were consistent in that the central and western areas with the greatest snow cover loss also experienced the greatest spring warming. However, it was interesting to note that in large areas of eastern Canada, particularly in the eastern Arctic, both snow cover duration and temperature have decreased. This is consistent with the results of Isaac and Stuart (1992) who found cooler temperatures associated with less winter and spring precipitation across most of northern and eastern Canada.

SNOW COVER DURATION MODEL

Model and input data

Snow cover duration data were reconstructed from observed daily snowfall and estimated daily snowmelt using a simple degree-day method proposed by Bruce and Clark (1966). Daily snowfall data are available from many climatological stations from the late 1800s. Snowfall is determined by measuring the depth of new snow in several places with a ruler to the nearest 0.2 cm. Less than 0.2 cm is called a "trace" and is not counted. This measurement involves a high degree of subjectivity when snow has been disturbed by the wind, and where snow has melted between observations. Snow drifting affects many Canadian stations, particularly in the Arctic and Prairies. Snowfall in the Arctic is also characterized by frequent trace events which are ignored by the ruler measurement method, but can contribute significantly to the local snow pack. In this study, a snow depth of 0.2 cm was assumed for all trace events.

The snowmelt method is based on the observation of Bruce and Clark (1966) that an average snowmelt degree-day index of 0.02 in/deg.-day (°F) of maximum temperature greater than 32°F was found to apply for snow-melt in Southern Ontario. Converting temperature to °C, yielded the following equation:

$$S_m = 0.9144\ k\ T_{max},\quad T_{max} > 0°C \qquad (1),$$

where S_m = snowmelt water (mm/day)
k = snowmelt index
T_{max} = max. daily air temperature (°C).

The snowmelt factor, k, varies with the degree-day base and temperature units used, as well as with latitude, aspect of the snow pack, albedo and season. Seasonal variation in k is particularly significant (Bruce and Clark, 1966).

Daily maximum air temperature was used in eqn. (1) as it consistently yielded the best model results. These data are available from the mid-1800s at many Canadian climatological stations. The quality controlled, archived data were used directly in this preliminary analysis. Corrections for inhomogeneities in the record (see Gullet et al., 1991) have not yet been incorporated in the daily data (note that stations with identified urban warming effects are excluded from the gridded data set of Jones et al., 1991).

Calibration

Eqn. 1 was calibrated with observed snow cover duration data over the period 1955-89. To obtain the value of k which resulted in zero snow cover duration bias, bias values were obtained for specified values of k, and a bias function created by fitting a bi-cubic spline. The bias function was then successively updated and re-fitted until the residual bias was less than ± 0.5 days. The calibration was carried out separately for the fall and spring periods. In the later case, the estimated snow depth at the end of the fall season was used as input to the spring calibration. It would have been preferred to split the calibration data into two halves for independent calibration and verification. Unfortunately, the observed snow cover data series were too short to allow this.

Seasonal values for k and the corresponding values of r^2 are shown in Figures 2 and 3. k showed strong variation with longitude and latitude: values were lowest over Alberta and B.C. interior, and increased toward the north and the east. Values were highest in the Arctic which is both a reflection of the rapid melt experienced in this region and the inability of the modelling method to take into account processes such as wind erosion, sublimation, snow aging and the effect of permafrost on delaying snow melt. The poor performance of the model in the Arctic (r^2 <0.5) is considered to be a reflection of these errors as well as noise in the snowfall data from frequent blowing snow and trace snowfall amounts. In areas south of the zone of continuous permafrost, the model was typically able to explain more than 70% of the variance in observed snow cover duration, and over large areas of the southern Prairies, model performance exceeded 80%. It was interesting to note that in spite of the quite different seasonal values of *k* obtained, seasonal calibration provided little benefit over a simpler annual calibration. This is most likely because the spring melt process is the dominant factor defining the total duration of snow cover on the ground.

Snow cover reconstruction and verification

To reconstruct snow cover duration data, the computed seasonal values of *k* were interpolated to a 200 km grid. This grid spacing provided a reasonable level of spatial smoothing while still retaining significant regional variation. Snow cover durations were then computed at stations with long periods of daily snowfall and temperature data by interpolating corresponding fall and spring values of *k*, and using these in equation (1). Stations with at least 18 years data in a 1961-80 reference period were retained for regional analysis.

The first step in verifying the model was to evaluate the ability of the interpolation scheme to select appropriate seasonal values of *k* which resulted in a zero bias estimate of snow cover duration at a station. A total of 63 stations with reconstructed snow cover duration data had corresponding observed snow cover data for comparison. An evaluation of the bias statistics revealed that 92% of the stations had annual snow cover duration biases of less than ±10 days, and 84% of stations had biases of less than ±5 days. These results are comparable to those reported for the DC method by Hughes and Robinson (1992).

There are currently no readily accessible Canadian snow cover data prior to 1955 for independent verification of the reconstruction method. Efforts are currently being made to obtain such data, and to verify the method in the US with data from Robinson (1993).

REGIONAL SNOW COVER ANALYSIS

Regional analysis of historical variation in snow cover duration was carried out by converting the reconstructed data to anomalies with respect to a 1961-80 reference period. Anomalies from stations falling within a prescribed search radius were averaged and filtered to highlight long-term variability. Only data from 1900 were investigated to reduce the impact of changes in station distribution over time. Average station anomalies for three regions; the Western Prairies, Southern Ontario and the Maritimes (Fig. 4). The areas used to select the regions are summarized in Table 1.

Table 1
Areas used in regional analysis.

Region	Centre		Radius (km)	Number of Stns.
W. Prairies	52.5°N	110.0°W	400	3-28
S. Ontario	45.0°N	80.0°W	350	8-32
Maritimes	45.4°N	63.3°W	350	5-16

The regional results show quite different responses and scales of variability. The Western Prairies exhibit a gradual increase in snow cover duration from the early part of this century up to about 1970, followed by a rapid reduction. In contrast, the dominant feature of Southern Ontario is a systematic reduction in snow cover during the first half of this century (this may be related to urban warming effects in the data). Both these regions exhibit significant fluctuations at decadal or shorter time scales in contrast to the Maritimes which is dominated by longer time scale variability.

To obtain an idea of the overall variation in snow cover duration across Canada, anomalies were averaged over all stations. Given the predominant distribution of stations close to the US border, this approximates a zonal average between 45° and 55°N. The Canadian results (Fig. 4) are similar to the Western Prairies with a gradual increase in snow cover duration from the late 1920s to the late 1960s, followed by a rapid decrease in the 1970s and 80s. Robinson and Hughes (1991) reported a similar trend in snow cover over the Great Plains. Separate analysis of fall and spring half year periods (not shown) revealed that annual snow cover variability in all regions was dominated by the spring period.

Further work is planned to investigate the relative roles of temperature and precipitation in the observed variability. Initial comparisons of the regional snow cover duration series with homogeneous annual maximum time series prepared by Gullet and Skinner (1992) suggest that while some features of the observed variability in snow cover are clearly related to temperature, e.g. the rapid decrease in snow cover since the 1970s, temperature alone cannot explain the gradual increase in snow cover duration from the 1920s to the 1970s observed over the Prairies and the Great Plains.

CONCLUSIONS

This study represents the first steps in a project to reconstruct historical cryospheric data in Canada in order to better understand the role of the cryosphere in the climate system. Analysis of observed data provided clear evidence of the recent reduction in NH snow cover documented by Robinson at al. (1991). This reduction is related to a recent rapid warming of spring temperatures over much of the interior of Canada. However, reconstructed historical snow cover data revealed no evidence of a close temperature relationship in the period prior to the 1970s. This finding, together with the different regional scales of variability documented in this study, suggest that snow-climate relationships in Canada are more complex than a simple response to long-term NH temperature fluctuations.

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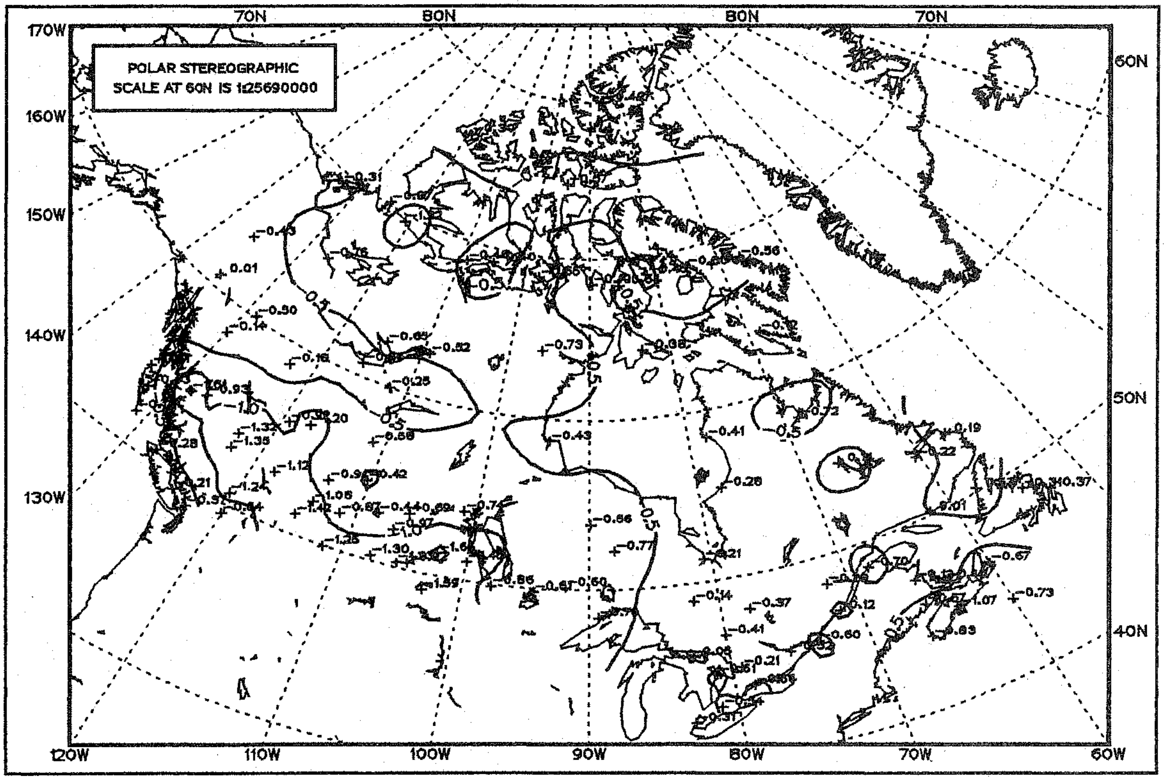

Figure 1: Change in duration of annual snow cover, 1955-89 (days/yr).

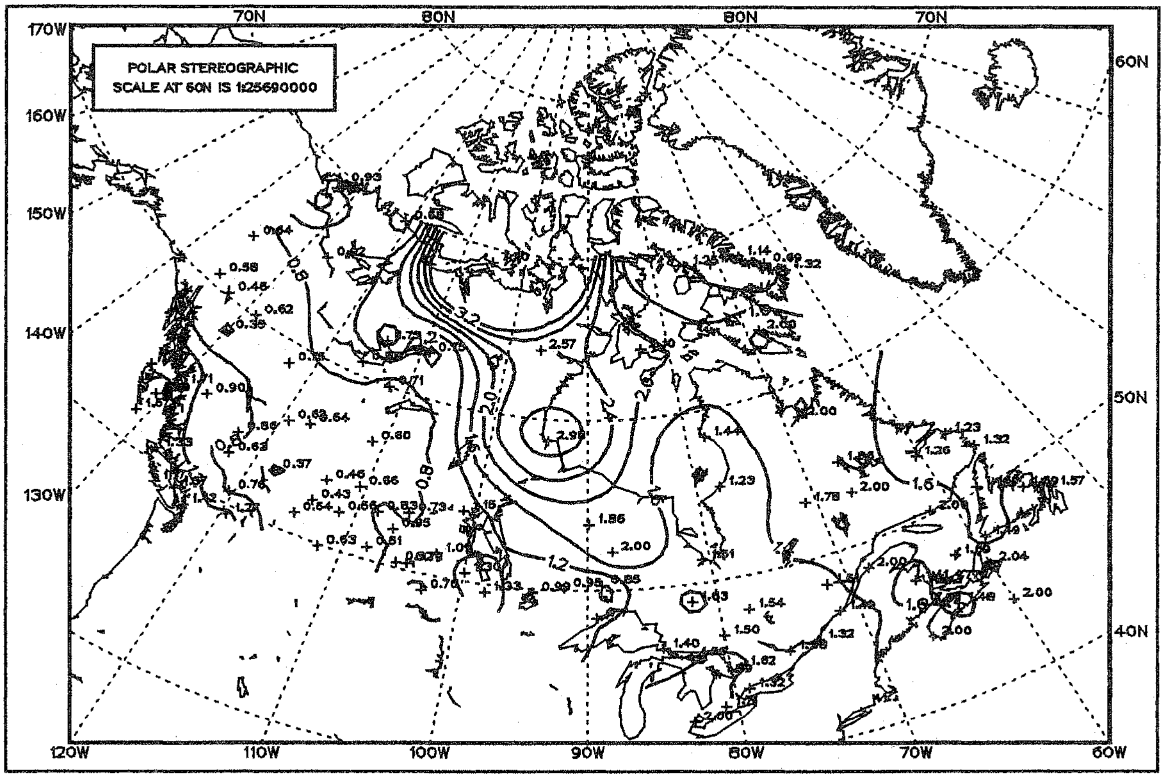

Figure 2a: Average fall values of model calibration factor, *k*.

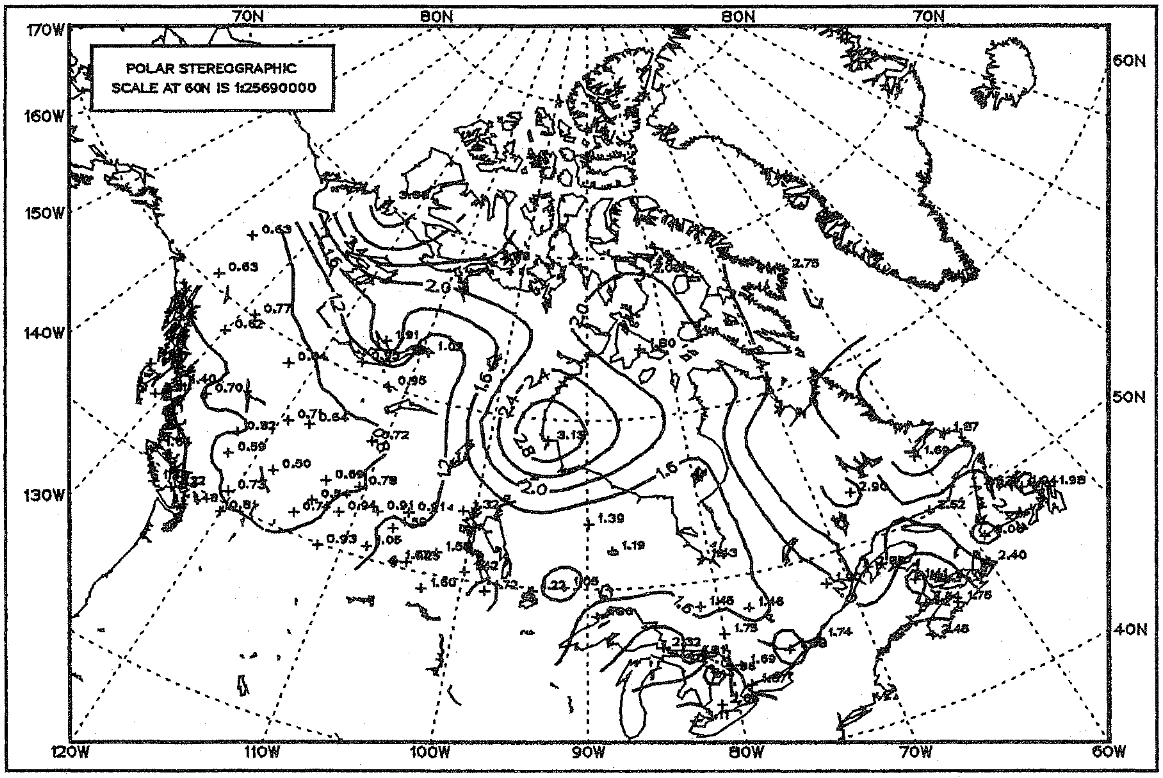

Figure 2b: Average spring values of model calibration factor, *k*.

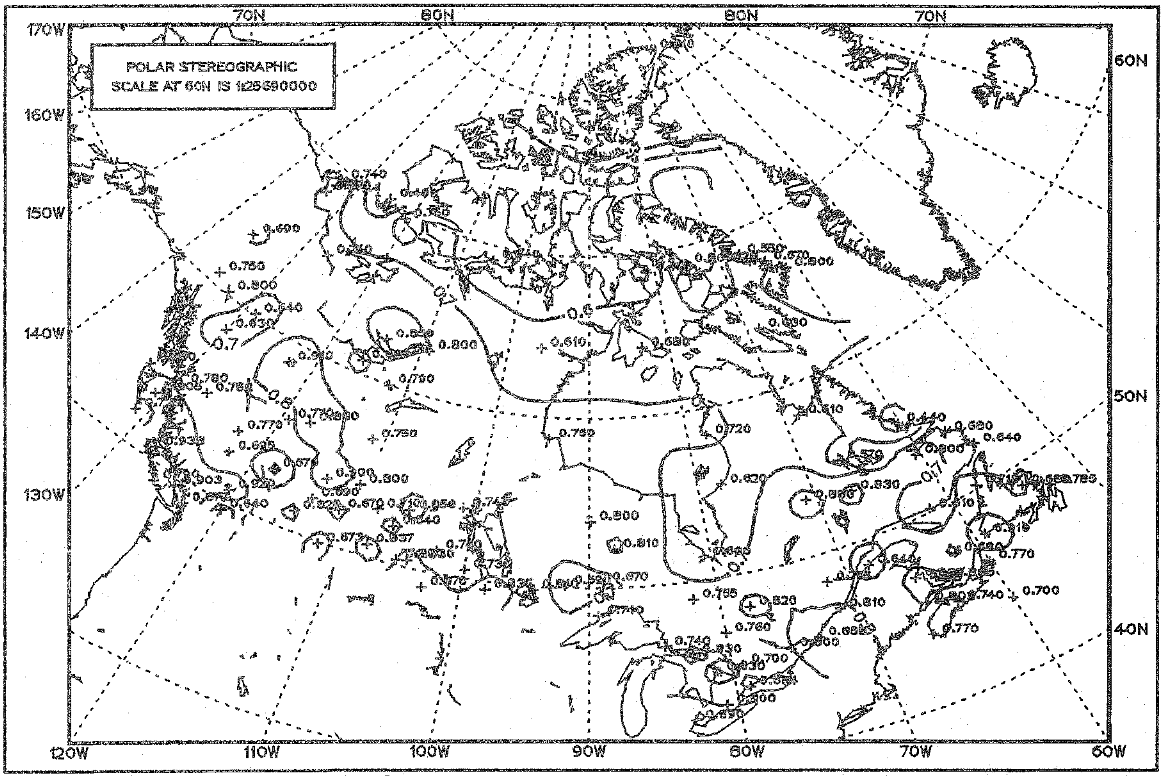

Figure 3a: Model performance (r^2) for fall (Aug.-Jan.) period.

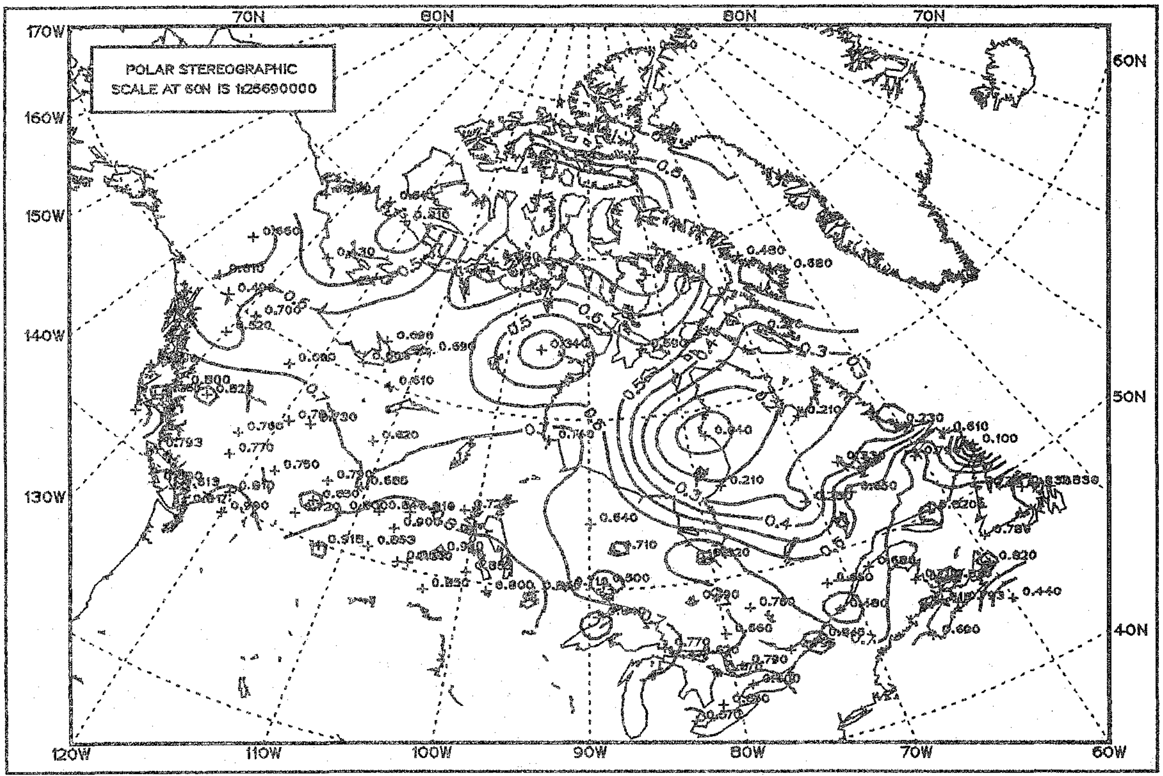

Figure 3b: Model performance (r^2) for spring (Feb.-July) period.

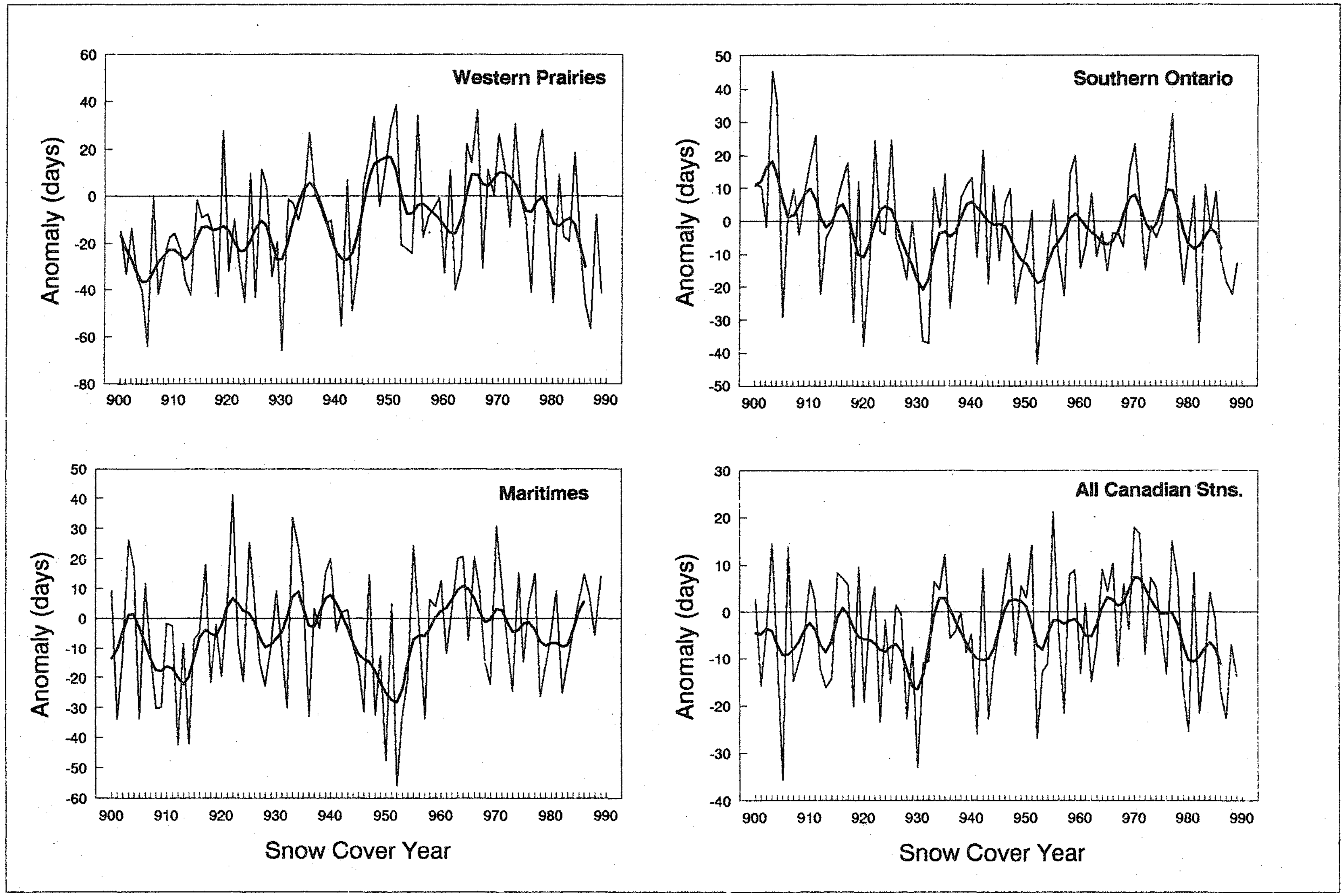

Figure 4: Annual variability in reconstructed annual snow cover duration. Anomalies were computed with respect to a 1961-80 reference period. The heavy line is the result of passing a 9-term binomial filter.