The challenge of predicting the glacial contribution to sea level rise

MARTIN TRUFFER
Geophysical Institute, University of Alaska, Fairbanks, AK 99775
truffer@gi.alaska.edu

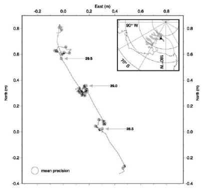
Introduction

The most recent report of the Intergovernmental Panel on Climate Change states that currently we have neither a best estimate nor a reasonable upper limit for the 21st century contribution from the ice sheets to global sea level rise. This is due to at least two things: 1) glaciology is observationally drastically undersampled, and 2) current ice flow models and their coupling to General Circulation Models are still in their infancy.

Observations on ice sheets

Some of the very basic observations needed for ice sheet modeling are currently not made. This includes observations of material properties of ice (a function of temperature and ice fabric, both of which depend on ice sheet history), and of the boundary conditions. The most important unknowns are the basal boundary condition (heat flux and basal motion) and ice-ocean interaction at the ice sheet margins.
But many of the physical processes remain poorly understood. I will illustrate this by showing several examples of recent discoveries that were entirely unanticipated. Observationally, the ice sheets still hold many surprises.

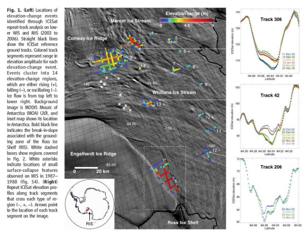
Ice stream stick slip motion



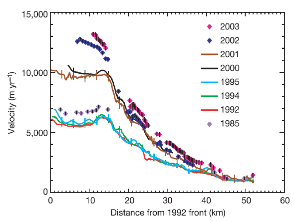
Bindschadler et al. (2003) discovered tidally controlled stick-slip motion on an Antarctic ice stream. During most of the day the ice is essentially stationary, but twice a day (controlled by tides) it moves during about twenty minutes. This is in contrast to the usual mechanism of non-linear viscous deformation.

Water displacement under the West Antarctic Ice Sheet

Fricker et al. (2007) discovered localized vertical motion exceeding several meters at several locations in West Antarctica. The most plausible explanation for this is the drainage and filling of large subglacial lakes. These lakes were known to exist, but it was not generally believed that the hydraulic system operated on such short time scales. The effect was measured via satellite borne laser altimetry, which is part of an effort to measure the mass balance of the ice sheets.



Thinning, acceleration, and retreat of Greenland's ice streams



Joughin et al. (2004) described a doubling of ice discharge from one of Greenland's largest ice streams. *Rignot et al. (2006)* showed that this increase was consistent over much of southern Greenland. The acceleration in flow occurred at the same time as glacier acceleration and terminus retreat. These discoveries led to a radical rethinking of the relevant ice sheet time scales (*e.g. Truffer and Fahnestock, 2007*)

Ice sheet modeling

Some basic features of ice sheet models

A state-of-the-art ice sheet model (such as UAF's Parallel Ice Sheet Model (PISM), (*Bueler et al., 2007*) includes the following components:

- An approximation of the incompressible non-linear Stokes equations that is based on a shallowness argument (ice sheets are **much** wider than thick). Two such approximations are known: the Shallow Ice Approximation and the Shallow Shelf Approximation. PISM is unique among publicly available codes in that it can solve either set of equations (depending on a given mask or the solution of a free boundary problem (*Schoof, 2006*)).
- A model of the energy balance, which includes advection and vertical conduction.
- A model of displacement of the Earth's crust.
- Some models (such as SICOPOLIS, *Greve, 1997*) treat polythermal ice (a mixture of ice at the pressure-melting point and cold ice).

Some basic problems with all ice sheet models

Some of the (currently) unanswered challenges for ice sheet modeling include:

- Missing data for initial conditions (temperature and ice fabrics)
- An incomplete map of geothermal heat flux
- An incomplete physical understanding of basal motion
- An incomplete understanding of ice-ocean interaction
- Insufficient model resolution to accurately represent ice topography and flow
- The approximations of the incompressible non-linear Stokes equations are insufficient to accurately describe ice flow in some areas of fast flow and in areas of transtioning flow

The issue of resolution

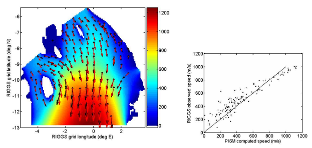
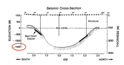
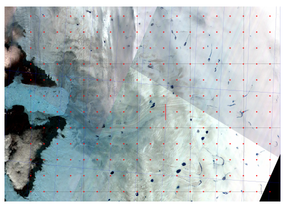


FIGURE 15. *Left*: Color is speed in m/a. Arrows are observed (black) and computed (red) velocities at RIGGS points. *Right*: Comparison between modeled and observed speeds at RIGGS points; compare figure 2 in [32].

Bueler et al. (1995, also http://www.pism-docs.org) modeled the Ross Ice Shelf in West Antarctica at relatively high horizontal resolution (grid spacing 6 km) and obtained excellent agreement between measured and modeled surface velocities. It is beyond the computing power of even large parallel supercomputers to run a continent wide model of Antarctica at this resolution for a significant amount of time (several millenia).

Ice streams





The satellite image shows the Ilulissat (Jakobshavn) Glacier in West Greenland. It drains about 7% of the entire Greenland Ice Sheet. Superimposed is a 5 km grid, which is the resolution of a good ice sheet model. Along the red line, *Clarke and Echelmeyer (1996)* measured a channel extending to 1500 m below sea level (top graph). The flow in this channel dominates the entire ice flow of the region. The physics of this flow is not captured by the shallow approximations that are usually used, and the channel is not resolved at the model resolution.

Acknowledgements

This poster draws from the work of many people. In particular I would like to acknowledge Ed Bueler at University of Alaska Fairbanks, who is the lead developer of PISM (which is available via www.pism-docs.org). The poster is a representation of my personal view on the state of glaciology in terms of observations and modeling.
I also acknowledge NSF and NASA for funding.

References

Bindschadler, R. A., King, M. A., Alley, R. B., Anandakrishnan, S., and Padman, L. (2003). Tidally Controlled Stick-Slip Discharge of a West Antarctic Ice Stream. *Science*, 301:1087–1090

Bueler, E., Brown, J., and Lingle, C. (2007). Exact solutions to the thermomechanically coupled shallow ice approximation: effective tools for verification. *J. Glaciol.*, 53(182):499–516

Clarke, T. S. and Echelmeyer, K. (1996). Seismic-reflection evidence for a deep subglacial trough beneath Jakobshavns Isbræ, West Greenland. *Journal of Glaciology*, 42:219–232

Joughin, I., Abdalati, W., and Fahnestock, M. (2004). Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier. *Nature*, 432:608–610

Fricker, H. A., Scambos, T., Bindschadler, R., and Padman, L. (2007). An Active Subglacial Water System in West Antarctica Mapped from Space. *Science*, 315:1544–

Greve, R. (1997). Application of a Polythermal Three-Dimensional Ice Sheet Model to the Greenland Ice Sheet: Response to Steady-State and Transient Climate Scenarios. *Journal of Climate*, 10:901–918 Rignot, E. and Kanagaratnam, P. (2006). Changes in the velocity structure of the Greenland Ice Sheet. *Science*, 311:986–990

Schoof, C. (2006). A variational approach to ice stream flow. *Journal of Fluid Mechanics*, 556:227–251

Truffer, M. and Fahnestock, M. (2007). Rethinking ice sheet time scales. *Science*, 315:1508–1510