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Interactive comment on "The role of grain-size evolution on the rheology of ice: Implications for reconciling laboratory creep data and the Glen flow law" *by* Mark D. Behn et al.

Anonymous Referee #1

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General comments The Behn et al. contribution tackles a persistent question in the glaciological community, namely whether the stress exponent of 3 typically used in ice flow constitutive laws has a robust physical justification, despite the lack of direct supporting experimental data (even in the classic Glen papers of the 1950s). The work is timely, of widespread interest, and with high potential impact. This study concludes that the combination of two deformation mechanisms – grain boundary sliding and dislocation creep – combine through a grain size dependency to produce a composite constitutive law with a stress exponent of approximately 3. I find the paper has a nice flow and clear macroscopic logic. At the same time, potentially ambiguous definitions and an incomplete treatment of uncertainty means that this paper as written is unlikely to be perceived in the community as close to the final word on the topic. Restructuring the analysis to more explicitly incorporate uncertainty will take some time but yield a contribution with stronger impact.

Specific comments In this section, I list a number of focused comments and questions that I feel the authors should address in a revised version of this manuscript.

Although we all have a mental picture of grain size, for the quantitative approach taken in this manuscript, a more exact definition of the term would be useful. Is grain size the diameter of the equivalent area of a circle, or some other measure? Tied to that, the grain circularity is a potentially critical concept yet barely mentioned. The comparisons with natural data evaluated size (and even that not clearly with the same definitions), but not circularity. Granted, circularity may not have a large practical effect, but some evaluation would assuage concerns.

Stress is used throughout the manuscript, and it too would benefit from clearer definitions and identification of the relationships among the various forms applied. For example, piezometers/wattmeters typically use differential stress, but Equations 17-19 use shear stress and Figures 3 and 4 plot effective stress. In earlier equations, such as Eq 5, the form of stress isn't specified. In addition, I did not see a definition for "effective stress", though I presume it represents the square root of the second invariant of the deviatoric tensor. By defining these terms and explaining how the equations use the appropriate formulations (e.g., shear stress cannot directly be used in the flow law), confidence will be higher in the calculation results.

This manuscript implies strongly that the grain size is a better wattmeter than piezometer. That may be, but which approach better matches geologic/glaciologic reality remains unresolved in the community: despite the availability of the wattmeter for over a decade, many studies still rely on a piezometric approach. As such, a more explicit comparison in this paper seems warranted. The partial approach presented here has some merit, but feels incomplete and, in places, inaccurate. For example, the authors present evidence for the wattmeter matching grain size data, and I agree in part. Taking Figure 5 for the moment, there is no illustrated scenario in which the model matches the experimental data for all three strain-rate cases. The highest strain rate (blue) never achieves a steady state, so we cannot really evaluate that case. The lowest strain rate case (black) and middle (red) are best fit with different lambda values, neither of which is what Austin and Evans use in their original study. Yet I don't see a treatment of this uncertainty in, for example, Fig 6. (At least, as far as I can understand from the text, the uncertainty shown in Fig 6 does not include a variation in lambda.) In addition, on line 122, the text implies that all internal energy goes to grain boundary area. That may be sufficiently accurate, but should be justified by exploring the potential of dislocations and elasticity to store energy. Austin and Evans (2009), for example, mention dislocation-driven energy variations after eq 19. The questions and notes I raise in this paragraph all lead to a concern that uncertainty in parameter values and applied processes preclude a robust conclusion about the stress exponent derived from the presented data.

Another significant discussion component that would lead towards a greater impact of this paper is a comparison of the effect of grain size against other rheological controls. The principle factor to address is anisotropy due to fabric development. The relationship will change with depth and affect the stress-strain-rate environment, and may affect grain size evolution.

Overall, my recommendations fall into two categories: (1) improving clarity of definitions and methods and (2) treating uncertainty more thoroughly. This topic is significant enough that a paper such as this could be one many people will rely on, once the readership can have more confidence in the conclusions.

Technical Comments Equations 17 and 18: I do not understand the source nor assigned value for viscosity; it doesn't appear in Table 1 and is somewhat at odds with the formulation of Eq. 16. I imagine I am missing something here, so an explanation would help.

Line 224: I do not follow how the iteration between Eqs 14 and 18 works in practice.

Figure 4: This is a relatively small comment, but can sow uncertainty. As I read it, the right panel is derived from the slope of the left panel. However, the right panel seems to have the same number of teal and blue dots. I am not clear how the authors calculate slope at the termini of the series of discrete points.

Lines 353-355: “In this scenario...” These two sentences feel to me to be a circular argument.

I concur with the comment provided by PD Bons that the manuscript should recognize that natural data do not necessarily require n=3, and in fact n=4 may be a more accurate representation.

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