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Sensitivities of Greenland ice sheet volume inferred from an ice sheet adjoint model

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We present a new and original approach to understanding the sensitivity of the Greenland ice sheet to key model parameters and environmental conditions. At the heart of this approach is the use of an adjoint ice sheet model.

Since its introduction by MacAyeal (1992), the adjoint method has become widespread to fit ice stream models to the increasing number and diversity of satellite observations, and to estimate uncertain model parameters such as basal conditions. However, no attempt has been made to extend this method to comprehensive ice sheet models. As a first step toward the use of adjoints of comprehensive three-dimensional ice sheet models we have generated an adjoint of the ice sheet model SICOPOLIS of Greve (1997). The adjoint was generated by means of the automatic differentiation (AD) tool TAF. The AD tool generates exact source code representing the tangent linear and adjoint model of the nonlinear parent model provided. Model sensitivities are given by the partial derivatives of a scalar-valued model diagnostic with respect to the controls, and can be efficiently calculated via the adjoint.

By way of example, we determine the sensitivity of the total Greenland ice volume to various control variables, such as spatial fields of basal flow parameters, surface and basal forcings, and initial conditions. Reliability of the adjoint was tested through finite-difference perturbation calculations for various control variables and perturbation regions. Besides confirming qualitative aspects of ice sheet sensitivities, such as expected regional variations, we detect regions where model sensitivities are seemingly unexpected or counter-intuitive, albeit "real" in the sense of actual model behavior. An example is inferred regions where sensitivities of ice sheet volume to basal sliding coefficient are positive, i.e. where a local increase
in basal sliding parameter increases the ice sheet volume. Similarly, positive ice temperature sensitivities in certain parts of the ice sheet are found (in most regions it is negativ, i.e. an increase in temperature decreases ice sheet volume), the detection of which seems highly unlikely if only conventional
perturbation experiments had been used.

An effort to generate an efficient adjoint with the newly developed open-source AD tool OpenAD is also under way. Available adjoint code generation tools now open up a variety of novel model applications, notably with regard to sensitivity and uncertainty analyses and ice sheet state estimation or data assimilation.