Second Author Response for "Impact of Snow Thermal Conductivity Schemes on pan-Arctic Permafrost Dynamics in CLM5.0" by Damseaux et al.

Reviewer comment:

The authors have not addressed the two major issues I raised in my initial review and their rebuttal seems to rely primarily on beliefs rather than on model experiments. For instance, they state that they "believe the Sturm scheme would likely still perform better"etc, yet concede that "this hypothesis cannot be fully tested and may not be testable in the foreseeable future." In the context of a modeling paper, this rationale is insufficient.

To address this issue, I had suggested to the authors to conduct a sensitivity analysis of the parametrization to modelled snow density. However, the authors argue that such an analysis "falls outside the scope of this paper." In my view, conducting a basic sensitivity analysis e.g. by developing a toy model —particularly when data may be unavailable—falls well within the scope of model testing and evaluation.

Additionally, the authors cite the study by Calonne et al. (2011) to justify their response. However, Calonne et al. estimated snow density using tomographic imaging, which represents the state-of-the-art approach to estimate snow density. As I mentioned in my previous review, the Sturm parameterization may well be suitable when snow density is modeled with high accuracy. However, neither the revised paper nor the authors' response offer convincing evidence that the Sturm parameterization is fit-for purpose if or when there are considerable errors in modelled snow density. Unless proven otherwise, it appears, instead, that the parametrization may simply serve to compensate for errors elsewhere.

In light of these points, my perspective remains unchanged since my previous review.

Authors answer:

We appreciate the reviewer's feedback and the opportunity to clarify our position further. Our responses aim to underscore the robustness of the Sturm parameterization in representing tundra snowpacks while addressing the limitations inherent in modeling tundra snow density.

The Sturm parameterization has been demonstrated in prior studies (e.g., Sturm et al., 1997, Dutch et al., 2022) to better represent tundra snowpacks thermal properties than the Jordan parameterization. This conclusion is not unique to our work but reflects established findings in the literature. While it is true that in our study, the Sturm parameterization may partially compensate for errors in modeled snow density, this does not imply that the Jordan parameterization would outperform Sturm under conditions of an idealized tundra snowpack.

We emphasize that the critical challenge lies not in column-averaged density—which is reasonably represented in CLM5.0—but in the vertical density structure of tundra snowpacks. Current simulations, including ours, exhibit a common issue where the upper snow layers are too low in density and the basal layers too high. This structural mismatch inherently limits our ability to evaluate the "true" impact of using Sturm versus Jordan on an accurate tundra snowpack. While a sensitivity analysis could explore the relationships between snow density, thermal conductivity, and soil temperature, it cannot address the fundamental problem of structural misrepresentation.

Additionally, the new snow density formulation in CLM5.0 proposed by van Kampenhout et al. (2017) is unlikely to change significantly in the near future. This underscores the importance of using the Sturm parameterization—a data-driven, empirically validated approach tailored to tundra snow—in regions where snow has the largest impacts on permafrost dynamics. While we explicitly caution that Sturm is not universally applicable (e.g., for polar or mountain snowpacks), it remains best suited for tundra snow. Tundra regions represent the majority of global seasonal snow mass and have the most significant influence on permafrost conditions, which are critical to the Arctic climate system.

To address the author's primary concern regarding the sensitivity of the Sturm parameterization to modeled snow density, we have conducted a new sensitivity analysis. Specifically, we performed simulations using both the Sturm and Jordan thermal conductivity parameterizations, modifying snow density by scaling factors of 0.9 and 0.7 to represent lower bulk snow densities typical of tundra environments. The description, results, and discussion of this analysis have been incorporated into the different sections of the manuscript, along with a new figure illustrating the RMSE comparisons for the different configurations, and explicitly address your question regarding the performance of the Sturm parameterization under conditions of reduced snow density. The text is as follows:

Introduction section:

"Additionally, we conduct a sensitivity analysis on snow density to test the robustness of our results for potential lower bulk snow densities characteristic of tundra environments."

Methods and data section:

"To assess the sensitivity of model outputs to snow density, additional simulations were performed using both the Sturm and Jordan thermal conductivity schemes, with adjustment factors of 0.9 and 0.7 applied to the snow density parameterization to better represent the lower bulk snow densities characteristic of tundra environments. In CLM5.0, the snow density is computed as follows:

$$\rho_{sno} = af \cdot (\omega(ice) + \omega(liq)) / (frac(snow) \cdot d(z))$$

where af is the adjustment factor used in this sensitivity analysis, ω(ice) is the ice lens mass per unit area in kg/m2, ω(liq) is the liquid water mass per unit area in kg/m2, frac(snow) is the fractional snow-covered area, and d(z) is the snow layer depth in m.

The simulations were conducted exclusively for the 2006–2010 period, selected due to its robust observational data availability, to balance computational efficiency with model reliability. The four additional runs include: (1) Sturm with af= 0.9, (2) Jordan with af= 0.9, (3) Sturm with af= 0.7, and (4) Jordan with af= 0.7. These sensitivity runs were compared to baseline simulations (with af= 1.0) as part of a broader analysis of snow density impacts on model performance."

Result section:

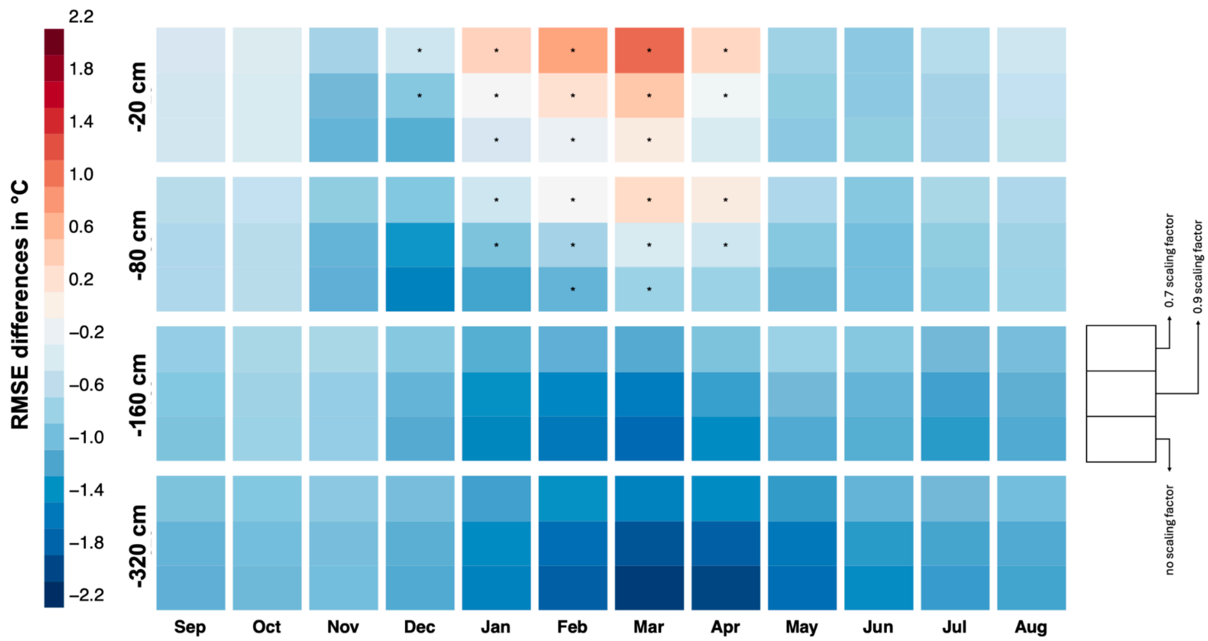

Figure 9. Period-averaged (2006–2010) differences in monthly soil temperature RMSE (Sturm minus Jordan) across 295 stations. Each row represents a different depth (at -20, -80, -160, and -320 cm), while each column represents a different month average. Each cell represents a different scaling factor: 0.7 scaling (top), 0.9 (middle), and no scaling - default (bottom). Rectangles with positive MAD values in the Sturm run (overshoots) are marked with an asterisk (*). Darker blue indicates improved RMSE scores in Sturm relative to Jordan.

"The sensitivity analysis to snow density shows that the Sturm parameterisation regularly yields lower RMSE values compared to Jordan (blue cells in Fig. 7). This improvement is most pronounced during winter months (FMA) in deeper layers of soil. As snow density is reduced, the relative benefit of Sturm over Jordan diminishes, particularly in JFMA months at soil depths of -20 cm and -80 cm. However, the Sturm parameterisation leads to a lower soil temperature error for most months and depths. During summer months (without snow cover), the winter influence of the Sturm parametrization continues, simulating a lower temperature error than that of Jordan, particularly in deeper soil layers."

Discussion section:

“As previously stated, studies show that state-of-the-art LSMs and snowpack models, including CLM5.0, have vertical density profiles often exhibiting significant discrepancies from observed snow density, both in the top wind slab and bottom depth hoar layers of the snowpack. Such discrepancies lead to over-densification in the simulated tundra snowpack. The misrepresentation arises because the scheme does not account for temperature-gradient metamorphism, a process that creates low-density depth hoar layers in tundra snowpacks (Dutch et al., 2022). Without this mechanism, the simulated snow can only increase in density with age, leading to bulk densities that exceed observed values in these regions. Incorporating temperature-gradient metamorphism in future model developments would likely result in lower simulated snow densities, improving agreement with field observations (Brondex et al., 2023).

Our sensitivity analysis shows that the RMSE reductions achieved by the Sturm parametrization remain robust, even if future improvements are made to tundra snow densification processes that result in lower bulk densities. This improvement is most pronounced in deeper layers during winter months (FMA), when the cold wave penetrates deeply, emphasizing the relevance for permafrost modelling. This suggests that the improved performance of Sturm over Jordan does not rely on unrealistically high bulk snow density values. However, the increase in RMSE caused by the overestimation of soil temperatures in upper layers during winter months is amplified when snow density is reduced. While this highlights a limitation of the Sturm scheme in certain scenarios, the overall benefits for permafrost modelling outweigh this drawback, particularly in the context of deeper soil layers where winter thermal dynamics are critical.”