Response to Referee #2 Adam Treverrow
Manuscript review: tc-2018-275

Using a composite flow law to model deformation in the NEEM deep ice core, Greenland: Part 2 the role of grain size and premelting on ice deformation at high homologous temperature

Ernst-Jan N. Kuiper, Johannes H. P. de Bresser, Martyn R. Drury, Jan Eichler, Gill M. Pennock, Ilka Weikusat

Response to general comments

We thank Adam Treverrow for providing us with such elaborate and useful feedback on the manuscript. The feedback was very helpful in improving the manuscript and we implemented most of the suggestions that were given. We recognize that the quality of the writing decreased in the last part of the discussion and conclusions. We have rewritten these sections and think that the quality of the writing is similar to the other parts of the manuscript now. Special attention during the rewriting of these sections was given to making sure that these sections are more concise and clearly stated the difference between interpretation of the data and speculative comments.
Below is our response to specific comments. The page and line numbers correspond to the first version of the manuscript.

P1 L2, L3: The wording in the abstract has been changed to "relatively impurity-rich and fine grained ice deposited during the glacial period" and "low impurity and much coarser grained ice deposited during the Eemian period". Throughout the manuscript we made several changes to clarify the difference in impurity content and grain size between the ice deposited in the glacial period and the interglacial period.
P1 L15-18: We added "based on the flow relation of Goldsby and Kohlstedt (2001)" to the abstract so that it is clear that these results were obtained using the G&K flow law.
P1 L19: Throughout the manuscript we have replaced "impurity-depleted Eemian ice" by "low impurity Eemian ice".
P2 L1: We have changed "shallower ice" for "ice closer to the surface"
P2 L2: Strictly speaking we do not know the shear stress profile along an ice core. The shallow ice approximation is an approximation, which might break down at the bottom of the ice core under influence of topographic constraints. Even if the shear stress increases linearly with depth, then the strain rate (or borehole inclination) does not have to increase linearly with depth either since the strain rate also depends on CPO, grain size, grain shape, etc. We feel that, as a first order approximation, the expression "shear stress increase towards the bedrock" is appropriate.
We changed 'bedrock variations' into 'variations in bedrock topography'.
P2 L5: Morgan et al. (1998) was added to the references.
P2 L8: 'shear heating' was replaced by 'strain heating'.
P2 L7-10: The sentence was ended after 'water'.
P2 L11-12: The citation of Morgan et al. (1991) was replaced in the paragraph.
Budd and Jacka (1989) was added to the paragraph. We have expanded the paragraph to mention that we used a simplified description for the temperature dependence of Glen's law, which is widely used in ice sheet models. As the only grain size sensitive flow laws available (Goldsby and Kohlstedt, 2001) use a constant activation energsy in the high temperature regime, we will follow this approach.
P3 L15-17: It was added that SIBM is likely more important than nucleation based on the coarse grain size.

P3 L23 - P4 L3: In the end of the paragraph it was added that comparing the results of the composite flow law with the results from Glen's flow law can be seen as a control.

P4 L8-11: For clarity we added the words "in the underlaying".

P4 L25-26: A sentence was added to clarify whether this introduces a bias or not.

P5 L7-9: The equation for the Woodcock parameter was added to the text, including some more explanation about the meaning of the Woodcock parameter (k).

P5 L11-15: It was added that the term 'grain size' in the remainder of this paper means 'effective diameter'.

P5 L28-29: The text in this sentence has been adjusted. Throughout the manuscript we also replaced the expression 'accommodated by' for 'rate limited by'.

P6 L6: With p≠0 the G&K flow law indeed reduces to a Glen-type flow law. However, the activation energy, pre-exponential factor and stress exponent are still different from (the most often used form) of Glen's flow law. We therefore prefer to leave this part of the text like it was.

P6 L16: To our knowledge there is no published density profile of the NEEM ice core. However, it is likely that the density profile along the NEEM ice core follows a similar pattern compared to other polar ice cores. Therefore, only in the upper ~100m the density of the ice deviates significantly from the 910 kg/m^3. The error induced by assuming a constant density of 910 kg/m^3 is likely much smaller than the error induced by other parameters and assumptions made in determining the stress distribution along the NEEM ice core.

P6 L29-30: We added some explanation for the choice of the equivalent stress level.

P7 L17-18 & Figure 1: We added in the paper that this could also be described as a multi-maximum CPO. The caption of Figure 1 (which became Figure 2 in the new version) has been adjusted so that LASM and FA are mentioned. The other referee of this manuscript preferred that in the results section it should be made clearer that the LASM and FA image that are shown have been extracted from the larger 90 x 55 mm ice core section. Showing the same region is techniqually not possible as the FA image and LASM image are not made from the same surface, but are a small distance apart (but parallel to each other).

P7 L28: We changed this to 0.3-10.

P8 L4-19: At the end of this paragraph we added a few lines that mentions the effect of stress relaxation due to the bedrock topography.

Table 1: We added the last column and the last sentence in the caption to show that the sudden change in CPO and grain size close to the bedrock does not always coincide with a transition from glacial ice to interglacial ice or vice versa. We think this shows that the sudden change in microstructure is not only caused by glacial or interglacial ice, but that a temperature 'threshold' also plays a role in this sudden change. We therefore prefer to leave the Table and the caption as it is.

P8 L27-32 & Figure 3: We have added a sentence to acknowledge that different versions of Glen's law could be used with higher temperature sensitivity, So the results shown what is now figure 4, are dependent on our use of the Paterson (1994) version of Glen's law.

We agree that the term 'end member' can lead to confusing or give the impression that these are the only members in the G&K flow law. We therefore changed 'end member' to 'member'.

P9 L8-9: We have changed the discussion of this result in the Discussion.

P9 L15-18 & Figure 4: We've added that the strain rate increase coincides with the increase in temperature.

The temperature profile along the NEEM ice core is shown in the companion paper (Figure 1). Since Figure 5 ((Figure 4 in previous version) is already quite full, we prefer to leave the figure as it is.

P9 L24-26: It was added that the similar increase is a similar increase in order of magnitude. We also added a sentence to say that the relative changes depend on the version of Glen's law that is used.

P11 L26-29: Budd and Janka (1989) was added to the list.

Sentence has been re-written to improve clarity.

P12 L1-11: Budd and Jacka (1989) was added to the paragraph.

P12 L26: It was added that the SIBM rate was expected to be lower in these layers.

P12 L30: ‘Using the available creep laws’ was replaced by ‘using the chosen creep flow laws’.

P13 L5: “In situ”was added to the end of the sentence.

P13 L10-12: “Schmidt” was replaced by “Schmid”.

It was added that this was based on the assumption that simple shear is the assumed sress configuration.

P13 L10-12: Both suggestions were implemented.

Section 4.5: This section of the paper has been rewritten.

P13 L26 – P15 L24: This part of the paper has been rewritten to consider the effect of CPO on the predicted strain rates.

P13 L26 – P14 L3: The comparison of the strain rates for ice with different CPO’s has been made to argue that ice with a multi maxima CPO has similar strain rates to ice with an isotropic CPO when deformed in simple shear. This similarity suggests that the flow laws obtained for isotropic ice are valid for ice with a multi maxima CPO when deformed in simple shear.

P13 L32-33: We have corrected this mistake.

P14 L2-3: This interpretation was indeed incorrect and the sentence was deleted.

P14 L16-17: The discussion sections have been rewritten and this sentence has been taken out of the discussion.

P14 L22: The discussion sections have been rewritten and this sentence has been taken out of the discussion.

P15 L3-5: We thank the referee for this suggestion and added the Law Dome example.

P15 L3-5: The interpretation of borehole logging data in terms of deformation mode has been removed from the discussion. As noted by the reviewer, there are complications with the interpretation and not all the examples that were quoted have been fully published.

P15 L18-24: This paragraph is rewritten to highlight the speculative nature in the beginning of the paragraph.

P16 L9-12: This part has been revised to mention that the strain rate predicted from Glen’s law is dependent on the choice of the temperature sensity in the flow law.

P16 L22-23: Has been revised by separating the discussion about the strainrates from the discussion of the deformation mode.