

Report of the CESM Land Ice Working Group

12-13 January 2011
Boulder, Colorado

The CESM Land Ice Working Group (LIWG) held its annual winter meeting on January 12-13, 2011, at the NCAR Mesa Lab in Boulder, Colorado. The meeting was co-chaired by William Lipscomb and Stephen Price and was attended by 52 registered participants. (Co-chair Jesse Johnson is on sabbatical in South Africa and was unable to attend.)

Most of the LIWG meeting consisted of short presentations. The first day, Wednesday Jan. 12, consisted of talks related to the DOE ISICLES (Ice Sheet Initiative for Climate Extremes) project along with general talks on land-ice modeling. The second day, Thursday Jan. 13, was organized as a workshop on ice-sheet hydrology. A report from that workshop appears at the end of this document.

Here is the URL for the agenda, with links to presentations:

http://www.cesm.ucar.edu/working_groups/Land+Ice/agendas/011211.agenda.pdf

The list of registered participants is here:

http://www.cesm.ucar.edu/working_groups/Land+Ice/agendas/011211.participants.pdf

Abstracts are shown below. Some talks had more than one author, but only the names of presenters are shown here.

Erik Boman – *Progress on Ice Mechanics Modeling and Scalable Algorithms for Ice Fracture*

The goal of our project is to model and simulate fracture in ice, to better understand and predict phenomena like the collapse of ice shelves, calving, and sudden lake drainage. We have developed a brittle-ductile visco-elastic model of ice. A damage model for the microscale feeds into a macroscale model for simulating fracture in ice. We propose a computational framework based on the extended finite element method (XFEM). We show that a new quasi-algebraic multigrid algorithm efficiently solves the large linear systems that arise.

Dmitry Karpeev – *Towards Robust and Scalable Implicit Stokes Solvers: Meshing and Preconditioning Tools*

We discuss recent progress towards scalable solvers for 3D fully nonlinear Stokes models of ice sheets. Accurate resolution of the geometry of the ice stream by the computational mesh, particularly near the grounding line, is of paramount importance for quantitative analysis of their stability. Furthermore, smooth surface normals are essential for artifact-free simulations of the free surface ice flow. Finally, scalable efficient preconditioners are instrumental in establishing fully implicit Stokes models as viable numerical tools in glaciological simulations. We present the recent results on meshing, free surface geometry modeling and preconditioners that advance the goal of predictive 3D Stokesian models of ice sheet dynamics.

Alex Tartakovsky – *Lagrangian Particle Model for Ice Sheet and Ice Shelf Dynamics*

Novel Lagrangian particle models for coupled ice sheet and ice shelf dynamics are developed. Smoothed Particle Hydrodynamics model is used to simulate flow of ice sheet and ice shelf. Discrete Element Method model is used to simulate fracturing of the ice shelf. Comparison with analytical solutions and experimental results confirms the accuracy of the models.

Dan Martin – *BISICLES Update*

The dynamics of ice sheets span a wide range of scales. Localized regions such as grounding lines and ice streams require extremely fine (better than 1 km) resolution to correctly capture the dynamics. Conversely, there are large regions where such fine resolution represents a waste of resources, making ice sheets a prime candidate for adaptive mesh refinement (AMR), in which finer spatial resolution is added where needed.

The Berkeley ISICLES (BISICLES) project is a collaboration among the Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, and the University of Bristol in the U.K. The goal of the BISICLES project is to construct a high-performance scalable AMR ice sheet model using the Chombo parallel AMR framework. We also use the vertically-integrated treatment of the momentum equation due to Hindmarsh and Schoof (2010). Autotuning techniques will be deployed to improve performance of key computational kernels. We present preliminary results showing the effectiveness of our approach.

Omar Ghattas – *Uncertainty Quantification with Advanced Ice Sheet Models*

We discuss progress of the PARADICE project toward building a full Stokes ice sheet simulation code that incorporates unstructured hexahedral meshing of Antarctic and Greenland ice sheets, parallel adaptive mesh refinement/coarsening to resolve the wide range of spatial scales; high order accurate discretizations; parallel scalable linear and nonlinear solvers; adjoint-based inverse methods to identify uncertain basal boundary conditions, constitutive parameters, geothermal heat flux, and basal topography; and Bayesian inference methods to estimate uncertainty in parameter inversion. In particular, we present results of meshing of Antarctic ice sheets with sub-2 km resolution at grounding lines, scalability of a Schur-preconditioned full Stokes solver to several thousand cores on full Antarctic meshes, and idealized inversions for basal drag and rheology parameters using adjoint-based Newton methods.

Kate Evans – *An Improved Solution Framework for Greenland Ice Sheet Simulation within Glimmer-CISM*

The current ice sheet modeling capability within the higher-order version of Glimmer-CISM solves the ice sheet momentum and thickness equations sequentially, so complex problems on fine grids experience convergence difficulties. Recently, a Jacobian-Free Newton-Krylov solution method has been implemented into the Glimmer-CISM model that provides efficiency gains over Picard for a suite of test cases and a suite of scenarios that mimic the Greenland ice sheet. Simulation results and performance analysis of the solution method and parallelization efforts show good scaling on the test cases. Near term work to extend the solution method to

connect CISM to CESM, include more dependent variables to be solved coherently, and scalable preconditioner development is outlined. Also, initial work to extend Glimmer-CISM to finite element grids is presented.

William Lipscomb – *An Update on Land-ice Modeling in CESM*

Mass loss from land ice, including the Greenland and Antarctic ice sheets as well as smaller glacier and ice caps, is making a large and growing contribution to global sea-level rise. Land ice is only beginning to be incorporated in climate models. The goal of the Land Ice Working Group (LIWG) is to develop improved land-ice models and incorporate them in CESM, in order to provide useful, physically-based sea-level predictions. LIWG efforts to date have led to the inclusion of a dynamic ice-sheet model (the Glimmer Community Ice Sheet Model, or Glimmer-CISM) in the Community Earth System Model (CESM), which was released in June 2010. CESM also includes a new surface-mass-balance scheme for ice sheets in the Community Land Model.

Initial modeling efforts are focused on the Greenland ice sheet. Preliminary results are promising. In particular, the simulated surface mass balance for Greenland is in good agreement with observations and regional model results. The current model, however, has significant limitations: The land-ice coupling is one-way; we are using a serial version of Glimmer-CISM with the shallow-ice approximation; and there is no ice-ocean coupling. During the next year we plan to implement two-way coupling (including ice-ocean coupling with a dynamic Antarctic ice sheet) with a parallel, higher-order version of Glimmer-CISM. We will also add parameterizations of small glaciers and ice caps. With these model improvements, CESM will be able to simulate all the major contributions to 21st century global mean sea-level rise. Results of the first round of simulations should be available in time to be included in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change.

Xylar Asay-Davis – *An Update on Modeling Land-ice/ocean Interactions in CESM*

This talk is an update on ongoing land-ice/ocean coupling work within the Community Earth System Model (CESM). The coupling method is designed to allow simulation of a fully dynamic ice/ocean interface, while requiring minimal modification to the existing ocean model (the Parallel Ocean Program, POP). The method makes use of an immersed boundary method (IBM) to represent the geometry of the ice-ocean interface without requiring that the computational grid be modified in time. We show many of the remaining development challenges that need to be addressed in order to perform global, century long climate runs with fully coupled ocean and ice sheet models. These challenges include moving to a new grid where the computational pole is no longer at the true south pole and several changes to the coupler (the software tool used to communicate between model components) to allow the boundary between land and ocean to vary in time. We discuss benefits for ice/ocean coupling that would be gained from longer-term ocean model development to allow for natural salt fluxes (which conserve both water and salt mass, rather than water volume).

David Bahr – *Scaling Techniques for Simultaneously Modeling Hundreds of Thousands of Glaciers and Ice Caps*

With an estimated 300,000 to 400,000 mountain glaciers and ice caps (GIC), these comparatively small but numerous ice masses are today's leading contributor to sea-level rise. GIC contributions are projected to be nearly as significant as Greenland and Antarctic ice sheet contributions over the next 100 years. Furthermore, the uncertainties in GIC sea-level predictions are just as large as the uncertainties for ice sheets over the next 100 years. For appropriate policy, planning and engineering decisions, GIC must become integral components of land-ice models in any climate simulation. Although modeling the dynamics of hundreds of thousands of glaciers is not feasible, the problem becomes tractable by using power-law scaling relationships which can track GIC changes in volume. To avoid explicitly simulating hundreds of thousands of individual glaciers, scaling is combined with statistical physics to follow entire regional distributions of glacier sizes (and volumes) rather than following individual glaciers. Sea-level changes are extracted from the volume distributions as they evolve with time. The scaling relationships are valid in non-steady state conditions and account for the varying response times of both larger and smaller GIC. Theoretical knowledge of the distribution's shape can be used to extend GIC inventories in regions where they are currently incomplete.

John Moore – *Summary of sea-level projections based on ESM and semi-empirical estimates*

IPCC estimate future sea level rise by modelling the major components of sea level budget: ocean thermal expansion and melting from ice sheets and glaciers (plus terrestrial storage). Physically based climate models have in the past only produced the thermal expansion component, which amounts to only 1/3 of observed sea level rise during the 20th century. While glacier mass balance estimates to date are for surface mass balance of Greenland and Antarctica plus parameterized estimates from small glaciers. More advanced models of ice sheet behaviour are in active development, but are yet to yield sea level rise estimates.

An alternative approach to model sea level is using statistical models; which are based on physically plausible semi-empirical relationships between histories of global temperature or radiative forcing, and sea level rise. Sea level in the semi-empirical approach is assumed to be an integrated response of the entire climate system (including feedback processes) to the changes in temperature or radiative forcing that reflects changes in the dynamics and thermodynamics of the atmosphere, ocean and cryosphere. Instead of projecting each individual component of sea level rise over the 21st century, semi-empirical models estimate global sea level rise using observationally tuned statistical models driven by mean global temperature or net radiative forcing scenarios.

Semi-empirical models, by construction, reproduce the 300 year tide gauge record of observed sea level very well. More surprisingly the semi-empirical models reproduce climate system modelled sea level behaviour at scales from centennial to multi-annual, including the impact of volcanic eruptions on sea level. Semi-empirical forecasts of 1993-2005 sea level rate is 3-4 mm/yr which is very similar satellite altimetry observations. However, projections by semi-empirical models are based on the assumption that sea level in the future will respond as it has in the past to imposed climate forcing. This may not hold in the future if potentially non-linear

physical processes (e.g. marine ice-sheet dynamics) emerge and dominate 21st century sea level rise.

Ute Herzfeld – *Connecting Observations and Modeling: Importance of Bed Topography in Dynamic Ice Sheet Models and Scale-dependent Simulations*

This talk presents two cases in data analysis that are deemed important in dynamic ice sheet modeling and other aspects of modeling relevant to the LIWG. Simply speaking, the first case is an example of "too much data", whereas the second one is an example of "not enough data". The first example concerns the role of subglacial topography in modeling changes in ice sheets using dynamic ice sheet models. The problem is that fast-moving outlet glaciers are the most sensitive part of the Greenland ice sheet to climatic warming and transport ice into the oceans, however their width may be smaller than the grid size of ~5 km, which is typically used in dynamic ice sheet modeling. For example, this is the grid used in SeaRISE assessments of maximal possible contribution to sea-level rise over the next 200 years from mass loss from the Greenland and Antarctic ice sheets. In this talk, we treat the problem of generalizing the bed topographic grid such that the trough of an outlet glacier is retained, by deriving a mathematical-morphological algorithm and using new data collected by CRESIS (Center for Remote Sensing of Ice Sheets), University of Kansas. Model runs with SICOPOLIS and PISM show the ice surface velocities resulting from properly including the bed of Jakobshvan Isbrae and demonstrate the importance of including bed topography of outlet glaciers. In the second example, an approach to simulating grids of ice-surface elevation with correct, natural roughness at every scale is presented. Data collected with the ICESat GLAS instrument serve to derive grids at 3km resolution. Then a set of simulation and interpolation algorithms are used to create increasingly finer grids, using spatial properties such as anisotropy, fractal dimension and roughness from field data.

Diandong Ren – *A Multi-rheology Ice Model: Formulation and Application to Greenland Ice Sheet Responses to Transient Climate Change*

Accurate prediction of future sea level rises requires models which can reproduce recent observed change in ice sheet behaviour. This study describes a new multi-phase, multiple-rheology ice dynamics model (SEGMENT-ice). Unique to SEGMENT-ice include a variable granular basal sliding layer, a novel treatment of spin-up, and a set of chemistry code dealing with ocean water interaction with ice shelves or water terminating glaciers. SEGMENT-ice is used to examine Greenland ice sheet (GrIS) responses to climate change.

When applied to the GrIS, SEGMENT-ice exhibits skill in reproducing the mass loss rate derived from the Gravity Recovery and Climate Experiment (GRACE), the interferometric synthetic aperture radar (InSAR) measured surface flow speed, and the microwave remotely sensed surface melt area over the past decade. When forced by the NCEP/NCAR reanalysis atmospheric parameters, the ice model simulates closely the GrIS mass loss rate obtained from GRACE. An increase of summer maximum melt area extent (SME) is indicative of an expansion of the ablation zone. The modelled SME from 1979-2006 also simulates well the observed interannual variability of SME, with a high correlation of 0.88 between the two time series. The geographical distributions of the modelled and observed SME also agree well. Comparison of

modelled and observed velocity over three regions, covering respectively the west, northeast and north sides of the GrIS, indicates a satisfactory model performance in delineating flow direction and magnitudes for regions with flow speed less than 500 m/year, with no region-specific systematic errors. However, the model cannot simulate extremes in the observations, mainly because it is limited by spatial resolution.

Stephen Price – *Integrating Glacier and Ice Sheet Hydrology Models in the Community Ice Sheet Model*

The content of this talk is included below in the report on the hydrology workshop.

Gwenn Flowers – *Progress in Modeling Glacier Hydrology*

Realistic models of glacier hydrology are needed to improve our characterization of subglacial water pressures, and therefore ice-flow velocities. Our early attempts to model glacier hydrology focused on a very simple but comprehensive two-dimensional treatment of the system that parameterizes morphological transitions in the basal drainage system, but does not properly account for the physics of efficient (channelized) subglacial drainage. More recent efforts have been focused on the development of a two-component model of subglacial hydrology describing an interacting sheet (“slow” or “distributed” system) and ice-walled conduits (“fast” or “channelized” system). This has been coupled to a higher-order flowband model with a Coulomb-friction law to describe the basal boundary condition. The basal water pressure determined by the hydrology model is used to calculate effective pressure for the Coulomb friction law. Simulations of a hypothetical seasonal transition qualitatively exhibit many features observed in the field. As surface meltwater impinges on the slow basal drainage system, basal water pressures increase, reducing the basal shear stress and producing higher basal flow rates. With sufficient water input, conduits develop out of the sheet and ultimately accommodate most of the discharge, relieving the high basal water pressures. This model has been used to explore aspects of ice-sheet drainage for Greenland outlet glaciers, but would require modification to be applied to a broader range of ice-sheet problems. Further developments should address the thermodynamics of the full system (basal hydrology and coupling to ice dynamics) and the extension to two- and three-dimensions.

Christian Schoof – *Subglacial Drainage Network Modeling*

Subglacial drainage is thought to occur through two distinct canonical models: distributed and channelized. The former is typified by subglacial cavities, which can co-exist at similar sizes and effective pressures. Channelized systems consist of drainage conduits such as Rothlisberger channels, whose main characteristic is that their size increases with increasing effective pressure. This dictates that larger channels draw water away from smaller ones, leading to an arborescent system that cannot be modelled straightforwardly as a continuum. Here I explore the use of discrete element models in which a predefined network of conduits carries water under an ice mass. The conduits all satisfy an evolution equation that has two possible steady states, a smaller one that is cavity-like and a larger one that is channel-like. I highlight the successes and problems encountered in modelling subglacial drainage in this way.

Matt Hoffman – *Review of Observations of West Greenland Summer Acceleration Relevant to Process-based Ice-sheet Modeling*

Numerous observations in west Greenland suggest surface meltwater draining through up to kilometer-thick ice can dramatically increase summer velocity, raising concerns about a positive feedback between warming climate and ice sheet mass loss. Though this process has only been well-studied in two areas of west Greenland, there is a consistent pattern of sustained speedup in early summer after the onset of melt that lasts through the melt season and is accompanied by diurnal variations in velocity, and in some cases, uplift. The seasonal speedup is from 10-100% depending on year and location, which is a small increase in the annual ice flux in most cases. A new set of GPS observations spanning 40 km of the ablation zone supports the idea that the seasonal signal is generated by daily pulses of meltwater. We see evidence that, like a temperate glacier, sliding is generated by increase in water storage, but we see high spatial variability in storage on the ice sheet, perhaps due to a lower spatial density of connections to the bed in cold, thick ice. However, we see evidence for lower temporal variability in dynamic response under thick ice, which may be related to the rapid creep closure rate of subglacial conduits under thick ice if water pressures are low. Manifestation of rapid drainage to the bed of supraglacial lakes is rare and short-lived in the velocity record, suggesting lakes predominantly drain slowly overland, which may provide a dampening effect to the dynamic response of the ice sheet to meltwater input. In summer 2011 a new borehole drilling campaign to the bed of the ice sheet will attempt to characterize the evolution of the subglacial drainage system through direct observations.

Slawek Tulaczyk – *Subglacial Hydrology and Ice Motion: Insights From a Natural Perturbation Experiment*

The recent discovery of active subglacial lakes beneath Whillans Ice Stream offered the opportunity to quantify the sensitivity of ice stream motion to large temporal changes in subglacial water fluxes. We installed a network of ten continuous GPS stations on the Whillans ice plain in late 2007 and operated it till early 2010. The network was installed when Subglacial Lake Whillans (SLW) was fully drained and captured a full filling-draining cycle of the lake during its operation. GPS data were processed in a PPP mode and analyzed for vertical and horizontal displacement and velocity. Preliminary results indicate that the Whillans ice plain did not experience a significant change in velocity either at the time of SLW filling or draining. However, they do indicate that the ice plain is still experiencing a slowdown that has been noted previously by other authors. Force budget analyses show that such slowdown is due to increasing basal resistance to ice motion that can be explained by dropping water availability/pressure. We propose that subglacial hydrological system in this region, and perhaps elsewhere, consists of two distinctly different elements: (1) a ‘fast, localized system’ which enables relatively quick transition of water into/from active subglacial lakes without much impact on ice motion, and (2) a ‘slow, widespread system’ which has a longer time constant and small water throughput rates but influences ice motion.

Liam Colgan – *A 2D, Computationally Light, Single-head Ice Sheet Hydrology Model*

We examine the en-/sub-glacial hydrology of the Sermeq Avannarleq ablation zone, ~ 50 km north of Jakobshavn Isbrae. We introduce a 1D (x; depth-integrated) hydrology model that is

capable of reproducing an observed time-space distribution of measured subglacial water pressures. The modeled annual cycle in the rate of change in glacier water storage with time (dS/dt) closely matches the annual cycle in basal sliding velocity observed at multiple stations. We outline equations which provide a framework for expanding the model into 2D (xy ; depth-integrated). While the model is capable of reproducing observed water subglacial pressures with high fidelity, its relatively small parameter space make it computationally tractable (1 transient variable and < 50 secondary variables per node). Decade-scale solutions for the entire Greenland Ice Sheet (at 1 x 1 km horizontal resolution) should be feasible with a quad-core processor. The ultimate goal of this project is to use modeled dS/dt values to reproduce the annual cycle in basal sliding velocities across the ice sheet.

Sam Pimentel – *Seasonal Evolution of Subglacial Drainage and Ice Motion in a Glacio-hydrodynamic Flow-band Model*

A flow-band model of ice dynamics is presented for experimenting with glacio-hydrodynamic interactions. The numerical model retains the so-called higher-order stress terms and parameterizes lateral drag and elastic uplift. The subglacial hydrological system is represented by interacting distributed and channelized drainage components and influences ice flow through a pressure-dependent regularized Coulomb-friction law that is used to represent the basal boundary layer. We use the model to demonstrate a seasonal transition for a hypothetical alpine glacier and replicate qualitative features such as diurnal and seasonal glacier accelerations, evolution of the subglacial system from a distributed to a channelized dominated drainage network, spring speed-up, and force-balance adjustments. Another example simulates a subglacial flooding event resulting from catastrophic drainage of a supraglacial lake. In this case we find that rapid subsidence and deceleration follows the deluge if the meltwater pulse to the glacier bed encounters a pre-existent channelized network. Future work will look to apply this model to outlet glaciers including the Belcher Glacier in the Canadian Arctic and the Russell Glacier in Western Greenland.

Ian Hewitt – *Over- and Under-pressure in Subglacial Sheets*

We propose a model for a porous subglacial water sheet comprising linked cavities. The depth of the water sheet evolves according to an evolution equation that includes opening, due to sliding over bedrock bumps, and closure, due to viscous creep of the ice and a positive effective pressure. Particular attention is given to situations in which the water pressure reaches the overburden ice pressure and in which the water pressure falls to atmospheric pressure. In the first of these the ice is assumed to float from the bed and the depth of the drainage system is no longer constrained by an evolution equation. In the second, analogous to cavitation in other fluid flows, a pocket of air or water vapour forms and the sheet is no longer water-filled. Idealised examples are given of steady states (constant meltwater input) when these situations can arise, and of the response to time-varying water inputs, which tend to involve high water pressures.

Thomas Phillips – *Cryo-hydrologic Warming as a Potential Mechanism for Rapid Thermal Response of Ice Sheets*

We propose a simple dual-column flow-line model to simulate the importance of cryo-

hydrologic warming. Our approach considers two interacting vertical columns representing ice and the cryo-hydrologic system, with exchange of energy (horizontal advection) between the two columns. Each ice column is connected to next ice column upstream by means of horizontal advection. However, there is no coupling between adjacent cryo-hydrologic columns. The cryo-hydrologic heat exchange coefficient ζ is defined as k/R^2 , where R is the characteristic spacing between en-glacial passages and k is the thermal conductivity of ice. Correspondingly, the characteristic time scale for cryo-hydrologic heat exchange is k/R^2 , where k is the thermal diffusivity of ice, and depends strongly on R . Our results suggest that a characteristic spacing between en-glacial passages or R in the range of a few 10's of meters. Cryo-hydrologic warming has the potential to accelerate the warming of ice sheets, and thus increase ice flow as the effective viscosity of ice decreases significantly with increasing temperature.

The temperature profile of a flow-line in the Sermeq Avannarleq Glacier in Western Greenland is derived using a steady-state flow-line model incorporating cryo-hydrologic heat exchange. Our results show that as the equilibrium line rises, the ice temperature rises by up to 7K to a new steady state temperature within a decade for an elevation rise of the equilibrium line during the past 25 years under the current local climate. Correspondingly, the ice velocity at the ice margin can increase by 60% even without invoking the influence of lubrication at the bed. The surface topography of the Sermeq Avannarleq Glacier shows a kink in the vicinity of the equilibrium.

Cryo-hydrologic warming may potentially explain this kink. The increased ice temperatures downstream of the equilibrium line altitude will decrease the ice viscosity in this region, leading to an increase in ice velocity. Because the region just upstream of the equilibrium line remains cold, a sharp spatial velocity variation will occur, leading to a kink.

Caroline Clason – *Modeling Meltwater Delivery to the Ice-bed Interface through Fractures at the Margin of the Greenland Ice Sheet*

Dynamic response to increased supraglacial meltwater generation and subsequent influx to the subglacial hydrological system is being increasingly documented on outlet glaciers of the Greenland Ice Sheet (GrIS). High velocity events may be a response to increased basal lubrication and basal water pressures when meltwater reaches the subglacial system directly through moulins. Supraglacial meltwater can provide hydrostatic stresses adequate to offset closure due to the lithostatic stress of the ice when streams intersect and enter surface crevasses. A crevasse will continue to propagate through the full ice thickness provided the meltwater head within the crevasse remains sufficient, thereby allowing this flux of meltwater to be delivered to the ice-bed interface. A spatially distributed model for prediction of full ice thickness water-driven fracture and quantification of meltwater delivery to the bed has been created. Here we present results of modelling applied to outlet glaciers of the south-west GrIS margin, centred around the Leverett glacier catchment. InSAR ice surface velocities are applied to determine the ice surface stress regime, and meteorological data acquired during the 2009 ablation season are used as inputs for degree-day melt modelling. A linear elastic fracture mechanics model for propagation of water-filled fractures is applied to calculate crevasse penetration depths. The sensitivity of the model to input variables is tested, and results suggest that the rate at which meltwater is delivered to a crevasse is the most important controlling factor on crevasse depth. Given the scenario of enhanced meltwater generation in a future warming climate, meltwater

delivery through full ice thickness fractures may become an increasingly significant mechanism for enhancing ice velocities and mass loss.

Sebastian Mernild – *Simulated Runoff from the Greenland Ice Sheet and Peripheral Glaciers*

Ample evidence indicates the Arctic climate, cryosphere, and hydrological cycle is changing. Long-term temperature observations show warming trends of variable strength throughout the Arctic and Greenland, with an average increase almost twice the global average rate in the past 100 years. Fluctuations in mass balance and freshwater runoff from the Greenland Ice Sheet (GrIS), and glaciers and ice caps peripheral to the Ice Sheet, follows climate fluctuations, and response has already been observed and marked by glaciers retreating and thinning along the periphery. The runoff contribution to the ocean is likely playing a role in ocean salinity, sea-ice dynamics, global eustatic sea level rise, and thermohaline circulation in the Greenland-Iceland-Norwegian Seas. Presently, we lack detailed information about the spatial and temporal runoff distribution to the ocean from non-glaciated and glaciated areas in Greenland. Runoff hydrographs at catchment outlets represents an integrated response of the upstream watershed to precipitation and other hydrometeorologic processes, e.g., snow and glacier melt. Here, we attempt to improve and simulate the spatial and temporal distribution of Greenland runoff to the ocean: (1) at a local scale from a test area in SE Greenland that includes the Mittivakkat Glacier, the local glacier in Greenland with the longest observed mass balance (since 1995) and front fluctuations (since 1931) time series; and (2) at a regional scale from the GrIS.

Sasha Carter – *Monitoring and Modeling Subglacial Lake Activity in the MacAyeal Ice Stream Catchment*

We have created a simple model for the response of subglacial water distribution to lake discharge events through assimilation of various satellite and airborne geophysical datasets, including: subglacial lake volume change estimated from Ice, Cloud and land Elevation Satellite (ICESat) altimetry; an inferred basal melt rate, and a digital elevation model of bedrock; and ice surface topography. In this steady-state 'D8' model, out flow is equal to inflow plus basal melt and is distributed among all downstream neighboring cells. At a given time step, cells in known subglacial lakes are treated as either sinks or sources depending on the ICESat-derived filling or draining rates. We then compare the observed filling rates with the modeled inflow to further tune the subglacial topography and obtain a better match. The resulting distribution shows that basal water availability varies widely over the 6 years of the ICESat observation campaign, and the understanding the dynamics of subglacial lakes is essential to understanding the influence of subglacial water on basal sliding in Ice Streaming regions. The observed filling rates of the Subglacial lakes in the downstream regions of all active ice streams in the study area is only possible if the entire hydraulic catchment of this system is taken into consideration. Moreover we demonstrate that in many cases the observed filling rates require piracy of water from ice stream catchment to another, confirming the hypothesized piracy of water from Upper Kamb Ice stream into Lower Whillans. Furthermore we show that water piracy is very sensitive to subtle changes in surface elevation on the order of a few metres and that the reorganization and piracy of subglacial water flow occurs over times frames of a few years or less.

Tim Creyts – *Drainage of Subglacial Water in Antarctica*

Recent results from the AGAP aerogeophysical survey ($\gg 250 \times 750$ km) resolve a richly detailed bed in the interior of the East Antarctic Ice Sheet near Dome A (80°22'S 77°22'E). Here we present evidence for widespread freeze-on to the base of the East Antarctica ice sheet from data collected by a seven nation research expedition. In the extensive radar data over the Gamburtsev Subglacial Mountains, we have identified distinct near-bed reflectors in the generally featureless basal ice. The near-bed reflectors originate at the ice sheet bed coincident with flat bright reflectors, sites associated with basal water. Water generation is coincident with deep mountain valleys where thick ice ($\gg 3000$ m) leads to basal melting. Subglacial water networks form, and water is driven towards areas of thinner ice. Because the valley network of the Gamburtsev Subglacial Mountains predates the present state of the ice sheet, flow of water is not necessarily codirectional with valley orientation. In many cases, water flows up valleys toward valley heads where ice is much thinner ($\gg 1500$ m). Water freezes either as result of enhanced heat conduction through thinner ice or through glaciohydraulic supercooling along steep subglacial slopes as water transits jagged mountain topography. Accreted ice can account for as much as 30% of the thickness of the ice sheet. We conclude by discussing how our data and interpretations affect understanding of other areas of the ice sheets, including other areas of East Antarctica, West Antarctica, and Greenland where radar data indicates similar features in basal ice.

John Moore – *Geoengineering, Sea Level, and China* (NCAR CGD seminar)

Sea level rise of 1 m will directly affect 150 million people. Semi-empirical sea level rise models predict that sea level will rise 0.6-1.6 meter in the next 100 years due to increase in greenhouse gases emission. A controversial alternative is to control climate with geoengineering. However the detailed impact of such proposals has been little researched to date. We examine the impact of 5 geoengineering approaches on sea level; SO₂ aerosol injection into the stratosphere, mirrors in space, afforestation, biochar, and bioenergy with carbon sequestration. In contrast with naïve statements in many previous articles that reduced sea levels will result from these scenarios, we show that considerable sea level rise will still occur in the 21st century unless the most aggressive greenhouse gas emissions scenarios are adopted, or most expensive and damaging geoengineering is done. This is because the ice sheets and oceans respond on centennial timescales to temperature changes. The most effective way of limiting sea level rise appears to be bioenergy with carbon sequestration, which would also naturally tend to be a relatively low emissions development path. A space mirror system reducing insolation at an accelerating rate of 1 W m^{-2} per decade from now to 2100 could limit or reduce sea levels. Aerosol injection delivering a constant 4 W m^{-2} of albedo increase (similar to a Pinatubo eruption every 18 months) could delay sea level rise by 40-80 years.

IMPROVING HYDROLOGY IN LAND ICE MODELS

*A workshop on implementing land ice hydrology in the Community Ice Sheet Model
Boulder, Colorado, January 13, 2011*

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Workshop Summary

Recent observations indicate that mass loss from glaciers and ice sheets (“land ice”) is increasing. The drivers for these changes are not well understood, and modeling land-ice response to them remains challenging. As a result, the IPCC explicitly avoided speculating on 21st century sea-level rise from ice dynamical processes in its 4th assessment report (IPCC, 2007). The mismatch between observations and model skill is behind recent efforts to develop next-generation land ice models (e.g. Lipscomb et al., 2009). In addition to improved dynamics and climate model coupling, better representations of important boundary conditions and physical processes are required. Basal sliding, the primary control on the rate of land ice delivery to the oceans, is one such boundary condition. In turn, the dominant control on glacier and ice sheet sliding is sub-glacial hydrology, with the supra- and en-glacial hydrological systems serving as key inputs.

The past decade has seen significant progress in the understanding and the process-scale modeling of glacier sliding (e.g. Schoof, 2005), sub-glacial hydrology (e.g. Creyts and Schoof, 2009; Flowers, 2008; Pimental and Flowers, 2010a, 2010b; Schoof, 2010), and supra- and en-glacial hydrology (e.g. Clason et al., 2010; Mernild et al., 2010; Phillips et al., 2010). To ensure that these advances are incorporated into next-generation land-ice models, a workshop was held at the National Center for Atmospheric Research as part of the annual winter meeting of the Land Ice Working Group (part of the Community Earth System Model). The meeting was attended by approximately 40 participants from institutions in the U.S., the U.K., Canada, and China. Following a series of scientific presentations highlighting the current state of research¹, participants discussed three themes: (1) identifying impediments to implementing current process-scale hydrology models into large-scale land ice models, (2) identifying key observations needed to constrain and improve land-ice hydrology models, and (3) identifying and prioritizing long- and short-term goals for land-ice hydrology modeling.

Impediments to the wider implementation of existing process-scale models include a disparity of spatial and temporal scales between process- and continental-scale models, poorly constrained model parameters, the lack of an accepted and unified land-ice hydrological model, the lack of a common model platform or code base to work from, absent or sparse (in time and space) observations of key model variables (e.g. sub-glacial water pressures), the lack of an agreed upon and unified (i.e. hard and soft bed) model for basal sliding with “hooks” to relevant hydrological

¹ See the list of abstracts attached to the first part of this report, above.

variables, and a lack of methods for model validation, verification, and intercomparison.

Observations deemed necessary for further progress in land-ice hydrology modeling include ice geometry at high-resolution (~1 km), maps of bed character (i.e. bedrock versus sediment covered) over relevant length scales, en-glacial and basal temperatures at relevant locations (i.e. coincident with observations of other hydrologic variables), locations and rates of surface water input, basal water pressures at relevant spatial and temporal scales (e.g. along outlet glacier flowlines and over the length of the melt season), statistical descriptions of important sub-grid scale properties (e.g. surface and basal roughness), surface channel morphology, and the spatial and temporal distribution of crevasses, moulins, supra-glacial streams and lakes.

The short-term goal identified as having the highest priority is the implementation of a conservative sub-glacial hydrology model with explicit calculation of water pressures and allowance for inputs from the ice sheet surface. That model should be coupled to an appropriate ice sheet model through a sliding “law” that is consistent with current theory and observations. Other short-term goals include the adoption of a common platform (i.e. large-scale ice sheet model and/or code base) for model development, the development of standardized test cases for use in comparing and contrasting different models, and models that allow for an accurate description of mass and energy redistribution and storage beneath ice sheets. The long-term goal for land-ice hydrology modeling is a unified (i.e. supra-, en-, and sub-glacial) model of land-ice hydrology that reproduces existing observations of the physical, chemical, and biological properties of the hydrological system and makes testable predictions of those properties. Note that the short-term goals are primarily focused on the effects of land-ice hydrology on ice sheet dynamics and mass balance, while the long-term goal establishes a clear link to other research communities that may not have an explicit interest in the understanding and modeling of land-ice hydrology.

Next Steps

After the workshop, the conveners devised the following plan for achieving several of short-term goals noted above. First, the sliding law of Schoof (2005) will be implemented and tested within the Community Ice Sheet Model (CISM). This sliding law provides an attractive starting point because (1) it is based on strong theoretical arguments (Schoof, 2005) and has observational support (e.g. Iverson, 2010), (2) it allows for links to the relevant sub-glacial hydrological variables (i.e. water pressure, basal roughness), (3) it is flexible enough to represent sliding over both hard and soft beds (i.e., its mathematical form is similar to other Coulomb-friction-based sliding laws already implemented within ice sheet models, including CISM), and (4) its implementation and solution are amenable to a number of well established, robust numerical methods (e.g. Price and Stadler, 2010). Second, an existing sub-glacial water “film” model already implemented within CISM (based on the work of Johnson et al., 2002) will be adapted to represent flow in a distributed sub-glacial drainage system (i.e. flow will be treated as occurring in a “macro-porous” sub-glacial sheet). The water pressure within this system will be obtained through the inversion of a functional relationship between subglacial water pressure and water depth. Third, a standard description of channelized flow will be added to this model (e.g. Flowers, 2008; Schoof, 2010). Transfer between the channelized and distributed systems will be

treated in a manner similar to Flowers (2008). Fourth, the complete model will be tested and compared with other existing models using the set of idealized domains and forcings suggested in Flowers and Clarke (2002). Ideally, the latter examples will serve as the beginning of a set of formal benchmark experiments to be used for the intercomparison and sensitivity testing of other land-ice hydrology models.

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