Toward a New Generation of Ice Sheet Models

PAGES 578–579

Large ice sheets, such as those presently covering Greenland and Antarctica, are important in driving changes of global climate and sea level. Yet numerical models developed to predict climate change and ice sheet–driven sea level fluctuations have substantial limitations: Poorly represented physical processes in the ice sheet component likely lead to an underestimation of sea level rise forced by a warming climate.

The resultant uncertainty in sea level projections, and the implications for climate policy, have been widely discussed since the publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [*IPCC*, 2007]. The assessment report notes that current models do not include "the full effects of changes in ice sheet flow, because a basis in published literature is lacking." The report also notes that the understanding of rapid dynamical changes in ice flow "is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise."

Credible predictions of ice sheet evolution and sea level change will require a new generation of ice sheet models (ISMs) coupled to atmosphere-ocean general circulation models (AOGCMs). Although the development of these new tools is ongoing, credibility (i.e., physically justifiable model assumptions) demands institutional support and the sustained efforts of researchers working on numerical algorithm development, software engineering, and the analysis of model output.

Perhaps more important, developing these tools will require collaboration with glaciologists, climate modelers, and end users to implement physically sound ice dynamics while working within the constraints of AOGCMs. A concerted effort to develop a new generation of ISMs should be pursued concurrently with observational efforts and glaciological process studies; yet progress is hampered by a lack of cross-disciplinary and cross-institutional coordination (and resources) focused on this goal.

Current Status

The comprehensive continental-scale ice sheet models used to predict global sea level change have not been substantially modified in the past decade. The models are based primarily on the assumption that gravitational driving stresses are balanced locally by basal traction, resulting in flow dominated by vertical shear (i.e., that the horizontal transmission of stress is unimportant) [e.g., *Huybrechts et al.*, 2004]. This assumption is appropriate where creep is the dominant ice flow process and where the effects of subglacial meltwater can be neglected. These ISMs have been partially coupled to AOGCMs (developed at leading centers in the United States and around the world), using surface fields such as air temperature and precipitation, to develop the projections of sea level change that have been used in the IPCC's Third and Fourth Assessments.

Why Scientists and Policy Makers Are Dissatisfied

In the past decade, our knowledge of ice sheet dynamics has improved dramatically, due to the application of satellite techniques such as radar altimetry and interferometry, together with airborne and surface observations (reviewed by *Shepherd and Wingham* [2007]). New, unexpected observations include the thinning and acceleration of Greenland outlet glaciers, rapid ice shelf melting and increased discharge in the grounded drainage basins of the Amundsen Sea embayment, West Antarctica, and the acceleration of many upstream glaciers following the collapse of the Larsen B ice shelf on the Antarctic Peninsula. In addition to the present-day evidence of rapid flow, paleoclimate records suggest that sea level rise during deglaciations may have occurred, at least episodically, at rates not attainable by current ice sheet models.

However, ice sheet simulations assessed by the IPCC cannot reproduce these observations because the simulations fail to fully account for ice shelves, subglacial processes, and changes in stress underlying these events. Additionally, observed changes in ice volume and discharge occur rapidly enough to modify ice sheet boundary conditions. The implicit assumption in current stand-alone ice sheet models—disparate atmospheric, oceanic, ice shelf, and ice sheet timescales—is invalid if this behavior is widespread. Without coupling these components in a climate model, we cannot assess the spatial and temporal extent of these potentially important feedbacks.

Underlying Problems

Continental-scale ice sheet models have the least skill where the influences of meltwater production and flow, ice shelf buttressing, and subglacial sediment deformation are prominent. These processes can interact to accelerate discharge near ice sheet margins. Current computer-based projections of ice sheet response to a warming climate are thus almost certainly biased against delivering fast responses, in turn underestimating the rate of sea level rise.

Key processes that should be incorporated into models to make reliable predictions of future ice sheet change include the following:

interaction of ice sheets with the ocean, requiring models of regional oceanic circulation, melting and freezing in subshelf cavities, a better representation of continental shelf processes, and coupling to the global ocean;

grounding line migration, requiring improved numerical algorithms (e.g., high-resolution with adaptive grids) and coupled models of inland and ice shelf flow;

production and flow of water at the surface and within and beneath the ice;

ice streaming, whose modeling requires higher-order flow physics, a basal processes submodel, and a nested mesh approach; and

iceberg calving, which is important in ice shelf collapse as well as outlet glacier dynamics and which requires the application of fracture mechanics.

Insights From AOGCMs

Incorporating physically accurate stand-alone ISMs into an AOGCM requires awareness of overall design constraints, including

conservation of heat and freshwater. AOGCM-ready ISMs will need to include a complete surface energy balance and hydrologic accounting (e.g., the disposition of basal and surface melt).

a time-dependent boundary. Incorporating this capability will necessitate a coincident change in ocean models, whose lateral boundaries need to be able to migrate as the ice sheet grows or shrinks in response to climate forcing.

acceptance of the large-scale nature of AOGCMs, which will not be able to provide or accept fluxes at the scale of individual ice streams or small ice shelves. The next generation of ISMs must resolve key small-scale flow features, either with statistical techniques (perhaps based on off-line high-resolution studies scaled up to the AOGCM grid scale), a uniform reduction of the grid spacing (≤5 kilometers), and/or by selective resolution using nested or unstructured grids.

Additionally, there are several lessons learned over the history of global coupled climate modeling, under way at many institutions since the 1960s, which should be applied to the model-coupling process.

Model building is a highly interactive process. A distributed mode of model building, where component development takes place at differing institutions, can work, but it increases the need for enhanced, sustained communication.

The development of new components should occur in close coordination with the rest of the model physics, since their interactions are crucial. The idea that a component can be developed in isolation, and then simply "plugged into" the model, is fraught with difficulties.

Clarity of purpose is essential. The specific goal for which a model is developed must always be clear, including the definition of what would constitute "success" of the model.

Model development usually takes longer than anticipated.

Recommendations

Ice sheet models currently used in conjunction with AOGCMs are process-poor, even when compared with our imperfect understanding of ice sheet dynamics. The computational demands of ice models are modest; a substantial increase in their complexity would not affect the ability of a coupled ISM-AOGCM to perform millennial-scale climate experiments. Success in constraining ice sheet response to climate forcing is thus limited (at least in part) by the validation of physically sound ice sheet models and their incorporation into AOGCMs. Model development should occur concurrently with ongoing and proposed observational programs, and with studies of physical processes controlling ice sheet dynamics, to improve the chances that models will be able to reproduce reality in a timely manner.

We therefore recommend increased support for ice sheet modeling at facilities developing comprehensive state-of-the-art AOGCMs. A key aspect of any such effort should include stronger links between government labs and researchers in the university community in order to maintain optimal allocation of tasks and resources. We encourage the development of different ice sheet dynamical cores and process parameterizations by various modeling groups. At the same time, we recommend the use of a shared modular software framework to avoid duplication of labor. Modularity will simplify the AOGCM-ISM coupling interface and allow meaningful intercomparisons, a large step forward toward the integration of ISMs into the modeling efforts in the climate community.

Acknowledgments

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NEWS

In Brief

PAGE 579

Protecting Louisiana's coasts With numerous wetlands restoration and protection projects slated for Louisiana, a well-developed implementation strategy that can address a number of uncertainties is important for the success of these projects, according to a 14 December report by the U.S. Government Accountability Office (GAO). GAO specifically urged maintaining the collaborative process that is used by Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) program agencies, with scientists, engineers, and others working together to plan and design restoration projects. The report also noted the need to address such other issues as having an integrated monitoring system to determine whether goals and objectives are met as well as to understand that projects can encounter significant setbacks due to storms and hurricanes, landscape and structural causes, and spiraling project costs. Louisiana state officials anticipate the state could receive about $8.5 billion over the next 10 years for coastal restoration and protection. Nearly 40% of all coastal wetlands in the lower 48 U.S. states are located in Louisiana. For more information, visit the Web site: http://www.gao.gov/new.items/d08130.pdf.

En route to comet Hartley 2 NASA has given the go-ahead for the Deep Impact spacecraft to fly to comet Hartley 2 after the original target, comet Boethin, could not be found despite extensive searching. The spacecraft, which successfully guided an impactor into comet Tempel 1 in July 2005, will fly by comet Hartley 2 on 11 October 2010 as part of a two-part extended mission known as EPOXI. During the first part of the mission—Extrasolar Planet Observation and Characterization—a large telescope on the spacecraft will observe and study several previously discovered extrasolar planetary systems. During the second part of the mission—the Deep Impact Extended Investigation—the spacecraft will fly to within 1000 kilometers of the 0.8-kilometer-wide comet and study it with two telescopes and an infrared spectrometer. "Hartley 2 is scientifically just as interesting as comet Boethin because both have relatively small, active nuclei," said Michael A'Hearn, principal investigator for EPOXI at the University of Maryland at College Park. Scientists speculate that comet Boethin may have broken up into pieces too small for detection. For more information, visit the Web sites: http://www.nasa.gov/deepimpact and http://www.nasa.gov/epoxi.

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