Recent Changes in Greenland & Antarctica

April 23, 2013
Ice and Climate, ATM S 514

Kristin Poinar
and Ian Joughin
Polar Science Center
Applied Physics Lab
University of Washington
What is 1 meter of sea level rise?

IPCC 21st Century Sea Level Change:
0.18 to 0.59 meters

From ice sheets /glaciers:
0.04 to 0.23 meters

... uncertainties about glacier basal conditions, ice deformation and interactions with the surrounding ocean seriously limit the ability to make accurate projections (IPCC, 2007).
Potential Cryosphere Contributions to Sea Level

- Glaciers: 0.37 meters
- Greenland: 7 meters
- Antarctica: 57 meters
- West Antarctica: 5 meters
This talk: Recent lines of thought on what controls and will control ice discharge.

Outlet glacier speedup and ice/ocean interaction (Greenland & Antarctica)

Surface melt & supraglacial lakes (Greenland)

Marine Ice Sheet Instability (Antarctica)
Ice movement: part deformation, part sliding

Zwally 2002 hypothesis:
Increasing the amount of water at the bed should* increase sliding, which would put more ice into the ocean.

*we now know this isn’t the case (see Schoof 2010)
Greenland – Wet and Warm

Antarctica – Cold and Dry
How surface meltwater could reach the bed
Recent observations of Greenland melt

Maximum melt extent (% of total ice sheet area)

Fettweis et al., 2007

+0.06 yr\(^{-1}\)

+0.03 yr\(^{-1}\)

Greenland surface melt – where does it go?

The ice melts and turns into water, and water flows downhill.

The ocean is downhill from the ice sheet, so all the water ends up there... right?

In a river, rocks on the bottom control the surface pattern of the fluid moving over them.

On an ice sheet, bumps on the bedrock control the surface pattern of the fluid moving over them.
These lakes are not exactly rare!

MODIS image, June 26 2008

Sarah Das, WHOI
Meltwater collects in surface depressions of the ice sheet

... What happens next?

photo by Ian Joughin, http://bigice.apl.washington.edu
What’s wrong with this situation?
(water sitting on top of ice)

Ice (low density) on top of water (high density)

Water (high density) on top of ice (low density)

$\rho_{\text{water}} > \rho_{\text{ice}}$
Hydrofracture

- $\rho_{\text{water}} > \rho_{\text{ice}}$

- Pressure from the water column can fracture the ice

- If enough water is available, it will drive the crack all the way down ~1 km

Ian Joughin, http://bigice.apl.washington.edu
Melt water can punch a hole in the ice sheet

To punch a hole in the Greenland Ice Sheet, all you need is 11 billion gallons of water and a slight depression in the ice sheet to put it in.
Hydrofracture causes lake drainage

How do the cracks form?

How long does draining take?
The fracture: cracks & blocks

Lake

Cracks open up during drainage

Network of cracks creates detached ice blocks
90 minute lake drainage

<table>
<thead>
<tr>
<th></th>
<th>Flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niagara Falls average</td>
<td>1,800 m³/s</td>
</tr>
<tr>
<td>South Lake drainage</td>
<td>8,700 m³/s</td>
</tr>
</tbody>
</table>

Lake used to be 8 m (24 ft) deep

her height \( \times 5 \) = old water level
Moulin: an in-glacier waterfall path

Photo by Ian Joughin, http://bigice.apl.washington.edu
1 day after lake drainage

1 week after lake drainage

10 years after first lake drainage

1 year after lake drainage
Hydrofracture causes lake drainage

South Lake, July, filling up with meltwater

South Lake site, July, crack the lake drained through

Where does the water go?
Why does it matter?
Field project: If meltwater reaches the bed, does it affect ice flow?

GPS stations:
- Horizontal motion (ice sheet velocity)
- Vertical position (ice sheet uplift)

Pressure loggers to measure water depth:
Volume of water in lake over time
Does the meltwater speed up ice sheet flow?

The meltwater "blisters" up the ice sheet locally and speeds it up temporarily...

... but the effects of lake drainage become small as you go far from the lake,

... and the speedup is short-lived (~24 hr).

Colors: ice velocity measured at GPS stations
Black/gray: air temperatures (→ ice melt)
Does the meltwater speed up ice sheet flow?

Large, far away glaciers are not perceptibly affected

Approximate area experiencing temporary speedup

Lake with drainage recorded

The meltwater “blisters” up the ice sheet locally and speeds it up temporarily…

… but the effects of lake drainage become small as you go far from the lake,

… and the speedup is short-lived (~24 hr).
Speeds on Jakobshavn Isbrae, a huge outlet glacier nearby

If the enhanced basal lubrication from nearby surface meltwater can’t explain this glacier’s acceleration, then what can?
• Melt-related seasonal speedup is widespread across the ablation zone in Greenland.

• Melt-related seasonal speedup is significant in regions of ice sheet flow (rather than outlet glacier flow).

• Season melt lubrication is **not** responsible for the rapid speedups on outlet glaciers (can explain <10% of speedup).

• Jakobshavn Isbrae shows much stronger seasonal sensitivity to ice front position, which supports the hypothesis that its large speedup is a response to the loss of a buttressing ice tongue or terminus retreat.
This talk: Recent lines of thought on what controls and will control ice discharge

Outlet glacier speedup and ice/ocean interaction (Greenland & Antarctica)

Surface melt & supraglacial lakes (Greenland)

Marine Ice Sheet Instability (Antarctica)
Iceberg calving and ice discharge is the source of much of our uncertainty in projecting sea level rise contributions from ice sheets.
Buttressing Effects
Jakobshavn Isbrae, Greenland

Icebergs, bergy bits, and sea ice

Ice sheet / outlet glacier
Ice Shelf Buttressing
Iceberg Discharge To The Ocean
Pine Island Glacier, west Antarctica

Acceleration & grounding line retreat

Grounding Line Position

1996

2009

Mar 09
Feb 09
Feb 06
00
96

Distance Along Profile (km)

Speed (m/yr)
Pine Island Glacier, west Antarctica

Acceleration & grounding line retreat

Strong Sensitivity to Warmer Ocean Temperatures

Grounding Line Position

1996

2009

Ice Shelf

Sea Ice

Continental Shelf

circumpolar deep water (WARM)

Strong Sensitivity to Warmer Ocean Temperatures
Observations of warming waters (more CDW) under Pine Island ice shelf

Warm ocean waters are melting the Pine Island ice shelf from below
  • Reduction of ice shelf buttressing
  • Speedup
We can also directly observe the thinning of the ice from this melt & acceleration

Jacobs et al., 2011
Thinning Rates

Lines: measured from space
Solid area: modeled

This model can tell us what’s likely to happen to Pine Island Glacier… how much ice will it discharge to the ocean over time?

Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica
Ian Joughin, Benjamin E. Smith, & David M. Holland (2010)
Projected sea level rise from PIG by year 2100

0.5 to 2.7 cm
depending on how quickly the ice shelf disappears

Earlier upper bound estimates (Pfeffer et al., 2008)
- Pine Island Glacier: 4 to 15 cm
- Amundsen Coast: 11 to 37 cm
  (Pine Island accounts for about 40% of the mass loss of the Amundsen Coast glaciers)
Why Better Predictions are Difficult

- Most of the processes just described are poorly understood and not represented in most models.
  - Calving dynamics and sensitivity to temperature.
  - Sliding law (response to change)

- Boundary conditions for ice flow models are poorly known (e.g., deep channels through which most Greenland glaciers flow are not resolved in bed topography maps).

- Resolution of ice sheet models (~20 km) is insufficient to include the fast flow features (~5 km) that influence the rate at which the ice sheet responds to climate change.
This talk: Recent lines of thought on what controls and will control ice discharge

Outlet glacier speedup and ice/ocean interaction (Greenland & Antarctica)

Surface melt & supraglacial lakes (Greenland)

Marine Ice Sheet Instability (Antarctica)
West Antarctic ice sheet and CO₂ greenhouse effect: a threat of disaster

J. H. Mercer

Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210

Fig. 3 a, Antarctic ice cover today, and b, after a 5–10 °C warming.
Marine Ice Sheet Instability
(the part driven by ice dynamics)
“Dynamical Changes”

Warming ocean causes retreat at the terminus

Ice flow

Reversed bed slope

Bedrock high

Bedrock

Ocean
“Dynamical Changes”

Retreat triggers thinning, steepening, and acceleration upstream.
Does the retreat stop?
If terminus stays on level or forward-sloped ground... YES
How an ice sheet works (roughly):

1. Force balance on a volume within ice sheet
   Surface slope leads to pressure gradient

Pressure gradient balances shear stress:

\[ \sigma_{ij} = -\int_{z}^{z_s} \frac{\partial p}{\partial x} \, dz \]
How an ice sheet works (roughly):

2. Ice responds to stress by **deforming** (creep flow)

Glen’s flow law: relates strain rate to applied stress

\[
\dot{\varepsilon} \left( \sim \frac{du}{dz} \right) = A(T) \times \sigma_{ij}^3
\]

Strain rate \( \propto \) (Stress)\(^3\)
3. Equilibrium state is a flux balance

Steady state mass balance:

\[ \text{Flux of ice} \propto H^5 \times \left( \frac{dh_s}{dx} \right)^3 = \int_0^x (\text{snowfall} - \text{melting}) \, dx \]

- ice flow is basically a very nonlinear diffusion equation
Flux out ($\sim H^5$) must balance snowfall in.
Does the retreat stop?
If terminus reaches reverse-sloped ground... NO

Flow speed ~ $H^5$ !!!
Does the retreat stop?
If terminus reaches reverse-sloped ground... NO

Flow speed $\sim H^5$ !!!
Does the retreat stop?
If terminus reaches reverse-sloped ground... NO

Flow speed $\sim H^5$ !!!
Marine Ice Sheet Instability hypothesis

This positive feedback has the potential to destroy WAIS anywhere with reverse-sloped bedrock, and will “float” any ice grounded below sea level (BLUE here)
Triggering MISI: warmer ocean water

Strong Sensitivity to Warmer Ocean Temperatures
Triggering MISI: tidal flexure at grounding zone

Ross Ice Shelf
Tides ~3m peak to peak
Tidal Flexure of ice shelf

High Tide

Ice flow

Reversed bed slope

Bedrock high

Bedrock
Tidal Flexure of ice shelf

Low Tide

Ice flow

Bedrock high

Reversed bed slope
“For now, this has not caused catastrophic melting because once high tide arrives, the glacial tongue floats back up and the inland ice settles, squeezing the water out. In the process, the glacier compacts sediment underneath the ice, cementing a muddy ridge that actually further stabilizes ice.” (News article on Richard Alley’s AGU talk, 2012)
Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet

Jonathan L. Bamber, Riccardo E. M. Riva, Bert L. A. Vermeersen, Anne M. LeBrocq
Summary

Greenland:
  Enhanced basal lubrication from surface melt
    - significant effect only locally, temporarily

  Speedup of outlet glaciers
    - tied to decreased buttressing in fjords

Antarctica:
  Speedup of Pine Island Glacier
    - tied to warm ocean waters melting ice shelf from below

  Marine Ice Sheet Instability hypothesis
    - reverse-slope bed below sea level (WAIS) is vulnerable
    - a wildcard; plausible and possible at Thwaites Glacier
Greenland / Lake drainages

Fracture Propagation to the Base of the Greenland Ice Sheet During Supraglacial Lake Drainage
Sarah B. Das, Ian Joughin, Mark D. Behn, Ian M. Howat, Matt A. King, Dan Lizarralde and Maya P. Bhatia
Science 9 May 2008: Vol. 320 no. 5877 pp. 778-781
doi: 10.1126/science.1153360

Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow
H. Jay Zwally, Waleed Abdalati, Tom Herring, Kristine Larson, Jack Saba, Konrad Steffen
Science 12 July 2002: Vol. 297 no. 5579 pp. 218-222
doi: 10.1126/science.1072708

The asterisk on Slide 5 (new developments since the assumption that more water at the bed means faster motion)
Ice-sheet acceleration driven by melt supply variability
Christian Schoof
Nature 468 803 (2010)
doi:10.1038/nature09618

Greenland / Jakobshavn velocities

Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier
Ian Joughin, Waleed Abdalati & Mark Fahnestock
doi:10.1038/nature03130

Seasonal speedup along the western flank of the Greenland Ice Sheet
Ian Joughin, Sarah Das, Matt King, Ben Smith, Ian Howat, Twila Moon
doi: 10.1126/science.1153288

Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters
David M. Holland, Robert H. Thomas, Brad de Young, Mads H. Ribergaard & Bjarne Lyberth
Nature Geoscience 1, 659-664 (2008)
doi:10.1038/ngeo316
Antarctica / Pine Island glacier

Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica
Ian Joughin, Benjamin E. Smith, David M. Holland
GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L20502, 5 pp., 2010
doi:10.1029/2010GL044819

Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf
Stanley S. Jacobs, Adrian Jenkins, Claudia F. Giulivi, Pierre Dutrieux
Nature Geoscience 4, 519–523 (2011)
doi:10.1038/ngeo1188

Marine Ice Sheet Instability hypothesis


Hannes Grobe. Marine Ice Sheet Instability at http://www.antarcticglaciers.org/marine-ice-sheets

Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet
Jonathan L. Bamber, Riccardo E. M. Riva, Bert L. A. Vermeersen, Anne M. LeBrocq
Science 324, 901 (2009)
doi: 10.1126/science.1169335

Ice sheet grounding line dynamics: Steady states, stability, and hysteresis
Christian Schoof
JGR 112, F03S28 (2007)
doi:10.1029/2006JF000664

Dynamic (in)stability of Thwaites Glacier, West Antarctica
JGR (accepted 2013)