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Analytical analysis of small-amplitude perturbations in the shallow ice stream approximation

G. H. Gudmundsson

British Antarctic Survey, High Cross, Madingley Rd, Cambridge CB3 0ET, UK, (ghg@bas.ac.uk)

New analytical solutions describing the effects of small-amplitude perturbations in boundary data on flow in the shallow ice stream approximation are presented. These solutions are valid for a non-linear Weertman-type sliding law and for Newtonian ice rheology. Comparison is made with corresponding solutions of the shallow ice sheet approximation, and with solutions of the full Stokes equations. The shallow ice stream approximation is commonly used to describe large-scale ice stream flow over a weak bed, while the shallow ice sheet approximation forms the basis of most current large-scale ice sheet models. It is found that the shallow ice stream approximation overestimates the effects of bedrock perturbations on surface topography for wavelengths less than about 5 to 10 ice thicknesses, the exact number depending on values of surface slope and slip ratio. For high slip ratios, the shallow ice stream approximation gives a very simple description of the relationship between bed and surface topography, with the corresponding transfer amplitudes being close to unity for any given wavelength. The shallow ice stream estimates for the timescales that govern the transient response of ice streams to external perturbations are considerably more accurate than those based on the shallow ice sheet approximation. In contrast to the shallow ice sheet approximation, the shallow ice stream approximation correctly reproduces the short-wavelength limit of the kinematic phase speed. In accordance with the full system solutions, the shallow ice sheet approximation predicts surface fields to react weakly to spatial variations in basal slipperiness with wavelengths less than about 10 to 20 ice thicknesses.