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Incorporating horizontal membrane stresses into calculations of balance velocities

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The prediction of ice-sheet behaviour is becoming increasingly important as observed changes in continental ice masses may be indicators of the operation of instability mechanisms which have the potential to have a significant impact on global sea levels. Predictive forward models require initialisation with existing data in order to best describe the current state of the ice-sheet. In particular, such models need to be calibrated with the viscosity and sliding conditions at the base of the ice-sheet, which in practice are largely unobservable. The balance velocity approach, in which depth-averaged velocities that conserve mass are calculated based on surface elevation and accumulation data, is a suitable method in many cases. Hitherto, balance velocities have been calculated using the Shallow Ice Approximation (SIA), where flow is always parallel to the direction of the slope. The SIA is usually applied to coarse resolutions and assumes that longitudinal stresses are averaged out over distances 10-20 times the ice thickness. However, this method does not capture any fine detail at which longitudinal stresses may be important and the assumption of downhill flow is not always appropriate. Moreover, it is ill-posed as results are severely dependent on grid size. Thus in this study horizontal membrane (or longitudinal) stresses are introduced into calculations for balance velocities. The numerical method is presented and the code is tested by comparing numerical results with various simplified analytical solutions for Newtonian rheology and linear sliding. These analytical and numerical solutions are then compared to the SIA solutions and are used to investigate the conditions under which membrane stresses become important.