Assessing the impacts of vegetation heterogeneity on energy fluxes and snowmelt in boreal forests

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Abstract

Aims

In the mid- and high-latitude regions, three quarters of the land surface is covered by boreal conifer forests, and snow lasts for 6–8 months of the year. Correctly modeling surface energy balance and snowmelt at mid- and high-latitudes has a significant influence on climate and hydrological processes. However, the heterogeneous and clumped forest structure exerts important control over the radiative energy at the forest floor, which results in large variations of underneath snow cover and snowmelt rate. The goal of this study is to investigate the impact of hierarchically clumped vegetation structure in boreal forest on snowmelt and exchanges of energy and water.

Methods

We used a simple Clumped Canopy Scheme (CCS) for canopy radiation transfer to characterize the impact of the clumped forest structure on net radiation at the snow surface underneath forests. The CCS was integrated with the Variable Infiltration Capacity macroscale hydrological model (herein referred to as VIC-CCS) to characterize the impact of clumped vegetation structure on surface energy balance and snowmelt during the snow season. A twin simulation, VIC-CCS and the standard VIC model, was performed to isolate the impact of CCS on the energy and water fluxes and snowmelt rates. The simulation results were compared to *in situ* measurements at four different forest stands: old aspen forest in the Southern Study Area (SOA), black spruce forests in the Southern and Northern Study Areas (SOBS and NOBS) and fen wetland in the Northern Study Area (NFEN) within the Boreal Ecosystem–Atmosphere Study (BOREAS) region in central Canada during 1994 to1996.

Important Findings

Simulations showed that the implementation of CCS has reduced incoming long-wave radiation at the underlying snow surface and, thereby, lowered the snowmelt rate. Comparison against ground observations of net radiation and surface flux rates showed a reasonable agreement while demonstrating implementation of CCS can markedly improve model surface energy budget and energy inputs computation for snowmelt. The modeled snowmelt matches reasonably well with observations with root mean square error (RMSE) ranging from 16.51 to 19.81 mm using VIC-CCS versus 29.86 to 32.61 mm for VIC only in the four forest sites. The improvement is the most significant for the deciduous forest (old aspen) site, reducing RMSE by16 mm. This study demonstrates that taking into account the effect of the clumped forest structure in land surface parameterization schemes is critical for snowmelt prediction in the boreal regions.

Keywords: clumping • snowmelt • VIC • boreal forests

INTRODUCTION

In the mid- and high-latitude regions, three quarters of the land surface is boreal conifer forests, and snow remains for 6–8 months of the year. Correctly modeling snowmelt in mid- and high-latitudes has a significant impact on meteorological and hydrological processes. Snowmelt affects surface energy and water balance, thus atmosphere boundary layer development. Spring water supply in those regions is highly dependent on snowmelt. However, the hierarchically heterogeneous and clumped forest structure modifies radiative fluxes in those regions and causes large variations of the surface albedo in boreal regions (Ni and Woodcock 2000). Low reflectivity of boreal forests results in lower albedo of these snow-covered landscapes compared to pure snow landscapes (Betts and Ball 1997). Many studies have demonstrated the

significance of low albedo in boreal regions on northern hemisphere climates (Betts *et al.* 2001; Thomas and Rowntree 1992).

A common approach to quantify the impact of snow in forested regions on climate is using low snow albedo based on satellite-observed surface albedo in coupled land surface and climate modeling work (Wang *et al.* 2004). However, this approach does not explicitly consider the impact of low net radiation for snow sublimation and melt. For example, the Noah land surface mode used in the National Centers for Environmental Prediction (NCEP) operational models and the Weather Research and Forecasting (WRF) model at the National Center for Atmospheric Research suffers from early snowmelt predictions (Wang *et al.* 2010).

Forest canopies strongly modify both the short-wave and the long-wave radiation reaching the underlying surface, which has important implications on snowmelt (Essery *et al.* 2008; Hardy *et al.* 2004). Short-wave radiation is attenuated through the canopy and results in less incoming short-wave radiation compared to an open area. However, the incoming long-wave radiation at the underlying snow surface includes radiation emitted by vegetation canopy and the sky, compared to bare surface this often results in larger long-wave radiation at the snow surface due to warmer vegetation layer and larger emissivities from vegetation. In most cases, the short-wave energy reduction is the dominant effect, resulting in a slower melting rate compared to open areas (Essery *et al.* 2008; Sicart *et al.* 2004).

Both empirical and modeling studies indicate a strong need to take into account the heterogeneous and clumped forest structure on radiative fluxes reaching the underlying snow surface. For example, Varhola *et al.* (2010) developed linear regression models to analyze ground snow data collected in 65 forest sites across the USA and Europe and confirmed that forest cover reduces snow accumulation and ablation. However, their study also indicates large variations on the relationship between snow accumulation and snowmelt with forest cover. In addition to forest cover, canopy geometry and their spatial distribution need to be included in order to fully take into count the effect of forest on snow accumulation and snow melt (Varhola *et al.* 2010).

To model the impact of clumped forest structure on radiative fluxes and snowmelt, most studies either consider the clumped impact only on short-wave radiation and ignore the long-wave impact (Essery *et al.* 2008; Hardy *et al.* 2004) or ignore the clumping effect. Often different forms of Beer's law or two-stream radiative transfer theory are used to estimate the attenuation of solar radiation through vegetation canopies (Essery *et al.* 2009; Pomeroy and Dion 1996; Wigmosta *et al.* 1994). For example, Wang *et al.* (2010) included the shading effect of vegetation and other snow processes in the Noah model and found improvement of snowmelt prediction. However, their study only considered the impact on solar radiation and also used Beer's law for solar radiation attenuation ignoring clumping (Wang *et al.* 2010).

Forest structure is highly heterogeneous and clumped. For any natural vegetation, leaves clump into twigs, twigs into branches, branches into tree crowns, crowns into forest stands (patches), and forest stands into landscape, often resulting in non-uniform gaps. For example, Figure 1 demonstrates the observed variation of the solar radiation component passing through the gaps, reaching the snow surface in an old jack pine forest in central Canada (Ni *et al.* 1997). The spatial variance of short-wave and long-wave radiation makes snowmelt highly dependent on the heterogeneous and clumped vegetation structure. Beer's law fails to describe the radiation transmission through the natural vegetation. Consideration of the spatial variability of radiation in vegetation canopies is a priority for accurately modeling snowmelt processes (Essery *et al.* 2008; Hardy *et al.* 2004).

To consider the impact of complex vegetation structure on radiation penetration through vegetation canopies, many complex canopy radiative transfer models have been developed and are compared (Pinty *et al.* 2001, 2004; Widlowski *et al.* 2011). However often those models include complex physics, which makes them hard to implement into complex land surface models at continental and global scales.

For example, the Geometric Optical and Radiative Transfer (GORT) model takes into account the impact of 3D vegetation structure on radiation regimes. It has proven that it can successfully provide solar and long-wave radiation transmitted to the snow surface (Hardy *et al.* 1997, 1998; Ni *et al.* 1997). However, it requires complex vegetation structure inputs such as crown geometry and foliage area volume density, which are difficult to measure. Essery *et al.* (2008) and Hardy *et al.* (2004)
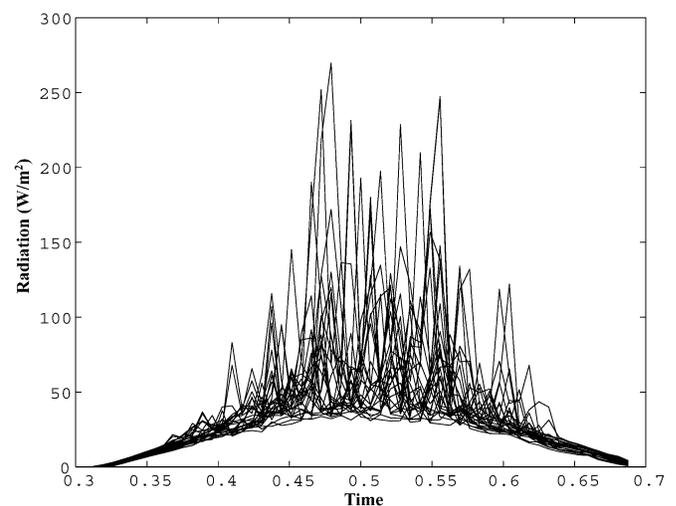
Figure 1: impact of clumped vegetation structure in an old jack pine forest stand in central Canada on incoming solar radiation measurements by nine randomly distributed pyranometers at the snow surface during 3 days in January in 1994, all are normalized to local time, i.e. 0.5 at local solar noon. The big spikes are direct beam radiation passing through big canopy gaps, the smaller spikes are direct beam radiation passing through the smaller canopy gaps and the bell-shaped baseline is diffuse radiation passing through the canopy gaps.

used the aerial photography and airborne laser scanning data to characterize vegetation structure inputs for a spatially explicit radiative transfer model and the modeled solar radiation matches well with solar radiation measurements underneath the canopy. However, those studies can only be applied at small scales.

To overcome this problem, we developed a simple but physically based Clumped Canopy Scheme (CCS) of canopy radiative transfer for photosynthesis, radiative fluxes and surface albedo estimates in dynamic global vegetation models (DGVMs), and particularly for the Ent Dynamic Global Terrestrial Ecosystem Model (Ent DGTEM) (Ni-Meister *et al.* 2010; Yang *et al.* 2010). This CCS scheme accounts for both vertical and horizontal heterogeneity of plant canopies by combining the simple two-stream scheme with a well-described actual vertical foliage profile, an analytically derived foliage clumping factor from geometric optical theory. This model provides better radiation estimates (light profiles, albedo) than the two-stream scheme currently being used in most Global Climate Models (GCMs) to describe light interactions with vegetation canopies. This scheme has the same computational cost as the current typical scheme being used in GCMs but promises to provide better canopy radiative transfer estimates for DGVMs, particularly for the modeling with heterogeneous canopies.

In order to demonstrate the impact of heterogeneous and clumped vegetation structure on snowmelt, this study used the CCS for canopy radiative transfer to estimate radiative fluxes reaching underlying forest floor for snowmelt. We integrated CCS into the well-developed land surface Variable Infiltration Capacity model (herein referred to as VIC-CCS). We chose the VIC model as it has a well-developed snowmelt scheme. To estimate energy balance at the snow surface underneath forests, like many land surface models, forest is still treated as a horizontally homogeneous vegetation canopy layer in VIC. In this study, we implement the simple CCS into VIC to model the impact of clumped forest structure on radiative fluxes at the forest floor and the snowmelt prediction in the boreal forest ecosystem. In order to isolate the impact of CCS on surface energy budget computation, the VIC-CCS and the standard VIC model (without CCS) simulations were compared with the field data collected during the Boreal Ecosystem–Atmosphere Study (BOREAS) in central Canada (Sellers *et al.* 1995). This study aims to demonstrate the importance of including the vegetation heterogeneity and clumping feature for snowmelt and energy balance prediction in a land surface model. It directly addresses the vegetation and snowmelt relations and is relevant to the theme of plant and water relations.

MODEL SCHEME

VIC is a macroscale hydrological model and includes land surface energy and water balances (Liang *et al.* 1994, 1996, 1999; Wood *et al.* 1998). The VIC model has been evaluated and applied at a range of spatial scales, from large river basins to continental and global scales (Nijssen, Lettenmaier, *et al.* 1997; O'Donnell *et al.* 2000; Su *et al.* 2005, 2006; Zhu and Lettenmaier 2007). VIC has been validated as part of the Project for Intercomparison of Landsurface Parameterization Schemes (PILPS)-2c (Wood *et al.* 1998) and PILPS-2e (Bowling *et al.* 2003). The current version of VIC includes an updated cold land processes (Cherkauer *et al.* 2003) and a lake/wetland algorithm (Bowling and Lettenmaier 2010).

The VIC model uses the mosaic approach to model the impact of land surface heterogeneity on surface energy and water fluxes due to different land surface types within a grid cell. Each land cover type is represented by a vegetation tile, and the energy and moisture fluxes for a grid cell are a sum of fluxes weighted by the fractional area of each tile. In addition, VIC is distinguished from other land surface processes models by multiple soil layers with variable infiltration and its nonlinear base flow generation. Thus, the spatial variability in soil properties at scales smaller than the grid scale is represented statistically without assigning infiltration parameters to specific subgrid locations. The effect of soil freeze–thaw processes on heat flux and moisture movement through frozen soils was also implemented (Cherkauer and Lettenmaier 1999).

Subgrid variations in snow accumulation and ablation are accounted for through the use of snow elevation bands based on the Distributed Hydrology-Soil-Vegetation Model (DHSVM) (Andreadis *et al.* 2009; Wigmosta *et al.* 1994). The VIC model snow parameterization includes snow interception and accumulation when an overstory is defined based on the canopy snow interception algorithm (Andreadis *et al.* 2009; Storck *et al.* 1999). The current cold land process in VIC includes a two-layer model for better snowmelt estimates, the effects of spatial variability of soil freeze–thaw state and snow cover on moisture and energy fluxes, and the effect of lakes and wetlands on moisture storage and evaporation (Cherkauer *et al.* 2003). Overall, VIC is designed to model all the complex land surface processes and is a good land surface parameterization scheme for GCMs.

Impact of clumped forests on radiation for snowmelt estimate

This study uses the latest VIC (VIC version 4.1.2). During the snow season, VIC uses a two-layer model, which solves energy balance for the overstory (vegetation) and understory (snow) then seeks the overall balance (Cherkauer *et al.* 2003). The two-layer radiative transfer scheme applies only to areas where there is an overstory and only when there is snow on the ground or in the canopy. In all other cases, the VIC model reverts to its original one layer scheme for simplicity.

The energy balance equation for the vegetation layer is:

$$ME_c = R_{net} - H_c - L_c - A_c \qquad (1)$$

where R_{net} is the net energy into the canopy; H_c, L_c and A_c are the sensible, latent heat and the fluxes for advection at the vegetation canopy layer and ME_c is the net energy for leaf temperature change. The energy balance for the snow layer is

$$\text{ME}_s = R_{(ns|g)} - H_{(s|g)} - G - A_{(s|g)} + \Delta CC \qquad (2)$$

where ME_s is the energy available for melt; $R_{ns|g}$ is the net radiation of the snow layer; $H_{s|g}$ is the sensible heat flux at the snow surface; $L_{s|g}$ is the latent heat flux at the snow surface; G is the ground heat flux; $A_{s|g}$ is the advective heat flux at snow surface and ΔCC is the change in cold content. The above two energy equations are solved separately to estimate canopy and snow surface temperature and the fluxes from both the canopy layer and the snow surface are calculated and summed together as the total fluxes.

The net radiation at the vegetation layer and the snow layer includes both the short-wave and the long-wave net radiation. Particularly the net radiation (net short wave + net long wave) at the snow surface provides the exact heat source for snowmelt. In the current VIC model, the vegetation layer is assumed to be homogeneous, the incoming short-wave transmission is adjusted using Beer's Law—an exponential decay of plant area index (PAI), the incoming long-wave radiation at the under canopy snowpack is the long-wave radiation emitted completely from the vegetation layer (Cherkauer *et al.* 2003). To estimate radiation penetration through canopy, Beer's law is only valid for homogeneous plant canopies.

Forests often have a heterogeneous and clumped structure, resulting in all sizes of canopy gaps. These gaps often allow more radiation attenuating to the forest floor. Beer's law underestimates radiation reaching the underlying forest floor. To account for the clumping, we include a clumping factor in an exponential decay for radiation attenuation (Ni-Meister *et al.* 2010):

$$t_{c(\theta)} = \exp\left(\frac{k\Omega\text{PAI}}{\cos\theta}\right) \qquad (3)$$

where k is the leaf orientation factor and uses 0.5 for randomly oriented leaves (Ni *et al.* 1997), θ is the incident solar zenith angles. The VIC model does not use the incident solar zenith angle, we simplified the above equation using daily averaged incident zenith angles. PAI is plant area index including both leaf and trunk (Ni-Meister *et al.* 2010). Ω is the clumping factor, which is a function of crown size, shape, density and spatial distribution (Ni-Meister *et al.* 2010) but can also be measured from the field or be derived from remote sensing data (Chen *et al.* 2005).

Large variations of gaps also allow long-wave radiation from the sky to pass through the vegetation layer and reach the snow surface. Long-wave radiation at the underlying snow surface is a combination of long wave from sky and from vegetation weighted by the sky-viewing factor. Long-wave radiation beneath canopies is increased compared to open areas due to warmer canopy elements from absorption of solar radiation and higher emissivities for canopy elements than for the atmosphere (Essery *et al.* 2009; Sicart *et al.* 2004). However, treating the vegetation layer as homogeneous could overestimate long-wave radiation at the underlying snow surface, thus resulting in faster snowmelt rate predictions. In this study, the long-wave radiation reaching the snow surface is calculated as the combination of long-wave radiation from sky and vegetation weighted by openness/sky-viewing factor, K_{open} (Ni *et al.* 1997):

$$K_{open} = 2\int_0^{\pi/2} t_{c(\theta)}\sin\theta\cos\theta\, d\theta \approx \exp(-2k\Omega\text{PAI}) \qquad (4)$$

In this study, we use both clumping factor and openness factor to parameterize the short-wave and long-wave radiation and the net radiation at the snow surface underneath vegetation canopy in VIC (see details in Fig. 2):

$$R_{(nls|g)} = R_{(ls|g\downarrow)} + R_{(sl|g\uparrow)} \qquad (5)$$

$$R_{(ls|g\downarrow)} = (1 - K_{open})R_{lc} + K_{open}R_{lc} \qquad (6)$$

where $R_{(nls|g)}$ is the net long-wave radiation at the snow surface, $R_{(ls|g\downarrow)}$ is the incoming long-wave radiation reaching the snow surface $R_{la} = \varepsilon_c\sigma T_a^4$, $R_{lc} = \varepsilon_a\sigma T_c^4$, T_a and T_c are air temperature and canopy temperature in Kelvin, is the Stefan–Boltsman constant. Emissivity from vegetation is assumed to be one, i.e. $\varepsilon_c = 1$, emissivity from sky varies with cloud conditions and ranges from 0.6 to 1.0 (Brutsaert 1982). Long-wave radiation from sky was estimated by V. R. N. Pauwels, J. Gu, B. Nijssen, A.K. Betts, K.R. Snelgrove, E.A. Whidden, N. Kouwen, D.P. Lettenmaier, E.A. Smith, E.D. Soulis, and E.F. Wood, (unpublished results) and is part of the meteorology inputs. $R_{(sl|g\uparrow)} = \varepsilon_s\sigma T_{(s|g)}^4$ is the upwelling long-wave radiation emitted from snow surface assuming the emissivity from snow ε_s is one, $T_{(s|g)}$ is the snow/ground temperature in Kelvin.

Another modification we made is the calculation of net short-wave radiation for the canopy layer during the snow season. VIC assumes that snow stays on canopy, the net short-wave radiation for canopy is calculated as

$$R_{snc} = (1 - t_c)(1 - \rho_s) \qquad (7)$$

where I is the incident solar radiation and ρ_s is snow surface albedo. However, snow may only stay on canopy for a short
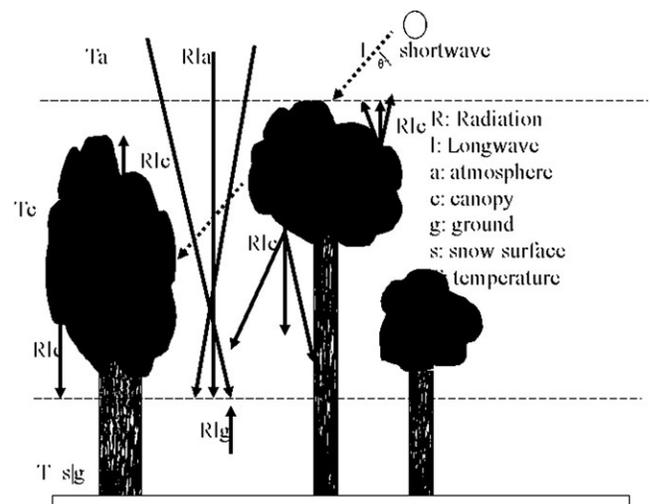
Figure 2: diagram showing the impact of vegetation heterogeneity on radiation in the vegetation canopy layer and at the ground surface.

period after the snow fall and then fall off during the snowmelt period. Our scheme for the net short-wave radiation for the canopy layer is

$$R_{snc} = (1 - t_c - \rho_c - t_c\rho_s)I \qquad (8)$$

where ρ_c is the canopy albedo, which will be much less than snow albedo.

STUDY SITES AND DATA SOURCES

Site description

During the BOREAS field campaign period (1994–96), intensive field measurements were conducted in two study regions in central Canada: Northern Study Area (NSA) and Southern Study Area (SSA) (Fig. 3). In each study region, tower measurements of energy and moisture fluxes and hydrological parameters were made in different forest stands. In this study, four different forest stands were selected: a deciduous old aspen forest stand in the Southern Study Area (SOA), coniferous old black spruce forest stands in the Southern Super Study site (SOBS) and the Northern Super Study site (NOBS) and a fen wetland in the Northern Study site (NFEN) (Fig. 3).

Data sets

Meteorological forcing data

The meteorological forcing data for each site were processed by a BOREAS follow-up group (BOREAS CDROM and V. R. N. Pauwels, J. Gu, B. Nijssen, *et al.*, unpublished results). These data are a continuous time series, having a time step of 1 h, covering the period from 1 January 1994 to 1 December 1996. The forcing data include hourly meteorological variables: air temperature, vapor pressure, wind speed, atmospheric pressure, incoming short-wave and long-wave radiation and precipitation. They were obtained through interpolation of *in situ* measurements from surface meteorological stations, flux towers, Geostationary Operational Earth Satellite (GOES) for short-wave and long-wave radiation and the National Science Foundation (NSF) Enterprise WSR-100 rain radar for precipitation. Nijssen *et al.* (2001) noted the underestimation of precipitation measurements during the cold season from 1995 to 1996 in the SOBS site, this will lead to underestimation of predicted snowmelt discussed in forest structure and snowmelt section.

Vegetation parameters

The vegetation parameters include vegetation type, fractional coverage, PAI, surface albedo, vegetation height, roughness height, minimum stomatal resistance, architectural resistance, root depth and relative root fraction in each soil layer. *In situ* measurements of PAI, and tree height by Chen (1996) and Aurela *et al.* (2009) and surface albedo by Betts and Ball (1997) at different tower sites were used to drive the model. The rest of the parameters were determined based on the different vegetation types. The clumping index is not an original VIC input. It changes with tree size, density, and foliage/stem volume density. It can be estimated using a geometric optical model (Ni-Meister *et al.* 2010; Yang *et al.* 2010) and can also be
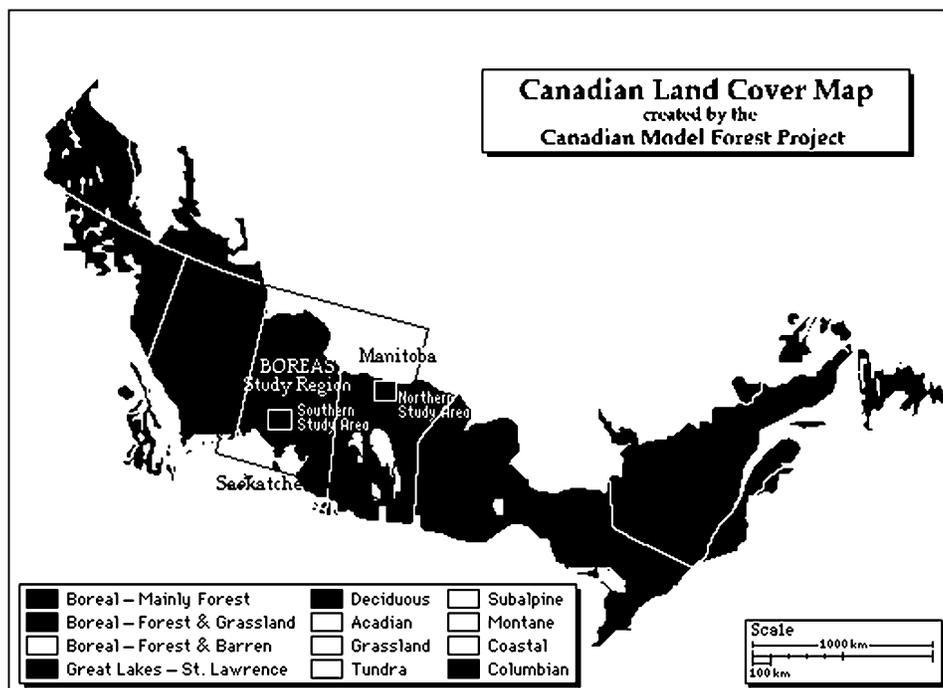
Figure 3: the BOREAS study region, SOA—old aspen in the Southern Study site, SOBS—old black spruce forest in the Southern Study site, NOBS—old black spruce forest in the Northern Study site and NFEN—fen in the Northern Study site.

measured using Tracing Radiation and Architecture of Canopies (TRAC) (Chen *et al.* 1997) and remote sensing data (Chen *et al.* 2005). To keep it simple in this study, we used a constant clumping index (0.5) for the three sites (SOA, SOBS and NOBS). The value was selected based on our modeling experience and the TRAC measurements (Chen *et al.* 1997).

LAI for the four stands shows different seasonal features (Fig. 4). SOA is a deciduous forest site and there is a seasonal change of PAI with only woody area index during snow season and largest PAI values during the growing season. SOBS and NOBS are two conifer forest sites and PAI keeps constant during the whole year. NFEN is a site with very short vegetation and PAI was approximated as zero during the snow season.

Soil parameters

Soil parameters include soil texture (percent sand and clay), residual soil moisture and total soil depth, saturated hydraulic conductivity, porosity, soil moisture at field capacity and wilting point. Soil properties were obtained from Cuenca *et al.* (1997) and the soil texture information made by the BOREAS Terrestrial Ecology-20 group (TE-20).

Different mosses exist in most black spruce forests. The moss layer influences the hydrological processes. Mosses contain a large volume of water. The low thermal conductivity reduces the heat flow into the soil layer and keeps the soil layer cool in summer. To model the effect of moss on the hydrological processes, this study follows the approach described in Nijssen, Haddeland, *et al.* (1997) and Haddeland and Lettenmaier (1995), where the moss layer was added on top of the soil layer and was treated as a special surface soil layer. Special hydrology property values for the moss layer were used in the simulation. The inputs for the moss layer were from Nijssen, Haddeland, *et al.* (1997) and Haddeland and Lettenmaier (1995).

Model simulation

The VIC model and the VIC-CCS scheme were run separately in full energy mode from 1994 to 1996 with the same meteorological drivers and the vegetation and soil parameters collected for the four stands as inputs. For the year 1994, VIC was run ten times consecutively to iterate the model state variables
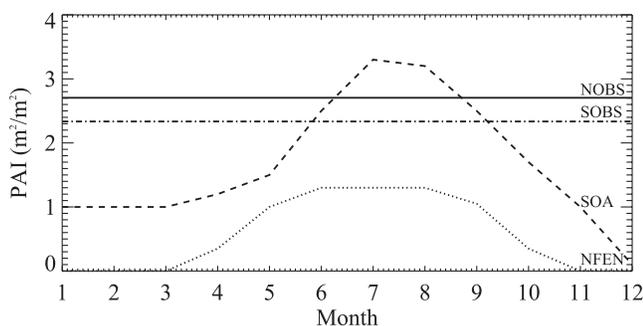
Figure 4: seasonal monthly PAI values used by VIC for the SOA, SOBS, NOBS and NFEN sites.

to reach equilibrium. In the following section, we first compared modeled and measured diurnal and seasonal patterns of energy fluxes at two different forest stands (SOA and NOBS), where continuous flux tower measurements were available to evaluate the performance of VIC on modeling the diurnal change of surface fluxes during the snow season. Then we compared the modeled snow water equivalence (SWE) with snow survey data at the four forest stands.

RESULTS AND DISCUSSION

Diurnal variations of energy fluxes

Figure 5 compares the simulated and measured mean (measurements were collected by the BOREAS Tower Flux (TF)-02 team) diurnal curves of net radiation (Rnet), sensible heat fluxes (SH) and latent heat fluxes (LE) in the SOA and NOBS stands during the snow season (January–March) in 1994 (for SOA) and 1995 (for NOBS). This comparison does not include other sites and years due to incomplete field measurements.

For the SOA stand, both the modeled net radiation and the latent heat fluxes by VIC-CCS match well with the field observations. There are no leaves on trees during winter, both the modeled and the measured latent heat fluxes are close to zero. VIC without CCS underestimates the net radiation and sensible heat fluxes but within the range of their standard deviations. It might be due to the underestimation of the net short-wave radiation absorbed by vegetation canopy. VIC assumes snow stays on branches during snow season and snow albedo determines surface albedo. However, in reality snow may only stay on trees for a short period of time and then fall off. Surface albedo should be vegetation albedo, which is much lower than snow albedo. Using snow albedo will lead to underestimation of net short radiation for the vegetation layer.

For the NOBS stand, the modeled net radiation, sensible and latent heat fluxes using VIC-CCS match well with the field measurements with a slight underestimation using VIC only. Comparing the energy partition during the growing season, we found almost zero latent heat fluxes during the snow season since the surface is frozen. Most of the net radiation absorbed by the surface is either returned to the atmosphere through sensible heat fluxes and snow sublimation or used for snowmelt.

Forest clumping and incoming long-wave radiation

To demonstrate the impact of our modified radiation scheme on incoming long-wave radiation reaching the snow surface under vegetation, we compared the modeled incoming long-wave radiation under vegetation estimated by VIC and VIC-CCS with incoming long-wave radiation from sky at the four sites (Fig. 6). Overall, the long-wave radiation estimated by VIC and VIC-CCS is larger than sky long-wave radiation for the three sites with tall vegetation (SOA, SOBS and NOBS). However, the long-wave radiation from VIC showed larger difference from sky long-wave radiation than the ones by VIC-CCS. The long-wave radiation estimated by VIC-CCS is
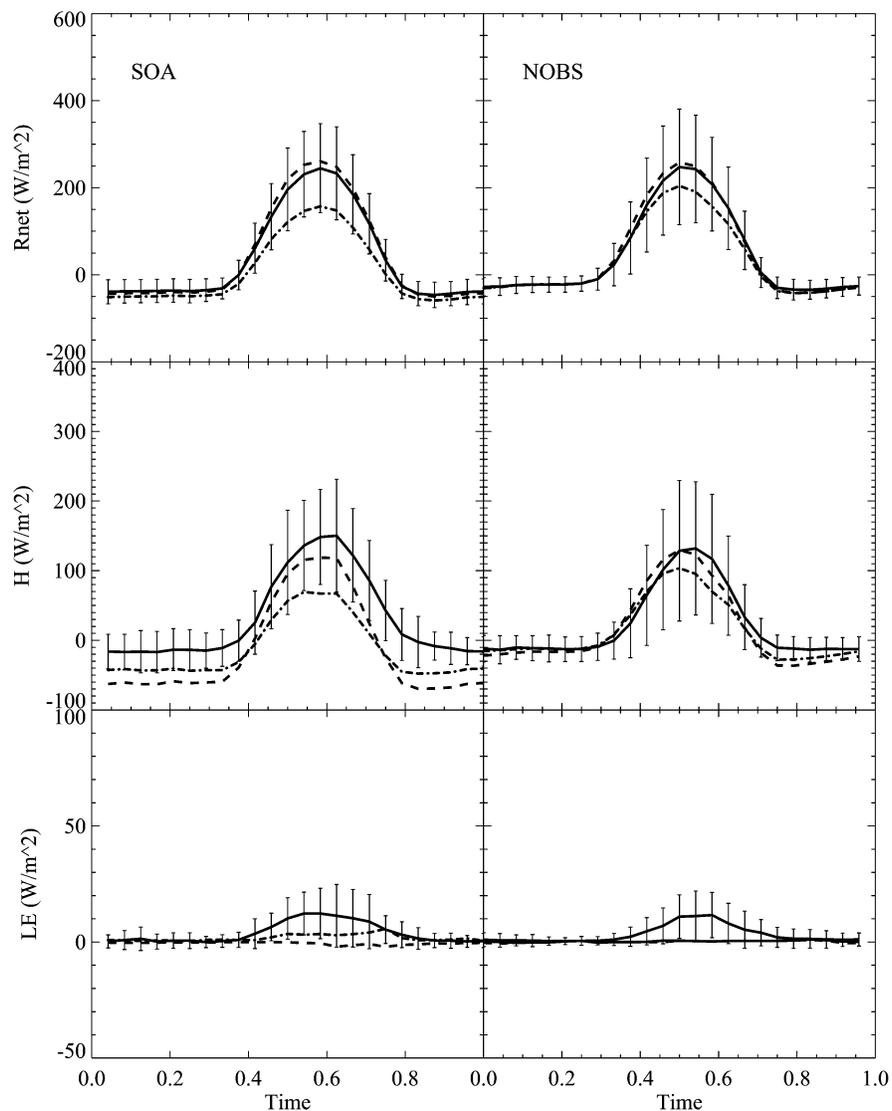
Figure 5: comparison of the measured (solid lines) with standard deviation and modeled (VIC: dashed and dotted lines and VIC-CCS: dashed lines) climatological winter diurnal curves of net radiation (Rnet), sensible heat fluxes (H) and latent heat fluxes (LE) in the old apsen stand in the southern study site (SOA, for 1994) and the old black spruce forest stand in the northern study site (NOBS for 1995) of the boreal forest in central Canada. 0.5 is the local solar noon.
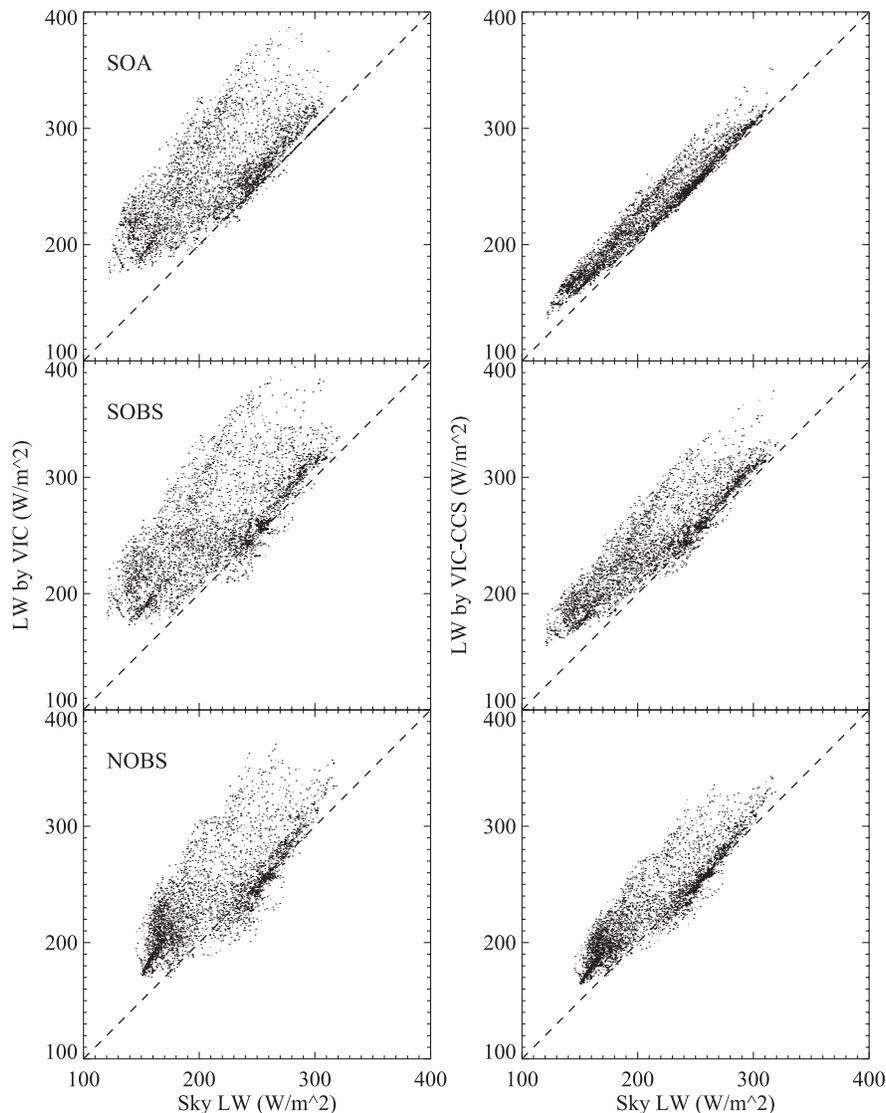
much closer to the incoming long-wave radiation from sky particularly for the deciduous old aspen stand (SOA) due to its large openness factor. The incoming radiation at snow surface estimated by VIC-CCS is a combination of incoming long-wave radiation from both sky and vegetation weighed by openness factor. Incoming radiation at snow surface estimated by VIC only is the incoming long-wave radiation emitted by the vegetation canopy. Warmer vegetation canopy and large emissivity result in larger incoming long-wave radiation estimated by VIC only than by VIC-CCS or sky long-wave radiation.

Forest structure and snowmelt

SWE represents the amount of water that would be produced if the snow were instantaneously melted at a point. It is an important hydrological variable for estimating the snowmelt rate. SWE snow surveys were conducted at special snow courses throughout the 1994/95 and 1995/96 winter seasons by the BOREAS Hydrology (HYD)-04 Team. These snow courses were located in different boreal forest land cover types to document snow cover variations throughout the season as a function of different land cover. The snow surveys collected at different sites in the BOREAS region were used to evaluate the modeled snowmelt rates.

Figure 7 compares both the modeled SWE by VIC and VIC-CCS with the snow surveys in the SOA, SOBS, NOBS and NFEN sites from 1994 to 1996. The snow surveys collected in five locations of the SSA are shown as crosses, pluses, triangles, dots and diamonds. None of these sites was located at the tower flux sites of SOA and SOBS. But

Figure 6: comparison of modeled incoming long-wave radiation at snow surface and with incoming long-wave radiation from the sky during snow season in the SOA, SOBS, NONS and NFEN sites.

they were the only available SWE data close to these tower sites and were used as an approximation of the SWE in the SSA tower sites.

For the leaf-off deciduous old aspen site, the modeled SWE by VIC-CCS in the SOA matches reasonably well with the snow survey data, whereas VIC itself overestimates the snowmelt rate. The RMSE of SWE predictions decreases from 32.52 to 16.52 mm from using VIC only to using the VIC-CCS scheme for the SOA site.

For the SOBS site, VIC-CCS improves snowmelt rate compared to VIC. But both schemes underestimate snowmelt rate, particularly for the winter from 1995 to 1996 due to the underestimation of precipitation measurements during the cold season from 1995 to 1996 in the SOBS site (Nijssen et al., 2001). RMSE decreases from 29.86 to 17.22 mm using the VIC-CCS scheme compared to using VIC only. For this

site, we only used 1994–1995 winter data to calculate RMSE due to incorrect precipitation forcing.

At the NOBS site, both modeled snowmelt rates match well with the observed data with a better match using VIC-CCS (RMSE 32.61 mm for VIC and 17.22 mm for VIC-CCS). For the NFEN site with very low vegetation, both modeled SWEs are the same and they match reasonably well with the snow surveys with RMSE 23 mm, demonstrating that VIC has a good snowmelt model. For some of these sites (NOBS and NFEN), both VIC and VIC-CCS suffer from underestimation of snow accumulation. This underestimate might be due to uncertainties of precipitation forcing.

Comparisons of modeled SWE and snow surveys at these four sites show the largest impact of the clumped vegetation structure on snowmelt rate prediction at the SOA site. SOA is a deciduous forest site with no leaves on branches during the snow season, the PAI includes only woody area index with
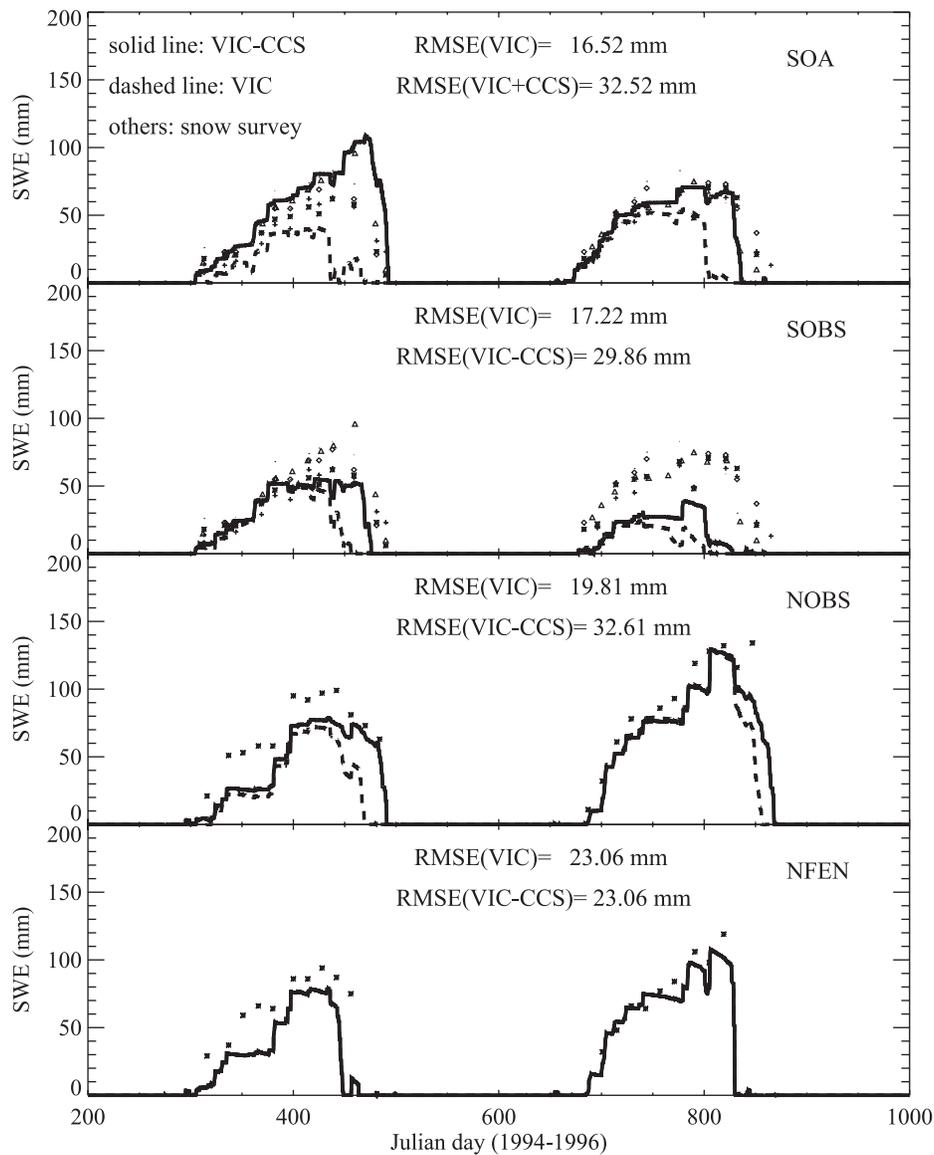
Figure 7: comparison of the modeled SWE and the snow surveys in the SOA, SOBS, NOBS and NFEN sites from 1994 to 1996.

much reduced values (Fig. 4). In this case, treating vegetation as homogeneous plant canopy will result in overestimated long-wave radiation at the snow surface, thus faster snowmelt rate. Both the NOBS and the SOBS sites are conifer forest stands with constant PAI through the whole year. Their PAI values are ~3 m^2/m^2, which are much larger than the value (~1 m^2/m^2) at the SOA site in the winter. As a result, the difference of predicted snowmelt rate is not as large as what is observed in the SOA site. However, snowmelt rate prediction is improved. For the NFEN site with very low vegetation, the plant area is very close to zero. The model is treated as bare ground with no vegetation above snow. Therefore, VIC and VIC-CCS predict the same snowmelt rate.

The SWE data comparison at four different sites shows that more snow was accumulated and snow stayed longer in the northern sites (NFEN and NOBS) than in the southern sites (SOBS and SOA) since the southern sites are 2° more southern than the northern site and are thus warmer. Also in the open site (NFEN), the snow melts faster than in the forest site (NOBS). In an open snow surface (the NFEN site), solar radiation is directly used as a major heat source for snowmelt. However, in forested areas, incoming solar radiation has to transmit through the forest before reaching the snow surface and part of the radiation will be absorbed by vegetation, resulting in less incoming solar radiation reaching the snow surface for snowmelt. This comparison study shows that our simple CCS scheme models the impacts of the clumped forest structure on both the short-wave and the long-wave transmission well, thus estimating the snowmelt rate correctly in the forested areas.

CONCLUSIONS

To correctly quantify the impact of heterogeneous vegetation structure on the radiation component at the snow surface underneath the canopy and snowmelt rate, we used a CCS for canopy radiative transfer (Ni-Meister *et al.* 2010) and integrated it with the VIC macroscale hydrological model for snowmelt and energy balance estimates in the boreal forests in central Canada.

Our results show that VIC-CCS was able to simulate the diurnal and seasonal changes of the energy and water fluxes during the snow season in different boreal forest stands reasonably well when compared to ground measurements. VIC without CCS slightly underestimates sensible heat fluxes and VIC-CCS modeled sensible heat fluxes match better with field measurements.

VIC-CCS also improves snowmelt estimates in the three forest stands in the boreal region. The overall RMSE was reduced by 13–15 mm for the two black spruce conifer stands and 16 mm for the deciduous SOA. The deciduous SOA shows the largest improvement of snowmelt rate. During the leafless season, treating vegetation as homogeneous overestimates incoming long-wave radiation reaching the snow surface, thus leading to faster snowmelt predictions by the original VIC without CCS. This study demonstrates that taking into account the effect of the clumped forest structure in land surface parameterization schemes is critical to model the snowmelt rate correctly in the boreal regions. In this study, CCS was integrated with VIC, but it could also be integrated with other land surface models for the same purpose. CCS needs both PAI and clumping factors as inputs for underneath radiative flux estimates. With the availability of remotely sensed global leaf area index (Knyazikhin *et al.* 1998) and clumping index (Chen *et al.* 2005; Pisek *et al.* 2010) maps, application of CCS in global coupled land surface model and climate modeling study is possible. Further evaluation for different climate regions is necessary before using CCS in coupled land surface and climate modeling studies.

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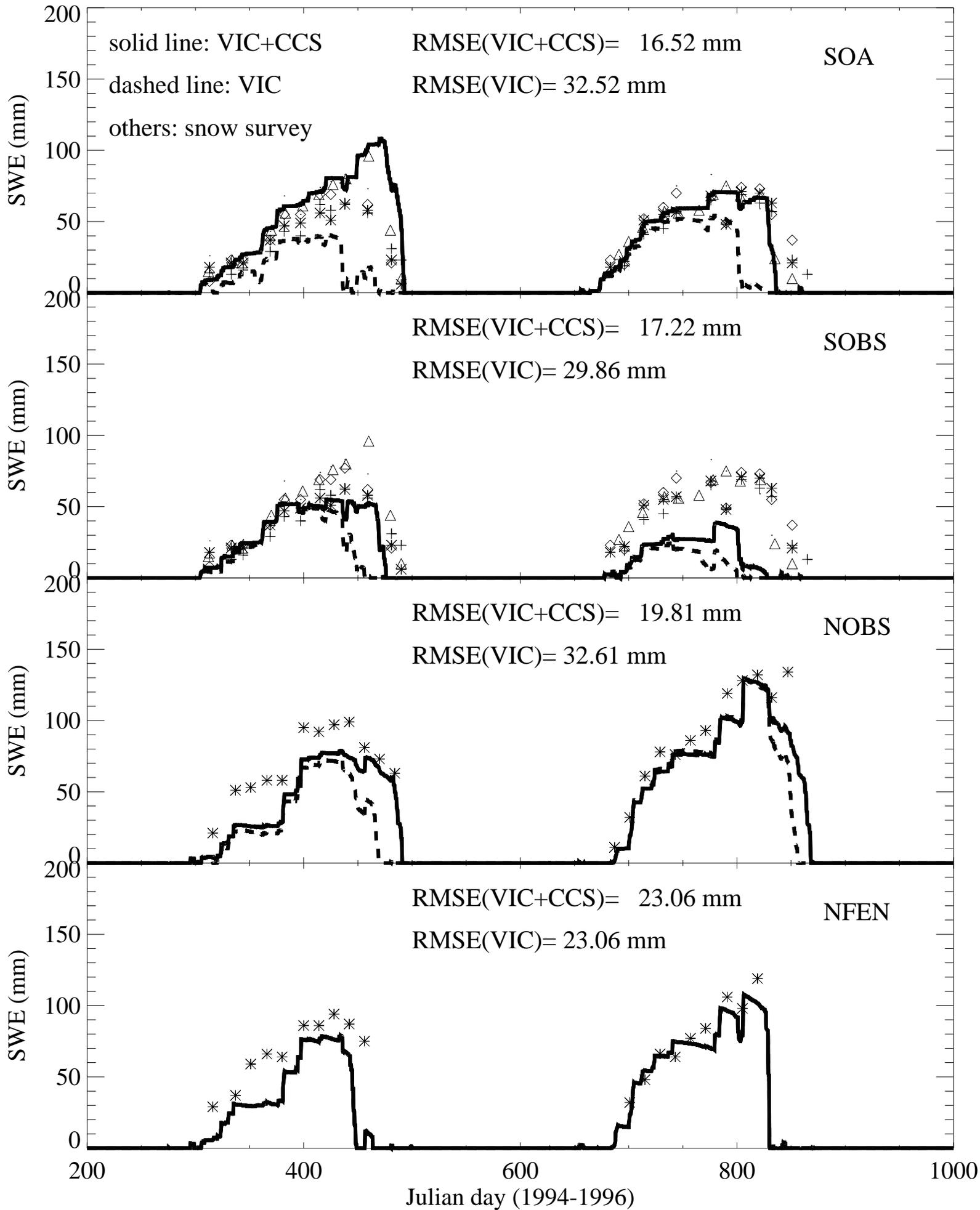
Figure 7