Interception of snowfall by the trees is the main challenge for snowpack simulations under forests

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ABSTRACT: The Crocus snowpack model is now coupled with the new vegetation scheme MEB (Multiple Energy Balance). This new system represents all the main snow-vegetation interactions by including 1 layer of high vegetation and 1 layer of litter. This work presents the first evaluations of this new system with a new dataset collected on a spruce forest at Col de Porte (1325 m a.s.l. Chartreuse massif, French Alps) during the winters 2016-2017 and 2017-2018. We illustrate that the processes linked with the interception of snowfall by the trees are the most challenging to simulate. The initial representation of this process in the model was based on empirical parameterizations from the literature with observations in Canada. This version fails to reproduce the very strong impact of interception on our dataset. We demonstrate that this error is much more significant than the spatial variability of the snowpack in the forest and than the uncertainties in the other processes of the model (including radiative effects of the canopy). Numerical experiments show that the melting of intercepted snow is likely to be highly underestimated. This suggests that a more physical parameterization of this process is required to improve snowpack simulations in this environment.

Keywords: snowpack modelling, forest, snowmelt, interception, French Alps.

1. INTRODUCTION

About 50% of alpine areas above an elevation of 600 meters are covered by forests and this fraction has been increasing during the last century (Bebi et al., 2017). The presence of forest strongly affects the evolution of the snowpack by different processes with a very high spatial variability: interception of precipitation by the trees, modification of surface meteorology by the canopy (wind, temperature), shadowing of solar radiation, longwave radiation of the trees, etc. (Varhola et al., 2010). Despite the key contribution of these processes over very extended surfaces, only few models currently represent these processes. The evaluations of such models remain scarce and most snow models have larger errors over forested sites than over open areas (Rutter et al., 2009; Krinner et al., 2018). This is a major issue for the application of snowpack models for hydrological purposes in moutainous areas or to describe snow cover extent and stratigraphy on forested slopes in mid-elevation ski resorts.

Recently, a new version of the surface model ISBA/MEB (Boone et al., 2017) has been coupled with the multilayer snowpack model Crocus (Vionnet et al., 2012), allowing the simulation of the most important processes affecting the snowpack under forest. The first evaluations of MEB over the French territory were not dedicated to snow processes and mountainous areas (Napoly et al., 2017). In the meantime, an observation campaign dedicated to snow under forest has been deployed at Col de Porte for the last two seasons (2016-2018). It provides meterological and snow measurements under a spruce forest. This mid-latitude and mid-elevation experimental site is unusual compared to most published studies in much colder environments (e.g. Bartlett et al., 2006). Warmer sites are also known to be more challenging for snowpack models (Krinner et al., 2018).

This work presents the first evaluation of the MEB-Crocus system in terms of snow mass, snow height and snow surface energy balance at Col de Porte. This is also the first use of this new dataset for model evaluation in a challenging environment. Section 2 presents the model and the evaluation dataset. The results are discussed in section 3.

2. MODEL AND DATA

2.1. Modelling system : MEB-Crocus

Crocus is the most sophisticated snow scheme of the SURFEX surface modelling system (Masson

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et al., 2013). It solves the heat diffusion equation in a stratified snowpack using up to 50 layers in a lagrangian vertical discretization, and including explicit representations of surface energy balance, absorption of solar radiation, metamorphism, compaction and liquid water percolation (Vionnet et al., 2012). In this work, all physical parameterizations of Crocus are chosen to the default ones as defined in Lafaysse et al. (2017).
MEB is a new scheme implemented in SURFEX by Boone et al. (2017) which adds an explicit layer for high vegetation and a layer of litter above the soil. It solves simultaneously the evolution of snow surface, ground surface and vegetation temperatures with an implicit scheme. The transmission of solar radiation in the canopy is represented with the scheme of Carrer et al. (2013) and the absorption of longwave radiation mainly depends on the Leaf Area Index (LAI). The parameterization of snow interception comes from Hedstrom and Pomeroy (1998). It includes paramaterizations of sublimation, melting and unloading of the intercepted snow. The coupling of MEB with Crocus is performed in the exact same way than with the ISBA-ES snow scheme as described in Boone et al. (2017).

2.2. Application of MEB-Crocus at Col de Porte

2.2.1. Site description

Col de Porte is an experimental site dedicated to meteorology and snow measurements located in the Chartreuse massif, French Alps (Figure 1). A high quality long and continous dataset is available in a grassy meadow (Morin et al., 2012; Lejeune et al., 2018).

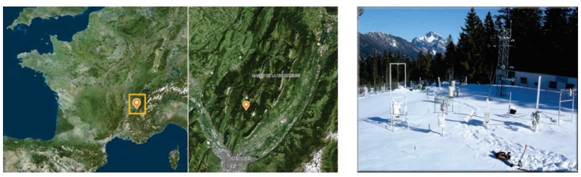

Figure 1: Location of the Col de Porte experimental station, in Massif de la Chartreuse, France.

Since the autumn 2016, within the *SNOUF* project (SNOw Under Forest), the spruce forest adjacent to this meadow has also been intrumented. Surface meteorological variables, incoming and upcoming radiations, and snow depth are measured at a hourly time step at an automatic station. Weekly manual measurements of snow depth and snow water equivalent (SWE) were also performed at 18 different locations to describe the spatial variability. For practical reasons, only 4 SWE measurements are performed each week.

During the second half of the 2017-2018 winter season, direct measurements of snow interception were also performed after each snowfall event. They consist in the deployment of 1 m X 0.39 m boxes along transects of 8 meters in 3 cardinal directions. The new snow mass is measured in each box, in order to describe spatial variabilty under the canopy from the center of a tree towards more opened areas (Figure 2). The boxes are cleared out after each measurement.

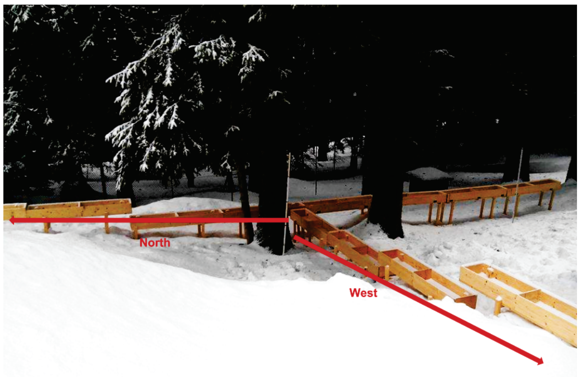

Figure 2: Snow interception measurement device.

Other measurements were also performed during this campaign but are not used here (mapping of canopy properties, spatial variability of radiations, soil temperatures, etc.).

2.2.2. Model setting

The MEB-Crocus system was applied to Col de Porte assuming that the meteorological forcing collected in the meadow (Lejeune et al., 2018) represents the meteorological conditions above the canopy. This assumption is done due to the lack of meteorological measurements above the trees although air temperature or wind speed may differ. The radiations are taken from different sensors on a 10-m mast. The soil internal properties are taken identical to the values commonly used for the meadow (Lafaysse et al., 2017) because no significant difference was found by Lejeune et al. (2018). The ground albedo is set to 0.1 consistently with the measurements. The depth of the litter layer is 4 cm. Classical values of vegetation properties for spruce are used to define the high vegetation layer, in particular a default value of 4 for LAI (Pomeroy et al., 2002). The height of the trees is set to 35m consistently with the measurements. The simulation is initialized by a 23-year spinup run (1993-2016).

To explore the sensitivity of LAI, three simulations runs were performed using three distinct values: 1, 4 and 6. This range of value is supposed to cover the uncertainty and the possible spatial variability of this parameter in the forest.

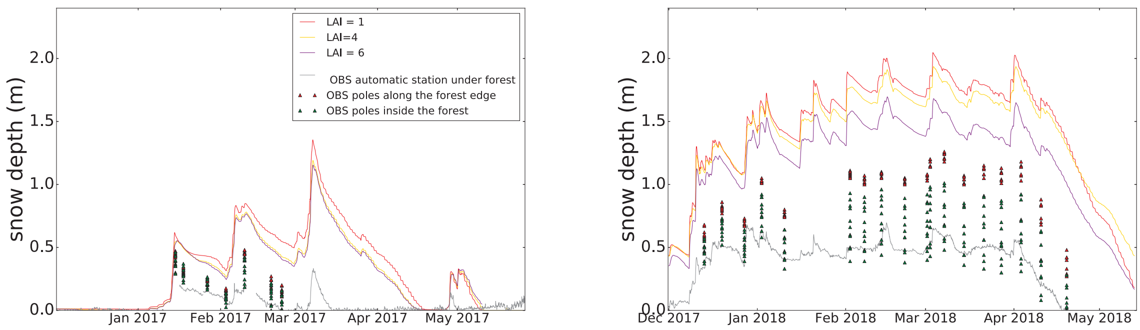

Figure 3: Snow depth observed at the forest automatic station and simulated by MEB-Crocus with different values of LAI. The triangles represent the weekly measurements at the 18 locations in the forest (green points in a denser part than red points). Winters 2016-2017 (left) and 2017-2018 (right).

3. RESULTS AND DISCUSSION

3.1. Snow depth

Figure 3 compares the simulated snow depth with the 3 different values of LAI and the observed snow depth at the automatic station and at the 18 locations of the weekly measurements. The model highly overestimates the snow depth during the whole seasons and the snow cover duration as well. The error magnitude is much higher than the impact of the LAI value in the simulation. The same applies for all the main vegetation parameters (not shown). The spatial variability of the observed snow depth is also relatively high due to a large range of branches coverage among the 18 points. However, the error is still higher than this spatial variability. Therefore, the model bias can not be explained by the uncertainty in vegetation parameters.

The error magnitude is also much higher than the known uncertainty of the physical parameterizations in the Crocus snowpack model (Lafaysse et al., 2017). The skill of the model in the meadow also eliminates the hypothesis of errors in the meteorological forcing sufficient to explain this overestimation. Therefore, significant errors in the simulated snow-vegetation interactions are expected to explain such a bias. In the following, we explore the ability of the model to simulate the radiative interactions and the mass interactions through snow interception.

3.2. Radiative balance

Figure 4 compares the downwards and upwards shortwave and longwave radiations between the observations and the simulations with the 3 different values of LAI. MEB is able to reproduce the strong attenuation of the solar radiation under the canopy with high values of LAI. The simulated shortwave flux is rather close to the observed one when LAI=4. Longwave incident radiations are also sensitive to LAI values. They fit also quite well the observations with LAI=4. Complementary analyses showed that this variable is also highly sensitive to the τ_{LW} transmission factor (see Boone et al., 2017) but the default 0.5 value actually provides the best agreement (not shown).

The magniture of absorbed solar radiation is correctly simulated as suggested by the good fit between simulated and observed upwards shortwave radiations during the snow-covered period. Upwards longwave radiation is an indicator of the accuracy of the whole surface energy balance as it is directly linked to surface temperature. Obviously, strong discrepancies appear when the model simulates a snow-covered ground whereas the real snowpack has melted out. However, during the snow-covered period, the simulation is very satisfactory. This suggests that the surface energy budget does not explain the strong mass biases of section 3.1.

3.3. Intercepted snow

Figure 5a compares the measured snow water equivalent in the boxes as described in section 2.2.1 (blue circles) with the observed new snow water equivalent in the clear meadow (purple circles). For the context, Figures 5b, 5c and 5d provide the meteorological conditions and the observed presence of snow in the trees. The spatial variability of the measured new snow water equivalent is significant (the closer to the center of the tree, the lower the snow amount) but all boxes have much less snow than the clear site. This is also true for the other transects (not shown here for a better readability, average of -60% over the 24 boxes and 8 events). The comparison with the simulated new snow water equivalent over the same period (event-scale, blue stars) exhibit a strong positive bias of the model for this variable for all events, regardless if the measurement was performed before of after the unloading. This

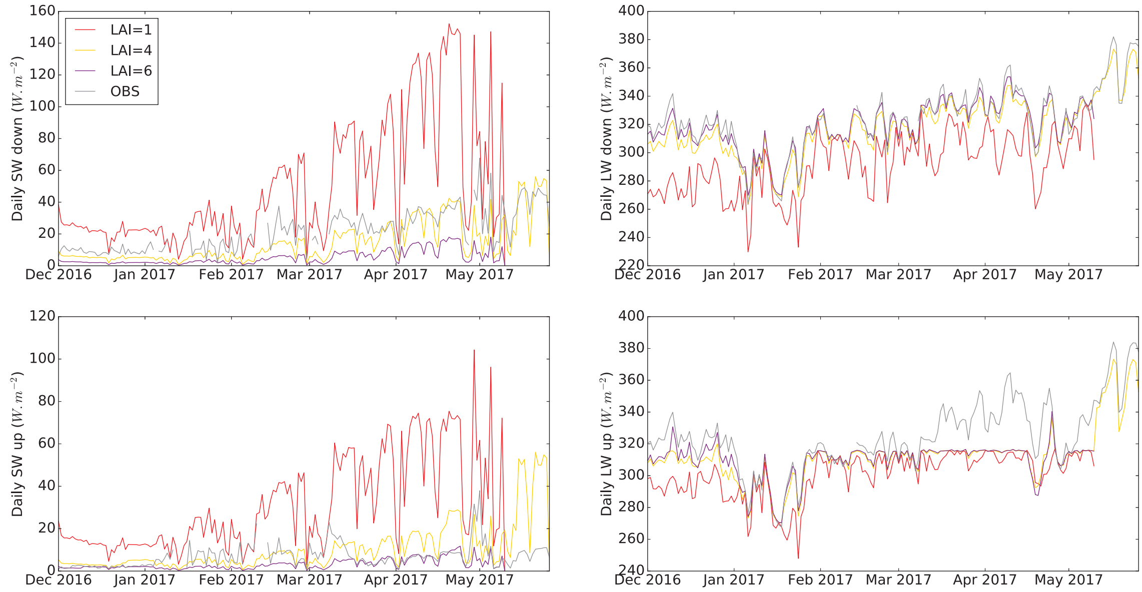

Figure 4: Downards (top) and upwards (bottom) shortwave (left) and longwave (right) observed and simulated radiations with 3 different values of LAI during the 2016-2017 season.

suggests that the positive bias of total snow depth is probably due to an initial bias after each snowfall event with too much snow reaching the surface even after unloading.

The parameterization of interception from Hedstrom and Pomeroy (1998) includes a number of empirical and uncertain parameters. If some of them have a significant impact on the intercepted snow amount at a given date, complementary analyses demonstrated that they do not affect significantly the total snow mass on the ground because the unloading is simply slightly advanced or delayed but the mass balance is not significantly affected by these changes. In cold high-latitudes sites, the sublimation prevails in the mass losses of the intercepted snow and melting is often neglected (Lundberg et al., 1998; Essery et al., 2003). However, in warmer conditions such as those of Col de Porte, the short stay of the snow in the branches reduce the potential impact of sublimation. Conversely, melting of the intercepted snow is frequent (frequent warmings can be seen in Figure 5c). Melting of intercepted snow is parameterized by a linear function of positive vegetation temperature with a melting factor of 5.556E-6 kg $m^{-2}s^{-1}K^{-1}$ = 0.48 kg $m^{-2}day^{-1}K^{-1}$. This value is about ten times lower than the classical degree-day factors in hydrological models for snow on the ground (Hock, 2003). Furthermore, it does not depend on the vegetation surface which is significantly higher than the ground surface when LAI >> 1. Therefore, the melting quantified by the current parameterization could be strongly underestimated. Unfortunately, this variable can not be observed directly. To investigate this assumption, we run a numerical experiment where the melting factor was multiplied by 100 (about 48 kg $m^{-2}day^{-1}K^{-1}$, *x100* experiment). This might not be unrealistic with the previous considerations. The obtained new snow masses (black triangles in Figure 5a are now much more consistent with observations. Figure 5b shows that the snow depth of this experiment is closer to the observed snow depth in the forest than the reference simulation although an overestimation still exists during this period. Evaluations during the whole two seasons show that the bias is significantly reduced with the *x100* experiment. This can also be seen in terms of total SWE for the 2016-2017 season in Figure 6.

4. CONCLUSIONS AND OUTLOOK

This work presented the first evaluation of the new MEB-Crocus system with a new evaluation dataset on a mid-elevation spruce forest. A major bias of the simulated snow depth under forest can not be explained by the uncertainty in the vegetation parameters or the spatial variability in the forest. It can neither be explained by the simulated radiative balance which is rather accurate or by the usual errors of snowpack models which have already been quantified at this site (Lafaysse et al., 2017). An incorrect impact of interception in the snow mass balance is the more likely explanation and this is supported by direct observations of new snow mass un-

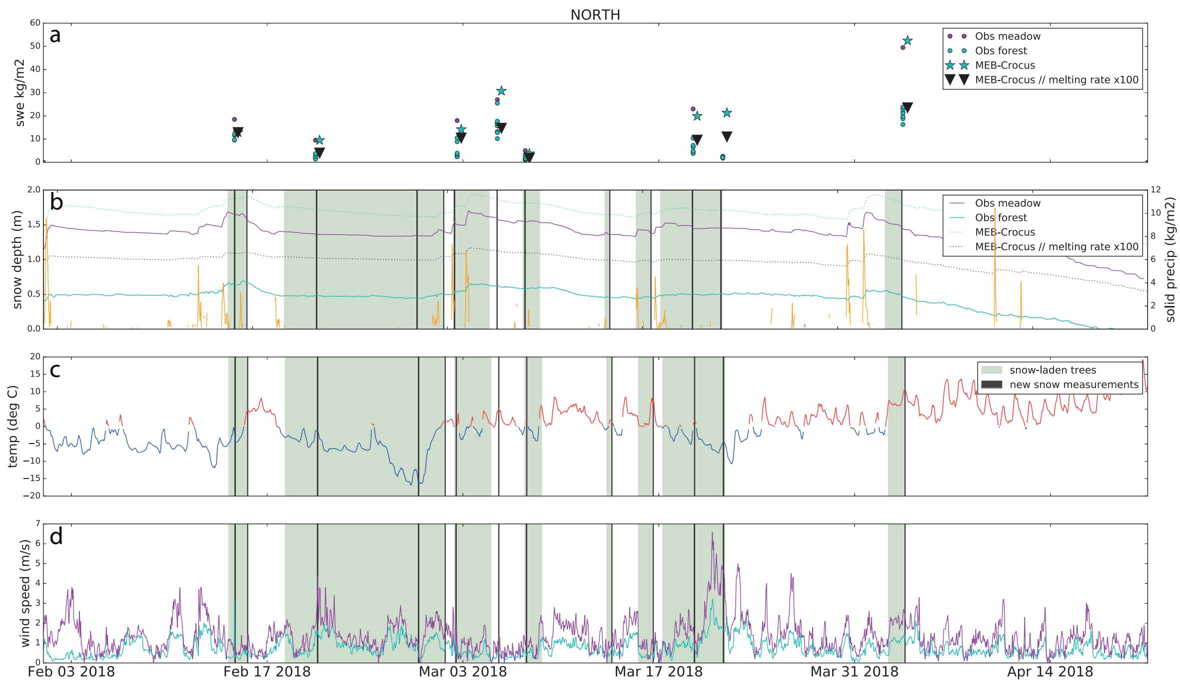

Figure 5: a) Comparison of measured snow water equivalent in the boxes of the North transect (blue circles) with the simulated new snow water equivalent by MEB-Crocus (blue stars) and by the *x100* experiment (black triangles). Purple circles correspond to the observed new snow water equivalent in the meadow. b) Observed snow depth in the forest (blue full line) and in the meadow (purple full line) and simulated snow depth in the forest by MEB-Crocus (blue dotted line) or by the *x100* experiment (black dotted line). The yellow line represents the solid precipitation forcing from the observation in the meadow. c) Air temperature (blue when negative, red when positive). d) Wind speed in the forest (blue line) and in the meadow (purple line). In b, c and d, green periods correspond to observed snow in the trees from a webcam and black lines correspond to the dates of the site visits.

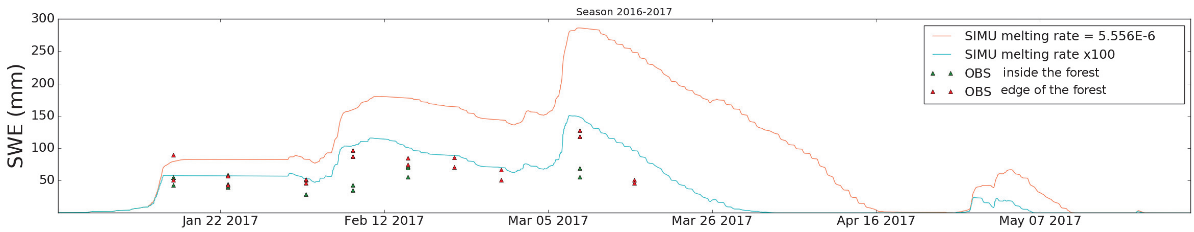

Figure 6: Simulated total snow water equivalent with the default melting factor of intercepted snow (red line) and the *x100* experiment (blue line) ; observed weekly snow water equivalent at the 18 locations (the 4 snow cuts are not performed at the same place each week)

der the trees. Numerical experiments suggest that the underestimation of the melting of intercepted snow may be the main model deficiency. However, a specific calibration of the process at Col de Porte is likely to lack from a robust validity in other areas. Therefore, a more physical representation of snow on the branches is required to improve the representation of this process. Computing a simplified energy balance for intercepted snow might be a promising solution. An improved understanding of this process at the local scale is crucial to extend the model over larger areas and to offer the possibility to better account for snow-vegetation interactions in various applications including hydrological studies, snow management on forested slopes, and climate change impact studies on snow cover over more than 50% of the alpine regions.

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