Building a Next-Generation Community Ice Sheet Model

Report on a workshop held at Los Alamos National Laboratory, 18-20 August 2008

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Executive Summary

A workshop entitled "Building a next-generation community ice sheet model" was held at Los Alamos National Laboratory on 18-20 August 2008. The workshop goal was to create a detailed plan (including commitments from individual researchers) for developing, testing, and applying a Community Ice Sheet Model (CISM). This model will be used to predict 21st century sea-level rise resulting from the retreat of the Greenland and Antarctic ice sheets. CISM will be freely available to the glaciology and climate modeling communities and will serve as the ice-sheet component of the Community Climate System Model (CCSM), a major contributor to the IPCC assessment reports. Because of the short time scale for including ice-sheet forecasts in the next IPCC assessment, participants prioritized model improvements according to their importance for sea-level prediction. The following improvements were deemed critical:

- A higher-order flow model, with a unified treatment of vertical shear stresses and horizontal-plane (lateral shear and longitudinal normal) stresses
- Improved models of basal sliding over hard and soft beds, including explicit treatment of surface, englacial, and subglacial hydrology
- A well-validated parameterization of melting and refreezing beneath ice shelves
- An accurate, semi-empirical law for iceberg calving
- An accurate, numerically robust treatment of grounding-line migration on a fixed grid

In addition, CISM should satisfy the following software requirements:

- The model should be modular, portable, and user-friendly, with transparent source code. This will be achieved by using internal code documentation, extending the existing Interactive System for Ice sheet Simulation (ISIS) framework, and upholding coding and format standards (e.g., NetCDF).
- The model must scale efficiently to hundreds or thousands of processors. This will be done using parallel libraries from other earth system models (e.g., POP and CICE) and/or existing solver packages (e.g., PETSc).
- The ice sheet model will need to be coupled to other earth system components. Since warm-water intrusions beneath ice shelves could drive rapid ice-sheet retreat, new methods are needed for coupling ocean GCMs to ice-sheet and ice-shelf models.

Software development is proceeding from the GLIMMER ice sheet model, which has already been coupled to CCSM. Source code will be developed simultaneously with tools and datasets for model initialization, forcing, verification, and validation.

CISM development requires ongoing project management, and six focus groups have formed for this purpose. These groups are working on hydrology, calving, ice-ocean coupling, software development, datasets, and sea-level assessment. In the near term the assessment group will use the best available current models to provide quantitative upper bounds for sea-level rise; these assessments will inform longer-term model development. Also, a new Land Ice Working Group is proposed to manage CISM development in the CCSM context. CISM source code and tools will be posted on a public web site, and a Trac site and Subversion repository are available for code developers; see http://oceans11.lanl.gov/trac/CISM.

1. Introduction

A workshop entitled "Building a next-generation community ice sheet model" was held at Los Alamos National Laboratory on 18-20 August 2008. The workshop was sponsored by the LANL Institute for Geophysics and Planetary Physics (IGPP), with additional support from the National Science Foundation and the Department of Energy. The workshop goal was to create a detailed plan for developing, testing, and applying a Community Ice Sheet Model (CISM) to aid in predicting 21st century sea-level rise resulting from the retreat of large ice sheets. This model will be freely available to the glaciology and climate modeling communities. In particular, CISM will serve as the ice-sheet component of the Community Climate System Model (CCSM), which has been developed over many years with support from NSF and DOE. CCSM is one of the world's premier global climate models and has been a major contributor to the assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

The importance of ice sheets was underscored in the IPCC's Fourth Assessment Report (AR4). The IPCC provided neither a best estimate nor an upper bound for 21st century sea-level rise because of uncertainties about the dynamical response of ice sheets (IPCC 2007). Recent observations show that ice sheets can respond to climate change on annual to decadal time scales and that the Greenland and West Antarctic ice sheets are losing mass at an increasing rate. This mass loss is dominated by acceleration and thinning of large outlet glaciers and ice streams. Also, the volume and extent of surface melting in Greenland have increased during recent years. These changes suggest that the AR4 sea-level projections, which exclude large dynamic changes in ice sheets, underestimate the risk of rapid sea-level rise (Rahmstorf et al. 2007). Fast retreat of the Greenland or West Antarctic ice sheet could result in sea-level rise of 1 meter or more during this century.

The current generation of ice sheet models cannot provide credible predictions of ice-sheet retreat, because these models do not represent key physical processes that are only beginning to be understood. In particular, models that use the "shallow-ice approximation" (SIA) do not capture processes in fast-flowing regions that control the flux of grounded ice to the ocean, a flux that can change rapidly. The GLIMMER ice sheet model (http://forge.nesc.ac.uk/projects/glimmer/), which was recently added to CCSM, uses the SIA. GLIMMER is appropriate for studying long-term changes in ice sheets but cannot simulate rapid dynamic changes. The CCSM ice-sheet component must be substantially improved in order to provide useful sea-level forecasts.

There is general agreement on the required elements of a next-generation model: for example, higher-order ice dynamics, improved subglacial hydrology and basal physics, high-resolution grids, coupling to global climate models, and realistic treatments of sub-shelf melting, iceberg calving, and grounding-line migration (Little et al. 2007). Support in the U.S. for ice sheet modeling is growing, with new efforts funded recently by NASA, NSF, and DOE. However, the ice sheet modeling community remains small compared to the groups developing atmosphere and ocean models. The LANL workshop was motivated by the belief that members of this community must share ideas and coordinate efforts in order to deliver a physically realistic, user-friendly, credible CISM in a timely fashion.

The workshop was held in the LANL Study Center over two and a half days. There were 35 registered participants from U.S., U.K, and Canadian institutions. (See the agenda and participant list in Appendices 1 and 2.) The first two days were divided into a series of plenary talks followed by afternoon breakout sessions. The final morning consisted of reports from the breakout sessions, followed by open discussion during which a work plan was developed. The discussion was organized around four focus areas: (1) ice-sheet dynamics and physics, (2) ice-shelf/ocean interactions, (3) software design and coupling, and (4) initialization, verification, and validation. Breakout sessions on these topics were moderated by Stephen Price, David Holland, Jesse Johnson, and Ed Bueler, respectively.

The primary near-term goal of CISM is to forecast sea-level rise on decadal to century time scales. In particular, we aim to contribute meaningfully to sea-level projections in the next IPCC assessment report, AR5, which is scheduled for release in 2013. Peer-reviewed publications must be accepted by the end of 2011 to be included in AR5. Our recommendations therefore focus on what can be accomplished within the next one to three years. CISM will continue to be developed after AR5 for future assessments.

2. Physical processes in CISM

Given the overarching goal of sea-level prediction, we aimed to reach a consensus on the physical processes that need to be represented in CISM in the near term, as opposed to those that should be deferred until later. Participants discussed a large number of components and processes that would be included in an ideal ice sheet model. These were prioritized according to their relevance to the near-term goal, the feasibility of implementation, and the availability of data needed to construct or constrain a sub-model or parameterization. A full list of processes is given in Appendix 3.

Ice-sheet dynamics and physics

It was agreed that ice flow dynamics in CISM must go beyond the SIA. At the same time, CISM should run efficiently at high resolution (~5 km) at the scale of an entire ice sheet (Antarctica or Greenland). Several flow models are available. In order of increasing complexity and computational expense, these include (1) shallow-ice models, which incorporate only vertical shear stresses; (2) shallow-shelf models, which include only vertically integrated horizontal stresses; (3) hybrid shallow-ice/shallow-shelf models, including those which treat the shallow-shelf approximation as a sliding law for shallow ice (Bueler and Brown, submitted); (4) higher-order approximations, which include all stresses in a unified way but which omit terms that are believed to be small for real ice sheets, and (4) full-Stokes models, which solve the full stress equations. The near-term CISM effort will focus on implementing a higher-order model (also called a first-order model) based on Blatter (1995) and Pattyn (2003). This reduced set of equations accounts for all leading-order terms in the stress equilibrium equations, including lateral and longitudinal stresses, and is a reasonable compromise between SIA and full-Stokes models.

Most of the flux of grounded ice to the ocean is delivered by fast-flowing ice streams and outlet glaciers, where the flow is dominated by basal sliding. The sliding rate is

controlled by processes involving liquid water at the base of the ice or in soft underlying sediments. Several model developments are of primary importance for improving the representation of basal sliding: (1) improved treatments of sliding over "hard" beds, (2) models of surface, englacial, and subglacial hydrology, (3) models or parameterizations describing the links between hydrology and sliding, and (4) spatial maps of the distribution of geothermal flux. It was agreed that uncertainties introduced by poorly constrained parameters in hydrological models are likely to be less detrimental to model behavior than the current "static" treatment of the basal boundary condition.

Other model components and processes, deemed less important in the near term, include (but are not limited to) constitutive relations other than Glen's flow law; the evolution of ice crystal size and orientation; polythermal ice; sediment transport; and the migration of shear margins and properties of shear margin ice.

Ice-shelf/ocean interactions

Ice shelves, the floating extensions at the periphery of ice sheets, are vulnerable to climate change but are not well represented in current models. Ice shelves (and smaller floating ice tongues) are important for sea level because they buttress the flow of inland ice to the ocean. Fluxes of grounded ice have been observed to increase following ice-shelf disintegration. Ice shelves can be eroded not only by atmospheric warming at the surface, as elsewhere on an ice sheet, but also by intrusions of warm ocean water. During the last decade, rapid changes have been observed at the surface (e.g., Larsen B in Antarctica) and at the base (e.g., Pine Island Glacier in Antarctica and Jakobshavn Isbræ in Greenland) of ice shelves and ice tongues.

Rapid sub-shelf melting could trigger major changes in ice shelf structure and stability. Warm water is observed in front of and beneath some ice shelves that are thinning rapidly (e.g., in the Amundsen Sea), and cold water is seen beneath others that are thinning slowly, if at all (e.g., the Ross Ice Shelf). An accurate representation of basal thermodynamics is critical. The most widely used parameterization of sub-shelf melting and refreezing is the viscous-sublayer model (Holland and Jenkins 1999), originally developed in the context of sea-ice basal thermodynamics. This model will be incorporated in CISM. Field observational studies are under way in certain locations, such as Pine Island Glacier, to validate and improve the viscous-sublayer model, and findings from these studies will be incorporated in CISM in due course.

The location of the ice front is critical to the overall force balance in ice shelves and thus to the flux of grounded ice to the ocean. Physical processes at the ice front, such as iceberg calving, are sparsely observed and poorly understood. For ice shelves the calving rate is thought to be related to the ice thickness, the length and width of the shelf, and the amount of damage that has occurred en route to the front. CISM will initially have a simple calving parameterization based on ice thickness or current ice-front location. A next step is a more realistic calving law based on strain rates (which correlate with weakening by crevassing) as well as ice geometry. A more detailed physical model might include damage evolution and crevasse formation and transport. Such a model is

likely to be impractical in the short term, however, given the computational complexity and the sparseness of validation data.

The flux of mass across the grounding line (the location at which grounded ice thins sufficiently to float, or basal topography drops away from the ice) contributes directly to sea-level rise. Because the ice flux at the grounding line is sensitive to the ice thickness, and because thickness changes at the grounding line cause it to move, an accurate treatment of the grounding line is essential for sea-level prediction. This is a sensitive numerical issue because the sudden change in basal friction between grounded and floating ice requires adequate grid resolution to capture the transition zone. A variety of potential schemes will be tested in CISM, with the goal of finding an accurate parameterization for fixed grids at computationally practical resolutions.

In summary, the following model improvements related to ice shelves are high priorities for CISM: (1) better treatment of ice shelf buttressing (generally agreed as coming along "for free" with higher-order dynamics), (2) better constraints on sub-shelf melting and freezing rates, (3) a calving law consistent with observed ice-front locations, and (4) numerical methods giving reasonable grounding-line behavior on fixed grids.

3. Software design and coupling

Several CISM requirements make software design an important part of development efforts:

- The ice sheet model will be coupled to other earth-system components such as land, atmosphere, and ocean models.
- The model must scale efficiently to hundreds or thousands of processors.
- The model should be modular, portable, and user-friendly, with transparent source code.
- Model development will begin from the GLIMMER model.
- The model must provide improved estimates of ice sheet retreat and sea-level rise for IPCC AR5.

The immediacy of the last requirement alters the approach to the other requirements, each of which is described in the following paragraphs. In particular, the fourth requirement is motivated by the desire for a rapid near-term development path, given that GLIMMER has already been coupled to CCSM and is familiar to CISM developers.

Coupling

We aim to provide the minimal plausible coupling for forecasting decadal- to century-scale sea-level rise. Realistic coupling and forcing may be achievable without using the most finely resolved or physically complete models. For example, one might choose to model only the basins that will likely contribute the majority of sea-level rise during the next several centuries. At the basin scale it is practical to use sophisticated, high-resolution, regional ocean models (e.g., MICOM and ROMS) and atmosphere models (e.g., WRF). Basin-scale models have problems, however, related to the migration of drainage divides and boundary fluxes. These problems can be avoided by coupling whole-ice-sheet models to global atmosphere and ocean models. It is computationally

feasible to simulate the entire Antarctic and Greenland ice sheets for several centuries on relatively fine grids (~5 km). On the other hand, the forcing would be provided by coarser global models that may be unable to resolve important processes (e.g., the transport of warm ocean water to the underside of an ice shelf, or the surface energy balance of a particular ice stream catchment). We take the view that the basin-scale and global approaches are complementary. CISM will be supported as a standalone model (for both basin-scale and whole-ice-sheet applications) and also as a coupled climate component.

Coupling to the atmosphere via the surface mass balance is fairly straightforward. The surface mass balance of ice sheets is generally computed either with a semi-empirical positive-degree-day (PDD) scheme or with a more physically based surface-energy-balance (SEB) scheme. SEB schemes are preferred for climate simulations because PDD parameters could change in a warming climate. For ice-sheet simulations in CCSM, the surface mass balance will be computed using an SEB scheme in the relatively coarse-resolution (~100 km) land model for each of ~10 elevation classes, and then downscaled to the ice-sheet grid. This choice was made for reasons of computational savings, energetic consistency, and avoidance of code duplication. As a result, CISM will not need its own mass-balance scheme when run coupled to CCSM. For standalone applications the surface mass balance will be prescribed (e.g., from GCM output) or computed with GLIMMER's existing PDD scheme. The PDD scheme will be useful for model comparisons and sensitivity studies where simple, standardized forcing is desired.

Coupling of an ice sheet model to an ocean model is more difficult. Ocean fields received from CCSM (e.g., temperature and salinity) are on a relatively coarse grid (~100 km) and are not readily downscaled. Also, existing ocean GCMs are unable to adapt to changing ice-sheet and ice-shelf topography. One approach under investigation is to couple a high-resolution ocean model, HYPOP, to CISM at regional scales. HYPOP has a hybrid vertical coordinate suitable for modeling the circulation beneath ice shelves and for adjusting to changing topography. HYPOP could eventually be nested within a global GCM. The coupling of HYPOP to CISM is a multiyear effort being pursued as part of the DOE IMPACTS project. In the short term, we will focus on coupling a 2D (*xz*-plane) version of HYPOP to a flow-line version of CISM. The 2D model will be used for sensitivity studies and preliminary regional estimates of ice-sheet retreat. In the longer term, CISM will benefit from ongoing efforts to improve the resolution and nesting capabilities of CCSM. For standalone applications, sub-shelf melting rates can simply be prescribed, but more realistic forcing can be obtained using a simple 2D (*xy*-plane) model of the sub-shelf ocean mixed layer.

Scaling

The computational demands of higher-order ice-flow models are much greater than those of shallow-ice models. CISM will need to scale efficiently to large numbers of processors in order to carry out multi-millennial simulations at high resolution for whole ice sheets. Most of the computational time in higher-order solvers is devoted to inversion of a large sparse matrix arising from a semi-elliptical partial differential equation. Efficient scaling could be achieved using a software library such as PARDISO

(http://www.pardiso-project.org/) or PETSc (http://www-unix.mcs.anl.gov/petsc/) for matrix inversion, while leaving the rest of GLIMMER as a serial code. An alternative strategy is to use parallel libraries from other earth system models—for example, POP and CICE (http://climate.lanl.gov/Models/), the ocean and sea ice components of CCSM. These libraries could handle advection, boundary communication, and perhaps the higher-order stress equations. (The conjugate gradient solver in POP could be applied if the higher-order equations were written in symmetric form.) This approach requires a more significant reworking of GLIMMER but would result in a dynamical core that is parallel throughout. The supporting infrastructure could then be used in new physical models and numerical schemes. We believe the second approach will be more fruitful in the long run, and we plan to adapt code from POP and CICE. We are also testing matrix solvers that later could be used in combination with the POP/CICE infrastructure.

Documentation and usability

Three strategies will be employed to assure documentation and usability of CISM. First, we will use documentation in the code itself, along with automated tools such as ProTeX (http://gmao.gsfc.nasa.gov/software/protex/). Second, we will continue development of the Interactive System for Ice sheet Simulation (ISIS; http://www.cs.umt.edu/ISIS/), which contains pre-compiled binaries, ready-to-run scenarios, and a graphical user interface for CISM. ISIS is designed to encourage people with an interest in ice sheet modeling to try the model and quickly obtain interesting results. Finally, relevant coding and format standards will be upheld: for example, CCSM coding standards (e.g., http://www.ccsm.ucar.edu/working_groups/Software/dev_guide/dev_guide/node7.html), netCDF data formats, and CF 1.3 naming conventions.

Development path

Starting from GLIMMER, we will develop a next-generation model that meets CISM requirements. We envision the following sequence of steps:

1. Refine the signatures of core GLIMMER subroutines that compute velocity, thickness evolution, and temperature evolution. Reduce the use of global derived types in favor of a more descriptive, albeit longer, set of arguments for input and output.
2. Import the dynamical core consisting of these rewritten subroutines into an infrastructure based on POP and CICE. This will be called CISM 1.0, and it will duplicate existing GLIMMER functionality.
3. Extend the dynamical core of CISM to include higher-order stresses. Incorporate the schemes developed independently by Payne and Price and by Pattyn and Johnson.
4. Alter the dynamical core to use an incremental-remapping transport scheme. This scheme allows simultaneous transport of mass and temperature, preserving second-order spatial accuracy except where the accuracy is reduced to preserve monotonicity.
5. Add other physics improvements described above (e.g., basal hydrology and iceberg calving) as they become available.
6. Develop other useful data products for initialization, forcing, verification, and validation, as described in the next section.

4. Tools and standards for initialization, forcing, verification, and validation

The CISM effort will make ice sheet modeling available to a larger community of researchers than ever before. This effort provides a unique opportunity to build usability, standardization, and evaluation tools into an ice sheet model from the beginning. The CISM website will include links not only to downloadable source code, but also to tools and examples. The website will be developed in parallel with the source code, with tools posted in advance of the source code when possible and appropriate.

Data prepared for input to CISM should be in a documented and machine-independent format which CISM can read and for which diagnostic tools are available. The format must be self-documenting (that is, it must carry its own metadata) and must be rapidly readable and writable by parallel supercomputers. NetCDF4 is a proven format that satisfies these requirements (http://www.unidata.ucar.edu/software/netcdf/). NetCDF is already used in many climate models, including GLIMMER and the Parallel Ice Sheet Model (PISM). The CISM website will include standards documents related to netCDF along with scripts that convert data in nonstandard forms to netCDF. The CISM community can be a unified voice promoting usable formats for cryosphere data.

NetCDF files have some structure, but the netCDF standard alone cannot make climate tools work smoothly together. The netCDF Climate and Forecast Metadata Convention ("CF" convention; http://cf-pcmdi.llnl.gov/) adds a set of rules about what metadata appears in netCDF files. These rules, which are created with community input, include standard names for climate modeling quantities and standard descriptions of projections, among other metadata. CISM development will include an effort to add to the CF convention those new metadata choices, especially standard variable names, which are relevant to ice sheet modeling but are not already included.

Ice sheets, unlike other climate model components, have a long memory of paleoclimate. Their behavior for centuries into the future depends significantly on the initial state (i.e., on how the model is "spun up"), not just the climate forcing experienced in coupled runs. Unfortunately, existing ice sheet observations are not sufficient to describe unique initial conditions (e.g, 3D temperature fields) for the equations of ice flow. For this reason, the CISM website should include standardized model output from paleoglacial runs ending at the current time. These initial states will be versioned and documented with reference to the physical model (e.g., SIA or higher-order dynamics) and numerical parameters (e.g., grid spacing and time steps) used in the spin-up runs.

Another useful tool for CISM is a "Lightweight Paleoclimate Driver" that mimics CCSM. Spin-up of an ice sheet model requires forcing with a greatly simplified climate model. Typically the climate history is based on ice core records and is modeled by simple formulas that represent the spatial variation in forcing fields (e.g, Huybrechts and de Wolde, 1999). CISM will be easiest to use and maintain if it has a common interface to climate models, so that it receives the same inputs from a simplified paleoclimate model as from CCSM.

Comparison of model results to known exact solutions and observational data, where available, is essential for establishing trust in the model. There are several ways to evaluate quality:

- Code verification, the comparison of CISM numerical output to exact or other highly trustworthy solutions of the equations approximated by the model.
- Code and data validation, where CISM is run with real-world data (climate and geometry, for example) in physically well-understood circumstances and its outputs are compared to observations set aside for this purpose.
- Uncertainty quantification, where the spread in CISM projections of future change can be understood in terms of under-constrained choices in model development and specification of boundary conditions.

Verification with exact solutions is easy when it is possible. A straightforward step is to build into CISM the suite of exact solutions already included in the PISM source code distribution (https://gna.org/projects/pism/). Automatic tools can generate a verification report for each CISM release. Time-dependent validation is more difficult for ice sheet modeling than for ocean and atmosphere modeling because the time scale for major ice sheet dynamical changes greatly exceeds the span of scientific observations. For this reason the CISM community could work with material scientists to identify laboratory-scale physical analogs that can inform validation efforts. The solid-earth community uses polymer models in this way, for instance.

Uncertainty quantification of CISM forecasts involves identifying an ensemble of alternate CISM configurations, boundary conditions, and forcing that represent the combined uncertainties in these factors. For coupled climate models participating in the IPCC evaluation process, this kind of information is suggested by ensembles obtained from several models developed independently. The CISM effort could provide these estimates in a more formal way within a single modeling framework. In a single framework it is easier to identify the processes, parameters, or data that are most critical for reducing uncertainties. Model intercomparison with other groups (as in the EISMINT and ISMIP exercises, for example) will continue to be beneficial as a check on our ability to capture and represent uncertainties.

5. Project management

CISM requires ongoing management to ensure that model development takes place in a cooperative and timely fashion. To this end, workshop participants created six focus groups or "clusters" to work on particular tasks. (Group leaders are shown in parentheses.)

- Hydrology (S. Price)
- Calving (C. Hulbe)
- Ice-ocean coupling (D. Holland)
- Software development (W. Lipscomb)
- Datasets (J. Johnson)
- Assessment (R. Bindschadler)

These groups, which are open to the entire ice sheet modeling community, have begun holding teleconference calls to establish goals and timelines. The assessment group is developing a suite of experiments to establish upper and lower bounds on the ice-sheet contribution to sea-level rise. Many models of varying degrees of complexity (not just CISM) will perform these experiments and compare results.

In addition, CISM should be included in the CCSM organizational structure. We recommend the formation of a Land Ice Working Group alongside the other working groups that manage the development and analysis of CCSM components. Like other working groups, this group would meet twice a year: during the winter and during the annual CCSM meeting in June. Meetings could be held jointly with other working groups that have overlapping interests: for example, the Climate Change, Polar Climate, Paleoclimate, and Land Model groups. CISM developers also could meet informally at the Fall AGU meeting and the annual West Antarctic Ice Sheet (WAIS) workshop. Another management structure that may emerge is an ice sheet modeling center, which would coordinate activities between national labs and academic institutions. Finally, CISM development could benefit from future small, targeted workshops on topics of special interest, with support from the LANL IGPP.

CISM will have a public website that includes downloadable source code along with the tools and data products described in the previous section. An umbrella web site could reside at the University of Montana, as a logical outgrowth of existing ISIS facilities. A Trac site for CISM developers is already available at http://oceans11.lanl.gov/trac/CISM. This site is linked to the new CISM subversion repository at http://oceans11.lanl.gov/svn/CISM.

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Acronyms

AGU	American Geophysical Union
CCSM	Community Climate System Model
CF	Climate and Forecast metadata convention
CICE	Community Ice CodE
CISM	Community Ice Sheet Model
COSIM	Climate, Ocean and Sea Ice Modeling group
DOE	Department of Energy

EISMINT	European Ice Sheet Modeling Initiative
GCM	General circulation model
GENIE	Grid ENabled Integrated Earth system model
GLIMMER	GENIE Land-Ice Model with Multiply Enable Regions
HYPOP	HYbrid coordinate Parallel Ocean Program
IGPP	Institute for Geophysics and Planetary Physics
IMPACTS	Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS
IPCC	Intergovernmental Panel on Climate Change
ISIS	Interactive System for Ice sheet Simulation
ISMIP	Ice Sheet Model Intercomparison Project
LANL	Los Alamos National Laboratory
MICOM	Miami Isopycnic Coordinate Ocean Model
NASA	National Aeronautics and Space Administration
netCDF	network Common Data Form
NSF	National Science Foundation
PETSc	Portable Extensible Toolkit for Scientific application
PISM	Parallel Ice Sheet Model
POP	Parallel Ocean Program
ROMS	Regional Ocean Modeling System
SIA	Shallow-ice approximation
WAIS	West Antarctic Ice Sheet
WRF	Weather Research and Forecasting model

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Appendix 1: Agenda

Building a Next-Generation Community Ice Sheet Model

18-20 August 2008
TA-3, Bldg. 207, J. Robert Oppenheimer Study Center
Jemez and Cochiti Rooms

Monday, 18 August 2008

8:30 Registration and refreshments

9:00 Welcome and introductions
Gary Geernaert, IGPP Director

9:15 "Why it matters"
Robert Bindschadler, NASA Goddard Space Flight Center

9:40 "Overview of the St. Petersburg ice sheet modeling workshop"
Kees van der Veen, University of Kansas

10:00 "Ice dynamics and physics in a next-generation ice sheet model"
Stephen Price, LANL, T-03

10:20 **Break**

10:40 "Solving the 3D Stokes system on a variable resolution mesh"
Todd Ringler, LANL, T-03

11:00 "Basal boundary conditions for ice sheet models"
Slawek Tulaczyk, University of California, Santa Cruz

11:20 "Modeling the transport of subglacial water discharge: A case study from Adventure Trench"
Sasha Carter, University of Texas, Austin

11:40 "New and old approaches to ice sheet modeling: Solid earth geophysics and the cryosphere"
Jeremy Bassis, University of Chicago

12:00 **Working Lunch**

1:00 "Review of progress in observations and modeling of ice-shelf physics"
David Holland, New York University

1:20 "Short time-scale variation in grounding line position on the Siple and Gould Coasts, West Antarctica"
Christina Hulbe, Portland State University

1:40 "Lessons from adaptive-mesh modeling of marine ice sheets"
Dan Goldberg, New York University

2:00 "Regional models of ice-shelf/ocean interaction"
Paul Holland, British Antarctic Survey

2:20 "Dynamic ice fronts: Implementing an empirical ice-shelf calving law"
Todd Dupont, University of California, Irvine

2:40 **Break**

3:00 **Breakout sessions:**

- Ice sheet dynamics and physics (Jemez Room)
- Ice-shelf/ocean interactions (Cochiti Room)

5:00 **Adjourn**

6:00 **Group dinner (La Vista restaurant, Best Western Hilltop House)**

Tuesday, 19 August 2008

8:30 Refreshments and announcements

9:00 "The CCSM and ice sheets"
Peter Gent, National Center for Atmospheric Research

9:25 "Software design issues for ice sheet models"
Jesse Johnson, University of Montana

9:45 "Performance portability, coupled components and the pirate code"
Philip Jones, LANL, T-03

10:05 "Implementing an ice sheet model in CCSM"
William Lipscomb, LANL, T-03

10:25 **Break**

10:40 "Community Modeling Environment at the Southern California Center: Principles, architecture, and lessons learned"
Jean-Bernard Minster, University of California, San Diego

11:00 "An overview of the University of Toronto Glacial Systems Model"
Gordan Stuhne, University of Toronto

11:20 "Integrating an ice-sheet/ice-shelf model into an EMIC: Progress and issues"
Jeremy Fyke, Victoria University

11:40 "Scientific questions to be addressed with a coupled climate-ice sheet model"
Miren Vizcaino-Trueba, University of California, Berkeley

12:00 **Working Lunch**

1:00 "Community tools for model initialization, spin-up, and evaluation"
Ed Bueler, University of Alaska, Fairbanks

1:20 "A new penalty based approach to large scale modeling of Antarctica using 2d-3d lower and higher order finite elements:
Eric Larour, Jet Propulsion Laboratory

1:40 "Data-driven model development"
Charles Jackson, University of Texas, Austin

2:00 General discussion

2:40 **Break**

3:00 **Breakout sessions:**

- Software design and coupling (Cochiti Room)
- Initialization, verification, and validation (Jemez Room)

5:00 **Adjourn**

Wednesday, 20 August 2008

8:30 Refreshments and announcements

9:00 Reports from breakout sessions

10:00 General discussion

10:20 **Break**

10:40 General discussion

12:00 **Adjourn**

Appendix 2: Participant list

Name	Institution	E-mail address
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Appendix 3: Ice sheet model components and processes

Participants generated the following list of components or processes to be included in an ideal ice sheet model. These were prioritized according to (1) their importance to the near-term goal of decadal-scale sea-level prediction, (2) model feasibility (the ease of implementation), and (3) data feasibility (the existence or absence of data needed to construct or constrain a sub-model or parameterization). For example, a model of subglacial hydrology was given a prioritization "index" of [1,2,3]; the "1" indicates that it is a high priority, the "2" indicates that it will be somewhat difficult to implement, and the "3" indicates that few data exist to constrain such a sub-model. A "0" denotes "not applicable." For high priority items, individuals and institutions who expressed interest in each development effort are shown in parentheses.

Ice sheet dynamics and physics:

(1,2,0) Higher-order dynamics (LANL, U. Montana)
(1,1,2) Ice shelf buttressing (LANL, U. Montana)
(2,2,0) Full-Stokes solvers
(2,1,3) Shear margin migration
(2,2,2) Rheology
(2,2,3) Polythermal ice
(3,2,3) Damage evolution
(3,2,3) Anisotropy

Hydrology and basal sliding:

(1,1,3) Basal sliding law for hard beds (Tulaczyk)
(1,1,3) Surface and englacial hydrology (Andres, Parizek)
(1,2,3) Subglacial hydrology (Carter, Johnson, Price)
(1,2,3) Evolution of hard bed boundary conditions, e.g. as function of hydrology (Tulaczyk)
(1,2,3) Till evolution, e.g. as function of hydrology (Johnson, Tulaczyk)
(1,1,3) Spatially variable geothermal flux (Jackson/UTIG, Van der Veen/CReSIS)
(3,2,3) Sediment transport and erosion

Ice shelves and ice-ocean coupling:

(1,1,2) Data to constrain sub-shelf melting rates (D. Holland, P. Holland)
(1,2,2) Iceberg calving (Bassis, Dupont, Hulbe, Parizek, Gladish)
(1,3,2) Grounding line migration (Bassis, Goldberg, Hulbe, Ringler)
(2,1,3) Crevasse formation

Other:

(1,2,2) Initialization (Larour, Bueler, Andres)
(2,1,1) Improved surface mass balance schemes (e.g., accumulation patterns, redistribution)
(2,3,0) Adjoint model development
(3,1,2) Isostatic adjustment