JOURNAL OF GEOPHYSICAL RESEARCH

Supporting Information for "Effect of Forest Canopy Structure on Wintertime Land Surface Albedo: Evaluating CLM5 Simulations With In-Situ Measurements"

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Introduction
The aim of this supplementary material is to expand on the performed adaptions of the original CLM5 model version (Section 2.5 in the main article) as well as to show resulting point-scale CLM5 simulations of seasonal snowpack evolution. The adjustments were necessary to achieve more realistic snow cover simulations, in particular to ensure melt-out occurred at the correct time so that simulated Land Surface Albedo (LSA) could be faithfully compared to observed LSA.

In the first part of this supplementary material, seasonal snow-depth measurements are compared with point-mode CLM5 simulations using a) the original and b) the adapted CLM5 model version (Figure S1, Text T1).

Part two explains in detail the performed model adaptions and parameter choices for the adapted CLM5 model version used in this study. Adaptations were made in three different areas: the turbulent transfer through the forest canopy (Figures S2 and S3, Text T2), the snow covered area shape function (Figure S4, Text T3), and the fraction of the canopy that is snow covered following interception events (Figure S5, Text T4).

In the third part of this supplementary material, point-mode CLM5 simulations of seasonal snow-pack evolution are shown for Davos Laret (CH) and Sodankylä (FIN) using the CLM5 adapted version. For each location, two figures are shown: a) snow depth and b) snow water equivalent (SWE) for a range of canopy densities (Figure S6-S7, Text T5).

Part 1: Measurements vs. simulations of snow depth

Text T1. Manual snow-depth measurements were performed along a linear transect of 48m length in Davos Laret (CH) throughout the 2017/18 winter season. Four measurement points along the snow-course transect coincided with waypoint locations used for LSA measurements and simulations in this study. Figure S1 compares snow-depth measurements with point-mode simulations at the respective locations using a) the original and b) the adapted CLM5 versions. For the purpose of this study, ensuring melt-out occurred at the correct time was the main concern, as the majority of the UAV-based LSA observations were obtained during spring. Simulations with the original CLM5 version showed that melt-out occurred too early when compared to observations (8, 13, 14 and 13 days too early for WP2, WP3, WP4 and WP5, respectively), while simulations with the adapted CLM5 version showed more realistic melt-out dates at all four waypoint locations (Figure S1). Note that all CLM5 simulations substantially overestimated maximum snow depth. However, this did not affect simulated LSA, which was the main focus of this study.

Part 2: Model adaptions

Text T2: Turbulent transfer through the forest canopy.

As seen in S1, initial simulations showed that snow melted too quickly at forested waypoint locations. Investigation of individual heat fluxes showed that the main issue, which led to exaggerated melt at forested sites, can be attributed to an overstated sensible heat exchange between the canopy air space and the snow surface. Figure S2 shows an exemplary plot of sensible heat flux from ground to canopy air space (negative = into snowpack) for the spruce site in Davos Laret. Sensible heat flux into the snow pack was as high as 793 W m^{-2} at times, which made simulated snow disappear at an unrealistically fast rate.

Parametrizations for turbulent transfer through the forest canopy are mostly developed for and validated against above canopy fluxes, as the turbulent exchange between the land surface as a whole and the above-canopy atmosphere is the main interest of land surface models. Furthermore, validation data for below canopy fluxes, e.g. the turbulent exchange between sub-canopy snow and within-canopy atmosphere, is lacking. Other studies (e.g. (Clark et al., 2015; Mazzotti et al., 2020)) have found similar problems with exaggerated sub-canopy turbulent heat fluxes.

In the default CLM5 version, the sensible heat exchange between the canopy air space and the snow surface is largely dependent on the unitless turbulent transfer coefficient under canopy ($csoil_{cn}$), which is a function of the turbulent transfer coefficient for soil under canopy ($csoil_c$), the turbulent transfer coefficient over bare soil ($csoil_b$) and canopy density (w). It is calculated by:

$$csoil_{cn} = csoil_b \cdot w + csoil_c \cdot (1 - w) \qquad (1)$$

$csoil_c$ [-] is set to 0.004, and $csoil_b$ [-] is parametrized based on the roughness length of the ground (z_0) and the sub-canopy wind speed (uaf) as:

$$csoil_b = \frac{0.4}{0.13(\frac{z_0 \cdot uaf}{1.5E-5})^{0.45}} \qquad (2)$$

0148-0227/21/$9.00

In this study, the problem of an overstated sensible heat exchange between the canopy air space and the snow surface was mitigated by reducing $csoil_b$ by a factor of 15, which led to more plausible sensible heat fluxes, as shown in Figure S3. Note that this adaption is a first order correction, which allowed CLM5 to be used for the purposes of this study. This adaption should be viewed as a necessary tuning exercise for this specific study. There is, however, a need to improve turbulent heat transfer parametrizations of forested environments in general, which will require attention in the future.

Text T3: Snow-covered area shape function

Fractional snow covered area ($FSno$) in CLM5 is calculated following Swenson and Lawrence (2012):

$$FSno = 1 - [\frac{1}{\pi} acos(2\frac{W}{W_{max}} - 1)]^{n_{melt}} \tag{3}$$

W is the simulated snow water equivalent (SWE) at the current time step and W_{max} is the maximum simulated SWE of the snow season. n_{melt} is the snow covered area shape functio, which is determined from σ_{topo}, the standard deviation of topography within a grid cell by:

$$n_{melt} = \frac{200}{\sigma_{topo}} \tag{4}$$

As the impact of topography was assumed to be small for all sites, the comparatively small value of 25 was chosen, which delayed the onset of fractional snow cover and showed a rapid decline in snow cover extent towards the end of the melt season (Figure S4).

Text T4: Fraction of canopy that is snow covered

The fraction of canopy that is snow covered ($fcansno$) has substantial effects on LSA, however, in the CLM5 default model version LSA was unrealistically responsive to even tiny amounts of snow in the canopy. In the default CLM5 version, $fcansno$ is based on the amount of intercepted snow in the canopy ($snocan$), forest density (PAI) and the maximum allowed dew ($dewmx$):

$$fcansno_{orig} = (\frac{dewmxi}{vegt \cdot 6 \cdot 10} \cdot snocan)^{0.15} = (\frac{snocan}{6 \cdot PAI})^{0.15} \tag{5}$$

$$vegt = fveg_{nosno} \cdot PAI \tag{6}$$

$$dewmxi = \frac{1}{dewmx} = \frac{1}{0.1} \tag{7}$$

$fveg_{nosno}$ is implemented as a logical operator that can only be set to 0 or to 1, which is referred to as $switch_{snow}$ in the main article. It can be seen that the maximum amount of intercepted snow that can be held by a canopy is limited to 6 * PAI, and because in the original parametrization $snocan$ as a fraction of $snocan_{max}$ is taken to the power of 0.15, even smallest amounts of $snocan$ result in relatively high values of $fcansno$ (e.g. 0.05 of $snocan$ will result in $fcansno$ of 0.64, leading to an unrealistically high LSA). Hence, if even the smallest amount of dew is formed overnight, it is already noticeable in the simulated LSA for the majority of the next day. This problem was mitigated by removing the power of 0.15, and omitting $fveg_{nosno}$ altogether. Results of implementing this adaption are shown in Figure S5.

Part 3: Seasonal snow-pack evolution

Text T5: For completeness, point-mode simulations with the CLM5 adapted model version of snow depth and snow water equivalent (SWE) are shown for the two main field sites of this study: Davos Laret (CH, Figure S6) and Sodankylä (FIN, Figure S7). For each location, two figures are shown: a) snow depth and b) SWE for a range of canopy densities (Plant Area Index range from 0 to 5 at 0.2 increments). In each plot, the red line shows a simulation at an open, unforested point.

References

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., … Rasmussen, R. M. (2015). A unified approach for process-based hydrologic modeling: 1. Modeling concept. *Water Resources Research*, *51*, 2498–2514. doi: 10.1002/2015WR017198

Mazzotti, G., Essery, R., Webster, C., Malle, J., & Jonas, T. (2020). Process-level evaluation of a hyper-resolution forest snow model using distributed multi-sensor observations. *Water Resources Research*, *56*, 1–25. doi: 10.1029/2020WR027572

Swenson, S. C., & Lawrence, D. M. (2012). A new fractional snow-covered area parameterization for the Community Land Model and its effect on the surface energy balance. *Journal of Geophysical Research Atmospheres*, *117*(21), 1–20. doi: 10.1029/2012JD018178

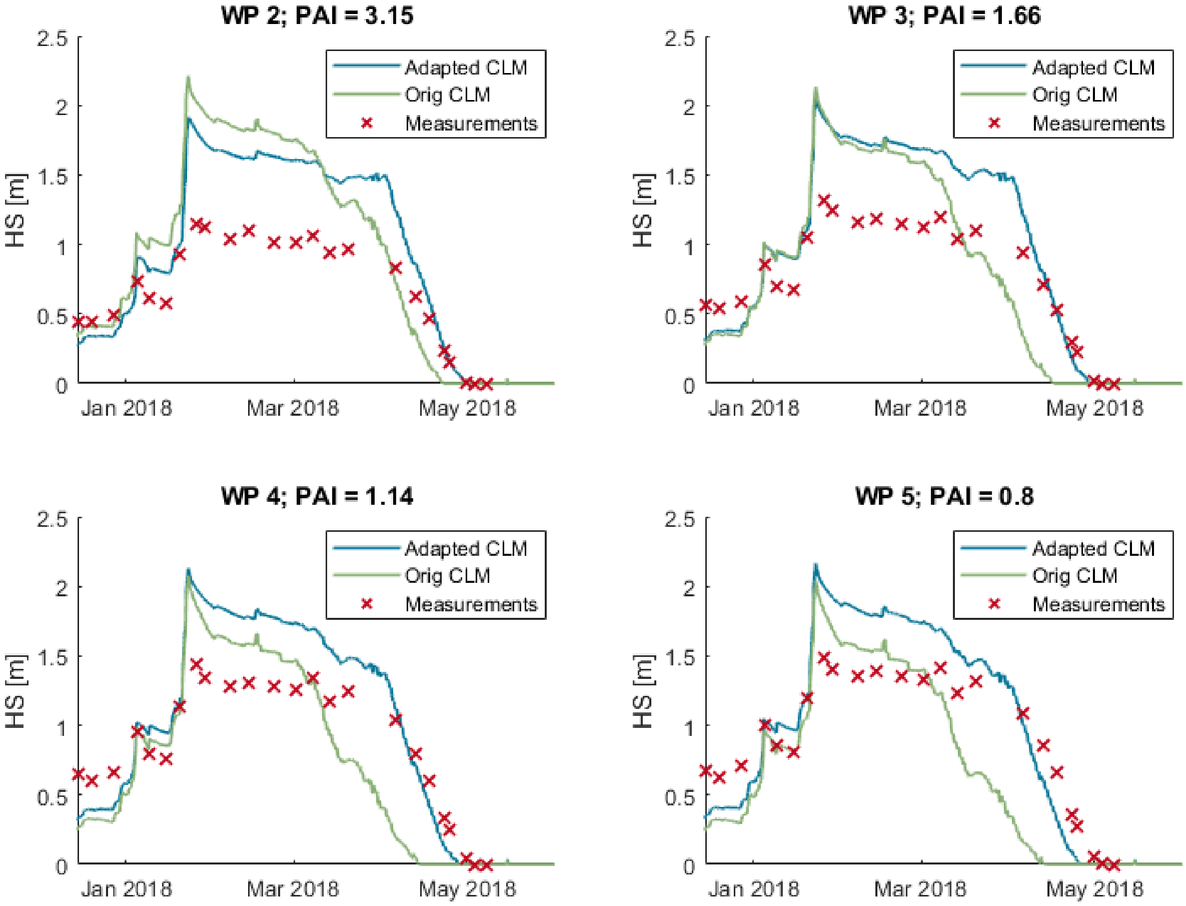

Figure S1. Comparison of seasonal snow depth evolution at four waypoint locations in Davos Laret (CH): Original model version of CLM5 (green lines), adapted model version of CLM5 (blue lines) and measurements (red dashed lines).

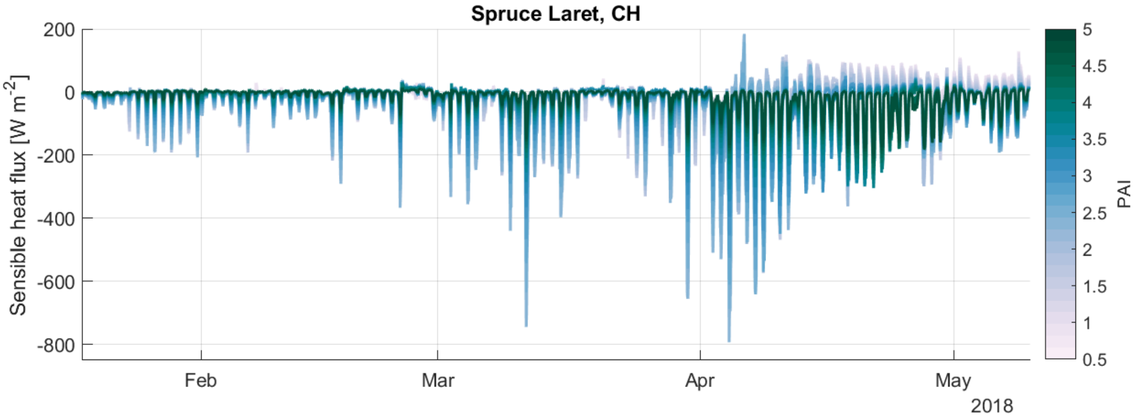

Figure S2. Seasonal sensible heat flux evolution for a range of canopy densities in Davos Laret (CH), using the original model version of CLM5.

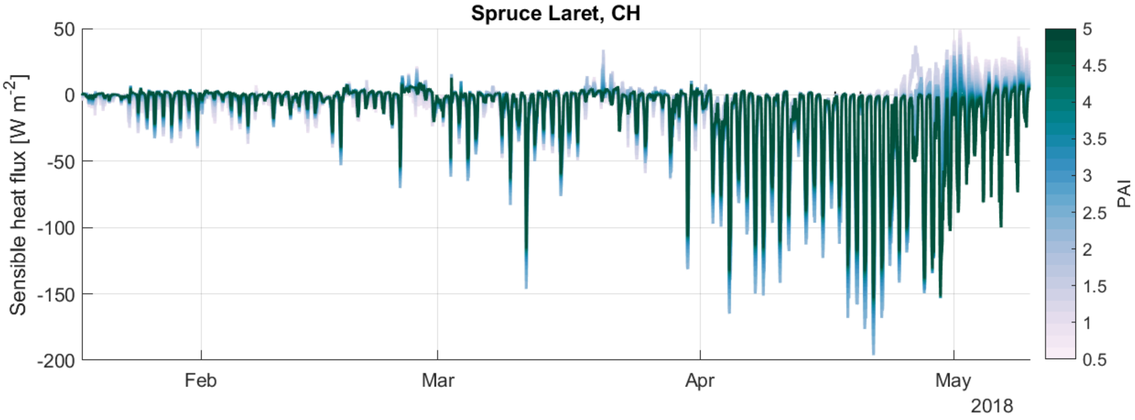

Figure S3. Seasonal sensible heat flux evolution for a range of canopy densities in Davos Laret (CH), using the adapted model version of CLM5.

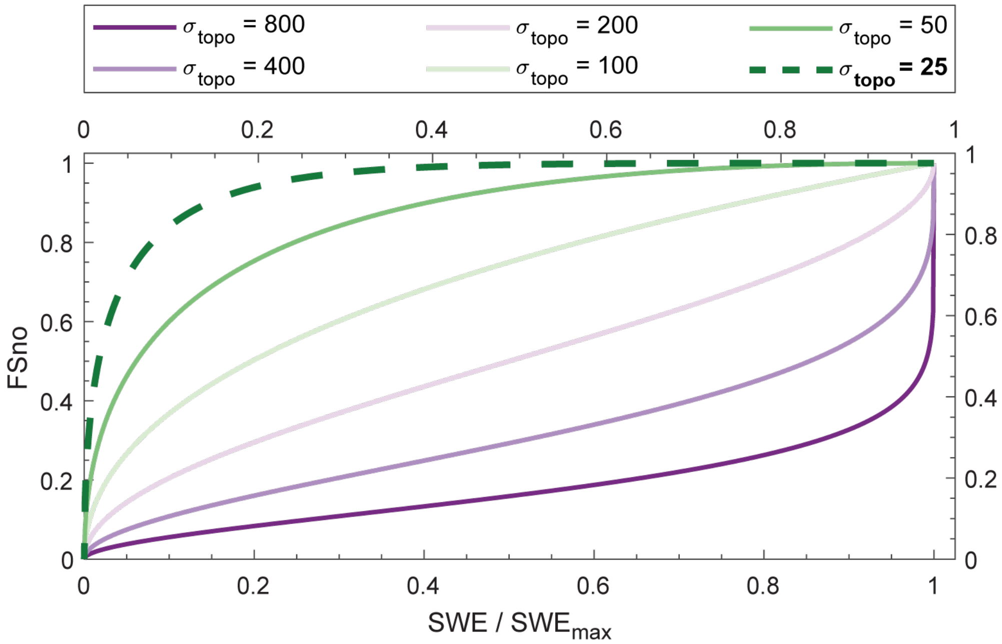

Figure S4. Fractional snow cover vs. dimensionless SWE during the melt period for grid cells with varying standard deviation of topography (σ_{topo}) as calculated by Equation 3 for FSno. Figure adapted from Swenson and Lawrence (2012). The green dashed line was used for this study.

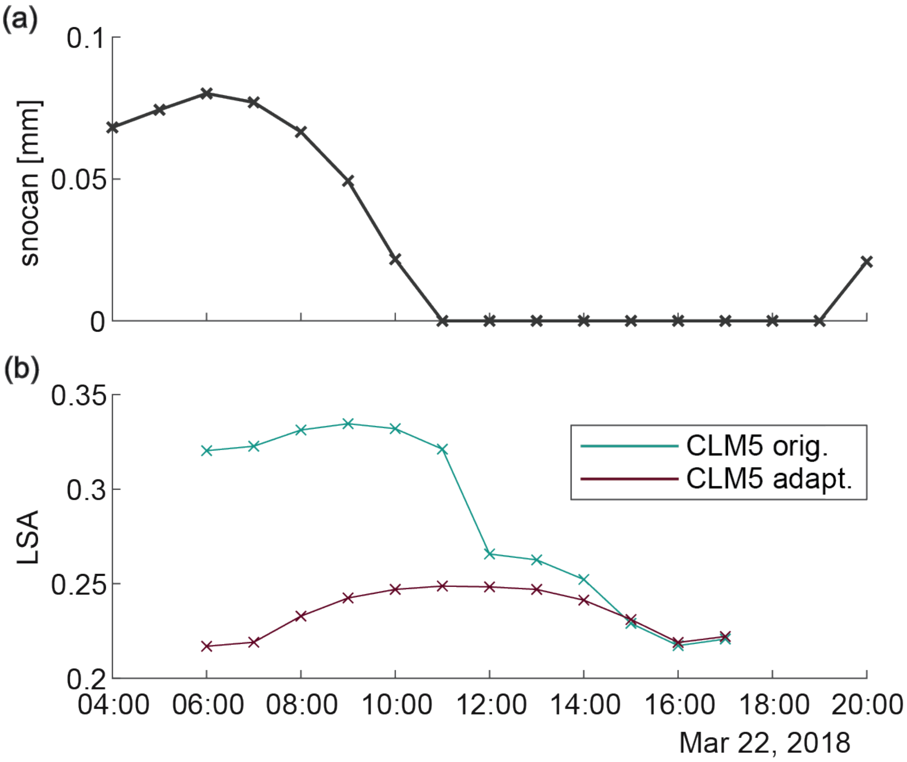

Figure S5. Intercepted snow (a) and the coinciding LSA (b) computed with the original and the adapted CLM5 model version for an exemplary clear sky day (22.3.2018) with no precedent snow fall event at a sparse forest canopy (PAI=1) site in Davos Laret.

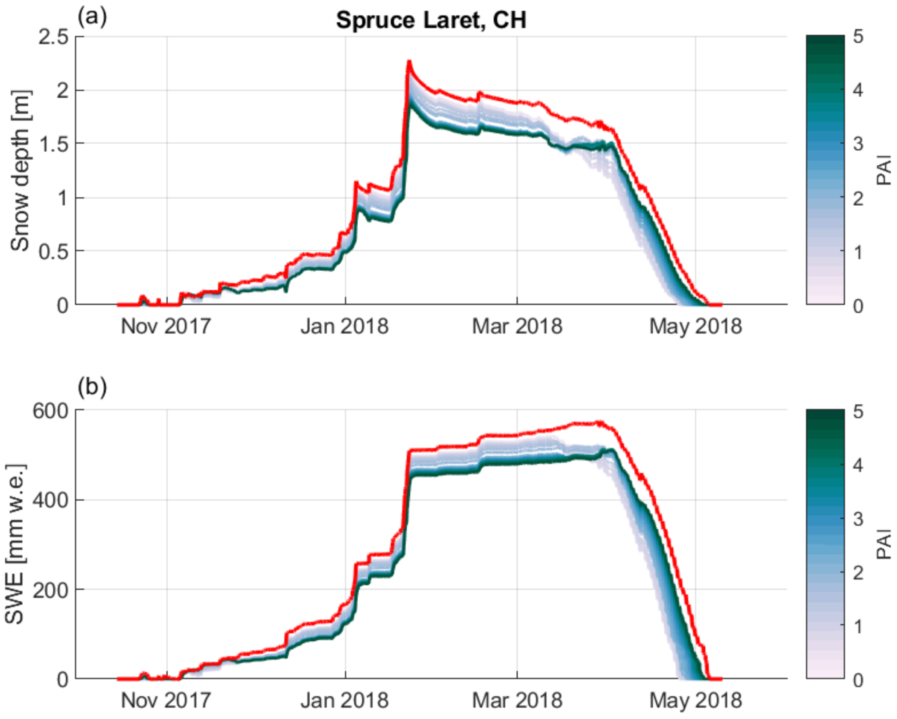

Figure S6. Seasonal snow-pack evolution for a range of canopy densities in Davos Laret (CH), using the adapted model version of CLM5. The red line shows a simulation at an open, unforested point.

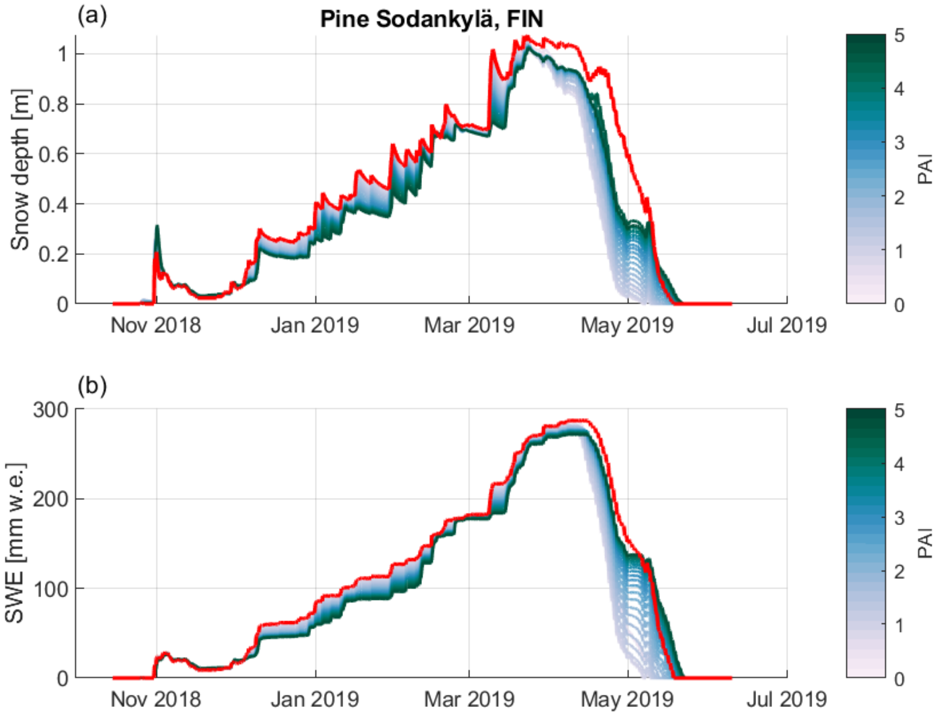

Figure S7. Seasonal snow-pack evolution for a range of canopy densities in Sodankylä (FIN), using the adapted model version of CLM5. The red line shows a simulation at an open, unforested point.