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Discussions

Interactive comment on "Implementing an empirical scalar tertiary anisotropic rheology (ESTAR) into large-scale ice sheet models" *by* Felicity S. Graham et al.

Anonymous Referee #1

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The paper present the implementation of a scalar anisotropic flow law (ESTAR) into the large-scale model ISSM. The model is applied to 3 idealised configurations (embayed ice-shelf, ISMIP B and D experiments) and the results compared to the Glen flow law with a uniform enhancement factor.

My main concern with this paper is that ESTAR is presented as a physically-based alternative to represent the anisotropic rheological properties of polar ice. There is 2 problems with this presentation; first ESTAR is not an anisotropic flow relation; second, ESTAR is based from laboratory measurements for tertiary creep of polycrystalline ice and thus does not apply in large portions of the ice-sheet. I detail these two points

below.

Anisotropy: It can only be applied to properties that depend on the orientation of the material. Here the flow relation (3) is stress-configuration dependant, but is isotropic; i.e. for a given stress state, the mechanical response (the strain-rate state) does not change by rotation of the sample as, by definition of ESTAR, the fabric instantaneously adapt to the stress state, and thus to any rotation of the stress state. The dependance of the flow law to the stress state, results from the mechanical anisotropy of the ice crystal and the anisotropy of the crystal orientations (the fabric) that develop during tertiary creep; but the mechanical behaviour predicted by ESTAR is isotropic. Note that this property is not due to the scalar relationship, the CAFFE model (e.g. Seddik et al., J. Glaciol. 2008) is anisotropic as its scalar enhancement factor depends on the direction of the stress state with respect to the ice fabric, and thus the mechanical response depends on the orientation of the stress state relative to the ice sample.

Tertiary creep: In the paper tertiary creep is presented as "the predominant mode of deformation in ice sheets", under the justification that it is usually reached after few percent of deformation in laboratory creep experiments. For a detail review on the ductile deformation of ice and textures in polar ice masses one can refer to the book "creep and fracture of ice" by Schulson and Duval. Tertiary creep in laboratory experiments is explained by softening processes associated with migration recrystallization. Textures resulting from migration recrystallization are indeed stress-configuration depend and the argument that the microstructure evolves more rapidly than the flow configuration sufficiently robust to assume a scalar isotropic relationship in the context of large scale ice flow modelling. In the central part of the ice-sheets, temperature and strain energy can be too low to initiate migration recrystallization and there is no evidence that it occurs except in the warm ice near the bed (the last 100-200 meters usually). See texture measurements in all deep ice cores in the central regions of Greenland and Antarctica. There is a general agreement that in the regions of normal grain growth and rotation recrystallization (most of the ice thickness in the central regions) textures basically develops as the results of lattice rotation due to intractrystalline slip; and thus reflect the deformation history. The combination of anisotropic textures and the high mechanical anisotropy of the ice mono-crystal makes the ice polycrystal highly anisotropic. This has been confirmed by laboratory experiments that have shown that the strain-rates for secondary creep of polycrystalline ice depends on the fabric and its orientation with respect to the test configuration; while the tertiary creep is independent of the initial fabric and depends only on the test configuration. All the studies presented in Sec. 2.1 as "microstructure approaches", where motivated by representing the mechanical anisotropy of polycrystalline ice that develops as a result of the development of strain-induced preferred orientations of the ice crystals. They can not be opposed or compared to the flow law presented here, as they don't represent the same physical processes.

Laboratory experiments for tertiary creep are certainly relevant for the regions where migration recrystallization occurs; i.e. in temperate glaciers, in the bottom part of the central regions of the ice-sheets and certainly in the margins where temperature and stresses are sufficiently high. These areas are potentially important for the flow dynamics of polar ice sheets. The flow law presented in this paper must be presented in this perspective, and not as an empirical approach to represent the strain-induced mechanical anisotropy that results from the development of ice fabrics as seen in all deep ice-cores. This implies to largely rewrite large parts of the abstract, introduction and second section, to discuss the validity of the assumptions of the flow law and their domain of applicability for large-scale ice flow modelling.

Concerning the rest of the paper, i.e. the implementation of the flow law in the ice sheet model and the applications I only have minor comments: ietmize

Application to the embayed ice shelf:
I think it would have been more interesting to test the model with larger transverse dimensions, i.e. to represent non-embayed ice-shelves, as I assume that simple shear

along the margin will be less important and the difference with Glen and a uniform enhancement factor for shear should increase ?

ISMIP-HOM experiments:
When discussing the results for Glen in the main text it is never clear for which value of the enhancement factor. The fact that the velocity scales with the enhencement factor is not a result, but as written in the manuscript follows from the definition of the experiment. So it would be more clear for the reader, to discuss the results for only one value of the enhencement factor or maybe better, find the value of the Glen enhancement factor that minimize the velocity difference with the tertiary creep flow law, and discuss this value and the results for this value.
The discussion in page 12 about the value of the shear fraction along the transition curve is not very clear.

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