

Better Physics in Embedded Models

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Modeling ice sheets such as Antarctica is an important scientific activity for a number of reasons: 1) ice sheets are an integral part of the world's climate system, both as a mechanism defining climate and as an indicator of change; 2) modeling allows us to test our understanding of the fundamental physical processes that control the behavior of ice sheets and their response to changing climate; 3) modeling provides a virtual laboratory where we can investigate the possible changes that will occur.

Physics-based modeling of ice sheets suffers from the same deficiencies that other fields such as global climate modeling have encountered. This deficiency involves the need for higher resolution than current computers are able to provide with reasonable runtime and memory requirements.

Climate modelers overcome this deficiency by designing mesoscale models which run inside their global climate models. This allows them to use higher resolution in a smaller domain which is driven by the output of the lower-resolution, global-domain model. These mesoscale models, since they run at higher resolution, can also improve on the physics used in the GCM, they can be specifically tuned to work in particular regions, they can examine the interaction between processes operating at different scales, they can look at the effects of processes originating outside their domain, and at processes too small to be picked up in the full GCM.

We propose to follow the climate modelers' lead and develop an embedded ice sheet model, one where a section of the ice sheet (mesoscale) is modeled either at higher resolution with the same physics or at the same resolution with better physics. This embedded model is driven by output from a low-resolution model of the entire ice sheet (global model). By this approach we either obtain higher-resolution results, better able to capture the behavior of small-scale features such as ice streams, or we can include processes such as longitudinal stresses, which are impossible to calculate within the constraints of the shallow-ice approximation.

One serious drawback to most ice sheet models is the basic assumption of the shallow-ice approximation. This approximation basically neglects all stresses except the familiar driving stress, which is assumed to be concentrated at the bed. While a good approximation for much of the ice sheet, it is probably not very good in the interesting regions of the ice streams. As the climate modelers have included different physics in the mesoscale models that is impractical to include in the full global model, so too do we feel it will be possible to provide a more complete solution of the momentum equation.

Another approach is to treat an ice stream as a barely-grounded ice shelf. This solution is considerably more expensive, computationally, requiring three degrees of freedom at each node (V_x , V_y , and h) instead of one (just h). These extra degrees of freedom require considerably more computation resources to calculate, resources that would be prohibitive for the whole ice sheet at even 20 km resolution, but which may be possible for an embedded model. One problem with this approach is that the basal drag that must be specified itself violates the assumptions that go into the derivation of the Morland equations used to model an ice shelf. A second drawback is that the positions and extents of the regions where this barely-grounded ice shelf exists must be externally specified, a requirement we would like to avoid, allowing instead for the model to determine in a self-consistent manner where the fast flow needs to occur.

The shallow-ice approximation and the barely-grounded ice shelf can be considered as end members: only the basal stress is considered in the first, whereas only the longitudinal stress is considered in the second.

Clearly the best physics can be included by abandoning both of these approximations and solving the full-momentum equation with all stress terms included. In this way no stresses are neglected which might be important for regions where longitudinal stresses may play an important role, such as ice streams.

Doing this requires solving simultaneously the full momentum equation for the complete velocity field, the mass conservation equation for the rate of change of thickness, and the energy equation for the internal temperatures. Both the temperature field, which affects the material properties through the ice hardness, and the ice-sheet configuration will affect the velocity solution of the momentum equation. The temperature

solution, of course, depends on the ice-sheet configuration, but also depends on the velocity field through the advection term of the heat-flow equation and through the shear-heating term, which contains the product of stresses and velocity gradients. The rate of change of ice thickness, and hence ice-sheet configuration, depends on the velocity-field solution, the current ice-sheet configuration, and the local mass balance.

We present details of the implementation of this full solution, and preliminary results.

We thank the NSF, which has supported the development of this model over many years through several different grants.