Evaluation of Methods for Climatological Reconstruction of Snow Depth and Snow Cover Duration at Canadian Meteorological Stations

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ABSTRACT

A comparison was carried out of several techniques for simulating point estimates of snow depth and snow cover duration (SCD) using daily climatological data from four different meteorological stations across Canada. The models were unable to properly simulate year-to-year and seasonal variations in snow depth, but a simple calibrated temperature index method was able to account for over 50% of the variance in interannual variability of annual SCD at all four sites. An evaluation of the snow cover simulated by the CLASS land surface process model revealed that CLASS provided good estimates of mean snow depth at all three different sites, but was unable to capture interannual variability in snow cover duration, especially during the spring period.

Key words: Snow cover models, CLASS, snow depth validation

INTRODUCTION

Snow cover is an important component of the global climate system. For example, snow and ice cover up to ~25% of the surface of the Northern Hemisphere during winter, which has major implications for the surface energy balance and atmospheric circulation. Documenting the natural variability of snow cover is important for assessing the significance of current changes in snow cover e.g. the recent trend toward reduced spring snow cover over much of western Canada (Brown and Goodison, 1996), and for better understanding the processes involved in snow cover variability, and snow cover-climate interactions.

Unfortunately, observational data bases of snow cover in Canada are limited to several decades e.g. from 1955 for daily snow depth observations, and from the early 1970s for reliable satellite observations of snow cover extent. Brown and Goodison (1996) used a calibrated melt-index method to reconstruct snow cover duration (SCD - number of days with snow depth ≥ 2 cm) back to 1900 for several hundred stations across southern Canada. However, there were no observations before 1955 to validate these estimates. To address this problem, the Atmospheric Environment Service began a major effort in 1995 to incorporate a large volume of pre-1955 daily and weekly snow depth observations into the existing snow depth archive.

The quality control and gap filling of these data is being carried out following the approach used by Hughes and Robinson (1993) to generate an historical snow cover data base for the Great Plains. Gap filling requires the simulation of daily snow depths from daily climate data. A variety of methods can be used for this purpose ranging from purely empirical relationships to more sophisticated snowpack energy balance models. A major constraint is that the methods must be able to run with only daily temperature and precipitation as input, since there are no long-term records of cloud cover, radiation and wind speed available in Canada (hence the term "climatological reconstruction" in the title).

The main purpose of this paper was to assess the performance of a number of climatological snow cover reconstruction methods to see if there was an approach which worked well in all snow cover climate regions in Canada. A secondary objective was to look at the ability of the CLASS land surface process model (Verseghy, 1991) used in the Canadian general circulation model (GCM) at simulating snow cover at these same sites, although in this case, CLASS was

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driven with hourly radiation and meteorological data.

SITE SELECTION

According to Sturm et al. (1995), there are six major snow cover regions in Canada which are classifiable on the basis of climate and snowpack characteristics: tundra, taiga (boreal forest), prairie, maritime, alpine and ephemeral (see their Figure 10). It would have been desirable to have several sites in each of these regions, however, a major constraint was that stations needed a continuous period of at least 15 consecutive years of hourly radiation data for running CLASS. This constraint was imposed because a major objective of the study was to determine how well models captured interannual variability in snow cover characteristics.

Only three sites were found which met this condition: Goose Bay (53.3°N, 60.4°W), Sable Island (43.0°N, 60.0°W) and Resolute Bay (74.7°N, 95.0°W). Resolute Bay is classified as a tundra climate, while Sable Island is classified as an ephemeral snow cover climate regime. Goose Bay is classified as a taiga snow cover climate according to Sturm et al. (1995), although it should be pointed out that the snow depth and meterological observations are made at the airport (an open site) and not in the forest. Saskatoon (53.2°N, 106.7°W) was included to permit an intercomparison of the climatological models for a prairie environment.

It would be unrealistic to consider these four stations as being representative of the corresponding snow cover classification since AES measurement sites are exposed sites by definition, and are often located adjacent to airports. The daily snow depth measurement program carried out at AES stations is rather rudimentary, requiring the observer to determine the "average" depth of snow on the ground from a series of ruler measurements. The depth measurements are not made at fixed stakes which means there is potential for considerable noise from the measurement process (e.g inadequate sampling, observer bias, changes in measurement locations). Nevertheless, it was clearly demonstrated by Brown and Goodison (1996) that regionally averaged values of SCD derived from AES daily snow depth measurements agreed closely with NOAA satellite-derived estimates of SCD over non-mountainous regions of Canada. The point data therefore do contain significant information on interannual variations in regional snow cover even though depth data alone is less than optimal for model validation purposes (snow water equivalent is a more useful parameter). Quality control checks of the AES daily snow depth data has revealed that over 98% of non-zero snow depths are internally consistent when compared with corresponding snowfall and temperature data. A summary of the periods used and snow cover conditions at each site is provided in Table 1.

Table 1: Mean snow cover characteristics at each site used in the model comparison.

Station	Period	Mean SCD (days)	Mean Depth (cm)	Mean Max. Depth (cm)
Resolute Bay	69/70 - 92/93	285	18.9	34.6
Goose Bay	68/69 - 83/84	192	58.5	138.4
Saskatoon	55/56 -92/93	131	13.5	28.0
Sable Island	70/71 -90/91	23	2.7	18.6

MODELS

The approach taken in model selection was to evaluate a variety of climatological methods with increasing incorporation of physical processes. It should be stressed that these models are crude compared to the many detailed energy and mass balance models that are available e.g. Anderson (1976), Gray and Landine (1988), Pomeroy (1989) and Loth et al. (1993). However, it is not possible to run these more sophisticated models with only daily temperature and snowfall as input. The models selected for testing are summarized below:

Depth change method (DC)

The DC method was developed by Hughes and Robinson (1993) as a simple technique for filling gaps in daily snow depth records. The method is based on an empirically-derived relationship between daily temperature and snow depth decreases for non-snowfall days. There is considerable scatter in the empirical relationship (correlations are typically in the 0.3 to 0.4 range), but when averaged over temperature classes, it yields a characteristic logarithmic relationship (Fig. 1). A best-fit log10 function was found to give a better-behaved fit to the data than the second-order polynomial used by Hughes and Robinson (1993). The temperature-depth change relationships were derived separately for the first and second halves of the snow cover year (either side of January 1), as Hughes and Robinson had observed different seasonal results. However, no significant seasonal differences were evident at any of the four sites, and a single curve was used in the snow depth reconstructions.

A major advantage of this method is that it includes snow settling and sublimation loss, albeit in a rather crude fashion, for air temperatures below freezing. The method was applied using separate curves derived from daily mean and daily maximum temperatures. Model performance was slightly better, especially with respect to SCD, when daily maximum temperature depth change relationships were used. The maximum temperature results were therefore included in all model performance summaries. At three of the four test sites, the DC method was observed to generate large positive biases in SCD. This was attributed to the method not taking into account the rapid settling of new snowfall. The bias was eliminated by assuming a fixed density of 100 kg m^{-3} for snowfall, and selecting a fixed density for new snow on the ground in the 100 to 150 kg m^{-3} range.

Calibrated melt-index (BG)

The BG method was used by Brown and Goodison (1996) to reconstruct SCD over Canada. It is a simple mass balance which accumulates daily snowfall and melts it via a calibrated melting-degree day index. The method does not take snow settling or sublimation into account, and the calibration is carried out with observed SCD data to optimize the ability to explain interannual variability in SCD. Because of this, the method is expected *a priori* to perform well at simulating SCD, but perform poorly at simulating daily snow depths (these will be overpredicted). It was included in the comparison as a benchmark for evaluating the SCD performance of other methods. Model input parameters were daily snowfall and daily maximum temperature.

Calibrated melt-index with snow settling (BG1)

This is the BG method with the inclusion of an empirical snow settling algorithm following Verseghy (1991):

$$\rho_s(t+1) = [\rho_s(t) - 300] \exp[-0.01\Delta t/3600] + 300$$

where $\rho_s(t+1)$ is the snow density at the next time step, Δt (seconds). An initial density of 100 kg m^{-3} was assumed for freshly fallen snow. Each day with new snowfall was treated as a new layer and the density tracked until it reached the maximum value of 300 kg m^{-3}. Model input parameters were daily snowfall and daily maximum temperature.

Calibrated melt-index method with rainmelt (JLANN)

This method is based on the water balance used for Canadian climate stations by Johnstone and Louie (1983). It is similar to BG except that snow melt from rainfall is included, and a fixed density is assumed for snow on the ground (300 kg m^{-3}). The same local calibration procedure was applied as the BG and BG1 models. Model input parameters were daily snowfall, daily rainfall, and mean daily air temperature.

Anderson (1973) snow accumulation and ablation model (ANDER)

This is a physically-based model of the accumulation and ablation of snow cover that uses daily climate data as input. It was designed for the U.S. National Weather Service River Forecast System to provide realistic estimates of snow water equivalent and snowpack runoff. The model accounts for energy storage in the snowpack, diurnal variations in air temperature, seasonal variation in melt factors, heat exchange with the snowpack, and melt from rain. The model permits ground melt to be specified, as well as snowmelt and snow/rain temperature thresholds which allow model performance to be optimized for a particular site. A series of sensitivity runs were made at each site to assess the optimal ground melt and temperature threshold values, as well as the density for converting from SWE to snow depth. Sensitivity testing of the model revealed that model performance was very sensitive to ground melt (GM) and snow density. In practice, the rain/snow criterion was fixed at 0°C, the snowmelt threshold at −0.56°C (31°F). Model input parameters were daily maximum and minimum temperature, and daily total precipitation.

A snowfall-only version of this model (**ANDER1**) was also run to investigate the importance of rain melt, and the impact of having to separate snowfall from total precipitation on the basis of an air temperature threshold.

Canadian Land Surface Scheme for GCMs (CLASS)

CLASS is the land surface processes component of the Canadian GCM. Within the model, snow is modelled as a fourth, variable depth "soil" layer, and snow settling and aging (increasing density and decreasing albedo) are parameterized as functions of time. The reader is referred to Verseghy (1991) for a more detailed description. Melting of the snow pack occurs when the solution of the surface energy balance indicates a temperature > 0°C, in which case T(0) is reset to 0°C, the energy flux terms are recomputed, and the excess energy used to melt a layer of snow. Melt can also take place at the bottom of the snow pack from conduction of soil heat. The model includes the storage of melt water within the snow pack, and the warming of the snow pack from the latent heat released from melt-refreeze cycles. It thus includes the major snow pack metamorphic processes. The most recent stand-alone version of CLASS (2.5-C) was used in the comparisons, where the model is run in point mode. The model was initialized as an open site with a short grass surface.

CLASS input parameters were 30-minute values of air temperature, precipitation rate, specific humidity, wind speed, solar radiation, and net longwave radiation. A threshold air temperature of 0°C was used to partition rainfall and snowfall from total precipitation. Adjustment of precipitation for gauge undercatch was only carried out at the Resolute Bay site where unadjusted values resulted in systematic underestimates of snow depth. Wind speeds were corrected to a height of 2 m using the FLXLND2 routine from the KNMI FLUXLILB package. The method is based on Holtslag and VanUlden (1983), and takes into account radiation and cloudcover in determining surface heating and atmospheric stability. A fixed roughness length of 0.001 m was assumed for snow-covered ground based on published values in Oke (1987). The gauge correction factor was then computed using a published catch ratio-wind speed relationship for the Canadian Nipher shielded snow gauge (Metcalfe et al., 1994). These results only applied to 2 m wind speeds $< \sim 9$ m s^{-1}. For 2 m wind speeds > 9 m s^{-1}, a constant 50% undercatch ratio was assumed, which corresponds to the lower limit of the curve fitted by Metcalfe et al. According to Metcalfe and Goodison (1993), trace precipitation amounts are very important in the Arctic where they can account for over 80% of total precipitation. Six hour trace values were therefore assigned a non-zero value of 0.03 mm following the recommendation of Metcalfe et al. (1994).

PERFORMANCE CRITERIA

For historical snow cover reconstruction purposes, a model should not only be able to accurately simulate the seasonal evolution of a snowpack, but it must also be able to replicate the observed interannual variability in key snow cover properties. Several statistics were used to measure these aspects of model performance: (1) the observed and predicted mean snow depth; (2) the best-fit slope between the observed and predicted daily snow depth values; (3) the correlation between observed and predicted snow depths; (4) the % of time the model correctly specified snow cover or no snow cover conditions; (5) the r^2 values between observed and reconstructed annual SCD over the period of record; and (6) the average bias between observed and reconstructed SCD. In computing the statistics, zero pairs were excluded to avoid biasing the results in sites such as Sable Island, where zero snow depths dominate the record. This causes observed averages to differ slightly between models. SCD was defined in this study as the number of days with 2 cm or more of snow on the ground.

The average performance statistics are summarized for each site in Tables 2 to 5. More detailed comparisons were carried out for the CLASS and JLANN models to contrast the performance of the more sophisticated energy balance model against a typical locally-calibrated temperature index model.

RESULTS

At the Resolute Bay site, the CLASS model had the highest mean snow depth correlation and achieved almost zero bias in SCD (Table 2). These are excellent results considering the difficulty observing precipitation at high latitudes, and that the model does not include wind-related processes such as snow redistribution, sublimation and compaction which are very important in the tundra snow climate zone. CLASS, however, was not as successful at replicating interannual variability in SCD as the melt index methods which typically explained 60% of the variability in annual SCD compared to only 27% for CLASS. Comparison of the observed and simulated mean snow depths for the CLASS and JLANN models (Fig. 2) revealed that both models provided qualitatively realistic simulations of the temporal evolution of snow cover at this site, although both underestimated snow depths in the first half of the snow year (JLANN more so than CLASS), and the mean rate of snow depth accumulation was greater than observed.

At the Goose Bay site (Table 3), two methods yielded mean snow depth correlations of 0.8: CLASS and BG1. In the case of CLASS, the model produced an annual SCD bias which exceeded 10 days, and it was unable to account for any of the interannual variability in annual SCD. In the case of the BG1 model, it was only able to account for 47% of the variance in annual SCD, which was substantially less than the JLANN model. Comparison of the observed and simulated mean snow depths for the CLASS and JLANN models (Fig. 3) showed that both models underestimated snow depths by about 20 cm in the first half of the snow year, and greatly overestimated snow depth in the early spring. In the case of the locally calibrated model, this error is taken into account through an adjusted melt rate which ensures that the snow cover disappears at the correct time. In CLASS, however, the excess snow depth contributes to excessive snow cover in the spring season. Comparison of CLASS results with snow course estimates of snow water equivalent (SWE) from a snow course located at Goose Upper Air station (3.8 km from Goose Bay Airport) revealed that temporal evolution in mean SWE was well-simulated (not shown), which suggests that the observed seasonal differences in snow depth are related to snow metamorphic processes rather than insufficient precipitation input to the model.

At the Saskatoon site, the highest mean snow depth correlations were obtained by the DC and BG models (Table 4). Unfortunately, both these models greatly overpredicted snow depths. The JLANN model was found to provide unbiased estimates of mean snow depth and also explained 78% of the interannual variability in annual SCD. Comparison of the observed and simulated mean snow depths for the JLANN and DC models (Fig. 4) revealed that while the JLANN method provided a realistic simulation of mean SCD at this site, the simulated snow depths had the maxima shifted about 20-30 days later in the season. This is similar to the Goose Bay results. The DC method greatly overpredicted snow depth at this site because the empirically-derived average snow settling rate does not account for the rapid settling and densification of new snowfall by wind action in the exposed prairie environment.

Sable Island represents a real challenge for snow cover modelling because of the ephemeral nature of the snow cover, and because the winter precipitation regime is frequently characterized by mixed precipitation types. The model results at this site (Table 5) were generally poor, with only two models (CLASS and BG1) able to correctly simulate the occurrence of a snow cover more than 50% of the time. Mean snow depth correlations at this site were low, with the best results obtained by CLASS. Once again however, CLASS was unable to replicate the interannual variability in annual SCD. Comparison of the observed and simulated mean snow depths for the CLASS and JLANN models (Fig. 5) showed that both models provided reasonable estimates of mean snow depths, with CLASS tending to overestimate snow depth and JLANN to underestimate snow depth. There is no evidence of the systematic differences observed at the Goose Bay and Saskatoon sites because of the ephemeral nature of the snow cover.

It should be noted that the performance of all the models was characterized by high interannual variability, with snow depth correlations exceeding 0.9 in some years, and approaching zero in others. An example of this is shown in Figure 6 for the JLANN model at Saskatoon. This result highlights the need to evaluate snowpack models over periods of 15-20 years, as single years, or blocks of 3-5 years may give a misleading picture of model performance.

DISCUSSION

The above model evaluation is obviously limited by the small number of sites, and by the nature of verification data which does not allow for validation of the modelled mass balance. Nevertheless, there are a few important points which can be made which are relevant to the problem of reconstructing SCD. First, calibrated temperature index methods provided the best estimates of interannual variability in SCD. CLASS provided better estimates of snow depths, but was less able to capture interannual variability in snow cover. This result is likely linked to the importance of advection in the spring melt process (Cohen and Rind, 1991) which is captured by simple melt-index models, but which is less dominant in energy balance models where the melt process is highly sensitive to incoming solar radiation and surface albedo. The more physically-based Anderson (1973) model was not found to provide any additional improvement over simpler climatological models, and the practical implementation of the model was complicated by the large number of parameters which had to be specified. Comparison of the total precipitation and snow only versions of the Anderson (1973) model revealed that in most cases, the snowfall-only version gave superior performance. This confirms the observation of Loth et al. (1993) that the selection of an appropriate rain/snow criterion is a serious problem for simulating snow cover from total precipitation data.

Second, the JLANN model appeared to provide the best all-round performance at all four sites; it gave similar snow depth results to CLASS, while managing to capture interannual variability in annual SCD. Comparison of the performance of the two models at replicating interannual variability in monthly snow depth and snow cover revealed that the JLANN model outperformed CLASS in nearly all months, particularly during the spring period. An example is provided in Table 6 for Goose Bay. Note that at this site all the observed variability in snow cover occurred in three months: October, November and May.

Third, no models were particularly successful at simulating the ephemeral snow cover conditions at Sable Island. This site is characterized by mixed precipitation types and a highly variable winter temperature regime which makes it difficult to simulate snow cover. Conversely, model performance was much better at cold climate sites with a well-defined snow cover season, although there was a noticeable tendency for models to underpredict snow depths in the first half of the snow season, and to overpredict snow depths in the second half. This appears to be most likely related to inadequate treatment of snow metamorphism.

On the basis of the evidence presented in this investigation, it appears that climatological models are unable to provide accurate simulations of snow depth at monthly time-scales for different sites across Canada. To investigate how well the JLANN model captured seasonal variability in snow cover, r^2 values were computed between mean and maximum snow depths simulated by the JLANN model and the corresponding observed annual values at all four sites (Table 7). The results revealed that the model was able to explain more than 50% of the variance in SCD at all sites, but only at the prairie site was the model able to explain more than 50% of the variance in mean and maximum snow depth. This begs the question of why it works well at the prairie site but not elsewhere. Part of the reason may lie in the fact that early melt events over the prairies are driven mainly by sensible heat rather than radiation e.g. Brown (1995) showed that there is a particularly strong negative relationship between SCD and air temperature anomalies over the continental interior of North America.

CONCLUSIONS

From the limited evaluation performed in this study, it appears that climatologically-based snow cover reconstruction techniques can only provide reliable information on SCD, and that these methods cannot be used to reliably reconstruct daily snow depths across a variety of snow cover climates. Even where mean and maximum snow depths were well-simulated, systematic errors were observed in the temporal evolution of the snowpack, namely an underprediction of snow depths in the first half of the snow year, and an overprediction of snow depths in the early spring. This systematic error is likely related to inadequate treatment of snow metamorphic processes, and results in simulated snow depth maxima occurring about one month too late on average. The good performance at reconstructing interannual variability in snow depth properties at a prairie site was encouraging, however, because the Prairies and adjacent Great Plains have been shown to be a key "centre of action" in explaining variations in winter and spring snow cover at the continental scale (Brown, 1995; Frei and Robinson, 1995).

While the complete simulation of snow depth from daily climate data was poor, ongoing work on blending observed snow depths into climatological snow cover simulation models has revealed that rms snow depth errors remain low as long as there is about one observation per week to keep the reconstruction method on track. Even the addition of regular month-end snow depth observations is observed to significantly improve snow depth simulations at stations with long snow cover seasons.

An evaluation of the snow cover simulated by a stand-alone version of the CLASS land surface process model revealed that CLASS provided good estimates of mean snow depth at three different sites, but was unable to capture interannual variability in snow cover duration during the spring period.

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Table 2: Model performance results, Resolute (1969/70 - 1992/93)

Model	Obs. Mean Sdep (cm)	Pred. Mean Sdep (cm)	Mean Slope	Mean Sdep Correl.	%SCD Correct	Ann. SCD r^2	SCD Bias (days)
DC	19.7	21.9	1.32	0.71	93.1	0.35	0.2
BG	20.1	50.0	3.00	0.79	94.8	0.59	0.0
BG1	20.0	17.7	0.98	0.78	95.4	0.60	0.0
JLANN	20.0	18.5	1.03	0.76	95.2	0.56	0.0
ANDER	19.7	18.7	1.10	0.67	95.3	0.54	8.7
ANDER1	19.7	20.8	1.11	0.71	95.4	0.62	9.6
CLASS	18.8	19.4	1.11	0.82	91.3	0.27	-0.3

Table 3: Model performance results, Goose Bay (1968/69 - 1983/84)

Model	Obs. Mean Sdep (cm)	Pred. Mean Sdep (cm)	Mean Slope	Mean Sdep Correl.	%SCD Correct	Ann. SCD r^2	SCD Bias (days)
DC	62.2	98.7	1.50	0.77	92.7	0.30	-0.1
BG	62.8	160.5	2.51	0.79	94.0	0.49	0.0
BG1	62.5	58.2	0.86	0.80	93.8	0.47	0.0
JLANN	62.7	61.8	0.99	0.71	94.3	0.62	0.0
ANDER	63.4	53.1	0.79	0.79	93.0	0.28	-6.9
ANDER1	63.0	71.2	1.16	0.76	93.6	0.41	-3.9
CLASS	56.8	55.7	0.96	0.80	91.9	0.01	11.2

Table 4: Model performance* results, Saskatoon (1955/56 - 1992/93)

Model	Obs. Mean Sdep (cm)	Pred. Mean Sdep (cm)	Mean Slope	Mean Sdep Correl.	%SCD Correct	Ann. SCD r^2	SCD Bias (days)
DC	12.6	25.2	1.64	0.70	87.5	0.66	0.6
BG	12.6	28.5	2.00	0.74	87.7	0.78	0.0
BG1	12.4	11.3	0.74	0.69	87.7	0.70	0.0
JLANN	12.7	12.7	0.94	0.60	89.8	0.78	0.0
ANDER	12.1	13.2	0.96	0.52	86.3	0.73	5.8
ANDER1	12.3	11.5	0.80	0.60	87.2	0.62	2.7

* Note: Hourly radiation data unavailable for running CLASS at this site.

Table 5: Model performance results, Sable Island (1970/71 - 1990/91)

Model	Obs. Mean Sdep (cm)	Pred. Mean Sdep (cm)	Mean Slope	Mean Sdep Correl.	%SCD Correct	Ann. SCD r^2	SCD Bias (days)
DC	3.8	4.3	1.04	0.45	40.0	0.45	-1.6
BG	3.7	6.3	1.70	0.57	47.7	0.71	0.0
BG1	3.7	4.3	1.23	0.50	50.2	0.67	0.0
JLANN	3.4	3.3	0.96	0.56	47.7	0.53	0.0
ANDER	3.4	3.6	0.86	0.22	36.0	0.10	1.7
ANDER1	3.9	3.5	0.87	0.46	39.9	0.36	-3.2
CLASS	2.3	2.9	1.28	0.59	53.8	0.03	16.4

Table 6: Correlation between observed and simulated monthly mean snow depth and monthly snow cover duration, Goose Bay, 1968-1983.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Snow Depth:								
JLANN	0.96	0.88	0.90	0.76	0.60	0.44	0.63	0.79
CLASS	0.79	0.87	0.89	0.75	0.61	0.42	0.34	0.22
Snow Cover:								
JLANN	0.94	0.79	-	-	-	-	-	0.85
CLASS	0.61	-0.04	-	-	-	-	-	-0.02

Table 7: r^2 values between simulated (JLANN) and observed annual snow depth, and snow cover duration (SCD).

Site	Mean Snow Depth	Max. Snow Depth	SCD
Resolute Bay	0.15	0.21	0.56
Goose Bay	0.50	0.26	0.62
Saskatoon	0.72	0.72	0.78
Sable Island	0.36	0.64	0.53

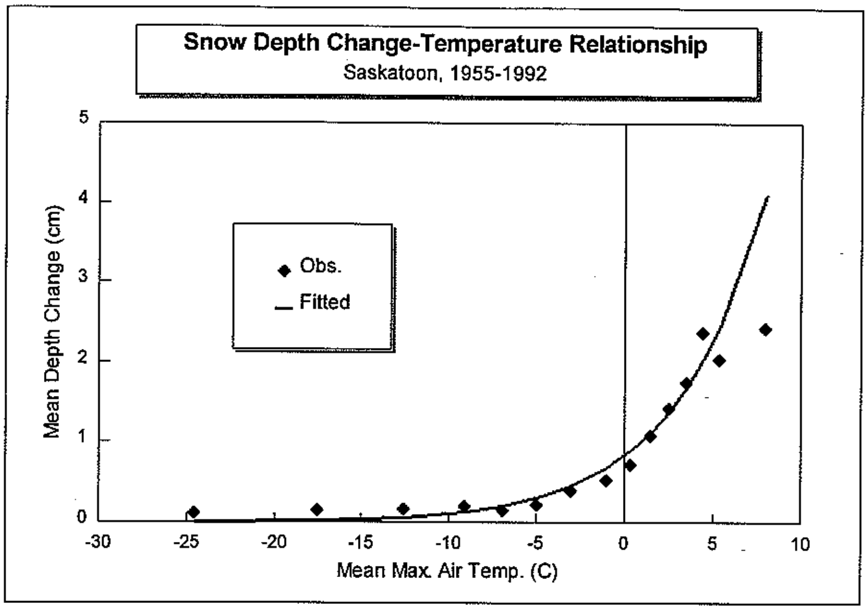

Figure 1: Example of empirically-derived snow depth change-maximum air temperature curve for Saskatoon.

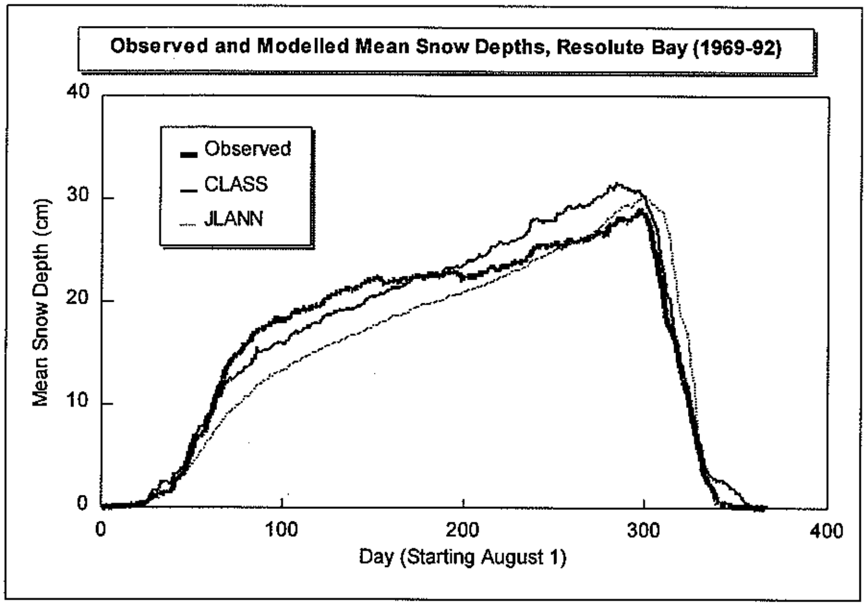

Figure 2: Averaged observed and simulated daily snow depths for the period 1969-1992 at Resolute, N.W.T.

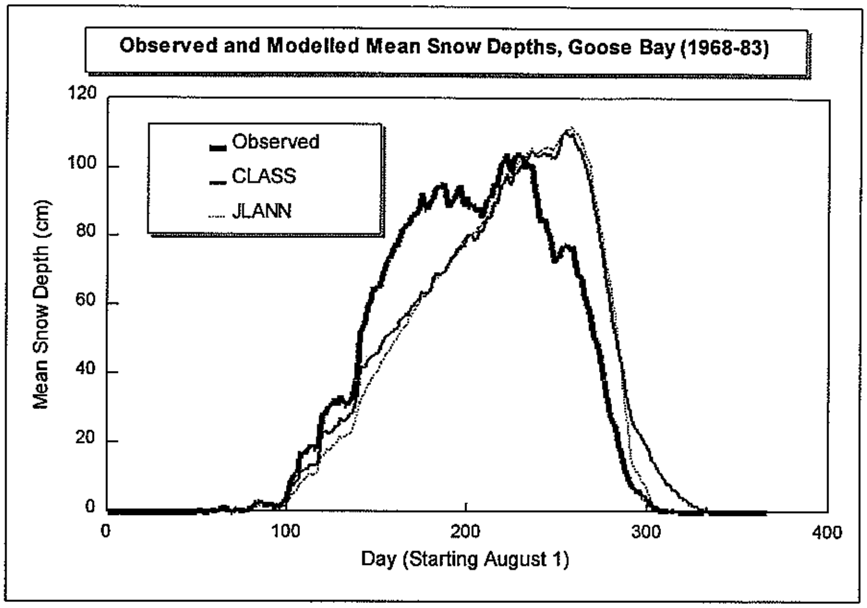

Figure 3: Averaged observed and simulated daily snow depths for the period 1968-1983 at Goose Bay, Labrador.

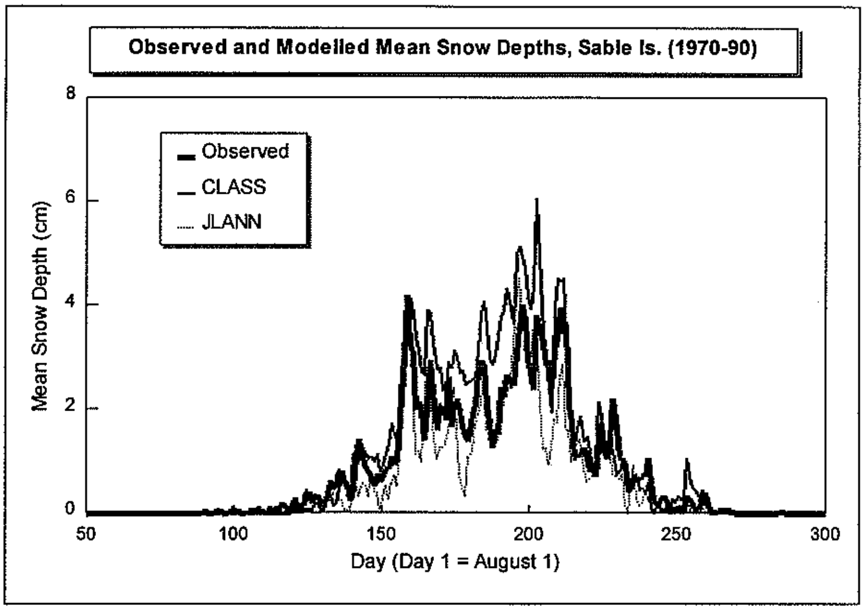

Figure 4: Averaged observed and simulated daily snow depths for the period 1970-1990 at Sable Island, Nova Scotia.

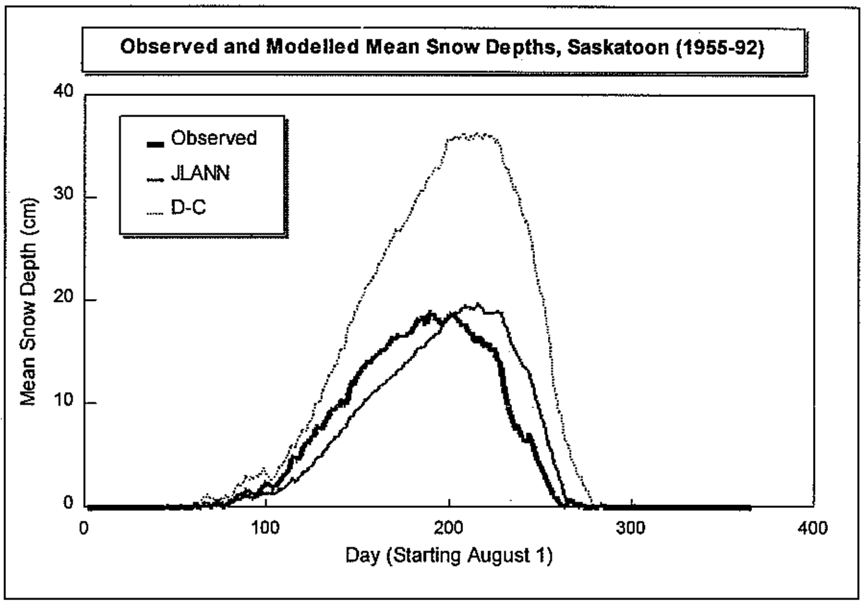

Figure 5: Averaged observed and simulated daily snow depths for the period 1955-1992 at Saskatoon, Saskatchewan.

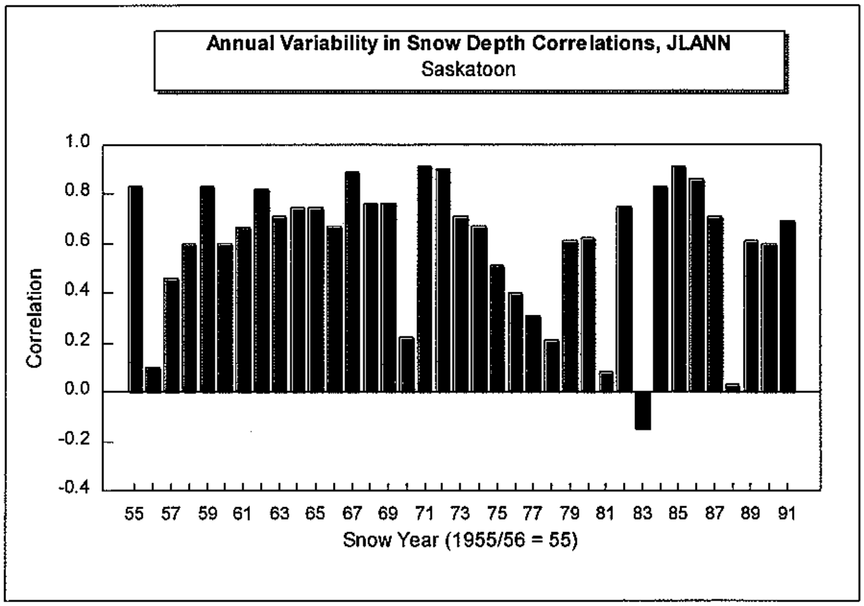

Figure 6: Interannual variability in snow depth correlations for JLANN model at Saskatoon, Saskatchewan.