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Simulation of Snow Water Equivalent (SWE) Using Thermodynamic Snow Models in Québec, Canada

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ABSTRACT

Snow cover plays a key role in the climate system by influencing the transfer of energy and mass between the soil and the atmosphere. In particular, snow water equivalent (SWE) is of primary importance for climatological and hydrological processes and is a good indicator of climate variability and change. Efforts to quantify SWE over land from spaceborne passive microwave measurements have been conducted since the 1980s, but a more suitable method has yet to be developed for hemispheric-scale studies. Tools such as snow thermodynamic models allow for a better understanding of the snow cover and can potentially significantly improve existing snow products at the regional scale.

In this study, the use of three snow models [SNOWPACK, CROCUS, and Snow Thermal Model (SNTHERM)] driven by local and reanalysis meteorological data for the simulation of SWE is investigated temporally through three winter seasons and spatially over intensively sampled sites across northern Québec. Results show that the SWE simulations are in agreement with ground measurements through three complete winter seasons (2004/05, 2005/06, and 2007/08) in southern Québec, with higher error for 2007/08. The correlation coefficients between measured and predicted SWE values ranged between 0.72 and 0.99 for the three models and three seasons evaluated in southern Québec. In subarctic regions, predicted SWE driven with the North American Regional Reanalysis (NARR) data fall within the range of measured regional variability. NARR data allow snow models to be used regionally, and this paper represents a first step for the regionalization of thermodynamic multilayered snow models driven by reanalysis data for improved global SWE evolution retrievals.

1. Introduction

Snow is an important element of the cryosphere, as it controls both conductive and radiative exchanges across the interface between land surface and 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 they are of primary importance for hydrological and climatological processes (e.g., Rango 1980; Schultz and Barrett 1989; Albert et al. 1993), especially in the Northern Hemisphere, where 40% of the land surface is influenced by seasonal snow. The strongest signs of warming climate have been observed over the recent few decades, and a detailed examination of snow properties is now required given its effect on surface energy balance (Lemke et al. 2007). Specifically, spatial and temporal variations of snow state variables (SWE in particular; refer to appendix for definition of acronyms) are significant, yet complicated indicators of a changing climate because they integrate temperature, precipitation, blowing snow, among others (e.g., Pomeroy et al. 2004). Snow cover also plays an important role in how other cryospheric elements (such as permafrost) respond to climate change (Zhang 2005). One of the main challenges remains, that of determining the spatial and temporal variability in SWE due to the scarcity of existing ground data, the logistical constraints of fieldwork

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in snow-covered regions, and uncertainties in existing satellite retrieval algorithms (e.g., Guo et al. 2003; Derksen et al. 2005a; Skaugen 2007).

The use of regional reanalysis data as inputs to drive the snow models can address the spatial limitations of driving the models with station data because the spatial coverage of meteorological towers per unit area in Canada is sparse, approximately 25 stations per 100 000 km^2 (Metcalfe and Goodison 1993). Spatially continuous snow model output coupled with microwave emission models, in turn, can contribute to improved understanding of regional SWE variability. Several snow multilayered models have been developed for various applications, such as avalanche simulations and mass balance studies (e.g., Brun et al. 1992; Lehning et al. 2002). Other studies have already produced operational SWE simulations based on meteorological and satellite observations (e.g., Liang et al. 1994; Rutter et al. 2008). Among them, the VIC macroscale hydrologic model (Cherkauer and Lettenmaier 1999) and the NOHRSC snow model (Rutter et al. 2008) do produce SWE simulations, however, their application to northern latitudes has yet to be validated. Extensive studies on the comparison of different snow models available were conducted in the SnowMIP and SnowMIP2 (Essery and Yang 2001; Rutter et al. 2009) using ground measurements from France, Canada, Switzerland, and the United States (Etchevers et al. 2004). Results from this work are available through multiple research papers (available online at http://www.cnrm.meteo.fr/present/publis.htm). Other regional work using hydrological models found that several models can provide accurate SWE simulations, but uncertainties remain from differences between modeled/measured precipitation (e.g., Slater et al. 2006) and temperatures, especially in mountainous and northern regions (e.g., Szeto et al. 2008). Models such as SNOWPACK and CROCUS were initially developed for avalanche forecasting, but they also produce accurate mass balance information (such as SWE). Results showed that the models mentioned earlier did provide reasonable simulations of snow water equivalent for the various study regions (Etchevers et al. 2004).

Although satellite microwave brightness temperatures exhibit strong sensitivity to the scattering properties of terrestrial snow, SWE retrieval solutions based solely on empirical relationships between microwave brightness temperature and SWE remain elusive. However, data assimilation approaches that can include a physical snowpack model coupled with a radiative transfer scheme are one possible solution. With this goal in mind, this study evaluates the feasibility of driving a physical snowpack model with reanalysis data. For that purpose, highly detailed snow models must be used, because they produce detailed snowpack information far beyond bulk properties such as density, depth, and SWE. Radiometric models require stratigraphy and grain size information that these physical models produce. In the future, uncertainty in model-simulated SWE can be reduced by incorporating passive microwave observations.

Thus, the purpose of this paper is not to compare model performance in SWE prediction but rather to evaluate the performance of driving thermodynamic multilayered snow models with reanalysis data with regards to SWE predictions. We specifically chose to assess the potential of improvement of such models because they interactively integrate metamorphism (snow grain size evolution), a key component of passive microwave emission that is the long-term goal of this study. The specific objectives are to (i) compare NARR (Mesinger et al. 2006) with ground-based meteorological measurements to use the reanalysis data as input data to three snow models (SNOWPACK, CROCUS, and SNTHERM); (ii) validate the SWE simulations from the three models (driven by both NARR and in situ meteorological observations) with field measurements for three different winter seasons (2004/05, 2005/06, and 2007/08); and (iii) apply the methods from (ii) to three intensively ground sampled sites spanning the boreal forest (50°N) to taïga and open tundra (60°N) in northern Québec, Canada, to determine spatial performance characteristics of the reanalysis-driven models.

2. Data and methods

a. *SIRENE station measurements (temporal analysis)*

The SIRENE from CARTEL is located on the Université de Sherbrooke campus (45.37°N, 71.92°W) and is representative of regional land cover characteristics (Fig. 1). The site is open (approximately 75 m × 75 m) and is surrounded by mixed deciduous and coniferous forest, protecting the sampling area from strong winds.

The station is fully equipped with a meteorological tower and various snow measurement devices (all at 2 m height except for an anemometer at 3 m). Basic meteorological data were collected every 30 s for the duration of the experiment. Incoming solar radiation was measured with a LI-COR pyranometer LI200SZ with a precision of ±5% at an operating temperature range between −40° and +65°C. Incoming longwave radiation was measured using a Kipp & Zonen CG1 pyrgeometer with an accuracy of ±10% and a temperature range between −40° and +80°C. Wind speed, gust, and direction were available through an R. M. Young 05103-10 anemometer with a published accuracy of ± 0.3 m s^{-1}. A Campbell Scientific CS500 probe measured air temperature and RH at an accuracy of ±3%, and surface

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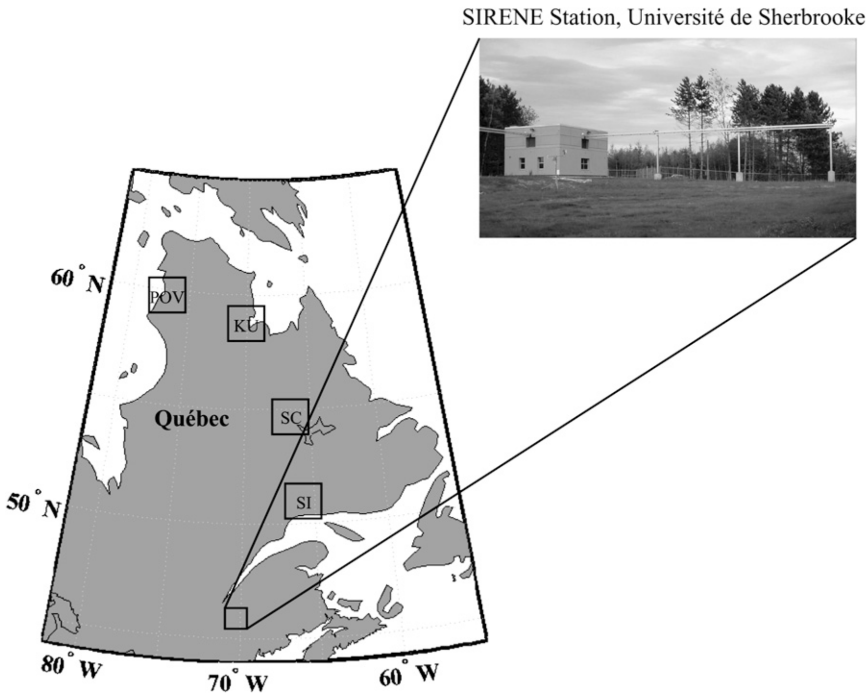

FIG. 1. Map of study regions.

temperatures were measured using an Everest 4000.3 infrared sensor at 8–14 μm ($\pm$0.5°C). Lastly, precipitation was measured using a Campbell Scientific CS705 tipping-bucket rain gauge with a funnel extension for snowfall measurements. There is no information on the precipitation phase because the measurements are the equivalent precipitated amount of water. One can only make assumptions on the phase given air temperature measured at the station. During 2007/08, a cosmic particles counter (NRC) was installed at the station, allowing direct hourly measurements of SWE. The system was developed by EDF in collaboration with the CNRS and Météo-France. The NRC counts the number of particles—emitted mainly by the sun—that interact directly with water (independent from phase). The ratio between incident count (reference over snow surface) and absorbed (sensor at snow–soil interface) allows the calculation of the amount of water (i.e., SWE).

Three winter seasons were analyzed in this paper. Snowpits were conducted at SIRENE station on a weekly basis from 7 January to 21 March 2005, from 9 January to 6 March 2006, and from 11 December to 8 April 2007/08. Each year, an undisturbed area was dedicated to snow sampling (approximately 10 m $\times$ 40 m). The snowpits were excavated facing south to avoid any direct illumination of the snow wall, and layered profiles of SWE were conducted. Snow samples were extracted at 3-cm intervals from the surface to the snow–soil interface with a 200 cm^3 density cutter. Each sample was weighed using a Pesola light series scale to obtain density. SWE was then calculated for each layer as a function of density and thickness and was expressed in mm:

$$\mathrm{SWE} = \frac{(\text{thickness} \times \rho_s)}{\rho_w} = \frac{\mathrm{m} \times \dfrac{\mathrm{kg}}{\mathrm{m}^3}}{\dfrac{\mathrm{kg}}{\mathrm{m}^3}} \Rightarrow \mathrm{mm}, \quad (1)$$

where ρ_s and ρ_w are the density of snow and water, respectively.

b. North American Regional Reanalysis

As mentioned in the introduction, all three snow models require meteorological input information to produce snow cover information. Meteorological data from ground-based towers usually provide good accuracy; however, they often present difficulties with regional studies given their sparse distribution, especially in subpolar and polar regions. Regional reanalysis data such as NARR from the NCEP EMC represent a good alternative (available online at http://www.emc.ncep.noaa.gov/mmb/rreanl/). The horizontal resolution is 0.3° (approximately 32 km), and the temporal resolution is 8 times daily (every 3 h). The description of input parameters available from NARR and required by each of the three snow models is given in Table 1.

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TABLE 1. Input meteorological parameters required by SNOWPACK, CROCUS, and SNTHERM. Asterisk identifies an optional parameter.

Description	Units	SIRENE	SNOWPACK	CROCUS	SNTHERM
Date		X	X	X	X
Air temperature	°C or K	X	X	X	X
RH	0–1 or %	X	X	X	X
Wind speed	m s^{-1}	X	X	X	X
Wind direction	Degrees	X	X*	—	—
SWd (direct)	W m^{-2}	X	X	X	X
SWd (diffuse)	W m^{-2}	—	—	X	—
SWu	W m^{-2}	—	X*	—	X*
LWd/cloudiness	W m^{-2}	X	X	X	X
	0–1		X	X	X
Tsurf	°C or K	X	X*	—	—
Snow–soil temperature	°C or K	—	X*		X
Precipitation	kg m^{-2} or mm	X	X	X	X
Phase of precipitation	—	—	—	X	X

c. Snow models

All three models (SNOWPACK, CROCUS, and SNTHERM) are multilayered thermodynamic models (one-dimensional). The temporal evolution of simulated snow properties are driven by surface meteorological conditions. Therefore, hourly meteorological input data are required and highlighted in Table 1.

1) SNOWPACK

The model does not require reflected shortwave and emitted longwave radiation to estimate SWE values, but it does require basic meteorological information, such as air temperature, relative humidity, wind speed and precipitations, and incoming shortwave and longwave radiations. SNOWPACK solves the partial differential equations governing snow mass and energy fluxes using a Lagrangian finite element implementation (Bartelt and Lehning 2002; Lehning et al. 2002). Thermophysical processes of interest in SWE studies such as phase change, water vapor transport (i.e., metamorphism), and loss (runoff, evaporation, and sublimation) are included. The details on the internal models will not be given here because further details can be found elsewhere (Lehning et al. 2002; Bartelt and Lehning 2002). Both snow surface and soil interface temperatures are only required if the user chooses Dirichlet boundary conditions. When used with a partial differential equation, the Dirichlet boundary conditions specify the values a solution needs to take on the boundary of the domain. In our application, this condition is used when surface temperatures are below 0°C. Otherwise, the model adjusts automatically to Neumann conditions where values for the derivative of a solution on the boundary of the domain are specified. The main difference between Dirichlet and Neumann conditions is that the former specifies the value of the function on a surface, whereas the Neumann conditions specify the normal derivative of the function on a surface.

Model settings are specified given the input data availability. Two main types of output data can be visualized through a user-friendly software (SN GUI), namely, scalar and vector data (Spreitzhofer et al. 2004). The scalar data are related to individual layers of the snowpack, such as SWE, whereas vector data are attributed to layered parameters, such as the simulated vertical profiles of snow density, temperature, grain size, and shape, among others. The amount of layers varies given predicted snow depth. The transition between solid and liquid precipitation occurs at +1.2°C.

2) CROCUS

The CROCUS model was developed by CEN of Météo-France and was extensively validated in Alpine conditions. The model was initially developed to simulate alpine seasonal snow and to assist in avalanche risk assessment; however, since then it has been used in various snow applications, such as polar snow over ice sheets (Dang et al. 1997; Genthon et al. 2007). The input data are similar to SNOWPACK, with the exception of diffuse shortwave radiation and precipitation phase requirements (Table 1). CROCUS has been described in detail by Brun et al. (1989, 1992), therefore only a brief description of the model is given here.

CROCUS computes the surface energy balance, including turbulent and latent heat exchanges, as well as reflected shortwave radiation, surface, and internal mass and energy fluxes. The model can compute up to 50 layers, parallel to the slope, through which mass and energy exchanges are accounted for given physical processes (e.g., absorption of solar radiation, heat diffusion using an effective thermal conductivity depending on

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TABLE 2. Study sites from the IPY project.

Site	Lat (N), Lon (W)	Dates	Number of measurements	Area (km)	Land cover
SI	50.32°, −66.28°	18–27 Feb 2008	54	8 × 14	Dense boreal
SC	54.86°, −66.70°	19–25 Feb 2008	214	8 × 14	Taïga
KU	58.13°, −68.53°	18–26 Feb 2008	155	5 × 8	Taïga and tundra
POV	59.83°, −76.42°	21–29 Feb 2008	7062	8 × 10	Tundra

snow density, surface fluxes exchange, dry and wet snow metamorphism, mechanical snow settlement, internal melting, percolation of liquid water, and refreezing). Each snow layer is characterized by its thickness, temperature, density, liquid water content, snow crystal characteristics, and age. Phase changes are also taken into account, and snow densification and metamorphism are parameterized, affecting mass–energy transfers and changing surface albedo. CROCUS has been calibrated at the measurement site Col de Porte in the French Alps (Brun et al. 1992), where meteorological conditions are very different from SIRENE (e.g., precipitation and air temperature). To improve the ground flux, the CROCUS–ISBA model has been tested at the SIRENE site, only for 2004/05. The model is constituted by coupling two one-dimensional models: the land surface ISBA model (Noilhan and Planton 1989; Boone et al. 2000) and the snow model CROCUS. Soil properties are adapted to the site but not the vegetation (site considered without vegetation). The mass and energy exchanges between soil and snow are explicitly simulated. Although wind erosion is a component of the snow cover surface mass balance and metamorphism, it is not accounted for in CROCUS. The phase of precipitations depends on the air temperature: below +2°C precipitation is considered as dry snow, above which all precipitation is liquid (there is no wet snowfall). The output data of interest includes layered profiles of snow geophysical properties.

3) SNTHERM

The SNTHERM model is a one-dimensional mass and energy balance model that predicts temperature profiles within snow and frozen soil. The model uses meteorological observations of air temperature, relative humidity, wind speed, precipitation and, if available, measured values of solar and incoming infrared radiation (Table 1). SNTHERM was first introduced to predict surface temperature (Jordan 1991). The model subdivides snow and soil layers into infinite control volumes so that a numerical solution can be obtained. As for SNOWPACK and CROCUS, SNTHERM takes into account the energy balance to compute net radiation. The model is initialized using snow temperature profiles and/or soil and requires the following characteristics for each layer: number of nodes, material code (snow, clay, sand, among others), quartz content, and roughness length. The user supplies the initial nodal volume values: temperature, elemental control volume thickness, bulk water density, and snow grain diameter. The output is the predicted surface and air temperatures. Optional output includes predicted temperature at the snow–ground interface. A more detailed output is available at hourly intervals at each node: temperature, phase, bulk liquid content, density, thickness, grain size, and thickness. The threshold temperature for phase of precipitation is +0.15°C.

d. Regional snow sampling (spatial analysis)

Snow measurements acquired during the Canadian International Polar Year (IPY) project Variability and Change in the Canadian Cryosphere were analyzed to compare measured SWE with predicted values from the three models. Four teams were located across a south–north transect over Québec in SI, SC, KU, and POV, respectively, where high-resolution sampling occurred throughout a field program conducted between 18 and 29 February 2008 (Fig. 1; Table 2).

The SWE data were collected over large areas covering a wide range of snow conditions, terrain, and land cover. The total area covered and the number of SWE measurements are highlighted in Table 2.

3. Results and discussion

a. NARR and SIRENE comparison

As mentioned in section 2, NARR data provide a good alternative to ground-based meteorological towers for input to snow models when spatially continuous output is required. Prior to using NARR data to drive the snow models, a comparison of the reanalysis with our ground-based measurements from SIRENE was performed. The following meteorological information (all required in SNOWPACK, CROCUS, and SNTHERM) was compared for the three winter seasons: daily air temperature (at 2 m, °C), relative humidity (2 m, %), wind speed (10 m, m s^{-1}), incoming shortwave radiation (surface, W m^{-2}), incoming longwave radiation (surface, W m^{-2}), and 3-h accumulated precipitation [m $(3h)^{-1}$ or kg m $(2–3h)^{-1}$].

Figure 2 displays an example of daily meteorological observations from both the SIRENE station and NARR

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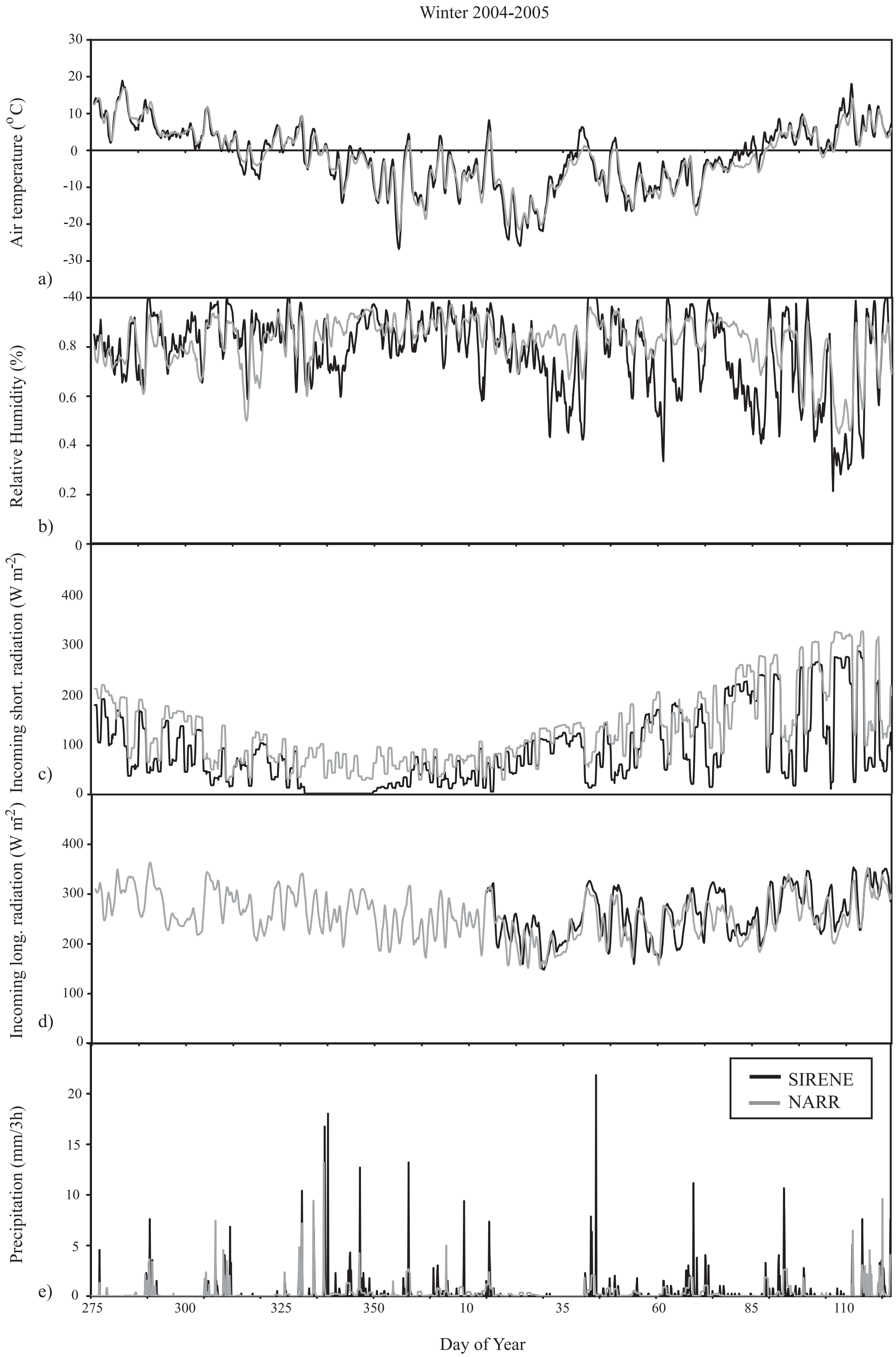

FIG. 2. Temporal evolution of (a) air temperature, (b) RH, (c) incoming shortwave radiation, (d) incoming longwave radiation, and (e) precipitation measured at the SIRENE station and from NARR data during the 2004/05 winter season.

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TABLE 3. Comparison between NARR and SIRENE meteorological data (correlation coefficient and root-mean-square error in mm). Asterisk means $p < 0.001$.

	T_{air}		RH		SWd		LWd		Precipitation	
Season	R^*	RMSE (°C)	R^*	RMSE (%)	R^*	RMSE (W m^{-2})	R^*	RMSE (W m^{-2})	R^*	RMSE (mm)
2004/05	0.95	2.85	0.66	0.17	0.9	95.13	0.6	47.95	0.35	1.81
2005/06	0.93	3.1	0.74	0.14	0.94	64.41	0.82	30.26	0.42	1.6
2007/08	0.96	2.56	0.76	0.14	0.92	93.68	0.86	29.23	0.41	1.51

data for the period 1 October 2004 to 30 April 2005, and Table 3 highlights the general statistics of the comparison for the three seasons analyzed.

Overall, the meteorological variables measured at the station and NARR agree quite well through each season. Strong correlation is found especially for air temperature, and incident shortwave and longwave radiation; weaker correlations are found for precipitation (Table 3). No significant bias was observed other than issues with the 2005/06 precipitation data, which will be discussed later in the paper. Overall, the results suggest that the NARR data are of sufficient quality to allow a user to ‘‘patch'' missing temporal information from meteorological towers as input to the snow models or to drive the models strictly with NARR data. (Further evaluation of NARR data can be found online at http://www.cdc.noaa.gov/data/reanalysis/.)

It was shown in Table 3 that precipitation values from both NARR and the SIRENE station do not agree as strongly as the other meteorological input parameters. Although the precipitation events are usually coincident, they are often of a different magnitude. We looked at accumulated precipitation to know the total amount of precipitation occurring at the station, as well as the timing and magnitude differences that could potentially explain discrepancies between measured and predicted SWE values (Fig. 3). In 2004/05, accumulated precipitation was in close agreement throughout the season analyzed. No significant differences were observed, and accumulated values were 531 and 500 mm for SIRENE and

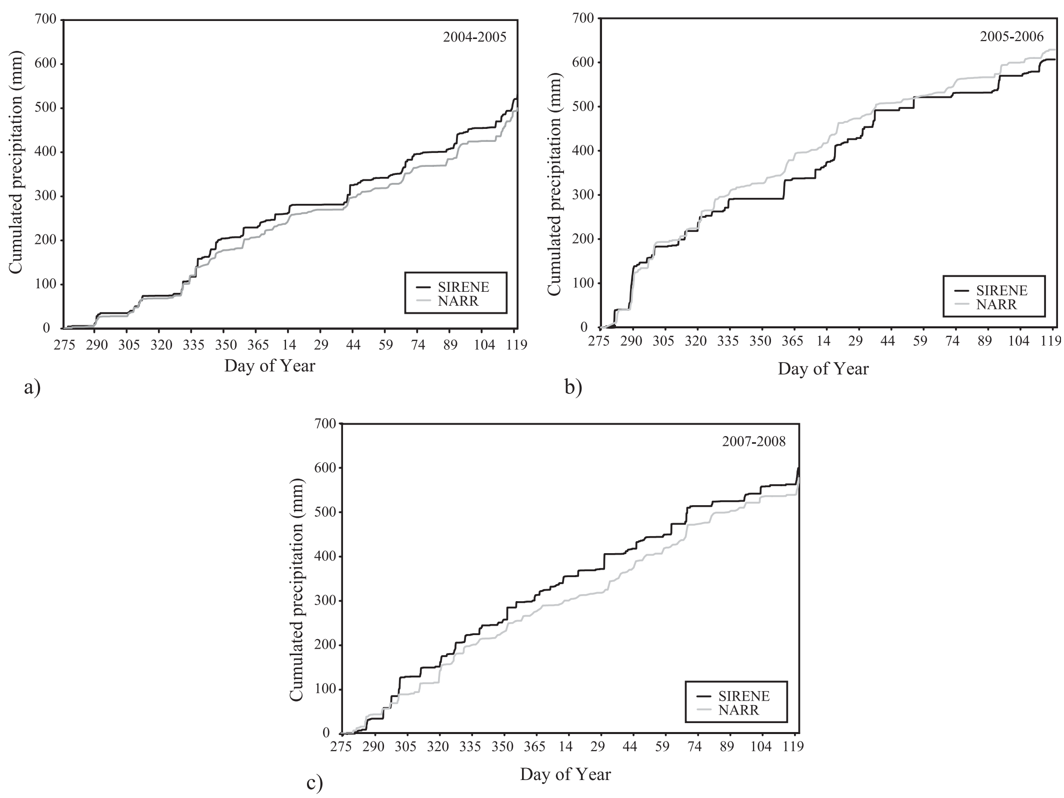

FIG. 3. Temporal evolution of accumulated precipitation measured at the SIRENE station and from NARR during the (a) 2004/05, (b) 2005/06, and (c) 2007/08 winters.

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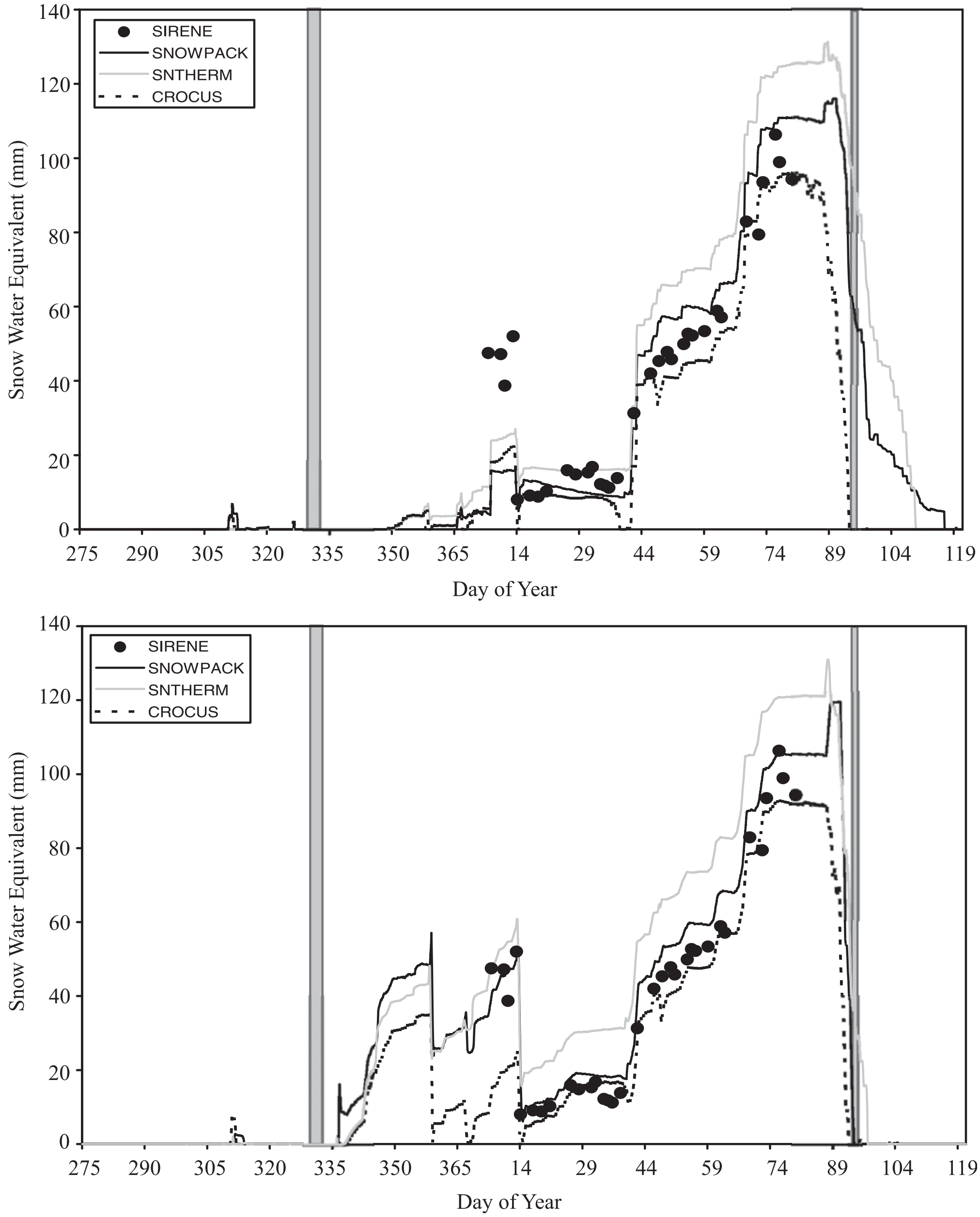

FIG. 4. SWE simulations from SNOWPACK, CROCUS, and SNTHERM using (a) SIRENE and (b) NARR meteorological information for the 2004/05 winter. Gray bars represent the duration between the first snow accumulation and melting observations from the Sherbrooke-A and Lennoxville Environment Canada weather stations.

NARR, respectively (Fig. 3a). In 2005/06, the evolution of accumulated precipitation was similar, with an average offset of the order of 40 mm starting from day 335, when SIRENE most likely missed a precipitation event (Fig. 3b). No significant differences were observed in 2007/08, when both NARR and the measurements remained in close agreement throughout the season. The largest differences were observed in the middle of the winter between days 1 and 60, approximately, with a measured difference of about 60 mm (Fig. 3c), explaining the smaller RMSE value from Table 3.

b. Snow water equivalent modeling

1) WINTER SEASON 2004/05

The SIRENE and NARR meteorological datasets were used to drive the three snow models. Figure 4a displays predicted SWE results using SIRENE meteorological

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TABLE 4. Comparison between measured and modeled SWE values (mm) for SNOWPACK, CROCUS, CROCUS–ISBA, and SNTHERM during the 2004/05, 2005/06, and 2007/08 winter seasons using SIRENE meteorological data.

	SWE (mm) 2004/05				Thickness (cm) 2005/06			SWE (mm) 2007/08*		
	SNOWPACK	CROCUS	CROCUS–ISBA	SNTHERM	SNOWPACK	CROCUS	SNTHERM	SNOWPACK	CROCUS	SNTHERM
Min	−43.31	−41.9	−41.5	−36.1	−25	−27	−3.4	−16.6	−83.9	−49.6
Max	+23.8	+10	+19.6	+38.2	+22.1	+12.1	+109.3	+254.7	+44.9	+160.8
Avg	−0.1	−7.9	−3.9	+9	+0.4	−3.1	+45.8	+71.2	−12.5	+32.6
R	0.93	0.95	0.94	0.93	0.09	0.14	0.31	0.78	0.97	0.82
RMSE	14.5	12.5	12.7	18.3	10.4	9	57.6	96.2	22.9	55.9

* Calculated from NRC measurements.

information from all three snow models for the 2004/05 winter season. The length of the observed accumulation or melt period (i.e., thickness of the gray band) represents the duration between the first observations of accumulation (until the ground is consistently covered with snow) and melting (until the ground is consistently snow free), observed at the Sherbrooke-A and Lennoxville Environment Canada weather stations, both located approximately 10 km from the station. It is clear that all three models do estimate SWE reasonably well, given the usual warm conditions typical of what is found in the midlatitudes, except for larger differences observed early in the season. Melting was observed in mid-January, and all three models did adjust to lower SWE values onward until day 38. After that point, snow accumulation increased with measured SWE values, reaching a maximum of 106 mm on day 76, which corresponds to an average rate of +2.4 mm day^{-1}. Throughout this period, all three models showed strong agreement between measured and predicted SWE values (Table 4). However, it appears that both SNOWPACK and SNTHERM are not melting the snow cover rapidly enough in spring with respect to the ''0'' snow depth values recorded in Sherbrooke-A. Only CROCUS matches measured 0 on day 93 (measured 0 on day 95 for Sherbrooke-A), whereas SNOWPACK and SNTHERM are not ''snow free'' until days 116 and 109, respectively.

Using NARR meteorological data, accurate results are also obtained, with all three models predicting higher SWE values early in the season (Fig. 4b). Stronger correlations are found between measured and modeled values for all three models (Table 5). Both SNOWPACK and CROCUS agreed very well to the melting period between days 12 and 38, with an average overestimation of approximately 6–10 mm. The main improvement obtained using NARR data is that both SNOWPACK and SNTHERM now agree with the measured values of 0 SWE. All three models completely melt the snow cover within a few days of the observed day 95 (day 92 for CROCUS, day 93 for SNOWPACK, and day 97 for SNTHERM).

For 2004/05, CROCUS was coupled with ISBA to investigate the influence of the ground flux on SWE simulations. Results showed that simulations were also very good when using SIRENE meteorological data (correlation coefficient *R* of 0.94); however, SWE values were generally overestimated using NARR data (Tables 4, 5). The overestimation ranged between +20 and +30 mm (average of +27.6 mm) throughout the season, whereas the average difference without the ISBA coupling was approximately −5 mm using NARR data. For this particular season, it appears that the simulations' results using NARR data were better using only CROCUS without ISBA (Table 5).

2) WINTER SEASON 2005/06

In 2005/06, no density measurements were available for the comparison of SWE measurements with the model simulations. Hence, we used snow depth data from the Sherbrooke-A meteorological station (Environment Canada), which was compared to depth simulations by the three snow models, as depicted in Figs. 5a,b.

TABLE 5. Same as Table 4, but using NARR meteorological data.

	SWE (mm) 2004/05				Thickness (cm) 2005/06			SWE (mm) 2007/08*		
	SNOWPACK	CROCUS	CROCUS–ISBA	SNTHERM	SNOWPACK	CROCUS	SNTHERM	SNOWPACK	CROCUS	SNTHERM
Min	−7.6	−34	−2.5	+1.1	−12	−12	−12	−61.7	−146.5	−101.1
Max	+19.9	+8.6	+48	+37.4	+14.9	+13.2	+16.9	+55	+0.2	+39.2
Avg	+5.6	−5.4	+27.6	+18.1	+2.3	+1.5	+2.3	+5.4	−36.6	−4
R	0.99	0.95	0.95	0.98	0.86	0.84	0.85	0.97	0.86	0.93
RMSE	7.4	10.8	29.7	19.3	5.6	4.5	5.2	15.5	46.2	23.7

* Calculated from NRC measurements.

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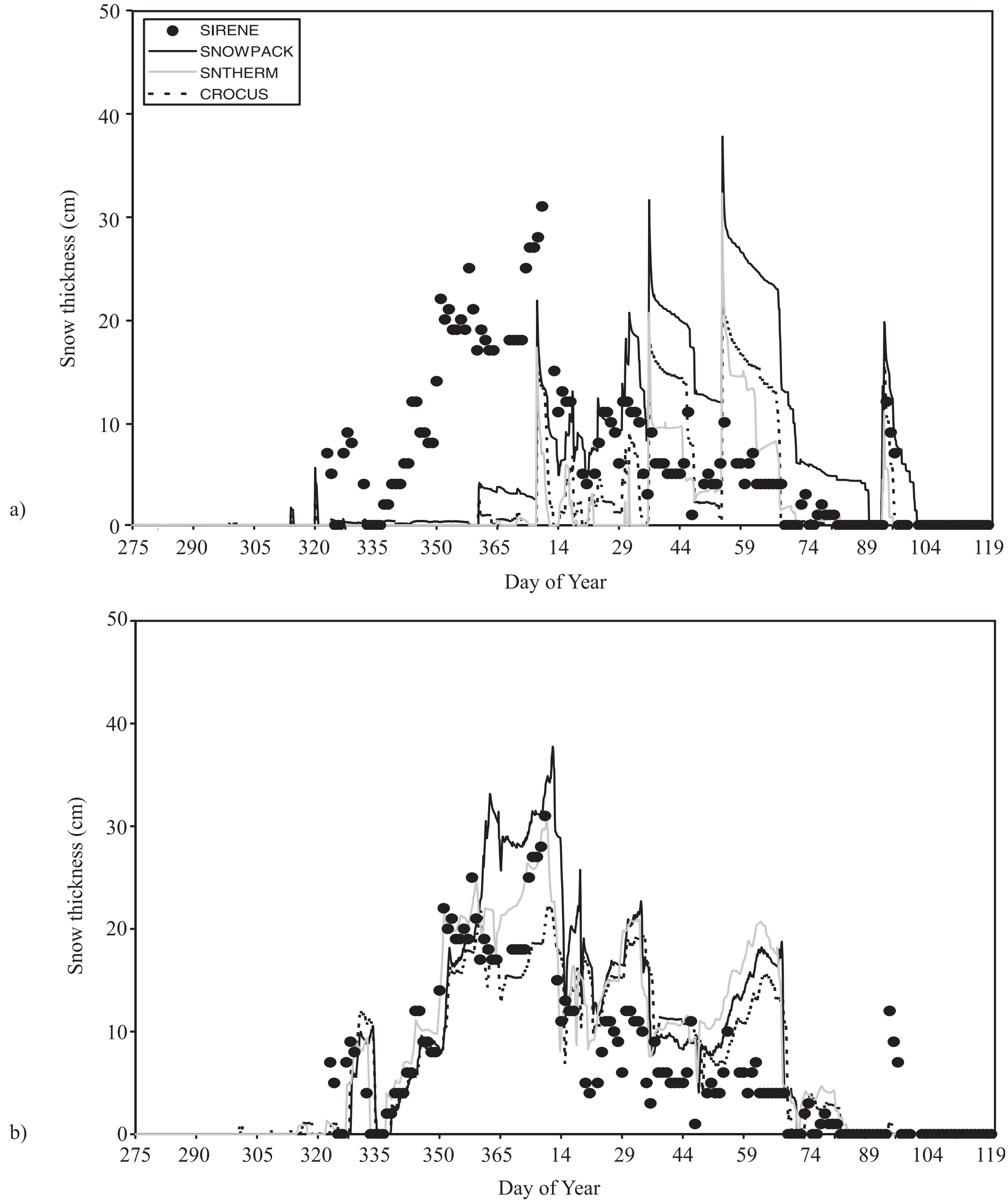

FIG. 5. Snow thickness simulations from SNOWPACK, CROCUS, and SNTHERM using (a) SIRENE and (b) NARR meteorological information for the 2005/06 winter.

Considering Sherbrooke-A snow depth data to be representative, it becomes obvious that using SIRENE data did not provide accurate thickness simulations (Table 4); however, results show good agreement between the models and ground data using NARR data (Table 5), where the RMSE was 5.6, 4.5, and 5.2 cm for SNOWPACK, CROCUS, and SNTHERM, respectively. However, it is clear that problems occurred with SIRENE (Fig. 5a) data given the large underestimation early in the season until day 10, when all three models predicted no snow, whereas the Sherbrooke-A station accumulated slightly more than 30 cm.

Looking back at the meteorological data from SIRENE, it appears that the problem occurred with the precipitation data because the simulations using NARR data provided more accurate snow depth (Fig. 5b). Although the correlation found in Table 3 between NARR and SIRENE precipitation values for 2005/06 is

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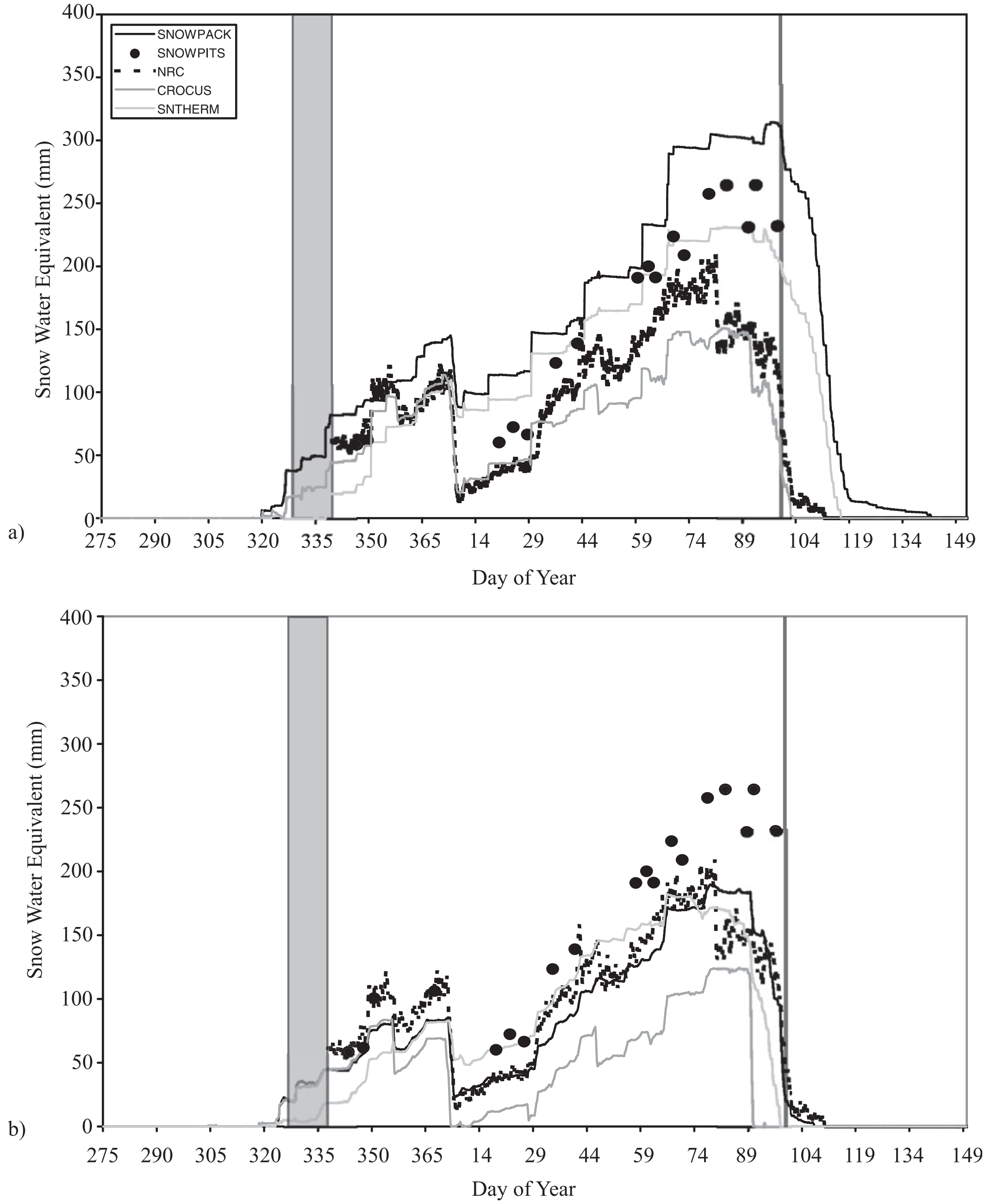

FIG. 6. Same as Fig. 4, but for the 2007/08 winter.

comparable to 2004/05, large differences were measured between SIRENE and NARR precipitation, especially between days 330 and 30, when snow first starts to accumulate, explaining the large gaps observed on Fig. 5a. Precisely, there is a period between days 330 and 360 when SIRENE measured no precipitation and NARR accumulated more than 46 mm. Given the averaged air temperature during this period (−6.2°C), precipitations were most likely solid (i.e., underestimation in depth and SWE).

3) WINTER SEASON 2007/08

In 2007/08, accurate SWE simulations were observed using SIRENE data as input to the snow models (Fig. 6a; Table 4). All three models predicted SWE quite accurately from the first days of accumulation observed at Lennoxville (gray band) until a melting period measured around day 10. SWE decreased from 121 mm on day 5 to 13 mm on day 10, corresponding to a melting

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rate of -22 mm day^{-1}. SNOWPACK and SNTHERM did respond to the melting, but at a weaker magnitude than observed with the NRC, whereas CROCUS captured the melt rate accurately when compared to the NRC measurements. Minimum values were observed on day 10 at 88, 21, and 80 mm for SNOWPACK, CROCUS, and SNTHERM, respectively. Afterward, SNOWPACK did overestimate SWE compared to both NRC and snowpit measurements, whereas SNTHERM remained within the range of snowpit SWE values. SWE values from CROCUS were slightly underestimated for a period between days 45 and 90. The first day of observed 0 snow at Lennoxville station was day 98 (agreeing with CROCUS); however, at SIRENE station, the NRC suggested day 113, in agreement with SNTHERM (Fig. 6a).

Using NARR reanalysis data, SWE simulations were accurate throughout the winter period, especially when using SNOWPACK and SNTHERM compared to NRC measurements (Fig. 6b; Table 5). The difference observed between snowpits and NRC SWE values is strictly because of the proximity of the site's fence near the sampling area, which preferentially accumulated snow as the season progressed (with higher SWE values than NRC, which was away from any local disturbances). Both SNOWPACK and SNTHERM did agree quite well with the melting period mentioned earlier, of which SNOWPACK followed the NRC values and SNTHERM agreed better with the snowpit measurements. CROCUS did underestimate SWE during the melting period and could not adjust to increasing SWE as measured by the NRC until the end of the season. From day 50 onward, SNOWPACK and SNTHERM followed NRC values, and melted the snow cover completely on days 110, 92, and 100 for SNOWPACK, CROCUS, and SNTHERM, respectively (Fig. 6b).

c. Vertical profile comparison

From the results shown earlier, the simulated SWE for 2004/05 and 2007/08 are statistically significant in comparison to observations with R values ranging between 0.72 and 0.95 using SIRENE data and 0.92–0.99 with NARR data. We looked at the detailed vertical profiles of density from the models (driven by NARR) to see how well they correspond to snowpit values. The profiles from all three models were normalized to a thickness scale between 0 and 1 to facilitate the comparison given the small differences observed in simulated snow thickness. We present the comparison on days 76 of 2005 (15 March) and 70 (10 March) of 2008, where a snowpit was conducted and SWE values were maximum prior to melt, of particular relevance for numerous hydrological processes.

On day 76 of 2005, both SNOWPACK and CROCUS agreed relatively well with the measured snow density, whereas SNTHERM overestimated for this particular date (Fig. 7a). The modeled density profiles from SNOWPACK and CROCUS agreed closely with the observed profiles. SNOWPACK increased density from 98 to 322 kg m^{-3}, whereas CROCUS varied from 240 to 450 kg m^{-3}, with a noticeable peak of 486 kg m^{-3} at 30 cm. In general, CROCUS was closer to measured values, which increased from 200 to 390 kg m^{-3}. The profile given by SNTHERM overestimated snow density at all layers. The overestimation was in the order of 100 kg m^{-3}, along with overestimation in thickness caused high SWE values compared to the two other models, as depicted on Fig. 4b.

On day 70 of 2008, more measured density values were available to compare with the predicted model results (Fig. 7b). All three models underestimated density between depths of 1 and 0.55. The strongest underestimation comes from CROCUS, which averages density at 200 compared to 299 kg m^{-3} for snowpit measurements. For that particular depth range, SNOWPACK and SNTHERM did better with averages of 213 and 260 kg m^{-3}, respectively. For the depth range 0.55–0, CROCUS matches well with measured data along with both SNOWPACK and SNTHERM. We highlighted the presence of an ice layer that was observed during the sampling. The ice layer comes from a rain event that occurred earlier in the season, most likely late in January. It is obvious that the models do not predict such high-density layers that can also result in slight overall underestimation of SWE. Overall, the underestimation of density values is translated to the lower-predicted SWE in Fig. 6b; however, we showed that the agreement was better with the NRC SWE measurements. Unfortunately, no snowpits were conducted near the NRC (to avoid disturbance, hence no comparison can be made).

d. Regional application

A comparison of meteorological station measurements with NARR data near Sherbrooke has shown that regional reanalysis can be used in snow models to predict SWE. Validation of the method was conducted at the SIRENE station, and it predicted values agreed quite well with field measurements (both from snowpits and NRC). Hence, we applied the same methodology to field measurements made across Québec during International Polar Year–supported activities during February 2008 (see section 2; Table 2). Intensive SWE sampling was conducted in four different ecological regions to account for various vegetation and snow types.

The areas sampled varied between 40 and 112 km^2, where spatial variability is more representative of the NARR pixel size than the SIRENE station. Results show very high spatial variability in SWE, with average

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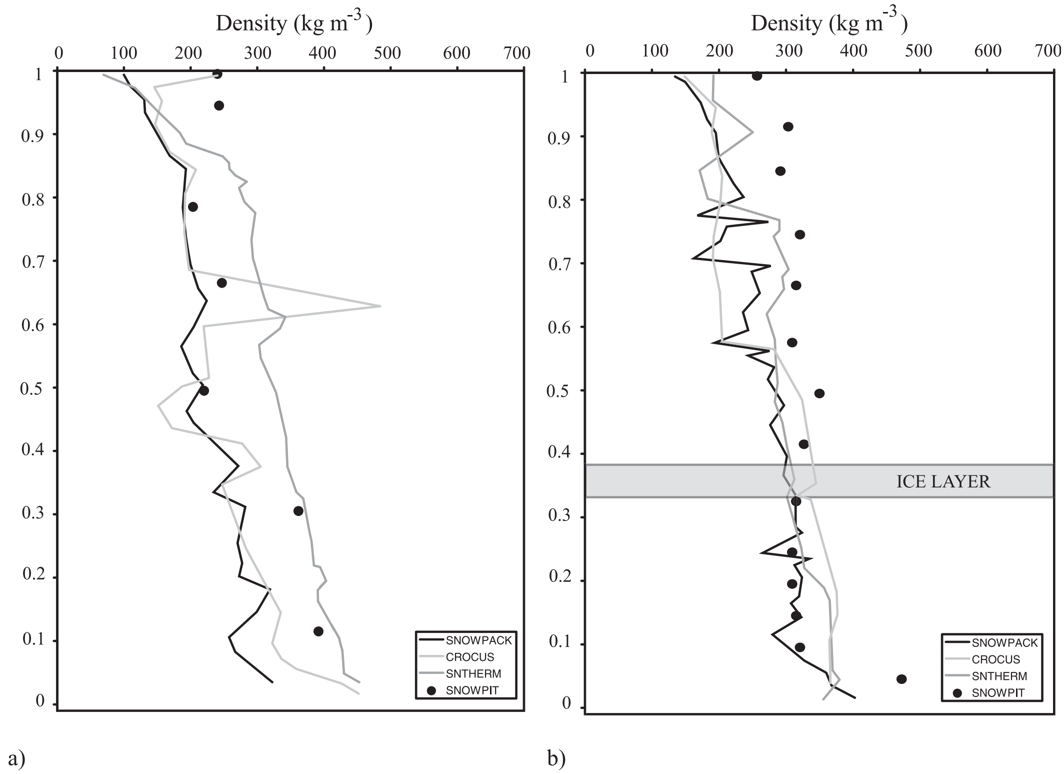

FIG. 7. Modeled and measured vertical profile comparison of density for (a) day 76 of 2005 and (b) day 70 of 2008.

values of 393 mm ± 130 mm (33%) for the coastal station SI (Fig. 8a), 210 mm ± 62 mm (30%) for SC (Fig. 8b), 127 mm ± 60 mm (47%) for KU (Fig. 8c), and 121 mm ± 84 mm (69%) for POV (Fig. 8d). These ranges are consistent with vegetation controls on snow depth variability in forested regions and topographic controls on snow depth variability in boreal and tundra regions (Derksen et al. 2005a, 2009). However, their effect is not linear with latitude, because great variations exist in measured stem volume and forest fraction. We measured stem volumes consistently below 100 m^3 m^{-2} and forest fraction below 30% north of 53°N, where values were close to 400 m^3 m^{-2} and 100% at 50°N (data not shown). Nonetheless, all three models predicted SWE within one standard deviation of measured ground data (except for Sept-Îles), with values close to the average for Schefferville, Kuujjuaq, and Puvirnituq. Predicted SWE values in Sept-Îles are underestimated overall. We looked at local precipitation data from the Environment Canada meteorological station at the Sept-Îles airport to determine if this is a matter of depth/density underestimation from the model or from precipitation underestimation from NARR. Accumulated precipitation suggests that NARR underestimated local precipitation quite significantly; however, issues with local gauge measurements are frequent and errors can be significant (Yang et al. 1999). Furthermore, because of its recent release, the strengths and weaknesses of NARR are largely undocumented. Although NARR provides much improved representation of precipitations when compared to other reanalysis products (Bukovsky and Karoly 2007), Mesinger et al. (2006) identified some of the known weaknesses, such as precipitation inaccuracies over Canada. Some discontinuities along the United States–Canada border appear in the NARR datasets, such as in the precipitation field (Luo et al. 2007). These can be attributed to the discontinuity across the border in the spatial density of rain gauge observations that were available to NCEP to construct the gridded analysis that was assimilated. The accumulated precipitation values were 753 mm for the meteorological data located at the airport, whereas NARR gave 639 mm—a deficit of 114 mm. Furthermore, this difference should be larger in reality because two months were flagged as missing precipitation data (December 2007 and March 2008). Hence, it is fair to say that the large difference in Fig. 8a is attributed to missing precipitation from NARR, given the reasonable results from our other three IPY sites (Figs. 8b–d). The reason for such underestimation from NARR at Sept-Îles, a coastal site, is still undetermined and would require further investigation by comparing precipitation datasets for previous years to see if the

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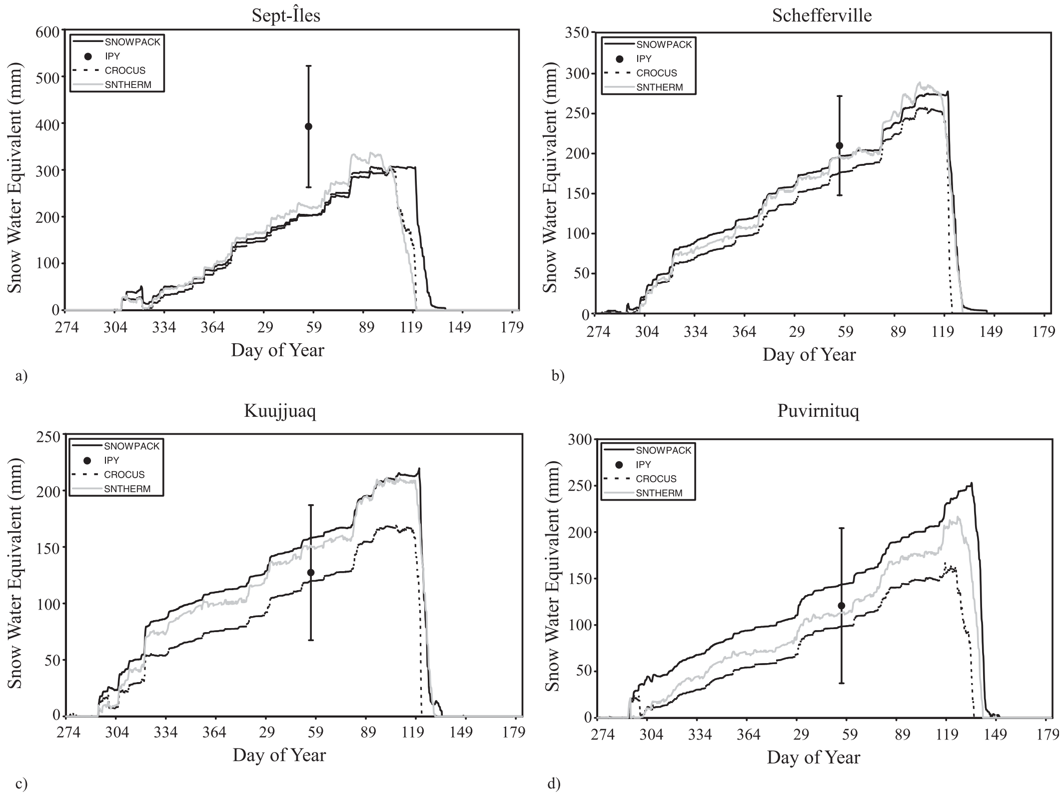

FIG. 8. Comparison between predicted and measured SWE values at (a) Sept-Îles, (b) Schefferville, (c) Kuujjuaq, and (d) Puvirnituq using SNOWPACK during the IPY project.

problem is recurrent. We looked at values from adjacent NARR pixels near Sept-Îles and the offsets were similar.

4. Conclusions

a. SIRENE versus NARR meteorological information

This analysis has illustrated that NARR data agree closely with meteorological tower measurements in Sherbrooke, Québec, Canada. Typical information required in snow models—such as air temperature, relative humidity, and radiative fluxes—were highly correlated between these two datasets through three consecutive winter seasons. Correlation coefficients ranged between 0.6 and 0.95 for those parameters. Larger differences were measured with regard to precipitations where their magnitude differed in some of the accumulation events (higher values from NARR). This could be explained through the usual uncertainties in precipitation gauge, where measurement errors increase significantly with increasing wind speed (e.g., Goodison 1978, 1981; Yang et al. 1999), as well as the difficulties in predicting precipitation through existing forecast systems, as shown at Sept-Île site for the 2007/08 winter. However, for general mass balance work, such as SWE studies, the results are quite satisfying, as the accumulated precipitations for both SIRENE and NARR are within 17% for 2004/05 and 4% for 2007/08.

b. SNOWPACK versus CROCUS versus SNTHERM for SWE simulation

It was shown that all three snow models delivered higher accuracy in SWE simulation when using NARR reanalysis data as input to the model simulations. Generally, in 2004/05 and 2007/08, both SNOWPACK and SNTHERM improved SWE simulations using NARR data, whereas CROCUS performance remained stable using either SIRENE or NARR meteorological data. As for 2005/06, snow depth was well predicted using NARR data, whereas significant underestimation occurred early in the season using SIRENE data. As mentioned in the introduction, the objective was not to conclude on the best model to be used but rather to investigate their respective utility for SWE retrieval using reanalysis data. The initial settings are different for each model,

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and thus one can perform better in different environments using the basic data highlighted in Table 1. Thus, given results presented in this paper, it is fair to conclude that all three models do provide accurate SWE simulation using NARR data (RMSE ranging between 9 and 46 mm), making the coupling possible at wider scale where meteorological tower information is not available.

Using NARR data, we also predicted SWE in subarctic regions, where ground meteorological data is very scarce to nonexistent in some cases (RMSE between simulated and measured SWE ranging between 5 and 49 mm). Figure 8 showed that the three snow models performed reasonably well in three regions where the predicted value was close to the average ground measurement. To the best of our knowledge, this represents the first validation of these models in those regions, and it provides very promising results toward developing regional or global SWE estimates by driving snow models with atmospheric reanalysis datasets.

c. *Future work*

Then, it is envisaged to couple the snow model with passive microwave remote sensing to adjust the observed bias in simulations when the snow model is driven by inaccurate meteorological data (mainly bias in precipitation). Extensive work estimating snow thickness or SWE using passive microwave radiometry from satellite remote sensing has been conducted since the 1980s (e.g., Cavalieri and Comiso 2000). Many of these studies have examined the relationship between SWE and passive microwave brightness temperature (e.g., Chang et al. 1982, 1987; Kunzi et al. 1982; Comiso et al. 1989; Walker and Goodison 1993; Tait 1998; Pulliainen and Hallikainen 2001; Walker and Silis 2002; Derksen et al. 2005b; Pardé et al. 2007; Durand et al. 2008) but large uncertainties still remain. The comparison with ground measurements still represents the biggest challenge, given the observed spatial variability of SWE at the scale of satellite measurements (more than 10 km × 10 km).

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APPENDIX

Acronyms and Expansions

CARTEL	Centre d'Applications et de Recherches en Télédétection
CEN	Centre d'Étude de la Neige
CNRS	Centre National de la Recherche Scientifique
CROCUS	
EDF	Électricité de France
EMC	Environmental Modeling Center
IPY	International Polar Year
ISBA	Interactions between Soil, Biosphere, and Atmosphere
KU	Kuujjuaq
LWd	Downwelling longwave radiation
NARR	North American Regional Reanalysis
NCEP	National Centers for Environmental Prediction
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRC	Nivomètre à Rayons Cosmiques
POV	Puvirnituq
RH	relative humidity
SC	Schefferville
SI	Sept-Îles
SIRENE	Site Interdisciplinaire de Recherche en Environnement Extérieur
SnowMIP	Snow Model Intercomparison Project
SnowMIP2	Snow Model Intercomparison Project, phase 2
SNOWPACK	
SNTHERM	Snow Thermal Model
SWd	Downwelling shortwave radiation
SWE	Snow water equivalent
SWu	Upwelling shortwave radiation
Tsurf	Surface temperature
VIC	Variable Infiltration Capacity

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