Report of the
Workshop on Ice Sheet Modeling

at the NOAA Geophysical Fluid Dynamics Laboratory

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PREFACE

The fact that recent changes observed in the ice sheets of Greenland and Antarctica were neither anticipated nor predicted underscores a strongly-held opinion among many glaciologists that a new generation of ice sheet models is long overdue. The shortcomings of current predictive models, the resulting limitations they impose on our ability to project sea level change during this century and beyond, and the implications for policy, have been widely discussed with publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The Summary for Policy Makers of this report recognized the shortcomings of its sea level rise projections in noting that current models do not "include the full effects of changes in ice sheet flow, because a basis in published literature is lacking… 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".

Accordingly, a one-day workshop on ice sheet modeling was held at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) on 8 January 2007. Sponsorship was provided by NOAA and by the Program in Science, Technology, and Environmental Policy of the Woodrow Wilson School of Public and International Affairs at Princeton University. The workshop focused on identifying key scientific issues and organizational requirements for a research effort appropriate to producing a new generation of models. Specific objectives included providing GFDL and other U.S. and international modeling centers with further insight into the role they could play in the ice-sheet modeling arena, and initiating a collaborative network that could engage several groups developing largely independent models over time.

Other community meetings, driven by the same concerns, have been held recently. What distinguished this workshop was the explicit intent to develop interactions among glaciologists, oceanographers, and some of those involved in the successful, multi-decade effort to develop atmosphere-ocean general circulation models (AOGCMs). It is hoped that experience with the latter can inform development of comprehensive, prognostic ice-sheet representations, eventually coupled in full Earth System Models.

This brief report, which summarizes the findings of the workshop, is provided in hopes that it will provide insights useful to NOAA, NASA, NSF, the White House Office of Science and Technology Policy, the US Congress, and other US and non-US agencies. A list of participants is included as an appendix.

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TOWARD A NEW GENERATION OF ICE SHEET MODELS (ISMs)

The basic design of comprehensive continental scale ice-sheet models has changed little in the last 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). This type of model is adequate for the large portion of an ice sheet where slow flows dominate, and is the basis of the results used in the IPCC's third and fourth assessments. The models have been coupled to Earth System Models (ESMs) using surface fields such as topographic altitude, air temperature and precipitation (i.e., coupling to the atmosphere). There has been no coupling to the ocean.

The last decade has seen a revolution in the quantity and quality of observations of the ice sheets due to the application of satellite techniques such as radar altimetry and interferometry, together with air-borne and surface observations. Unexpected observations include the collapse of the Larsen B ice shelf in Antarctica and the consequent acceleration of adjoining glaciers; rapid thinning and other changes in many of the outlet glaciers of the Greenland ice sheet; and the thinning of the ice shelves and streams of the Amundsen Sea embayment, West Antarctica. Each of these phenomena contributes significantly to the rate of global sea level rise. Ice sheet models currently used in IPCC simulations do not reproduce the key features of these observations.

Shortcomings of existing whole-ice-sheet models

In general, ice sheets are process-rich, whereas current large-scale numerical ice sheet models are process-poor. Although deficient in this respect, the models have produced some credible results. They can adequately simulate the onset of the last ice age and the associated growth of Northern Hemisphere ice sheets. The models have greatest skill where ice creep is the dominant flow process and the effects of subglacial meltwater can be neglected - as was probably the case for the first 50,000 years of the most recent glaciation. The models have least skill where the effects of subglacial meltwater, impingement of warm ocean waters at the ice sheet margins, and fast flow processes are prominent. For these reasons, computer-based projections of ice sheet response to a warming climate are almost certainly biased against delivering fast responses and thus underestimate the likely rate of sea-level rise. To substantially improve predictions of ice sheet behavior, the models must be improved. Compared to coupled ocean atmosphere climate models, the computational demands of ice dynamics models are modest. Thus a substantial increase in model completeness and complexity would not greatly affect the performance of coupled ocean atmosphere ice sheet models.

Workshop participants agreed that the source of greatest uncertainty in sea level predictions is the interaction between the Southern Ocean and Antarctic ice shelves and the response of grounded ice to changes in these shelves. Remarkable rates of bottom melting, as high as 40 m/yr, have been attributed to warm circumpolar deep waters intruding onto the continental shelf under some small ice shelves around Antarctica. The extent to which such warm waters are related to the larger global trend is unknown, although there are plausible mechanisms that could connect these processes. Lack of observational information and poor representation of oceanic heat transport on the continental shelf by AOGCMs are important limitations to modeling the ice response. Nevertheless, current large-scale ice sheet models have inadequate physics to capture the response of the Antarctic Ice Sheet to large changes in its floating margins.

A second critical shortcoming of existing large-scale models is that they do not adequately resolve ice streams. These river-like arteries of fast-flowing ice connect the interior regions of ice sheets to the ice sheet periphery. In current models these high-flux features are either sub-grid or poorly resolved. The next generation of models must resolve ice streams, either by a uniform reduction of the grid spacing to around 5 km or by selective resolution using nested or unstructured grids. A closely related problem is that different processes govern the flow of the sheet, stream, and shelf components of large ice sheets and these domains are separated by complex boundaries at ice stream margins and at the grounding line between streams and shelves. The numerical representation of these margins must be mobile and governed by correct physics. Recent studies indicate that higher-order or full-stress treatments will be required to model this behavior properly.

Another pressing matter is to include fully-coupled surface and subglacial hydrology. The pressure and the areal extent of subglacial water have a dominant influence on the fast flow processes that control ice streaming. Future models must treat surface and subglacial water as distinct components and avoid convenient but unjustified parameterizations. This is especially important for assessing Greenland "melt-down" scenarios. Recent results using hydrologically-coupled models to predict the future of Iceland's ice caps suggest that the models with the most realistic treatments of hydrology respond fastest to climate warming.

Accordingly, the range of processes that should be incorporated into models if they are to be used to make reliable predictions of future ice sheet change includes:

- ice streams, whose modelling requires higher-order flow physics, a basal processes sub-model and a nested mesh approach,

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

- interaction of ice sheets with the ocean, which requires models of regional oceanic circulation, melting and freezing in sub-shelf cavities, a better representation of continental shelf processes, and coupling to the global ocean, and

- flow of water at the surface, within, and beneath the ice.

Insights from AOGCMs

Global coupled climate modeling has been underway at GFDL, NASA/GISS and NCAR since the 1960s. In all three laboratories, major transformations took place in the late 1990s/early 2000s, which resulted in the groups moving away from multiple models developed and used by small groups towards common modeling tools and infrastructure. Based on these experiences, several important lessons emerge when looking forward to coupling land-ice models into more complete Earth System Models, a goal that is of high interest to scientific staff at the three institutes.

- Model building is a highly interactive process. Communication among component developers, overall model builders, and model users is essential to success. A distributed mode of model building - where component development takes place at differing institutions - can work, but increases the need for enhanced, sustained communication.

- The coupled system itself is highly interactive. 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.

- Model development usually takes longer than anticipated.

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

Specifically, incorporating existing stand-alone ISMs into a GCM requires awareness of the overall design constraints of GCMs. ISMs must conserve heat (latent and sensible) and freshwater (including snow, runoff, evaporation, etc.). This implies that GCM-ready ISMs will need to include a surface energy balance (not a degree-day scheme) and some accounting for the hydrology (e.g., the disposition of surface melt).

Secondly, ISMs must make assumptions about the ice interface that are consistent with those in AOGCMs, or at least are sufficiently explicit to avoid inconsistencies that could arise in coupling models. To achieve the desired objective of predicting sea-level change in a fully-coupled climate model, a major modification of the atmospheric and oceanic components of the existing codes will be required to permit simulation of a time-dependent boundary, i.e. as the ice sheet changes its size. This is particularly relevant for the ocean models whose lateral boundaries need to be able to migrate freely as they either invade the ice sheet or vice-versa. The current generation of ocean GCMs does not possesses this capability.

Thirdly, acceptance of the large-scale nature of GCMs is a prerequisite for coupling. GCMs generally will not be able to provide fluxes or take information at the scale at which interesting things happen on the ice (i.e. at the scale of individual ice streams or small ice shelves). These effects will most likely have to be treated statistically (or with nested models) - possibly based on very high resolution studies and scaled up to the GCM-grid box scale.

These concerns underscore the need for an hierarchy of ISMs ranging from high resolution models that incorporate detailed individual topographic features (~5km resolution), to models that, while still including necessary physics, will treat issues like ice streams in a statistical or parameterized manner.

Existing collaborations

The GLIMMER community ISM, developed at the University of Bristol, UK, has been proposed as a starting point for US-based International Polar Year (IPY) efforts to develop a better validated, more accessible, transparent, and long-lived ice sheet modeling platform. Such a platform will be essential for future assessments of sea level change, student training, hypothesis testing, ESM coupling, and data assimilation. Its developers believe that GLIMMER is very close to being what is needed as a starting point, and their strategy will be to address shortcomings in GLIMMER that prevent it from being used more widely.

Three complementary efforts are to be advanced.

- Software engineers, working in collaboration with scientists, will develop improvements to GLIMMER that extend from the underlying source code to the end user interface. These improvements will focus on ability to maintain, extend, document, and use GLIMMER.

- Engineering efforts must be driven with the requirements of end users in mind. Accordingly, the GLIMMER proposal is to build a user base of glaciology researchers. The researchers would coordinate with other NSF IPY initiatives to conduct numerical experiments and data assimilation on the Amundsen Sea Embayment of West Antarctica. The researchers would relay their modeling experience back to the software engineering team to assure that code developments taking place are indeed advancing the platform.

- A third effort would adapt the user interface for GLIMMER to the needs of a broader community of users.

Such approaches provide a framework for the coupling interface (AOGCM to ISM) of future ISMs, a large step forward towards the integration of ISMs into the modeling efforts in the climate community.

RECOMMENDATIONS: A COMPREHENSIVE APPROACH

In order to enable credible predictions of ice sheet evolution and sea level change, improved ice sheet models need to be incorporated in coupled climate models. This will require sustained efforts in numerical algorithm development, software engineering, and analysis of model output. Current progress is hampered by a lack of resources focused on this goal. We therefore recommend increased support for ice sheet modeling at the government labs developing IPCC-class GCMs (e.g., the Community Climate System Model, the GFDL model, and the GISS model in the U.S. and the Hadley Centre model in the U.K.). For each GCM we suggest ongoing support for three ice sheet modelers. At least one scientist per GCM should be assigned to ice sheet model development as soon as possible, with others hired as funds become available.

To maintain diversity, we encourage the development of different ice sheet dynamical cores and process parameterizations by the various modeling groups. At the same time, we recommend the use of a shared modular software framework to avoid duplication of labor. This framework would define data structures and would include utilities for generic functions such as input-output and boundary communications. The GLIMMER ice sheet model could serve as the starting point for a unified modeling framework. A key aspect of such a collaborative effort would be stronger links between government labs and researchers in the university community in order to maintain optimal allocation of tasks and resources. Furthermore, expansion of a collateral observational program in coordination with model development is crucial in order to improve the chances that models can actually reproduce reality.

APPENDIX

Workshop Participants

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