

Response to Reviewer #1's comment on "Temperature sensitivity of snow viscoplasticity: evidence from controlled creep experiments"

Louis Védérine, Marius Brun, Mathis Bozon, Benoît Laurent, and Pascal Hagemüller

Reviewer #1:

General comments on the manuscript:

The manuscript by Védérine et al. presents an experimental investigation of the temperature dependence of snow viscoplasticity using a newly developed thermo-mechanical cell coupled with in situ X-ray tomography. The experimental protocol, in which temperature is systematically varied on the same snow sample while monitoring microstructural evolution, represents a clear improvement over previous approaches that rely on separate samples at different temperatures and initial bulk densities. The resulting measurements provide insight into the temperature sensitivity of snow deformation and have important implications for constitutive models of snow settlement and snowpack evolution.

Specific comments for the authors' consideration:

1. The identification of two activation-energy regimes is one of the central conclusions of the manuscript. While the data are certainly consistent with a bi-Arrhenius relationship, Section 4.3 also demonstrates that the observations can be explained by introducing a temperature-dependent stress exponent. I wonder whether the authors might consider framing the proposed transition near -13°C somewhat more cautiously, emphasizing that the data are consistent with—but do not uniquely require—a distinct physical transition.

Response: We agree with the reviewer that the data are consistent with a two-regime Arrhenius relationship but do not uniquely require a distinct physical transition near -13°C . As discussed in Section 4.3, the observations can also be described by introducing a temperature-dependent stress exponent, and we explicitly state that "this apparent similarity should be interpreted with caution" (Section 4.3). Accordingly, we have revised the Abstract and Conclusion to frame this result more cautiously.

2. I wonder whether the discussion in Section 4.3 could also briefly consider the possible contribution of grain-boundary sliding to the observed temperature sensitivity. While the authors discuss basal slip as the dominant deformation mechanism based on Védérine et al. (2024), it seems worthwhile acknowledging whether grain-boundary sliding might also contribute to the mechanical response, particularly given the fine-grained, porous nature of snow.

Response: We thank the reviewer for this suggestion. To the best of our knowledge, grain-boundary sliding has not been shown to contribute significantly to snow creep at low temperatures (below approximately -6°C), and basal slip alone has been shown to reproduce creep experiments (Védérine et al., 2025).

However, as noted by Reviewer #2, grain-boundary processes are known to contribute to the strongly nonlinear temperature sensitivity of creep in polycrystalline ice near the melting point (Duval et al., 1979). They may therefore also become relevant to snow creep in this temperature range. We have added a short paragraph in Section 4.3 discussing

grain-boundary sliding as a possible mechanism near the melting point, while leaving its experimental investigation in snow for future work.

Overall assessment:

Overall, the manuscript is well written, the experiments are well designed, and the conclusions are generally supported by the presented data. The manuscript presents a novel and technically strong experimental study that substantially improves our ability to isolate the influence of temperature on snow viscoplasticity. The newly developed thermo-mechanical cell and experimental protocol represent an important methodological advance, and the resulting observations provide useful constraints for the future development of constitutive models of snow deformation. Subject to minor revision, I believe this manuscript is well suited for publication in The Cryosphere.

We thank the reviewer#1 for his valuable comments 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 comments from the reviewer.

Editorial comments keyed to line numbers:

- 282 – Change "a activation energy" to "an activation energy."

Response: Corrected

- General – Several figure axis labels, legends, and mathematical symbols appear corrupted in the review PDF, likely due to a font-embedding or PDF rendering issue. I recommend verifying that the figures are exported with all fonts properly embedded before publication.

Response: Thank you for pointing this out. The font-rendering issue was introduced during the TC production process and was subsequently corrected by the TC editorial team on June 16.

Response to Reviewer #2's comment on "Temperature sensitivity of snow viscoplasticity: evidence from controlled creep experiments"

Louis Védérine, Marius Brun, Mathis Bozon, Benoît Laurent, and Pascal Hagenmüller

Reviewer #2:

The viscoplastic creep of snow and ice is highly temperature-sensitive, following an Arrhenius-type relationship where strain rate increases exponentially with increasing temperature. The activation energy term governing this temperature dependence remains among the most uncertain parameters in constitutive formulations due to the difficulty of isolating thermal effects during deformation from the simultaneous microstructural evolution, i.e., grain growth, recrystallization, geometric hardening from densification.

The manuscript by Védérine et al. provides novel experimental constraints on the values of apparent activation energy for snow viscoplasticity with a newly developed thermo-mechanical cell. This methodology improves on previous approaches as it (1) eliminates the variations of the initial microstructure and bulk density by varying the temperature of the same sample and (2) accounts for the concurrent microstructural evolution through *in situ* X-ray tomography coupled with a viscoplastic model previously developed by the authors in Védérine & Hagenmüller, 2025.

Overall, the manuscript is well-written, the experiments presented therein are novel and rigorous, and the reported apparent activation energies may be readily applied to snowpack modeling. The conclusions reached are reasonably supported by the data but would benefit from an expanded discussion on the micro-scale origin of the presented two-regime Arrhenius relationship. The manuscript is well suited for publication in The Cryosphere but would benefit from some minor revisions.

We want to thank the reviewer#2 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.

Comments:

1. The activation energy is fundamentally the intrinsic energy barrier associated with a single thermally activated mechanism. However, deriving this quantity from the temperature dependence of the strain rate using an Arrhenius plot is only justified if the measured deformation is controlled by a single mechanism over the temperature range considered. Given the potential of enhanced recovery or the influence of grain-boundary processes especially at higher temperatures, I do not believe this can be stated with certainty from the data presented in this manuscript. I would therefore suggest referring to the fitted Q values reported in section 3.2 as an *apparent activation energy*, and elsewhere throughout the manuscript as pertinent.

Response: We agree with the reviewer that the fitted Q values represent an *apparent activation energy* of snow deformation, as the temperature dependence of the strain rate does not, by itself, allow us to identify the underlying thermally activated mechanisms. Accordingly, we have revised the manuscript to refer to these quantities as *apparent activation energies* throughout, where appropriate.

The bi-linear fit reported in Section 3.2 appears to be in respectable agreement with the mechanical data and occurs at a transition temperature that is generally consistent with that observed in dense polycrystalline ice. In Section 4.3, the authors argue that this behavior may not reflect a true transition in regime but could instead arise from enhanced basal slip activity in the ice matrix. Supporting this interpretation, experiments in which single crystals of ice favorably oriented for basal slip were deformed at various temperatures, report an increase in the stress exponent, n , with increasing temperature from -20 °C to -0.2 °C (Jones and Brunet, 1978). When this stress exponent temperature sensitivity is considered ($n(T) = 2.15 - 0.00726 \times T$), the bilinear trend disappears, and the scaled strain rate prefactor becomes quasi-linear with respect to the temperature on the Arrhenius plot shown in Figure A.3. For the author's consideration, I have some specific comments concerning this treatment:

- It is unclear to me how the equation describing the temperature sensitivity of the stress exponent is obtained in section 4.3. A quick fit to the data from Jones and Brunet, 1978 returns $n(T) = 1.95 - 0.0061 \times T$ which differs slightly from the equation presented ($n(T) = 2.15 - 0.00726 \times T$). I assume that this equation may have been normalized to the mechanical data in some way to ensure that the fit passes through a stress exponent of $n = 2.2$ at a given temperature, but this should be stated more explicitly in the manuscript for clarity particularly given the difference in slope between the two equations.

Response: We thank the reviewer for pointing this out. The equation reported in the original manuscript was obtained by normalizing the temperature dependence of the stress exponent to that of snow, assuming that the relative sensitivity of n was identical for all slip systems. We agree that this assumption is not necessarily justified. In the revised manuscript, we therefore use a simpler formulation, assuming that the temperature dependence of n for snow follows that reported for basal slip, while normalizing its value to the stress exponent measured for snow at -10°C, a temperature commonly used in creep experiments. This yields $n(T) = 1.14 - 0.006T$. This change does not affect our conclusions, and the derivation and underlying assumption are now clarified in Section 4.3.

- The linear trend of the temperature sensitivity of the stress exponent persists from -20 °C to -0.2 °C, but the mechanical data reported in this manuscript covers a temperature range of -6 °C to -18 °C. In polycrystalline ice, there is evidence that the creep rate accelerates above $T = -5$ °C as the temperature approaches the melting point beyond what would be predicted from a linear fit to the -5 °C to -10 °C behavior (e.g. Russel-Head and Budd, 1979, Jacka and Budd, 1989, Morgan, 1991). This may be present in snow as well, manifesting as apparent activation energies ranging between 201 and 426 kJ mol⁻¹ above -5 °C reported in Scapozza and Bartelt, 2017 (though they are unable to isolate the microstructural effect without in-situ x-ray tomography). This suggests the creep rate, especially above -5 °C, may appear non-linear on an Arrhenius plot approaching the melting point, and it is unlikely that the linear change in the stress exponent that the authors attribute to basal slip activity will fully capture the change in activation energy approaching the melting point. Section 4.3 would benefit from an expanded discussion to include the potential role of intercrystallite mechanisms such as grain-boundary sliding in

the high temperature regime and encourage the readers to exercise caution extrapolating the apparent activation energies above the experimental range presented here.

Response: We agree with the reviewer that extrapolating the fitted trends up to -0.2°C could be misleading, as our data cover the more limited range from -18 to -6°C . In the revised manuscript, the fits are now shown only over the experimental temperature range.

We have also clarified in Section 4.3 that our data do not allow us to draw conclusions above -6°C , and expanded the discussion to consider the possible role of intercrystallite deformation mechanisms at higher temperatures. In particular, we discuss the contrasting behaviors reported for polycrystalline ice and basal-slip-dominated deformation, and caution against extrapolating the apparent activation energies beyond the experimental range. We have added the following paragraph:

“In this study, we did not investigate the behavior of snow above -6°C , where additional experiments could provide further insight into the active deformation mechanisms. In polycrystalline ice, a strongly nonlinear increase in creep rate as the melting point is approached has often been reported, with grain-boundary processes suggested as a possible explanation (e.g., Jacka and Budd, 1989; Morgan, 1991). In contrast, Jones and Brunet (1978) showed that a system deforming predominantly by basal slip, as may be the case for snow (Védrine et al., 2025), does not necessarily exhibit such an acceleration of creep close to the melting point. Whether the temperature dependence observed here persists at higher temperatures or whether additional mechanisms lead to a nonlinear increase in creep rate therefore remains an open question for future work.”

- One of the limitations of the treatment of the stress exponent derived in the Jones and Brunet, 1978 is the use of yield stress, corresponding to the stress at which dislocations become mobile and multiply, as a fitting parameter which may not be appropriate to apply to the creep behavior; necessitating some additional justification from the authors.

Response: Indeed, Jones and Brunet (1978) used the yield stress, corresponding to the stress at which dislocations become mobile and multiply, since there is no steady-state in the creep of single crystals of ice. In the present study, we use the stress exponent, (n) , as an alternative interpretation of the temperature sensitivity observed. This interpretation is motivated by the work of Scapozza and Bartelt (2003), which suggests that the stress exponent of snow may exhibit a temperature dependence.

We have clarified this point in Section 4.3 of the manuscript as follows:

“The temperature dependence of the stress exponent has received little attention in both ice and snow (e.g., Jones and Brunet, 1978; Scapozza and Bartelt, 2003). Given its strong influence on the temperature sensitivity of the creep response of snow at low stress, this parameter warrants further investigation.”

