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Evaluating the importance of grain size sensitive creep in terrestrial ice sheet rheology

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The rheology of ice in terrestrial ice sheets is generally considered to be independent of the size of the grains (crystals), and appears well described by Glen's flow law. In recent years, however, new laboratory deformation experiments on ice as well as analysis of in situ measurements of deformation at glaciers suggested that grain size and variations therein should not be discarded as important parameters in the deformation of ice in nature. Ice, just like crystalline rock materials, exhibits distributed grain sizes. Taking now that not only grain size insensitive (GSI; dislocation) mechanisms, but also grain size sensitive (GSS; diffusion and/or grain boundary sliding) mechanisms may be operative in ice, variations in the shape of the distribution (e.g. the width) can be expected to affect the rheological behaviour. To evaluate this effect, we have derived a composite GSI+GSS flow law and combined this with full grain size distributions. The constitutive flow equations for end-member GSI and GSS creep of ice were taken from the work of Goldsby and Kohlstedt (2001, J.Geophys.Res., vol. 106). We used their description of grain boundary sliding controlled creep as representative of GSS creep. The grain size data largely came from published measurements from the top 800-1000 m of two Greenland ice cores (NorthGRIP and GRIP) and one Antarctic ice core (Epica, Dome Concordia). Temperature profiles were available for both core settings. The grain size data show a close to lognormal distribution in all three settings, with the median grain size increasing with depth. We constructed a synthetic grain size profile up to a depth of 3100 m (cf. GRIP) by allowing the median grain size and standard deviation of the distribution to linearly increase with depth. The percentage GSS creep contributing to the total strain rate has been calculated for a range of strain rates that were assumed constant along the ice core axes. The results of our calculations show that at realistic strain rates in the order of 10^{-11} to 10^{-12} s^{-1}, GSS mechanisms can be expected to dominate creep in the parts of the ice sheets investigated (i.e. the top ~1000 m). In the synthetic core, the GSS contribution decreases if going to greater depth (~2500 m), but increases again close to the contact with the bedrock (at 3100 m). Although many assumptions have been made in our approach, the results confirm the important role that grain size might play in ice sheet rheology. The application of full grain size distributions in composite flow equations helps to come to reliable extrapolation of lab data to nature.