Evaluation of CLASS 2.7 and 3.5 Simulations of Snow Properties from the Canadian Regional Climate Model (CRCM4) over Québec, Canada

A. Langlois,* J. Bergeron,* R. Brown,# A. Royer,* R. Harvey,* A. Roy,* L. Wang,# and N. Thériault†

* Centre d’Applications et de Recherches en Télédétection, Université de Sherbrooke, Sherbrooke, Québec, Canada
# Climate Research Division, Environment Canada, Toronto, Ontario, Canada
† Ouranos, and Canadian Centre for Climate Modelling and Analysis, Environment Canada, Montreal, Québec, Canada

(Manuscript received 15 April 2013, in final form 17 January 2014)

ABSTRACT

Snow cover simulations from versions 2.7 and 3.5 of the Canadian Land Surface Scheme (CLASS) coupled to the Canadian Regional Climate Model, version 4 (CRCM4), are evaluated over northern Québec and the larger Québec domain using in situ and remotely sensed datasets. Version 2.7 of CLASS has been used in the operational version of CRCM4 at Ouranos since 2006. Version 3.5 includes a number of improvements to the snow processes as well as a more realistic parameterization of snow thermal conductivity. The evaluation shows that version 3.5 provides improved simulations of snow water equivalent, density, depth, and snowpack temperature values. However, snowpack density still contains systematic biases during the snow season that need to be addressed. The snow albedo parameterization in CLASS was found to be very sensitive to an empirical snowfall rate threshold for albedo refreshment and does not keep track of the snow accumulation history in estimating the snow surface albedo. A modified albedo scheme based on snow-specific surface areas is proposed to address this problem.

1. Introduction

Snow is an important element of the cryosphere and the climate system in general. When present on the land surface, it tends to dominate both conductive and radiative exchanges across the interface between the land surface and the atmosphere (e.g., Male and Granger 1981; Brun et al. 1989; Gustafsson et al. 2001). Geophysical and thermophysical properties of snow are known to be sensitive to climate variability and change and are of primary importance for simulations of hydrological and climatological processes (e.g., Rango 1980; Schultz and Barrett 1989; Albert et al. 1993).

* Supplemental information related to this paper is available at the Journals Online website: http://dx.doi.org/10.1175/JHM-D-13-055.s1.

Corresponding author address: Prof. Dr. Alexandre Langlois, Assistant Professor, Centre d’Applications et de Recherches en Télédétection (CARTEL), Département de Géomatique Appliquée, Université de Sherbrooke, 2055 Blvd. de l’Université, Sherbrooke, QC J1K 2R1, Canada.
E-mail: a.langlois2@usherbrooke.ca

DOI: 10.1175/JHM-D-13-055.1
snow. This has major implications for ground thermal and permafrost regimes (Romanovsky et al. 2010).

One of the main aims of this paper is to use new data obtained during International Polar Year (IPY) intensive surveys over northern Québec to evaluate the snowpack characteristics simulated by the Canadian Regional Climate Model, version 4 (CRCM4), coupled to two versions of the Canadian Land Surface Scheme (CLASS): CLASS 2.7 and CLASS 3.5 (Verseghy 1991; Verseghy et al. 1993). The evaluation also makes extensive use of existing observed and satellite gridded datasets. The reason for comparing the versions of CLASS in coupled mode is twofold: 1) we want to evaluate snow cover simulations made with the operational version of CRCM4 (CRCM4–CLASS 2.7) in use at Ouranos since 2006 to see how well it performs against the new data sources developed for the study (and also to see if performance improves with the inclusion of CLASS 3.5), and 2) we want to see what impact the differences in the two surface schemes may have on local climate through local feedback processes such as albedo and snow surface temperature (outgoing longwave radiation). CLASS “offline” snow performance in a column mode has been evaluated previously in several papers (i.e., Brown et al. 2006; Bartlett et al. 2006), but this does not provide any insights into the local climate feedbacks. This paper mainly addresses item 1 above, with a major effort to document and evaluate the snow cover datasets available for model evaluation. Item 2 is the focus of a paper by Wang et al. (2014) that looks at the snow cover–atmosphere interactions of the coupled runs. The results from this evaluation will be used to highlight the snow processes in CLASS that need additional work for improving the representation of snow cover over the entire Québec domain but with an emphasis over northern regions (north of ~50°N).

2. Experimental design and evaluation data

a. CRCM4 and CLASS 2.7

The starting point for this evaluation was the current operational version of the Canadian Regional Climate Model, CRCM4 (de Elia and Côté 2010; Music and Caya 2007; Caya and Laprise 1999), in use at the Ouranos Consortium (www.ouranos.ca) on climate change since 2006. It is a gridpoint, limited-area, nested model driven at its lateral boundaries by vertical profiles of temporally varying, large-scale atmospheric data linearly interpolated to the model’s time step. The model dynamical core is based on the Mesoscale Compressible Community (MC2) atmospheric model developed by the Cooperative Center for Research in Mesometeorology (CCRM) and described by Laprise et al. (1997). The CRCM4 land surface model is dynamically coupled to the overlying atmosphere through the vertical exchange of radiative, heat, and moisture fluxes at every time step. The physical parameterizations are in part based on the Canadian Centre for Climate Modelling and Analysis (CCCma) third-generation Atmospheric General Circulation Model (AGCM3) package (Scinocca and McFarlane 2004). This includes large-scale precipitation that is produced when the grid-scale relative humidity exceeds an invariant threshold of 95% accompanied by the appropriate release of latent heat. At this point the excess humidity is converted to precipitation (which falls instantaneously to the ground) and the appropriate amount of latent heat is released in the environmental air. As for the subgrid-scale deep convection scheme of AGCM3, it has been replaced in CRCM4 by the Bechtold–Kain–Fritsch (BKF) mass flux scheme (Bechtold et al. 2001), which handles both deep and shallow convection. During CRCM4 development, the BKF scheme was judged to be more suitable for the higher spatial resolutions with which CRCM4 is typically used (Laprise et al. 2003).

The operational version of CRCM4 is coupled to CLASS 2.7 (Verseghy 1991; Verseghy et al. 1993), a second-generation land surface scheme that provides physically based energy and water exchanges between land surface, vegetation canopy, and atmosphere. The soil column is exclusively mineral in content and includes three nominal layers: a 10-cm surface layer, a 25-cm vegetation root zone, and a 3.75-m deep soil layer. Soil temperatures vary with time following a one-dimensional heat conduction equation with appropriate heat capacities and thermal conductivities that depend on liquid and frozen moisture content and soil texture. In particular, soil thermal conductivity follows the formulation of Johansen (1975). The fluxes in the heat conduction equation are calculated by assuming that the “true” soil temperature in each soil layer varies quadratically with depth. The mean layer temperature is then obtained by integrating the quadratic function over the layer’s depth. Doing so for each soil layer results in a set of three linear equations that depend on the unknown heat fluxes and the unknown surface temperature. The latter is solved iteratively before being substituted back in the linear set, thus allowing for the heat fluxes (and its divergence) to be determined. Liquid and frozen moisture are also prognostic variables and follow Darcy’s equations of soil water flow. Treatment of vegetation is explicit and includes processes such as precipitation interception and unloading (both liquid and solid), solar and terrestrial radiative exchanges with the surface, and transpiration through a root system. Four vegetation types are modeled: needleleaf trees, broadleaf trees, crops, and grass.
Snow cover is represented as a fourth variable-depth bulk “soil” layer with a thermal regime distinct from the underlying soil. This implies that snow temperature is also a prognostic variable computed using the same quadratic temperature variation assumed for the soil layers. Snow surface temperature is then the result of an iteratively solved surface energy balance. Snow accumulates when surface air temperatures are at or below the freezing point. Snow albedo (density) decreases (increases) exponentially with time from a prescribed fresh-snow value using an empirical function based on data given in Aguado (1985), Robinson and Kukla (1984), and Dirmhirn and Eaton (1975). Specular reflections and dependence on solar zenith angle are ignored in the calculation of snow albedo. It is important in this paper to clearly distinguish between snow albedo and total surface albedo. The total surface albedo is calculated from prescribed base albedo values for canopy and bare soil which are then modulated from contributions from both the vegetation canopy [through its leaf area index (LAI) and snow/rain interception] and from the underlying ground through the presence of soil moisture or snow. Both vegetation albedo and ground albedo are weighted by cover fractions (canopy with snow, canopy without snow, ground snow, and bare soil) to produce the total surface albedo. The total surface albedo is therefore the quantity ultimately affecting albedo-based solar energy exchange with the overlying atmosphere, with snow albedo contributing in a manner proportional to its extent.

Snow thermal conductivity is a function of density only following Mellor (1977) and is assumed to be constant with depth. Melting occurs either as a result of snow surface temperature or bulk snow layer temperature being projected above 0°C at the next time step. In this case, the excess energy is used to melt the snowpack partially or completely and the temperature is set back to 0°C. Snow meltwater is then said to percolate into the snowpack and to refreeze (which will cause density to increase). This will go on until the entire pack reaches 0°C, after which the meltwater is allowed to pond on the surface and eventually infiltrate into the soil. Snowmelt can also occur through heat conduction from the underlying soil leading the bulk snow temperature to reach 0°C. In this case, the snow temperature is reset to 0°C and, since meltwater is assumed to form at the bottom of the snowpack, it gets directly infiltrated into the soil. Finally, when snow depth reaches a value of 0.1 m, the grid snow cover fraction is assumed to reach 100%. If snow depth is projected below 0.1 m, it is set back to 0.1 m and a fractional ground coverage is calculated based on mass conservation. Additional details on specific items of CLASS snow physics are presented later in section 3.

CLASS has been extensively tested in snow-dominated environments (Bartlett et al. 2006; Brown et al. 2006; Frigon et al. 2007, 2010; Music et al. 2009; Marsh et al. 2010). In particular, studies such as those from Bartlett et al. (2006) have shown that CLASS 3.5 (driven by re-analysis data) provides realistic snow cover simulations for a number of different snow climates. However, there has not been a detailed evaluation of CRCM–CLASS over northern Québec, owing in part to a lack of validation data. For instance, Dorsaz and Brown (2008) were unable to reach any conclusions about the performance of CRCM4 over northern Québec because of a lack of observational data as well as major discrepancies between available evaluation datasets. We hope in this study to shed more light on snow processes that are specific to boreal and arctic climates through the use of a comprehensive land surface scheme such as CLASS, evaluated with a suite of in situ, remotely sensed and gridded observational data, all of which will be described in the next section.

### b. Model experimental setup

In this paper, two simulations are analyzed; run C2.7 [following the nomenclature of Bartlett et al. (2006)] used the operational configuration of CRCM4 coupled to CLASS 2.7 (as described in the previous section), while run C3.5 is an experimental version of CRCM4 coupled to CLASS 3.5. The latter includes improved treatments of snow aging and canopy interception and new features such as liquid water retention in the snowpack and the modeling of mixed precipitation for air temperatures near the freezing point. In addition, organic soils are allowed in

### Table 1. CRCM4–CLASS2.7 (C2.7) and CRCM4–CLASS3.5 (C3.5) simulation characteristics.

<table>
<thead>
<tr>
<th>Simulation*</th>
<th>CLASS</th>
<th>Soil levels</th>
<th>Soils</th>
<th>Precipitation phase</th>
<th>Thermal conductivity of snow</th>
<th>Snow albedo refreshment threshold (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991–2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2.7</td>
<td>v. 2.7</td>
<td>3</td>
<td>Mineral</td>
<td>0°C threshold</td>
<td>Mellor (1977)</td>
<td>0.0013</td>
</tr>
<tr>
<td>C3.5</td>
<td>v. 3.5</td>
<td>3</td>
<td>Mineral/organic</td>
<td>0°–6°C polynomial function</td>
<td>Sturm et al. (1997)</td>
<td>0.0050</td>
</tr>
</tbody>
</table>

* This period excludes a 2-yr spinup (1989–90).
all layers and snow thermal conductivity $k_s$ (W m$^{-1}$ K$^{-1}$) is estimated from mean snowpack density $\rho_s$ (kg m$^{-3}$) following Sturm et al. (1997) [Eq. (1)], which replaced the Mellor (1977) expression [Eq. (2)] used in C2.7:

$$k_s = 3.233 \times 10^{-6} \rho_s^2 - 1.01 \times 10^{-3} \rho_s$$

$$+ 0.138 \quad \text{for} \quad 156 \leq \rho_s \leq 600 \text{ kg m}^{-3}$$

$$k_s = 0.234 \times 10^{-3} \rho_s + 0.023 \quad \text{for} \quad \rho_s < 156 \text{ kg m}^{-3} \quad \text{and}$$

$$1$$

It was shown in R. Harvey et al. (2010, poster presentation) that $k_s$ values calculated from Mellor (1977) are 2 times larger than results obtained using the relationship from Sturm et al. (1997). The Sturm et al. (1997) relationship will therefore lead to a stronger vertical temperature gradient across the snow–ground domain, in particular to much warmer ground and bulk snow temperatures and slightly cooler near-surface air temperatures. Hence, low values of snow thermal conductivity will cause a lower sensitivity of winter air temperatures to ground temperatures and any cold bias in air temperature will tend to be slightly enhanced.

Both treatments of organic soils and snow thermal conductivity are important features for simulating the ground thermal regime in northern regions. Recent offline CLASS simulations at three Québec forest sites (R. Harvey et al. 2010, poster presentation) have shown that using the Sturm et al. (1997) formulation leads to much more realistic snow and soil temperatures compared to Mellor (1977) and that the presence of organic soils—at least in the first soil layer when under a canopy—is crucial for realistic soil temperatures in the summer (R. Harvey et al. 2010, poster presentation).

Both CRCM4 simulations were run in a domain centered over Québec, Canada ($111 \times 87$ grid points), with a horizontal grid-size mesh of 45 km (polar-stereographic projection true at 60°N with a 15-min time step). A spectral nudging technique was applied to large-scale winds (Riette and Caya 2002) within the interior of the regional domain to keep the CRCM’s large-scale flow close to its driving data. The model was driven at its lateral boundaries by the 6-hourly Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim; Dee et al. 2011) for the 1989–2010 period (the full period of ERA-Interim starting in 1979 was not available for driving CRCM when this project began). Simulations were evaluated for snow seasons 1991/92 through 2009/10 after allowing for a 2-yr spinup. Table 1 provides the configuration details for both CRCM4 runs C2.7 and C3.5.

---

c. In situ datasets

1. **FIELD CAMPAIGNS**

Sampling occurred during four main field campaigns, namely the IPY, the Cold Regions Hydrology High-Resolution Observatory (CoReH2O) mission, and two separate campaigns in the James Bay area, northern Québec, Canada. The primary goal of the Canadian IPY
project “Variability and Change in the Canadian Cryosphere” was to improve our understanding of snow-related processes in subarctic and arctic regions. An intensive field campaign was conducted in February 2008 and included four nodes (sites with high-resolution sampling) and a 2000-km transect in northern Québec (Fig. 1a). The transect included a transition from dense boreal forest in the south to open tundra in the north. At the first three sites, located in Sept-Iles (SI), Schefferville (SC), and Kuujjuaq (KU), in situ sampling was conducted at 1-km intervals over an 8 × 16 km² grid. At the fourth site, located north of Puvirnituq (POV), depth measurements were acquired with GPS-equipped automated probes (MagnaProbes produced by SnowHydro) along the sample transect. Along the main 2000-km transect, in situ snow and vegetation information was gathered by helicopter-based large-scale sampling approximately every 40 km. Further details on the IPY campaign are provided in Langlois et al. (2011, 2012).

The CoReH2O campaign took place between November 2009 and May 2010 in Churchill (CH), Manitoba (Derksen et al. 2012; Fig. 1a), where intensive and extensive observation periods were conducted. The data used in the present paper were collected during four intensive observation periods (IOPs) each of 2–3 weeks duration in January (IOP 1), February (IOP 2), March (IOP 3), and April/May 2010 (IOP 4). During the IOPs, snow property measurements were acquired at multiple sites with a mixed land cover along the forest/tundra transition. The observations were matched to passive microwave measurements and included snow water equivalent (SWE), thickness, density, and temperature, as well as grain size and shape from infrared measurements (Langlois et al. 2010; Montpetit et al. 2012). The mobile nature of the experimental approach facilitated the measurement of distinct snowpack types as they evolved through the winter, including deep taiga snow, snow in an open wetland fen, and snow over lake ice.

Two separate field campaigns were conducted in the James Bay (JB) area (Fig. 1a) of Québec, Canada, in March 2003 and 2009 to measure spatial variations in snow properties, both over latitudinal variations (north–south 600-km transect) and over longitudinal variations (east–west 400-km transect). The spatial distribution of sampling sites included dense taiga forest to open tundra, allowing for a snapshot validation of CRCM4 snow cover over a range of typical boreal and arctic vegetation land cover types.

### 2) Historical Snow Depth and Water Equivalent Data

Seventeen stations with daily snow depth measurements during the 1991–2009 study period were obtained from the Environment Canada “Climate Data Online” database (Fig. 1b). Daily snow depth measurements at these sites were made manually by ruler or by ultrasonic ranging at open short-grass-covered sites that may not be representative of the prevailing land cover.

Snow course data for the study period were obtained from the Ministère du Développement durable, de l’Environnement et des Parcs du Québec (MDDEP of the Gouvernement du Québec) and Hydro-Québec (HQ; Fig. 1c). The data tend to be concentrated in the boreal forest zone (mixed forest and open areas) and in basins contributing to hydroelectricity production. The dataset includes the survey-averaged snow depth (cm) and SWE

<table>
<thead>
<tr>
<th>Datasets</th>
<th>n sites</th>
<th>Type</th>
<th>Validation</th>
<th>Depth (cm)</th>
<th>SWE (mm)</th>
<th>Density (kg m⁻³)</th>
<th>Temp. (°C)</th>
<th>Snow cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPY**</td>
<td>143</td>
<td>In situ</td>
<td>Spatial</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CoReH2O**</td>
<td>127</td>
<td>In situ</td>
<td>Spatial</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>James Bay 2003**</td>
<td>18</td>
<td>In situ</td>
<td>Spatial</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>James Bay 2009**</td>
<td>45</td>
<td>In situ</td>
<td>Spatial</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Environment Canada</td>
<td></td>
<td>In situ</td>
<td>Spatial</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>HQ</td>
<td>519</td>
<td>In situ</td>
<td>Spatial, temporal</td>
<td>X</td>
<td>X*</td>
<td>X*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDDEP</td>
<td>2143</td>
<td>In situ</td>
<td>Spatial, temporal</td>
<td>X</td>
<td>X*</td>
<td>X*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANSA</td>
<td></td>
<td>Global</td>
<td>Remote sensing</td>
<td>Spatial, temporal</td>
<td>X</td>
<td>X*</td>
<td>X*</td>
<td></td>
</tr>
<tr>
<td>CMC</td>
<td></td>
<td>NH</td>
<td>Gridded</td>
<td>Spatial, temporal</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMS</td>
<td></td>
<td>NH</td>
<td>Gridded</td>
<td>Spatial, temporary</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple SWEs</td>
<td></td>
<td>Varies</td>
<td>Gridded</td>
<td>Spatial, temporal</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

* Derived from the snow core weight/volume ratio (all other measurements from stratigraphic analyses, see snow sampling section).

** For the IPY, CoReH2O, and James Bay datasets, spatial variability was accounted for by conducting 50–100-m transects of depth and SWE, a sufficient distance to catch spatial variability according to Clark et al. (2011). No spatial variability information was available for the Environment Canada, HQ, and MDDEP datasets.
Fig. 2. Differences in mean seasonal air temperature between (a) C2.7 and (b) C3.5 simulations with CRU2 for 1992–2000: (top left) summer (Jun–Aug), (top right) fall (Sep–Nov), (bottom left) winter (Dec–Feb), and (bottom right) spring (Mar–May).
FIG. 3. As in Fig. 2, but for differences in mean seasonal precipitation (mm day$^{-1}$).
Measurements are made more-or-less biweekly and are concentrated around the time of maximum snow accumulation. A total of 81 sites were obtained north of 50°N with measurements during the 1991–2009 study period (for a total of 1509 observations). There is no stratigraphic information in the snow course dataset.

d. Gridded snow datasets

1) BLENDED REMOTE SENSING SNOW PRODUCT

The Foster et al. (2011) blended snow product was used to evaluate the number of days with snow on the ground [snow cover duration (SCD)] in the first (August–January) and second (February–July) halves of the snow year. This variable is more straightforward to compute than dates of start/end of snow cover and the two are highly correlated (Brown 2010). The dataset provides daily snow on/off information at a 25-km resolution over the 2002–09 period (data for 2004 are missing) using a newly developed Air Force Weather Agency (AFWA)–National Aeronautics and Space Administration (NASA) Snow Algorithm (ANSA) to blend information from snow products derived from the Earth Observing System (EOS)–Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Microwave Scanning Radiometer for EOS (AMSR-E), and Quick Scatterometer (QuikSCAT). Validation of the ANSA product showed systematically higher agreement between the ANSA product and field observations than MODIS and AMSR-E alone.

2) CMC AND IMS DATASETS

Daily snow depth analyses from the Canadian Meteorological Centre (CMC) over the Northern Hemisphere are available from 1998 (Brown and Brasnett 2010). The analysis method is based on optimal interpolation of real-time snow depth reports (Brasnett 1999) and includes surface snow depth observations from synoptic observations, meteorological aviation reports, and special aviation reports acquired through the World Meteorological Organization (WMO) information system. The historical archive includes daily and monthly snow depth interpolated to a 24-km polar stereographic grid and monthly SWE estimates using snow density information obtained from snow course data (Brown and Mote 2009). The Interactive Multisensor Snow and Ice Mapping System (IMS; Ramsay 1998; Helfrich et al. 2007) provides daily charts of snow cover presence/absence at a nominal resolution of 24 km. The data is archived at the National Snow and Ice Data Center (NSIDC; http://nsidc.org) from February 1997 to the present. A summary of datasets used in the CRCM4 evaluation is presented in Table 2.

3. Results and discussion

a. CRCM validation

1) SCREEN-LEVEL AIR TEMPERATURE AND TOTAL PRECIPITATION

Biases in temperature and precipitation in the two CRCM runs were assessed prior to the snow cover

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA-40 2.50°</td>
<td>Snowfall estimated from 6-h, 2-m air analyzed temperature and 6-h forecast precipitation rate assuming a 0°C threshold for rain/snow separation.</td>
</tr>
<tr>
<td>ERA-Interim 0.75°</td>
<td>Snowfall estimated from 6-h, 2-m air analyzed temperature and 12-h forecast precipitation rate assuming a 0°C threshold for rain/snow separation. The computed solid fraction of monthly precipitation was applied to monthly total precipitation from CRU, GPCC, and CANGRD to estimate monthly snowfall amounts.</td>
</tr>
<tr>
<td>CRU TS3.0 0.50°</td>
<td>Monthly precipitation series from spatially interpolated station data. Update to 2006 of CRU2 dataset of Mitchell and Jones (2005). Monthly snowfall fraction from ERA-Interim used to partition monthly total precipitation into snowfall.</td>
</tr>
<tr>
<td>GPCC 0.50°</td>
<td>GPCC Full Data Reanalysis Product, version 6 (Dec 2011; Rudolf and Schneider 2005). Global 0.5° reanalysis of station-based observations of monthly total precipitation. Event-based corrections for undercatch following Fuchs et al. (2001). Monthly snowfall fraction from ERA-Interim used to partition monthly total precipitation into snowfall.</td>
</tr>
<tr>
<td>CANGRD 50 km</td>
<td>Monthly precipitation series from spatially interpolated station data (Milewska et al. 2005, updated 2012). Data corrected for inhomogeneities and SWE adjusted for regional variation in mean snowfall density (Mekis and Vincent 2011; Mekis and Brown 2010). Monthly snowfall fraction from daily ERA-Interim surface air temperatures used to partition monthly total precipitation into snowfall.</td>
</tr>
</tbody>
</table>
evaluation as part of the standard validation procedures followed at Ouranos. Figures 2 and 3 present the differences in seasonal mean temperature and precipitation for the two simulations versus the University of East Anglia Climatic Research Unit (CRU; CRU2) dataset (Mitchell and Jones 2005) derived from climate station observations. The seasonal temperature plots (Fig. 2) indicate that both CRCM runs have cold biases over northern regions.

Fig. 4. Estimates of mean annual (1979/80–2001/02) total snowfall (mm water equivalent) over the Québec region from five different sources.

Fig. 5. Multidataset (ERA-Interim, GPCC, CRU3, and CANGRD) (left) average annual total snowfall (mm water equivalent) and between-dataset standard deviation [(middle) mm and (right) percent of mean] for the 1979–2001 averaging period.
of the model domain in the fall and winter periods that exceed 5°C over the Ungava Peninsula. Regional cold biases in CRCM4 air temperatures have been documented with various driving data (Paquin 2010), and while the precise reasons for these are unclear, underestimation of downwelling longwave radiation under cold, clear-sky conditions (Markovic et al. 2009) likely plays a role in the winter bias. The C3.5 simulation has a stronger cold bias in the fall but is warmer than C2.7 in the spring season. The lower thermal conductivity of snow in the C3.5 run is likely contributing to these differences through lower heat transfer from the ground at the start of the snow season and warmer soils at the end of the winter.

The two simulations have similar bias signs for seasonal precipitation with tendencies to overestimate precipitation over western Québec and underestimate precipitation over eastern Québec and Labrador compared to CRU2 (Fig. 3). The difference in mean annual total precipitation between the two runs was less than ±40 mm (<10%) over northern Québec.

2) SNOWFALL

As part of this study, an assessment was made of uncertainties in snowfall in several gridded observational and reanalysis datasets over the Québec region (Table 3). Snowfall is a difficult variable to measure accurately. Ruler measurements of accumulated snowfall are affected by drifting, snowmelt, and snow settlement (Doesken and Judson 1997) while precipitation gauges typically underestimate snowfall because of wind disturbance around the gauge orifice (Goodison et al. 1998). The average density of new snowfall exhibits important regional gradients across Canada (Mekis and Brown 2010). This is taken into account in the Canadian Gridded Temperature

![Image of annual total snowfall for (left) C2.7 and (right) C3.5 vs CANGRD.](image_url)

![Image of average annual total snowfall (mm) from small events (<1 mm day⁻¹).](image_url)
and Precipitation Anomalies (CANGRD) 50-km gridded adjusted monthly precipitation dataset developed by Environment Canada (Milewska et al. 2005; Mekis and Vincent 2011). The CANGRD dataset is considered the reference in this analysis as it 1) uses homogenized and corrected precipitation data (Mekis and Vincent 2011); 2) is interpolated using the Australian National University Splines (ANUSPLIN) interpolation method, which provides consistent and accurate results for precipitation in high mountain regions (Milewska et al. 2005); and 3) has undergone extensive evaluation. Monthly snowfall amounts in all the datasets were estimated from monthly total precipitation by applying the monthly rain/snow fraction estimated from daily ERA-Interim surface air temperatures assuming a 0°C threshold for the phase transition. All the datasets were interpolated to the CRCM grid using linear inverse distance weighting with comparison made for a common 1979–2001 overlap period.

The mean annual snowfall climatologies (Fig. 4) show spatial patterns of snowfall distribution that are in agreement, with the exception of the 40-yr ECMWF Re-Analysis (ERA-40), which considerably underestimates snowfall over the Labrador coast compared to the other datasets. CRU3 exhibited the closest agreement to CANGRD (rms difference of 20.2 mm over the entire Québec domain) followed by Global Precipitation Climatology Centre (GPCC), ERA-Interim, and ERA-40 (rms differences of 25.5, 30.7, and 41.3 mm, respectively). The between dataset standard deviation of the four better-performing datasets was found to be less than ±10% of mean snowfall over most of Québec with the largest differences (though mostly not exceeding ±20%) over northern Ungava Peninsula and the Torngat Mountains in Labrador (Fig. 5).

Evaluation of CRCM mean annual total snowfall with the CANGRD estimates (Fig. 6) shows run C3.5 consistently overestimating snowfall over almost the entire domain compared to C2.7. Run C2.7 snowfall totals were within ±40 mm of CANGRD over most of Québec. The difference in the two runs is mainly attributed to the different treatments of precipitation phase by CLASS. Run C2.7 assumed a 0°C rain/snow hard transition while run C3.5 applied a sixth-degree polynomial to give mixed phase precipitation for air temperatures between 0°C and

![Image of snow cover duration difference for C2.7 and C3.5 runs](image_url)
Almost continuous small precipitation amounts less than 1 mm day\(^{-1}\) in the CRCM output. This is a feature of climate models (Dai 2006), and these small values are typically ignored in many applications. However, for CRCM4 it was found that precipitation amounts less than 1 mm day\(^{-1}\) contribute more than 50 mm water equivalent to the annual total snowfall over northern Québec (Fig. 7, run C2.7), which represents \(\sim 20\% - 25\%\) of the mean annual maximum snow accumulation.

### Validation of Snow Variables

1) **Snow Cover Duration**

The duration of snow on the ground was evaluated using the blended global snow product of Foster et al. (2011) for the snow year (August–July) and the first and second halves of the snow year (August–January; February–July) to assess the variability in snow cover onset and disappearance. Differences in mean SCD between ANSA and CRCM over the 2005–09 period are shown in Fig. 8 and summarized in Table 4. Both simulations had larger positive biases in the fall (snow onset too early by 2–3 weeks) while spring biases were less than 1 week, with a decrease in the positive bias observed in Nunavik in the C3.5 run. The performance statistics (RMSE and \(R^2\)) were similar for both simulations. The C2.7 and C3.5 runs are shown separately for the fall and spring periods. It is clear that the SCD is overestimated in both C2.7 and C3.5 in the snow onset period, which is attributed to the observed fall season cold bias (Fig. 2). Wang et al. (2014) showed that snow feedbacks enhance this cold bias. Similar conclusions were reached evaluating SCD over a longer 1998–2009 period with the IMS and CMC datasets (Table 5).

The mixed phase parameterization used in C3.5 [see section 3b(2)] is likely contributing to the stronger fall period cold bias as snowfall is generated earlier in the season than with the 0°C threshold used in C2.7. Recent test runs with CRCM4 and CLASS 3.5 indeed showed that the cooling effect of using its mixed phase precipitation scheme is around \(-0.2^\circ\) to \(-0.5^\circ\C\) (not shown).

The lower spring SCD bias in C3.5 is attributed to the higher snow albedo refresh threshold (i.e., the fresh snowfall depth above which the snow albedo is refreshed to 0.84, which is the maximum all-solar spectrum albedo value), which is 1.3 mm of new snow depth in CLASS 2.7 versus 5 mm in CLASS 3.5. Consequently, the albedo in C3.5 is consistently lower and contributes to earlier melt compared to C2.7. The lower snow thermal conductivity in C3.5 also contributes to earlier snowmelt through a warmer snowpack and underlying soil temperatures.

2) **In Situ Evaluation Results: Snow Depth and SWE**

Although the spatial distribution of the Environment Canada in situ daily snow depth observations is limited, there is good temporal coverage throughout the simulation period. CRCM4 C2.7 and C3.5 simulations were compared at each station (Fig. 9) using scatterplots of the modeled and measured snow depth values.

Results show that both the C2.7 and C3.5 runs overestimate the snow depth with a positive bias (y axis intercept values) of 10–14 mm. However, although the biases are similar, C3.5 shows a better correlation (\(R^2\) of 0.55 for C2.7 and 0.65 for C3.5) and regression slope (0.83 for C2.7 and 0.95 for C3.5). While the snow depth simulations are in general well correlated to observations at individual meteorological stations (average \(R^2\) of 0.64 and 0.74 for C2.7 and C3.5, respectively; Table 6), we looked at the maximum snow depth (Table 6, section at right) in order to validate the timing and magnitude.

---

**Table 4. Seasonal and annual comparison (CRCM minus ANSA) of snow cover duration between CRCM4 C2.7 and C3.5 runs and the ANSA product over the 2005–09 period. Statistics computed for the entire Québec domain (Fig. 1).**

<table>
<thead>
<tr>
<th>CRCM4 run</th>
<th>Mean bias (days)</th>
<th>RMSE (days)</th>
<th>Spatial correlation (R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2.7 (fall)</td>
<td>11.0</td>
<td>17.3</td>
<td>0.51</td>
</tr>
<tr>
<td>C3.5 (fall)</td>
<td>19.8</td>
<td>24.4</td>
<td>0.43</td>
</tr>
<tr>
<td>C2.7 (spring)</td>
<td>6.4</td>
<td>13.1</td>
<td>0.72</td>
</tr>
<tr>
<td>C3.5 (spring)</td>
<td>-3.3</td>
<td>12.8</td>
<td>0.65</td>
</tr>
<tr>
<td>C2.7 (annual)</td>
<td>16.5</td>
<td>26.1</td>
<td>0.69</td>
</tr>
<tr>
<td>C3.5 (annual)</td>
<td>15.4</td>
<td>27.3</td>
<td>0.62</td>
</tr>
</tbody>
</table>

**Table 5. Seasonal comparison of SCD between CRCM4 C2.7 and C3.5 runs and the IMS product over the 1998–2009 period.**

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CRCM4 run</td>
<td>Mean bias (days)</td>
</tr>
<tr>
<td>C2.7</td>
<td>18.3</td>
</tr>
<tr>
<td>C3.5</td>
<td>26.6</td>
</tr>
</tbody>
</table>

+6°C (see Auer 1974). However, the positive snowfall bias in C3.5 does not translate into a positive bias in the maximum SWE [see section 3b(2)] since the additional snowfall mainly occurs outside the main accumulation period when air temperatures are close to 0°C.
The evaluation results for the HQ and MDDEP snow course data (Fig. 10) suggest an overall overestimation of the SWE for both simulations, with a decrease nevertheless in the SWE bias from 30.8 to 14.6 mm for C3.5. The more realistic density parameterization used in C3.5 is clearly evident; maximum dry snowpack density in C2.7 is limited to 300 kg m\(^{-3}\) (Bartlett et al. 2006). The modified aging scheme used in C3.5 appears to age snow too rapidly over the snow season (Fig. 10f) in agreement with Lafleur et al. (2000), who found that CLASS 3.5 overestimated density for a subarctic open woodland site. A more complete SWE spatial analysis using gridded SWE datasets is presented as supplemental material.

Fig. 9. Daily snow depth evaluation at 14 Environment Canada weather stations (north of 50°N; see Fig. 1) for (top) C2.7 and (bottom) C3.5.
3) SNOW TEMPERATURE AND DENSITY ANALYSIS

The thermodynamic properties of the CRCM4-simulated snowpack were evaluated with snow stratigraphic measurements of density and temperature from field campaigns. In terms of snow temperature (Fig. 11), the C3.5 run performs better overall, with a decrease in the bias and RMSE, although we observe a lower $R^2$ of 0.40 compared with 0.48 in the C2.7 run. The modification of the snow thermal conductivity in C3.5 was observed to eliminate much of the cold bias (bias at 6.2 K) observed in the C2.7 run compared to field measurements whereas the bias in C3.5 is negligible at 0.5 K. This aspect is improved in C3.5, which has a negligible bias and warmer snow temperatures compared to C2.7.

Snow density simulations are shown in Fig. 11, and again the saturation at 300 kg m$^{-3}$ in C2.7 is clearly shown, which is consistent with the observations from the HQ and MDDEP datasets (Fig. 10). Also, as observed in the previous section, C3.5 provides marginally improved density simulations spread over a wider range of values above 300 kg m$^{-3}$ and a reduction of the positive bias observed for values below 300 kg m$^{-3}$. Although the final statistics are not significant, the slope and y axis intercept are improved in C3.5.

### Table 6: Results of the daily snow depth and mean annual maximum snow depth (SDmax) and timing (JDmax) at individual stations over the 1991–2009 period. Bias is computed as modeled minus observed. No maximum snow depth information was available for the Churchill Falls station (NA).

#### C2.7

<table>
<thead>
<tr>
<th>Station</th>
<th>$R^2$</th>
<th>$b$</th>
<th>$a$</th>
<th>Bias (cm)</th>
<th>RMSE (cm)</th>
<th>SDmax Bias (cm)</th>
<th>SDmax RMSE (cm)</th>
<th>JDmax Bias (days)</th>
<th>JDmax RMSE (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chibougamau</td>
<td>0.58</td>
<td>0.82</td>
<td>14.81</td>
<td>8.85</td>
<td>17.95</td>
<td>16.45</td>
<td>21.31</td>
<td>30.23</td>
<td>21.00</td>
</tr>
<tr>
<td>Churchill Falls</td>
<td>0.87</td>
<td>0.43</td>
<td>12.61</td>
<td>−19.57</td>
<td>20.56</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Eastmain</td>
<td>0.91</td>
<td>0.53</td>
<td>3.31</td>
<td>−17.24</td>
<td>26.77</td>
<td>−52.39</td>
<td>52.54</td>
<td>46.91</td>
<td>6.50</td>
</tr>
<tr>
<td>Fermont</td>
<td>0.74</td>
<td>0.68</td>
<td>9.83</td>
<td>−0.97</td>
<td>21.38</td>
<td>−13.71</td>
<td>31.92</td>
<td>28.93</td>
<td>29.17</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>0.51</td>
<td>0.85</td>
<td>17.19</td>
<td>13.59</td>
<td>33.02</td>
<td>19.18</td>
<td>43.24</td>
<td>39.73</td>
<td>35.22</td>
</tr>
<tr>
<td>Kuujjuarapik</td>
<td>0.55</td>
<td>0.99</td>
<td>10.71</td>
<td>10.55</td>
<td>19.12</td>
<td>27.93</td>
<td>33.24</td>
<td>76.37</td>
<td>46.47</td>
</tr>
<tr>
<td>LG-2</td>
<td>0.61</td>
<td>0.57</td>
<td>8.26</td>
<td>5.70</td>
<td>15.95</td>
<td>13.70</td>
<td>25.84</td>
<td>50.96</td>
<td>33.35</td>
</tr>
<tr>
<td>LG-4</td>
<td>0.63</td>
<td>1.47</td>
<td>8.26</td>
<td>5.70</td>
<td>15.95</td>
<td>13.70</td>
<td>25.84</td>
<td>50.96</td>
<td>33.35</td>
</tr>
<tr>
<td>Makkovik</td>
<td>0.64</td>
<td>0.01</td>
<td>10.18</td>
<td>12.26</td>
<td>29.84</td>
<td>4.18</td>
<td>43.53</td>
<td>37.89</td>
<td>23.35</td>
</tr>
<tr>
<td>Matagami</td>
<td>0.60</td>
<td>0.17</td>
<td>13.31</td>
<td>17.36</td>
<td>32.17</td>
<td>−3.92</td>
<td>4.35</td>
<td>5.54</td>
<td>78.50</td>
</tr>
<tr>
<td>Nain</td>
<td>0.51</td>
<td>0.66</td>
<td>15.85</td>
<td>7.22</td>
<td>22.37</td>
<td>−20.85</td>
<td>39.06</td>
<td>32.61</td>
<td>37.53</td>
</tr>
<tr>
<td>Schefferville</td>
<td>0.62</td>
<td>0.66</td>
<td>11.53</td>
<td>0.55</td>
<td>24.41</td>
<td>−19.84</td>
<td>36.94</td>
<td>32.58</td>
<td>37.16</td>
</tr>
<tr>
<td>Wabush</td>
<td>0.61</td>
<td>0.66</td>
<td>11.58</td>
<td>1.14</td>
<td>24.23</td>
<td>−5.25</td>
<td>34.49</td>
<td>43.37</td>
<td>31.10</td>
</tr>
<tr>
<td>Mean</td>
<td>0.64</td>
<td>0.83</td>
<td>11.99</td>
<td>9.43</td>
<td>23.71</td>
<td>24.56</td>
<td>31.24</td>
<td>43.37</td>
<td>31.10</td>
</tr>
</tbody>
</table>

#### C3.5

<table>
<thead>
<tr>
<th>Station</th>
<th>$R^2$</th>
<th>$b$</th>
<th>$a$</th>
<th>Bias (cm)</th>
<th>RMSE (cm)</th>
<th>SDmax Bias (cm)</th>
<th>SDmax RMSE (cm)</th>
<th>JDmax Bias (days)</th>
<th>JDmax RMSE (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chibougamau</td>
<td>0.62</td>
<td>0.90</td>
<td>21.24</td>
<td>18.09</td>
<td>23.87</td>
<td>24.56</td>
<td>32.68</td>
<td>46.36</td>
<td>2.00</td>
</tr>
<tr>
<td>Churchill Falls</td>
<td>0.86</td>
<td>0.45</td>
<td>26.96</td>
<td>−4.10</td>
<td>7.39</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Eastmain</td>
<td>0.92</td>
<td>0.64</td>
<td>2.85</td>
<td>−12.60</td>
<td>20.65</td>
<td>−41.11</td>
<td>41.27</td>
<td>36.85</td>
<td>26.00</td>
</tr>
<tr>
<td>Fermont</td>
<td>0.82</td>
<td>0.76</td>
<td>10.02</td>
<td>2.03</td>
<td>17.73</td>
<td>−8.73</td>
<td>31.44</td>
<td>28.50</td>
<td>8.67</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>0.66</td>
<td>1.01</td>
<td>17.69</td>
<td>17.96</td>
<td>31.33</td>
<td>23.77</td>
<td>46.51</td>
<td>42.73</td>
<td>22.89</td>
</tr>
<tr>
<td>Kuujjuarapik</td>
<td>0.69</td>
<td>1.61</td>
<td>10.50</td>
<td>18.50</td>
<td>25.97</td>
<td>40.93</td>
<td>44.42</td>
<td>102.04</td>
<td>37.12</td>
</tr>
<tr>
<td>LG-2</td>
<td>0.67</td>
<td>1.25</td>
<td>11.21</td>
<td>15.35</td>
<td>23.60</td>
<td>29.39</td>
<td>37.42</td>
<td>72.36</td>
<td>18.65</td>
</tr>
<tr>
<td>LG-4</td>
<td>0.62</td>
<td>1.00</td>
<td>10.09</td>
<td>10.12</td>
<td>19.75</td>
<td>23.66</td>
<td>33.72</td>
<td>66.50</td>
<td>22.65</td>
</tr>
<tr>
<td>Makkovik</td>
<td>0.76</td>
<td>1.57</td>
<td>11.70</td>
<td>21.52</td>
<td>28.09</td>
<td>39.77</td>
<td>42.16</td>
<td>87.37</td>
<td>4.25</td>
</tr>
<tr>
<td>Matagami</td>
<td>0.73</td>
<td>1.19</td>
<td>12.08</td>
<td>16.52</td>
<td>28.09</td>
<td>38.49</td>
<td>52.25</td>
<td>58.57</td>
<td>4.43</td>
</tr>
<tr>
<td>Nain</td>
<td>0.69</td>
<td>0.94</td>
<td>16.94</td>
<td>15.21</td>
<td>27.90</td>
<td>8.78</td>
<td>41.49</td>
<td>36.12</td>
<td>18.35</td>
</tr>
<tr>
<td>Schefferville</td>
<td>0.87</td>
<td>0.96</td>
<td>8.88</td>
<td>7.87</td>
<td>13.44</td>
<td>5.59</td>
<td>8.15</td>
<td>10.38</td>
<td>28.00</td>
</tr>
<tr>
<td>Wabush</td>
<td>0.76</td>
<td>0.80</td>
<td>11.74</td>
<td>5.12</td>
<td>19.86</td>
<td>−13.16</td>
<td>32.57</td>
<td>27.19</td>
<td>25.71</td>
</tr>
<tr>
<td>Mean</td>
<td>0.74</td>
<td>0.99</td>
<td>13.15</td>
<td>9.83</td>
<td>22.04</td>
<td>12.58</td>
<td>36.68</td>
<td>49.49</td>
<td>13.74</td>
</tr>
</tbody>
</table>
4. Summary and conclusions

Two snow cover simulations from the Canadian Regional Climate Model, version 4 (CRCM4), over the eastern North American Québec domain were compared and validated with an extensive ensemble of observational datasets from in situ, satellite, and reanalyses. The two runs compared the operational version of CRCM4 used at Ouranos since 2006 with CLASS 2.7 (C2.7) with an experimental version of CRCM4 coupled to CLASS 3.5 (C3.5). The main differences in the treatment of snowpack processes between the two versions of CLASS were an improved snow aging scheme, inclusion of liquid water in the snowpack, and a new parameterization of snow thermal conductivity. Our evaluation of these runs demonstrated that CLASS 3.5 provided more accurate seasonal snow depth values (when compared to Environment Canada climate stations), a reduction of a cold bias in snowpack temperatures, and improvements in simulated snow density. However, further refinements are still required in the snow aging scheme as the evaluation data indicate there are systematic biases in the simulation of snowpack density over northern Québec.

The evaluation also found that snow cover duration and maximum snow depth were overestimated in both runs related to a cold bias in CRCM4. This cold bias was exacerbated in the C3.5 run by the polynomial precipitation phase expression that increased snowfall frequency early...
in the snow season. Wang et al. (2014) showed that the additional snow cover reinforced the cold bias through surface albedo and outgoing longwave radiation feedbacks to the atmosphere. It was found that the albedo refresh parameterization used in CLASS was particularly sensitive to the parameterization of precipitation phase and the selection of the time step snowfall depth threshold for snow albedo refresh. Phase parameterization is not normally an issue since most atmospheric models provide this information to the land surface scheme.

A more physically based snow albedo scheme based on snow specific area (SSA) is being developed to address the snow albedo refresh problem. Although C3.5 seems to perform better based upon in situ and satellite snow measurements, there are still many questions to answer. The reason for the better performance in C3.5 might be...
for the wrong reason. The results in this paper identified several sources, two of which seem to have greater impact on snow simulations: 1) precipitation phase and 2) albedo parameterization. Current work is focusing on these aspects and is expected to provide improved parameterization of both precipitation phase and treatment of albedo. Additional work is also planned on the parameterization of snow thermal conductivity given its importance for snowpack and ground temperatures. It was recently shown by Calonne et al. (2011) that the formulation of Sturm et al. (1997) used in CLASS 3.5 might be too high for snow densities below 150 kg m$^{-2}$ and too low for values above 150 kg m$^{-2}$. Furthermore, we suspect that some of the bias observed in the albedo and density can be explained by the absence of a snow grain characterization in CLASS. It is clear from the literature that thermal conductivity is influenced by the grain size and shape (Taillandier et al. 2007; Flin et al. 2011; Pinzer et al. 2012). Recent studies have developed methods to measure the snow specific surface area (SSA) in the field (Gallet et al. 2009; Langlois et al. 2010; Montpetit et al. 2012). We plan to integrate an SSA “module” in CLASS based on the formulation of Taillandier et al. (2007) and Jacobi et al. (2010) as results presented in Roy et al. (2012) have shown improvement in snow simulations when the historical evolution of SSA is taken into account.

Acknowledgments. This project was funded by the Fonds de Recherche en Science du Climat (FRSCO) and the Consortium Ouranos. The CRCM output used in this paper was generated and supplied by Ouranos. The authors express their thanks to the Climate Simulation and Analysis Group for producing the necessary CRCM simulations and to Blaise Gauvin St-Denis from the Ouranos Climate Scenarios and Services Group for providing output from the CRCM runs in NetCDF format. The field data presented in this paper were collected during several field campaigns supported by the Canadian IPY project—Environment Canada, the National Sciences and Engineering Research Council of Canada (NSERC), the Collaboration Québec–France, the Centre Jacques Cartier, the French Remote Sensing program (Programme national de télé-détecteur spatial), and the Canadian Space Agency. The authors thank the Churchill Northern Studies Centre (CNSC), Dr. Chris Derksen, and Environment Canada staff who participated in several projects for their collaboration and support. Special thanks to Dr. Jim Foster (NASA), HQ, and MDDEP for providing evaluation data.

REFERENCES


