Comparison of Model, Snow Course, and Passive Microwave Derived Snow Water Equivalent Data for Western North America

C. DERKSEN,[1] R. BROWN,[1] A. WALKER[1], AND B. BRASNETT[2]

ABSTRACT

Synoptic monitoring of terrestrial snow water equivalent (SWE) is important because of the climatological impacts of snow distribution on local, regional and hemispheric energy exchange and the hydrological significance of snowpack water storage. Unfortunately, few temporally consistent and spatially continuous SWE datasets are available over North America. To address this need, a 1/3° resolution gridded daily snow depth and density reanalysis (and therefore, SWE) was developed for North America using a modified version of the operational Canadian Meteorological Centre (CMC) snow depth analysis scheme.

Passive microwave SWE monitoring capabilities provide an opportunity to compare the CMC analysis output with SWE estimates derived using a suite of land cover sensitive passive microwave algorithms developed by the Meteorological Service of Canada (MSC). In this study, CMC analysis, passive microwave SWE retrievals, and *in situ* snow course data are compared. An examination of the three datasets at point snow course locations shows a high degree of variability in the level of agreement between the three SWE datasets. Stronger dataset agreement is achieved when the resolution of the data are spatially and temporally coarsened, with a regional comparison over a sixteen-year data record showing a similar level of interannual variability in all three datasets. A comparison of monthly averaged passive microwave and CMC model snow covered area patterns with NOAA snow extent charts shows close agreement, while CMC and passive microwave derived monthly averaged SWE fields show consistent spatial distributions of SWE across the Prairie and boreal forest areas of western North America.

Keywords: snow water equivalent, passive microwave, SWE modelling, snow course

INTRODUCTION

While snow cover variability has strong impacts on both atmospheric energy exchange and the terrestrial water balance, an implication of this variability is that snow cover is difficult to measure in a truly representative manner. *In situ* estimates of the depth of snow on ground are obtained by ruler measurement, or by continuously logging sonic snow depth sensors, but these data are limited to point locations that may not be representative of the prevailing land cover. Measurement of solid precipitation, expressed as snowfall, is hindered by the simple fact that falling snow is difficult to capture in a stationary target. Conventional manual survey methods (snow courses) are spatially constrained and temporal repetition is labour-intensive. Since surface snow measurements tend to be site specific, an important issue is the extent to which these observations

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[1]Climate Research Branch, Meteorological Service of Canada, 4905 Dufferin St., Downsview, Ontario, M3H 5T4 chris.derksen@ec.gc.ca
[2]Canadian Meteorological Centre, Meteorological Service of Canada, 2121 TransCanada Highway, Dorval, Quebec, H9P 1J3

are applicable to a broader area. Conversely, remote sensing technology provides spatially integrated snow cover data, but can be adversely influenced by wavelength-specific issues ranging from cloud obscuration to the influence of land cover. The key issue with these remote estimates is how a larger imaging footprint captures within-pixel variability. As the coarseness of remote snow monitoring technologies increases, variability features are absorbed into single pixel measurements.

The purpose of this study is to review and compare three methods for estimating SWE in western Canada:

1. *in situ* snow course measurements,
2. passive microwave derived SWE estimates using Meteorological Service of Canada (MSC) algorithms, and
3. Canadian Meteorological Centre (CMC) SWE estimates from analysis of snow depth observations.

The passive microwave derived SWE data are derived from unique, linear relationships between brightness temperature and SWE for open and forested land cover classes in western Canada (Goodison and Walker, 1995; Goita et al., 1997), while the CMC estimates are produced from a gridded analysis of station snow depth observations with snow density estimated from an empirical snow aging scheme (Brown et al., in press). Assessing spatially continuous SWE fields has traditionally been a difficult task due to a lack of independent datasets on snow depth, mass, and water equivalent that are suitable for regional scale comparisons. Foster et al. (1996) note that the passive microwave time series provides the only interannually varying dataset for snow depth evaluation, with other options limited to climatologies (for example, Schutz and Bregman, 1975; Foster and Davy, 1988), which may not be representative of recent snow cover conditions. The regional approach to passive microwave algorithm development adopted by MSC (see Walker and Goodison, 2000) limits comparison with the CMC analysis to the Prairie and boreal forest regions of western Canada – passive microwave data is not suitable for a continental scale comparison due to problems retrieving SWE in mountainous terrain and densely forested regions.

The results of three comparative studies will be presented. First, the general level of agreement between the three SWE datasets was determined for a distributed network of snow course locations throughout western Canada. The winter season (December, January, February) of 1992/93 was used for this comparison. Second, an evaluation of interannual variability in areally averaged SWE was performed for a region of Southern Saskatchewan, using data from 1980 – 1995. Third, an assessment of the spatial distribution of snow cover and SWE as characterized by the CMC and passive microwave SWE products was performed by examining the monthly averaged SWE fields and weekly snow extent charts produced by NOAA (National Oceanic and Atmospheric Administration). Of particular interest is the similarity in spatial patterns north of 55 degrees where the network of surface observations ingested by the CMC analysis is very sparse.

SWE DATASETS

Snow Courses

A snow course consists of a series of sampling points where depth and SWE measurements are made. Snow course length, and the frequency of sampling points are defined depending on site specific conditions such as slope, aspect, land cover, and uniformity of snow cover (Goodison et al., 1981). If a snow course sampling scheme adequately considers local landscape characteristics, basin scale estimates of SWE can be derived for regions where remote measurement techniques are not operational (for example, Elder et al., 1998). Snow course data are, however, subject to a systematic bias because the measurements (obtained by inserting a tube through the snowpack to the soil to cut and hold a snow core) tend to underestimate SWE due to sampling difficulties associated with ice lenses, ground ice, and depth hoar (Carroll, 1987). The size of the sampling cutter can also influence accuracy (Goodison et al., 1987). Beyond these practical issues, other questions regarding snow course data must be considered, including the consistency of equipment, procedures, and measurement locations over time, and the degree to which areal snow cover conditions can be represented by a series of point measurements.

Snow course data are collected by a number of national and provincial agencies across Canada, and tend to be located in river basins near the populated regions of southern Canada. Most snow course programs are focused on data collection during the second half of the water year in order to yield estimates of pre-melt SWE. The snow courses operated by MSC are an exception to this, with data acquired weekly or biweekly through the snow cover season. MSC snow courses, therefore, provide the most frequent winter season snow course data, and were selected for use in this study.

A CD-ROM compilation of Canadian snow course data was produced as the result of a data rescue project undertaken by the Canadian CRYSYS project (*http://www.crysys.ca/crysys_freecd.cfm*). Selected MSC snow courses from this CD-ROM (MSC, 2000) were used for comparison with the passive microwave and CMC analysis datasets. As with all point to area comparisons, this is an imperfect exercise with some clear limitations. For example, the snow course SWE estimates may be unrepresentative of the snow cover conditions characterized by the 25 by 25 km gridded passive microwave and CMC analysis data. Still, insight on general dataset agreement, any potential systematic bias, and the corresponding levels of variability can be achieved given the time series of data available for comparison.

Passive Microwave Estimates

A suite of land cover sensitive SWE algorithms have been developed by the Climate Research Branch at MSC through a series of ground, airborne, and satellite data acquisition programs (see Goodison and Walker, 1995; Goita et al., 1997). For each pixel, SWE is derived as an area weighted average of four separate algorithms that estimate SWE for open prairie environments, and coniferous, deciduous, and sparse forest cover. Brightness temperatures from both Scanning Multichannel Microwave Radiometer (SMMR: operating from 1978 to 1987) and Special Sensor Microwave/Imager (SSM/I: operating from 1987 to present) can be used as inputs to the algorithms. The brightness temperatures are available from the National Snow and Ice Data Center (Knowles et al., 1999; Armstrong et al., 1994) in a common gridded projection – the Equal Area Scalable Earth Grid (EASE-Grid; Armstrong and Brodzik, 1995), with grid cell dimensions of 25 km for all channels. The microwave emission recorded at longer wavelengths (such as 19 GHz) is actually taken from a larger field of view (approx. 50 km), and resampled to the 25 km EASE-Grid.

The open environment algorithm utilizes the brightness temperature gradient between the 37V and 19V (18V for SMMR) channels (37V-19V/18.0; for full details see Goodison and Walker, 1995), while coniferous, deciduous, and sparse forest cover algorithms are based on unique linear relationships between brightness temperature difference (37V-19V; for full details see Goita et al., 1997) and SWE for the three forest types. Land cover for each pixel is taken from the International Geosphere–Biosphere Programme (IGBP) 1 km global land cover classification (Loveland et al., 2000), resampled to the EASE-Grid by the National Snow and Ice Data Center (NSIDC). The 17 IGBP land cover classes are aggregated into the four land cover types (open, coniferous, deciduous and sparse forest cover) associated with the SWE algorithms.

MSC algorithm performance is largely limited by three general factors:

(1) *Characteristics of the spaceborne data*. How well does an integrated estimate for 625 km^2 characterize SWE distribution within that region?

(2) *Integration of auxiliary data*. Second order land cover variables such as canopy density, stem volume, and lake cover fraction can impact microwave emission and scatter to the point that the snow cover signal is confounded, but these variables are not integrated into the MSC algorithm suite.

(3) *Seasonal variability in snow physical properties*. The physical state of the snowpack can strongly influence microwave emission and scattering, yet seasonally evolving variables such as ice lenses and within-pack liquid water content are very difficult to account for in empirically derived algorithms such as those developed at MSC.

Still, recent evaluation studies (for example, Derksen et al., 2002) show that SWE estimates derived using the MSC algorithm suite are typically within 10 to 15 mm of surface observations, except in areas of dense forest cover where marked SWE underestimation is a problem. An additional issue is the consistency of passive microwave derived geophysical variables produced from a cross-platform SMMR and SSM/I time series of brightness temperatures. A series of tests (Derksen et al., in review) showed that SWE estimates during SMMR seasons are significantly lower than SWE estimates during SSM/I seasons. The degree to which this is a climatologically driven difference as opposed to a brightness temperature consistency issue is not entirely clear. The results of this study may help to clarify this situation, as the CMC analysis data provide an independent time series of SWE information against which the temporal consistency of the passive microwave SWE estimates can be compared.

CMC Gridded SWE Analysis

Numerical weather prediction models rely on snow depth and snow cover extent information for the computation of surface radiation fluxes, the parameterization of melt processes, and the partitioning of available heat to both melting snow and sensible heat fluxes (Brasnett, 1999). Daily snow depth and snow cover extent information at CMC are generated by an operational snow depth analysis scheme described by Brasnett (1999). The analysis has similar spatial resolution to the passive microwave data. The CMC analysis was modified and applied by Brown et al. (in press) to generate daily SWE estimates over North America from analyzed snow depths and snow density estimates produced with an empirical snow aging scheme.

The analysis was run with historical daily snow depth observations from the U.S. and Canada covering the 1979/80 to 1996/97 winters. These observations provided a dense network of data across the contiguous US and southern Canada, but the network is sparse north of ~ 55°N. A background snow depth field was generated using a simple snow accumulation and melt model driven by ECMWF ERA-15 6-hourly air temperature and precipitation data. This model takes account of mixed precipitation type, melt by rain, variable snowfall density, blowing snow and sublimation loss. Snow aging is modelled as a function of time and depth using empirically derived settling rates for warm and cold snow thermal regimes. Snow melt is estimated from a degree-day melt factor expressed as a function of land cover type (vegetation/open) and snow density. Comparison of the gridded SWE climatology with *in situ* data revealed good overall agreement, however, it should be noted that the SWE estimates are likely to be more reliable in areas south of ~55ºN where the snow depth analysis is largely driven by snow depth observations (Brown et al., in press). In more northern areas, the results will be more strongly influenced by the background field (i.e. snow model). The CMC gridded SWE estimates were interpolated to the EASE-Grid projection to facilitate comparison with the passive microwave data.

The characteristic strengths and weaknesses of the previously described sources of SWE data are summarized in Table 1. The following comparison of these datasets will provide insight into the variable nature of SWE estimates yielded by these different techniques.

DATASET COMPARISONS

Point Comparisons

An initial comparison of the three SWE datasets was performed for the point locations of snow courses distributed through the study area (Figure 1). The EASE-Grid pixel with coordinates nearest the snow course was used for comparison. Dataset agreement was determined by calculating mean bias error (MBE) in the form:

$$\text{MBE} = \frac{\Sigma \left| SWE_{Obs} - SWE_{Est} \right|}{n} \tag{1}$$

where n is the number of compared measurements.

Table 1. Summary of snow course, passive microwave and CMC SWE data.

	Snow Course	Passive Microwave	CMC Analysis
Time Series	1946 to present	1978 to present	1979 to 1997
Synoptic Sensitivity	Poor – requires commitment of field personnel. Data biased to second half of water year.	Daily to pentad	Daily
Domain	Biased towards southern Canada	MSC algorithms developed only for prairie and boreal forest land cover	North America
Advantages	Provides information at local scale. Snow courses can be selected to represent vegetation and terrain	All-weather imaging. Rapid scene revisit. One of the longest satellite records.	Consistent method and data over period – independent benchmark data for evaluating satellite methods
Disadvantages	Labour intensive. Areally representativity?	Problems mapping SWE during wet snow periods. Large pixel dimensions. Land cover complications.	Relies on spatial interpolation. SWE estimates based on snow aging scheme.

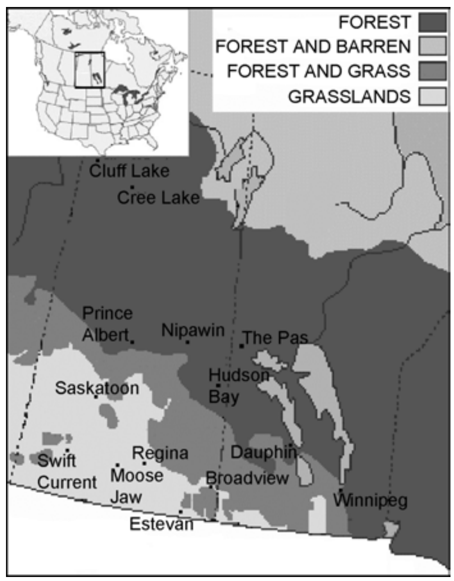


Figure 1. MSC snow course locations used for direct comparison of SWE estimates.

The limited temporal continuity of the snow course data was a factor in this comparison. These data are interspersed less frequently through the winter season, relative to the temporally continuous passive microwave and CMC analysis data (five-day averages for the microwave data; daily output for the CMC analysis), so only those dates for which there was snow course data could be considered. For this initial comparison, MBE was determined separately for each snow course location and for each winter month (December, January, February) of 1992/93. A monthly interval was chosen in order to track the evolution of dataset agreement through the winter season. A full analysis using the complete 1978 to 1997 CMC time series is currently in progress.

The monthly MBE results are summarized in Table 2. Microwave and snow course SWE estimates tend to agree more closely during early winter as opposed to late winter: average MBE for the passive microwave and snow course comparison increases from 10 mm in December, to 27 mm in February. This seasonal bias is not evident in the comparison between the CMC analysis and snow course data where average MBE only increases from 7 mm in December to 12 mm in February.

Table 2. Mean bias error (mm) results for the winter season of 1992/93.

	SSM/I vs. Snow Course			CMC vs. Snow Course		
Station	**MBE Dec.**	**MBE Jan.**	**MBE Feb.**	**MBE Dec.**	**MBE Jan.**	**MBE Feb.**
Winnipeg	24	24	25	7	21	18
Estevan	1	13	22	10	12	12
Moose Jaw	5	16	30	6	15	9
Regina	na	5	13	na	0	15
Swift Current	6	6	31	3	6	9
Saskatoon	na	12	38	na	24	26
Broadview	5	20	na	9	40	na
Prince Albert	8	18	42	3	10	21
Nipawin	18	10	16	12	10	3
Dauphin	5	17	na	12	2	na
Cree Lake	8	18	20	2	3	6
The Pas	15	12	9	4	16	11
Cluff Lake	na	43	50	na	3	8
Hudson Bay	9	14	23	5	6	7
Monthly Mean	*10*	*16*	*27*	*7*	*12*	*12*
Monthly SD	*6.8*	*9.3*	*12.2*	*3.6*	*10.8*	*6.7*

The level of agreement between the SWE datasets is highly variable. At Cree Lake for instance, the CMC and snow course SWE estimates fall within 6 mm through the entire winter season, however at Broadview in January, MBE for these two datasets reaches 40 mm. The agreement between passive microwave SWE retrievals and snow course data are also highly variable between stations and months, ranging from 1 mm disagreement at Estevan in December, to 50 mm difference at Cluff Lake in February.

The complete 1992/93 winter season time series of the three SWE datasets was investigated more closely at select locations in order to account for the variability in MBE results contained in Table 2. The plots for Hudson Bay (Figure 2a) and Nipawin (Figure 2b) are encouraging as they depict three independent datasets that capture a similar evolution of seasonal SWE with closely agreeing absolute values. The data from Estevan (Figure 2c) and Saskatoon (Figure 2d), however, highlight the potential challenges in resolving SWE estimates produced for the same location, but by different methods. While the passive microwave and snow course data are in very close agreement at Estevan through December, the datasets diverge through the rest of the winter. The comparison plot for Saskatoon (Figure 2d) shows three SWE estimates that, in both magnitude and seasonal evolution, do not agree well at any point in the season.

Interannual Variability of Areal Averages

Brown et al. (in press) produced a time series (1980 – 1995) of regionally averaged SWE for a region in southern Saskatchewan, comparing the CMC analysis with observed and estimated SWE values taken from the *Canadian Snow Data CD-ROM* (MSC, 2000). This plot is reproduced in Figure 3, with data added from the passive microwave time series. The three series are strongly correlated (r = 0.93 for CMC vs. surface data; r = 0.76 for passive microwave vs. surface data), and show that interannual variability in regional SWE is similarly captured by the passive microwave and CMC datasets for this region.

There has been some concern regarding the consistency of SWE estimates produced with the MSC algorithms when a cross-platform (SMMR and SSM/I) time series of brightness temperatures is utilized (Derksen et al., in review). SWE retrievals during SMMR years are significantly lower than during SSM/I years. Further evidence of this issue is contained in Figure 3. For six of the eight SMMR seasons, microwave SWE retrievals represent the lowest areal SWE value of the three datasets, and are lower than the surface data for seven of the eight seasons. This consistent bias is not evident during the SSM/I seasons, suggesting systematic SWE underestimations are produced during the SMMR seasons.

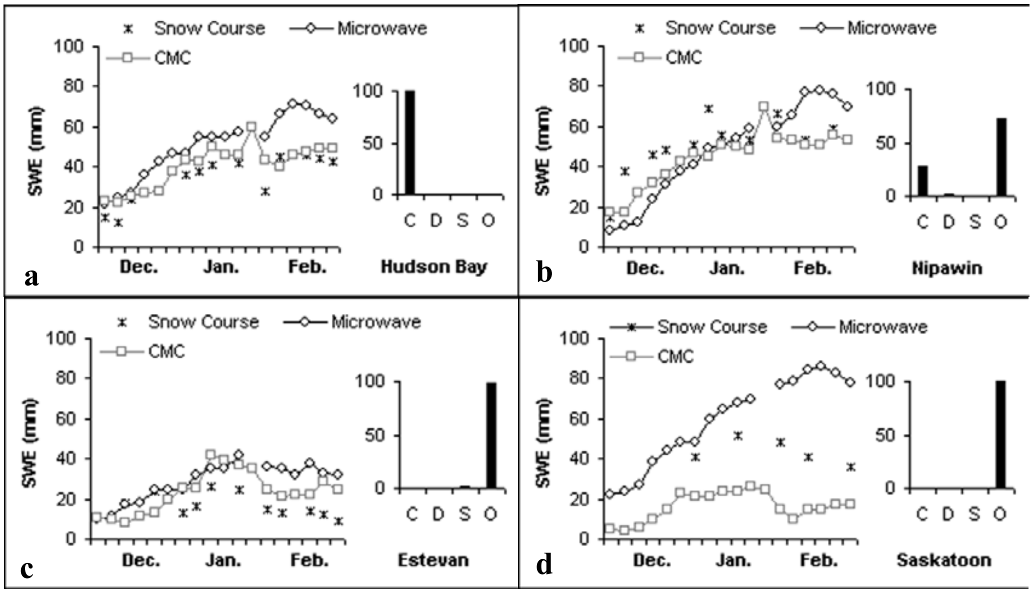


Figure. 2. SWE dataset comparisons for select locations, 1992/93. Columns summarize fractional land cover (Coniferous; Deciduous; Sparse; Open).

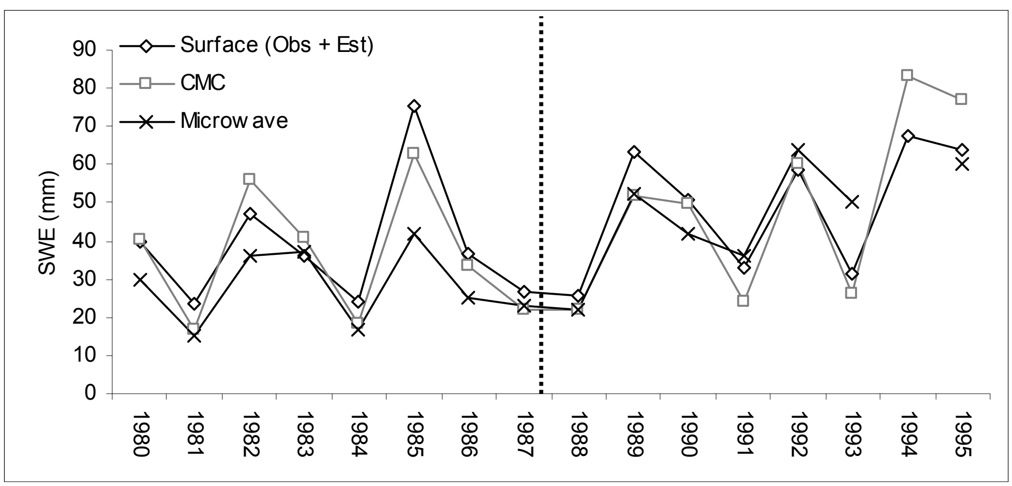


Figure 3. Comparison of areally averaged SWE for the month of February, Southern Saskatchewan (49–52°N; 100–105°W). Dashed line denotes transition from SMMR to SSM/I brightness temperatures. Passive microwave data for 1994 are missing due to sensor-based data storage and transmission problems.

Spatial Distributions

In addition to the CMC and passive microwave SWE data, snow cover frequency data produced from NOAA snow extent charts have also been compiled in the EASE-Grid for the years 1978 through 1996. While approaches to quantitatively assessing the similarity of the spatial patterns produced by these datasets are still being evaluated, there is no doubt to the potential of this multi-source data for contributing to improved understanding of snow cover variability over time. A necessary first step, however, is the assessment of the patterns characterized by these various datasets. Figure 4 shows the spatial distribution of snow cover parameters from NOAA, CMC, and passive microwave data through the winter season of 1992/93.

The macro features of snow cover distribution are captured in a similar fashion by all three datasets. An assessment of snow extent indicates that the study area was largely snow covered for the entire winter. Using December as an example, the same snow free regions—southwestern Saskatchewan, northern Montana, and most of Nebraska—are identified by all three datasets. Average per-pixel SWE is also very similar throughout the entire winter (within 5 mm) when the CMC and passive microwave monthly averages are compared. SWE magnitude and distribution, however, shows some marked differences, notably in southern Manitoba and North Dakota where the CMC SWE estimates exhibit greater spatial variability, and consistently exceed the passive microwave retrievals.

Agreement between the two spatially continuous SWE fields degrades as the winter season advances. When the two datasets are compared in December, nearly 75% of the EASE-Grid pixels in the study area have SWE values within ± 15 mm of each other. The 15 mm threshold was chosen as this is the approximate error range of the passive microwave algorithm (Derksen et al., 2002). By February, this agreement has dropped to below 40%, driven primarily by CMC SWE estimates that exceed passive microwave retrievals in southern Manitoba and North Dakota.

CONCLUSIONS AND DISCUSSION

This study has described an initial comparison of three SWE datasets: snow course measurements, passive microwave derived estimates, and model produced fields:

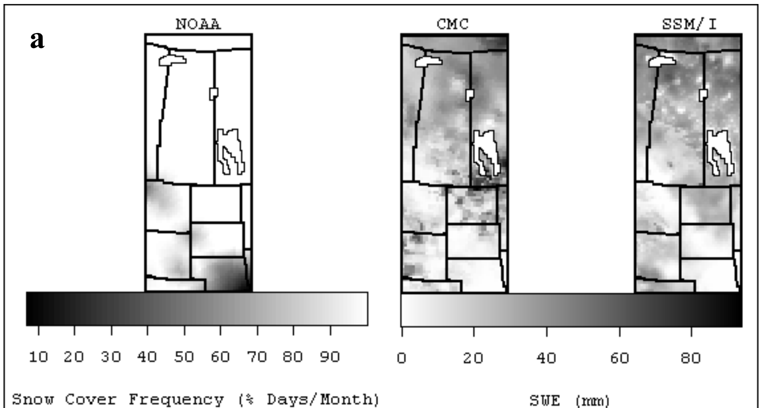
(1) A comparison of passive microwave and CMC SWE analysis to point snow course data has shown that the three SWE datasets agree well throughout a complete winter season at some stations, but disparate SWE estimates are produced at other locations. Commenting on the cause of these differences is very difficult. Are they the result of errors in the passive microwave and/or CMC SWE estimates? Are they a function of the different spatial characteristics between the spatially continuous (remotely sensed and modeled) and snow course datasets? Are snow course data even suitable for assessing gridded data with pixel dimensions of 25 km?

(2) Spatial and temporal averaging of SWE values improved dataset agreement: strong correlations were found between monthly averages of the three datasets, examined over a sixteen-year time series for an integrated region of Southern Saskatchewan. This comparison also showed evidence of inhomogeneity in the passive microwave time series, with SWE retrievals during SMMR seasons consistently too low relative to the CMC and snow course SWE datasets.

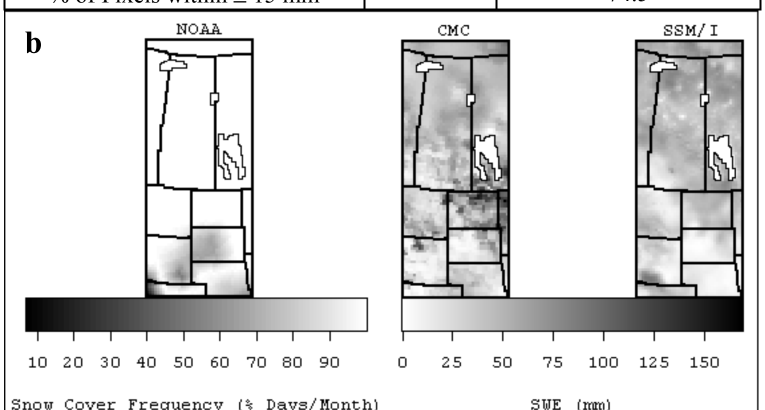
(3) The passive microwave and CMC snow cover patterns were very similar to those characterized by NOAA snow charts, and average per-pixel SWE values over western North America were very similar. Differences in SWE distribution were most marked in late winter.

There are unique uncertainties associated with deriving snow cover data using *in situ*, remote sensing, and modelling approaches. Snow course measurements can be subject to systematic errors due to the sampling equipment, and do not necessarily represent snow cover conditions beyond the immediate points of data collection. The passive microwave derived SWE estimates described in this study were produced from linear algorithms that do not account for the full range of snowpack and vegetative controls on passive microwave emission and scatter. The CMC analysis relies on the spatial interpolation of point snow depth measurements at open locations, and relatively simple model parameterizations to produce snow density information for generating spatially continuous SWE fields.

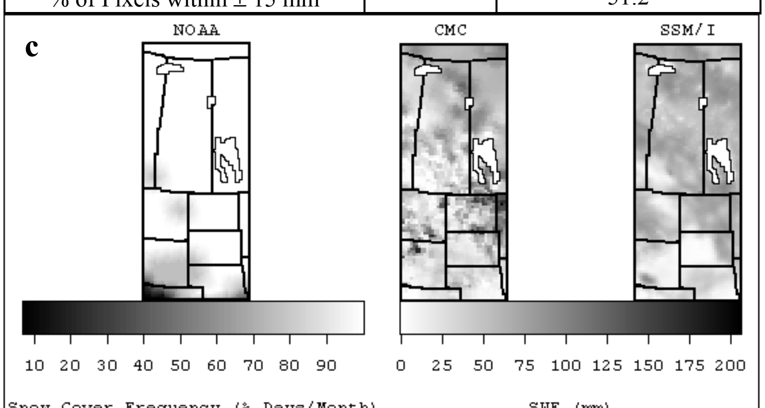
Derivation of the ‘best’ SWE product may require physically based data assimilation methods, merging *in situ*, satellite and modelled information. In order to pursue this approach, however, the error characteristics of the various data streams must be defined. The diversity of currently available methods for estimating SWE, along with the growing time series of these data, has produced a significant volume of data for comparison and evaluation, and the opportunity to utilize these datasets in a complementary fashion.



	NOAA	CMC	SSM/I
Average SWE		22.2	21.9
% of Scene with Snow Cover	97.2	97.1	94.3
% of Pixels within ± 15 mm		74.5	



	NOAA	CMC	SSM/I
Average SWE		41.4	36.7
% of Scene with Snow Cover	99.8	99.7	98.8
% of Pixels within ± 15 mm		51.2	



	NOAA	CMC	SSM/I
Average SWE		45.0	48.6
% of Scene with Snow Cover	98.2	99.2	99.4
% of Pixels within ± 15 mm		39.1	

Fig. 4. Monthly averaged patterns of snow cover parameters for December (a), January (b), and February (c), 1992/93. NOAA pixels considered snow covered if snow cover frequency > 50% days/month.

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