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

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**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 Vérdine 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 Vérdine & Hagenmuller, 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 × 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× T which differs slightly from the equation presented ($n$(T) = 2.15 – 0.00726 × 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 exorcise 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."*