Water Resources Research

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Key Points:
- Evaluation of SNODAS SWE against observations showed persistent deficiencies in estimating SWE for needleleaf forest and open landscapes
- SNODAS data were assimilated into a hydrological model that calculated blowing snow redistribution and forest snow interception
- The coupled SNODAS-CRHM was found to improve SWE prediction, when compared to SNODAS data, in a Canadian Rockies mountain research basin

Supporting Information:
- Supporting Information S1
- Data Set S1

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Research Significance: This paper evaluates Snow Data Assimilation System (SNODAS) snow water equivalent (SWE) against snow survey observations in a wide variety of environments in western Canada and finds persistent deficiencies in the product under evergreen forest canopies, in mountains, and in open, windswept areas. To correct this, SNODAS precipitation was used to drive a physically based modular Cold Regions Hydrological Model (CRHM) platform that includes wind redistribution of snow, snow interception, and melt on slopes and under forest canopies. The simulated SWE was updated by SNODAS assimilations obtained through water balance calculations. This simulation incorporated missing processes from the SNODAS National Operational Hydrologic

Evaluation of SNODAS Snow Water Equivalent in Western Canada and Assimilation Into a Cold Region Hydrological Model

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Abstract Snow water equivalent (SWE) is one of the most hydrologically important physical properties of a snowpack. The U.S. National Weather Service's Snow Data Assimilation System (SNODAS) provides snow products at high spatial (~1 km^2) and temporal (daily) resolution for the contiguous United States and southern Canada. This study evaluated the SNODAS SWE product in the boreal forest, prairie, and Canadian Rockies of western Canada against extensive snow survey measurements. SNODAS was found to work well in sheltered environments, to overestimate SWE under needle-leaf forests, and to be unable to capture the spatial variation of SWE in windswept prairie and alpine environments. Results indicate that SNODAS SWE accuracy is strongly influenced by the missing blowing snow redistribution and canopy energetics and snow interception and sublimation processes in the mass balance calculations of the SNODAS model and by erroneous precipitation data forcing the model. To demonstrate how errors caused by missing processes can be corrected in areas with low assimilation frequency, SNODAS data were assimilated into a physically based hydrological model created using the modular Cold Region Hydrological Modelling (CRHM) platform that includes blowing and intercepted snow redistribution and subcanopy melt energetic processes. This approach decreased the overestimation of SWE compared to SNODAS from 135 to 79% in the study area and suggests that snow assimilation modeled SWE quality can be improved if snow redistribution, sublimation, and subcanopy melt processes are incorporated.

1. Introduction

Snow is a crucial resource for water supply in cold regions where much of the precipitation falls as snow and the main portion of annual streamflow runoff is generated by snowmelt (Gray & Male, 1981; Doesken & Judson, 1996). Therefore, accurately monitoring snow processes such as snowfall, accumulation, redistribution, sublimation, and melt along with tracking snow properties such as depth, density, and water equivalent are necessary and important for ecology, agriculture, forestry, industry, and other human activities. Snow water equivalent (SWE) is one of the most important physical properties of a snowpack, as it combines the information of snow depth and density to provide the amount of available water within the snowpack (Pomeroy & Gray, 1995).

One way to determine the SWE of a snowpack is by observation (e.g., field survey and remote sensing monitoring). However, ground observations typically do not provide enough information because they usually measure the SWE with limited spatial support or temporal resolution. Remote sensing SWE observations using microwaves have very coarse spatial resolution and limited ability to measure deep snow, redistributed snow, and snow under forest canopies (Derksen et al., 2003; Frei et al., 2012; Kinar & Pomeroy, 2015; Nolin, 2010; Peterson & Brown, 1975; Pulliainen & Hallikainen, 2001; Tait, 1998). In addition, hydrological models can simulate SWE continuously over a wide geographic range at various spatial scales for fine temporal resolution. However, these are simplified representations of reality, whether empirical or physical, and simulation quality relies on accurate forcing data and parameterization (Knoche et al., 2014; Vrugt et al., 2008). Due to these observation and model simulation problems, data assimilation, which is widely used in atmospheric and oceanic sciences, has been introduced to hydrology to improve SWE estimation in recent decades (Andreadis & Lettenmaier, 2006; Liston et al., 1999; Liu et al., 2012).

To provide better estimates of snow cover and associated snow properties in the United States, National Oceanic and Atmospheric Administration (NOAA)'s National Operational Hydrologic Remote Sensing Center (NOHRSC) has developed the SNOw Data Assimilation System (SNODAS) project (Barrett, 2003).

Remote Sensing Center (NOHRSC) Snow Model and vastly improved the simulated SWE. This shows how snow data assimilation models might be improved if missing processes such as blowing snow transport and snow interception are included.

SNODAS provides fine spatial and temporal scale snow products for the conterminous United States since October 2003 and southern Canada since December 2009. There are three main components in SNODAS: data ingest and downscaling of meteorological information from Numerical Weather Predication models, a physically based NOHRSC Snow Model (NSM) that simulates snow mass and energy balance, and a data assimilation component that updates snowpack estimates using various ground-based and satellite observational data. The daily 30-arc-second resolution SNODAS products are archived by NOHRSC and are openly available to researchers from all over the world for various modeling and research purposes.

Many researchers have used SNODAS data in their research as it is the only data set that provides real-time spatially distributed snow properties in North America (Vuyovich et al., 2014). In hydrology research, SNODAS data have been used to validate remotely sensed SWE data (Azar et al., 2008; Tedesco & Narvekar, 2010; Vuyovich et al., 2014), to evaluate hydrological model performance (Artan et al., 2013; Barlage et al., 2010; Rittger et al., 2011), and for model calibration in ungauged basins (Boyle et al., 2014). SNODAS data have also been applied to the field of ecology to study wildlife habitats and populations (Kays et al., 2008; Millington et al., 2010).

Although SNODAS data have been used in a wide variety of research, there are only a few studies that have validated their accuracy. SNODAS assimilates most available observations and rarely leaves other ground truth data for its evaluation. Anderson (2011) conducted a SNODAS validation in a watershed near Boise, Idaho, USA, by using snow survey data and found that SNODAS underestimated SWE on the ground at most times and locations. Clow et al. (2012) evaluated SNODAS SWE and snow depth data in the Colorado Rocky Mountains, USA, by using independent, ground-based snow survey data and water balance calculations in headwater basins. They found that the accuracy of SNODAS data in forested areas was higher than in alpine areas, with SNODAS capturing 77% and 72% of variation of SWE and snow depth in forested areas but only 30% and 17% variation of SWE and snow depth in alpine areas. Schneiderman et al. (2013) found SNODAS SWE estimation fitted to snow survey SWE data performed better than that using two temperature index models in the Catskill Mountain region of New York State, USA. Hedrick et al. (2015) compared snow depth change during the accumulation season derived from SNODAS and light detection and ranging (LiDAR) in northern Colorado and found that there was a reasonable correlation between two data sets, but the differences between two data sets were great in some locations. The National Aeronautics and Space Administration (NASA) Airborne Snow Observatory (Painter et al., 2016) can provide snow depth data for unforested alpine terrain. Bair et al. (2016) and Yang et al. (2018) used these data and density estimates to evaluate a few SWE estimation methods, including SNODAS, at the basin scale in the Sierra Nevada, California, USA. Both studies showed that SNODAS had the lowest accuracy among all the methods tested. Dozier et al. (2016) suggested that SNODAS overestimates SWE during the melt period, possibly because of over-reliance on snow pillows, which can overmeasure SWE during melt due to lack of meltwater drainage from the pillow. They also noted that where elevational ranges are large, SNODAS can underestimate SWE at higher elevations due to over-reliance on assimilation of lower elevation snow pillow data. In Canada, despite the use of SNODAS by provincial water management and flood forecasting agencies, validation and application of the SNODAS product have not been evaluated. The SNODAS assimilation frequency for boreal forest, prairie, and mountain regions is relatively low (Fall et al., 2014), and the impact of this low frequency on the accuracy of SNODAS SWE is unknown.

The objectives of this research are therefore (1) to evaluate SNODAS SWE data in various Canadian environments such as mountains, prairies, and boreal forests by comparing model products to historical snow survey data; (2) to determine whether more accurate simulations of SWE in these environments can be achieved by assimilating SNODAS SWE data into a physically based Cold Region Hydrological Modelling (CRHM) platform; and (3) to show what would be necessary to improve snow assimilation models in this environment.

2. Study Area and Field Observations

The study was conducted in the well-instrumented and carefully observed Boreal Ecosystem Research and Monitoring Sites (BERMS), Smith Creek Research Basin (SCRB), and Marmot Creek Research Basin (MCRB) that represent three main Western Canadian landscapes of boreal forest, prairie, and mountain, respectively (Figure 1a). These research sites are operated as part of the Changing Cold Regions Network

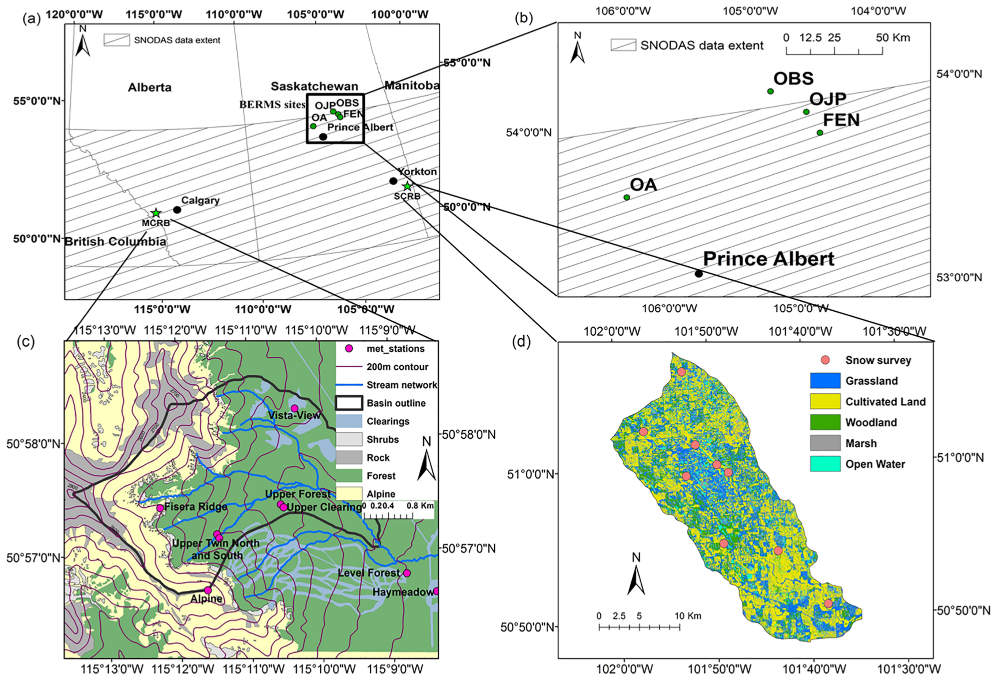

Figure 1. Study locations: (a) Marmot Creek Research Basin (MCRB), Smith Creek Research Basin (SCRB), and three Boreal Ecosystem Research and Monitoring Study (BERMS) sites, all in Canada. (b) The extent of Snow Data Assimilation System (SNODAS) data and BERMS site locations. (c) Land cover and meteorological stations in MCRB, Alberta, Canada. (d) Land cover types and snow survey locations in SCRB, Saskatchewan, Canada.

(DeBeer et al., 2015) and have excellent quality and well-documented snow surveys and site characteristics. A brief introduction of these sites is included here together with landscape and elevation range information of the snow survey transects and the corresponding SNODAS grid cells in the three sites (Table 1).

2.1. Boreal Ecosystem Research and Monitoring Sites

The BERMS area is located in the southern Boreal Forest within the mid-Boreal Upland and Boreal Transition ecoregions, north of Prince Albert, Saskatchewan, Canada. It is a follow-on to the Boreal Ecosystem-Atmosphere Study (BOREAS) (Nichol et al., 2000) that aimed to determine the long-term water, carbon, and energy exchanges between the atmosphere and boreal forest. Seven flux tower sites are located in various land cover types in BERMS (Barr et al., 2012). Snow survey data from four sites were available for the study period. Old Black Spruce (OBS) was excluded from the analysis as it is located beyond the extent of SNODAS data. The other three sites were chosen for this study based on precipitation measurements, snow survey data availability, and SNODAS data extent (Figure 1b). These sites are the needleleaf Old Jack Pine (OJP, 53°54′N, 104°41′W, elevation 570 m), deciduous Old Aspen (OA, 53°38′N, 106°12′W, elevation 600 m), and Fen (FEN, 53°57′N, 105°57′W, elevation 525 m). OJP is a mature jack pine forest located in a relatively flat landscape (mean slope 2 to 5%) with a 13.5-m mean canopy height and 1.9 to 2.2 winter leaf area index (Baldocchi et al., 1997; Nichol et al., 2000). OJP experiences about one third of total seasonal snowfall loss by interception sublimation (Pomeroy & Gray, 1995). OA is mature trembling aspen overstory with heights from 18 to 22 m and a winter LAI of 0.72 and 2-m hazelnut understory with winter LAI of 0.33 (Barr et al., 2004; Hogg et al., 1997). Pomeroy and Gray (1995) showed that snow accumulation in aspen forests closely matched cumulative snowfall in the cold boreal winter. FEN is located in an approximately 4,000 m long and 450-m wide fen surrounded by black spruce and jack pine forests. Bog birch shrubs at 0.5- to 1.5-m height and widely scattered, stunted deciduous tamarack trees are the main vegetation types in this site (Nichol et al., 2000; Sukyer et al., 1997). Because of its sparse vegetation cover, it can be subject to snow redistribution by wind.

Researchers from Environment and Climate Change Canada (ECCC) and the Global Institute for Water Security, University of Saskatchewan, conducted snow surveys on a transect around each site, one to

Table 1
Summary of Land Cover and Elevation Range of Snow Survey Transects With Corresponding SNODAS Grid Cells at All Survey Locations in Western Canada

Site	Location	Transects	Samples	Transects/Grid cell elevation range (m)	Grid cell main landscapes (Percentage (%)/Samples)
BERMS	OJP	1	25	509–510/508–512	Coniferous forest (100/25)
	OA	1	25	509–510/508–511	Deciduous forest (100/25)
	FEN	1	25	482–483/481–486	Fen (100/25)
SCRB	LR-3	2	25,25	528,528/527–529	Grassland (9/0), Stubble (63/25), Wetland (15/13), Woodland (13/12)
	LR-6	2	25,25	529,529–530/525–530	Grassland (10/0), Stubble (64/25), Wetland (17/5), Woodland (9/20)
	SCR-2	3	25,25,10	525–526,524–525, 524–525/522–528	Grassland (15/25), Stubble (46/25), Wetland (27/0), Woodland (12/10)
	SCR-6	3	25,25,25	524,524,524/521–530	Grassland (36/25), Stubble (39/25), Wetland (13/14), Woodland (12/11)
	SC-1	2	25,25	510–511,511–512/509–515	Grassland (2/25), Stubble (71/25), Wetland (14/0), Woodland (13/0)
MCRB	HM	1	35	1,430–1,431/1,422–1,448	Forest (74/0), Clearing (26/35)
	UC	2	30,30	1,834–1,846,1,830–1,852/1,737–1,872	Clearing (16/30), Forest (84/30)
	LF	1	11	1,503–1,509/1,435–1,560	Clearing (12/0), Forest (88/11)
	VV	1	30	1,939–1,950,1,930–1,939/1,850–2,022	Clearing (30/20), Forest (70/10)
	FR	3	10,15,30	2,286–2,306,2,302–2,308, 2,280–2,306/ 2,230–2,508	north face slope (23/10), ridge top (14/15), south face slope (31/20), larch forest below south face slope and at end of ridge top (32/10)

three times per winter month. This was done using an ESC30 snow sampling tube to measure density and a ruler for depth following methods outlined by Pomeroy and Gray (1995). Along each 100-m transect, 25 depth measurements were taken at equal interval, with a density sample taken at every fifth depth measurement point. Average snow depth and density were used to calculate the mean SWE at each site. From the 2010 to 2015 water year, 89 mean SWE values were surveyed at three sites.

2.2. Smith Creek Research Basin

SCRB is located approximately 60 km southeast of Yorkton, Saskatchewan, Canada, in the windswept, open landscape of the Canadian Prairies (Figure 1d). It has an area of approximately 393 km^2 and a relatively flat landscape, with slopes ranging from 2 to 5% and elevation ranging from 490 to 548 m (Fang et al., 2010). The major landscape types of SCRB are cultivated cropland, pasture, native grassland, natural wetland, and deciduous woodland. Because snow is heavily redistributed by wind in the prairie during winter (Fang & Pomeroy, 2009; Pomeroy et al., 1993), 13 transects were chosen to represent the major landscapes (i.e., grassland, grain stubble, roadside ditch, woodland, and wetland) at survey sites throughout the whole basin. Except for SCR-2 Woodland transect with 10 sample points, other transects contained 25 sample points with a 5-m interval. Snow depth was measured at each point, and snow density was measured every fifth depth measurement using the ESC30 snow tube. Mean SWE was calculated from average snow depth and snow density following method by Pomeroy and Gray (1995). There were 67 mean SWE values produced from these transects within the 2010 to 2012 water year at SCRB (Pomeroy et al., 2014). Precipitation data available for this research were from two meteorological stations, which are separately operated by University of Saskatchewan (the UofS station) and by ECCC (the Langenburg station), located inside the SCRB.

2.3. Marmot Creek Research Basin

MCRB (50°57′N, 115°09′W) is a mountain research basin located in the Front Ranges of the Canadian Rockies (Figure 1c) and has an area of approximately 9.4 km^2 including three upper sub-basins: Cabin Creek, Middle Creek, and Twin Creek, as well as a lower confluence sub-basin. The elevation of MCRB ranges between 1,450 and 2,825 m. The main land covers are dense needleleaf Lodgepole Pine and Engelmann Spruce in the lower elevations with small aspen coverage near the basin outlet; the middle upper elevation forests are mainly deciduous Alpine Larch, shrubs, needleleaf Engelmann Spruce, and Sub-alpine Fir; talus and bare rocks are present in the high alpine region (DeBeer & Pomeroy, 2009). The basin has been subject to experimental forestry treaments leaving large clearcuts and small forest clearings in the needleleaf forest zone (Ellis et al., 2013). There are substantial snow interception losses from needleleaf forests (Ellis et al., 2010) and wind redistribution of snow from alpine ridges and windward slopes to sheltered slopes and treeline forests (MacDonald et al., 2010). The average annual precipitation in MCRB is approximately

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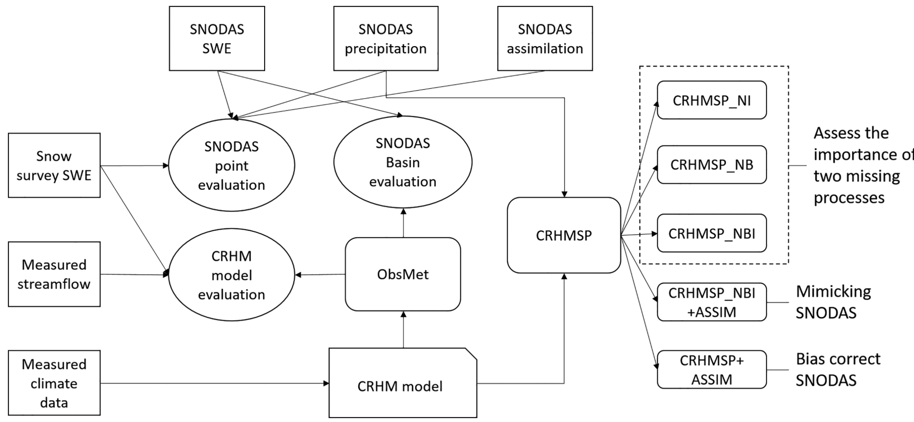

Figure 2. Workflow of this research. Rectangles represent the data used in this research. Ovals denote the evaluations. Single cornered rectangle means the model. Rounded rectangles mean the model simulations with different inputs or model configurations. Abbreviations of model simulations are defined in text.

900 mm, which increases with elevation. The precipitation can reach 1,140 mm at the regions above treeline where 60–75% falls as snow (DeBeer & Pomeroy, 2009). Snow usually accumulates from November to March and starts to melt in late April or early May. Ten permanent meteorological stations have operated since 2005 at various locations throughout the basin (Figure 1c). These stations continuously measure short- and long-wave radiation, air temperature, humidity, wind speed, and snow depth. Precipitation is measured with Alter-shielded Geonor weighing precipitation gauges at the Hay Meadow (HM), Upper Clearing (UC), and Fisera Ridge (FR) stations and is corrected for wind-induced undercatch (Smith, 2009).

Snow surveys have been conducted at the UC, Vista View, FR, Level Forest, and HM sites regularly since 2007. The survey method is same as that for SCRB with varied transect lengths. There are 348 mean transect SWE values for SNODAS validation in MCRB for the 2010 to 2015 water years.

3. Methods

SNODAS data from October 2010 to September 2015 were downloaded and processed to extract SWE, precipitation, snowmelt runoff under the snowpack, blowing snow sublimation, and snowpack sublimation for all three study areas. In all study areas, SNODAS SWE data were compared to ground snow survey data to evaluate its point scale accuracy. In MCRB, SNODAS SWE was also compared with a CRHM simulation to assess accuracy at the basin scale. The accuracy of a snow data assimilation system is mainly controlled by two factors: model simulation accuracy and data assimilation accuracy and frequency. The main factors influencing model simulation accuracy are driving force, parameters, and model structure. Both blowing snow transportation and canopy snow interception simulations are missing in the SNODAS NSM. Precipitation data are the only available driving force in the archived SNODAS data sets, and data assimilation can be determined by using a water balance calculation (see section 3.1). Therefore, the influence of these factors on accuracy of SNODAS SWE data was also examined. The main works of this research are shown in Figure 2, and the details are provided in the rest of section 3.

3.1. Determination of Assimilation in SNODAS

In addition to SWE, SNODAS also provides daily cumulative precipitation (rain and snow), snowmelt runoff at the base of snowpack, sublimation from snowpack, and sublimation of blowing snow data for each pixel. These variables together can be used to compute the snowpack water balance to estimate assimilation in the SNODAS system. In the NSM simulation, single-day SWE should equal previous day SWE plus snowfall minus snowmelt runoff and sublimation under condition without any data assimilation. If there is considerable difference between these two data sets, assimilation must be the cause. Therefore, equation (1) was used in this research to determine the assimilation amount in SNODAS system.

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$$\text{Assim} = \text{SWE}_i - (\text{SWE}_{i-1} + S - \text{SM} - \text{BSS} - \text{SPS}) \quad (1)$$

where Assim is the assimilation amount, SWE_i denotes SWE on the ith day of year, S is snowfall, SM is snowmelt runoff, BSS is blowing snow sublimation, and SPS is snowpack sublimation.

3.2. Spatial Representation of Snow Survey Data

For model or remote sensing validation, ground truth and target data should have same spatial resolution. To satisfy this requirement for validation of SNODAS data, previous researchers conducted their snow surveys in an approximately 1-km^2 area to represent the SNODAS grid cell (Anderson, 2011; Clow et al., 2012). In this study, snow survey transects are usually 100 to 125 m long, such that the survey area only represents a small part of the 30-arc-second SNODAS grid cell. SWE distribution is highly varied in different land covers because of the snow redistribution caused by wind in open environments and needleleaf canopy interception (Liston et al., 2007; Lv & Pomeroy, 2019; Pomeroy et al., 1993; Pomeroy & Gray, 1995; Pomeroy et al., 1998). This makes a direct comparison between the snow survey data and the correspondent SNODAS data challenging in areas with complex terrain or heterogeneous land covers.

For each site in BERMS, topography is flat and land cover is primarily uniform. The mean SWE from each survey site can represent the SWE of the larger area around that site. Therefore, the observed mean SWE of each site was directly compared to the extracted SNODAS SWE data at BERMS sites.

In SCRB, snow surveys at one site contain several transects that represent the dominant landscapes or surveys have one transect covering several landscapes. This study assumes that the SWE in each landscape type is regionally consistent in this flat area and that snow surveys of about 125 m in length can represent SWE in that landscape type over a larger area, following the stratified snow sampling method for prairie landscape by Steppuhn and Dyck (1974). The following equation was used to upscale the snow survey data to ~1 km^2:

$$\text{SWE}_{1K} = \sum_{i=1}^{n} (\text{SWE}_i * W_i) \quad (2)$$

where SWE_{1K} is the upscaled, approximately ~1 km^2 observed SWE; SWE_i is the observed SWE at ith landscape type; and W_i is the fractional coverage weight of the ith landscape type and equals the area of ith landscape type divided by ~1 km^2. The area of each landscape type was calculated from a 30-m land cover map at each snow survey site.

MCRB has highly heterogeneous land cover and complex terrain. The Steppuhn and Dyck (1974) method might not be suitable for upscaling the ground snow survey to the SNODAS pixel scale. The snow surveys in MCRB contain samples from most landscapes around each site, but they might not be sufficient to cover the elevation range, slope, and aspect within each SNODAS cell. Various approaches were developed to upscale point snow survey data to catchment scale based on the influence of elevation, slope, aspect, radiation, vegetation condition, wind effect, and other factors on snow distribution (Elder et al., 1991; López-Moreno & Stähli, 2008; Harshburger et al., 2010). However, Grünewald et al. (2013) found that the influence of elevation, slope, slope, and sheltering index on snow depth distribution was weak in MCRB. These factors explained less than 30% of local snow depth variation. There is no existing optimal method to upscale 150-m snow survey transect data to the SNODAS cell level (approximately 582×926 m) in MRCB, and developing a new approach is beyond the scope of this research. Thus, the snow survey transect SWE data from different landscapes were directly compared to the corresponding SNODAS cell SWE.

3.3. Point Scale Comparison

To examine the influence of missing processes (i.e., blowing snow transport and canopy interception) in the NSM on SNODAS accuracy, the observed and SNODAS SWE were compared using linear regression at different landscape types (i.e., forest and clearings and leeward and windward slopes) in all three study areas. The root-mean-square error (RMSE, equation (3)), correlation coefficient (R^2, equation (4)), and model bias (MB, equation (5)) between the two data sets were also calculated to evaluate accuracy.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(Xo_i - Xs_i)^2}{n}} \tag{3}$$

$$R^2 = 1 - \frac{\sum_i (X_O - X_S)^2}{\sum_i (X_O - \bar{X}_O)^2} \tag{4}$$

$$\text{MB} = \frac{\sum Xs}{\sum Xo} - 1 \tag{5}$$

where *Xs* and *Xo* are SNODAS SWE and observed SWE, respectively, and $\bar{Xo}$ is the average of observed SWE.

Time series of SNODAS SWE were compared to the observed SWE at sites where observed precipitation was available. Cumulative SNODAS precipitation and cumulative observed precipitation as well as the amount of data assimilation were also included in the time series to assess the influence of these factors on SNODAS accuracy.

3.4. CRHM Model and Basin Scale Comparison

CRHM is a modular system used to assemble hydrological models for Canadian and other cold environments. It can be used to create distributed physically based hydrological models using the Hydrological Response Unit (HRU) as the control volume for modeling. HRUs are conceptual landscape groups, which are subdivisions of the basin based on the elevation, slope, aspect, vegetation cover, soils, and other hydrological or biophysical characteristics. CRHM has various modules to simulate the snow processes for each HRU. Users can construct their own model by selecting modules from the CRHM module library based on input data availability, research scale, and predictive variable of interest. These modules can be used to interpolate meteorological data and to simulate rainfall and snowfall interception, snow redistribution, snow sublimation, snow albedo decay, canopy transmittance, snow energy and mass balance, evaporation, snowmelt, snowcover depletion, infiltration, soil moisture, flow and storage of the surface and subsurface, and streamflow routing. Pomeroy et al. (2007) provide a full description of CRHM. For the basin scale comparison in MCRB, the CRHM model configuration by Fang et al. (2013) was used here. The main modules used in the MCRB model are (1) radiation module (Garnier & Ohmura, 1970) for calculating theoretical global radiation, and direct and diffuse solar radiation including to slopes; (2) albedo module (Verseghy, 1991) for simulating the snow albedo change due to snow condensation, melt, and snowfall throughout the winter; (3) SNOBAL module (Marks et al., 1998) for simulating the mass and energy balance of snowpack; (4) canopy module (Ellis et al., 2010) for estimating forest canopy interception of rainfall and snowfall and subcanopy shortwave and longwave radiation; and (5) blowing snow module (Pomeroy & Li, 2000) for simulating blowing snow transportation and sublimation. Details on the modules used, model setup, and parameterization are described in several recent publications (Fang et al., 2013; Fang & Pomeroy, 2016; Pomeroy et al., 2016).

The output of the SNODAS system at the centre of each grid cell is assumed to represent the whole grid cell. This assumption is likely valid in flat terrain in BERMS and SCRB but may not be appropriate for complex terrain in MCRB. To address this, SNODAS SWE in MCRB was compared to the CRHM-simulated SWE data at the basin scale. The CRHM-simulated SWE used the observed forcing data (hereafter referred to as ObsMet). First, ObsMet-simulated SWE was compared to snow survey data at several sites to assess the ability of CRHM to predict the timing and magnitude of snow accumulation and depletion at a point scale. Second, ObsMet-simulated streamflow was compared to streamflow observation at the basin outlet to evaluate the ability of CRHM to predict the surface and subsurface hydrological processes for streamflow generation, snow accumulation, and depletion at the basin scale. Third, the ObsMet-simulated SWE for the whole basin was compared to the average SNODAS SWE in MCRB. The resolution of SNODAS SWE data is 30 arc-seconds, and as MCRB is located at 51°N, each SNODAS grid cell covers approximately 0.54-km^2 area at that latitude. There are 30 SNODAS grid cells overlapping MCRB, and the average SNODAS SWE in MCRB was calculated based on areal-weighted SWE of each cell. RMSE_m (equation (6)) and MB_m (equation (7)) were calculated to compare the MCRB basin mean SNODAS and ObsMet-simulated SWE. The assimilation amount, cumulative SNODAS precipitation, and cumulative observed precipitation data were included in

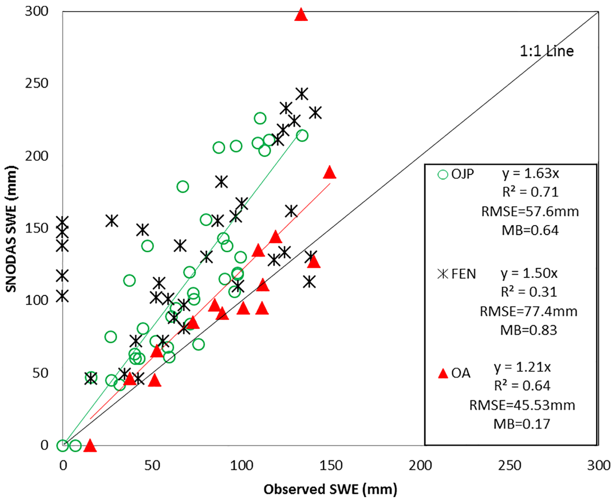

Figure 3. Comparison of observed and Snow Data Assimilation System (SNODAS)-predicted snow water equivalent (SWE) for water years 2011–2015 at Boreal Ecosystem Research and Monitoring Study (BERMS) sites (Saskatchewan, Canada) along with linear fits for old jack pine (OJP; green line) and old aspen (OA; red line) sites to a 1:1 relationship (black line). The fen (FEN) site has no significant linear fit.

the time series of SNODAS and ObsMet-simulated SWE to examine their influence on SNODAS SWE accuracy in MCRB.

$$\text{RMSE-m} = \sqrt{\frac{\sum_{i=1}^{n}(\text{Xm1}_i - \text{Xm2}_i)^2}{n}} \tag{6}$$

$$\text{MB}m = \frac{\sum \text{Xm1}}{\sum \text{Xm2}} - 1 \tag{7}$$

where xm1 and xm2 denote the SWE simulated by SNODAS and ObsMet.

3.5. Mimicking SNODAS Simulations Using CRHM

One possible cause for error in SNODAS SWE is the structure of the NSM embedded in SNODAS. The NSM is spatially uncoupled such that it does not consider the spatial redistribution of snow by wind even though it includes blowing snow sublimation following Pomeroy and Li (2000). The NSM also does not simulate canopy snow interception and sublimation in forested regions (Carroll et al., 2001; Jordan, 1990; Tarboton & Luce, 1996). These model limitations might cause SNODAS to overestimate local SWE in MCRB because of the presence of both windy open alpine and dense evergreen forest land covers in MCRB. Thus, one simulation was generated from an incomplete CRHM model in which blowing snow transportation and canopy interception modules were turned off but used observed precipitation in MCRB (hereafter the ObsMet_NBI).

Another possible cause for SNODAS SWE error is an inaccurate driving force. To determine the influence of an inaccurate driving force and missing processes on SNODAS SWE quality, five simulations were conducted in MCRB by replacing observed precipitation with SNODAS precipitation in the forcing data to run CRHM with different configurations of missing processes. These were compared to ObsMet and SNODAS SWE. The first four simulations are (1) a complete CRHM model (CRHMSP), (2) an incomplete CRHM model with blowing snow transportation module turned off (CRHMSP_NB), (3) an incomplete CRHM model without canopy snow interception module (CRHMSP_NI), and (4) an incomplete CRHM model with both blowing snow transportation and canopy snow interception modules turned off (CRHMSP_NBI). To make a simulation that closely matches the SNODAS system, a fifth simulation was conducted by incorporating data assimilation into the CRHMSP_NBI simulation. The assimilation amount used in the SNODAS system for MCRB was used to update the CRHMSP_NBI-simulated SWE based on a nudging method. In the nudging process, the updated SWE equals simulated SWE plus the assimilation amount greater or lesser than zero. This simulation is referred to as CRHMSP_NBI+ASSIM hereafter. If the CRHMSP_NBI+ASSIM-simulated SWE can closely match SNODAS SWE, then CRHM is able to mimic the SNODAS NSM.

4. Results and Discussion

4.1. SNODAS Accuracy at Point Scale

4.1.1. Boreal Forest

The mean SWE of each site was compared to the extracted SNODAS SWE data (Figure 3). The SNODAS SWE explained 64%, 71%, and 31% of variability of SWE at the OA, OJP, and FEN, respectively, with RMSE of 45.5, 57.6, and 77.4 mm, suggesting better correlation between the SNODAS and measured SWE in the OA and OJP sites but not in the FEN. SNODAS overpredicted SWE at all sites with overestimation ranging from 17 to 83%. The results indicate that among sites at BERMS, SNODAS had best simulation at OA, had a good correlation with observations but with a relatively high overestimation at OJP, and is poorly correlated to measurements at FEN. These results suggest model limitations in SNODAS. In the needleleaf jack pine forest, ground snow accumulation is attenuated by canopy interception and sublimation losses of roughly one third of winter snowfall (Hedstrom & Pomeroy, 1998; Pomeroy et al., 1998; Pomeroy et al., 2002), while snow interception and sublimation of intercepted snow are not represented in the SNODAS model simulation. Pomeroy et al. (2002) found that the ratio of forest to clearing snow accumulation was

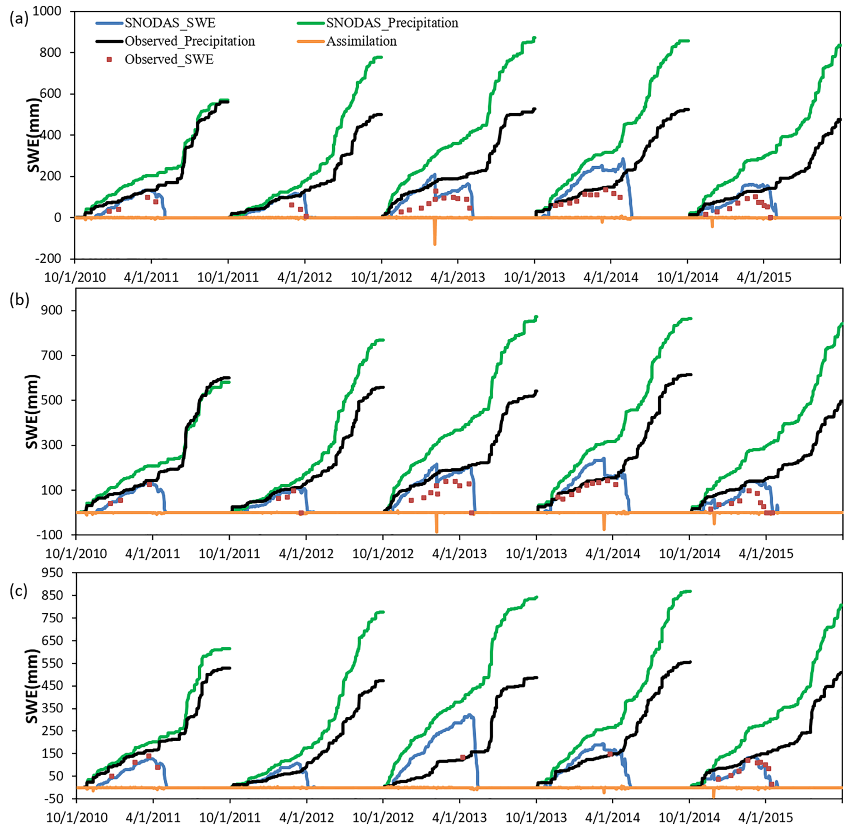

Figure 4. Time series comparisons of observed and Snow Data Assimilation System (SNODAS) snow water equivalent (SWE) and precipitation at Boreal Ecosystem Research and Monitoring Study (BERMS) sites for (a) old jack pine (OJP), (b) fen (FEN), and (c) old aspen (OA) sites in Saskatchewan, Canada.

negatively related to winter LAI and canopy density of needleleaf boreal forests. In contrast, the influence of canopy interception on snow accumulation under deciduous forest canopies was found to be very small to negligible (Kuz'min, 1960; Pomeroy & Gray, 1995). This explains why SNODAS achieved better simulation in OA site (i.e., deciduous aspen) than that in OJP (i.e., needleleaf jack pine forest).

Although SNODAS model simulates blowing snow sublimation, it does not include blowing snow transport from open area to sheltered area, which is an important process affecting snow accumulation in open areas such as FEN (Pomeroy & Gray, 1995). The missing blowing snow transport in the SNODAS model is likely responsible for high overestimation of SWE at FEN. Another missing component in SNODAS is advective energy. Midwinter ablation events in boreal forest clearings that are driven by advection of turbulent energy can result in lower midwinter snow accumulation in clearings such as the FEN but not under the forest canopy with relatively stable and sheltered conditions in this region (Pomeroy & Granger, 1997). This explains why SNODAS overestimated SWE in the range of 100 to 160 mm when no snow was observed at FEN (i.e., five points from FEN shown along the *y* axis of Figure 3). At the end of the snow season, snow melts early in this open site, which is not reflected in the SNODAS SWE data (Figure 4b) and also partially contributed to the low R^2 of FEN. In addition to wind redistributed snow being a problem for SNODAS found in open Colorado sites (Clow et al., 2012), this study revealed additional causes for SNODAS's poor performance in the open areas of the Canadian boreal forest. Missing components in the SNODAS model, such as blowing snow transport, advection of turbulent energy for mid-winter ablation, and canopy effects on radiation, explain why SNODAS had the lowest SWE accuracy in the FEN site amongst the three BERMS sites.

The cumulative precipitation data from SNODAS and observations at three sites were calculated to understand the effect of precipitation data quality on SNODAS SWE accuracy (Figure 4). There was an increasing overestimation of SNODAS precipitation data as the study period proceeded at all three sites at

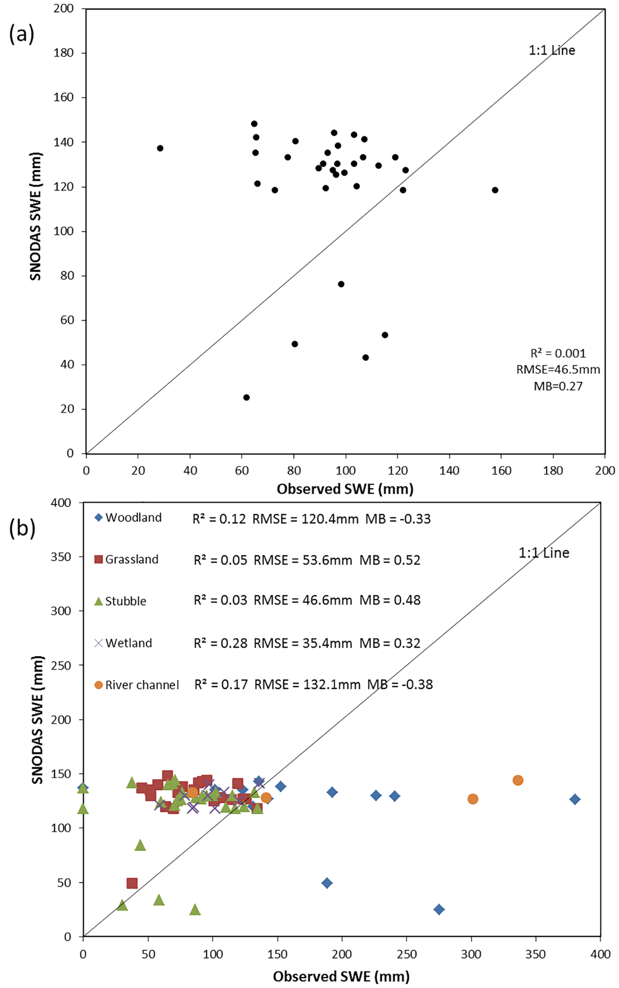

Figure 5. Comparisons of observed and Snow Data Assimilation System (SNODAS)-predicted snow water equivalent (SWE) at Smith Creek Research Basin, Saskatchewan, Canada, for water years 2011–2013. (a) SNODAS data and upscaled 1-km snow survey data comparison and (b) SNODAS data and transect level snow survey data from different land cover type comparison.

BERMS. SNODAS precipitation was close to observed precipitation in the 2011 water year, while SNODAS overestimated precipitation by 37–76% in four following water years. Correspondingly, SNODAS SWE accuracy varied among the five water years at each site. At OJP and FEN sites, SNODAS SWE agreed very well with observations in the 2011 water year, while the difference between the two data sets was larger in the other four water years, with RMSE values ranging from 51.7 to 100.2 mm at OJP site and from 46.3 to 89.1 mm at OJP site. SNODAS SWE was in good agreement with observations at OA site except for the 2013 water year. Besides precipitation data quality, assimilation also contributes to SNODAS SWE accuracy. There were several noticeable assimilations at these sites from the 2013 to 2015 water years, and SNODAS SWE accuracy increased after assimilations. In the 2013 water year, SNODAS had the highest precipitation overestimation bias among all years, and there was assimilation at OJP and FEN but not at OA. Consequently, RMSE was 164.3 mm for OA, higher than that of OJP (100.2 mm) and FEN (61 mm) although SNODAS precipitation in this year was similar in all three sites. However, in the years when assimilation occurred in all sites, OA had the highest accuracy. Take the 2015 water year for example, RMSE was 21.7 mm for OA, much lower than that at OJP (70.6 mm) and FEN (64.9 mm). This suggests that missing model structure (i.e., canopy interception process at OJP and missing blowing snow transport at FEN) played bigger role in SNODAS SWE accuracy than did assimilation. The data assimilation frequency for this region was extremely low (less than once a year on average during the 2011 to 2015 water years; Figure 4). This is much lower than in mountainous areas in the United States (https://www.nohrsc.noaa.gov/pro/earth/archive.html). With such low frequency, erroneous precipitation data and the incomplete model structure of NSM together contribute more to the poor SNODAS performance in this region than does assimilation. Overall for BERMS sites, the main cause of the poor performance of SNODAS SWE was the high overestimation bias in SNODAS precipitation data in 2012–2015 water years (Figure 4). The major cause for SNODAS SWE inaccuracy was the missing processes in SNODAS model when SNODAS precipitation data bias was low. In all, the influence of erroneous precipitation data is important but only for certain years, while that of missing processes is important every year.

4.1.2. Prairie

Upscaled snow survey data were compared to SNODAS predicted SWE at SCRB during 2011 to 2013 water years (Figure 5a). Results show a low R^2 value of 0.001 with relatively large RMSE value of 46.5 mm and MB value of 0.27, suggesting that SNODAS SWE is not correlated with observed SWE at SCRB. This may be mainly caused by a SNODAS NSM structural deficiency—missing blowing snow transport simulation, while the spatial variation of winter SWE in the prairie environment is primarily controlled by wind redistribution of snow (Fang & Pomeroy, 2009; Pomeroy et al., 1993; Pomeroy & Li, 2000). To verify the influence of this missing process, the SNODAS SWE was also directly compared to snow survey transect data from different land covers at SCRB (Figure 5b). SNODAS overestimated SWE in grassland, stubble field, and wetland with MB of 0.52, 0.48, and 0.32, respectively. In blowing snow sink areas, such as woodland and river channel, SNODAS underestimated SWE with MB of −0.33 and −0.38 for woodland and river channel, respectively. RMSE values ranged from 35.4 to 132.1 mm, and R^2 values were lower than 0.3 for all land covers. This suggests that it is challenging for SNODAS to capture spatial distribution of SWE in the Canadian prairie without including blowing snow transport simulation.

SNODAS overestimated precipitation at both UofS and Langenburg stations during the 2011 to 2013 water years with a varied overestimation rate that increased year by year (Figure 6). In the 2011 water year,

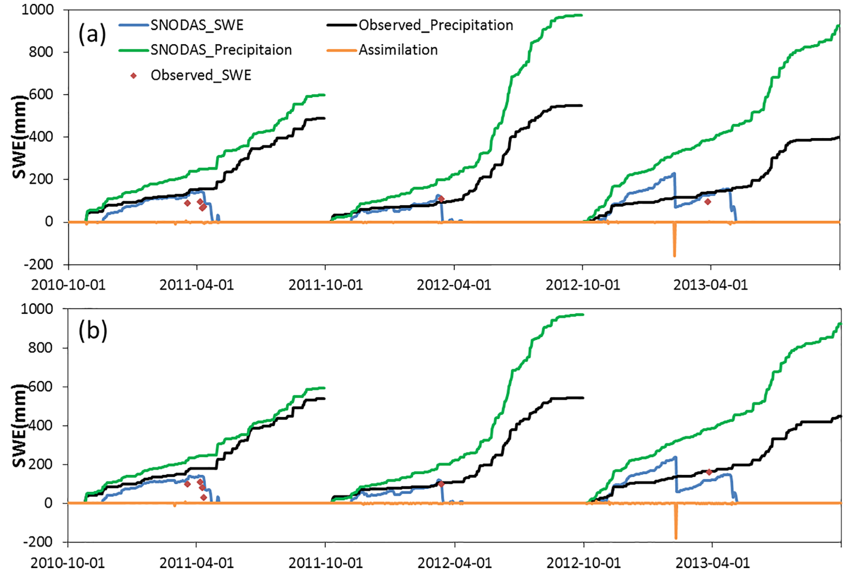

Figure 6. Time series comparisons of observed and Snow Data Assimilation System (SNODAS) predicted snow water equivalent (SWE) and precipitation at two meteorological stations at Smith Creek Research Basin (SCRB): (a) University of Saskatchewan station and (b) Langenburg station.

SNODAS overestimated the precipitation by only 21% and 9% at UofS and Langenburg stations, respectively. SNODAS overestimated precipitation at these two stations ranged from 78 to 132% in the following water years. In addition to SNODAS precipitation accuracy, assimilation affects SNODAS SWE accuracy at both stations. Despite large SNODAS overestimated precipitation at both stations in the 2013 water year, RMSE was 31.9 and 39.6 mm for UofS and Langenburg, respectively. This was much lower than RMSE in other years with an exception of RMSE of 22.3 mm at Langenburg in the 2012 water year. The higher SNODAS SWE accuracy in 2013 is attributed to a noticeable assimilation on 8 February 2013 at both stations. However, there were only a few noticeable assimilations (less than once a year) in SCRB during the study period. Consequently, the NSM simulation itself was the major factor controlling the accuracy of SNODAS products in this area.

4.1.3. Canadian Rockies

In MCRB, observed SWE was compared to SNODAS SWE in three landscape groups. Figure 7a shows the comparison of SNODAS and observed SWE from all samples from coniferous forests and clearings in MCRB. SNODAS SWE was not correlated to SWE observations for either forest or clearing land cover, with R^2 values of 0.26 and 0.20, respectively. SNODAS grossly overestimated SWE at both land covers with MB of 4.76 for forests and MB of 1.79 for clearings. SNODAS SWE accuracy was lower in forests than in clearings as RMSEs were 374.8 and 323.9 mm for forests and clearings, respectively. Poorer SNODAS SWE accuracy at forest sites, especially the high SWE overestimation, is likely attributed to the structure of the SNODAS NSM in lacking simulation for canopy snow interception, which in turn reduces model accuracy for subcanopy snow accumulation and ablation.

In addition, clearings at MCRB are relatively small and are surrounded by dense forest. Snow accumulation at them should have minimal impact from missing blowing snow and forest canopy interception processes in SNODAS. This means theoretically SNODAS SWE should closely match forest clearing observations. However, SNODAS overestimated SWE in clearings with relatively high MB and RMSE. This is likely caused by a precipitation error that drives SNODAS NSM in MCRB.

Influence of precipitation and assimilation from the SNODAS model on SNODAS SWE accuracy was evaluated by comparing SNODAS SWE and cumulative SNODAS precipitation to observed SWE and cumulative observed precipitation at UC and Upper Forest (Figures 8a and 8b). SNODAS precipitation overestimation bias increased from the 2011 to 2015 water years. SNODAS and observed precipitation were comparable in the 2011 and 2012 water years with MB of −0.15 and 0.17, respectively. While SNODAS overestimated precipitation in following water years with MB of 0.41, 1.64, and 1.48 in 2013, 2014, and 2015,

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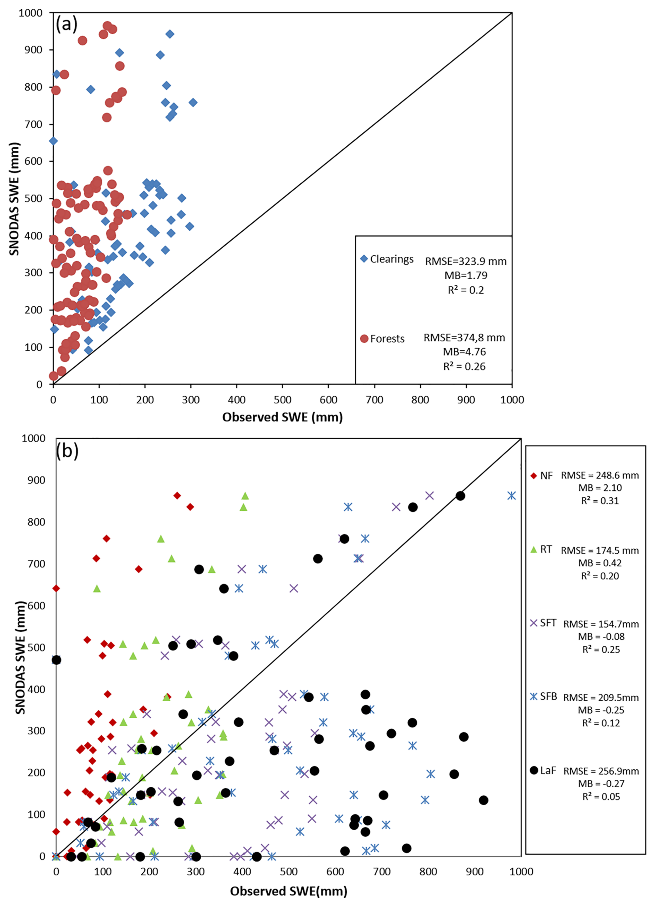

Figure 7. Comparisons of snow surveyed snow water equivalent (SWE) and Snow Data Assimilation System (SNODAS)-predicted SWE across various sites at Marmot Creek Research Basin: (a) Clearings and Forests sites and (b) alpine slopes around Fisera Ridge (NF: north facing slope, RT: ridge top, SFT: south facing slope top, SFB: south facing slope bottom, LaF: larch forest below south facing slope and at end of ridge top).

respectively. RMSE between SNODAS and observed SWE were much lower in the 2011 and 2012 water years than other years at both forest and clearing sites. For UC, RMSEs were 181.6, 139.9, 264.7, 505.2, and 247.2 mm from 2011 to 2015 water years. Assimilation clearly plays a negative role in SNODAS SWE accuracy at this site in the 2011 and 2012 water years in MCRB. The cumulative precipitation from SNODAS and observation were nearly identical before the peak SWE in 2011 and 2012 water years at UC, but RMSEs between SNODAS and observed SWE were still quite high. This relatively large discrepancy in SNODAS and observed SWE is likely caused by the total assimilation of 162.6 and 102.1 mm in the SNODAS system before peak SWE in the 2011 and 2012 water years.

At FR, snow was usually redistributed from the windward sites (north facing slope [NF] and ridge top [RT]) and deposited on the leeward sites (south facing top [SFT], south facing bottom [SFB], and larch forest [LaF]; Figure 7b). SNODAS SWE accuracy was low in all five sites with RMSE higher than 150 mm. SNODAS overestimated SWE at windward sites and underestimated SWE at leeward sites. MB values at windward sites were 2.1 and 0.42 for NF and RT, respectively, and were −0.08, −0.25, and −0.27 for SFT, SFB, and LaF, respectively (Figure 7b). This is likely attributed to missing blowing snow transportation simulation in the SNODAS NSM.

Time series of SNODAS and observed SWE were compared to assess the SNODAS precipitation data influence on SNODAS SWE accuracy at FR (Figure 8c). SNODAS underestimated precipitation by 44% and 22% in the 2011 and 2012 water years, respectively, causing SNODAS to underestimate SWE for all sites except for NF. In the 2014 and 2015 water years, SNODAS overestimated precipitation at FR by 57% and 67%, and this led to the overestimation of SWE in all five sites. Although the overestimation of SNODAS precipitation in the 2015 water year was higher than that in 2014, RMSE of SWE was lower in 2015 than in 2014 as a result of a few more significant cases of assimilation in which SWE was reduced in the 2015 water year.

4.2. CRHM Evaluation

To evaluate the performance of CRHM, the ObsMet-simulated SWE was compared to snow survey data at a middle elevation mature coniferous forest (i.e., Upper Forest) and clearing (i.e., UC), and alpine open slopes and deciduous forests at FR in MCRB for the 2011 to 2015 water years (Figure 9). ObsMet captured the magnitude and timing of SWE for most years at the coniferous forest and clearing sites (Figures 9a and 9b). RMSE ranged from 22.5 to 78.5 mm with a 5-year mean value of 50 mm for the forest and was in the range from 30.9 to 78.2 mm with a 5-year mean value of 53.5 mm for the clearing (Table 2). MB was relatively low, with 5-year mean values of 0.37 and −0.16 for the forest and clearing, respectively. At the alpine FR site, ObsMet captured the SWE by simulating a blowing snow sequence from source to sink areas (Figures 9c–9g) with 5-year mean RMSE ranging from 106 to 180.4 mm and 5-year mean MB from −0.1 to 1.19 (Table 2). Although RMSE in the alpine is much higher than that in the forest, it is still acceptable because the SWE magnitude in the alpine is much higher. Evaluation of SWE at a landscape point scale indicates that CRHM adequately predicted snow accumulation and ablation at various landscapes in MCRB.

To assess the ability of CRHM to simulate basin hydrology, the ObsMet-simulated basin outflow was compared to the streamflow measurements at the MCRB basin outlet during 2011 to 2015 water years (Figure 10). The ObsMet-simulated daily mean streamflow agreed well with the observations; annual RMSE ranged from 0.08 to 0.39 m^3/s with a mean value of 0.18 m^3/s for these five water years. Annual MB value ranged from −0.27 to 0.25 with 5-year mean value of −0.06. This suggests that CRHM had

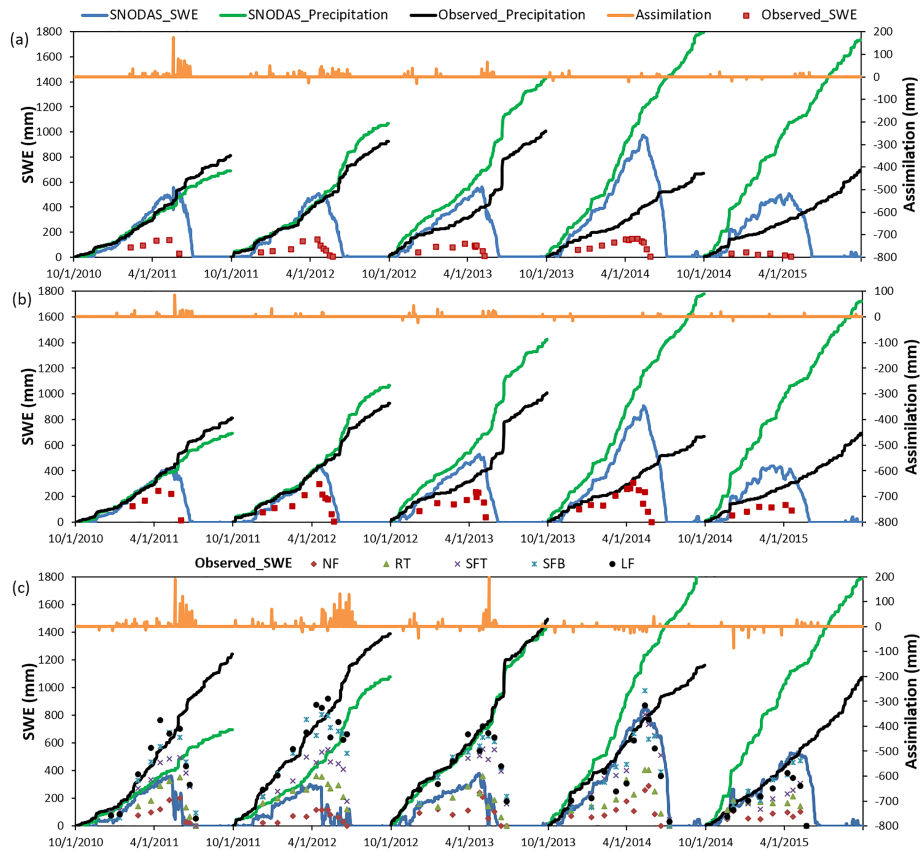

Figure 8. Time series comparisons of observed and Snow Data Assimilation System (SNODAS)-predicted snow water equivalent (SWE) and precipitation at meteorological observation sites in Marmot Creek Research Basin, Alberta, Canada. (a) Upper Forest, (b) Upper Clearing, and (c) alpine slopes around Fisera Ridge (NF: north facing slope, RT: ridge top, SFT: south facing slope top, SFB: south facing slope bottom, LaF: larch forest below south facing slope and at end of ridge top).

capability for simulating the timing and magnitude of surface and subsurface processes for streamflow generation in MCRB.

4.3. SNODAS Performance at Basin Scale

To assess SNODAS SWE accuracy at basin scale, basin mean SNODAS SWE was compared to the ObsMet-simulated basin average SWE in MCRB during 2011 to 2015 water years (Figure 11). Basin mean SNODAS SWE was much higher than ObsMet-simulated basin mean SWE for these 5 years; overestimation of basin mean SNODAS SWE ranged from 37% in 2012 to 327% in 2015 with 5-year mean overestimation value of 135% compared to ObsMet-simulated basin mean SWE. The RMSE between SNODAS and ObsMet-simulated basin SWE was also high, ranging from 66.75 mm in 2012 to 302.34 mm in 2014 with 5-year mean RMSE value of 180.01 mm.

To examine the effect of SNODAS precipitation on SNODAS SWE accuracy, the cumulative basin average precipitation from SNODAS and observations were compared during 2011 to 2015 water years (Figure 11). The basin average SNODAS precipitation was calculated by averaging the precipitation data from SNODAS grid cells covering MCRB. The basin average observed precipitation was calculated by interpolating the precipitation measured from three Geonor gauges: HM, UC, and FR at MCRB using the observed elevation precipitation gradient (Fang et al., 2013). The accuracy of SNODAS precipitation data at MCRB was low during the 5-year study period (mean RMSE = 371 mm and mean MB = 0.37) and varied in different water years. SNODAS underestimated precipitation data at MCRB with MB of −0.25 and −0.15 and RMSE of 152.09 and 95.35 mm for 2011 and 2012 water years, respectively. In contrast, SNODAS overestimated precipitation at MCRB by 18 to 145% for 2013 to 2015 water years. For 2013 to 2015 water years,

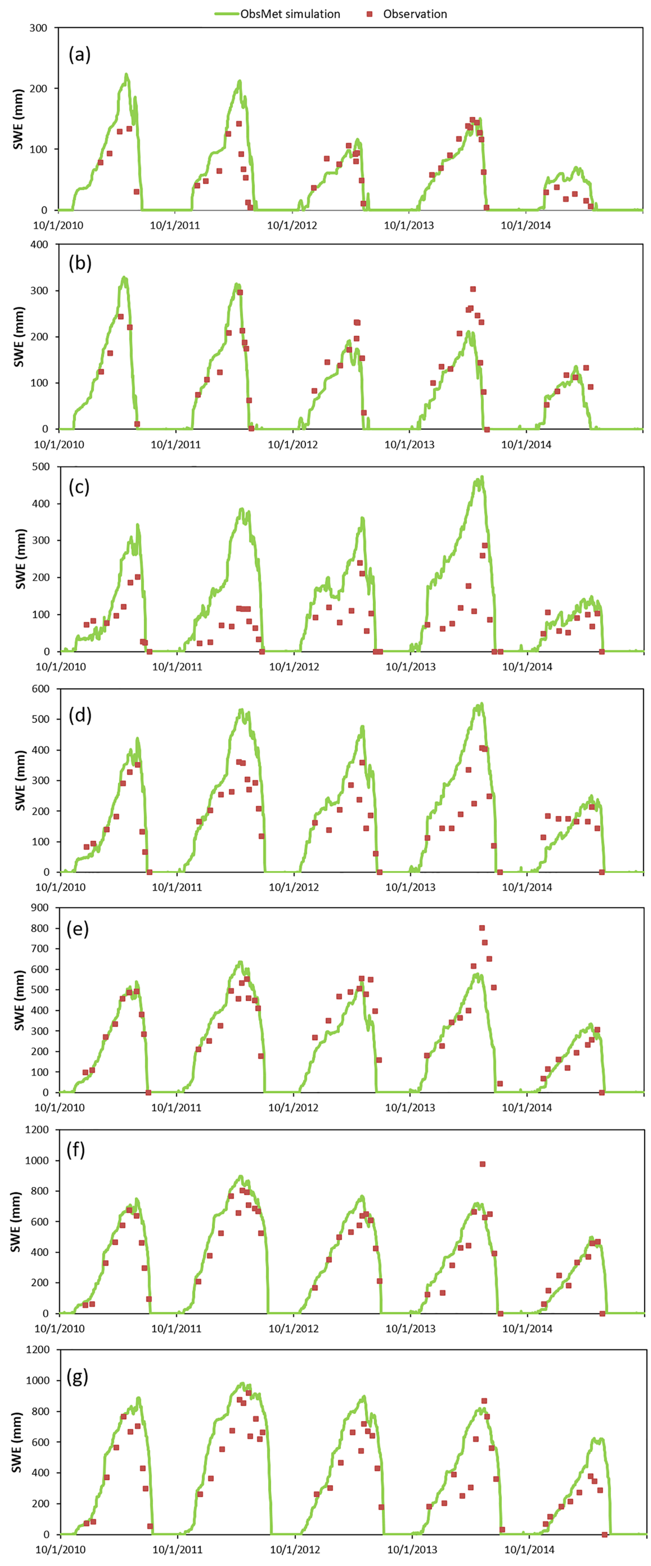

Figure 9. Comparison of observed and ObsMet-simulated snow water equivalent (SWE) at Marmot Creek Research Basin, Alberta, Canada: (a) Upper Forest, (b) Upper Clearing, and Fisera Ridge sites: (c) north facing slope, (d) ridge top, (e) south facing slope top, (f) south facing slope bottom, and (g) larch forest.

SNODAS overestimated basin precipitation by 18%, 95%, and 145%, but SNODAS overpredicted basin SWE by 117%, 230%, and 327% compared to ObsMet-simulated basin SWE (Table 3). This suggests that the accuracy of SNODAS SWE is influenced by other factor in addition to the accuracy of the SNODAS precipitation.

The lack of blowing snow transport and canopy snow interception simulations in the SNODAS NSM is another factor that leads to overestimation of basin SWE in MCRB. To verify this, a CRHM simulation with two process modules turned off (ObsMet_NBI) was conducted with local observed driving forces. Figure 11 shows that the ObsMet_NBI-simulated SWE was much higher than ObsMet-simulated SWE in MCRB; on average overestimation was 50% for five water years and varied annually from 38% in 2011 to 72% in 2012 (Table 3). Compared to ObsMet simulation, ObsMet_NBI-simulated peak SWE for MCRB was 44 to 83% higher during the five water years. ObsMet_NBI simulation implies that missing blowing snow transport and canopy snow interception simulations in SNODAS are other factors causing the SNODAS SWE overestimation in MCRB.

Impact of assimilation frequency and magnitude on SNODAS SWE accuracy were also analyzed (Figure 11). There were approximately 91 data assimilations related to water balance calculations in MCRB in SNODAS system during 2011 to 2015 water years. Assimilation was more frequent in first three water years: 19 times and 798.7 mm in total for 2011, 31 times and 848.4 mm in total for 2012, and 19 times and 384.4 mm in total for 2013. Frequent and higher positive assimilations in the 2011 to 2012 water years partially compensated underestimation of SNODAS precipitation. This explains why SNODAS overestimated SWE at MCRB in those two years while it underestimated the precipitation. There were fewer assimilations in the 2014 and 2015 water years: 10 times and −17.1 mm in total for 2014 and 12 times and −34.4 mm in total for 2015. Assimilations before peak SWE in the 2014 and 2015 water years were mainly negative, with more negative total assimilation amount in 2014 (−31.4 mm) than in 2015 (−99 mm). This leads to much lower SNODAS peak SWE in 2015 despite similar SNODAS precipitation in both years.

4.4. Mimicking SNODAS Simulations Using CRHM

To quantify the contribution of erroneous precipitation, model structure shortcomings, and SNODAS data assimilation accuracy in MCRB, five CRHM simulations with different model structures using SNODAS precipitation were conducted during 2011 to 2015 water years (Figure 12). Details for these five simulations can be found in section 3.5. Figure 12 show that compared to ObsMet-simulated SWE in MCRB, CRHMSP grossly overestimated SWE, with 5-year mean overprediction of 57%, and that was directly related to 5-year mean 37% overestimation of SNODAS precipitation data (Table 3). CRHMSP-simulated SWE accuracy varied annually and was strongly influenced by SNODAS precipitation bias. In comparison with ObsMet-simulated SWE in MCRB, CRHMSP underestimated SWE by 31% and 50% in 2011 and 2012, when SNODAS underestimated precipitation by 25% and 15%, respectively. Overestimation of CRHMSP-simulated SWE in other water years ranged from 31% in 2013 to 338% in 2015 compared to ObsMet-simulated SWE, which is related to overestimated SNODAS precipitation by 18% in 2013 to 145% in 2015 (Table 3). Figure 12a shows that CRHMSP_NB overpredicted basin SWE

Table 2
Statistics Comparing Observed and ObsMet-Simulated SWE at Marmot Creek Research Basin Sites in Alberta, Canada: Upper Forest (UF), Upper Clearing (UC), and Fisera Ridge, Which Contains the North Facing Slope (NF), Ridge Top (RT), South Facing Slope Top (SFT), South Facing Slope Bottom (SFB), and Larch Forest (LaF) Sites

Year	UF			UC			NF		
	RMSE	NRMSE	MB	RMSE	NRMSE	MB	RMSE	NRMSE	MB
Five-year mean	50.0	0.67	0.37	53.5	0.35	−0.16	139.87	1.56	1.19
2010	78.5	0.84	0.68	39.8	0.26	0.19	89.3	1.00	0.65
2011	75.9	1.15	0.97	30.9	0.21	0.002	202.0	3.12	2.89
2012	22.5	0.32	0.11	46.8	0.30	−0.23	98.1	0.97	0.83
2013	24.7	0.24	−0.04	78.2	0.44	−0.33	181.2	1.56	1.41
2014	29.8	1.31	1.22	51.7	0.52	−0.24	36.0	0.46	0.26
		RT			SFT			SFB	
	RMSE	NRMSE	MB	RMSE	NRMSE	MB	RMSE	NRMSE	MB
Five-year mean	125.2	0.65	0.47	106.0	0.29	−0.10	107.3	0.25	0.14
2010	79.8	0.30	0.30	22.8	0.08	0.03	125.8	0.35	0.29
2011	155.2	0.61	0.53	94.2	0.24	0.20	112.5	0.18	0.16
2012	117.6	0.66	0.56	128.5	0.30	−0.25	92.4	0.20	0.14
2013	170.1	0.90	0.77	151.9	0.34	−0.23	126.5	0.29	0.02
2014	39.7	0.25	−0.01	75.6	0.28	−0.23	56.1	0.22	0.12
		LaF							
	RMSE	NRMSE	MB						
Five-year mean	180.4	0.40	0.31						
2010	218.2	0.54	0.43						
2011	196.3	0.30	0.27						
2012	189.3	0.39	0.33						
2013	115.9	0.26	0.18						
2014	167.6	0.67	0.44						

Note. RMSE and MB are defined in the text. NRMSE is the normalized RMSE and is the ratio of RMSE to mean observed SWE.
Abbreviation: SWE: snow water equivalent.

compared to CRHMSP, and overestimation in CRHMSP_NB basin SWE ranged from 8.1% in 2011 to 31.5% in 2015 with 5-year mean of 22.0% (Table 3). For CRHMSP_NI simulation, the simulated basin SWE was 14% in 2015 to 50% in 2012 higher with five-year mean of 21% overestimation compared to CRHMSP-simulated SWE. With both blowing snow transportation and canopy interception simulations turned off, CRHMSP_NBI simulated much more SWE than CRHMSP (Figure 12a), overestimation ranging from 36% in 2011 to 66% in 2012 with 5-year mean of 42% (Table 3). One source of this annual variation may be the changing climate conditions across water years.

This study shows on average, blowing snow transport and canopy interception accounted for approximately 35% of snow loss in MCRB, with annual snow loss ranging from 24 to 49% for 2011 to 2015 water years. Without simulating these two processes, the simulated peak SWE increased by 57% on average for 2011 to 2015 water years when comparing CRHMSP-simulated peak SWE to that simulated by CRHMSP_NBI, and higher peak SWE in CRHMSP_NBI simulation varied from 55.7% in 2013 to 132.3% in 2011 (Figure 12). These results highlight the importance of including the two processes when modeling the snowpack in Canadian Rockies.

Although CRHMSP_NBI-simulated SWE is closer to SNODAS SWE than other simulations demonstrated above, it is still far from matching SNODAS SWE. This is because SNODAS SWE includes the influence of data assimilation. To completely mimic SNODAS, a fifth simulation CRHMSP_NBI+ASSIM was conducted, in which the assimilation derived from the water balance calculation was added to CRHMSP_NBI simulation (Figure 12b). CRHMSP_NBI+ASSIM was comparable to SNODAS with 1 to 22% more SWE estimated for 2011 to 2015 water years and 5-year mean overestimation of 7% (Table 3). The 5-year mean RMSE_m was 41.1 mm, with annual RMSE_m ranging from 22.8 mm in 2011 to 49.6 mm in 2012 (Table 3). This difference can be explained by different parameters and forcing variables (other than precipitation) used in two models, but aside from that, CRHMSP_NBI+ASSIM is able to mimic the SNODAS NSM system.

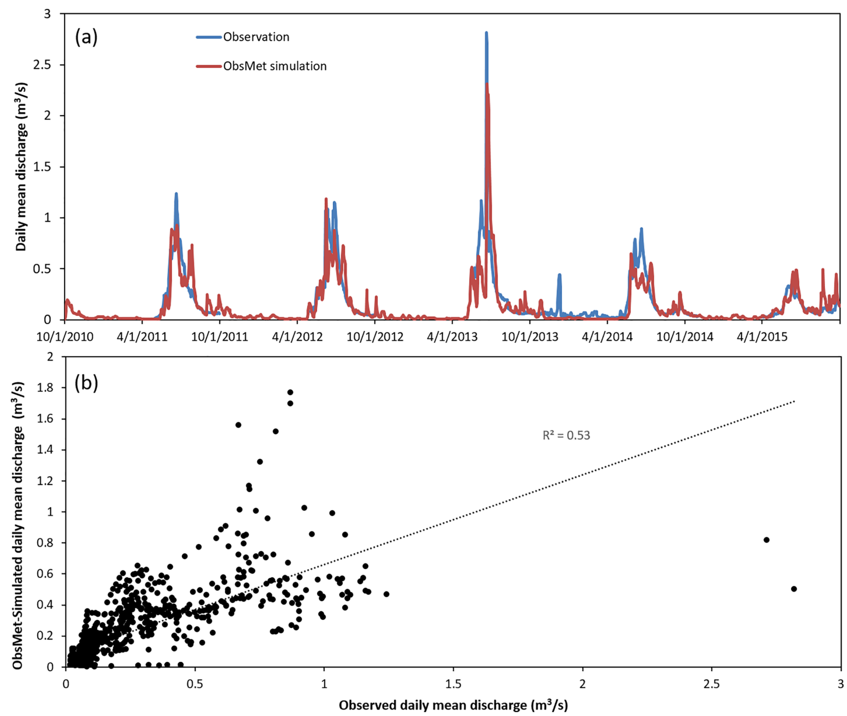

Figure 10. Comparisons of observed and ObsMet-simulated daily mean discharge at the outlet of Marmot Creek Research Basin, Alberta, Canada. (a) Time series comparison and (b) scatter plot comparison.

Simulated SWE in MCRB from CRHMSP, CRHMSP_NBI, and CRHMSP_NBI+ASSIM was compared to ObsMet-simulated SWE to quantify the influence of precipitation, missing processes, and data assimilation on SNODAS SWE accuracy (Table 3). RMSE_m for CRHMSP simulation representing inaccurate SNODAS precipitation had 5-year mean of 132.1 mm and varied from 33.5 mm in 2013 to 202.3 mm in 2015. RMSE_m for CRHMSP_NBI simulation mimicking inaccurate precipitation and two missing processes in SNODAS was higher, with 210.01 mm for 5-year mean. CRHMSP_NBI simulation increased RMSE_m in most years, except for 2012, in which RMSE_m decreased to 34.09 mm from 60.91 mm for CRHMSP simulation. This lower RMSE_m in 2012 could be explained by that SNODAS precipitation underestimation bias in 2012 was compensated by the missing processes. After data assimilation, the mean RMSE_m of CRHMSP_NBI +ASSIM-simulated SWE reduced to 193.2 mm during the five water years. In all, data assimilation contributed positively to SNODAS accuracy, but the influence was varied among water years. It decreased the RMSE_m by 2.6 and 107.3 mm in the 2014 and 2015 water years, respectively. However, in the 2011,

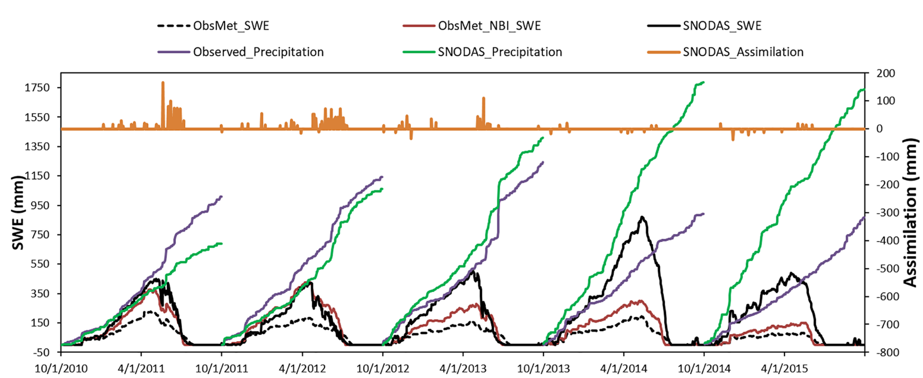

Figure 11. Comparisons of Snow Data Assimilation System (SNODAS), ObsMet, and ObsMet_NBI-simulated basin average snow water equivalent (SWE), cumulative SNODAS and cumulative observed precipitation, and data assimilation magnitude in SNODAS at Marmot Creek Research Basin, Alberta, Canada.

Table 3
RMSE_m and MB_m Between SWE That Simulated by Various Simulations, and RMSE and MB Between Observed (Ob_P) and SNODAS (SNODAS_P) Precipitation at Marmot Creek Research Basin, Alberta, Canada

Year		SNODAS			SNODAS_P	
		RMSE_m	MB_m		RMSE	MB
All	ObsMet	180.01	1.35	Ob_P	371.79	0.37
2011		89.68	0.63		152.09	−0.25
2012		66.75	0.37		95.35	−0.15
2013		140.09	1.17		116.79	0.18
2014		302.34	2.3		518.68	0.95
2015		196.35	3.27		613.68	1.45
		ObsMet _NBI			CRHMSP_NBI+ASSIM	
		RMSE_m	MB_m		RMSE_m	MB_m
All	ObsMet	66.58	0.5	SNODAS	41.1	0.07
2011		57.95	0.38		22.76	0.02
2012		103.08	0.72		49.58	0.22
2013		59.5	0.47		42.2	0.09
2014		59.15	0.43		41.55	0.01
2015		33.54	0.46		44.26	0.08
		CRHMSP			CRHMSP_NI	
		RMSE_m	MB_m		RMSE_m	MB_m
All	ObsMet	132.13	0.57	CRHMSP	45.05	0.21
2011		46.04	−0.31		29.86	0.26
2012		60.91	−0.5		39.11	0.5
2013		33.49	0.31		34.68	0.2
2014		198.68	1.41		67.3	0.18
2015		202.25	3.38		44.68	0.14
		CRHMSP_NBI			CRHMSP_NB	
		RMSE_m	MB_m		RMSE_m	MB_m
All	ObsMet	210.01	1.23	CRHMSP	57.25	0.22
2011		46.92	−0.06		19.32	0.08
2012		34.09	−0.17		22.15	0.15
2013		104.27	0.83		41.2	0.18
2014		312.53	2.32		69.03	0.2
2015		329.73	5.35		95.22	0.31
		CRHMSP_NBI+ASSIM			CRHMSP_NBI	
		RMSE_m	MB_m		RMSE_m	MB_m
All	ObsMet	193.18	1.51	CRHMSP	91.77	0.42
2011		90.78	0.66		45.6	0.36
2012		98.11	0.68		58.07	0.66
2013		152.51	1.37		72.84	0.39
2014		309.93	2.33		121.23	0.38
2015		222.45	3.62		129.09	0.45
		CRHMSP+ASSIM				
		RMSE_m	MB_m			
All	ObsMet	109.71	0.79			
2011		42.24	0.28			
2012		41.57	0.19			
2013		79.66	0.74			
2014		192.44	1.4			
2015		115.4	1.94			

Abbreviations: MB: model bias; RMSE: root-mean-square error; SNODAS: Snow Data Assimilation System; SWE: snow water equivalent.

2012, and 2013 water years, data assimilation increased the RMSE_m by 43.9, 64.0, and 48.2 mm, respectively. This indicates that data assimilation that conducted in the SNODAS system did not always improve the accuracy of SNODAS SWE at MCRB. This might be a result of using inaccurate snow observation data in the SNODAS data assimilation system. The details of snow observations used for SNODAS assimilation

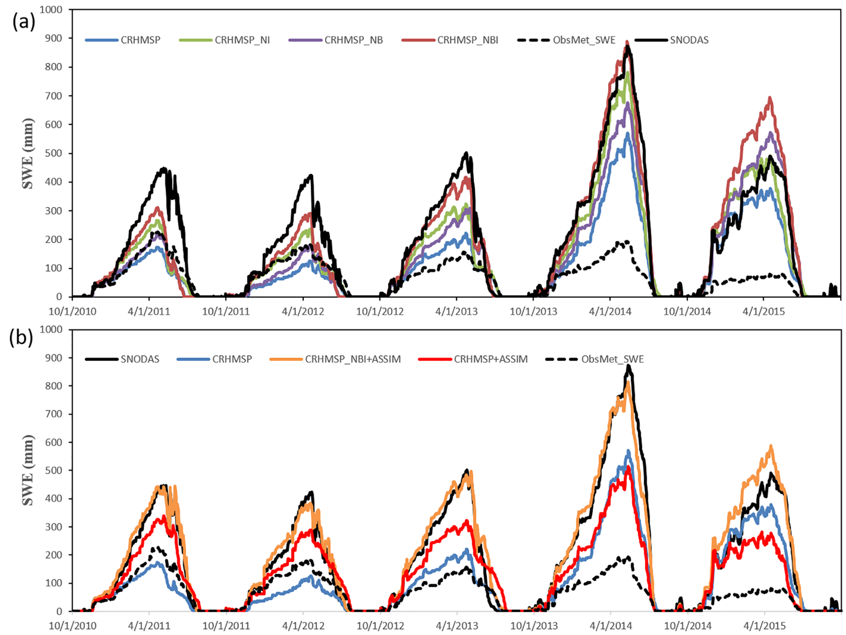

Figure 12. Comparisons of Snow Data Assimilation System (SNODAS) and ObsMet snow water equivalent (SWE) to simulations driven by SNODAS precipitation at Marmot Creek Research Basin, Alberta, Canada. (a) Influence of precipitation, snow interception, and blowing snow transport simulations on basin SWE accuracy and (b) Cold Regions Hydrological Model (CRHM) mimicking SNODAS simulation.

in this area during these years were not explored. Snow-pillow measurement sites in the Canadian Rockies are commonly located in small level clearings at medium elevations and are not representative of areas with dense forests and varying topographic exposure to radiation and wind (Pomeroy et al., 2002; Pomeroy & Gray, 1995). If data from such sites are used to nudge the SNODAS product, then additional uncertainty occasionally may be spatially propagated (Dozier et al., 2016). Information about the type of data used for SNODAS data assimilation would be beneficial to researchers and water resources managers.

4.5. Assimilating SNODAS Into CRHM

SNODAS overestimated SWE at all sites in three Canadian environments for 2011 to 2015 water years. This overestimation was caused by overestimated precipitation and missing components to the SNODAS model structure. Data assimilation can compensate for this problem in many places. However, the frequency of data assimilation in the boreal forest and prairie was very low—once or twice a year. Although the assimilation frequency is higher in the Canadian Rockies (18 times a year on average), more frequent data assimilation does not always make for better results. To correct SNODAS SWE bias, one must fix the problems of missing processes and precipitation prediction. The complete CRHM model (CRHMSP) can solve the problem of missing processes. Although the assimilation data in the Canadian Rockies are not always correct, it is believed that the precipitation problem can be partially solved after incorporating assimilation into the CRHMSP simulation. Therefore, assimilation data calculated from the water balance were incorporated into CRHMSP simulation (CRHMSP+ASSIM) to correct some of the bias of SNODAS SWE.

The CRHMSP+ASSIM-simulated SWE in MCRB is shown in Figure 12b. Compared to the original SNODAS-simulated SWE, CRHMSP+ASSIM improved SWE accuracy after assimilation into CRHM in MCRB. When comparing to ObsMet-simulated SWE, 5-year mean RMSE_m dropped from 180.01 mm for SNODAS simulation to 109.7 mm for CRHMSP+ASSIM simulation, and 5-year mean MB_m also decreased from 1.35 for CRHMSP+ASSIM simulation to 0.79 for SNODAS simulation (Table 3). This indicates that assimilation of SNODAS into CRHM can potentially improve SNODAS SWE accuracy even though the problem caused by erroneous SNODAS precipitation cannot be completely solved.

In a data assimilation system, product accuracy is heavily reliant on two factors: model simulation and assimilation. In a region like MCRB where there are no frequent and reliable data resources for assimilation, a correct model structure is much more important than data assimilation. Therefore, there are two recommendations to the SNODAS system team from this study. Recommendation 1 is to incorporate blowing snow redistribution, subcanopy snowmelt energetics, and forest canopy snow interception and sublimation into the SNODAS NSM or develop a new model that includes these processes. Although this would reduce computational efficiency and add parameterization complexity, the benefits of improved product accuracy in all regions, especially those with infrequent and unreliable assimilation input data, would appear to be substantial. Recommendation 2 is to increase the frequency and coverage of assimilation of snow information into snow modeling in Canada in whatever data assimilation platform is used for this country. Additionally, the SNODAS team should make the algorithms and code of the system and the surface measurements that assimilated into the system publicly accessible. This would help the user understand SNODAS better and may further improve the system.

5. Conclusions

This study evaluated SNODAS SWE in three western Canadian environments: boreal forest, prairie, and mountain. In the boreal forest, SNODAS worked very well in deciduous forest stands, less well in the mixed deciduous and needleleaf forests, and poorly in an open, windswept fen. In the prairie, the SNODAS-predicted SWE was not correlated with observed SWE, and the RMSE and MB of prediction were relatively high. This suggests that SNODAS poorly captures spatial variation of SWE in the open, windswept Canadian Prairie environment. In the Canadian Rockies, SNODAS data quality varied from year to year, and SNODAS overestimated measured SWE on the ground at forest, clearing, and alpine exposed slope sites in all years as there was consistent overestimation in the precipitation that drove SNODAS NSM. A trend of increasing bias for SNODAS precipitation data was noted for all three study areas for the 2011 to 2015 water years. Like other independent evaluations (e.g., Bair et al., 2016; Dozier et al., 2016), this research also found that SNODAS sometimes can produce drastic and serious errors and that these could be persistent. Therefore, it is not recommended to use SNODAS to validate other models or measurements of spatially distributed SWE in the environments studied here.

In MCRB, a well-studied headwater basin in Canadian Rockies, SNODAS SWE accuracy was evaluated by comparing it to the CRHM physically based hydrological model. Several CRHM simulations with different model configurations were conducted to mimic the SNODAS system and were used to identify sources of SNODAS errors. Results show that the accuracy of SNODAS SWE data is greatly influenced by (1) missing blowing snow transport, subcanopy snowmelt energetics, and canopy snow interception and sublimation processes in the SNODAS mass balance calculation and (2) erroneous precipitation in the SNODAS NSM. Data assimilation to the SNODAS system in MCRB could not always improve simulations. Results show that including the missing snow redistribution, melt, and sublimation processes could improve the accuracy of SNODAS SWE predictions. An additional benefit is that the CRHM assimilation process downscales the SNODAS data to the HRU scale that permits multiscale snow and hydrological modeling in a mountain basin. Overall, results show promise for assimilation-based bias correction of SNODAS-like data products for basins in Canada with sparse precipitation measurements and the ability to use these products to estimate peak SWE at different spatial scales. To improve the SNODAS SWE accuracy and public accessibility, especially in the regions with sparse reliable input data for assimilation, three recommendations are also provided to the NOHRSC SNODAS team and others who would build snow data assimilation models: (1) the snow redistribution, sublimation, and subcanopy melt processes that are missing from NSM should be included; (2) the frequency and coverage of assimilation of snow information into snow modeling should be increased in Canada; and (3) documentation on SNODAS algorithms and code and metadata on surface measurements for SNODAS assimilation run can be made publicly accessible.

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