The Wedge, Grease and Heat: Why Ice Sheets Hate Water

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My Impressions

😊 “Include land ice component” is one of 6 Science Priorities
😊 CCSM is a very large community
😊 CCSM has lots of young people
😊 Ice sheet inclusion assigned to just two persons
😊 Polar continental-shelf oceanography seems to be missing
Ice-Sheet Surprises

• Ice shelf disintegrations
  – Suddenly unbuttressed land ice
• Summer acceleration of Greenland ice
• Accelerating outlet glaciers
  – Rapidly declining ice-sheet volume
• Subglacial water activity
• Tidal modulation of ice stream speed

Definitely NOT yo’Mama’s ice sheets
Ice Sheets matter NOW:

Maldives

London
“...but..flow rates could increase or decrease in the future.”

“Larger values cannot be excluded...”

“...understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise.”
Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (a.k.a. NRC Decadal Survey)

Key Question #1 (of 6):
“Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctica and, if so, how rapidly will this occur? What will be the time patterns of sea level rise as a result?”
Ice Sheets matter Globally

Land area lost by 1-meter rise in sea level

Source: CReSIS and NASA
Impact of 1-meter sea level rise:

An immediate and significant impact on economies and ecosystems worldwide

From Anthoff et al., 2006
Sea Level Rise Components

- Ocean Thermal Expansion
- Glaciers and Ice Caps
- Ice Sheets

Source: IPCC FAR
Potential Sea Level

2-6% of all water on Earth
70-80% of all fresh water on Earth
In a Warming Climate

- Warmer air temperatures should lead to increased snowfall
  - slow ice-sheet growth right away
- Warmer air temperatures should melt ice faster
  - slow ice-sheet shrinkage right away
- Warmer ice deforms and flows slightly faster
  - smaller ice sheets after a long time
- Changes in boundary conditions at base or ice front might accelerate ice flow significantly
  - much smaller ice sheets almost right away

Changes in ice flow may dominate near-term sea level change
Sea-Level History Lessons

• Warmer climates **always** lead to less ice and higher sea level
• Sea level rises much faster than it falls
• Sea level has risen 20x the present rate
• Humans have never dealt with **rapid** sea level rise

Source: Fairbanks, 1989
### “Old” Greenland Ice Sheet

<table>
<thead>
<tr>
<th>Sea level Change (mm/a)</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>accumulation</td>
<td>450 Gt/a</td>
<td></td>
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<tr>
<td>melting</td>
<td>225 Gt/a</td>
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<tr>
<td>ice flow</td>
<td>225 Gt/a</td>
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</tbody>
</table>

Approximately in “mass balance”
Observations

• Thickening in the high elevation interior of Greenland
  – Big change can be 10%
  – Climate models get this about right

• Increase in surface melting around perimeter
  – Big change can be 50%
  – Climate models also get this about right

• Large acceleration, retreat and thinning of outlet glaciers
  – Big change can be 100’s%
  – 500% observed already
  – Ice flow models can’t get this right
Tomorrow’s Greenland Ice Sheet

Sea level Change (mm/a)

-1  0  +1

accumulation

melting

ice flow

Things could get a little better or a lot worse. Increased ice flow will dominate the future rate of change.
Fastest Flow at the Edges

Interior: 1000’s meters thick and slow
Perimeter: 100’s meters thick and fast

Response time and speed of perturbation propagation are tied directly to ice flow speed
Declining “Health” of Greenland

Contact Scott Luthke, NASA Goddard Space Flight Center for permission to use this figure

(Source: Luthcke et al., unpub.)
Mass Balance Results

GREENLAND

ANTARCTICA
Ice-Sheet Surprises

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- Tidal modulation of ice stream speed
All caused by

- Ice shelf disintegrations
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- Tidal modulation of ice stream speed
The most sophisticated ice-flow models can’t reproduce recent ice-sheet behavior.
Water as The Wedge

- Air
- Ice
- Water
- Stable
- Propagation
Disintegrating Ice Shelves

2000 km² of Larsen Ice Shelf disintegrated in 2 days.

Require >10,000 years to form
Disintegrate in weeks

Source: T. Scambos
Consequence of Ice Shelf Loss

Formerly buttressed glaciers accelerate up to 400% faster in 2 years (Scambos et al., 2004)

up to 510% faster in 2 years

Formerly buttressed glaciers accelerate
Water as Grease

well understood for mountain glaciers

Summer meltwater penetrates to glacier bed reducing basal friction

Black Rapids Glacier (Rabus and Fatland, 2006)
Summer acceleration of Greenland’s margins

Glacier flow increases 10-15%
Slower ice increases up to 70%

(from Joughin et al., 2008)

(from Zwally et al., 2002)
More Melt = More Lubrication = Faster Flow

Flow increase is proportional to amount of melt

(Source: M. Tedesco)
The deepest outlet glaciers exiting into the ocean are responding most. WHY?
Accelerating Outlet Glaciers

(Rignot and Kanagaratnam, 2006)

95% increase (1996-2005)
210% increase (2000-2005)
60% increase (2000-2005)

(Source: I. Joughin)

(Rignot and Kanagaratnam, 2006)
Warm Water Spotted Offshore

Sea surface temperature anomaly for August 2003

(Source: Howat et al., submitted)
Rapid Retreat

Jacobshavns Isbrae

Kangerdlugssuaq Glacier

50 years

60 years

5 years

40 years

50 years

2005

2004

2003

2002

2001

2000

1999

1998

1997

1996

1995

1994

1993

1992

1991

1990

1883

1881

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1855

1853

1851
Extreme Sub-Ice-Shelf Melt Rates

10 m/a melt per 1K temperature difference

Freezing point depression due to 1000-m thick ice
Pine Island Glacier (PIG) Ice Shelf

This project's official title is "Ocean-Ice Interaction in the Amundsen Sea: the Keystone to Ice-Sheet Stability". A real mouthful, but it captures the essence of what we intend to do, where we will do it and why we feel it is important to do it. Various other measurements have captured the West Antarctic ice sheet changing very rapidly in the region where it flows into the Amundsen Sea, one of the sectors of the Southern Ocean. The spatial pattern strongly suggests that the cause of this change is weaker ice shelves, the floating apron of ice that fringe the perimeter of the ice sheet. Our hypothesis is that warm water is melting the undersides of these ice shelves decreasing the "back pressure" from the ice shelves to help hold the ice sheet. Less backpressure means the ice sheet can flow faster. Faster flow-smaller ice sheet-higher sea levels-slow motion coastal flooding worldwide.

Doubled speed in 20 years
Now moving One foot per hour!

http://pigiceshelf.nasa.gov
Our Hypothesis
Ice Shelf Sensitivity

• Thinning
  – reduces buttressing (recall Larsen-B)

• Grounding line retreat replaces friction controlled flow (slow) with stretching flow (fast)
  – Speed of floating ice controlled by “creep thinning”, goes as (ice thickness)$^3$
Start in the Atmosphere

Increased temperature gradient increases circumpolar winds
Now Some Oceanography
Some More Oceanography

Circumpolar Deep Water (CDW)

3-layer polar ocean

2-layer tropical ocean

Source: S. Jacobs
Upwelling of CDW

Ekman Drift

CDW
Getting Hot Water (CDW) to the Glaciers

Marie Byrd Seamounts

Thinning Rates (from Shepherd et al.)

Amundsen Sea

Figure 2. Pie and Smith available evidence suggests that the majority of the East Greenland Thwaites Glacier is grounded on a thin sediment layer that is anchored along a seaward escarpment. The Thwaites Glacier flows southward from the margins of the Thwaites Glacier Ice Shelf and is supported by the subglacial bed on the east side of the escarpment.

F. Nitsche 2007
An Interdisciplinary Process

Meteorology

Oceanography

Marine Geophysics

Glaciology

- Ozone hole causes stratospheric cooling and tropospheric warming
- Southern Ocean westerlies intensify
- Circumpolar Current increases
- Ekman transport cause upwelling of Circumpolar Deep Water (CDW)
- CDW brings heat onto Amundsen Sea continental shelf
- Glacially eroded troughs funnel warm water toward outlet glaciers
- Increased basal melt of ice shelves results in ice acceleration
Field studies of all three (and more) processes are underway.

Meanwhile…
Tidewater glaciers are a good analogue to anticipate ice sheet future.

Muir Glacier, Alaska

Large outlet glaciers are displaying classic “drastic retreat” traits similar to Alaskan tidewater glaciers.
Tidewater Glacier “Drastic Retreat”

- Altitude (m.a.s.l.)
- Distance (km)

Quasi-stable

Sea level
Tidewater Glacier “Drastic Retreat”

- Still retreating
- Retreating
- Quasi-stable
• Central region of Greenland is below sea level
• Jacobshavns Isbrae occupies subglacial channel connected to central depression
Nearly all of West Antarctica ice sheet and much of East Antarctica ice sheet rests on bed below sea level.
Just one more water-driven effect to leave you with...
Ice Stream Sensitivity

- Tidal modulation
  - $\pm 50\%$ speed modulation is typical
  - Stick-slip is extreme case

(Source: Bindschadler et al., 2003)
Summary

• Ice sheets HATE water
• Ice sheet loss (and rising sea level) will accelerate
  – Need to include rapid response characteristics in global climate models
• New modeling activities can lead, guide and leverage off of current and ongoing field studies
  – Must connect deep oceans to ice sheets
  – Tidewater glacier retreat an excellent analogue, but also unsolved
  – A 2-person effort is woefully inadequate
IPY is a Good Time to Learn about Ice Sheets

"Gentlemen, it's time we gave some serious thought to the effects of global warming"
Thank you!

Questions?

Photo: I. Joughin