Computational Methods in Ice Sheet Modeling for Next-Generation Climate Simulations

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Recent observations show that both the Greenland and Antarctic ice sheets are losing mass at increasingly rapid rates [1]. In its fourth assessment report (AR4), the Intergovernmental Panel on Climate Change (IPCC) declined to include estimates of future sea-level change from dynamics of the polar ice sheets due to the inability of ice sheet models to mimic or explain observed dynamic behaviors, such as the acceleration and thinning then occurring on several of Greenland's large outlet glaciers [2].

In recent years, there has been a push to develop "next generation" land-ice models and codes for integration into global Earth System Models (ESMs) to address this acknowledged limitation. This talk will give an overview of one such next-generation land-ice dynamical code (dycore) known as Albany Land-Ice (ALI) [3], currently under development at Sandia National Laboratories. Unlike many of its predecessors, ALI: (1) is able to perform realistic, high-resolution, continental scale simulations, (2) is robust, efficient and scalable on next-generation hybrid systems (multi-core, many-core, GPU, Intel Xeon Phi), (3) possesses built-in advanced analysis capabilities (e.g., sensitivity analysis, optimization, uncertainty quantification), and (4) is hooked up to the U.S. Department of Energy's Energy Exascale Earth System Model (E3SM) as well as NCAR's Community Earth System Model (CESM).

The ALI dycore is based on the so-called "First-Order Stokes" equations for the ice momentum balance [4], an attractive alternate to the more expensive "Full Stokes" model. Both the Full Stokes and the First-Order Stokes models assume that ice behaves like a very viscous, shear-thinning, non-Newtonian fluid, similar to lava flow. Following an overview of our land-ice model and project, I will describe some of the algorithms and software we have developed as a part of this project that have contributed to our dycore's robustness and scalability. These include robust automatic-differentiation-based nonlinear solvers, scalable algebraic-multigrid-based iterative linear solvers [5], and stable semi-implicit First-Order Stokes-thickness coupling methods. I will also discuss some of the advanced analysis capabilities in ALI, namely a large-scale inversion approach we have developed for obtaining optimal ice initial conditions [6], our workflow towards quantifying uncertainties in land-ice models, and performance-portability of the ALI code to new and emerging architectures using the Kokkos library [7,9]. I will show results which demonstrate that the ALI dycore is scalable, fast and robust for production-scale land-ice problems on state-of-the-art HPC machines. I will also discuss results from a recent validation study in which ALI was used to simulate the Greenland ice sheet during the period 1991-2013 with realistic climate forcing, and the simulation data were compared with observational data collected by NASA satellites [8]. Finally, I will show some predictive dynamic experiments and simulations we are beginning to perform using ALI.

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