ANALYSIS OF REGIONAL CLIMATE MODEL SIMULATIONS OF TRANSPORT-RELATED CLIMATE INDICES OVER SOUTHERN QUEBEC

R.D. Brown
Climate Research Branch, Environment Canada @ Ouranos, Montreal, Canada
ross.brown@ec.gc.ca

D. Chaumont
Ouranos Climate Change Consortium, Montreal, Canada
Chaumont.diane@ouranos.ca

ABSTRACT

An evaluation was carried out of the capacity of the Canadian Regional Climate Model (CRCM) to simulate 11 winter climate indicators relevant to transportation infrastructure and road conditions in the southern Québec region when driven by the third generation Canadian Coupled General Circulation Model, CGCM3. CRCM provided realistic spatial patterns for all variables with the exception of the number of daily freeze-thaw cycles and winter thaw events. CRCM future climate simulations driven with a five member ensemble of GCCM3 runs for the A2 emission scenario indicated a generally warmer and wetter future winter climate by 2050, with a 13-day later start to the freeze period, an 11-day earlier start to thaw season and an average 24-day shorter winter freeze season with 428 less freezing degree-days. The number of snowfall events was projected to decrease but with an increase in winter rainfall events and winter thaw events that will likely increase stress on transportation infrastructure. Precipitation amounts are simulated to increase ~10% and ~20% for snowfall and rainfall events respectively. The number of daily freeze-thaw cycles was simulated to decrease but is contrary to observational evidence which suggests daily freeze-thaw events increase in warm years. The spatial patterns of change typically exhibited a north-south gradient with changes of the same sign over the entire region with the exception of the number of winter thaw events which decreased in the south and increased in the north. Analysis of the variance between the five model runs showed that the amount of noise due to internal climate variability was lowest for indices related to changes in mean temperature such as the duration of the freeze period, and highest for indices related to changes in synoptic phenomena such as winter thaw and rainfall events.

KEYWORDS

REGIONAL CLIMATE MODEL / WINTER CLIMATE CHANGE / SOUTHERN QUEBEC

1. INTRODUCTION

Most of Québec’s population and transport infrastructure are concentrated in the southern region of the province containing the two major urban areas of Montreal (population 3.6 million) and Québec City (population 0.7 million) (Fig. 1). This region is characterized by harsh but highly variable winter climate conditions that pose major challenges for winter driving, winter road maintenance and construction [1] (see Table 1). For example, over the 1971-2000 period the region experienced an average of ~75 daily freeze-thaw cycles per winter and ~9 winter thaw events per year that contribute to the development of the infamous “nids de poules” or potholes that are a characteristic of the Quebec urban landscape. Frequent snowfall is also a challenge as the region lies along the path of preferred tracks for winter cyclones from Alberta, the Great Lakes and the Appalachians that generate an average of 30 snowfall events per year. The region also experiences strong regional gradients in temperature and precipitation particularly when moving into elevated sections of the Laurentian Shield to the north of the St Lawrence Valley or in the Appalachians to the south.

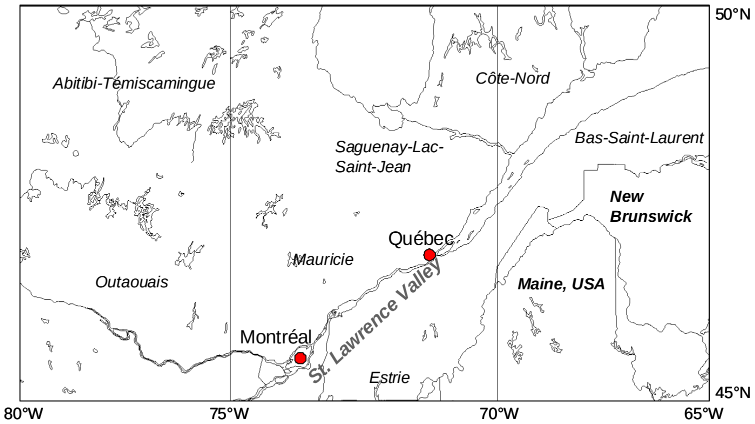


Figure 1: Southern Quebec study region.

Climate model simulations over this region of North America from the 4th IPCC assessment [2] indicate winter warming is *very likely* with a *likely* increase in precipitation and a *very likely* reduction in snow cover duration and depth. This will bring some benefits such as reductions in snow and ice removal costs and an extension of the construction season [3]. On the other hand, there may be potential for more freeze-thaw conditions in some parts of the study region, increases in snowfall extremes and increased risk of mixed precipitation events which make road and sidewalk clearing more challenging especially in municipalities attempting to reduce the application of de-icing materials for ecological reasons.

Table 1: 1971-2000 average winter climate indices for 5445 NLWIS grid points in the southern Québec study domain shown in Figure 1. See Section 2.2 for description of data and Section 3.1 for definitions of indices.

Variable	**Regional Mean, 1971-2000**	**Avg Std. Deviation, 1971-2000**
Winter freeze onset date	Nov. 7	7.36 d
Spring thaw onset date	Apr. 7	7.98 d
Winter duration	148.4 d	9.83 d
Cumulative sum of FDD	1634.5	181.2
# Daily freeze-thaw cycles	73.3 / y	9.10 / y
# Winter rainfall events	6.8 / y	2.33 / y
winter rainfall event duration	1.7 d	0.46 d
winter rainfall event amount	10.0 mm	4.44 mm
# Snowfall events	31.6 / y	3.95
snowfall event duration	2.5 d	0.40 d
snowfall event amount	9.7 mm we	1.94 mm we
# Winter thaws	9.1 / y	2.53 / y
winter thaw event duration	2.4 d	0.55 d
thaw event TDD	7.4	2.84

FDD = freezing degree-days; TDD = thawing degree-days; we = water equivalent

Simulations from Global Climate Models (GCMs) provide useful information for evaluating the impacts of climate change on climate sensitive infrastructure and operations but their relatively coarse resolution is a major limitation for assessing winter climate changes over the Southern Québec (SQ) region where spatial gradients are high for many variables. The Ouranos Consortium (www.ouranos.ca) has a major research and development program to produce regional climate change projections with the Canadian Regional Climate Model (CRCM) [4] as well as other recognised RCMs such as the French Arpège-climat and

German REMO models, where the higher resolution allows the generation of more pertinent information for analysis of changes in the mean and variability of climate indicators. Ouranos also has the largest ensemble of climate simulations over North America that permit estimates to be made of the uncertainty in simulated changes of winter climate indices over southern Québec related to the internal natural variability of the climate system.

The objectives of this study are to: (1) evaluate the capacity of CRCM to simulate winter climate indicators relevant to transportation infrastructure and road conditions in the SQ region and (2) present information on simulated changes in these indicators and their levels of consistency based on an ensemble of regional climate simulations. The analysis also includes an instrumental analogue to look at the response of winter climate indices to warming over the past 40 years of observational data.

2. STUDY AREA AND DATASETS

2.1. Study Area

The study area (Fig. 1) covers the main urban corridor of southern Québec and adjacent areas from the Québec-Ontario border in the west to the more maritime regions around the St. Lawrence River in the east. The southern half of this region is classified as Humid Mid- to Humid High-Cool Temperate with the northern half of the region classified as Low Boreal or Humid Mid-Boreal [5]. The region is characterized by a relatively high mean annual precipitation ~1000 mm with a strong north-south temperature gradient. Mean annual total snowfall accumulation ranges from ~250 cm in the area around Montreal to over 600 cm in elevated areas of the Laurentian Shield northeast of Québec City.

2.2. Observed Climate Data

Observed climate data were obtained from the new Agriculture and Agri-Food Canada National Land and Water Information Service (NLWIS) 10 km gridded daily temperature and precipitation dataset for Canada south of 60°N [6]. The dataset contains daily minimum/maximum temperature and daily total precipitation from Environment Canada climate station observations interpolated to a 10 km grid using a thin plate smoothing spline surface fitting method [7]. For this study, precipitation was separated into rainfall or snowfall using a mean daily temperature threshold of 0°C. Cross-validation of the dataset [6] indicated it can be used with confidence across southern Canada in applications that depend on daily temperature and accumulated seasonal and annual precipitation but should be used with care in applications that depend critically on daily precipitation extremes which is not the case in this study.

2.3. Regional Climate Model Simulations

The climate simulations analysed in this study were run with version 4.2.3 of the CRCM limited area nested regional climate model [8] driven by an ensemble of 5 runs of the Canadian General Circulation Model version 3 (CGCM3) [9] for the current climate period from 1958 to 2000 (simulations *aet*, *aev*, *aey*, *aez* and *afa*) and with the SRES A2 emission scenario [10] for the future climate from 2038-2070 (simulations *aeu*, *aew*, *afb*, *afc* and *afd*). The 5 GCM ensemble members have slightly perturbed initial starting conditions (at the start of the simulations in 1850) to allow an assessment of the internal natural variability of the climate system. The CRCM was run over the North American (or *AMNO*) domain at a resolution of 45 km at 60°N with large scale spectral nudging [11] to weakly force CRCM's large-scale circulation towards the GCM. CRCM includes the Canadian Land Surface Scheme (CLASS) version 2.7 [12] for treatment of surface processes. A detailed description of CRCM 4.2 is provided in references [13] and [14]. Model output was averaged over 1971-2000 to represent the current or reference climate, and over 2041-2070 to provide an estimate of the mean future climate state in 2050. The differences (or "deltas") between these two periods are plotted and analyzed in Section 4.

3. METHODOLOGY

3.1. Definition of Winter Climate Indices

The following winter climate indices were selected for analysis based on a review of the available literature and discussions with individuals involved in transportation planning:

Number and intensity of winter thaws: A winter thaw event was defined to start on day i when the maximum air temperature (T_{max}) for day i is > 0°C and the average mean daily temperature over a moving window of $i \pm 14$ days was < -5°C. The -5°C criterion was applied to limit thaw events to the central winter period and avoid the generation of frequent events during the start and end of the winter season (these are captured by the daily freeze-thaw cycle index below). The intensity of thaw events was computed by summing the thawing degree-days (T_{max} > 0°C) over the duration of the event. These winter thaw events are synoptic in origin and are often associated with a persistent high pressure system off the east coast of North America that pushes warmer air northward into New England and Québec [15].

Number of daily freeze-thaw cycles: A daily freeze or thaw cycle was defined as occurring when the daily temperature went from below-freezing to above-freezing to back to below-freezing (thaw cycle) or the inverse freeze cycle. When this definition is used with a daily time step there can be overlap between the two cycles so the average of the number of freeze and thaw cycles was used in the analysis. These freeze-thaw cycles are responsible for weathering and deterioration of construction materials and contribute to pothole formation.

Winter freeze onset date; Spring thaw onset date; Winter duration: The start date of the winter freeze period was defined as the first day when the mean daily air temperature over a ± 14 day moving window went below 0°C. This reflects the start of the period when air temperatures are consistently below-freezing and freezing processes dominate. Conversely, the spring thaw period was defined to begin when the mean daily air temperature over a ± 14 day running window went above 0°C. The duration of the winter freeze period was the period between these two dates.

Winter severity index: The cumulative sum of freezing degree-days (FDD) for each winter was computed as the sum of daily mean temps < 0°C between November and April. This is an indicator of the severity of a winter season.

Frequency and intensity of snowfall events: A snowfall event was defined as any event lasting for 1 day or more with measured daily snowfall. Daily snowfall was estimated from the NLWIS dataset by assuming a 0°C threshold for rain/snow separation. The annual number of events, their mean duration (days) and mean total snowfall accumulation (mm water equivalent) were generated from the event information. CRCM generates its own snowfall amounts but the above definition was also used with the climate model to maintain consistency in the analysis.

Frequency and intensity of winter rainfall events: The same analysis was carried out for winter rainfall events over the period between the winter freeze onset date and spring thaw date defined above. This ensured a consistent treatment of the winter period in the future climate scenario.

The analysis of precipitation events in CRCM required some additional filtering as the model generates a higher frequency of “wet days” with small precipitation amounts than observed [16]. Setting a minimum precipitation threshold of 1 mm/day was found to give numbers of snowfall events that were consistent with the observations. The event durations (winter thaws, snowfall and winter rainfall) were not included in the climate change analysis results as these fields were spatially uniform in the current and future climate simulations and did not show much evidence of changes in response to climate warming.

3.2 Instrumental Analogue

An instrumental analogue (e.g. [17]) was included in the analysis to provide an indication of the observed response of the winter indicators between warm and cold years in the 1961-2002 period of observed data. This approach has some obvious limitations [18] the main one being that the observed anomalies are more likely associated with naturally occurring changes in atmospheric circulation than changes in GHG concentrations, thus we cannot be certain the climate will respond in the same way in the future. However, the results are internally consistent and physically plausible, are available at a high resolution, and correspond to people’s experience of regional climate changes over the last 40 years. The instrumental analogue was constructed from the 5-year periods with the warmest (1997-2001) and coldest (1969-1973) winter (Nov-March) temperatures in southern Quebec (SQ) over the period of NLWIS data (1961-2002). The selected warm and cold periods are separated by 28 years and correspond to a period when Northern Hemisphere (NH) mid-latitude winter temperatures increased ~1°C. The warm and cold periods are significantly different based on Student’s T-test at a 0.05 level of significance for both the SQ region and the NH land area over the same latitudinal band based on the gridded CRUTEM3 air temperature dataset [19]. 5-year composites formed from the individual warmest and coldest years in the 1961-2002 period of NLWIS data (not shown) yielded similar patterns of change as the 5-year blocks for all variables with the exception of the number of winter rainfall events which indicating some consistency in the regional climate response to local warming. The statistical significance of changes in indices between the two periods was evaluated with the standard Student’s t-statistic for differences in means with 8 degrees of freedom but using the entire period of data to provide a better estimate of interannual variability. T-statistics exceeding ± 2.31 indicate a local statistically significant difference in means at the 0.05 level of significance (ignoring spatial autocorrelation).

3.3 Evaluation Strategy

A realistic simulation of current climate is not a necessary condition for a climate model to generate useful information on future changes in climate. However, for local-to-regional scale applications it is important for a RCM to generate realistic simulations of spatial and temporal variability in climate variables. The performance of CRCM was evaluated by comparing the area-averaged means and the standard deviations over the 1971-2000 period with corresponding statistics from the NLWIS gridded dataset. The NLWIS data were spatially averaged over the CRCM grid to provide a comparable level of spatial filtering and the spatial correlation coefficient computed to provide a quantitative estimate of the ability of the model to capture the observed spatial pattern.

4. RESULTS

4.1. CRCM Evaluation

The results of the evaluation (Table 2 and Figure A-1) show that CRCM provides realistic simulations of winter climate over the study domain for most variables with the notable exception of the number of daily freeze-thaw cycles which were overestimated and had a low spatial correlation. The spatial correlation was also relatively weak for winter thaw events. The model has a cold bias over Québec [20] that generates an 11-day longer winter season length and a ~10% higher FDD total. The coefficient of variation (CV = standard deviation divided by the mean) provides an indication of the “noisiness” of the indices and the potential of a variable to exhibit significant changes under a changed climate regime. CRCM provides realistic CVs for most of the variables with the exception of those related to precipitation amount and thaw event TDD totals which are markedly higher than the observed values.

Table 2: Comparison of the mean 1971-2000 climate simulated by CRCM driven with CGCM3 versus the observed climate from the NLWIS gridded dataset interpolated to the CRCM grid.

Winter Climate Variable	**NLWIS Mean 1971-2000**	**CRCM Mean 1971-2000**	**NLWIS Mean CV 1971-2000**	**CRCM Mean CV 1971-2000**	**Spatial Correl.**
Freeze onset date	Nov. 8	Nov. 5	n/a*	n/a*	0.95
Thaw onset date	Apr. 8	Apr. 17	n/a*	n/a*	0.90
Freeze period duration	151 d	163 d	0.07	0.08	0.95
Cumulative sum of FDD	1637.1	1812.9	0.11	0.10	0.97
# daily freeze-thaw cycles	73.4	91.9	0.12	0.12	0.38
# winter rainfall events	6.4 / yr	8.3 / yr	0.34	0.33	0.83
Winter rainfall event amt.	10.0 mm	10.3 mm	0.44	0.90	0.75
# snowfall events	31.2 / yr	30.5 / yr	0.12	0.15	0.80
Snowfall event amount	9.7 mm we	7.3 mm we	0.20	1.08	0.78
# winter thaws	9.1 / yr	9.8 / yr	0.28	0.29	0.50
Thaw event TDD	7.1	12.3	0.39	1.12	0.63

FDD = freezing degree-days; TDD = thawing degree-days; CV = coefficient of variation

* The CV can only be calculated for physical quantities and is meaningless for dates

4.2. CRCM Climate Change Simulations

The average differences in winter climate indices between 2041-2070 and 1971-2000 simulated by CRCM are plotted in Figure A-2 along with the standard deviation of the 5 different climate simulations used to compute the mean change. The spatial pattern of the standard deviation provides an estimate of regional variation in the uncertainty due to natural climate variability. It should be emphasized that 5 runs is a very small sample size but it nevertheless does provide some guidance on the relative differences between climate indices. The CRCM results are also summarized on a regionally-average basis in Table 3 and compared with the instrumental analogue based on the 5 warmest and coldest years in the period of observed data.

The CRCM and the analogue are quite consistent in the response of the first four temperature-related indices in Table 3 with the CRCM showing an average 13-day later start to the freeze period, an average 11-day earlier start to thaw season resulting in an average 24-day shorter winter freeze season with 428 less FDD. The largest reductions in winter season length are found south of the St-Lawrence Valley with the largest decreases ~30 days over the Estrie Region south of Montréal. This pattern is reversed for reductions in FDD which are highest over northern regions of the study area.

The two other indices displaying widespread significant changes in the CRCM simulations are reductions in the number of daily freeze-thaw cycles and number of snowfall events. The later agrees well with the instrumental analogue but CRCM and the analogue disagree on the sign of the change in the number of daily freeze-thaw cycles. It is possible the number of freeze-thaw cycles may experience transient increases and decreases over time that is not being captured in the difference of the two 30-year averages. Analysis of the evolution of daily freeze-thaw cycles at four different locations in the study domain for the *aet* transient climate simulation over the 1971 to 2100 period (Fig. 2) shows evidence of large decadal- and multi-decadal variability superimposed on a long-term downward trend that includes periods with significant increases in freeze-thaw cycles (e.g. 2011 to 2051 for Québec). Thus the future climate response of this index could include periods with increasing freeze-thaw cycles in agreement with the analogue.

Table 3: Comparison of CRCM simulated changes in winter indices between 1971-2000 and 2041-2070 averaged over the study domain with those obtained from an instrumental analogue from the warmest and coldest 5-year blocks in the 1961-2002 period of observed data. CRCM cells are coloured green (pink) when they agree (disagree) in sign and tendency with the analogue.

Winter Index	**CRCM**		**Analogue**	
	Mean Change 2041-2070 minus 1971-2000	% points with sig. local inc. (↑) or dec. (↓)	Mean Change 1997-2001 minus 1969-1973	% points with sig. local inc. (↑) or dec. (↓) in mean
freeze onset date	13 d later	100% later	7 d later	91.4% later
thaw onset date	11 d earlier	98.3% earlier	9 d earlier	100% earlier
winter duration	-24 d	100%↓	-16 d	100%↓
cumulative sum of FDD	-428.1	100.0%↓	-361.0	100%↓
# daily freeze-thaw cycles	-6.3	81.6%↓	+9.6 / yr	79.6%↑ 6.7%↓
# winter rainfall events	+0.5 / yr	< 1%	+0.4 / yr	34.5%↑ 13.0%↓
winter rfall event amount	+1.8 mm	0%	+0.4 mm	31.1%↑ 27.0%↓
# snowfall events	-3.5 / yr	93.3%↓	-3.0 / yr	82.9%↓
snowfall event amount	+0.6 mm we	0%	-0.7 mm we	15.2%↑ 50.4%↓
# winter thaws	-0.9 / yr	27.1%↓	-0.9 / yr	8.7%↑ 51.5%↓
thaw event TDD	+0.4	0	-0.4	6.7%↑ 29.2%↓

The amount of precipitation is simulated to increase ~10% for snowfall events but by ~20% for winter rainfall events. The analogue is less equivocal about the sign of the changes in snowfall and winter rainfall which is not unexpected as it does not take account of increasing precipitation in response to climate warming. The only variables to display a mixed sign response over the study region in the climate change simulations in Figure A-2 are the number of winter thaws and the sum of melting degree-days during winter thaw events. The number of thaw events decrease over the southern half of the study region but increase over the northern half, while the pattern is reversed for the sum of melting degree-day during thaw events. What this is saying is that winter thaw events are simulated to be less frequent but more intense over the southern half of the region, but more frequent and less intense over the northern half. However, it should be noted that these two variables have the highest noise from internal climate variability, with the standard deviation exceeding 10% of the mean in the eastern and southern portions of the study area (see right hand column in Fig. A-2). Winter rainfall events also display higher noise levels compared to the temperature-related and snowfall variables where the standard deviations are typically less than 5% of the mean.

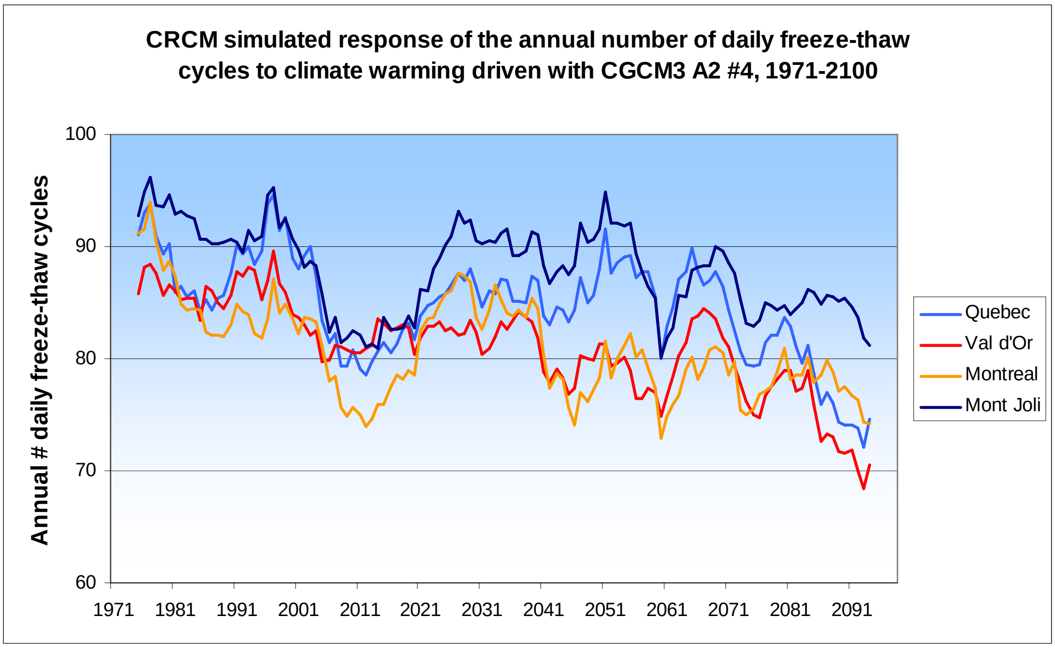


Figure 2: CRCM simulated variability in the number of daily freeze-thaw cycles for a transient climate simulation from CGCM3 (run 4, SRES A2 scenario) at four grid points from different regions of Québec. Values have been filtered with a centred 9-year running mean.

Statistical analysis of changes in the interannual variability of winter indices between the current and future climate periods (not shown) provided no evidence of major changes with the exception of snowfall and winter rainfall event precipitation amounts where the variability decreases significantly in the future climate at more than 60% of grid points. This decrease in variability is consistent with a warmer and moister atmosphere in the future climate.

5. CONCLUSIONS

The CRCM regional climate model was found to provide realistic simulations of most aspects of current winter climate conditions over southern Quebec relevant to transportation. Future climate simulations for the 2041-2070 period indicate a generally warmer and wetter winter climate with a 13-day later start to the freeze period, an 11-day earlier start to thaw season resulting in an average 24-day shorter winter freeze season with 428 less FDD. The number of snowfall events is simulated to decrease but with an increase in winter rainfall events and winter thaw events that enhance conditions for pothole formation. Precipitation amounts are simulated to increase ~10 and ~20% for snowfall and rainfall events respectively. The number of daily freeze-thaw cycles is simulated to decrease; good news for pothole formation but contrary to observational evidence from the analogue which shows daily freeze-thaw events increasing in warmer years. This discrepancy may be more a reflection of multi-decadal variability in freeze-thaw cycles than a lack of realism in CRCM based on a transient simulation that showed the presence of 20-30 year periods with significant increases and decreases in freeze-thaw cycles superimposed on a long term decreasing trend. This sort of variability increases the challenge of adapting to a changing winter climate.

ACKNOWLEDGEMENTS: The CRCM outputs used in this study were generated by the Climate Simulation Team of Ouranos (www.ouranos.ca). Dr. Daniel Caya (Ouranos) is acknowledged for providing helpful comments on the draft manuscript.

REFERENCES

[1] Bourque, A. and G. Simonet, 2008: From Impacts to Adaptation: Canada in a Changing Climate, Chapter 5, Québec, p. 172-226. (http://adaptation.nrcan.gc.ca/assess/2007/index_e.php)
[2] Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[3] National Research Council, 2008: Potential Impacts of Climate Change on U.S. Transportation. Transportation Research Board special report 290. Transportation Research Board, Washington, DC, 280 pp. http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf).
[4] Caya, D. and R. Laprise, 1999: A semi-mplicit semi-Lagrangian regional climate model: The Canadian RCM. Monthly Weather Review, 127, 341-362.
[5] Environment Canada, 1989: Ecoclimatic Regions of Canada, Ecological Land Classification Series No. 23, Sustainable Development Branch, Canadian Wildlife Service, Conservation and Protection, 118 pp.
[6] Hutchinson MF, McKenney DW, Lawrence K, Pedlar JH, Hopkinson RF, Milewska E, Papadopol P, 2009: Development and Testing of Canada-Wide Interpolated Spatial Models of Daily Minimum-Maximum Temperature and Precipitation for 1961-2003. J. Appl. Met. and Climatol., 48, 725-741. http://www.agr.gc.ca/nlwis-snite
[7] McKenney, D., Papadopol, P., Lawrence, K., Campbell, K., and Hutchinson, M., 2007: Customized spatial climate models for Canada. Can. For. Serv., Great Lakes Forestry Centre, Frontline Technical Note 108, Sault Ste. Marie, ONT, 7pp.
[8] Plummer, D.A., Caya, D., Frigon, A., Côté, H., Giguère, M., Paquin, D., Biner, S., Harvey, R., and de Elia, R, 2006: Climate and climate change over North America as simulated by the Canadian RCM. J. Climate, 19, 3112-3132.
[9] Flato, G. M., 2005: The third generation coupled global climate model (CGCM3). http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml
[10] Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi Z., 2000: IPCC Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 599 pp.
[11] Riette S., and D. Caya, 2002: Sensitivity of short simulations to the various parameters in the new CRCM spectral nudging. Research activities in atmospheric and oceanic modelling, 32, 7.39-7.40.
[12] Verseghy, D., 2000: The Canadian Land Surface Scheme (CLASS): Its history and future. Atmos.-Ocean, 38, 1-13.
[13] Music, B., and D. Caya, 2007: Evaluation of the Hydrological Cycle over the Mississippi River Basin as Simulated by the Canadian Regional Climate Model (CRCM). J. Hydromet., 8, 969-988.
[14] Brochu, R., and R. Laprise. 2007: Surface Water and Energy Budgets over the Mississippi and Columbia River Basins as Simulated by Two Generations of the Canadian Regional Climate Model. *Atmos.-Ocean*, 45, 19-35.
[15] Dumont, D., 2009: North Country winter thaws. Bi-Annual Weather Newsletter, Volume 11 Number 1 May 2009, U.S. National Weather Service, Burlington, Vermont, p. 2-4. (http://www.erh.noaa.gov/btv/html/Newsletters/NCCSpring2009.pdf).
[16] di Luca, A, 2009 : Valeur ajoutée dans le modèle régional canadien du climat : comparaison de la précipitation aux échelles du modèle global canadien du climat. Mémoire présenté comme exigence partielle de la maîtrise en sciences de l'atmosphère l'Université du Québec à Montréal, janvier 2009, 95 pp.
[17] Lough, J.M., Wigley, T.M.L. and J.P. Palutikof, 1983: Climate and climate impact scenarios for Europe in a warmer world. Journal of Climate and Applied Meteorology, 22, 1673-1684.
[18] Mearns, L.O., F. Giorgi, P. Whetton, D. Pabon, M. Hulme, and M. Lal, 2003: Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments. http://www.nceas.ucsb.edu/scicomp/Dloads/SpatialAnalysisEcologists/RegClimModelGuide.pdf
[19] Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett and P.D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J. Geophys. Res., 111, D12106.
[20] Dorsaz, F., 2008: Évaluation des simulations du couvert nival sur le Québec par les modèles MRCC 4.2.3 et GEMCLIM 3.3.0. Rapport de stage, Ouranos, 41 pp.

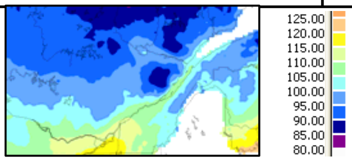
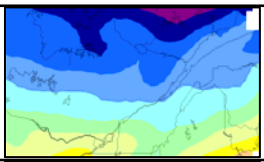
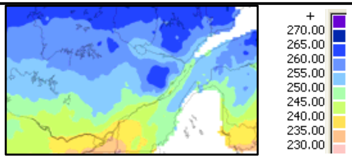
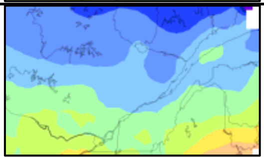
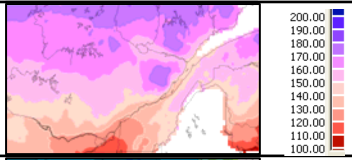
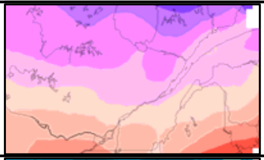
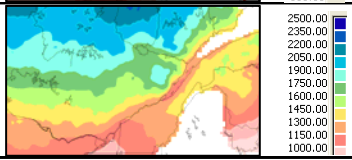
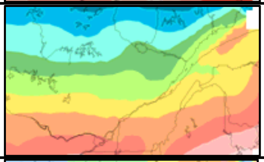
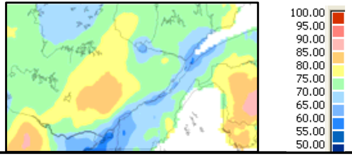
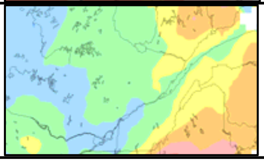
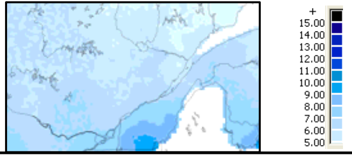
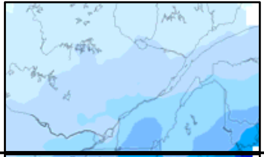
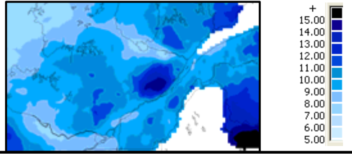
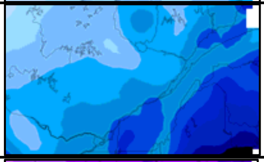
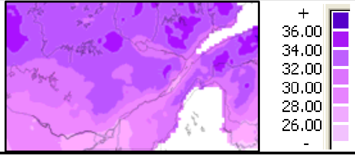
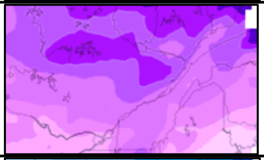
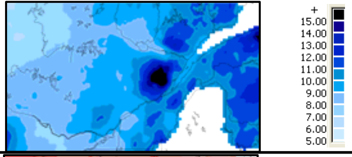
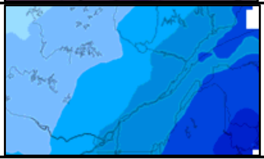
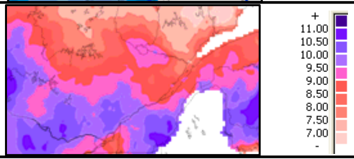
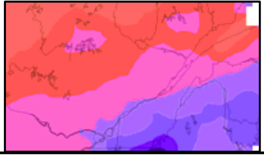
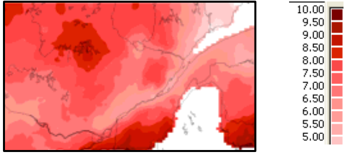
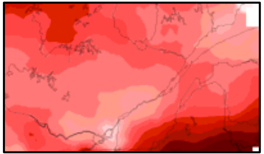
Winter climate index	**Obs. Current Climate 1971-2000**	**CRCMS Current Climate 1971-2000 (avg. of 5 simulations with mean bias removed)**
Mean date of freeze onset (Julian day wrt Aug 01)		
Mean date of thaw onset (Julian day wrt Aug 01)		
Mean duration of freeze period (days)		
Mean cumulative sum of FDD		
Mean annual number of daily freeze-thaw cycles		
Mean annual number of winter rainfall events		
Mean rainfall event precipitation amount (mm)		
Mean annual number of snowfall events		
Mean snowfall event precipitation amount (mm we)		
Mean annual number of winter thaw events		
Mean thaw event sum of thawing degree-days		

Figure A-1: Observed and simulated mean winter climate variables over the study area for 1971-2000. The mean spatial bias in CRCM (Table 2) was removed to facilitate the comparison.

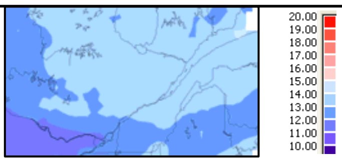
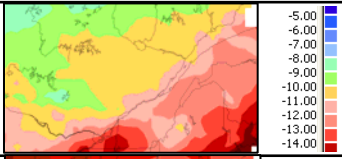
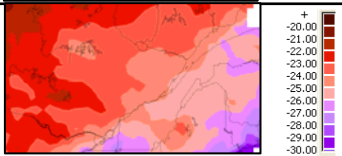
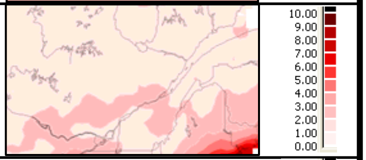
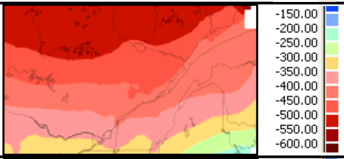
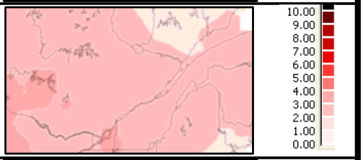
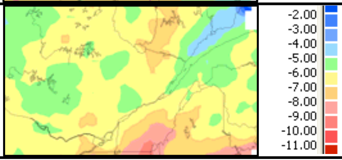
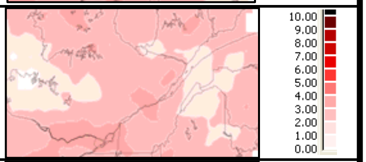
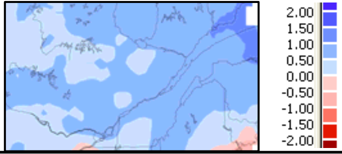
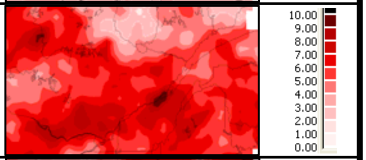
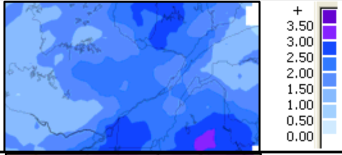
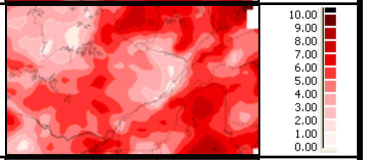
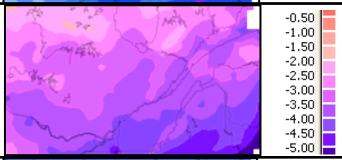
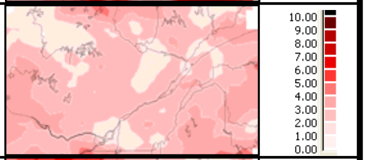
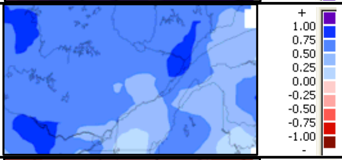
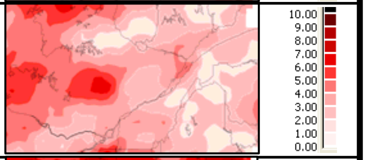
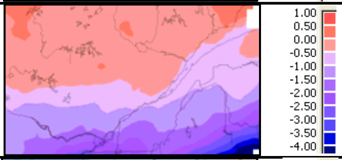
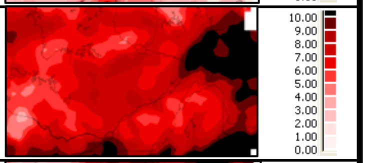
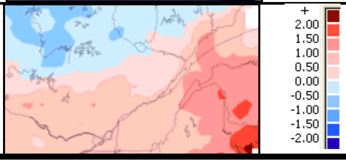
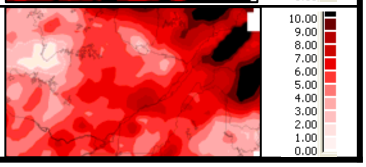
Winter climate index	**Mean simulated change 2041-2070 minus 1971-2000 from 5 CRCM simulations**	**Standard deviation of 2041-2070 averages from 5 CRCM climate simulations (% of mean)**
Mean date of freeze onset (Julian day wrt Aug 01)		Not possible to show stdev as % of mean
Mean date of thaw onset (Julian day wrt Aug 01)		Not possible to show stdev as % of mean
Mean duration of freeze period (days)		
Mean cumulative sum of FDD		
Mean annual number of daily freeze-thaw cycles		
Mean annual number of winter rainfall events		
Mean rainfall event precipitation amount (mm)		
Mean annual number of snowfall events		
Mean snowfall event precipitation amount (mm we)		
Mean annual number of winter thaw events		
Mean thaw event sum of thawing degree-days		

Figure A-2: Change in simulated mean winter climate variables over the study area between 1971-2000 and 2140-2070. The second column shows the standard deviation of the 5 model simulations which provides an indication of the uncertainty due to internal climate variability.