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Discussions

Interactive comment on "Basal sliding of temperate basal ice on a rough, hard bed: pressure melting, creep mechanisms and implications for ice streaming" *by* M. Krabbendam

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Reply to interactive comment by M Montagnat (referee)

Thank you very much for a very constructive and helpful review. I will make changes in the revised manuscript according to the suggestions, but a few points are worth discussing beforehand, if only to other interested readers.

The experiments of de La Chapelle et al. (1995; 1999) are, unfortunately, not strictly relevant for deformation of temperate ice. These experiments were performed with pure ice at -5 °C and -13°C, with the intragranular liquid provided by a brine, with a much lower melting point. Thus, this experiment contained two materials with different melt-

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ing temperatures, where the liquid and the solid cannot freely interact through normal melting/freezing. Thus, whereas these experiments are interesting to study dislocation creep in the present of a different liquid phase (compare the hydrolytic weakening of geological materials, e.g. the difference in behaviour of ‘dry quartz’ and ‘wet quartz’), they are in essence experiments on cold ice. Therefore, it is not surprising that these experiments document a n$\sim$3 power-law exponent, and that dislocation creep remains dominant. But, the results cannot be extrapolated to true temperate ice, where ice and water are in thermodynamic equilibrium, which can melt or refreeze at the smallest perturbation of temperature or stress.

The behaviour of temperate ice is NOT very similar to other geological materials and metals at high temperatures. No other such material (with the apparent exception of plutonium!) shows the near-unique behaviour of H2O, namely that the liquid phase is denser than the solid phase. This fundamentally different phase-transition behaviour is likely to lead to a fundamentally different deformation behaviour. In other words, the whole concept of pressure melting, namely that higher pressure leads to a lowering of the melting temperature only works for H2O. I will emphasise this difference more strongly in the revised paper as follows: “Comparisons with other materials (rocks, metals) are no help, as water is (almost) unique in that its solid phase is less dense that its liquid phase. This fundamentally different phase transition behaviour means that the liquid-solid mixture of H2O may have a fundamentally different deformation behaviour at the pressure melting point. “

Both the dramatic and sudden increase in strain rate close to the melting temperature, and the (albeit limited) evidence for near-Newtonian (n $\sim$ 1) behaviour in temperate ice do suggest there is a switch in rate-controlling deformation mechanism, rather than ‘merely’ a variation of dislocation creep.

Grain boundary sliding (GBS) is indeed commonly invoked to explain sudden weakening in a variety of materials, i.e. by superplasticity. This is worth emphasising and discussing, and I will do so in the revised paper. GBS is thought to be favoured by small grain size, and (for most grain shapes) needs to have an accommodation mechanism (for grain edges to move past each other) which may be diffusion-dominated or dislocation-creep dominated. GBS behaviour has been simulated in ice in experiments at temperatures between -37°C and -80°C and with grain sizes between 3-40μm (Goldsby and Kohlstedt, 1997, 2001; Goldsby and Swainson, 2005). Such conditions may be relevant for icy planets, but are very different from the temperate ice below terrestrial ice sheets under consideration here. Basal temperate ice is observed to be coarse (mm-cm scale grain size, e.g. Tison and Hubbard (2000), 3-4 orders of magnitude coarser than in the experiments mentioned above, again not compatible with the GBS experiments. GBS in rocks can destroy, or prevent the formation of, crystal C-axis fabrics (e.g Krabbendam et al. 2003); whether this occurs in ice or not is ambiguous (Goldsby and Kohlstedt, 2001; 2002; Duval and Montagnat, 2003; Goldsby and Swainson, 2005). Overall, I feel that GBS is unlikely to be the rate-controlling factor in the deformation of coarse, temperate ice, but I agree this needs to be discussed in the revised Manuscript and I will do so.

I will reword the part on ‘grain boundary pressure melting’, but this is not “another” new mechanism: it has been documented before by Barnes and Tabor (1966, 1967) and Barnes et al. (1971), but referred to as ‘internal pressure melting’ or ‘grain boundary melting’. I will change the manuscript to reflect this better. Extensive melting along grain boundaries was observed by Wilson et al. (1996) whereas and Hubbard et al. (2000) and Lovell et al. (2015) also invoke melting and refreezing to explain the deformation metamorphism in basal temperate ice into bubble-free basal ice. There is thus ample evidence that melting along grain boundaries does occur in deforming temperate ice. In terms of deformation mechanisms, can ‘grain boundary melting’ be seen as a very fast version of grain boundary diffusion creep (Coble Creep)? This is hinted at by Goldsby & Kohlstedt (2001). This is then likely to result in n<3 behaviour, although the problem of grain-size sensitivity remains. For some reason, the process has been rather ignored in ice rheology – maybe because it is unlikely to operate in other materials?

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I think we all agree that too little is known about the mechanical behaviour of temperate ice. . ..

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