Response to Referee #1 Dave prior
Manuscript review: tc-2018-275

Response to general comments

We would like to thank Dave Prior for the detailed and elaborate comments and suggestion on the manuscript. These were very helpful and improved the manuscript significantly. We have largely implemented the suggestions from the referee in the revised manuscript.

Referee's first comment
Premelting
Authors response We have modified the writing about premelting as suggested by the reviewer and we have also added some lines (and references) describing the indirect evidence for premelting obtained from attenuation experiments.

Referee's second comment
A schematic overview at start
Authors response A schematic overview of the structural and stratigraphic complexities has been added to the manuscript (figure 1). It shows the age of the ice, in-situ temperature, $\delta^{18}O_{ice}$ record and the stratigrapic discontinuities. Parameters like grain size and CPO were already shown in Figure 4 (Figure 5 in new version), so they were left out of the overview figure at the start. Related to this new figure we have also changed the descriptions of the finer-grained ice that occurs between 2207 and 2432 m of depth. In the original paper we described the finer-grained ice as glacial, however this ice is late Eemian in age according to the reconstruction of NEEM community members (2013).

Referee's thrid comment
Grain numbers in fig 1.
Authors response The second sentence of section 3.1 mentions that only a part of the 90 x 55 mm ice core section is shown, while the pole figures shows all the grain in the 90 x 55 mm ice core section.

Referee's fourth comment
Woodcock parameter
Authors response The explanation of the Woodcock parameter has been extended in Section 2.1. The equation that calculates the Woodcock parameter (k) from the principal eigenvalues has also been added (Equation 1)

Referee's fifth comment
Names for the modified flow laws
Authors response

Referee's sixth comment
Eemian Glacial Facies vs. Eemian ice
Authors response

Referee's seventh comment
Strain energy during GBS
Authors
We agree that the micrographs show evidence for grain boundary migration, which implies differences in internal strain energy that are probably produced by the basal slip component of deformation. Even when GBS is the rate limiting process both GBS and basal slip accommodate similar

amounts of strain as they are sequential processes. A line has been added Page 11 line 6-8 to cover this comment.

Referee's eighth comment
Split Figure 2 into 2 graphs
Authors response Figure 2 (Figure 3 in the new version) has been split into two graphs.

Referee's nineth comment
Fig 4.
Authors response the Figure has been adjusted and is much clearer not. However, we feel that all the information in the caption is needed to interpret the figure correctly, so we decided not the change the caption of this figure.

Referee's tenth comment
Minor things: through manuscript
Authors response We have followed the suggestions from the reviewer. The change in Q concerning Glen's temperature dependency is taken from Paterson (1994). In response to reviewer 2, we have added several lines to acknowledge that the temperature dependency we have used is a simplification (Budd and Jacka, 1989).

Referee's eleventh comment
"Accommodated by"
Authors response Throughout the entire paper (and the companion paper tc-2018-275) we have adopted the 'rate limiting' terminology instead of the 'accommodated by' terminology. The two bullet points are incorporated in the methods now (Equation 2 and 3 in the new version).

Referee's twelfth comment
The "Glen" law
Authors response Similar to the companion paper (tc-2018-274) we added at the end of section 2.2 that "the form of Glen's flow law that is most often used has a stress exponent of n=3". The value of n=3 was taken from Paterson (1994) and has been cited accordingly.

Referee's thirteenth comment
Girdle
Authors response We describe the CPO in the coarse grained Eemian ice as a 'small circle girdle type CPO' or a 'partial girdle'. The last sentence of section 3.1 it is also mentioned that 'the c-axes are distributed in a partial girdle spanning about 30° to 40° from the vertical axis'. The pole figures in Figures 2 and 5 will help the reader further to clearify what kind of girdle type CPO is found in this coarse grained Eemian ice.

Referee's fourteenth comment
CPOs during GBS in ice.
Authors response we have referenced the Craw et al. paper in part 1.

Referee's fifteenth comment
Figure Captions
Authors response A few words were removed at some of the figure captions. However, we think that the most of the figure captions explained the figures well and therefore they were not changed or shortened any further.

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

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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.