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The Cryosphere
Discussions

Interactive comment on "The temperature change shortcut: effects of mid-experiment temperature changes on the deformation of polycrystalline ice" *by* Lisa Craw et al.

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We would like to thank Nicolas Stoll for his very helpful and constructive comments. We have responded to each comment in turn below, and describe changes we have made to the manuscript to address the issues raised.

Reviewer 1

1. **Abstract p1. L.2 We can do this by... Is "this" referring to understanding the mechanical properties of flowing ice, modelling of the dynamics of ice sheets, or predicting the behaviour in the future? Please rephrase to enhance clarity.**

   We have changed "We can do this..." to "We can increase our understanding of ice physical properties...".

2. **Abstract p.1 l.4 conditions in ice sheets and ice shelves extend to low temperatures (<-5 °C). The temperatures in the majority of ice sheets and ice shelves is well below -5 °C, a lower temperature value might be more appropriate. See more detailed comment below.**

   This is a good point. We have changed "<-5 °C" to "«-10 °C"

3. **Aims of the study are explained on p.2 l.32 and on p.5 l.43. They differ in details (e.g., tertiary creep only mentioned on p.2. l.32), thus it might be appropriate to combine both sections into one, placed at the end of the introduction to increase readability.**

   We removed the last sentence of section 1.1, and combined with the final sentence of the introduction as suggested.

4. **P.2 l.45 Primary creep: The definition is a little bit too simplified, maybe include some information from e.g., Faria et al. (2014b)...**

   We inserted more detail from (Faria, et al., 2014) as suggested: "strain rate decreases rapidly due to work hardening, as strain incompatibilities between grains and the load transfer from easy-glide to hard-glide systems result in heterogeneous internal stresses and the formation of dislocation tangles and subgrain boundaries (Faria et al., 2014). The decreasing rate of deformation is controlled by crystals which are unfavourably oriented for creep (Duval et al., 1983)."

5. **P4. L10: The impact of GBM is strong on texture (grain size, grain shape, SPO) and on grain growth and reduction (dynamic grain growth, see Steinbach et al., 2017), but not so much on CPO (fabric)(e.g., Llorens et al., 2016a, b). Terminology is not always used in the same way in earth and material sciences, so please define "microstructure" in the beginning. Otherwise it is difficult to distinguish between microstructure (glaciology: fabric + texture), fabric and texture (see also comment 8).**

   Good point. We are using the word "microstructure" in the glaciological sense, incorporating fabric and texture. We have added this definition in the text (now pg.2, L4-5).

6. **P. 5 l. 25: references for examples of other experiments, in-situ data, extrapolations missing.**

   To incorporate referenced examples, we have changed this passage to read:

   "Consequently, the majority of experimental ice deformation studies are performed at temperatures of $>-10\,^{\circ}$C, at a narrow range of stresses (e.g. Kamb, 1972; Jacka, 1984; Wilson et al., 2014; Montagnat et al., 2015), with a much smaller number of studies extending to lower temperatures and higher stresses (e.g. Goldsby and Kohlstedt, 2001; Wilson and Peternell, 2012; Qi et al., 2017). This means there is a bias in the available data favouring a small range of conditions which are seldom present in nature."

7. **P. 5 l. 43 it should be clarified that the systematic study is undertaken on laboratory ice.**

   Changed to specify "laboratory ice".

8. **It is mentioned on p. 9 l. 101 that SPO data was derived, but this data is not further used in the manuscript. Showing and discussing SPO data would be a good way to further quantify the microstructural changes, i.e. changes in the ice texture. In this case it is possible to visually analyse the microstructure of the thin section images, however, I would suggest to add SPO data to fully fulfil the statement of "quantifiable differences in the microstructure" as described in the abstract on p.1 l. 14. Otherwise, if only CPO-data is used to quantify changes I suggest to rephrase the wording to e.g., "quantifiable differences in the fabric" to avoid confusion.**

   Initially we had left the SPO data out as it does not show anything immediately relevant to the discussion, but you are right that it is good to include for completeness. We have added it as an appendix alongside grain size statistics, as suggested by reviewer 2, and mentioned it in the results section.

9. **For practical reasons the temperatures of the conducted experiments are rather high compared to temperatures in deep ice sheets (-30 °C- -20 °C) (e.g., Dahl-Jensen et al., 1998, Mony et al. (2020) and, to a lesser degree, in ice shelves (-25 - -10 °Cfor meteoric ice) (e.g., Rist et al., 2002). Temperatures of >-10 °Care rather found in shallow, or the deepest parts of deep ice sheets, close to bedrock. There are studies on warm ice from glaciers (e.g., Hellmann TCD https://tc.copernicus.org/preprints/tc-2020-133/) so this shouldn't be mixed up. This is especially important since samples from set 2 did not match the desired outcome, thus there are still limits to the usability of this method. On p. 14 l.16 you state that the microstructure is "failing to match those conducted entirely at -10 °C". In the conclusion on p. 14 l. 40 this is slightly emphasized by stating that the microstructure is "not [..] truly representative", please clarify this. Deformation mechanism maps might help to bring together different regimes (glaciers, ice sheets, ice shelves) e.g., RX diagram in Faria et al. (2014b), Frost and**

Ashby (http://engineering.dartmouth.edu/defmech/) and Shoji and Higashi (1978, https://doi.org/10.3189/S002214300003358X). This might go beyond the scope of the manuscript, but should be kept in mind.

You're right that it's important to make this disctinction more clearly, and remind the reader that at even lower temperatures the balance of deformation mechanisms will be different. We have added a sentence at the end of section 4: "The temperatures we have tested here are comparable to those found in temperate glaciers, and in the lower and upper extremities of polar ice sheets. For experiments aiming to replicate colder conditions, it would be best to use a lower starting temperature, so that the balance of deformation mechanisms active at the beginning of the experiment is more comparable to that at the final target temperature.".

10. **Tests were conducted on laboratory ice only. Natural ice has different, and highly variable, properties regarding e.g., absolute impurity content and spatial distribution of inclusions (cloudy bands) etc., which are reported to affect the rheological parameters, and thus the deformation, of ice. It should be emphasized in the discussion and the conclusions that the discussed results are not as simply transferable to natural ice as currently concluded (p.15 l.45). The study is an important step forward, but more research is needed to verify the easy upscaling to ice sheets and ice shelves.**

    We have added a sentence in the discussion: "It should also be noted that natural ice has different rheological properties to standard ice, (Budd and Jacka, 1989; Dahl-Jensen et al., 1997; Castelnau et al., 1998; Craw et al., 2018), and so the balance of deformation mechanisms active in experiments may be different to those active under the same conditions in nature."

    We have also changed the concluding remarks to separate the specific contribution of this study (extending the temperature conditions that are feasible for laboratory experiments by reducing experiment time) and the hopeful outcome of

this (allowing experiments to become more representative of *in situ* conditions, therefore leading to more accurate flow law parameters).

11. **2.1 Laboratory: After cutting and polishing the samples, were they left for sublimation? Please address this issue briefly in the text since this can have an impact on the texture (grain shape and size) and on the quality of the FA measurements.**

    Samples were cut into thin sections with a microtome, and then repeatedly thinned and checked under cross-polarised light until birefringence was minimal. Occasionally where the fabric analyser data was of lower quality, then section was left for $\sim$1hr to sublimate and then the scan was repeated. We have clarified this in the methods.

12. **P. 12 Fig 5: LC023 has visibly, and measurably, much smaller grains than LC021, LC025, and LC026 and a rather homologous bulk grain size. This should be briefly mentioned in the final section of the results indicating the small-scale differences in polycrystalline ice.**

    Yes, this is a good example of the possible variability between experiments conducted under the same conditions. See our more in-depth response to Reviewer 2, comment #4, below.

13. **I suggest to combine the first sentences on p. 13 l. 47 or to add some references in the first sentence.**

    We have changed this to: "The microstructural characteristics observed in these samples after deformation are comparable to those from other compression experiments in the literature; the development of a vertical small-circle girdle CPO centred around the compression direction has been observed many times in polycrystalline ice above $-15\,^{\circ}$C (e.g. Kamb, 1972; Jacka, 1984; Treverrow et al.,2012; Wilson et al., 2014), and the interlocking, irregular grain boundaries seen in all deformed samples in this study are comparable to those observed by Montagnat et al. (2015) and Jacka and Jun (1994) after similar experiments."

14. **References needed in final discussion paragraph on p. 14 l. 17 discussing GBM, BLG, and other lower-temperature experiments.**

    Added references to Alley, 1992; Montagnat et al., 2015; Qi et al., 2017.

15. **Fig. 4 and Fig. 5: What is the reason for showing the c-axis orientation of 5000 pixels rather than using the c-axes of the actual grains as described for deriving the CPO in section 2.3? The number of grains is lower than 5000 and CPO contour plots thus probably look different when referring to the grains.**

    Well spotted, the statement in section 2.3 is incorrect.. We ultimately chose to use randomised pixel data for the CPO because, while we do remove all very fine and low geometric quality grains, smaller grains have a higher chance of being artefacts of the data processing. Plotting one point per grain would amplify the contribution of smaller grains to the CPO data. In fact the difference is very minimal, and so for our purposes it is a fairly arbitrary choice (see figure 1).

    We have corrected this in section 2.3.

16. **Appendix p. 15 l.5f. What is the reason to remove elongated small grains? Is it motivated by the possibility of artificially introduced grains due to segmentation/grain reconstruction? Were images manually checked for such grains? Please explain.**

    Thank you for pointing this out. The elongated small grains are a common artefact in two-dimensional ice deformation experiments, which we were working on while we developed the process, and they are not present here. We have removed that step, and the results are unchanged.

17. **Do you have ideas what could have caused the two troughs in strain rate observed at LC025 at -10 °C? (Fig.3d)**

    All of the raw strain rate data have these periodic jumps, which appear when we increase the loads to approximate constant stress (see section 2.1). For the most part they are obvious as an instantaneous increase in displacement, and are straightforward to remove during data processing to avoid large artefacts in the results. However, they are often accompanied by more complicated disturbances to the apparatus (adjusting other equipment, opening and closing neighbouring freezers, etc). This means that some of these jumps are harder to remove without "doctoring" the data, and so we err on the side of caution when trying to correct them. Another clear example is in LC009 at a strain of ~ 0.07. We have clarified this slightly in section 2.2: “Sudden jumps in displacement from load increases and disturbances to the apparatus were removed manually. Some more gradual jumps in displacement (e.g. in **LC021** and **LC025**) could not be easily removed, and so were left to avoid overprocessing the data."

- **Technical corrections**

  All corrected, thank you.