Recent changes in the ice sheets as observed through remote sensing
What is the IPCC?
(Intergovernmental Panel on Climate Change)

• Intergovernmental Panel on Climate Change

• Organization of scientists created in 1988 by two United Nations organizations
  • World Meteorological Organization
  • UN Environment Program

• Purpose: “to assess the state of knowledge about the human role in climate change”

• Fourth Assessment Report (AR4): 2007
• Fifth Assessment Report (AR5): 2013
• Sixth Assessment Report (AR6): 2022
Outline

• Sea level rise and “rapid dynamical processes”

• Ice-sheet mass balance

• Ice-shelf melting in Antarctica

• Outlet glacier speedup in Greenland

• Marine ice sheet instability
Sea level rise
and “rapid dynamical processes”

1. How important are the ice sheets for sea level rise?

2. What are some of the “rapid dynamical processes” occurring on the ice sheets, and where are they occurring?
How much water is currently locked up in the ice sheets?

Sea-level rise potential:
- West Antarctic Ice Sheet: 3-5 m
- East Antarctic Ice Sheet: 60 m
- Greenland Ice Sheet: 5-7 m
- Glaciers: 0.5 m

Total: ~70 m
Sea level rise rate in 1992: $\sim 2.2 \text{mm/yr}$

Source: IPCC AR5
Current sea level rise rate: \(~3.2\text{mm/yr}\)

- Antarctica: \(0.4\text{mm/yr}\)
- Glaciers: \(0.7\text{mm/yr}\)
- Greenland: \(0.7\text{mm/yr}\)
- Thermal expansion: \(1.4\text{mm/yr}\)

Source: IPCC AR5
Rates of sea level rise from Earth’s ice
(Thermal expansion of ocean water also contributes to SLR, but isn’t shown here)

Source: IPCC AR5
In 2007, science couldn’t fully explain changes observed on the ice sheets, so the IPCC sea level prediction did not account for that rapid dynamical changes in ice flow.
Sea-level rise predictions in AR4/AR5
Are they different? How? Why?

AR4 (2007)

AR5 (2013)

x-axes: different emissions scenarios
(we don’t know how much CO₂ we will emit, so these are various guesses)
• Sea level rise and “rapid dynamical processes”

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Measuring the **mass balance** of Greenland and Antarctica

1. What are the three methods that we use to measure ice-sheet mass balance?

2. What are the strengths and limitations of each method?

3. Should all three methods come up with the same answer? Do they?
Measuring mass balance

1. Mass Budget method, also called Input-Output method

Input: Snowfall / surface mass balance

How do we measure these things?

Output: Glacier flow/discharge
Measuring mass balance

1. Mass Budget method, also called Input-Output method

An example: Jakobshavn Isbrae, West Greenland

\[
\text{Ice discharge} = \text{velocity} \times \text{width} \times \text{ice thickness}
\]

Modified from Howat et al., 2011
Measuring mass balance

2. Repeat altimetry
Measuring mass balance

2. Repeat altimetry

Surface-elevation change rates from ICESat (2003-2007)

Pritchard et al., 2009

How do we convert a change in ice thickness to a change in mass?

Firn density

So... what are the potential limitations of this method?
Measuring mass balance

3. Geodetic method: changes in gravity

Earth’s mass is NOT distributed evenly!

How is gravity measured with the GRACE satellites?

- Distance between two satellites

Red = high; blue = low
Measuring mass balance
3. Gravimetry

What other processes might cause mass change near the poles?

**Isostatic rebound**
The flow of the mantle messes with the gravity signal from the ice sheet.

Viscous component (happens slowly)

Elastic component (happens immediately)
Measuring mass balance
3. Gravimetry

Antarctic surface mass balance measured by GRACE

- Red: Observed by GRACE
- Blue: After correcting for isostatic adjustment

Shum et al. 2008
Changes in the Antarctic ice sheets measured by the GRACE satellite

![Graph depicting changes in Antarctic ice mass from 2003 to 2013](image)
Changes in the Greenland ice sheet measured by the GRACE satellite

Greenland

Ice Mass (Gt)

Calendar Year


-1800 -1500 -1200 -900 -600 -300 0 300 600 900 1200

2012 –

2008

2004

2000

Changes in the Greenland ice sheet measured by the GRACE satellite
What measurements do we need for each method?

(1) Mass budget  
(2) Repeat altimetry  
(3) Gravimetry
Combining all three mass balance techniques
Combining all three mass balance techniques

Shepherd et al., 2012

“Good agreement was obtained between the estimates from different methods and, while the uncertainties of any method are sometimes large, the combination of methods considerably improves the overall certainty.”

- IPCC AR5
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Ice-shelf buttressing

1. Why are ice shelves important to ice flow?

2. How might the ocean and atmosphere affect the ice shelves?

3. What observations do we have of how ice shelves affect ice flow?
Why are ice shelves important?

With an ice shelf

Ice shelves “buttress” grounded ice if they come in contact with rock or slower moving ice.

Without an ice shelf

Loss of an ice shelf can cause speedup of grounded ice.
Ice shelves are important because they can buttress grounded ice.

Which ice shelf is likely more important for buttressing upstream flow? Why?

An “unconfined” ice tongue  
A “confined” ice shelf

Source: ESA  
Source: Landsat 7
Ice shelves & surface melt

Larsen B partial collapse (Antarctic Peninsula)

How might surface melt have contributed to the collapse?
Ice shelves & surface melt

Larsen B partial collapse (Antarctic Peninsula)

Speedup of outlet glaciers after ice shelf collapse

Before collapse | After collapse | Velocity increase

Wuite et al., 2015
Significant ice shelf thinning in the Amundsen Sea (AS) region, including on Pine Island Ice Shelf.
Ocean circulation under an ice shelf

Warm, salty Circumpolar Deep Water (CDW) can get up on the continental shelf and melt the ice shelf.

Source: David Ferreira
Observations of the ocean water under Pine Island ice shelf

Ocean temperature in 2009

Circumpolar Deep Water

Dutrieux et al., 2014
Observations and modeling of the ocean water under Pine Island ice shelf in 2009 and 2012

Amount of CDW getting onto the shelf changes from year to year.

Dutrieux et al., 2014
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Fast, unanticipated changes observed in Greenland glaciers

1. Which glaciers are retreating? Which are speeding up? Which are thinning? Are they the same, and why or why not?

2. Are these speedups consistent? Persistent?
Glacier speedup and thinning along the margins of the Greenland Ice Sheet

Speedup from 2000-2010

Surface elevation change from 2003-2007

Moon et al., 2012

Pritchard et al., 2009

Red = thinning
Jakobshavn Isbræ, West Greenland
Its floating ice shelf broke up in 2000-2003
Jakobshavn Isbræ, West Greenland
Its floating ice shelf broke up in 2000-2003 – and the glacier sped up

Ian Joughin, University of Washington
Speeds on Jakobshavn Isbrae, West Greenland

Ian Joughin, University of Washington
The general picture: Greenland vs. Antarctica

Ocean is likely important for both Antarctica and Greenland. Why?

Joughin et al., 2012
Outline

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• Marine ice sheet instability
1. Which ice sheets are vulnerable to MISI and why are they vulnerable?

2. What processes might “kick off” MISI?
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

[Diagram showing ice flow, maximum stable retreat position, reversed bed slope, bedrock high, and ocean]
Why thicker ice flows MUCH faster

Pressure difference creates stress

\[ \tau = \rho g H \alpha \]

Ice responds by flowing

\[ \dot{\varepsilon} = A(T) \tau^3 \]

\[ \frac{du}{dz} = A(T) \tau^3 \]
Why thicker ice flows MUCH faster

Strain rate gives average ice flow over the thickness of the glacier, locally

\[
\frac{du}{dz} = A(T)\tau^3
\]

\[
u = A(T)\tau^3 H
\]

Total flux through any area of the glacier:

\[
u H = A(T)\tau^3 H^2
\]
Why thicker ice flows MUCH faster

Total flux through any area of the glacier:

\[ uH = A(T)\tau^3H^2 \]

How does stress depend on ice thickness?

\[ \tau = \rho gH\alpha \]

Final expression for ice flux

\[ uH = A(T)\rho g\alpha H^5 \]
Why thicker ice flows MUCH faster

Final expression for ice flux

\[ uH = A(T) \rho g \alpha H^5 \]

Main Point:
Ice flux increases *nonlinearly* with ice thickness.
Stable and unstable steady-state grounding-line positions

A marine ice sheet is in steady state when the ice flux across the grounding line \((q)\) equals the upstream accumulation \((ax)\).

Yellow = unstable
Green = stable

Is a real ice sheet likely to ever be in an unstable steady state?

Joughin et al., 2011; modified from Schoof 2007
Marine Ice Sheet Instability
(the part driven by ice dynamics)
"Dynamical Changes"
Warming ocean causes retreat at the terminus
“Dynamical Changes”
Retreat triggers thinning, steepening, and acceleration upstream 

Ice flow
Reversed bed slope
Bedrock high
Bedrock
Ocean
Does the retreat stop?
If terminus stays on level or forward-sloped ground... YES
Does the retreat stop?
If terminus reaches reverse-sloped ground... NO

Ice flux $\sim H^5$ !!!

Maximum stable retreat position

Ocean

Bedrock high

Reversed bed slope

Bedrock
Does the retreat stop?
If terminus reaches reverse-sloped ground... NO

Ice flux $\sim H^5$ !!!
Marine Ice Sheet Instability hypothesis (MISI) 
Understood since 1978

MISI has the potential to affect glaciers with a reverse bed slope.

WAIS is a “marine ice sheet” and very sensitive to MISI. Why?
Marine Ice Sheet Instability hypothesis (MISI)
Understood since 1978

We generally talk about MISI in Antarctica, but some Greenland glaciers have reverse bed slopes, too.

MISI is often called the “tidewater glacier cycle” in Greenland.

An example in Greenland is Jakobshavn, the glacier we looked at earlier.

Blue areas are below sea level
Morlighem et al., 2014
The end! Here’s what we covered...

- How important the ice sheets are for sea level rise
- How to measure ice sheet mass balance
- Why ice shelves are important and how they might behave in a warming climate
- Why outlet glaciers are likely speeding up and thinning in Greenland
- How bed geometry exerts a strong control on a glacier’s response to climate