Ice Sheets and Ice Shelves: Characteristics and Processes in Antarctica and Greenland

ESS431: Principles of Glaciology
ESS505: The Cryosphere

Wednesday, 10/30 – Knut Christianson
1) Accumulation (Atmosphere)
2) Accumulation (in situ)
3) Ablation
4) Balance (dynamics)
Global Balance

Temperature of Planet Earth

- Millions of years before present
- Thousands of years before present (2015 CE)

Legend:
- Cr: Cretaceous
- D: Devonian
- O: Ordovician
- P: Permian
- T: Triassic
- J: Jurassic
- K: Cretaceous
- Eocene
- Oligocene
- Miocene
- Pliocene
- Pleistocene
- Holocene

Data sources:
- Ruffel and Weis (2005)
- Shackleton et al. (2003)
- others
Global Balance
Global Balance
sea level ~120 m lower (last ice age)
sea level 6 m higher (WAIS or Greenland)
sea level \(\sim 50 \text{ m higher (EAIS)}\)
Today’s focus -

Characteristics of the Modern Ice Sheets
- Their Substrate
- Their Ice Flow Structure

Processes that control their stability
- Ice Shelf Melt
- Marine Ice Sheet Instability
Modern Characteristics
Modern Characteristics
Modern Characteristics
What Controls the Subglacial Topography in Greenland and Antarctica?
Greenland Surface and Bed Topography
Isostatic Depression

a. Peak glaciation

- Soft material in asthenosphere is squeezed out
- Lithosphere bends and sinks
- Fore-bulges rise due to elasticity

http://www.pgc.nrcan.gc.ca/geodyn/docs/rebound/glacial.html
Isostatic Rebound

b. During deglaciation

- Soft material in asthenosphere returns
- Lithosphere rises
- Fore-bulges drop

http://www.pgc.nrcan.gc.ca/geodyn/docs/rebound/glacial.html
Uplift in Scandinavia

The lithosphere still remembers that there was an ice age.
Postglacial Rebound - Coronation Gulf, Nunavut

http://gsc.nrcan.gc.ca/landscapes/
Greenland Topography 15 ka after Ice Melts

Why is the bedrock now above sea level in the interior?

Greenland:

- Tectonically stable for a long time
- Old, thick continental crust, weighed down by the modern ice sheet

Is this an accurate depiction of Greenland?
Higher geothermal flux in central Greenland?
Modern Characteristics
• Antarctica is composed of many distinct geologic terranes, many of which are quite old.

Spiegel et al. (2016)
• Antarctica is composed of many distinct geologic terranes, many of which are quite old.

• The West Antarctic Ice Sheet is mostly younger, thinner crust, formed from recent rifting
Greenland:

- Tectonically stable for a long time
- Old, thick continental crust, weighed down by the modern ice sheet

Antarctica:

- East Antarctica is old, thick, cratonic crust
- West Antarctica is young, thin, rift generated crust
What consequences do the substrate have on Ice Flow?
Ice Flow is Controlled by Geometry + Material
Ice Flow is Controlled by Geometry + Material
Sliding and Geology

(modified after Joughin and others, 2002)
- Soft, sea-floor sediments promote faster flow.
- Hard, crystalline bedrock promotes slower flow.

The availability of soft sediments is one factor that dictates the location and speed of ice streams.

Studinger and others (2000, WAIS Workshop)
ice sheet flow

stiff bed resists
driving stress mainly dissipated by "vertical shear" in the ice

bedrock

soft bed deforms
driving stress mainly dissipated by "longitudinal stretching" and by "lateral shear" at boundaries

soft sediments, water

(courtesy of C. Hulbe, Portland State Univ.)
Schematic Ice Stream Cross Section

- **Schematic Ice Stream Cross Section**

  - **Ice Stream Parameters**
    - **Ice Thickness** $H \sim 10^0$ km
    - **Half Width** $W \sim 10^1$ km

  - **Bed Structure**
    - **Cold - Stuck**
    - **Melting - Slippery**
    - **Failed Till-laden Bed**

  - **Ice Flow Velocities**
    - **Slow** $\sim 10^0$ m a$^{-1}$
    - **Fast** $\sim 10^2$ to $10^3$ m a$^{-1}$
    - **Slow** $\sim 10^0$ m a$^{-1}$
Ice Stream B (Whillans)

Note abrupt shear margins

(source: http://nsidc.org/data/ramp/gallery/icestreamb_mapw.html)
Margin of Ice Stream D (Bindschadler)

Photo by Nadine Nereson
Forces Resisting Driving Stress: Ice Stream
Side Drag is Huge on Ice Streams

Ice Stream B (Whillans)

Side drag > 50% of $\tau_d$

(Here $\tau$ is not a characteristic time)

$\tau_d = \rho g h \sin(\theta)$

would be the basal shear stress, in absence of side drag and longitudinal forces.

From Echelmeyer et al. (1994, JGlac.)
Abstract. The transition in the middle Pleistocene (~0.9 Ma) seen in δ¹⁸O deep-sea-core records from relatively low-amplitude, high-frequency (41 kyr) to high-amplitude, low-frequency (100 kyr) ice volume variations under essentially the same orbital forcing can be attributed to a change from an all soft-bedded to a mixed hard-soft bedded Laurentide ice sheet through glacial erosion of a thick regolith and resulting exposure of unweathered crystalline bedrock. A one-dimensional
• Antarctica and Greenland are Tectonically and Geologically Distinct

What are the consequences for Ice Sheet stability?
Ice Flow is Controlled by Geometry + Material
The problem with a retrograde bed

The bedrock under the front of some Antarctic glaciers slopes down and away from the sea bed, making the glaciers especially vulnerable to collapse. Warm, circumpolar deep water flows in under the glacier’s ice shelf, melting the glacier’s base, causing it to race into the sea at a faster pace, which leads to thinning and recession of the ice sheet.

Source: NASA
PATRICK CLARK/THE WASHINGTON POST
marine ice sheet instability hypothesis

1. resistive stresses in the ice shelf resist driving stress at the grounding line
2. removal of ice shelf increases lateral spreading at the grounding line, causing the ice to go afloat
3. floating ice spreads more quickly than grounded ice
4. grounding line retreats into inland-deepening basin

(courtesy of C. Hulbe, Portland State Univ.)
The Marine Ice-Sheet Instability: Flux Explanation

(Mercer, 1968; Weertman, 1974; Schoof, 2007, Joughin and Alley, 2011)
This makes marine ice sheets prone to episodic retreat.
• Antarctica and Greenland are Tectonically and Geologically Distinct

• The subglacial topography under West Antarctica (reverse bed slope, below sea-level) makes it prone to catastrophic retreat.

What might trigger it?
Ice Shelf Backstress

- Ice Shelves restrain flow from grounded ice by:
  - friction at ice rises
  - side drag on fjord walls
Ice Shelf Backstress

- Ice Shelves restrain flow from grounded ice by:
  - friction at ice rises
  - side drag on fjord walls
Breakup of Larsen B Ice Shelf
March 2002

http://nsidc.org/iceshelves/larsenb2002/
ice shelf disintegration events

1. tensile stress opens crevasse
2. lithostatic stress limits crevasse depth
3. water pressure deeper crevasse
Ocean Conditions under the Pine Island Glacier

(Christianson et al., 2016)
Thwaites and Pine Island Glacier
Is a marine ice-sheet collapse underway?
Work at UW suggests....

Dynamic (in)stability of Thwaites Glacier, West Antarctica
Received 4 June 2012; revised 30 January 2013; accepted 11 February 2013.

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica
Ian Joughin, Benjamin E. Smith, Brooke Medley

Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More
Richard B. Alley, Sridhar Anandakrishnan, Knut Christianson, Huw J. Horgan, Atsu Muto, Byron R. Parizek, David Pollard, and Ryan T. Walker

Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica
Ian Joughin, Benjamin E. Smith, and David M. Holland
Received 22 July 2010; revised 3 September 2010; accepted 15 September 2010; published 21 October 2010.

Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability
Pierre Dutrieux, Jan De Rydt, Adrian Jenkins, Paul R. Holland, Ho Kyung Ha, Sang Hoon Lee, Eric J. Steig, Qinghua Ding, E. Pou Abrahamsen, Michael Schröder
How do we judge what’s significant when it comes to Ice Sheet change?
• Is this unexpected?
• How will it change the ice sheet mass balance?
• How much ice is affected?