Authors’ Response to Reviews of

Revisiting snow settlement with microstructural knowledge.

Louis Védrine, Pascal Hagenmuller
The Cryosphere,

Comment: ***Reviewers’ Comment***, Response: Authors’ Response

Comment: ***Reviewer 1: November 10, 2025 To the Editors/Authors, I have reviewed the manuscript “Revisiting snow settlement with microstructural knowledge” submitted by Louis Védrine and Pascal Hagenmuller to The Cryosphere. Overall, I find this to be a very strong and well-crafted study that makes a meaningful contribution to our understanding of the viscoelastic and microstructural controls on snow settlement. The work combines microstructure-based crystal plasticity modeling with a thoughtful analysis of previous creep data, and the synthesis presented here brings valuable physical clarity to a problem that has long been described in more empirical terms. The manuscript fits well within the aims and scope of The Cryosphere. It meets the journal’s criteria for originality, scientific rigor, and clarity, and it provides new insights of practical importance to snowpack and firn modeling communities.***

1. General Evaluation

Comment: ***The study is carefully designed and well executed. The modeling approach is technically sound, the connection to experiments is well argued, and the presentation is clear. The results convincingly show why seemingly linear settlement laws appear to work under typical Alpine conditions, while also explaining where and why these relationships may fail. I have only a few points that I believe should be clarified before publication. These are primarily matters of explanation rather than scientific substance.***

Response: We want to thank the Reviewer 1 for his positive and motivating feedback, and constructive suggestions that helped us to improve the quality of our paper. In the following, we provide detailed point-by-point answers to the general comments from the reviewer.

2. Specific Comments

Comment: ***1. On the 1% strain and the strain-rate minimum Around line 175, the authors use 1% strain to determine the steady (minimum) creep rate. This is a reasonable and widely accepted choice: for many materials, including polycrystalline ice, the minimum creep rate occurs at about 1% strain. Jacka (1984) reported the minimum at roughly 0.6%, and Treverrow et al. (2012) found steady conditions near 1%. I suggest the authors briefly note this and include one or two references to show that their cutoff corresponds to the transition from transient to steady-state creep.***

Response: Reply: Indeed, these results are consistent with what is commonly observed for polycrystalline ice. We have added experimental references for comparison as follows, "In our simulations, the permanent viscoplastic regime is reached after a typical strain of 0.5%. This is consistent with the steady (minimum) strain rate of polycrystalline ice, commonly measured around 1%(Mellor and Cole, 1982; Jacka, 1984; Treverrow et al., 2012). Consequently, we conduct simulations up to 1% strain to determine the flow stress σ_Y."

Comment: ***2.On the stress exponent and grain boundary sliding. Lines 307–308 state that the observed stress exponent ($n \approx 2$) does not require invoking grain boundary sliding (GBS). This conclusion seems plausible given the microstructure-based modeling. However, previous studies—such as Alley (1987) and Goldsby & Kohlstedt (1997, 2001)—have associated $n \approx 2$ with GBS in fine-grained ice. It would be helpful to acknowledge that this similarity exists and to explain that the present work offers an alternative physical explanation (based on constrained basal glide in a porous polycrystal) for the same effective exponent. Doing so would better situate the results in the context of existing literature.***

Response: We have clarified this discussion as: "Furthermore, this suggests that the reduction of the stress exponent from dense ice to snow does not require introducing grain boundary sliding (GBS) as an additional deformation mechanism. GBS was originally proposed by Alley (1987) and Goldsby and Kohlstedt (1997) to explain observations of low stress sensitivity at low solid fractions and is associated with a stress exponent of $n \approx 2$ in fine-grained ice (Goldsby and Kohlstedt, 2001). Our work shows that the low crystalline frustration in snow provides an alternative physical explanation for the reduced stress exponent observed in snow."

Comment: ***3. On crystal orientation and slip systems The model includes basal, prismatic, and pyramidal slip systems. Because basal slip dominates and is rotationally symmetric about the c-axis, the specific a-axis orientation typically has little effect on mechanical behavior at these stress levels. Still, it would be worth clarifying whether the simulations explicitly included full crystal orientations, or if c-axis randomization alone was used. A short note referencing Schulson & Duval (2009) or Weikusat et al. (2017) would be helpful to reassure readers that this simplification is appropriate.***

Response: Our simulations explicitly include full crystal orientations; both the c-axis and a-axes are randomly sampled from a uniform distribution. We have clarified this point as follows: "Then, each crystal was assigned a full crystallographic orientation (c-axis and a-axes) randomly sampled from an isotropic distribution."

Comment: ***4. On the word "frustration" The term "frustration" appears several times and is used correctly in the mechanical sense—referring to geometric or kinematic incompatibility between neighboring grains that limits basal glide. For readers unfamiliar with materials-science terminology, I suggest adding a brief clarification at its first occurrence (e.g., "Here, 'frustration' refers to mechanical incompatibility between neighboring grains that constrains easy slip."). Beyond that, no change is needed.***

Response: Indeed, reviewer 2 required clarifications about this term from material-science terminology. We have clarified the use of the term "frustration" as follows: "Here, 'frustration' refers to the mechanical incompatibility between neighboring crystals that constrains soft deformation mechanisms."

3. Other Comments

Comment: ***The discussion connecting the microstructural simulations to settlement parameterizations in snowpack models is one of the most valuable aspects of this paper. The authors also do a good job highlighting the role of missing microstructural descriptors such as bond size (Hagenmuller et al., 2014a), connectivity (Schleef et al., 2014b; Schöttner et al., 2025), and inter-crystalline surface area. It might be helpful to indicate briefly which of these factors could most readily be incorporated in future work.***

Response: As mentioned in lines 385-392, we chose not to introduce additional microstructural descriptors in order to maintain compatibility with existing experimental datasets and with detailed snowpack models, in which the microstructure is typically reduced to its ice fraction. From an experimental standpoint, integrating such descriptors into settlement parameterizations is relatively straightforward, for instance through the analysis of topology. However, incorporating these descriptors into snow models is more challenging, as their temporal evolution must also be predicted. In the current version of Crocus (Vionnet et al., 2012; Lafaysse et al., 2017), the state variables related to the snow microstructure are density, specific surface area and sphericity. Unfortunately, these quantities do not contain information about the topology or the intercrystalline surface, and their use is not straightforward for physically based modelling. A first step could be the development of empirical relationships derived from in-situ measurements during settlement experiments. This point has been added as "Therefore, monitoring these indicators during in-situ compression tests (e.g. Bernard et al., 2023) could help identify their evolution laws." The integration of the inter-crystalline surface area appears more complex, as mentioned on lines 403-406 . Capturing both the geometry and the crystallographic structure of the microstructure requires coupling micro-CT tomography with DCT. Substantial work will be needed to understand the evolution of inter-crystalline surface area and to relate it to metamorphism.

4. Recommendation

Comment: ***This is an excellent paper that represents a meaningful step forward in understanding snow rheology and densification from a microstructural perspective. I recommend minor revision to address the small clarifications noted above. Once these are implemented, I would be happy to see the paper accepted for publication in The Cryosphere.***

References

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