Reviewer #1

This study describes the implementation of a new snow albedo scheme in the GLASS land surface component of the GFDL climate model, accounting for the effects of light-absorbing particles (LAPs). It then evaluates the simulation of snow mass, snow depth, and surface albedo at several sites contributing to the SnowMIP effort. Overall, this study represents an advance in scientific capabilities of the GFDL climate model. I found it particularly useful that the model was run in "single point" mode for comparisons with the SnowMIP sites. The quantification of the reduction in number of snow cover days due to the presence of LAPs was also useful, though it would be helpful to also include an evaluation of LAP concentrations in snow, compared with observations, to help understand how realistic the simulated LAP-induced albedo effect is. The manuscript is generally well-written and well-organized. Aside from one major suggestion, I have only minor comments.

We thank the referee for the insightful comments on our work. Please find below a point-by-point response to the comments on the manuscript. We believe addressing these comments would significantly improve the manuscript with respect to our first submission. In particular, to address the major comment in this review we extended our analysis by comparing our modelling results to additional observations of dust-on-snow. In the following, we report the text of the review in black, and our response in light blue. Excerpts from the manuscript with the proposed changes are reported here in *Italic*. The line numbers referenced in our response refer to the position of the excerpts in the proposed revised manuscript.

Major comments:

The new model prognoses the mixing ratios of dust and black carbon in surface snow, and I believe that concentrations of these particles have been measured at some of the SnowMIP sites used in the evaluation, such as Senator Beck and Col du Port. It would be quite helpful to know how the simulated mixing ratios compare with observations, as this would inform on potential sources of bias in the simulated SWE evolution throughout the seasons. Such an evaluation could suggest, for example, that biases in impurity concentrations are responsible for SWE biases, or conversely if the particle mixing ratios appear realistic, that there are other problems with the snow model.

We agree that comparing our modelling results to measured concentrations of LAPs in snow would be a helpful addition to our analysis. For the Col de Porte site, we have already compared our results with spectral measurements from Dumont et al., 2017, which estimate an equivalent concentration of LAPs at the snow surface for one snow season (Figure 3).

For the Senator Beck Basin (snb) and Swamp Angel (swa) sites, we have now added an additional comparison with i) a dataset for the the 2013 snow season which includes mineral dust and black carbon concentration data published by Skiles and Painter (2017), and ii) a multi-year dataset of end-of-season dust concentrations in snow (Skiles and Painter, 2015).

We propose to add a description of these additional datasets used in the analysis as follows (proposed addition at line 309 of the revised manuscript):

In addition, for validation over the Senator Beck Basin (snb) site, we employ a dataset of dust-in-snow observations collected by Skiles and Painter (2015, 2017). These include end-of-year concentrations of dust within the snow for the years 2005-2012 (Skiles and Painter, 2015), and a sequence of measurements characterizing the seasonal evolution of MD and BC concentration in snowpack for the year 2013 (Skiles and Painter, 2017). Measured concentration values in this dataset correspond to average concentrations within the uppermost 30 cm of the snowpack. In the following, we compare these values to average modelled concentrations within the entire snowpack, and to the predicted concentration values over the snow near-surface layer.

We have now performed an evaluation of our simulations based on these additional measurements. We propose to add two additional figures to the manuscript reporting the results of this new analysis as follows (the new proposed figure 4 and figure 5 to be added to the manuscript are reported below):

"We further compared modelled and observed concentration of impurities in snow by using the dataset collected from field campaigns at the Senator Beck Basin (snb) and Swamp Angel (swa) sites in Colorado (Skiles and Painter, 2015; 2017).

Figure 4 shows a comparison between observed and modelled concentration of LAPs in snow for the Senator Beck Basin site for the year 2013, which includes the occurrence of intense dust deposition events during spring. In Figure 4A we compare the total LAP content in snow as equivalent concentration of black carbon ($c_{eq,BC}$) as defined in eq. (10). During the first part of the year, the magnitudes of measured and modelled concentration over the model near-surface layer are comparable. However, during spring the intense LAP deposition events recorded at the site are underestimated by the model. We also note that the rapid increase in modelled LAP concentration at the end of the snow season happens later compared to the observations due a slower snow ablation. Average $c_{eq,BC}$ within the entire snowpack is lower than that modelled for the near-surface layer during the entire season, until the very end of the season. Figure 4B *further compares MD and BC observations with the column-average model predictions. For dust, model predictions are lower than observations throughout the season, and again increase rapidly towards the end of the snow season driven by snow ablation. BC modelled concentrations are small throughout the season, and tend to be in better agreement with observed values (Figure 4B).*

We extend this comparison by examining a multi-year dataset of dust concentration collected at the end of the snow season at the Senator Beck Basin (snb) and Swamp Angel (swa) sites, respectively an high-elevation alpine site, and a lower evelation "sub-alpine" site (Skiles and Painter, 2015). Note that again these observations correspond to average MD concentrations over the top 30 cm of the snowpack. As a comparison with observed data, we report both modelled MD concentration averaged over the snow column, and near-surface equivalent LAP concentration, expressed as dust content ($c_{eq,MD}$*).*

For the swa site, we find that the model underestimates observed concentrations throughout the season, with the near surface $c_{eq,MD}$ *being generally larger than the average snowpack concentration and closer to observations (Figure 5A). For the snb site, the model still underestimates measured concentrations, but the underestimation is smaller than that observed for the swa site. Modelled concentration values at snb are larger compared to the case of swa, and exhibit a larger year-to-year variability (Figure 5B). Furthermore, the variability in observed concentrations between the two sites is significant, with the high-elevation site (snb) exhibiting lower dust concentration values, thus suggesting a large spatial heterotegeneity in dust content. In particular, the model underestimates dust concentration for the years characterized by extremely high dust loads at this site (in particular, year 2010).”*

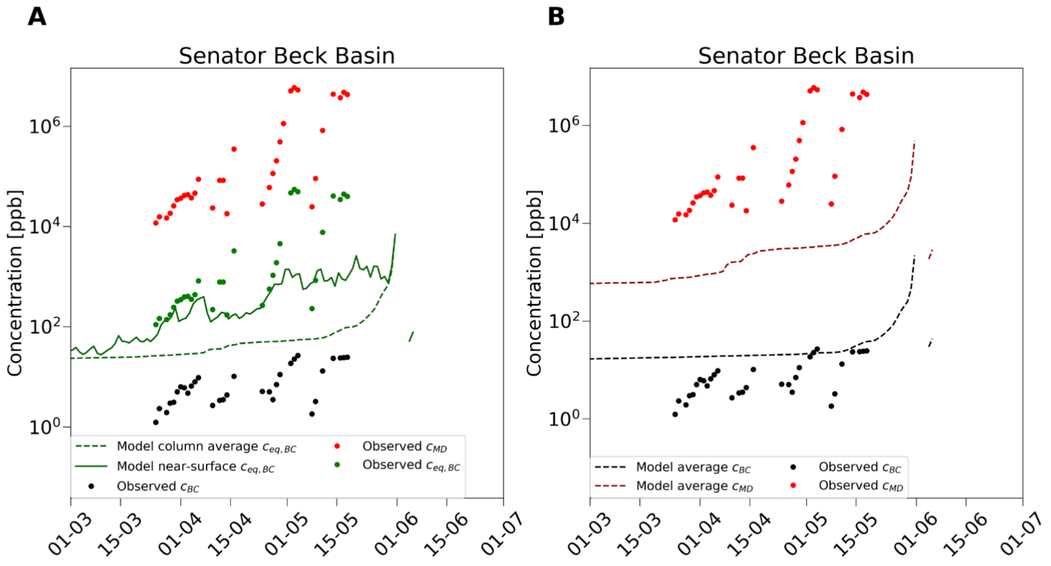


Figure 4. Comparison between modelled and observed LAP concentrations for the Senator Beck Basin (*snb*) site for spring 2013. Panel (A): Observed MD (red circles) and BC concentration (black circles) in the top 30 cm of snow. The total LAP concentration $c_{eq,BC}$ observed (greed circles) and modelled in the near-surface layer (green line) and averaged over the entire modelled snowpack (green dashed line) are also shown for comparison. Panel (B): The same observed MD (red circles) and BC concentration (black circles) are now compared to the vertically-averaged modelled concentrations of BC (black dashed line) and MD (red dashed line).

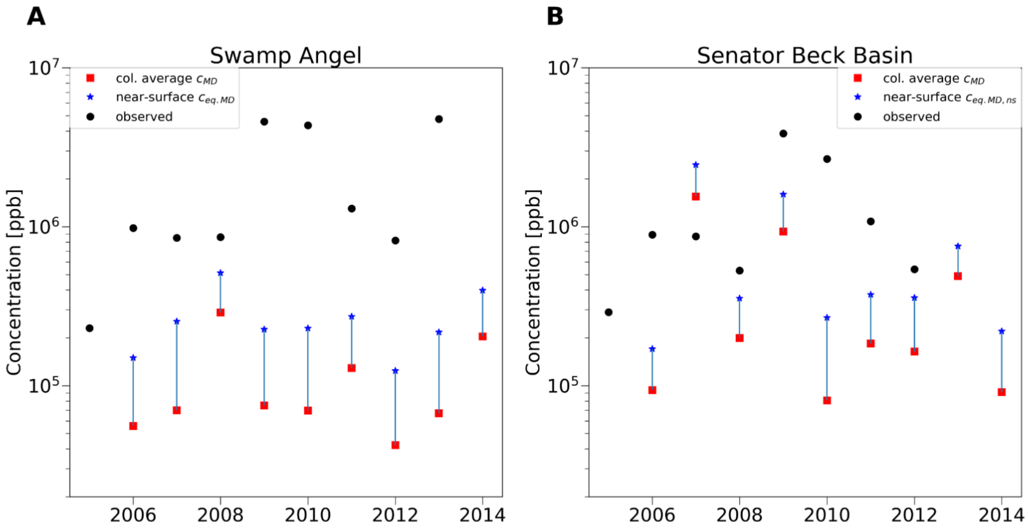
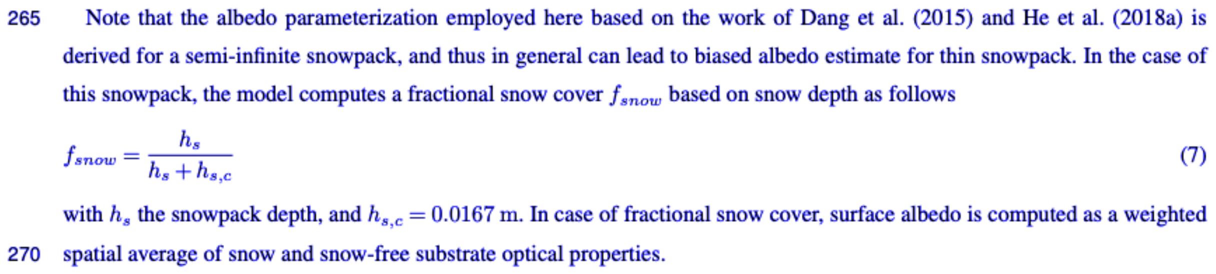


Figure 5. Comparison between modelled and observed end-of-year dust concentrations for the Swamp Angel (*snb*, panel A) and the Senator Beck Basin (*snb*, panel B) sites in southern Colorado. Dates are in format day-month. Data are obtained from Skiles and Painter (2015) and correspond to the average dust concentration C_{MD} averaged over the top 30 cm of the snowpack (black circles). Model values are the column vertical average MD concentration c_{MD} within the snowpack (red squares). The equivalent concentration of LAPs in the near-surface layer of the snowpack is also reported as comparison (blue star markers).

Section 2.6: It was not apparent to me how/if the albedo of the ground underlying snow and snow thickness affect the snow albedo calculation. Is the snow assumed to be optically "semi-infinite" regardless of snowpack thickness? If so, this would cause a high bias in the albedo of thin snowpack, and it should be acknowledged.

We agree that this limitation of the model should be discussed in the manuscript. The parameterization is for semi-infinite snowpack and thus can give rise to errors in case of thin snowpacks. We now propose to clarify this point in the revised manuscript instead of just referring to Zorzetto et al., 2024 and to He et al., 2018 for details on the albedo parameterization used.

We proposed to explicitly specify in the revised manuscript that in the case of thin snowpacks, a snow area fraction is computed and used for albedo calculations. At line 265:



Note that the albedo parameterization employed here based on the work of Dang et al. (2015) and He et al. (2018a) is derived for a semi-infinite snowpack, and thus in general can lead to biased albedo estimate for thin snowpack. In the case of this snowpack, the model computes a fractional snow cover f_{snow} based on snow depth as follows

$$f_{snow} = \frac{h_s}{h_s + h_{s,c}} \qquad (7)$$

with h_s the snowpack depth, and $h_{s,c} = 0.0167$ m. In case of fractional snow cover, surface albedo is computed as a weighted spatial average of snow and snow-free substrate optical properties.

In the discussion we now propose to explicitly mention this issue by stating that (line 467):

“Furthermore, the model could be improved by using more detailed optical models such as the Two-stream Analytical Radiative TransfEr in Snow (TARTES) model (Libois et al, 2013) or the Snow, Ice, and Aerosol Radiative (SNICAR) model (Flanner and Zender, 2005), which are not limited to the case of semi-infinite snowpack as is the case for the albedo parameterization used here. “

Minor comments:

1. line 55: "Black carbon has the largest absorption..." -> Black carbon has the largest absorption *per unit mass* ..."

We agree, and propose to revise the text as suggested.

2. line 119: "sol-snow" -> "soil-snow"

We agree, and propose to revise the text as suggested.

3. Lines 132-146, section 2.2: Overall, this is a helpful summary. Briefly, though, could you please also list the maximum number of snow layers allowed in this model, along with maximum/minimum layer thicknesses (especially near the top)? This info is probably available in the companion paper, but it would be helpful to include it here, too.

We now propose to discuss more in detail the layering scheme used in GLASS. At line 146 of the revised manuscript we propose to add the following:

“The vertical structure of the snowpack consists of a dynamic number n_L *of snow layers. New layers are created on top of the existing snowpack following snowfall events of large enough magnitude, so that the vertical layering structure preserves snow physical properties in each layer. Depending on snowfall rate, up to 5 new snow layers can be created during a single model time step.*

The vertical layers are also updated based on computational considerations. At each time step, the snow vertical structure is compared to an optimal vertical discretization defined for each given snow depth. If the layers are too coarse or too thin for a given snow depth, the layers undergo splitting or merging. In the current configuration, the optimal thickness of the uppermost snow layer is set to 3 cm , and each snow layer optimal thickness is set to 1.5 that of the layer immediately above it, so that in general the model allows for thinner layers closer to the surface, while within the snowpack layer thickness increases with depth. The model does not prescribe a maximum number of layers, while if snow is present the minimum number of layers is 3, as required for numerical solution of mass and energy vertical balance equations.

These operations are designed in order to strike a trade-off between computational cost and vertical detail, to satisfy requirements of numerical efficiency (to avoid too large number of layers) and to ensure a proper description of the snowpack vertical structure (too coarse a vertical discretization would hinder the representation of some physical processes, such as the vertical heat diffusion). If two snow layers are characterized by values of density, optical diameter or impurities content which are too different, merging of the two layers is not permitted in order to preserve the vertical heterogeneity of the snowpack. "

4. lines 158-164: Would it be accurate to state that the mixing ratio of LAPs within precipitation is held constant throughout the month? Also, is there any interpolation between the months, or does the mixing ratio change abruptly on the first day of the month?

The mixing ratio is kept constant within each month and then indeed changes abruptly to the next value. While this is not ideal, we believe it was the simplest approach given the available data. We now propose to clarify this at line 189 of the revised manuscript:

"Since we force the snow model with in-situ observations, we adopt the following strategy to estimate wet deposition fluxes for each snowfall or rainfall event: We first compute the monthly average concentration of each LAP specie in the precipitation (as the mass ratio of monthly average wet deposition to monthly precipitation, in [ppm]). We then assign in each model time step the total amount of wet-deposited LAPs as proportional to the rainfall and/or snowfall rate for that time step, so that the flux of tracer i due to liquid and solid precipitation is respectively \$ $c_{l,i} f_l$ *and* $c_{s,i} f_s$*. Note that based on this procedure the mixing ratio of LAPs in precipitation is constant during each month, and exhibits step changes across months. For the purpose of this study, we assume that rainfall and snowfall carry the same concentration of LAPs, and neglect any possible dependence of deposition fluxes e.g., on precipitation intensity."*

5. lines 158-168: Related, is there an interactive, coupled version of the atmosphere and land models, where prognosed aerosol deposition is coupled with GLASS each timestep? (Or, are there plans to extend this modeling framework to the coupled model?)

While the model was tested here in a “land-only” configuration, it was indeed designed for coupled Earth System Model simulations. While not included with the software package distributed with this publication, a coupled version of the model is currently under development and its evaluation will be the object of future research. The current land-only model version is ready for such coupled runs, with the caveats that deposition fluxes for each LAP species will need to be provided by the atmospheric model. In this setup, the computation of the monthly constant mixing ratio of LAPs in precipitation (see our response to the previous comment) will no longer be needed as both liquid/frozen water fluxes and LAP deposition fluxes will be provided by the atmospheric model. We plan to test this coupled configuration in future research. We propose to add a brief note about this in the discussion section of the revised manuscript (line 480):

“While the model was here tested in a land-only configuration forced by an offline atmosphere, LM4.1 and GLASS are designed as components of an Earth System Model and are thus used for coupled simulations with an atmospheric model. In this coupled model configuration, currently under development, the computation of the monthly constant mixing ratio of LAPs in precipitation will no longer be needed as both liquid/frozen water fluxes and LAP deposition fluxes will be provided by the same atmospheric model.“

6. line 193: Is the same scavenging ratio assumed for hydrophilic and hydrophobic BC? It seems that the scavenging ratio should be larger for hydrophilic BC, as specified by Flanner et al (2007).

In the current configuration, we consider a single species of BC which includes both hydrophobic and hydrophilic components, with total BC deposition fluxes provided by in the input dataset. We agree that scavenging ratios as well as optical properties should distinguish between the two. We propose to explicitly state that this is the case for the current model configuration, and note that it can be extended to treat hydrophilic and hydrophobic BC separately as long as scavenging coefficients and optical properties are available. At line 173 of the revised manuscript, we propose to add the following:

“These quantities ($w_{IM,i,k}$ *and* $w_{EM,i,k}$*) in [kg* m^{-2}*] are tracked for each tracer species i, so that in our current application we have 6 types of LAP in each layer (IM and EM, for each species: BC, OC and MD). The model considers a single LAP size distribution for mineral dust, without tracking separately dust particles of different sizes. Similarly, the current model considers a single BC species and does not distinguish between hydrophobic and hydrophilic components. This is a limitation as hydrophobic and hydrophilic BC species have different*

optical properties and scavenging coefficients (Flanner et al., 2007). However, we note that the model can in principle be extended to track multiple BC species (or multiple dust size bins) as long as their optical properties and scavenging coefficients are known."

7. line 196-197: "... snow properties are averaged over a near surface layer of thickness set equal to up to 3cm." - Is this simply the top thermodynamic snow layer in GLASS, or is this a weighted average of multiple snow layers? When is it less than 3cm? Please elaborate a bit on this scheme.

This surface layer is always 3 cm deep, or as deep as the entire snow depth, whatever is thinner. If the top snow layers are thinner than this value, a weighted average over multiple snow layers is performed. We propose to clarify this feature of the model at line 228 of the revised manuscript:

"In this work, the snow surface albedo is computed based on snow properties (optical diameter and shape) and on the concentration of LAPs near the snowpack surface. In this section, snow properties are averaged over a near-surface layer of thickness set equal to up to 3 cm. If the snowpack is thinner than 3 cm, the near-surface layer includes the entire snow depth. If the upper snow layers are thinner than 3 cm, the near-surface snow properties are computed as weighted average across snow layers of the snow properties in each layer, up to a 3 cm depth."

8. lines 215-232 (Section 2.7): Do LAPs influence albedo in both spectral bands, or only the visible band? Line 221 mentions "as a function of spectral band", but line 230 lists only single absorption cross-sections for each type of LAP. Are these absorption cross-sections for the visible band only, and if so, what is assumed for the near-IR band? Also, what are the spectral intervals of the two bands used in this model? (Often they are separated at 700 nm)

The LAPs affect only snow optical properties in the visible range. We propose to clarify this at line 243:

"This effect is present only for the visible band (b=VIS) as described in Section 2.7, while $\Delta\alpha_{NIR} = 0$*."*

Furthermore, we propose to clarify eq. (6) and to we specify that this albedo reduction only applies to the visible band (line 272):

"The effect of LAPs is accounted for using the parameterization by He et al., (2018), in which the albedo reduction in the visible range is obtained as.."

The separation between bands is indeed at 700 nm; We propose to explicitly state this in the revised manuscript as follows (line 232):

"In GLASS, the shortwave radiative balance is resolved for two bands, visible (VIS) and near infrared (NIR), separated at 700 nm*. Based on the work of Dang et al., (2015) and He et al., (2018), in GLASS the snow surface albedo for each band (b=VIS or b=NIR) is expressed as a function of snow grain effective radius…"*

9. lines 290-295: The assumption of constant LAP mixing ratios within precipitation throughout the month could also explain some of this discrepancy.

We agree this is indeed likely the case, and we propose to discuss this in the revised manuscript as follows:

"The concentration of LAPs in the near surface snow layer is also well captured by the model (Figure 3B), considering that forcing values are obtained from an atmospheric model climatology dataset. For this reason, we do not expect the model to closely match variations in $c_{eq,ns}$ *throughout the entire snow season. The order of magnitude of observed LAP concentration is comparable with simulations, but intra-seasonal variations are not captured by the model. This could partially be due to the fact that the mixing ratio of LAPs in precipitation is assumed constant for each month. During spring, the snow ablation phase is characterized by a sharp increase in LAP concentration driven by the combined effect of sublimation and melt. During this phase, the increase in* $c_{eq,ns}$ *is overall well represented in the model."*

10. Figure 3: Please explain this "retrieval parameter" for the different observational curves, perhaps in the text.

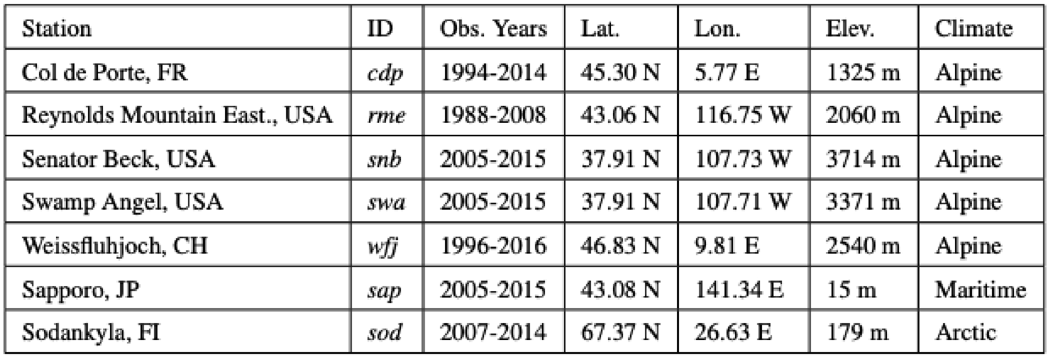
We propose to explicitly discuss the meaning of the retrieval parameter in the revised manuscript. At line 303:

"Additionally, spectral measurements were carried out in the snow year 2013-2014 at the Col de Porte site (Dumont et al, 2017), which were then used to estimate snow specific surface area (SSA) and concentration of LAPs. Dumont et al;, (2017) used a theoretical spectral model to infer snow surface properties from a set of observed spectra. To quantify the uncertainty and artifacts in the measurements, a scaling factor a was used to relate theoretical and observed spectra. To quantify the uncertainty of these retrievals, here we use the snow surface properties computed by Dumont et al;, (2017) for three values of this scaling factor, corresponding to the 25th *(a=0.920),* 50th *(a=0.963), and* 75th *(a=0.964) quantiles of its distribution. "*

11. Please include a table describing the acronyms of the SnowMIP sites (clp, snb, etc), including the long names and locations of the sites.

We propose to add the following table summarizing the main characteristics of the study sites:

Table 1. Characteristics of the experimental sites used for model validation.



Station	ID	Obs. Years	Lat.	Lon.	Elev.	Climate
Col de Porte, FR	*cdp*	1994-2014	45.30 N	5.77 E	1325 m	Alpine
Reynolds Mountain East., USA	*rme*	1988-2008	43.06 N	116.75 W	2060 m	Alpine
Senator Beck, USA	*snb*	2005-2015	37.91 N	107.73 W	3714 m	Alpine
Swamp Angel, USA	*swa*	2005-2015	37.91 N	107.71 W	3371 m	Alpine
Weissfluhjoch, CH	*wfj*	1996-2016	46.83 N	9.81 E	2540 m	Alpine
Sapporo, JP	*sap*	2005-2015	43.08 N	141.34 E	15 m	Maritime
Sodankyla, FI	*sod*	2007-2014	67.37 N	26.63 E	179 m	Arctic

12. Section 4.2: As mentioned under Major Comments, this analysis would be augmented with an evaluation of the impurity amount (mixing ratio) in snow.

In addition to the comparison with spectral measurements at Col De Porte, we have now performed a comparison for the Senator Back Basin and Swamp Angel sites using data published by Skiles and Painter (2015) and Skiles and Painter (2017).

See our detailed response to this comment under “major comments”.

13. Figures 4-6: Which "single year" was simulated and observed at each site? (And were they the same?) Please explain and/or include this information in the table of sites requested two comments above

When reporting a single year of our results (Figs 4, 5, and 6) we have selected the same snow year for all sites (year 2013-2014) except for the *“rme”* site, where we show the 2003-2004 year instead because no observations were available at the site for the 2013-2014 year. The plots x-axis in the original manuscript already report the dates for all sites, but we now propose to mention this explicitly in the revised manuscript (in each figure’s caption) in order to emphasize this difference and to avoid any confusion. This will be further clarified as in the newly introduced Table 1 we indicate the start and end year of the observational record available for each site (see our response to the previous comment # 11)

14. Overall, the grammar is good, but there are numerous instances of minor issues that should be fixed prior to publication. Lines 79-80 demonstrate just one example of a sentence that needs to be cleaned up.

We checked the grammar and style throughout the manuscript correcting multiple issues. For example, the sentence at lines 79-80 will be rephrased as follows:

“Therefore, understanding to what extent the representation of LAP-on-snow processes contributes to the uncertainty in snow predictions from regional and global modeling efforts is a key scientific question which in the last decade has received increasing attention in the Earth System Modelling community (Qian et al., 2015, Réveillet et al., 2022; Hao et al., 2023)”.

References

Dumont, Marie, et al. "In situ continuous visible and near-infrared spectroscopy of an alpine snowpack." ***The Cryosphere*** **11.3 (2017): 1091-1110.**

Skiles, S. McKenzie, and Thomas Painter. "Daily evolution in dust and black carbon content, snow grain size, and snow albedo during snowmelt, Rocky Mountains, Colorado." ***Journal of Glaciology*** **63.237 (2017): 118-132.**

Skiles, S. M., and Thomas H. Painter. "A nine-year record of dust on snow in the Colorado River Basin." Proceedings of the 12th Biennial Conference of Research on the Colorado River Plateau, edited by: Ralston, B., US Geological Survey Scientific Investigations Report. Vol. 5180. 2015.

Zorzetto, Enrico, et al. "A Global land snow scheme (GLASS) v1. 0 for the GFDL Earth System Model: Formulation and evaluation at instrumented sites." EGUsphere 2024 (2024): 1-41.

Flanner, Mark G., et al. "Present‐day climate forcing and response from black carbon in snow." ***Journal of Geophysical Research: Atmospheres*** **112.D11 (2007).**

Hao, Dalei, et al. "A cleaner snow future mitigates Northern Hemisphere snowpack loss from warming." ***Nature Communications*** **14.1 (2023): 6074.**

Qian, Yun, et al. "Light-absorbing particles in snow and ice: Measurement and modeling of climatic and hydrological impact." ***Advances in Atmospheric Sciences*** **32.1 (2015): 64-91.**

Réveillet, Marion, et al. "Black carbon and dust alter the response of mountain snow cover under climate change." ***Nature communications*** **13.1 (2022): 5279.**

Dang, Cheng, Richard E. Brandt, and Stephen G. Warren. "Parameterizations for narrowband and broadband albedo of pure snow and snow containing mineral dust and black carbon." ***Journal of Geophysical Research: Atmospheres*** **120.11 (2015): 5446-5468.**

He, Cenlin, et al. "Impact of grain shape and multiple black carbon internal mixing on snow albedo: Parameterization and radiative effect analysis." ***Journal of Geophysical Research: Atmospheres*** **123.2 (2018): 1253-1268.**

Libois, Q., et al. "Influence of grain shape on light penetration in snow." ***The Cryosphere*** **7.6 (2013): 1803-1818.**

Flanner, Mark G., and Charles S. Zender. "Snowpack radiative heating: Influence on Tibetan Plateau climate." ***Geophysical research letters*** **32.6 (2005).**

Shevliakova, E., et al. "The land component LM4. 1 of the GFDL Earth System Model ESM4. 1: Model description and characteristics of land surface climate and carbon cycling in the historical simulation." ***Journal of Advances in Modeling Earth Systems*** **16.5 (2024): e2023MS003922.**

Vionnet, Vincent, et al. "The detailed snowpack scheme Crocus and its implementation in SURFEX v7. 2." ***Geoscientific model development*** **5.3 (2012): 773-791.**

Flanner, Mark G., et al. "Present-day climate forcing and response from black carbon in snow." ***Journal of Geophysical Research: Atmospheres*** **112.D11 (2007).**