Geophysical Research Abstracts
Vol. 13, EGU2011-1786, 2011
EGU General Assembly 2011

New approximations for large-scale ice sheet flow: Towards a happy marriage between the shallow-ice and shelfy-stream approximations

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Realistic predictions of the glaciological contribution to sea level rise require numerical ice sheet models that include both fast flow near the ice sheet margins and more traditional, sluggish ice-sheet like behavior in the ice sheet interior. This has led to the development of full Stokes and so-called 'Batter' models. These fully three-dimensional models are more realistic than previously used shallow-ice models, but the greater accuracy is bought with a steep price; models are computationally expensive and difficult to implement numerically. Moreover, since ice dynamics is highly sensitive to basal conditions and variation in terminus position and even under the best conditions these are poorly known, the increased accuracy of three-dimensional models may not translate into improved predictions. An alternative approach to fully three-dimensional models is hybrid models. Hybrid models are essentially two-dimensional approximations that seek to sew the shallow-ice and shelfy-stream approximations together. Here, I propose a spectral decomposition for the velocity field (in the vertical direction) and show how to develop a suite of hybrid approximations that stitches the shallow-ice (SIA) and shallow-shelf approximations (SSA) together using the Rayleigh-Ritz method. Numerical examples show that the approximation yields realistic steady-state ice sheet configurations for a variety of basal tractions and sliding laws. Moreover, the approximation transitions smoothly between the two end member cases of the SIA and SSA and analytically reduces to the SIA and SSA solutions respectively, depending on whether a non-dimensional number called the basal traction number is large or small. Finally, I show that uncertainty/error in the basal traction number (e.g., due to incomplete knowledge of ice temperature, basal hydrology and the sliding law) provides a fundamental limit of the accuracy of the ice dynamics predicted by models, thus providing an objective criterion to determine when inclusion of the additional stresses/accuracy of a full Stokes or Blatter model would be beneficial or spurious.