GUEST EDITORS' INTRODUCTION

Computational Modeling of Ice Sheets and Glaciers

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Mass loss from the polar ice sheets of Greenland and Antarctica is expected to be a major contribution to future sea-level changes. Together, the Greenland and Antarctic ice sheets store enough water to raise global sea level by approximately 65 m, and recent projections indicate that meters of sea-level rise is possible within a few centuries. Recent research has suggested that the Antarctic ice sheets may be on a path toward a tipping point, namely, the irreversible, self-reinforcing collapse of the West Antarctic Ice Sheet caused by the loss of Antarctica's floating ice shelves, which serve as a buttress that slows down advancing ice, thereby preventing it from being lost into the ocean. At the same time, the Greenland ice sheet may be approaching a tipping point whereby surface melting exceeds surface snow accumulation, making it impossible for the ice sheet to persist long term. The timing and consequences of these tipping points lead to deep uncertainty in projecting future sea-level change. Further, recent observations show that the evolution of both ice sheets can be strongly affected by small-scale processes and interactions with the rest of the Earth's system relating to surface meltwater, basal sliding, marine melting, iceberg calving, and ice rheology, complicating efforts to project future behavior.

Scientifically meaningful projections of sea-level change in the 21st century and beyond require accurate and efficient computational modeling of the Greenland and Antarctic ice sheets. The past 10–15 years have seen tremendous progress in the development of community-supported ice sheet model (ISM) "dynamical cores" capable of performing realistic, high-resolution, continental-scale simulations. Much of this work was spurred by the fourth assessment report of the Intergovernmental Panel on Climate Change.[a] Issued in 2007, this report declined to include estimates of future sea-level rise from ice-sheet dynamics due to ISMs' inability to mimic or explain observed dynamic behaviors, such as the then-occurring acceleration and thinning in several of Greenland's outlet glaciers. It is only recently that ISMs have begun to be included in coupled climate simulations involving large-scale high-performance computing (HPC) models, following some significant improvements in ice-sheet modeling frameworks. These improvements include 1) the development and implementation of 3-D partial differential equation-based models for ice momentum balance through the inclusion of both vertical shear and membrane stresses over the entire model domain; 2) the switch from finite-difference to finite-element and finite-volume method discretizations, which enable the use of unstructured meshes; 3) the integration of unstructured and/or adaptive meshing, which allow the focusing of resolution and computational power in regions of dynamic complexity; 4) the use of formal optimization and data assimilation techniques for generating realistic model initial conditions given available (and possibly uncertain) observational data; 5) the development of scalable, fast, and robust linear and nonlinear solvers that circumvent the computational challenges posed by floating ice shelves and thin ice-sheet geometries; 6) the creation of performance-portable ISM implementations capable of utilizing next-generation HPC architectures, including hybrid systems containing GPUs; 7) the use of formal uncertainty quantification (UQ) methods and ISM ensembles; and 8) the development of models for key ice-sheet physical processes such as calving and subglacial hydrology.

Although the aforementioned efforts are significant advancements, today's ISMs are still faced with challenges resulting from the desire to apply these models

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[a]https://www.ipcc.ch/assessment-report/ar4

to continental-scale high-resolution problems to quantify uncertainties within the model outputs, and to improve the representation of subgrid-scale processes within the models (e.g., ice calving). This special issue of *Computing in Science & Engineering* features four articles related to the development and efficient implementation of numerical, computational, and data-driven methods for reliable, next-generation ISMs, toward addressing some of these challenges. These articles span a variety of topics, ranging from mechanics-based modeling of hydrofracture and ice calving, to novel, compatible finite-element discretizations, to data-driven methods that can enable UQ within the field of ice-sheet modeling.

IN THIS SPECIAL ISSUE

The first article, by Gao et al.,[A1] presents a new poro-damage cohesive zone model (CZM) for simulating ice hydrofracture: the nonlinear fracture process during the propagation of water-filled surface crevasses in floating ice tongues and ice shelves. The new CZM, implemented in the commercial software ABAQUS, is used to estimate crevasse penetration depth and to study sensitivity to several factors, including ice rheology, cohesive strength, density, and temperature. These studies demonstrate that temperature-dependent viscous deformation (creep) and depth-varying ice density promote crevasse propagation, and can influence ice calving; hence, it is important to incorporate these effects within ice flow models and ice calving laws.

The second article, by Brinkerhoff,[A2] describes the first application of two mixed-finite-element methods to the equations of glacier evolution under different simplifying assumptions. These compatible spatial discretizations are combined with a fully implicit time-integration scheme, which allows for larger time steps. After verifying the method's convergence on some canonical and manufactured test cases, the author demonstrates that his method exhibits several desired properties, including numerical stability and mass conservation, on a test case with a realistic topography corresponding to a mountain basin in western Montana.

The third article, by Shivaprakash Muruganandham et al.,[A3] develops and evaluates an approach for generating realistic and independent realizations of internal climate variability from a single climate simulation, that is, without incurring the prohibitive computational expense of running large climate model ensembles. The new technique uses empirical orthogonal function decomposition and Fourier-phase randomization to generate statistically consistent realizations of spatiotemporal variable fields for a requested climate variable. The method is used to generate realizations of basal melt variability for ice shelves in Antarctica.

The final article, by Schoedl et al.,[A4] presents a Python multiprocess implementation of sequential Gaussian simulation (SGS) for efficiently generating multiple nonunique realizations of geological phenomena for UQ analyses. The authors demonstrate that, whereas the traditional sequential SGS algorithm is prohibitively expensive at large scales and for large ensembles due to its inherently sequential nature, the multiprocessing version of this algorithm significantly reduces the time cost associated with generating simulations, achieving speedups as high as 8×. To maximize impact and reduce the barrier to spinning up SGS models for use with ice-sheet workflows, the authors have released their software, along with well-documented user tutorials, on GitHub and Zenodo.

APPENDIX: RELATED ARTICLES

A1. Y. Gao, G. Ghosh, S. Jiménez, and R. Duddu, "A finite-element-based cohesive zone model of water-filled surface crevasse propagation in floating ice tongues," *Comput. Sci. Eng.*, vol. 25, no. 3, pp. 8–16, May/Jun. 2023, doi: 10.1109/MCSE.2023.3315661.

A2. D. J. Brinkerhoff, "Compatible finite elements for glacier modeling," *Comput. Sci. Eng.*, vol. 25, no. 3, pp. 18–28, May/Jun. 2023, doi: 10.1109/MCSE.2023.3305864.

A3. S. Muruganandham, A. A. Robel, M. J. Hoffman, and S. F. Price, "Statistical generation of ocean forcing with spatiotemporal variability for ice sheet models," *Comput. Sci. Eng.*, vol. 25, no. 3, pp. 30–41, May/Jun. 2023, doi: 10.1109/MCSE.2023.3300908.

A4. N. W. Schoedl et al., "A Python multiprocessing approach for fast geostatistical simulations of subglacial topography," *Comput. Sci. Eng.*, vol. 25, no. 3, pp. 42–49, May/Jun. 2023, doi: 10.1109/MCSE.2023.3317773.

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