Validation of the Snow Cover Variation of the Canadian Regional Climate Model (CRCM) Using Passive Microwave Satellite Data

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ABSTRACT:

The spatial/temporal variation of the snow cover can be simulated by models such as the Canadian Regional Climate Model (CRCM) developed by Université du Québec à Montréal that simulates the snow water equivalent (SWE), a key parameter for hydrological cycle investigation. Better understanding of snow cover dynamics and the validation of these models suffer from the sparse observational record available and passive microwave satellite data appears as a very useful tool for such an objective. The data are derived from the daily Special Sensor Microwave / Imager (SSM/I) data from the DMSP satellite time series and also from the Northern Hemisphere Weekly Snow Cover and Ice Extent from the NSIDC in the EASE-Grid format. A threshold adapted for four vegetation density classes (derived from the AVHRR Canadian land cover 1km-resolution image) is applied to the normalized difference brightness temperature signal between 37GHz and 19GHz to extract snow cover. This satellite database was compared to a short CRCM run simulation driven by the NCEP atmospheric objective analysed for the period between August 1992 and June 1995 over Eastern Canada. The results show that the model underestimates snow cover, the snow onset tending to arrive later and the snow melting faster in spring compared to SSM/I. For the overall studied area, it appears that the CRCM is modeling snow cover with an error of 9.3% in term of number of days. Locally, this error can be as large as 30–40%. This paper shows the potential of satellite microwave data for the comprehensive spatial and temporal evaluation of model behavior.

Keywords: Passive microwave SSM/I, Snow cover, Snow water equivalent SWE, Canadian Regional Climate Model CRCM, Validation, Eastern Canada

INTRODUCTION

Understanding the physics of snow is essential to the comprehension of climate dynamics as well as for water resources management. Snow cover is directly related to winter air/soil temperature and precipitation and is one of the most complicated climatologic aspects to study. Thus, climate model simulations are very useful to predict some parameters such as snow cover. In this paper, we consider a new generation of high spatial resolution climate models, such as the Canadian Regional Climate Model (CRCM), developed by the Canadian Network for Regional Climate Model at the Université du Québec à Montréal (UQÀM). This type of model allows simulating the physical and thermodynamic aspects of the climate such as the snow water

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equivalent at the regional scale over a long period of time. The objective of this research is to validate the snow surface field simulated by this model. The fact that this regional model is nested by real atmospheric data (NCEP analyses in this case) and not by a General Circulation Model allows to analyze the outputs with real data over a specific period of time. However, the lack of snow data at high latitudes (Brown et al., 2003) is a real problem for such a validation experiment. For example, the distance between surface weather stations can reach 400 km in some parts of the Québec/Labrador territory (SMC, 2000) which makes essential the validation with other types of data. The AVHRR (Armstrong and Brodzik, 2002) and SSM/I (National Snow and Ice Data Centre, 1998) satellite data can be used to validate such models.

Snow cover can be extracted from daily passive microwave satellite measurements (Mätzler, 1987, Prigent et Aires., 2003) and presents many advantages in climatic studies for two major reasons. These data are independent from the atmosphere and solar conditions and are also taken twice daily which is a major advantage in the spatial and temporal analysis of snow cover variability. This is a major advantage compared to the weekly AVHRR snow cover database. The passive microwave database used in this research is derived from the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. In the first section, we briefly describe in a first section the CRCM used to simulate the dynamics of the snow cover extent over Eastern Canada from June 1992 to June 1995, and the second section presents the snow extraction method from passive microwave satellite data. The results and the analysis of the observed difference between model and satellite data are then presented and discussed.

The Canadian Regional Climate Model (CRCM)

The CRCM is a limited-area regional climate model developed at the Université du Québec à Montréal. A detailed description of this model can be found in Caya and Laprise (1999). This numerical formulation allows the model to use some larger time steps than with conventional Eulerian methods. The horizontal grid of the model is in a polar stereographic projection and the vertical resolution follows the Gal–Chen scaled-height terrain-following coordinates (Gal–Chen and Sommerville, 1975). The CRCM sub-grid scale physical parameterization uses the Canadian GCMii (General Circulation Model Version II; McFarlane et al. 1992) package, which was adapted to the CRCM itself. The model was run with the Bechtold–Kain–Fritsch (Bechtold et al. 2001) mesoscale convective scheme along with a large-scale condensation process for stratiform precipitation formation. The one-layer surface scheme consists of prognostic equations for liquid and frozen ground water contents, for surface soil temperature and for snow amount. The ground temperature is calculated using the force-restore method with a deep soil temperature defined as the mean value of surface temperature over the last 24-hour period (Giguère et al. 2000). Complete melting (or freezing) of the unique layer must be completed before the surface soil temperature can go above (or below) the 0°C value which will be discussed later in the discussion. If the temperature of the lowest atmospheric level is at the freezing point or below, then precipitation is assumed to fall in solid form (Frigon et al., 2002). To compare the CRCM with SSM/I, we used the snow water equivalent data (kg/m^2) output field computed on a 101 x 101 points. Figure 1 presents the entire simulation domain of the CRCM experiment along with the land cover types derived from AVHRR database (Cihlar and Beaubien, 1998). The regional domain covers a total 9 x 10^6 km^2 and it encompasses the province of Québec, the Maritime provinces (New Brunswick, Nova Scotia and Prince Edward Island), most of Ontario and the Island of Newfoundland, located on its southeastern edge. Results are analyzed on a 82 x 82 points grid, delimited by the smaller square on Figure 1 in order to consider only the CRCM's free domain.

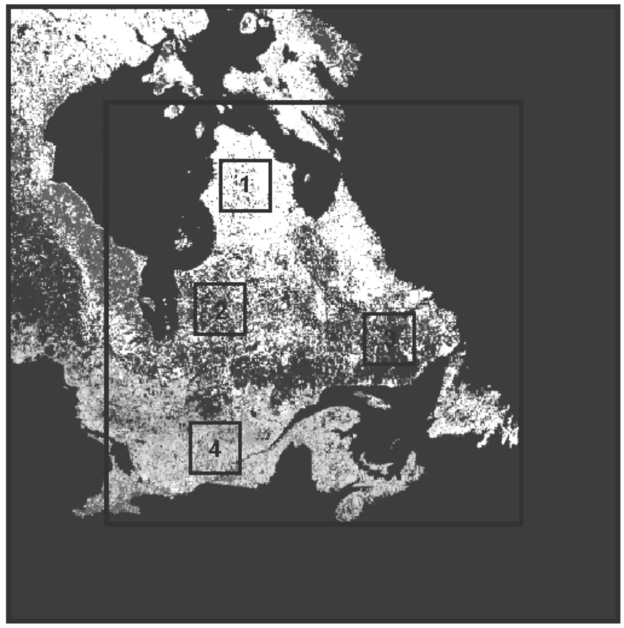


Figure 1: The studied area of the CRCM over Eastern Canada. The free domain 82 × 82 within the black square is considered in the model's validation. Comparisons between the SSM/I and CRCM data are made over 4 sub-areas (1-North, 2-East, 3-West, 4-South) of 75 625 km^2 each.

This CRCM simulation uses a 10-minute time step starting on the 1st March 1992 and ending on the 1st July 1995 on a 30-km grid point spacing and 18 vertical levels. The first three months, used to spin-up the model and allowing the different fields to adjust, were not retained for analysis. This period was chosen because of the availability and reliability of surface observational datasets. We verified that this period does not exhibit a particular trend for temperature and precipitation as compared to the climatic normals (Fillol et al., 2003). In this simulation, the model is driven by the atmospheric objective observational analyses from the National Center for Environmental Protection (NCEP) over a 9-point nesting zone. Therefore, only the free domain (82 × 82 pixels) was analysed for this study (Frigon et al. 2002). Throughout the simulation, the CRCM snow and ground temperature output fields were archived at a time step nearest to 16h local time for every grid point, in order to be approximately synchronous with NOAA satellite overpass time observations.

Snow cover extraction from passive microwave radiation

The Special Sensor Microwave/Imager (SSM/I) sensor is transported on the Defense Meteorological Satellite Program Satellites (DMSP F-8, DMSP F-10, DMSP F-11, and DMSP F-13). This sensor is the version that followed SMMR (Scanning Multichannel Microwave Radiometer) in 1987. The data are available from 1978 to now on the same EASE-Grid (Equal Area Scalable Earth) projection at a 25 km resolution as provided by the NSIDC, Boulder, Colorado. It contains 7 channels at 19.35, 22.235, 37.0 and 85.5 GHz, which are vertically and horizontally polarized except for 22.235 GHz, which is polarized only horizontally. This passive microwave system measures the brightness of the atmosphere and the surface at these frequencies (Grody and Basist, 1996). We will use the 19.35GHz (here in after desingnated as 19 GHz) data polarized vertically and horizontally as well as 37.0 GHz polarized vertically. For the frequency considered, the brightness temperature at polarization p (Tbp) is a function of surface emissivity (ε_p), surface temperature (Ts) and atmospheric functions as:

$$Tbp = (\varepsilon p\ Ts + (1 - \varepsilon p)\ Ta\downarrow)^{*} \tau + Ta\uparrow \qquad \textbf{[1]}$$

where Ta↓ and Ta↑ correspond to the atmosphere temperatures emitted downwelling and upwelling respectively, and τ is the transmittance of the atmosphere. To extract snow cover from passive microwave satellite data, we use a normalized difference of the brightness temperature signal between 37GHz and 19GHz which has been already proven as efficient to detect snow on the ground (Goodison and Walker., 1993):

$$
\begin{aligned}
Tb_1 - Tb_2 &= [(\varepsilon_1 Ts + (1-\varepsilon_1)\, Ta\downarrow_1)\, \tau_1 + Ta\uparrow_1] - [(\varepsilon_2 Ts + (1-\varepsilon_2) Ta\downarrow_2)\, \tau_2 + Ta\uparrow_2\,] \\
&= (\varepsilon_1\tau_1 - \varepsilon_2\tau_2)\, Ts + \Delta Ta\downarrow \; + \; (\varepsilon_2\tau_2\, Ta\downarrow_2 - \varepsilon_1\tau_1\, Ta\downarrow_1) + \Delta\, Ta\uparrow \qquad \textbf{[2]}
\end{aligned}
$$

With the presence of snow cover on the ground, the scattering effect at 37 GHz is more important than at 19 GHz (due to shorter wavelength at 37 GHz) so that the difference between the signal at two frequencies (37 GHz – 19 GHz) will be greater and negative with snow cover (Matzler, 1987). We normalize the difference at the horizontally polarized 19GHz to minimize the surface temperature effect such as:

$$\Delta Tb \approx (\, \Delta \varepsilon p \;\, T_s \, + b\,) \,/\, (\varepsilon p \;\, T_s \, + c\,) \qquad \textbf{[3]}$$

where b and c are atmospheric functions weighted by emissivities.

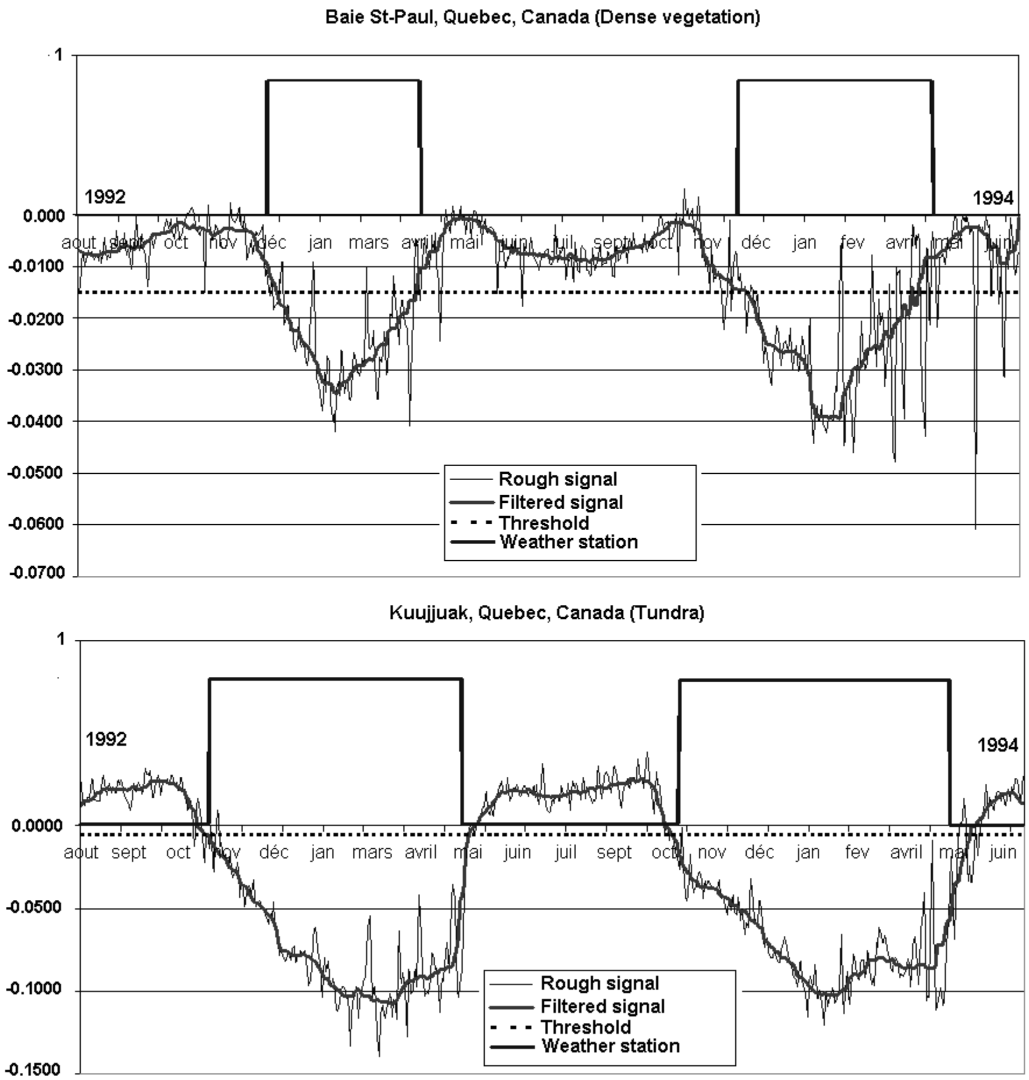
On these normalized images ΔTb = ((37 GHZ Vpol.–19 GHz Vpol.) / 19 GHz Hpol.), the emissivities of the surface at 37GHz and 19GHz are influenced by the presence of snow and thus we have to apply a threshold that will determine the presence of snow. However, a number of different perturbing factors such as snow metamorphism (Rosenfeld and al., 2000), melting snow (Pivot et al., 1998, Prigent et al., 2003), and ice crust formation (Mätzler, 1987, Rosenfeld et al., 2000) generates noise in the signal (see Figure 2). Errors, which can occur from the threshold application with noise peaks (Figure 2), can be reduced by filtering the signal. A 25-day running median filtering smoothed the signal enough without modifying the transitional period. Moreover, vegetation also attenuates the signal (i.e. reducing the signal) (Kurvonen and Hallikainen, 1997, DeSève, 1999) (Figure 2a presents the ΔTb for a pixel over dense forest area, which has lower values than a pixel over the tundra in Figure 2b). Thus, we must define a threshold for each vegetation type, which was determined by comparing the ΔTb data with meteorological data (snow cover). Each of the meteorological stations considered is located in a particular vegetation density derived from the 1-km resolution land cover database provided by the Canada Centre for Remote Sensing (Cihlar and Beaubien, 1998). The threshold was determined for each vegetation density to give the best similarity between both databases (SSM/I and meteorological) in terms of number of days with presence of snow. Table 1 gives the threshold values for each of the 16 weather station and Figure 3 shows the difference in the number of days with snow cover for each weather station between SSM/I snow cover results and meteorological data.

Table 1. Thresholds applied on the normalized difference of the brightness temperature used for each station considering the land cover type. Note that for meteorological data, we have considered only values > 5 cm of snow excepted for tundra data (0cm).

No station	Station	Coordinates	Veg. Density	SSM/I threshold
1	Baie St-Paul	47.25N 70.30W	Dense	-0,015
2	Brome	45.11N 72.34W	Dense	-0,015
3	Bécancour	46.20N 72.26W	Dense	-0,015
4	Duchesnay	46.52N 71.39W	Dense	-0,015
5	Causapscal	48.37N 67.23W	Dense	-0,015
6	La Pocatière	47.30N 70.30W	Dense	-0,015
7	Ormstown	45.12N 74.05W	Agricultral	-0,02
8	Iberville	45.33N 73.25W	Agricultral	-0,02
9	St-Hubert	45.50N 73.42W	Agricultral	-0,02
10	LG2-A	53.38N 77.42W	Non dense	-0,005
11	Chapais-2	49.47N 74.51W	Non dense	-0,005
12	Shefferville	54.48N 66.49W	Non dense	-0,005
13	LG4-A	53.54N 73.40W	Non dense	-0,005
14	Nain-A	56.33N 61.41W	Tundra	-0,005
15	Saglek	58.20N 62.35W	Tundra	-0,005
16	Kuujjuak	58.60N 68.25W	Tundra	-0,005
** derived from the Canadian 1-km Land Cover*				

Results show a mean residual positive difference of +12 days between meteorological and SSM/I data for the transitional periods considered and for the 16 meteorological stations selected. This means that this methodology slightly underestimates (–6% as compared to 200 days over the transition period) the number of days with snow cover during seasonal transitions (fall and spring). This error may be due to thin layers (about 5cm) which can not be seen at 19 and 37GHz (Rosenfeld et al., 2000). The residual error is significantly lower than the one derived from the NSIDC AVHRR weekly snow cover extent database. To illustrate it, we have compared the number of days or weeks covered with snow from SSM/I and from AVHRR compared to meteorological data for seasonal transitions (Table 2). For the 4 weather stations selected, the root mean square difference between meteorological data and SSM/I data is 2 weeks (13.98 days), significantly lower than for AVHRR (5.88 weeks).

(A)



(B)

Figure 2: Comparison for two winters (1992/93 and 1993/94) between the snow cover extracted from weather stations (Table 1), rough and filtered (median on 25 days) SSM/I signals (ΔTb, equation 3) and the threshold for (A) a dense vegetation region (Baie St-Paul) and (B) a tundra region (Kuujjuak). The threshold applied on the filtered signal is defined to fit the meteorological data.

Table 2. Comparison between SSM/I and meteorological data [number of days with snow cover and difference Δ % : (satellite – met. data) / number of days relative to the transition] and between AVHRR and meteorological data [number of weeks with snow cover and difference Δ %: (satellite – met. data) /number of weeks relative to the transition].

Weather stations	METEROLOGICAL DATA		DAILY SSMI DATA		WEEKLY AVHRR DATA	
	Fall 92-93	Fall 93-94	Fall 92-93	Fall 93-94	Fall 92-93	Fall 93-94
Baie St-Paul 47.25N 70.30W	40	61	24	43	2	3
Ormstown 45.12N 74.05W	14	44	18	40	1	1
LG4-A 53.54N 73.40W	95	119	88	105	5	7
Kuujjuak 58.60N 68.25W	84	105	97	115	5	8

Weather stations	METEROLOGICAL DATA		DAILY SSMI DATA		WEEKLY AVHRR DATA	
	Spring 1993	Spring 1994	Spring 1993	Spring 1994	Spring 1993	Spring 1994
Baie St-Paul 47.25N 70.30W	44	58	26	35	12	9
Ormstown 45.12N 74.05W	42	28	34	29	11	6
LG4-A 53.54N 73.40W	41	67	67	73	15	13
Kuujjuak 58.60N 68.25W	73	68	80	86	15	15

Fall: October 1st to January 31st
Spring: March 1st to June 30th

Results clearly show the advantage of the SSM/I data over AVHRR for a validation experiment. Taking into account the weakness of meteorological data (for example errors which could result from wind during the snowfall, from losses due to wet snow or losses due to evaporation, (Brown and Goodison, 1996), and considering that this data corresponds to punctual measurements, we estimate that the SSM/I data can be considered as reference for the CRCM validation. With the threshold application, we can extract snow cover from the SSM/I satellite data. For pixels that contain different land cover types, we apply a weighted threshold as a function of the fraction of each land cover type within the 25 x 25 km pixel, giving a different threshold for each pixel in the satellite image.

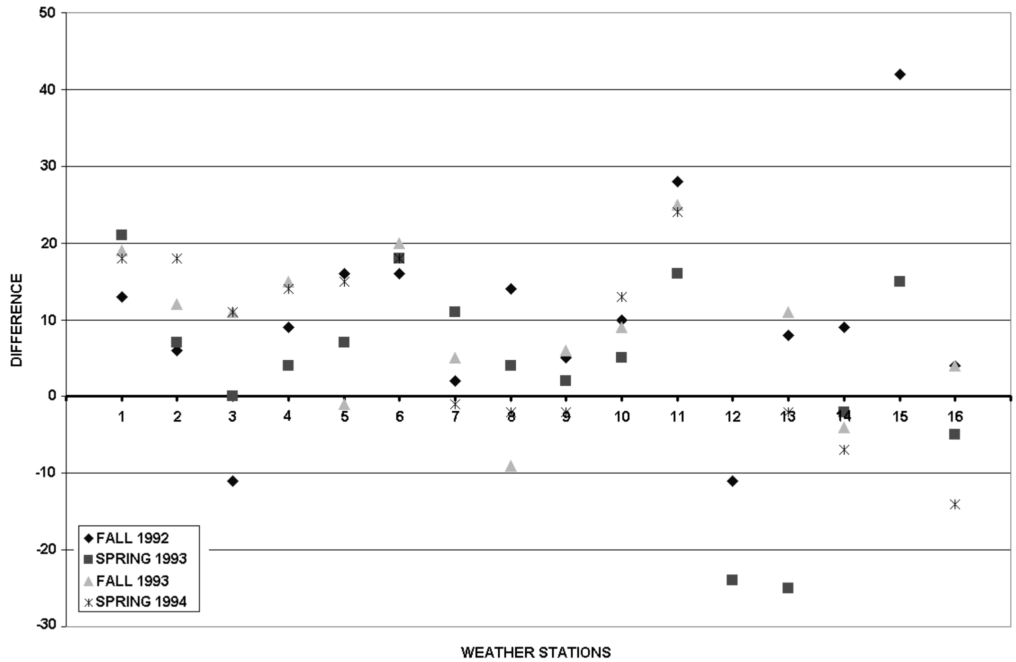


Figure 3: Difference in the number of days with snow cover for each weather station between meteorological data SSM/I snow cover results. The difference was considered for four seasonal transitions (Fall 1992, Spring 1993, Fall 1993 and Spring 1994). Meteorological stations are defined in Table 1. Fall corresponds to October–January period and spring to March–June period.

RESULTS

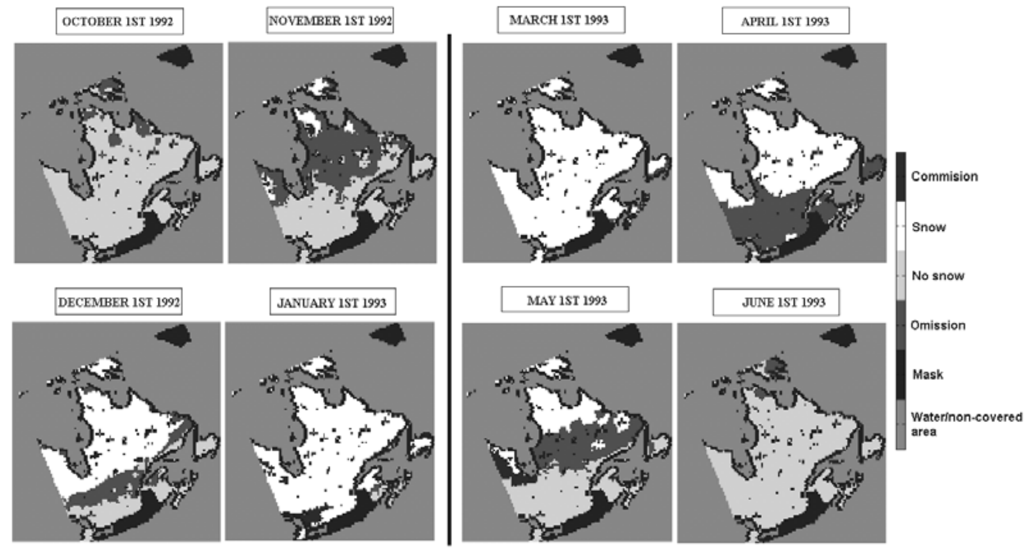
Spatial variation of the snow cover extent difference

Figure 4 shows the spatial behavior of the snow cover extent variation expressed by the omissions and commissions made by the CRCM considering the SSM/I satellite data as reference. We have an omission when the model generates no snow while SSM/I does, and we have a commission when the model shows snow while SSM/I does not. The coastal areas are masked to eliminate the effect of water on the signal. It appears that the model globally underestimates snow cover (large omission area). Figures 4a clearly shows that the CRCM snow is generated too late in fall, and that the snow melts too early in the spring. The average omission for the cumulated period is 100 days corresponding to 9.4% of the period considered (1064 days from August 1992 to June 1995), while the average commission is 10 days (1.9%). We analyze here the spatial variation of the difference between the model and the satellite data, in terms of snow cover extent for the 6 transition periods, and for the 4 subareas (defined in Figure 1) and for the entire studied area (Québec), by computing the mean values of ΔN:

$$\Delta N = \frac{\text{Pixel covered with snow (SSM/I)} - \text{Pixel covered with snow (CRCM)}}{\text{Total number of pixels considered in the area}}$$

Table 3 summarizes the ΔN values (mean error and root mean square error) showing that during the transition period, the model underestimates the snow cover extent by about 30–40 % for the subareas considered; but this corresponds only to 9 % relatively to the entire area. There are no significant differences between the years (except for 1995 : +15%, without particular reason) and neither between spring or fall.

(A)



(B)

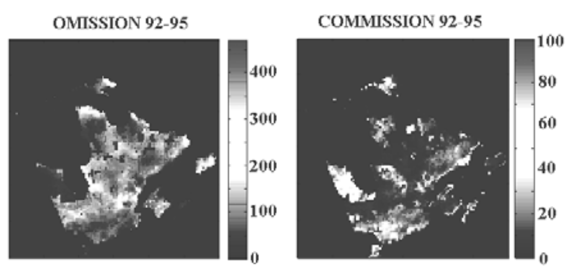


Figure 4: CRCM omissions and commissions of snow cover based on SSM/I satellite data as reference,(A) for the first day of October, November, December 1992 and January, and for March, April, May 1993 and (B) cumulated days for all the studied period (August 1992 to June 1995).

Table 3. Relative mean and root mean square (RMS) snow cover extent error (DN in % of snow cover extent) for the four sub-areas selected (75 625 km2 each) : North, South, East, West (see figure 1) and for the entire area (Quebec), for each seasonal transition.

	AUG-FEB 1992-1993		MARCH-JULY 1993		AUG-FEB 1993-1994	
	FALL transition		**SPRING transition**		**FALL transition**	
	Mean error	**Quad error**	**Mean error**	**Quad error**	**Mean error**	**Quad error**
NORTH	25,0	25,0	-8,3	12,0	15,8	17,1
SOUTH	-6,7	28,5	64,5	64,5	-5,5	23,9
EAST	64,6	68,3	24,6	33,2	35,5	36,2
WEST	21,6	30,5	47,9	48,0	8,9	14,5
QUÉBEC	***6,6***	***7,8***	***9,4***	***9,5***	***7,5***	***9,6***

	MARCH-JULY 1994		AUG-FEB 1994-1995		MARCH-JULY 1995	
	SPRING transition		**FALL transition**		**SPRING transition**	
	Mean error	**Quad error**	**Mean error**	**Quad error**	**Mean error**	**Quad error**
NORTH	-15,8	18,2	10,37	10,55	26,31	26,31
SOUTH	35,7	47,3	10,64	33,88	32,61	34,35
EAST	26,1	37,1	15,75	28,98	8,77	37,68
WEST	37,3	41,9	22,67	22,67	63,71	63,72
QUÉBEC	***8,3***	***9,6***	***3,16***	***4,59***	***14,1***	***14,57***

Temporal variation of the snow cover extent difference

We analyzed the temporal variation of the ΔN difference which shows exactly when the underestimation occurs for the 4 subareas considered and for Québec (see Figure 1). Figure 5 illustrates these variations for the North and the South subareas. In summary, it appears that the CRCM snowfall occurs from 24 days (1992, South) to 52 days (1992, North) too late in the fall (depending on the year and the region), and that the snow disappears from 23 days (1992, North) to 52 days (1995, West), (not shown), too early in the spring (Langlois, 2003).

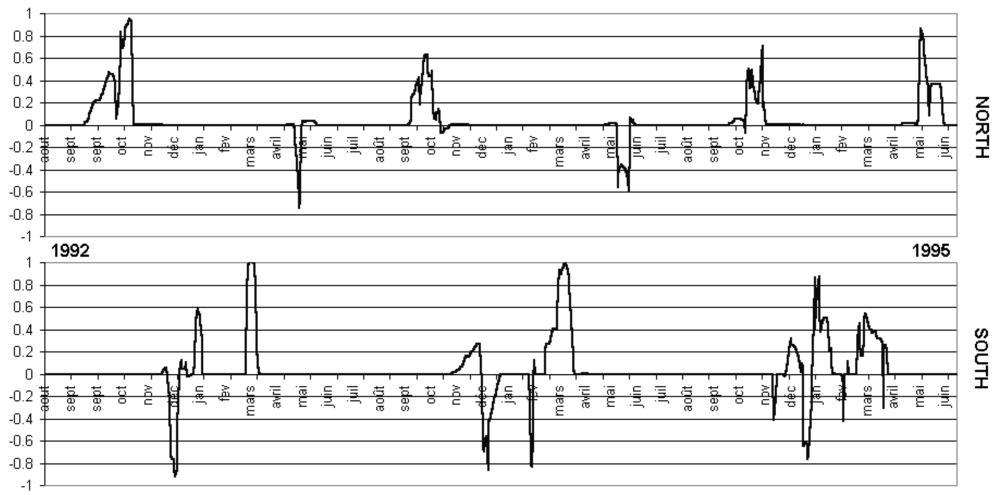


*Figure 5: Daily evolution of the amplitude of the error (*ΔN*) on the Y axis and time on the X axis from August 1992 to June 1995. We have omission by the CRCM with ΔN from 0 to 1 and commission from 0 to –1. The errors occur mostly during seasonal transitions (spring and fall).*

Spatio-temporal variation of the snow cover extent difference

We have characterized the combined spatial and temporal variation of the difference between the model and the satellite data by averaging the error (SSM/I – CRCM) over each latitude for each day of the simulation (Figure 6). One can see the variation of the error, which begins in September in the North and occurs progressively later when going toward the South. The reverse behavior appears in the spring, with a significant error in March in the South, shifting in time when moving toward the North. In both cases, the error, which is mostly underestimation of snow cover, follows the propagation of the snow line.

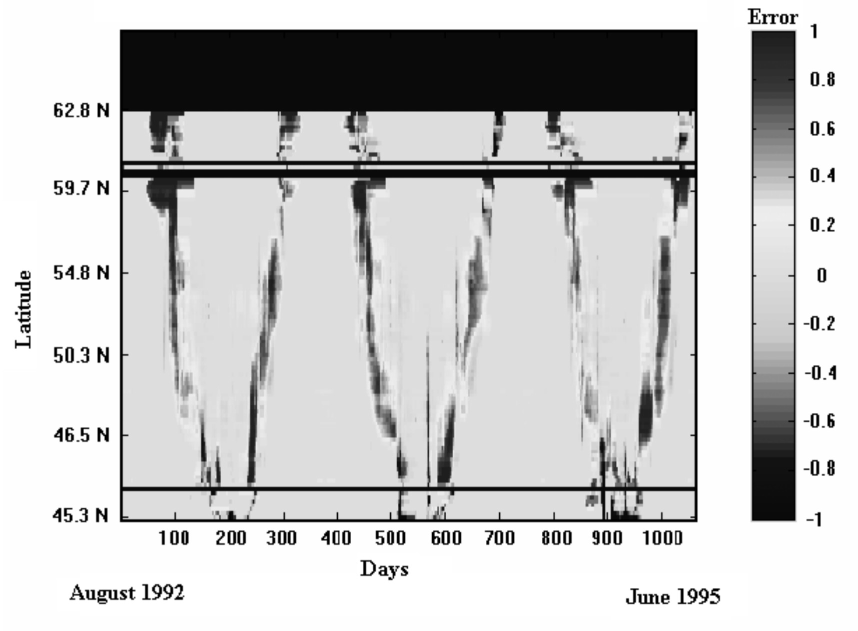


Figure 6: Evolution of the normalized error (SSM/I – CRCM) through latitude and time between August 1992 and June 1995 (% of pixel with snow cover).

Discussion

The observed differences between the CRCM snow cover simulation and the SSM/I product, corresponding to a systematic underestimation of the model's snow cover extent during the transition period (fall and spring), can be related either to a deficit in CRCM winter precipitation or to thermal behavior of its single-layer surface scheme. Figure 7 gives the difference between the model precipitation and the meteorological data; it does not show a systematic underestimation of precipitation during the winter, even though a mean overestimation of about 1.5 mm/day is observed during the summer. The latter effect may be due to a too strong turnover in the water cycle (precipitation/evaporation) during a too warm summer (Fillol et al., 2001). Thus, for the snow analysis, the surface energy budget must be considered as discussed by Frigon et al. (2002). With its surface scheme of the CRCM during the fall, the ground layer must freeze throughout before cooling its surface below 0°C, which brings the CRCM to be usually too warm near the ground, as can be seen in Figure 8. From September to November, the model minimum and maximum mean screen temperatures are higher than gridded meteorological data by about +4 °C and +1 °C respectively, which reduces the snow cover extent. During spring, the inverse behavior is observed, melting the snow too early. The CRCM surface scheme first uses the available energy to melt the snow cover before heating the ground, producing a rapid snow cover melt with maximum screen temperatures maintained colder than observed under 0°C (March, April), though minimum screen temperatures stay warmer than observed by about + 1°C in March and +2°C in April (Figure 8). Also, this increase in temperature tends to increase evaporation, creating an overflow of cloud cover that enhances a greenhouse effect and so on. This leads to a difference ($T_{min\_CRCM} - T_{min\_meteo}$) genrally higher than ($T_{max\_CRCM} - T_{max\_meteo}$) (Figure 8).

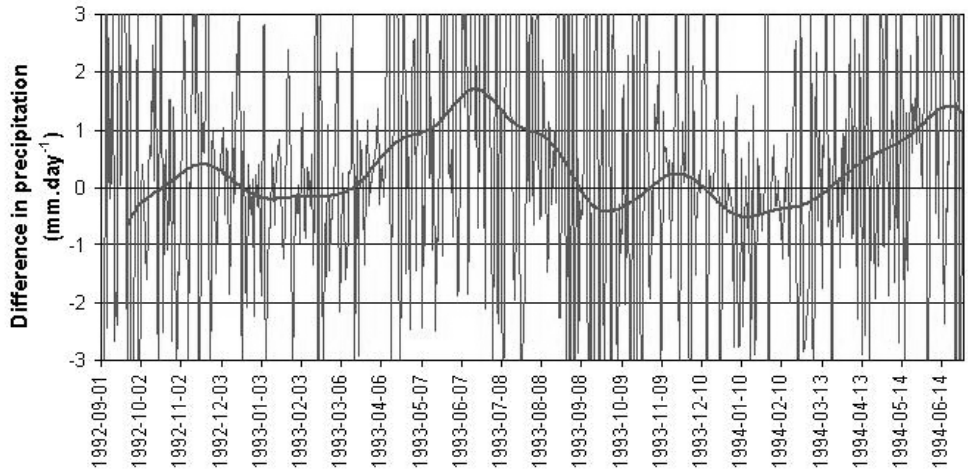


Figure 7: Mean difference in daily precipitation (mm/day), computed pixel by pixel between CRCM and gridded meteorological data (Fillol, 2003) over the entire area (see Figure 1) from September 1992 to June 1994. The thick line represents a 21-day running mean.

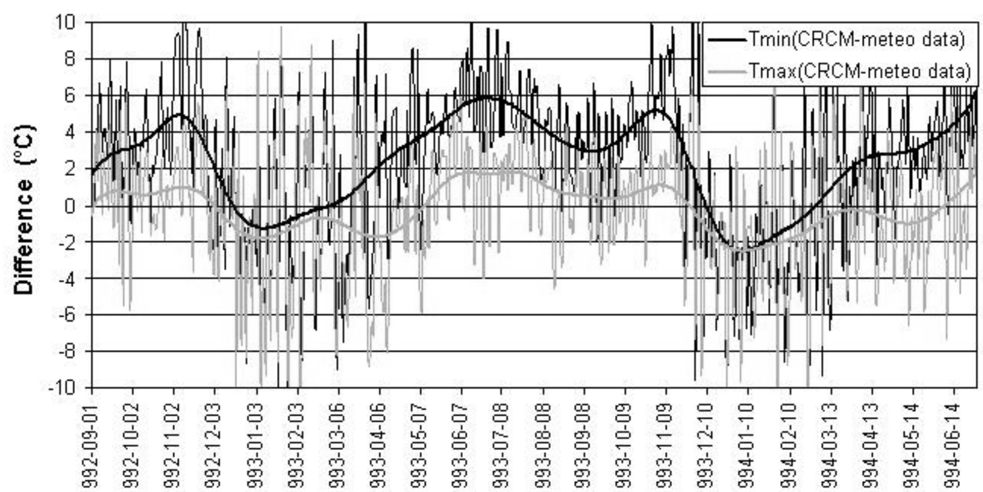


Figure 8: Mean difference in daily minimum (Tmin) and maximum (Tmax) screen temperature (°C), computed pixel by pixel between CRCM and gridded meteorological data (Fillol, 2003), over the entire area (see Figure 1) from September 1992 to June 1994. The thick line represents a 21-day running mean.

CONCLUSION

Snow cover extent data based on the daily Easy-Grid SSM/I images are analyzed to validate the temporal and spatial variation of this parameter simulated by the CRCM (Canadian Regional Climate Model) driven by NCEP atmospheric analyses during 3 years (Fall 1992 to Spring 1995) over Eastern Canada. We first show that snow cover can be derived from the normalized brightness temperature gradient (Tb ((37V–19V)/19H with a threshold weighted by the vegetation density derived from the 1 × 1km AVHRR data corresponding to each 25 × 25 km SSM/I pixel. Across a North (tundra) to South (closed forest) transect, this simple approach gives a slight overestimation of 6% in terms of number of days with snow compared to meteorological stations during the transition (fall and spring) periods. It is shown that the CRCM underestimates the snow cover extent by generating snow too late in the fall and melting the snow too early in the spring. These differences can be explained by the thermal behavior of the CRCM single-layer surface scheme. This research shows the feasibility of using remotely sensed snow cover variation for evaluating the performance of a regional climate model, in order to account for the sparse meteorological observations which cannot be interpolated over very large distances, as in the Northern high latitudes. Microwave data, with comparable spatial spatial resolution (25 km for SSM/I and 30 km for CRCM) and time scale, without significant atmospheric perturbations (as when using AVHRR data for example), appears to be an effective means for characterizing the time and space variability of snow cover. The improvement generated by such an evaluation experiment, even if satellite-derived snow cover likely contains small errors, contributes to improve model evaluation.

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