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Numerical homogenization of the viscoplastic behavior of snow based on X-ray tomography images.

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Response to Anonymous Referee's comments (RC2)

We gratefully acknowledge the anonymous reviewer for his comments to clarify some points and improve the quality of our manuscript. Based on the reviewer comment, we understand that the aim of our paper is not outlined clearly enough neither in the abstract, the introduction nor the conclusion. We took this remark into consideration and provided a revised version of our paper making this goal easier to understand without any required mechanical background.

All the reviewers's comments have been taken into account to provide a revised version of our manuscript. The major modifications of the manuscript consist in:

- an enriched introduction containing an improved state of the art and a clearer statement of the objectives and the scope of our manuscript.
- a more detailed assessment of both the elastic and viscous material parameters on the homogenized viscous behavior of snow. A slight change in the postprocessing procedure has been made by introducing a characteristic time.

Below, we recall the reviewer's comments and provide some explanations.

1. *After reading the abstract, introduction and conclusion, looking at the various figures, and skimming the somewhat "over my head" mathematical development, I am still quite confused about what this paper is about and what it is trying to do. I take it that there is an ultimate goal of providing a simple rule (or demonstration of a rule?) known as "homogenization" that, when applied to snow, allows the treatment of the tortuously complex micro-structure of the snow grain assemblage to be done as if the whole mess were a single homogeneous fluid. I struggled to see where the paper demonstrates either success or failure (and by what criteria?) in achieving this overall goal.*

Reply: The reviewer mostly get what "homogenization" is. The idea is to replace a heterogeneous material by an equivalent homogeneous one whose macroscopic behavior take into account the complex heterogeneities existing at the microscale. This procedure is of particular interest when the scale of study (typically the scale of the snowpack in our case) is too big compared to the scale of the heterogeneities (typically here the grain scale) to model these heterogeneities extensively.
Based on the use of snow volumes large enough to be representative of the overall mechanical behavior, our paper provides a systematic method to derive the macroscopic homogeneous

visco-plastic behavior of snow. The main goal of the article is to provide a macroscopic formulation of the snow visco-plastic behavior of snow, valid for any type of isotropic snow. To this respect, our goal is reached and the obtained formulation is summarized in the beginning of section 5. This formulation can be implemented quite easily in finite element codes to compute the densification of the snowpack induced by any kind of mechanical loading and resulting from the secondary creep of the ice skeleton at microscale.

2. *I also found the paper to be very loosely tied to a snow phenomena that I am familiar with. Of course, not being a specific snow scientist, but rather a generalist in glaciology, I could be simply too unaware of what is specific to the field. But usually, I get hints from reading the gist of the introduction and abstract as to what the specific phenomena to be illuminated is. I did not get such a hint in this paper.*

Reply: The specific phenomena dealt with in this paper is the study of the visco-plastic mechanical behavior of snow resulting from the secondary creep of the ice skeleton at the microscale.

3. *Finally, I don't understand why viscoelasticity is being examined. Aren't the two end member rheological treatments (pure viscous for long-term creeping problems, or pure elasticity for short term shock events) good enough for practical snow problems? What is the motivation for developing a viscoelastic treatment? What problem needs it?*

Reply: The objective of the paper is to characterize the visco-plastic behavior of snow. However, from a numerical point of view, the computation of the visco-plastic response of ice cannot be achieved without also modeling its elastic behavior. This is the reason why ice is modeled as an elasto-visco-plastic material.

4. *The demonstration is also somewhat opaque due to the fact that a black-box software tool (ABAQUS) is used for much of the computation... Some of this computation is non trivial...*

Reply: Even if ABAQUS is a commercial software, it is flexible enough to be widely used for research purpose. We chose to use this software because:

- the ABAQUS plugin HomTools developed by researchers at the LMA (acoustic and mechanics laboratory at Marseille, France) enables an easy implementation of the KUBC boundary value problem;
- the constitutive behavior for ice used in this paper is one of the standard constitutive law already implemented in ABAQUS.

5. *The paper reads very much like a textbook; and I wonder how much of the mathematical development is simply boilerplate that is also published elsewhere.*

Reply: The references for the mathematical development are given in the paper. The mathematical formulations are recalled for the sake of clarity and to justify the homogenization approach carried out in the paper. They are a mean to derive rigorously the 3D macroscopic visco-plastic behavior of snow which is, to our knowledge a new and original contribution to snow mechanics.