Dear Dr. Védrine,

We thank you very much for your comments to improve the manuscript.
Please find your comments below in blue font and our responses in black font.

The authors introduce a method to quantify the influence of temperature on firn creep. Through laboratory creep tests conducted at various temperatures and with different initial microstructures, they investigate how firn responds under these conditions. The microstructure of the samples is assessed before and after the tests using microtomography and thin-section analysis. Subsequently, the activation energy is determined and compared with the activation energy for grain-boundary sliding, which is estimated based on the observed grain growth rates.

This study represents a notable advancement in modelling the mechanical behaviour of firn, enhancing our understanding of ice material properties and informing the interpretation of ice-core data relevant to paleoclimatology.

However, the methodology used to determine the activation energies is not sufficiently detailed (lines 385–390). Specifically, the authors assume a fixed value for the stress exponent (without providing the actual value) and neglect to mention that the pre-factor A is considered constant across different microstructures and test temperatures. These omissions represent significant methodological shortcomings. I have serious concerns about the validity and applicability of the methodology, raising doubts about the reliability of the results. Therefore, I recommend major revisions.

Thank you for these comments, which we've used to improve the clarity of our manuscript. Please find our detailed explanations after each of your comments below.

General comments:

To determine the activation energy, the authors use the Glen-type power law (line 386). This equation introduces the activation energy (Qc), the stress exponent (n), and the pre-factor (A). Thus, to identify the value of Qc, assumptions about A and n must be made

Prefactor: The authors assume that the pre-factor in the power law remains constant across the different temperatures tested. However, the sample densities vary from 589 kg/m³ to 615 kg/m³ at 20 m depth. This approximation is not mentioned by the authors and must be acknowledged as a limitation of the method.

The pre-factor (A) in the Glen's flow law is typically regarded as a constant in studies of firn and ice mechanics to derive stress exponents and activation energy. Notably, this assumption has often been omitted in the literature, e.g. Goldsby & Kohlstedt

(1997; 2001). For completeness, we've included the following sentence in Section 3.5 to describe the role of A used in our calculations:

"Based on Glen-King's results in deriving the activation energy (Glen, 1955) $\dot{\varepsilon} \; A \quad Q_c/RT) = B\sigma^n \exp(-Q_c/RT)$, *the pre-factor A, the material parameter B (Glen, 1955; Goldsby & Kohlstedt, 2001), and the stress exponent n (Li and Baker, 2022a) are assumed to be constant as performed in the literature."*

In this research, samples with densities ranging from approximately 550 to 830 kg/m³ are utilized to investigate the deformation of firn plasticity, aligning with a widely accepted power law deformation mechanism (Li & Baker, 2022a). A significant challenge in experimental science arises from discrepancies between theoretical predictions and laboratory results, particularly when using natural samples from Greenland and Antarctica. However, the observed density variation between 589 and 615 kg/m³ at a depth of 20 m is deemed acceptable for mechanical experiments involving natural porous samples. These variations stem from multiple factors, including the intrinsic properties of the samples, e.g. inclusions (impurities, dust, bubbles, clathrate hydrates), the effects of deformation and partial annealing of firn due to stress distribution and temperature changes during drilling, extraction, transportation, or storage, and also the fact that the samples are taken from adjacent parts of the core, and might sample heterogeneous density layers, as well as potential measurement errors associated with the equipment used. To clarify this point, we've add the following sentence to Section 3.5:

"The variability in density for the samples from a depth of 20 m on the mechanical behavior are negligible due to a small difference (up to ~4%), between them, which falls within an acceptable error range in the literature. This is likely related to multiple factors, including the intrinsic properties of the samples, e.g. inclusions (impurities, dust, bubbles, clathrate hydrates), the effects of deformation and partial annealing of firn due to stress distribution and temperature changes during drilling, extraction, transportation, or storage, and the fact that the samples are taken from adjacent parts of the core, and might sample heterogeneous density layers, as well as potential measurement errors associated with the equipment used."

Stress exponent: The stress exponent is only mentioned toward the end of the section (lines 462-470), where the values 0.1 and -1.2 are considered. However, the method for determining these values is not explained. Moreover, these exponents are inconsistent with those reported in the literature and in Li and Baker (2022), and they do not align with any known physical behaviour of materials.

We agree with you that the stress exponent values of n = 0.1 and n = -1.2 are inconsistent with the literature, and we tried to highlight that point in Lines 463–464:

This is in disagreement with the reported n = ~4.3 by Li and Baker (2022a). To make this point clearer, we modified the text to:
"We found n to be ~0.1 and ~-1.2 for the -5°C and -18°C samples, respectively, which is in disagreement with the reported n = ~4.3 by Li and Baker (2022a). This significant discrepancy implies that the uncalibrated SRMin value from all the samples is not appropriate for estimating the stress exponent, and hence the activation energy during their deformation."

To clarify our methods in this section, we added the following text to describe our method of obtaining the stress exponent:

"The value of n is determined by plotting the line fitted the logarithm relation of the steady-state strain rate, $\dot{\varepsilon}$, versus the effective stress, σ, thereby being the slope of this line."

A "post-calibration" method is then introduced, which imposes a fixed stress exponent but fails to account for density dependence. This approach leads to variable results, depending on the chosen reference sample. These inconsistencies arise from the identification of the power law using data in which both stress and density vary simultaneously. As demonstrated in Li and Baker (2022a), the strain-rate minimum (SRMin) is dependent on density, with the strain rate decreasing by a factor of 12 when the density increases from 756 to 861 kg/m³. However, the effect of microstructure is overlooked in this study, as it treats samples with densities ranging from 589 to 790 kg/m³ as identical.

Stress exponents reported during the creep of polar firn range from 4.1 ± 0.37 to 4.6 ± 0.16 (Li and Baker, 2022a). It is crucial to emphasize that the stress exponent does not depend on the density of the tested samples, thereby negating any basis for discussing a relationship between the stress exponent and sample density. Instead, variations in stress corresponding to density will manifest in the strain rate, ensuring that the derivation of the stress exponent and activation energy remains consistent, as noted by the reviewer. Further, the minimum strain rate is indeed influenced by density (Li and Baker, 2022a), which is typically utilized to derive the stress exponent in accordance with Glen's law, considering the effective stress's impact on porous firn reflected in strain rates. Consequently, the stress exponents are expected to be similar across samples of varying densities. To highlight this distinction in the manuscript, we added the following text:

"It is important to note that the stress exponent does not depend on the density of the tested samples, thereby negating any basis for discussing a relationship between the stress exponent and sample density. Instead, variations in stress corresponding to density manifest in the strain rate, ensuring that the derivation of the stress exponent and activation energy remains consistent."

The authors need to improve the methodology and clearly outline the assumptions made, particularly regarding the density dependence of viscoplastic behaviour. This could be based on their previous work (Li and Baker, 2022) or by considering other models from the literature. Finally, the discussion in the "activation energy" section should be revisited in light of these methodological assumptions.

Thank you for pointing out our omissions in the methodological steps described above. In addition to the relevant methodological assumptions we've added above, we also included the following description of the method to calculate Qc:

"The value of Q_c is equal to the slope of a line fitted $\ln \dot{\varepsilon}$ versus 1/T as did in Goldsby & Kohlstedt (1997; 2001)."

Specific Comments:

Lines 43-48: What about the study of Burr et al., (2019) for the in-situ compression test ? Does it relate or include relevant data to evaluate the results of this study?

We chose to not include this reference in our introduction. Burr et al. (2019) extensively examined the influence of pore closure and ice crystal grain growth on the densification of polar firn, utilizing *in situ* micro-computed tomography imaging while neglecting airflow effects. Although their study addressed thermal treatments of samples 801, 806, and 901, the effects were predominantly attributed to pressureless sintering, as these samples underwent strain without an applied load. Sample 806 was initially compressed at –10°C before being thermally treated at –2°C. In contrast, our research focuses on the deformation of firn samples subjected to constant stress across varying temperatures.

Lines 57-59: Using homogenization approaches, considering the behaviour of ice, is common for studying the physical properties of firn and snow.

Yes, porous snow and firn primarily consist of an ice matrix interspersed with air. Hence, research on their mechanical properties often centers on the solid ice component, while also considering the influence of airflow.

Lines 233-235: Please provide more details on how the thermal gradient was evaluated during your experiments.

We've added the following text to address how the thermal gradient was generated:

"The thermal gradient is likely related to the inherent fluctuation of 0.5°C around a test temperature due to the thermometers' accuracy, thereby thermal sensitivity-heightened temperature cycling within the firn (Mellor and Testa, 1969; Weertman, 1985)."

Lines 285-289: As deformation mechanisms are not directly measured in this study, please add references to the literature in this discussion.

We added the following relevant references to the text:

"*The transient creep stage may be caused by strain hardening that occurs from the yield point to the ultimate strength (Glen, 1955; Jacka, 1984). The plastic deformation is accommodated by an increase in dislocation density through dislocation multiplication or the formation of new dislocations (Frost and Ashby, 1982; Duval and others, 1983; Ashby and Duval, 1985), which leads to an increase of the firn strength as the dislocations become pinned or tangled, and thus more difficult to move.*"

Line 336: Unclear, it is the temperature which is a state variable of the strain-rate.

In these experiments, strain rate is considered a state variable of temperature. Under optimal conditions, the strain rate of a creep sample subjected to a specific stress to achieve a certain strain can be exclusively determined by the temperature.

Lines 410-411: The word "methods" can be misleading. Using 2 or 3 data points to identify a parameter is not a separate method. Either remove the word "method" or include the data point at -10 °C in the overall dataset.

We replaced "methods" with "avenues".

Lines 453-455: The statement about the activation energy of firn should be nuanced. While older studies show lower values than those of ice, you have already discussed that values of Qc are highly scattered and debated (as mentioned in lines 416-426 of your manuscript).

Indeed, the activation energies derived in this work exhibit a wide range, which are consistent with a broad spread of 58.6–113 kJ/mol estimated by Landauer (1958). We've highlighted the factors that likely contribute to differences in Q_c values from the older literature in Table 3, e.g. the sample density, temperature inaccuracies during testing, and differences in the methodologies used for derivation. For further clarification, we explained this in the text:

"The increase of Q_c from mono-crystalline and bi-crystalline to polycrystalline ice implies that the greater the reduction in the constraint from grain-boundaries, the greater is Q_c. Alternatively, firn creep is easier than that of polycrystalline ice due to either the easier sliding of grains in firn along more directions in the more porous and heterogeneous structure (Sect. 3.3), or the decrease of viscosity associated with inclusions (e.g. Baker and Gerberich, 1979; Goodman et al., 1981) that facilitate the intra- and inter-grain sliding (Salamatin et al., 2009)."

Lines 475-480: It's not clear that each brace corresponds to a depth. Please clarify it.

To further indicate what each bracket refers to, we added "20-m samples; 40-m samples; 60-m samples" above their respective bracket.

Technicals Comments:

Figure 6: Please specify in the title of the y-axis in Figure 6 that this is the logarithm of SRmin, to ensure consistency in the names used.

Corrected.

Figure 6: The text and colours in the caption do not appear to correspond to the figure. Please check.

Corrected.

Sincerely,
Yuan Li, Kaitlin Keegan, Ian Baker