From ice stream to ice cream:

Glaciological insight into ice deformation and movement

Marianne Haseloff
Dept. of Geoscience
UW-Madison

FDC
2024 Annual Technical Conference

Glaciology group at UW-Madison

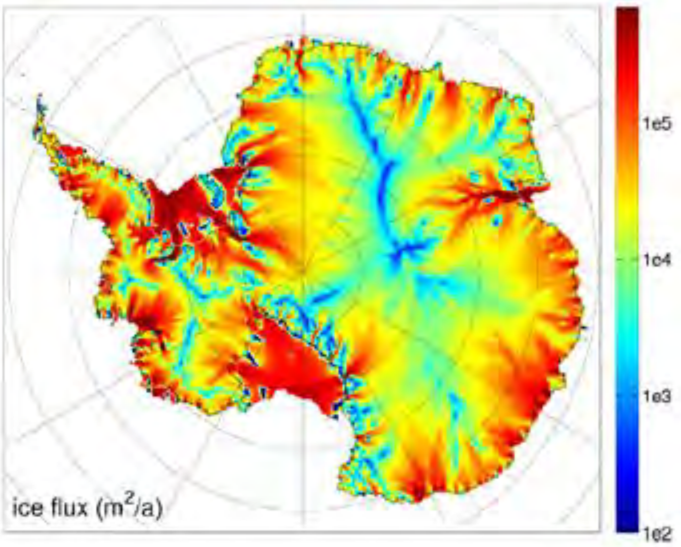
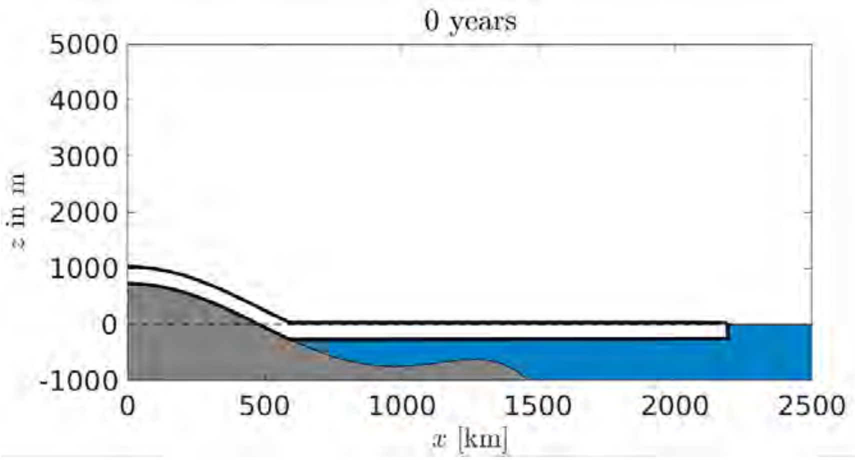
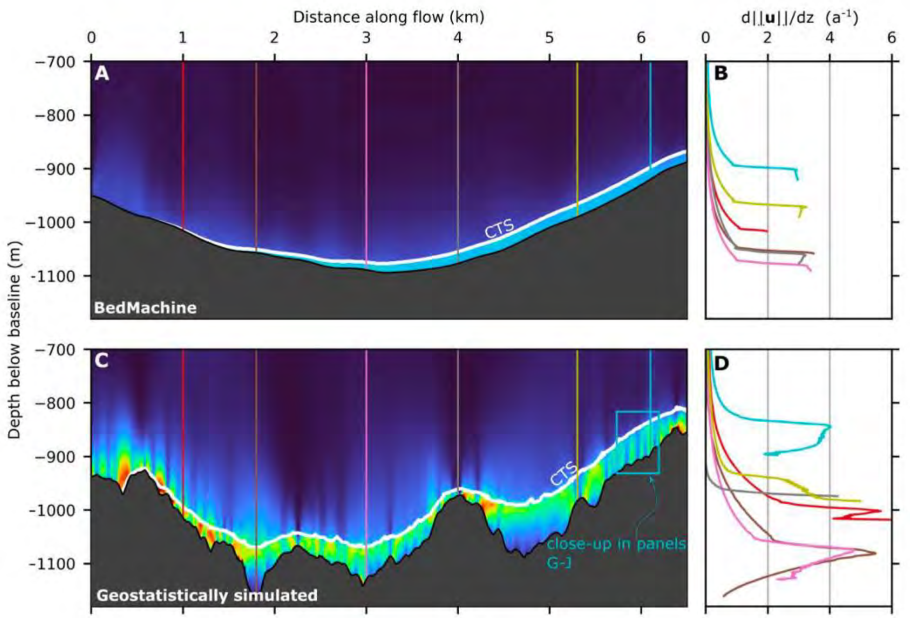


Fig. 11. Modeled vertically-integrated horizontal ice flux. Ice streams are outlined in black, grounding line position in white.

Winkelmann et al, 2011 (The Cryosphere)





Englacial heating rates estimated with different basal roughness
Law et al, 2019 (Science Advances)

Use of mathematical models to understand glacier and ice sheet dynamics.

Spatial scales: mm to continental-wide

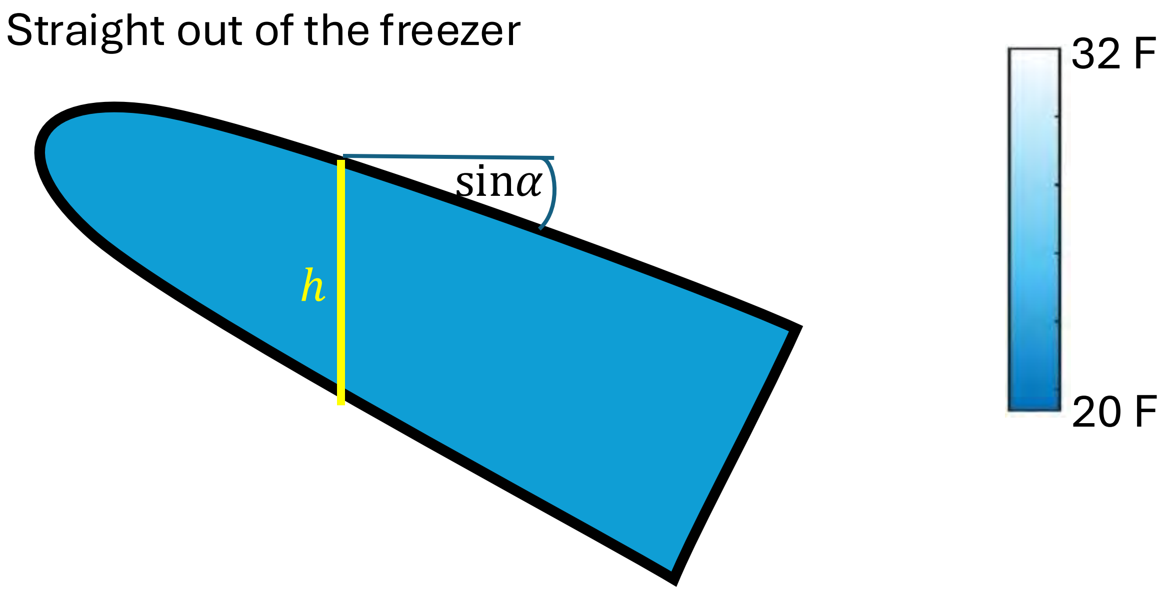
Temporal scales: days to millennia

How does the ice get out of the tube?

Ice Lolly Tubes

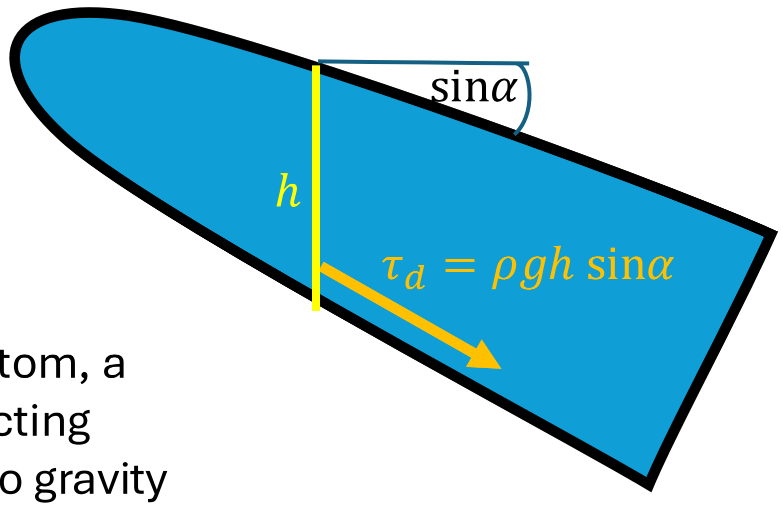
How does the ice get out of the tube?

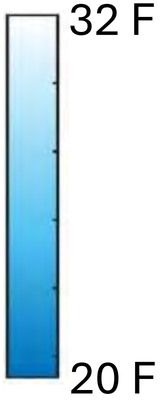
Imagine you hold an ice lolly/freezie (?) at an angle and you are wondering when it will start to slide out of tube and how quickly:



How does the ice get out of the tube?

Straight out of the freezer

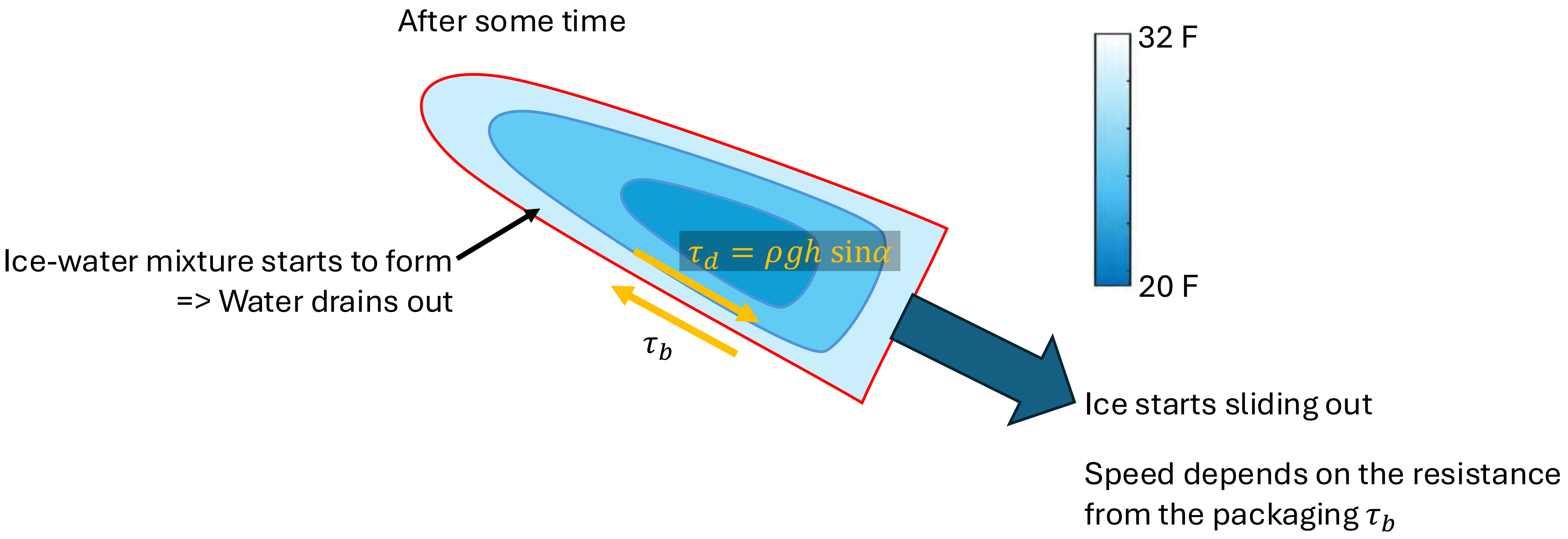




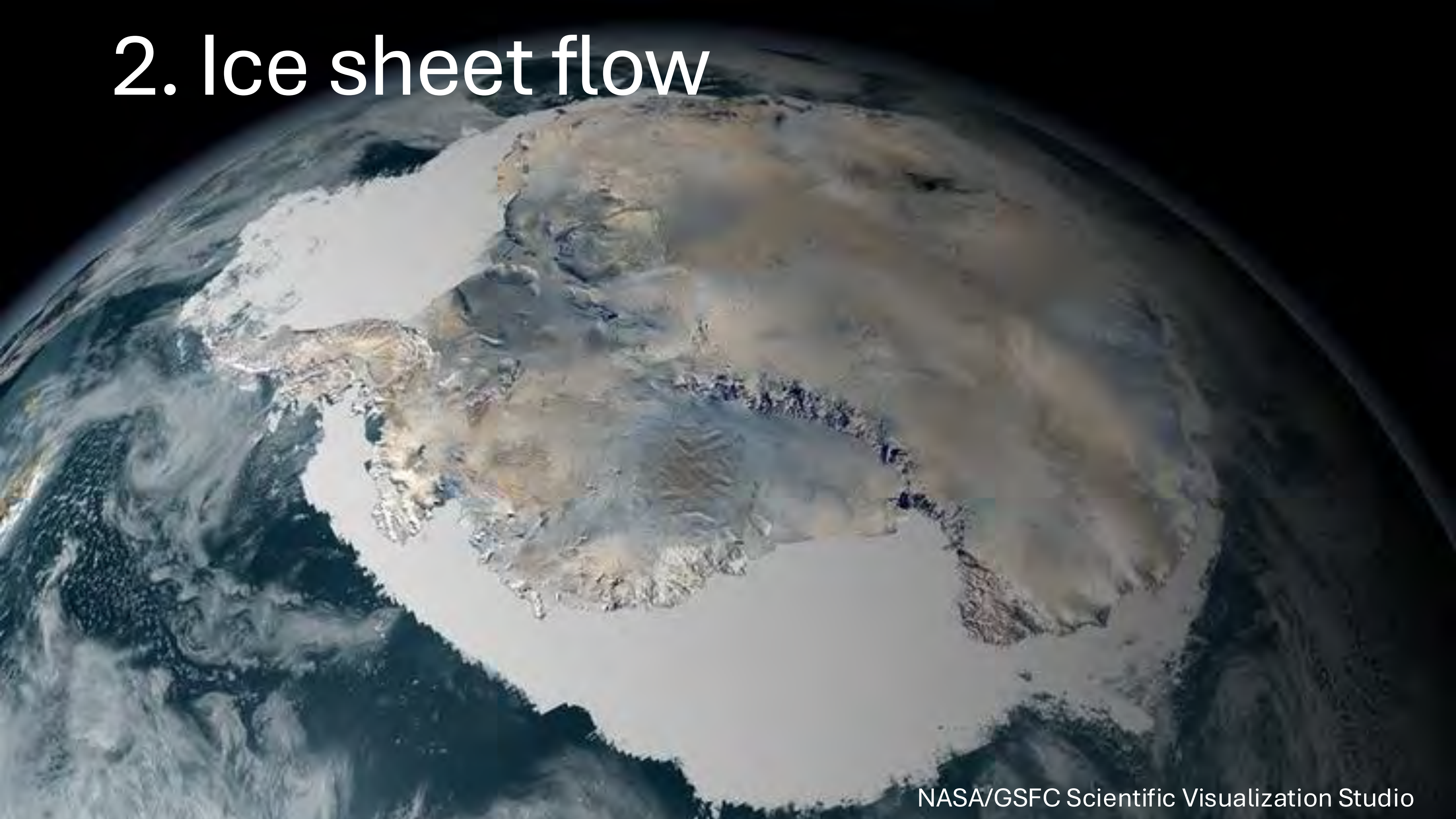
At a given point along the bottom, a stress τ_d (force per area) is acting tangentially to the base due to gravity

ρ: density of ice
g: Acceleration due to gravity
h: ice thickness
$\sin\alpha$: surface slope

How does the ice get out of the tube?

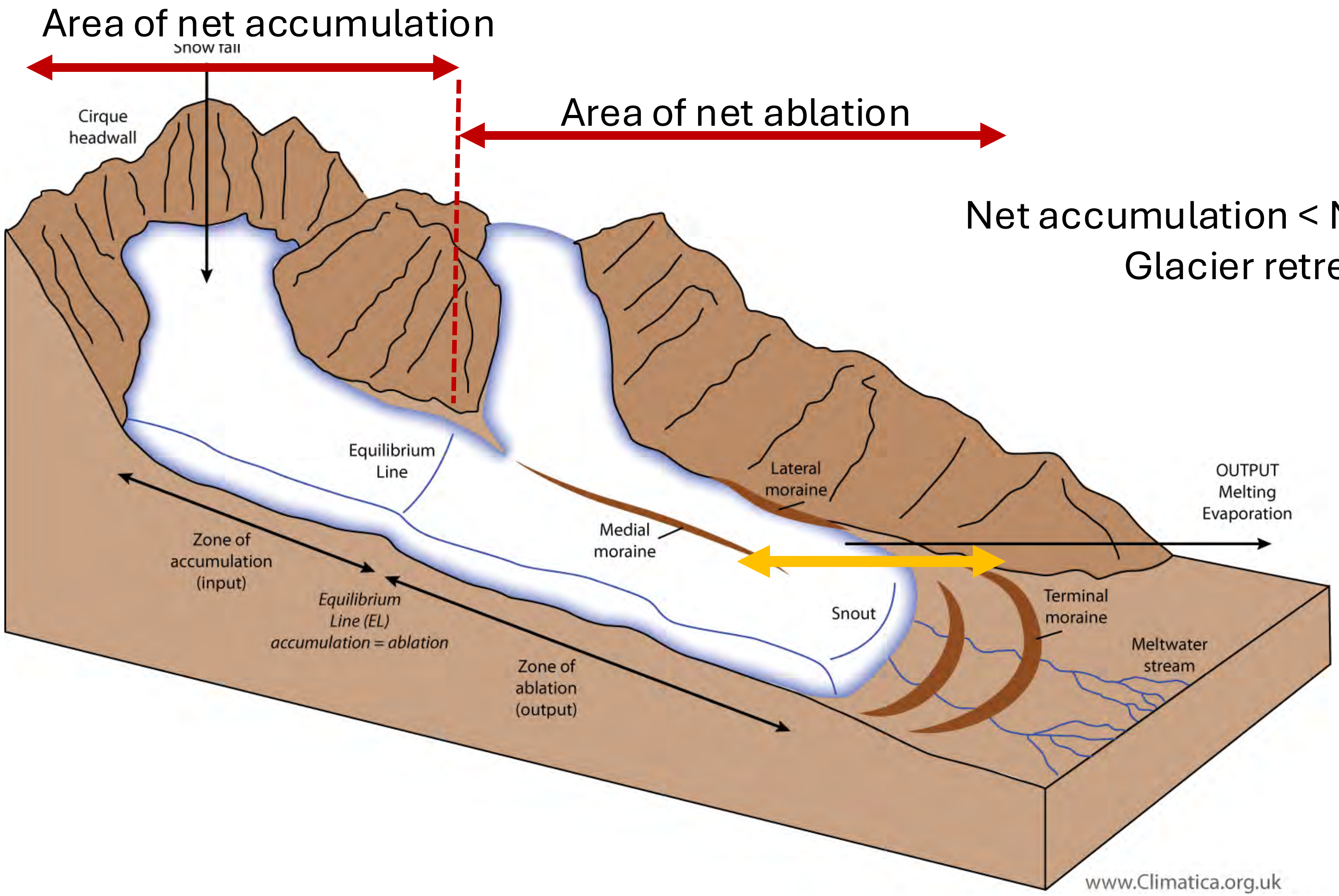


2. Ice sheet flow



NASA/GSFC Scientific Visualization Studio

Glacier mass balance



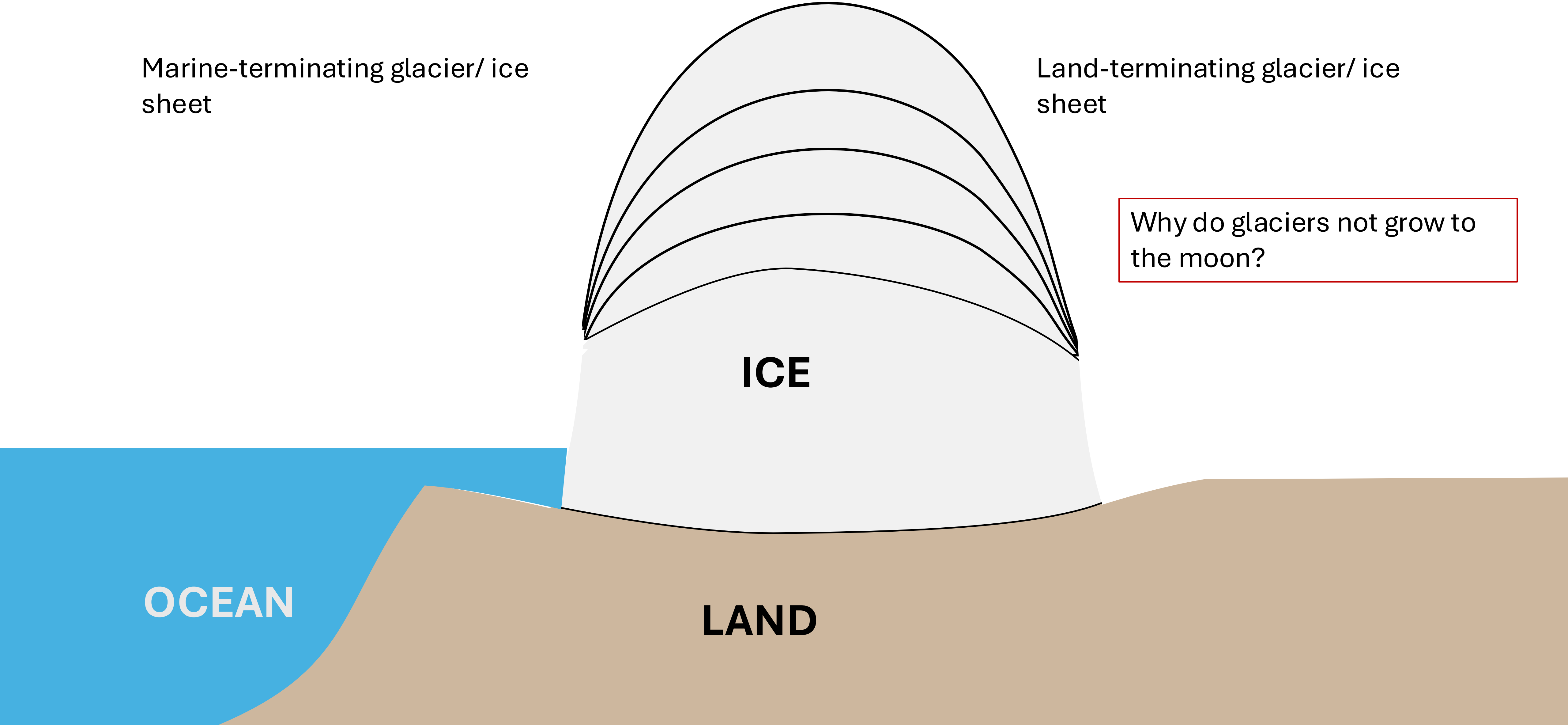
Net accumulation < Net ablation:
Glacier retreats

Every year, snow is added on top of the glacier/ice sheet and taken away at the sides by melting

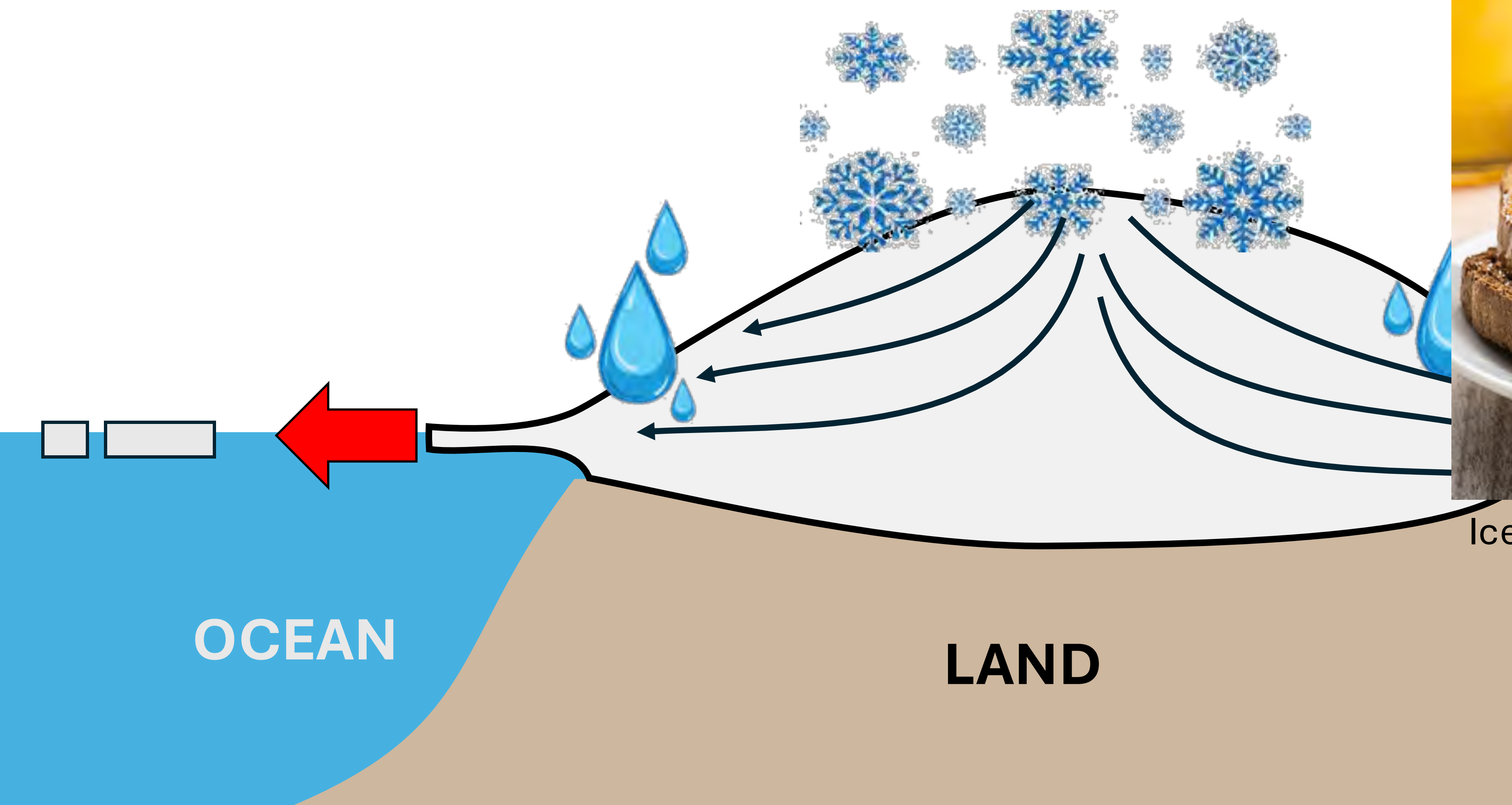
Marine-terminating glacier/ ice sheet

Land-terminating glacier/ ice sheet

Why do glaciers not grow to the moon?

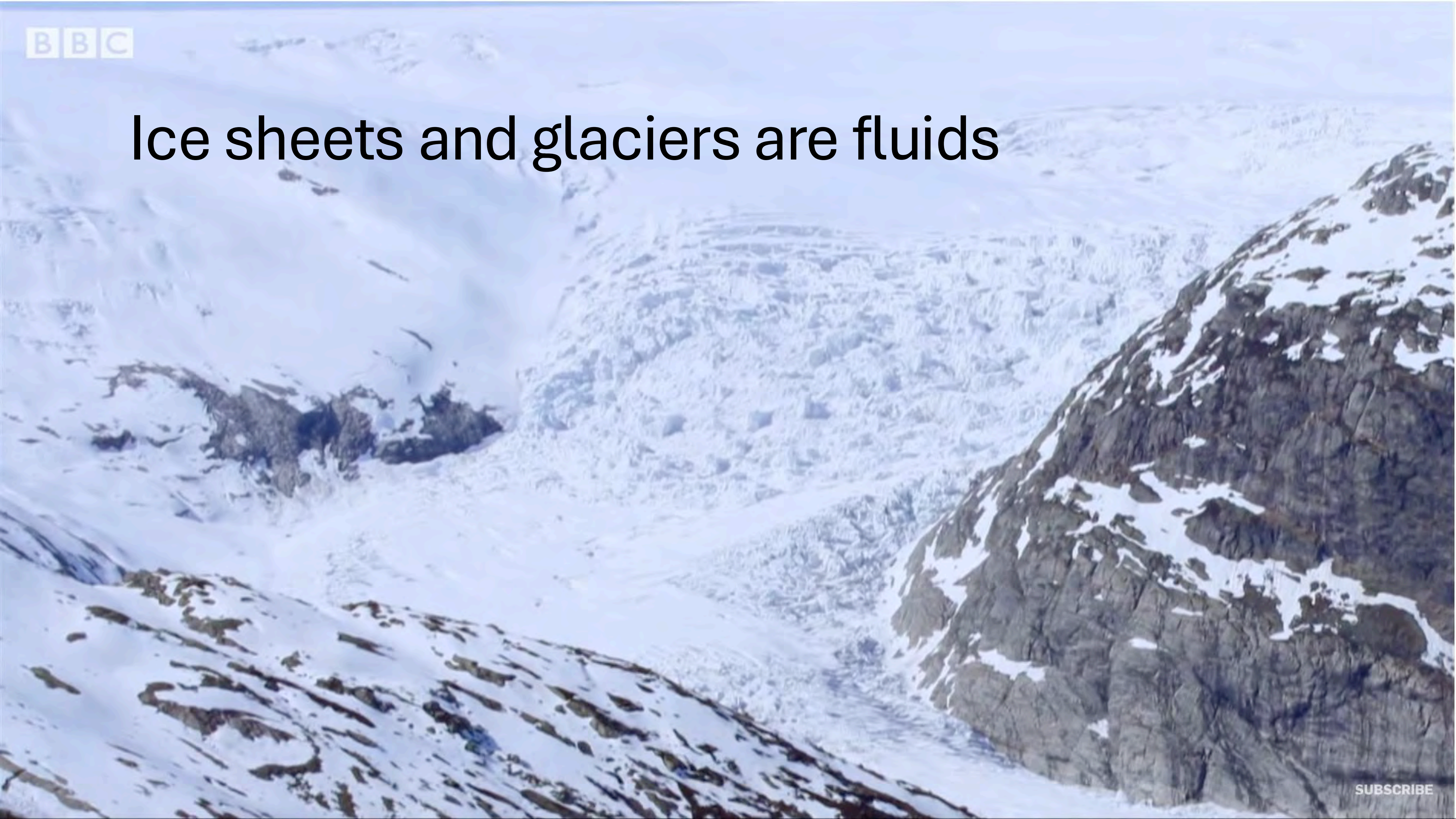


Glaciers move, continuously distributing mass from regions of accumulation to regions of ablation

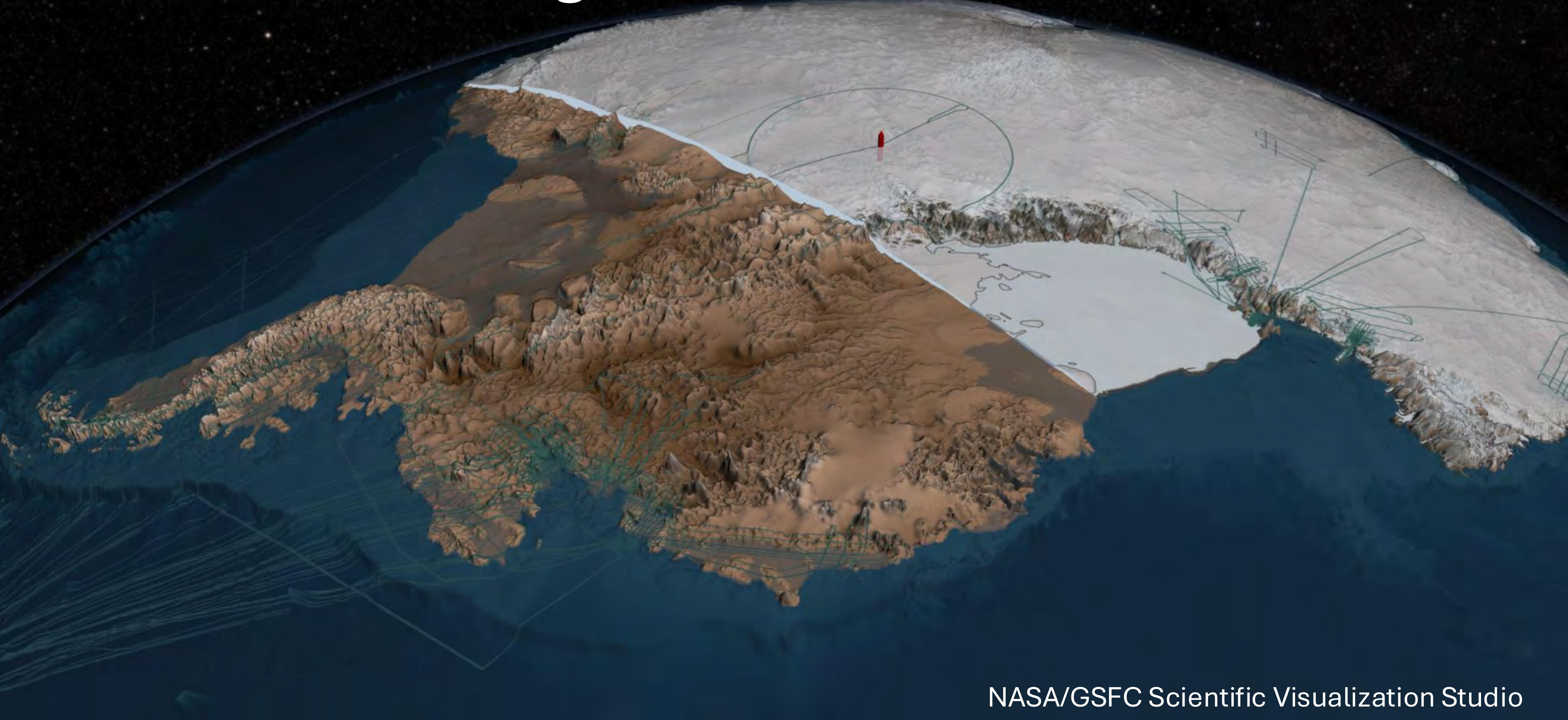


Ice moves quite similarly to honey.

Ice sheets and glaciers are fluids



Ice sheets and glaciers are thin films



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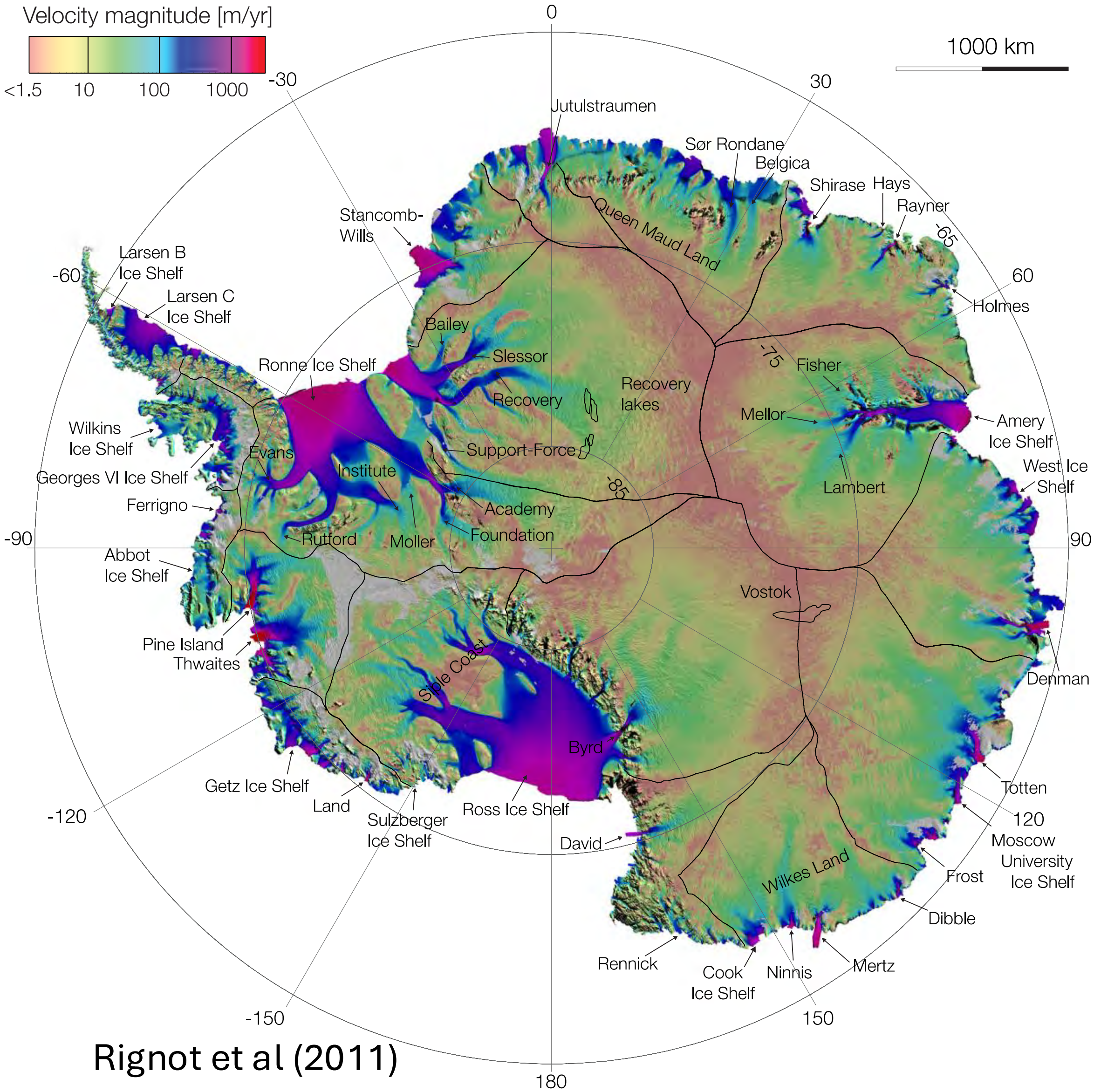
Ice sheet flow is heterogeneous

- Regions of fast flow (= ice streams) can border regions of slow slow

- Regions of fast flow account for the majority of Antarctic ice loss (90%$^{?}$)



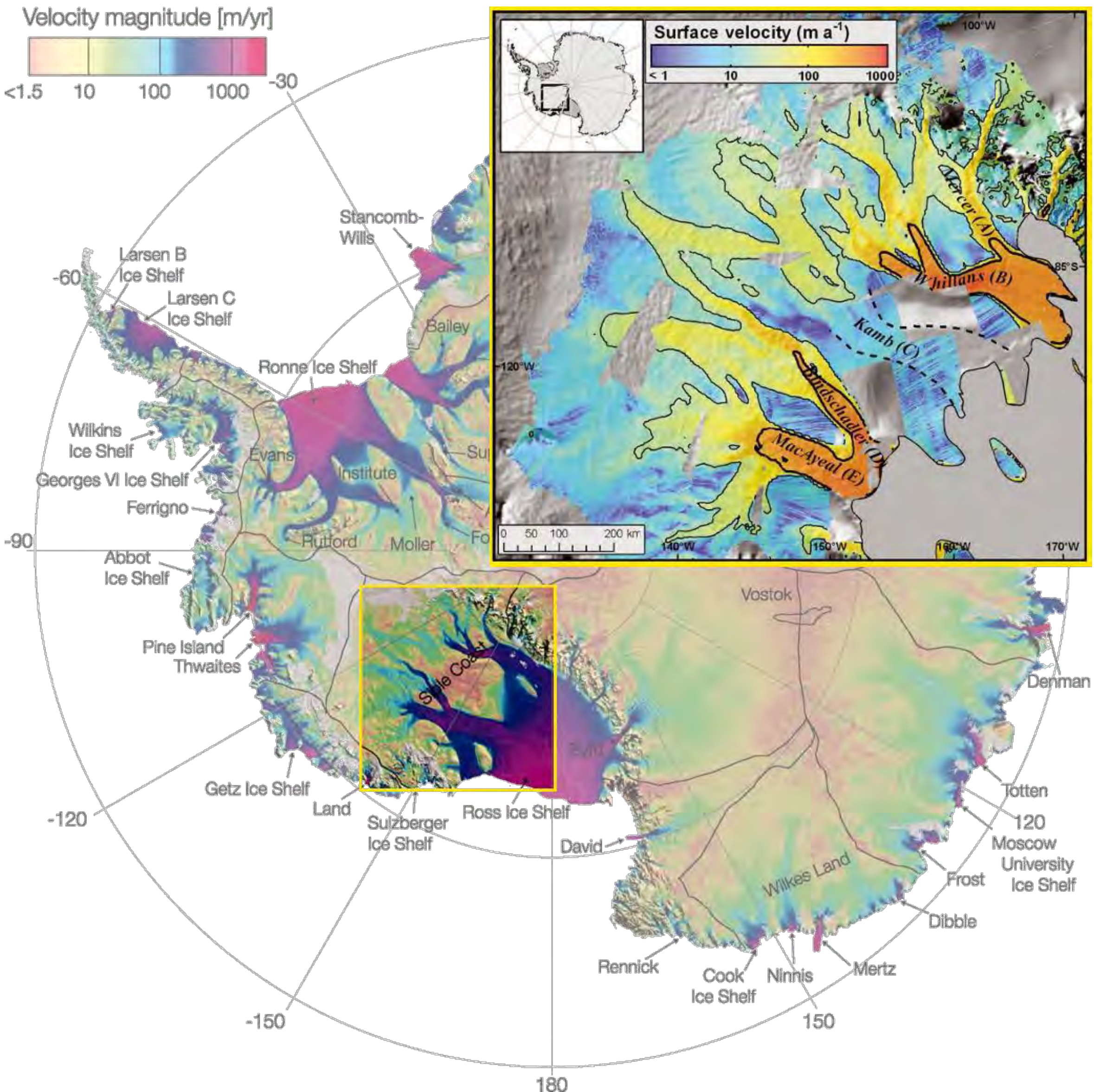
Rignot et al (2011)

Antarctic ice streams

Siple Coast ice streams have received particular attention because:

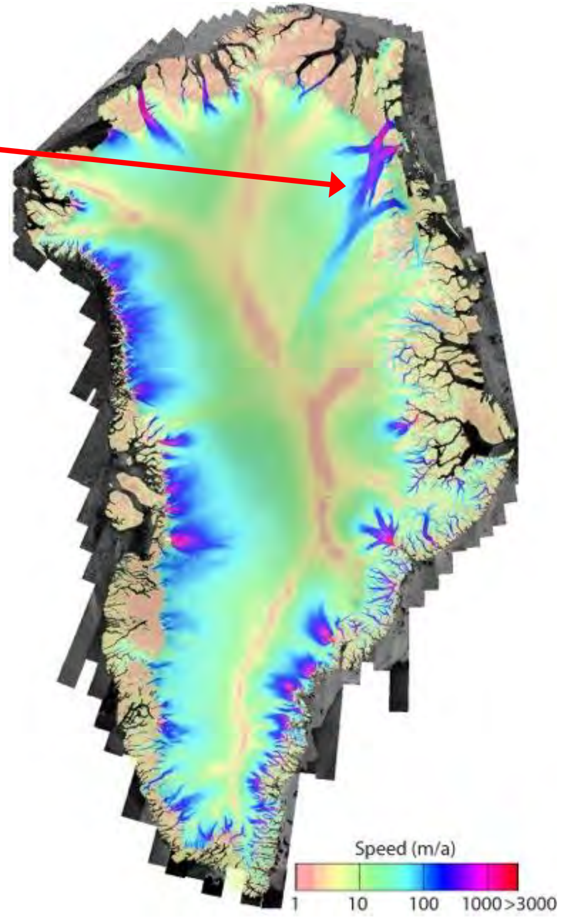
- Temporal variations:
  Ice streams can switch on and off, oscillating between fast and slow flow

- Apparent patterning



Non-Antarctic ice streams

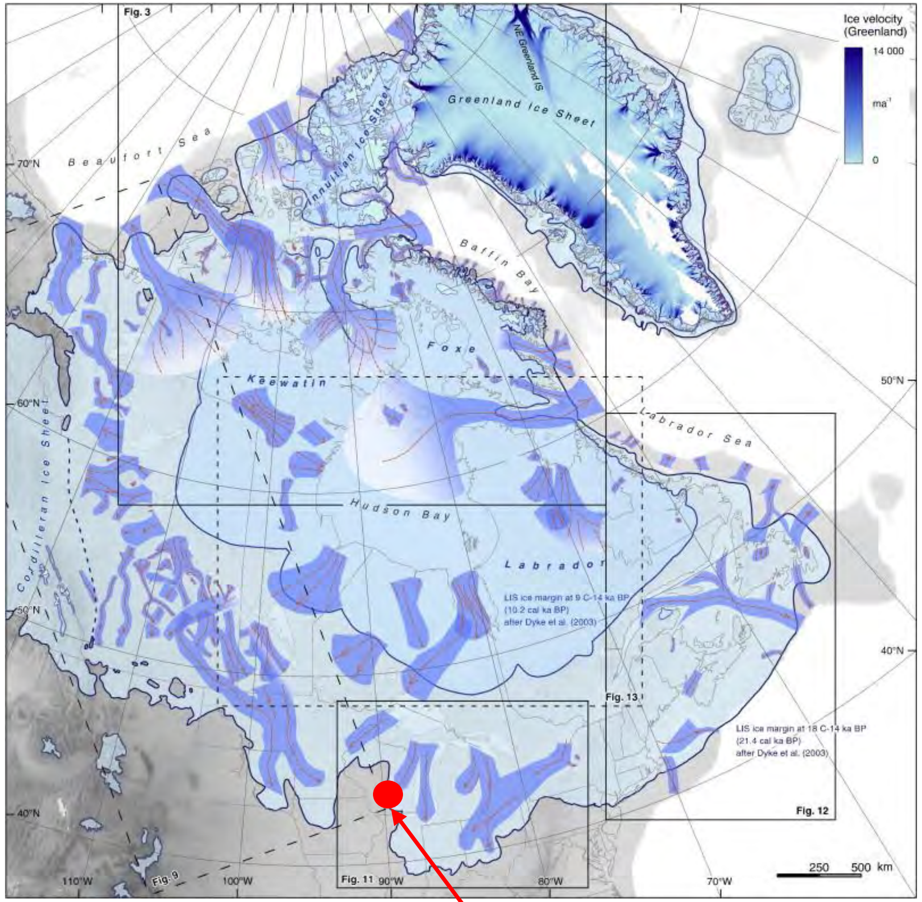
- Greenland: Northeast Greenland Ice Stream



Joughin et al (2018)

Non-Antarctic ice streams

- Greenland: Northeast Greenland Ice Stream
- Laurentide Ice Sheet:
  at least 117 ice streams have been mapped from paleo-data
  - Evidence for topographically confined and unconfined ice streams
  - Evidence for repeated and sudden change in flow pattern



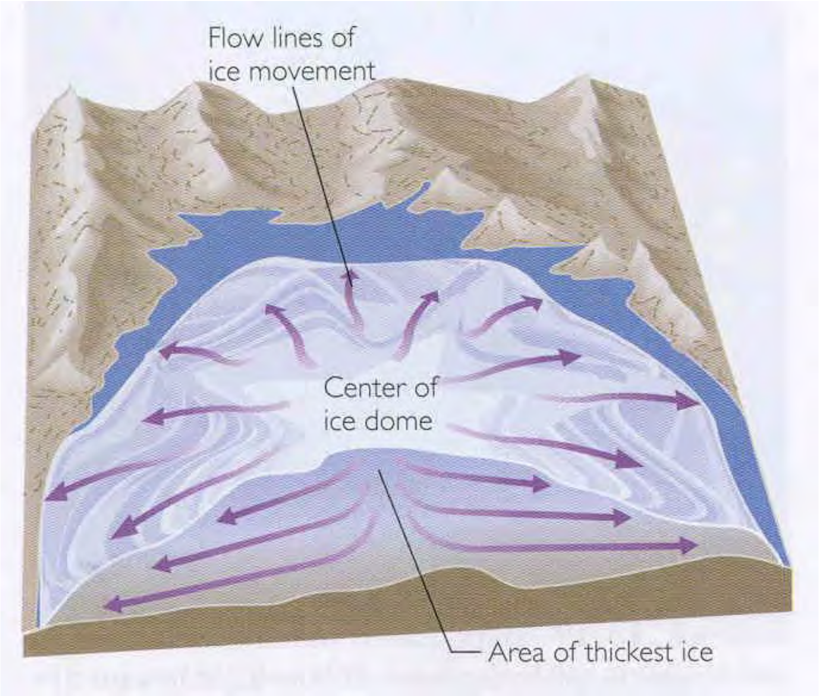
Margold et al. (2015)

Why do glaciers move?

Ice moves due to **gravity** from regions of high potential energy to regions of low potential energy.

High elevation = high potential energy
Low elevation = low potential energy

As glaciers move, the potential energy is converted to kinetic energy and heat.



What factors are important?

Glacier flow, velocity and motion is controlled by several factors, including:

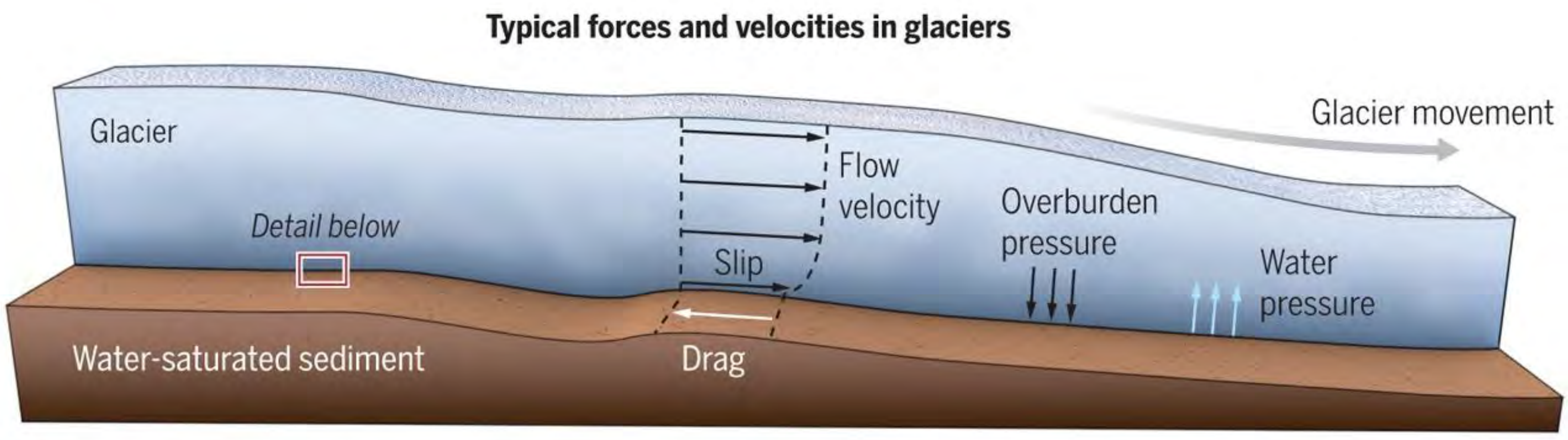
- Topography (e.g. valley geometry; terminal environment: land, sea, ice shelf, sea ice)
- Geology (hard or soft bed)
- Climatic conditions (rate of accumulation and ablation, temperature)
- Ice properties (temperature, density),
- Internal glacier dynamics, which in turn affect:
    - Bedrock conditions: frozen or thawed bed, subglacial hydrology
    - Ice temperature

Glacier movement

Glaciers move by three mechanisms:

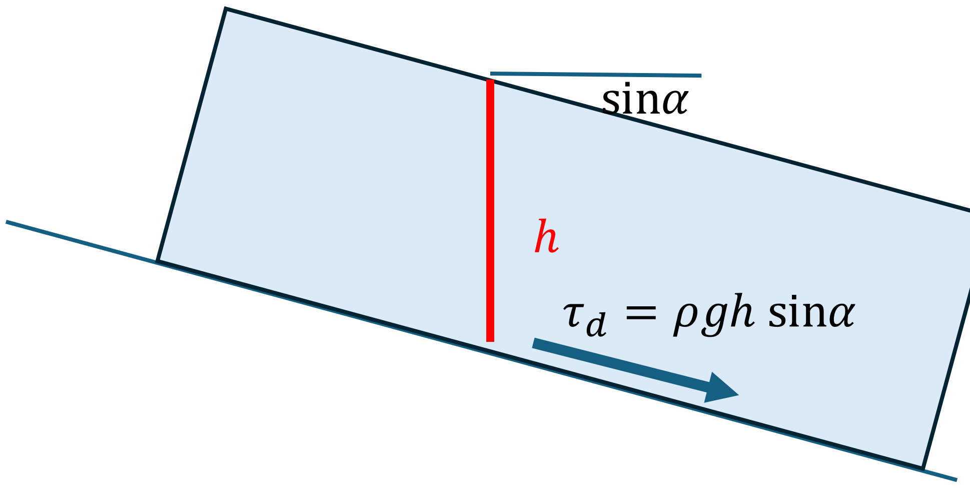
1. by internal plastic deformation (like a very viscous fluid)
2. by sliding of ice along the bed
3. by deformation of the bed itself

(2 and 3:) Facilitated by water at the bed



Credit: Minchew & Joughin, Science, 2020, DOI: 10.1126/science.abb3566

Flow by internal deformation



Definition *driving stress*: $\tau_d = \rho g h \sin \alpha$

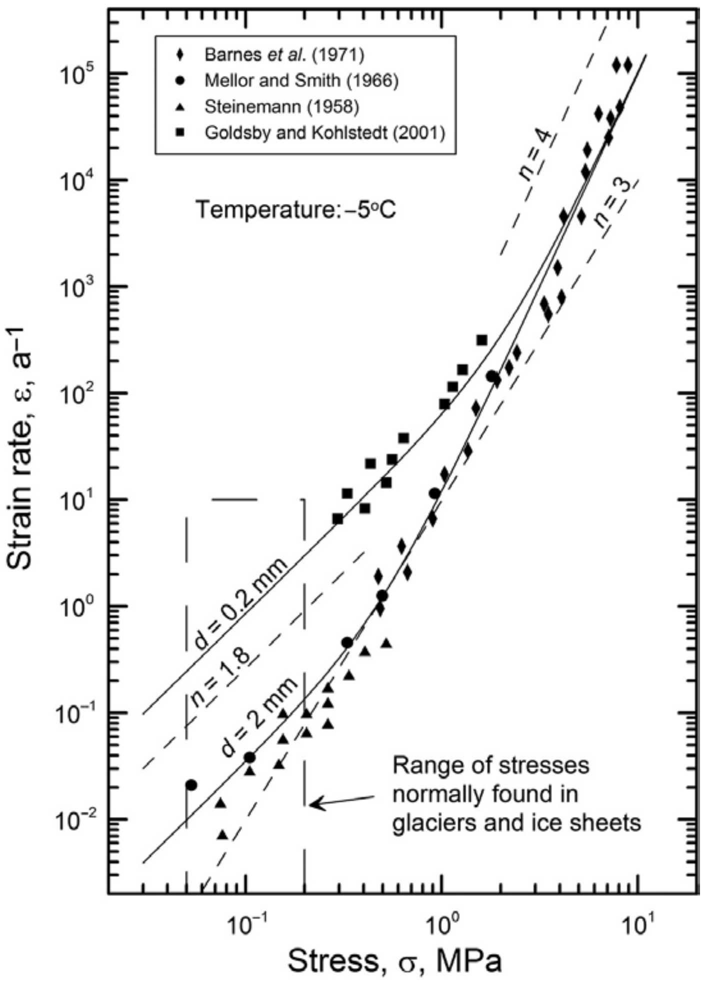
To determine ice velocity, we need to relate deformation (strain) to stress (force per area)

$\Rightarrow$ This is done through *Glen's flow law*.

ρ: density of ice
g: Acceleration due to gravity
h: ice thickness
$\sin \alpha$: surface slope

Glen’s Flow law

Rate of deformation



doi:10.1017/9781108698207.007

Laboratory measurements of strain rate at various stresses for 0.2 mm and 2 mm ice at −5°C.

- Strain rate: $\dot{\varepsilon} = \frac{\partial u}{\partial x}$ [1/time]

- At higher stress ice deforms more easily

$$\dot{\varepsilon} = B^{-n}\tau^{n} \quad \text{with } 1.2 \lesssim n \lesssim 4$$

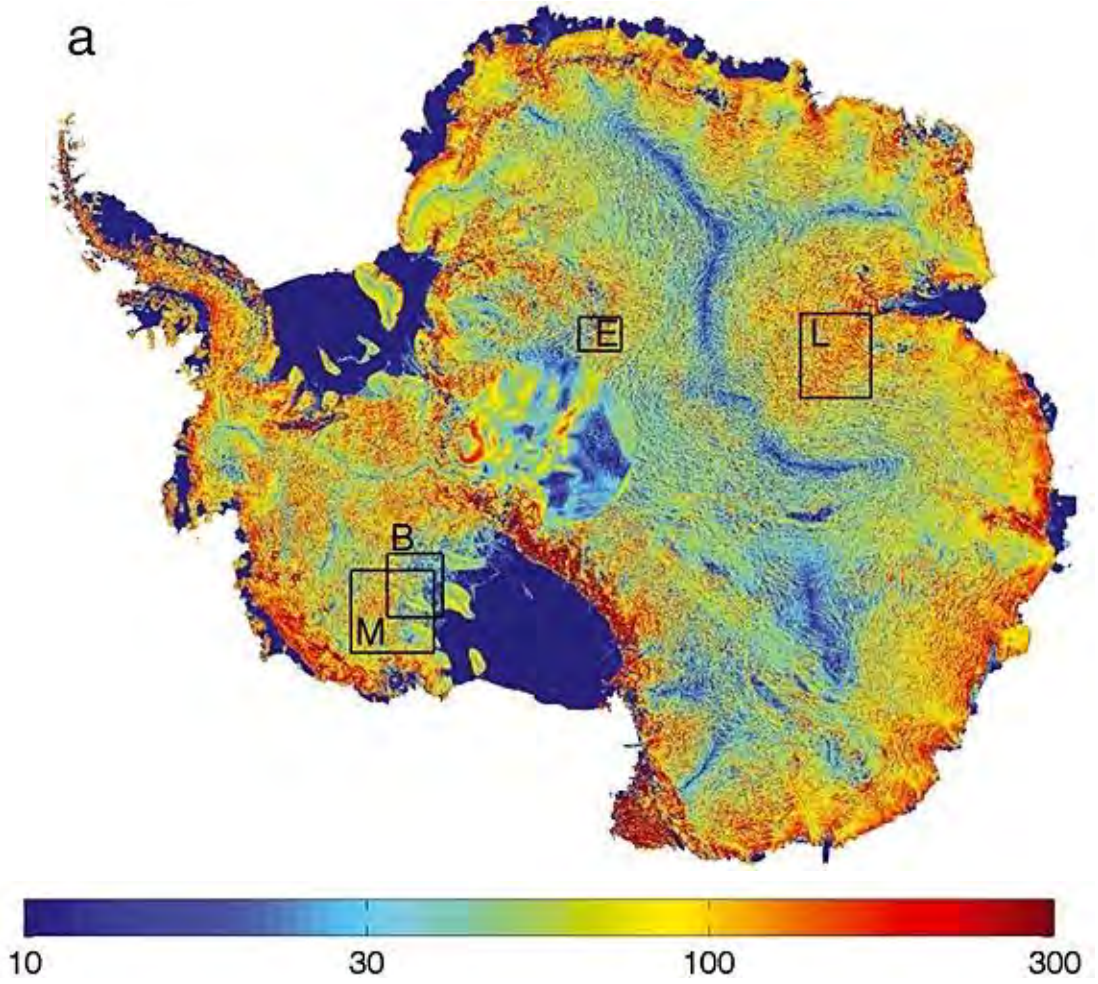
n: dimensionless constant
B: viscosity parameter [MPa $yr^{1/n}$]

- *B* and *n* are empirically determined
- *B* depends on the ice temperature, crystal orientation, impurity content, water content, and perhaps other factors

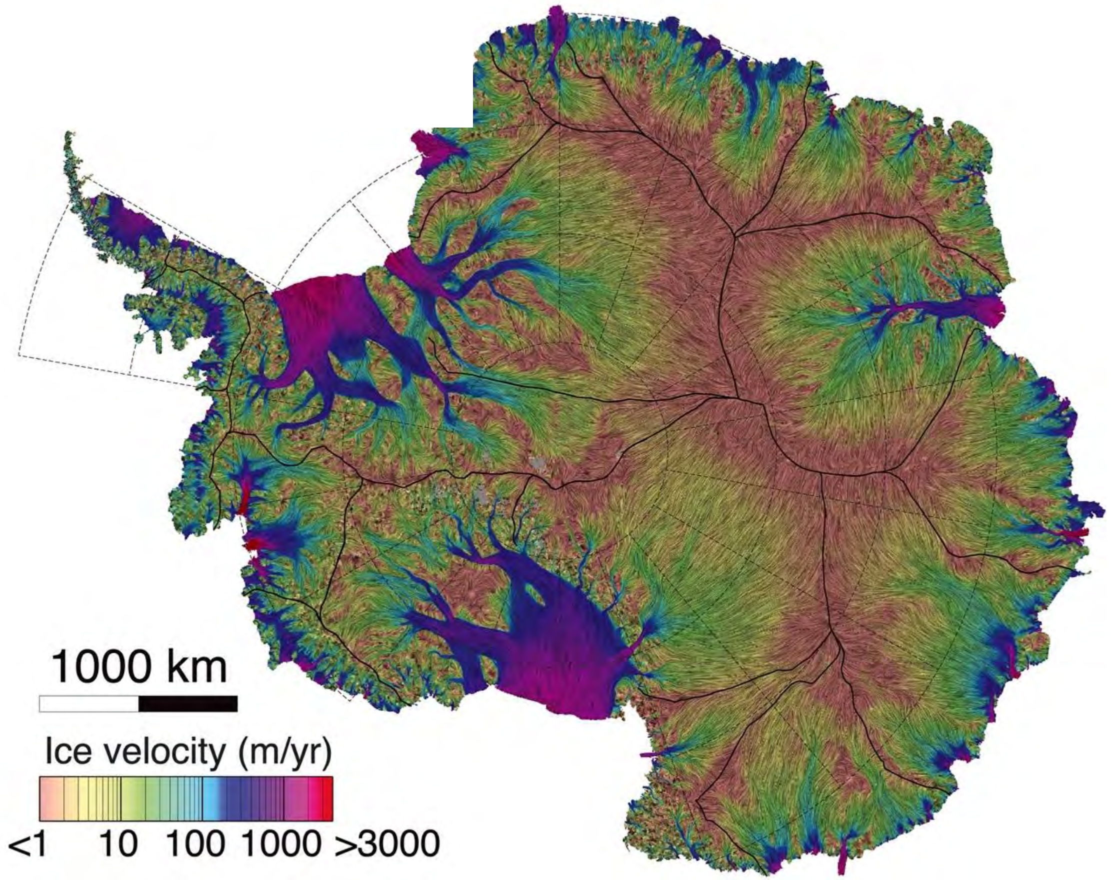
=> Ice is a non-Newtonian fluid

Flow by internal deformation: Limitations

=> Not a good description for regions of fast flow



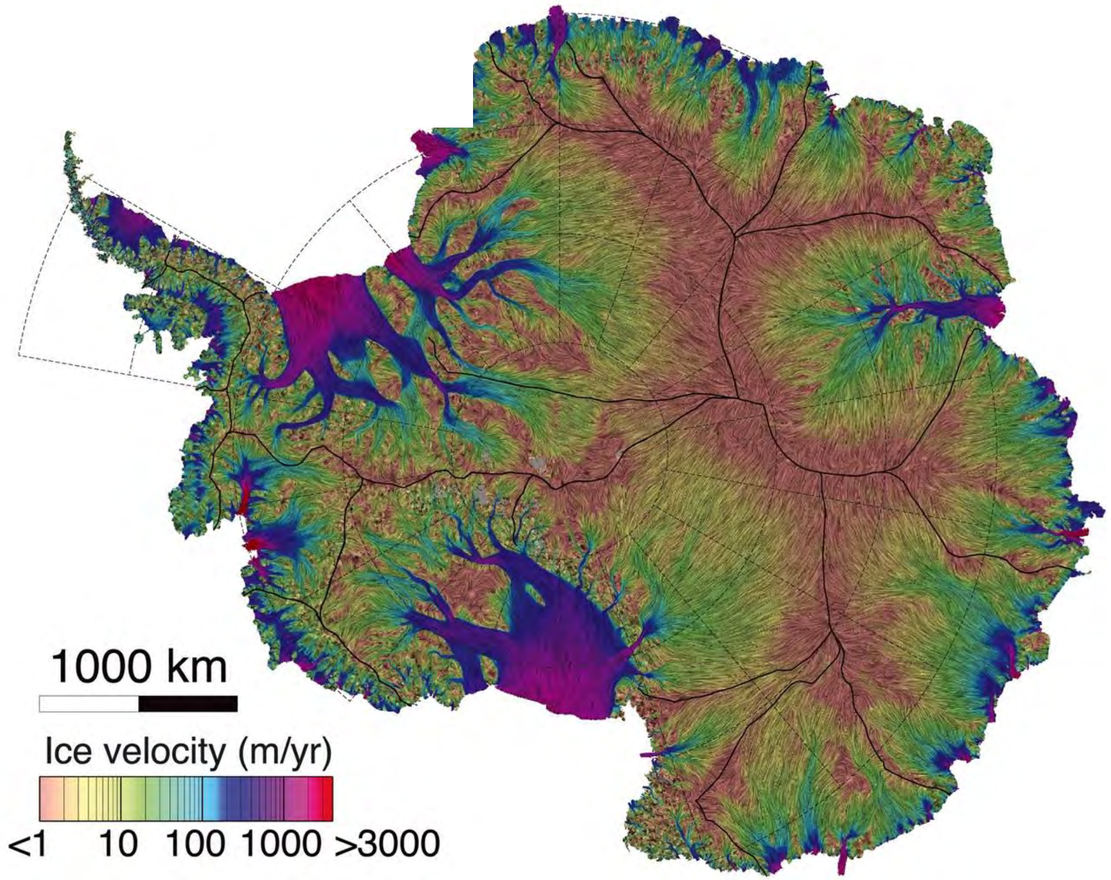
Driving stress $\tau_d = \rho g\, h\vec{\nabla}S$ [kPa]



Ice sheet flow is heterogeneous

Fast flow requires sliding of the ice along the bed

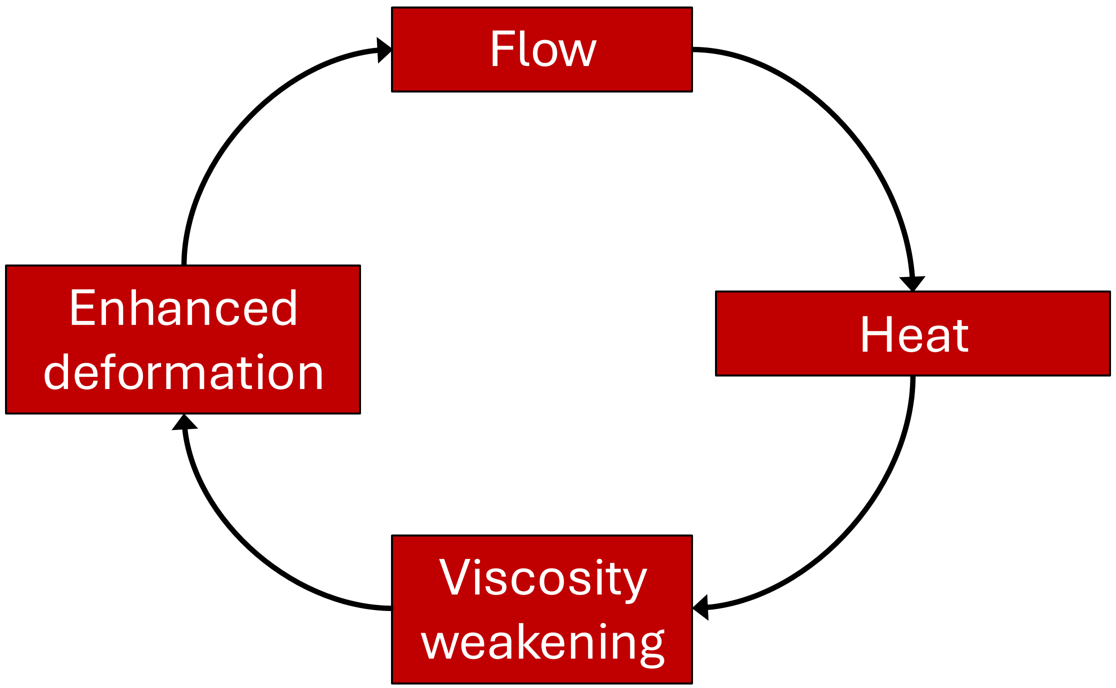
This requires water.



Rignot et al (2011)

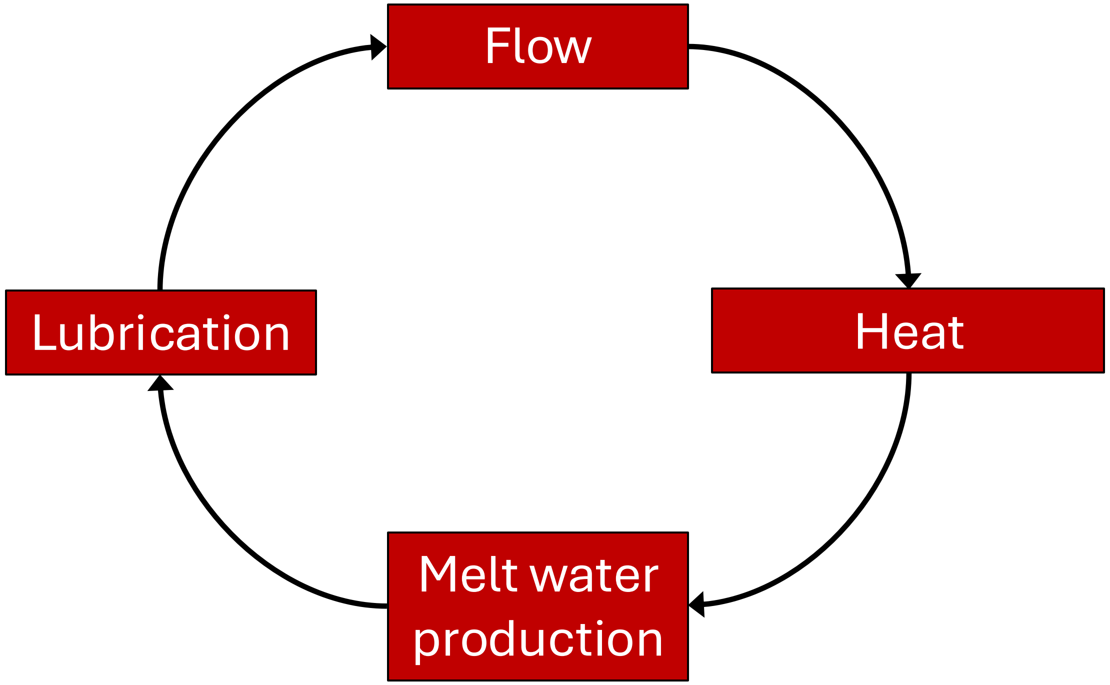
Thermomechanical feedbacks

- Can distinguish 2 flavours:
  - Thermo-viscous feedback: heat generation due to internal deformation



Thermomechanical feedbacks

- Can distinguish 2 flavours:
  - Thermo-viscous feedback: heat generation due to internal deformation
  - Thermo-frictional feedback: heat generation due to basal sliding

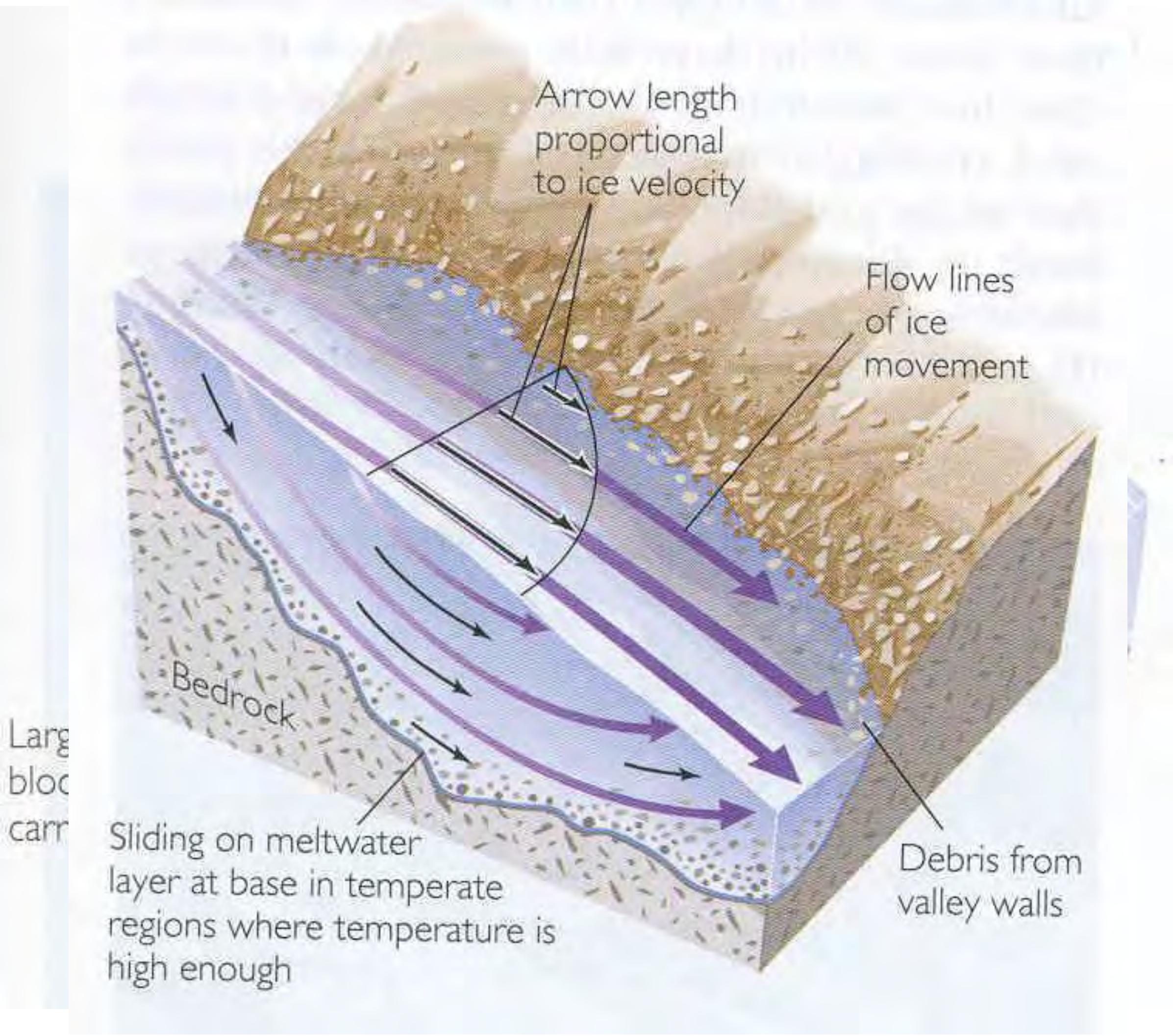


3. Sliding

Sliding

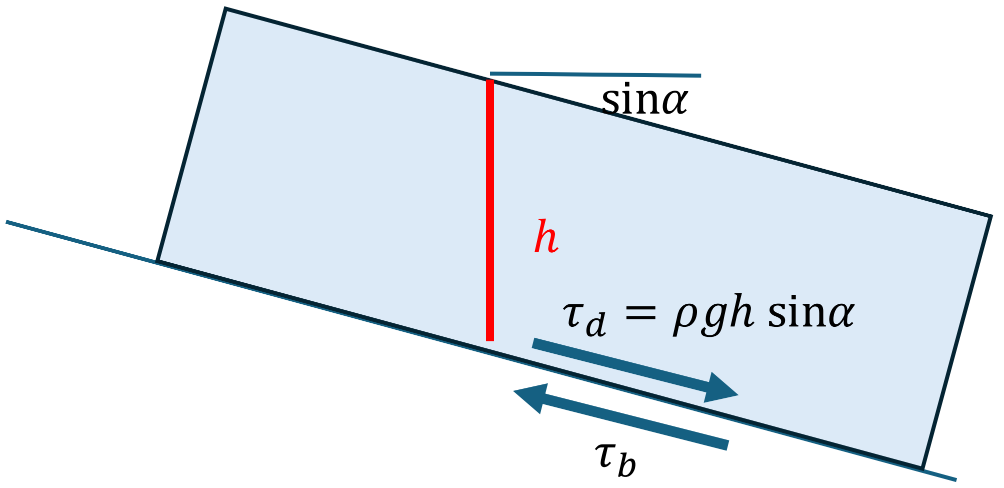
- If basal temperature below the pressure-melting point: main glacier movement by internal deformation
- If basal temperature at the melting point: sliding

Sliding refers to slip between a glacier and its bed.



Benn & Evans, 2010

Sliding laws



τ_d: Driving stress
τ_b: Basal shear stress

Sliding law:

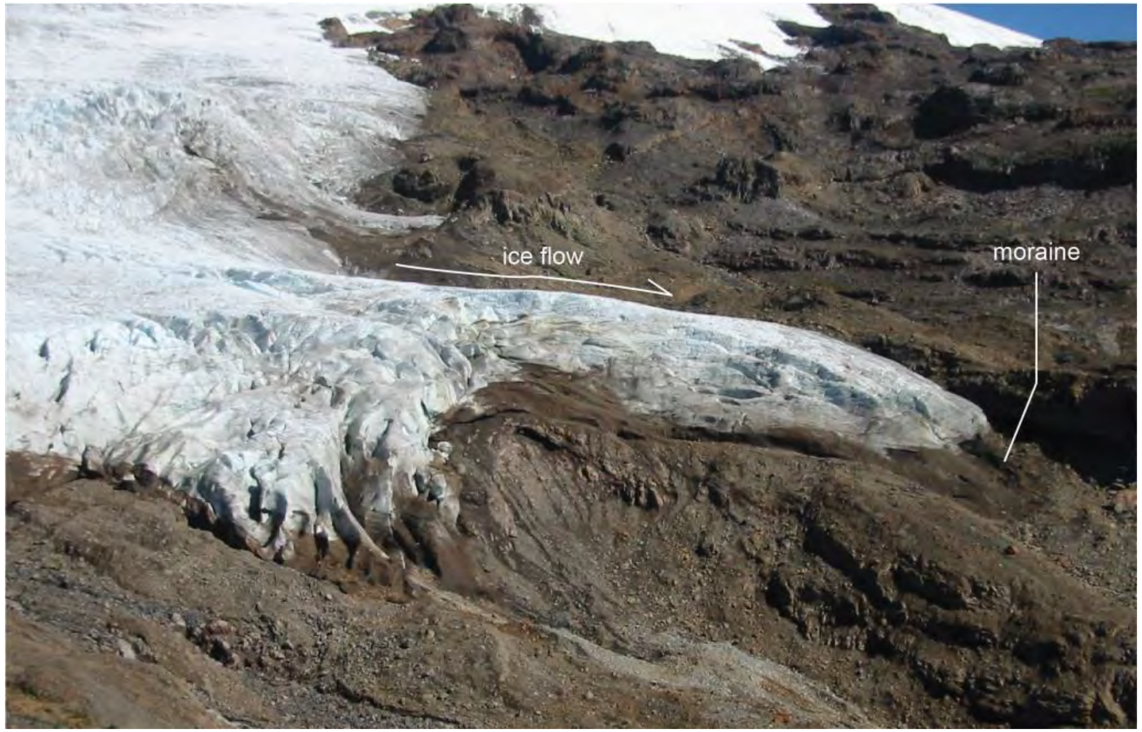
$$\tau_b = f(u, T, \ldots)$$

Sliding of wet-based ice

Hard bed sliding

Glacier in contact with underlying bedrock. Photo: Jacob M. Bendle, http://www.antarcticglaciers.org

Soft bed sliding

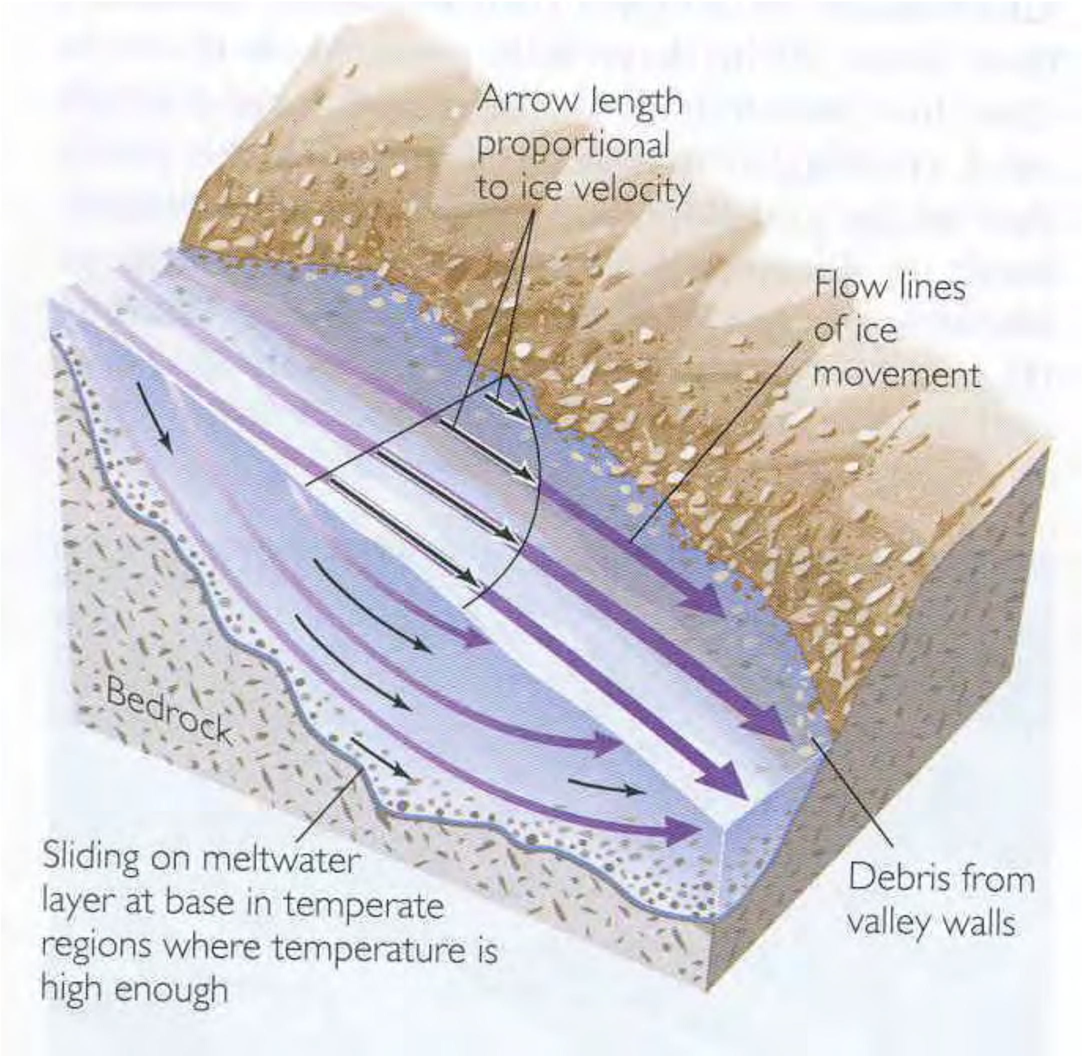


Glacier in contact with till. Photo: Photo: W. Siegmund, http://www.antarcticglaciers.org

Hard bed sliding

Resistance to sliding arises from:

- Bumps and obstacles at the bed
  => form drag
- Debris entrained in basal ice generates friction between a glacier and the bed
  => frictional drag
- Topography



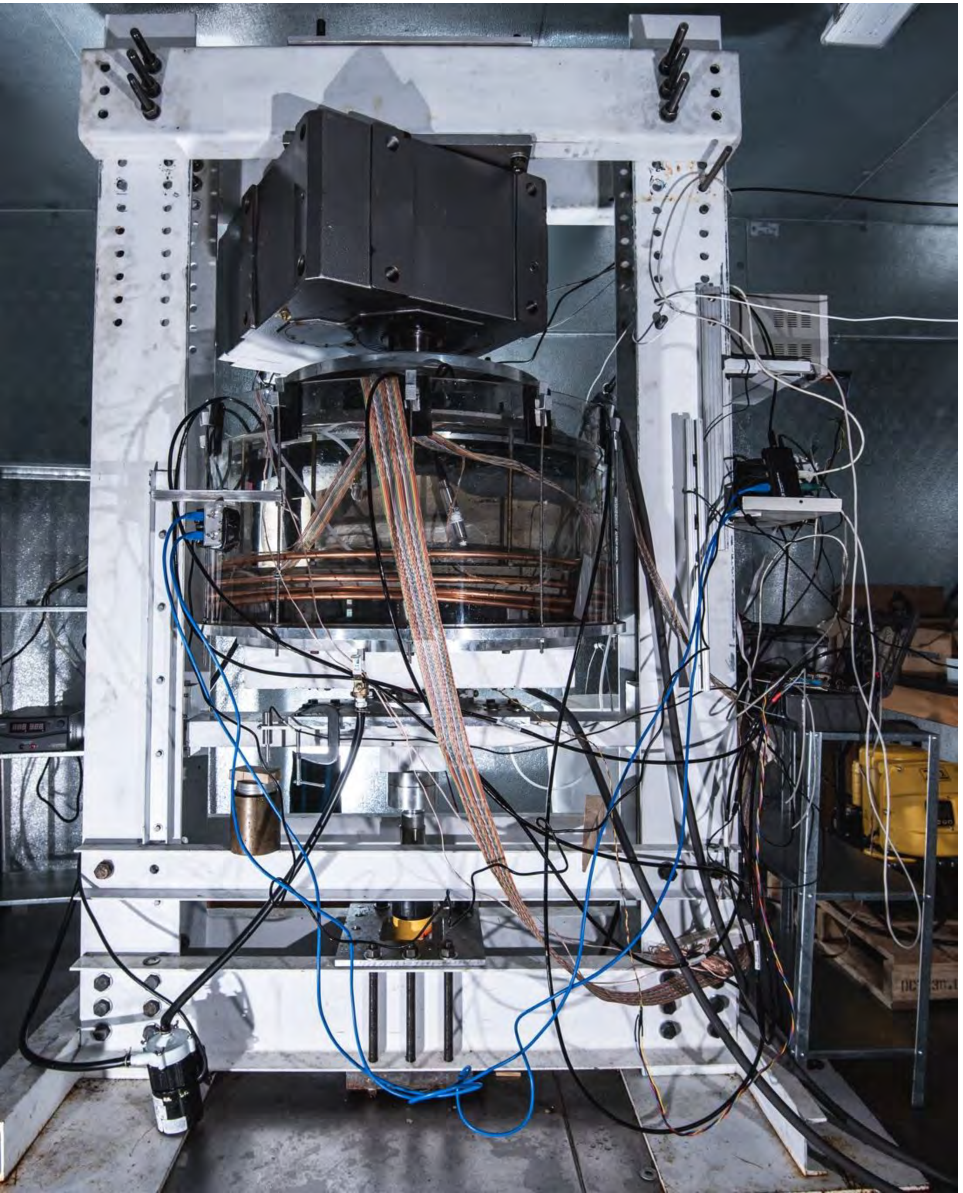
How do you determine the slip law

It’s very hard to do this in the field because:

1. Cannot isolate the independent and dependent variables with remote observations
2. Observations are limited to small sample sizes
3. Drilling to the bed disrupts the basal slip significantly

=> Go to the lab

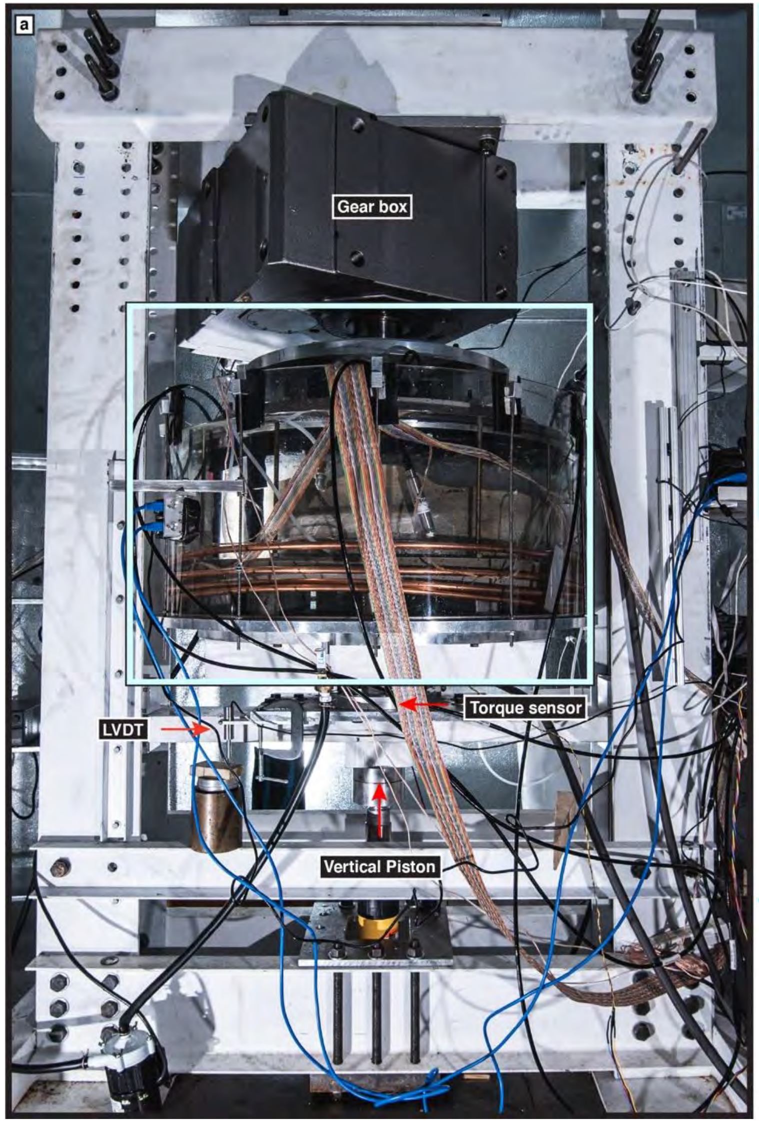
Ring shear device to simulate basal slip

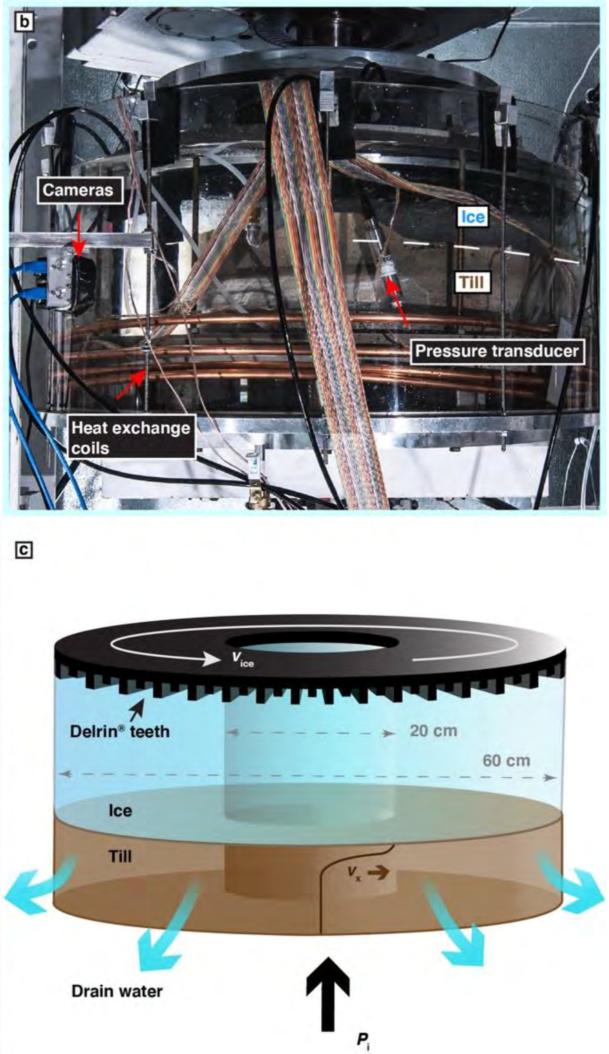


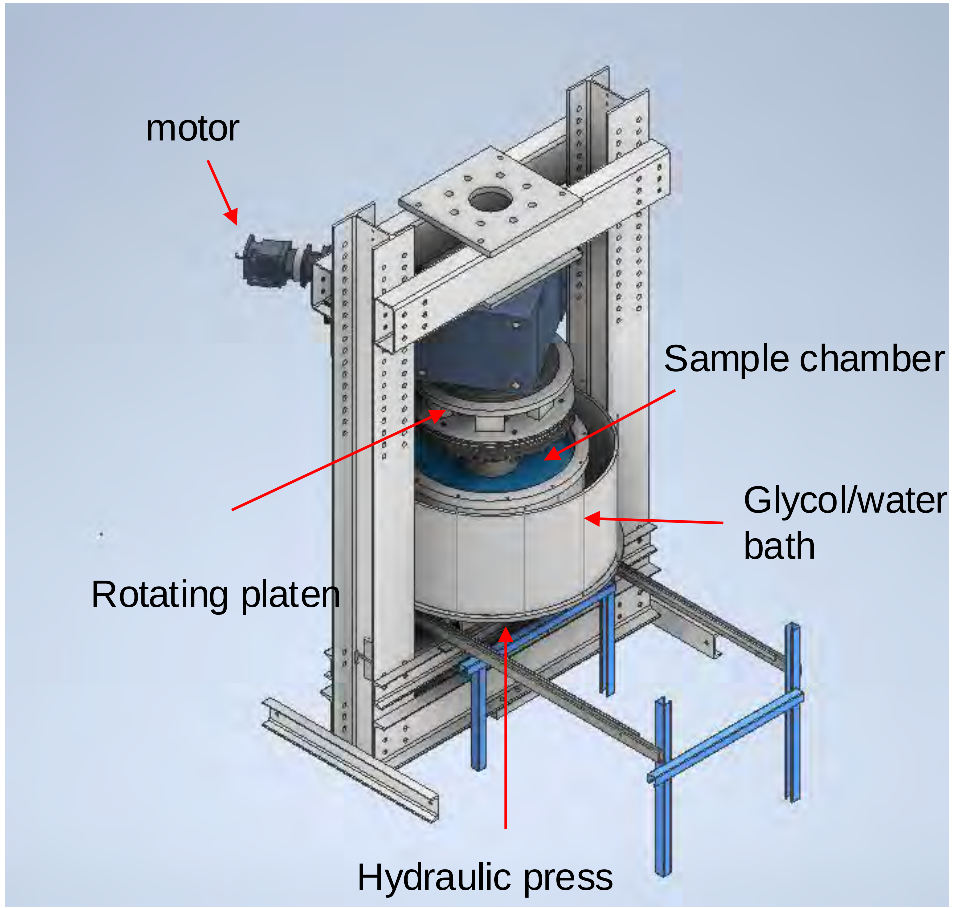
Lucas Zoet
Dean L. Morgridge Associate Professor
Dept. of Geoscience

UW-Madison cryo ring shear device

Ring shear device to simulate basal slip







Figures. Ring shear apparatus, sample chamber and schematic

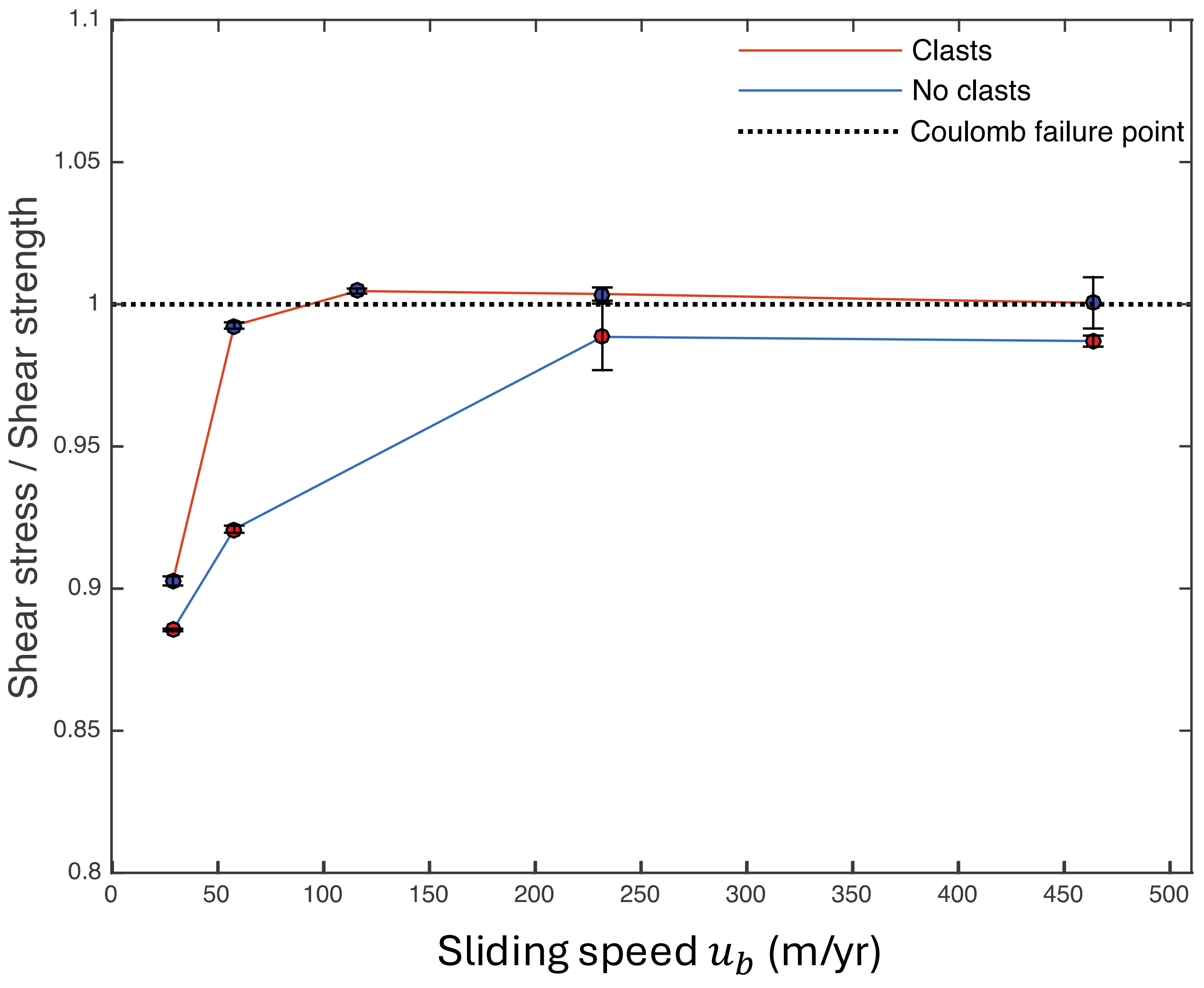
Photo credit: Ethan Parrish, UW-Madison

Experimentally derived sliding laws

Example of a sliding law for a soft-bedded glacier:

$$\tau_b = \mu N \left(\frac{u_b}{u_b + u_t} \right)^{1/5}$$

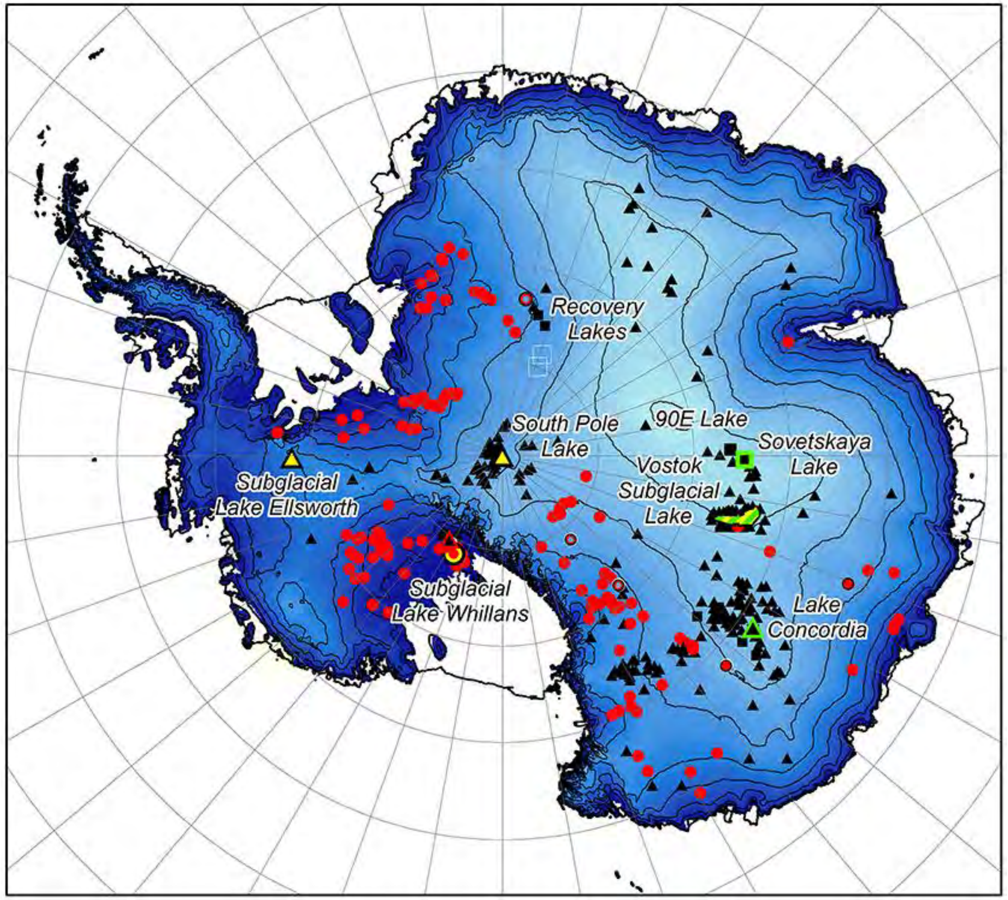
N: effective pressure
The higher the water content of the bed, the lower is N



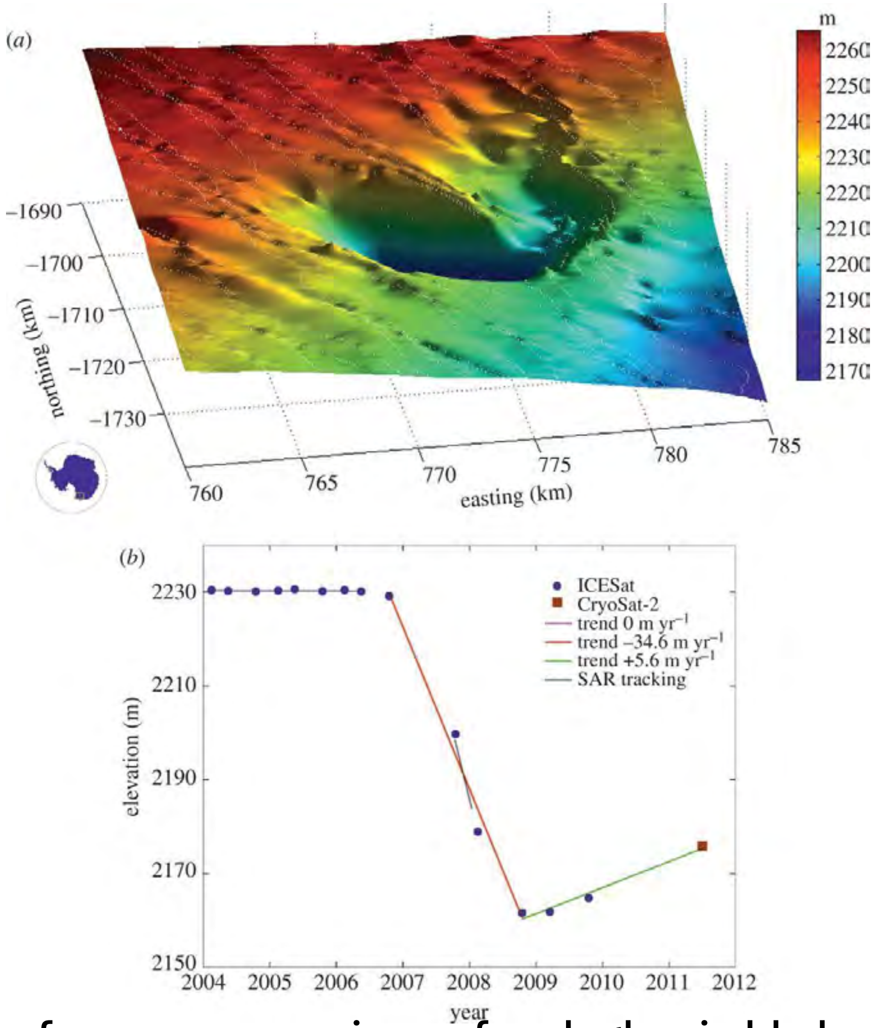
Zoet and Iverson, 2020 (*Science*)

4. Subglacial hydrology

Water is abundant at the Antarctic ice sheet bed – and it moves



Known subglacial lakes in Antarctica (Siegert & Kenniutt, 2018)



Top: Surface expression of subglacial lake
Bottom: Evolution of ice surface height above the lake (Fricker et al, 2016)

Water is abundant at the Antarctic ice sheet bed – and it moves

Boreholes drilled to the bottom of Whillans ice stream, Antarctica found water pressures close to ice overburden, i.e., low effective pressures:

$$N = \rho_i g h \ - p_w$$

N: Effective pressure
ρ_i: Density of ice
g: Standard gravity
h: Ice thickness
p_w: Water pressure

E&K (1997) also recovered **subglacial till** from the ice sheet bed

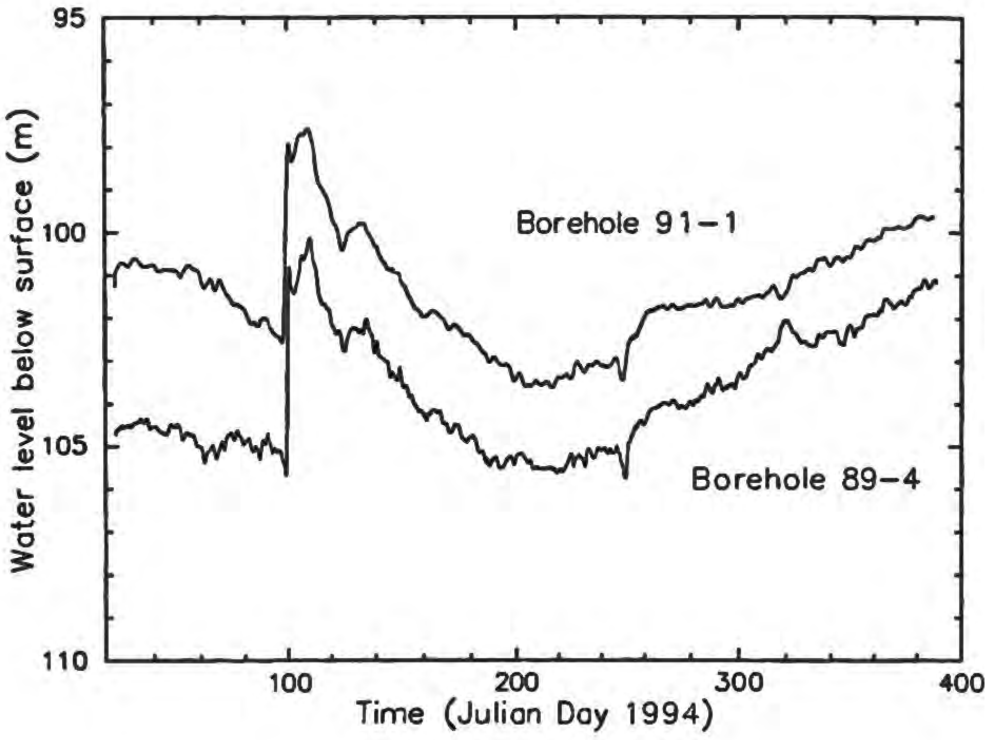


Fig. 14. Comparison of basal water-pressure records from boreholes 89-4 and 91-1 during most of 1994.

Borehole data from Engelhardt & Kamb (1997)

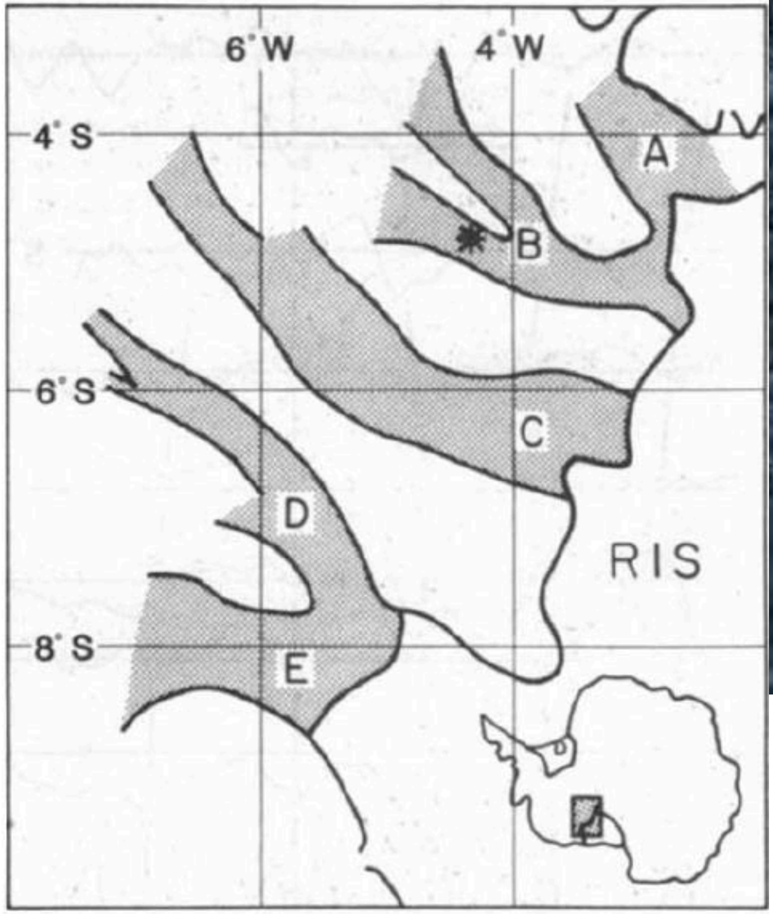
Water moves within or on top of subglacial till

Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream

D. D. Blankenship, C. R. Bentley, S. T. Rooney & R. B. Alley

Geophysical and Polar Research Center,
University of Wisconsin-Madison,
1215 West Dayton Street, Madison, Wisconsin

(1986)



Example of subglacial till
(Evans et al, 2006)

Many known hydraulic systems exist

Evidence for channelized and distributed flow exists

But:

- Most models are developed for hard beds (i.e., not tills)
- Detailed models resolving individual conduits etc are not suitable for long-term coupled simulations

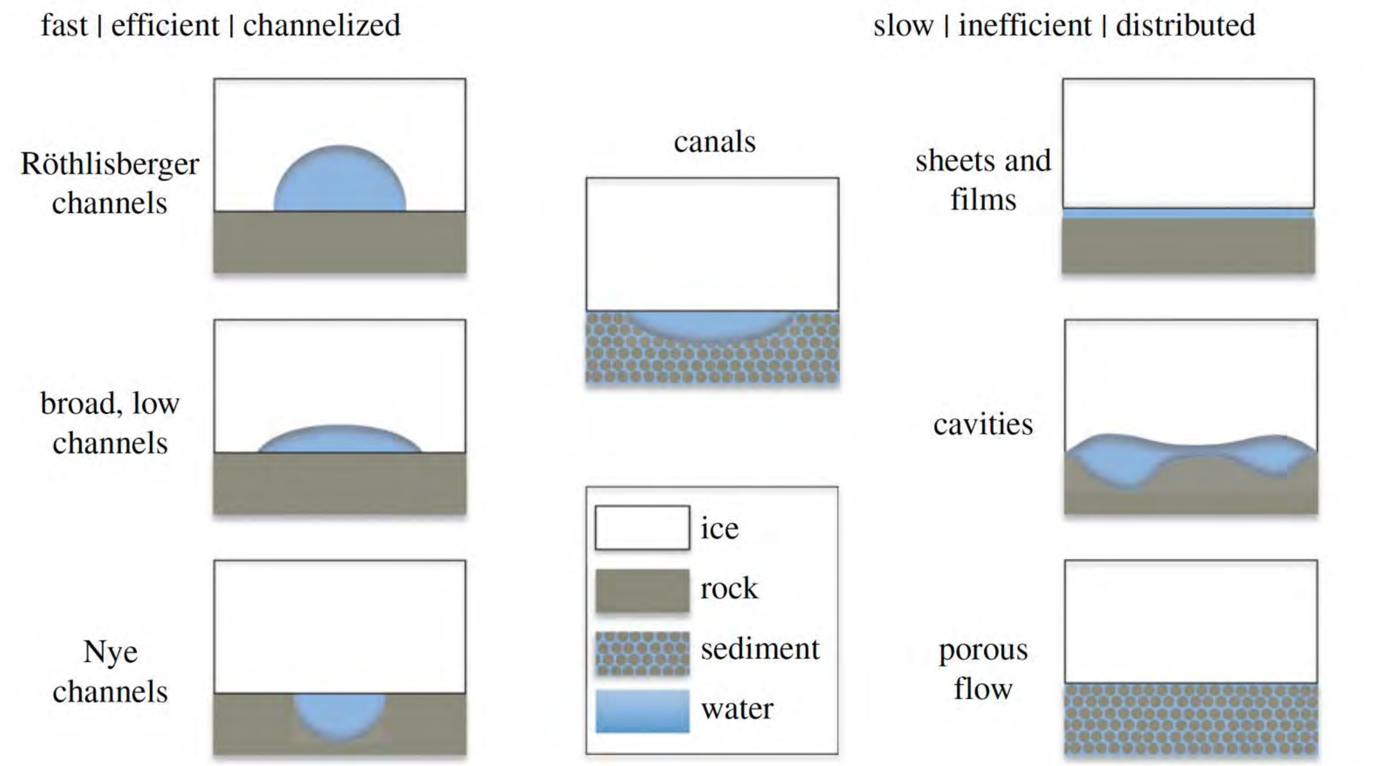


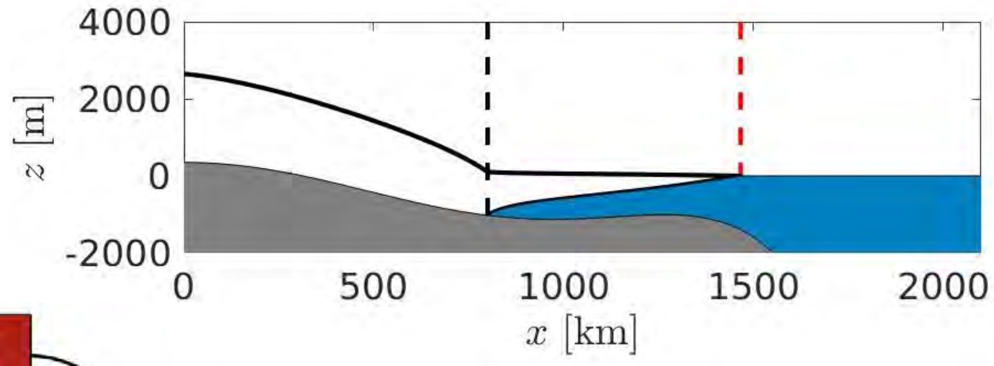
Figure 2. Idealized 'elements' of the subglacial drainage system as described in the literature. Elements are grouped into those associated with 'fast', 'efficient' or 'channelized' drainage, versus those associated with 'slow', 'inefficient' or 'distributed' drainage. Canals may be classified either way, depending on the relative efficiency of opening and closure processes.

(Flowers, 2015)

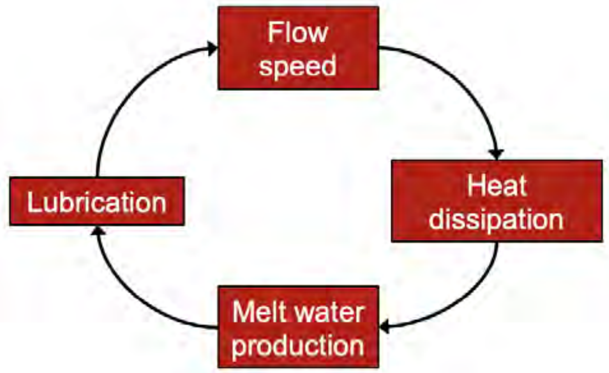
5. Example simulation

Three components:

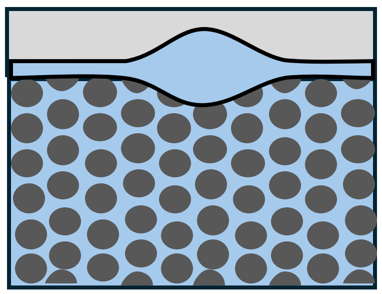
1. Marine ice sheet dynamics
(Dynamics of an ice sheet in contact with the ocean)



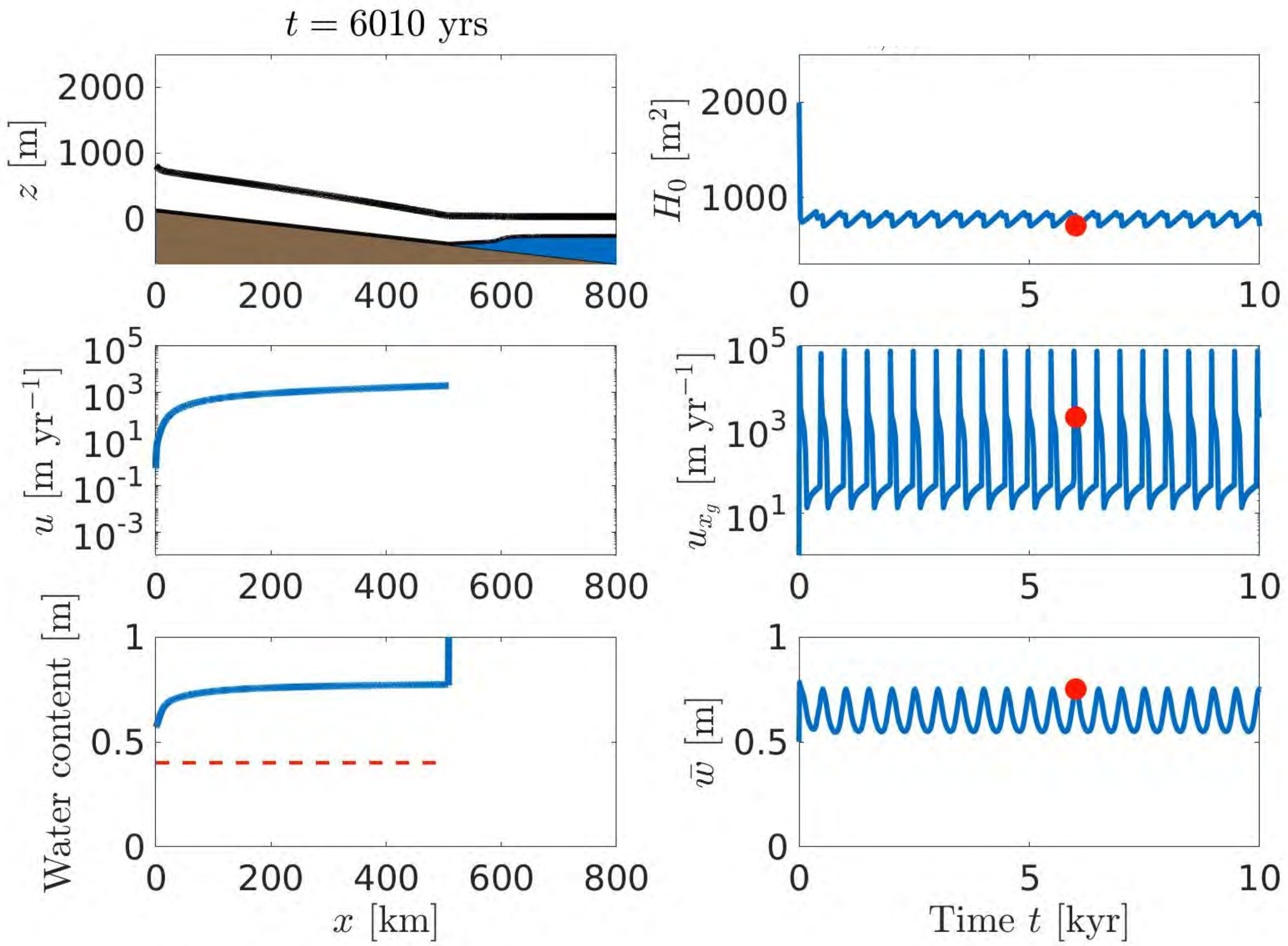
2. Thermo-mechanical coupling and fast flow



3. Subglacial hydrology



Example of typical ice sheet simulation



Oscillations of flow speed

$\Rightarrow$ Controlled by the water content of the bed which is controlled by the ice thickness (thicker bed: warmer) and movement of water at the bed

High water content:

Bed is slippery

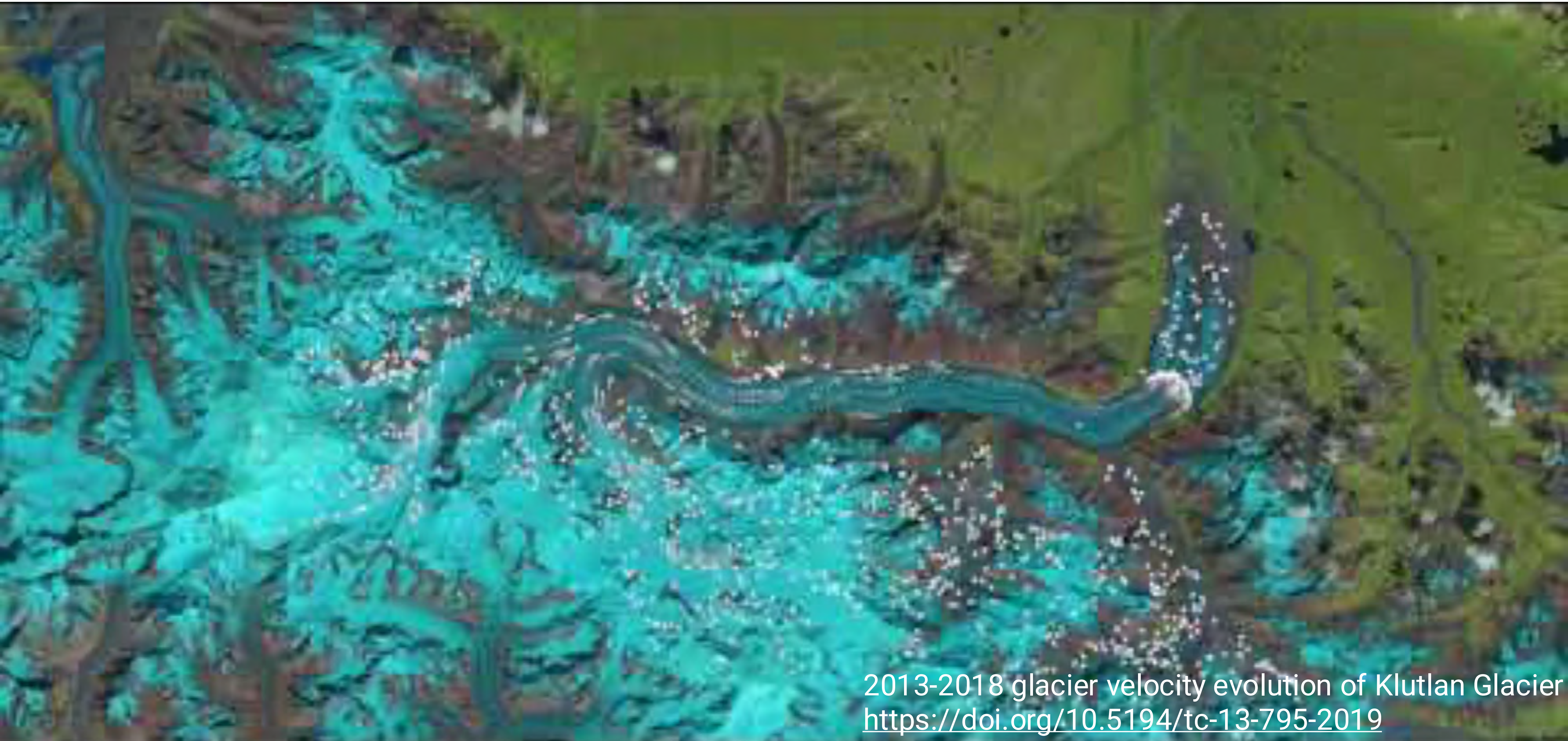
High discharge & thinning

Low water content:

Bed stronger

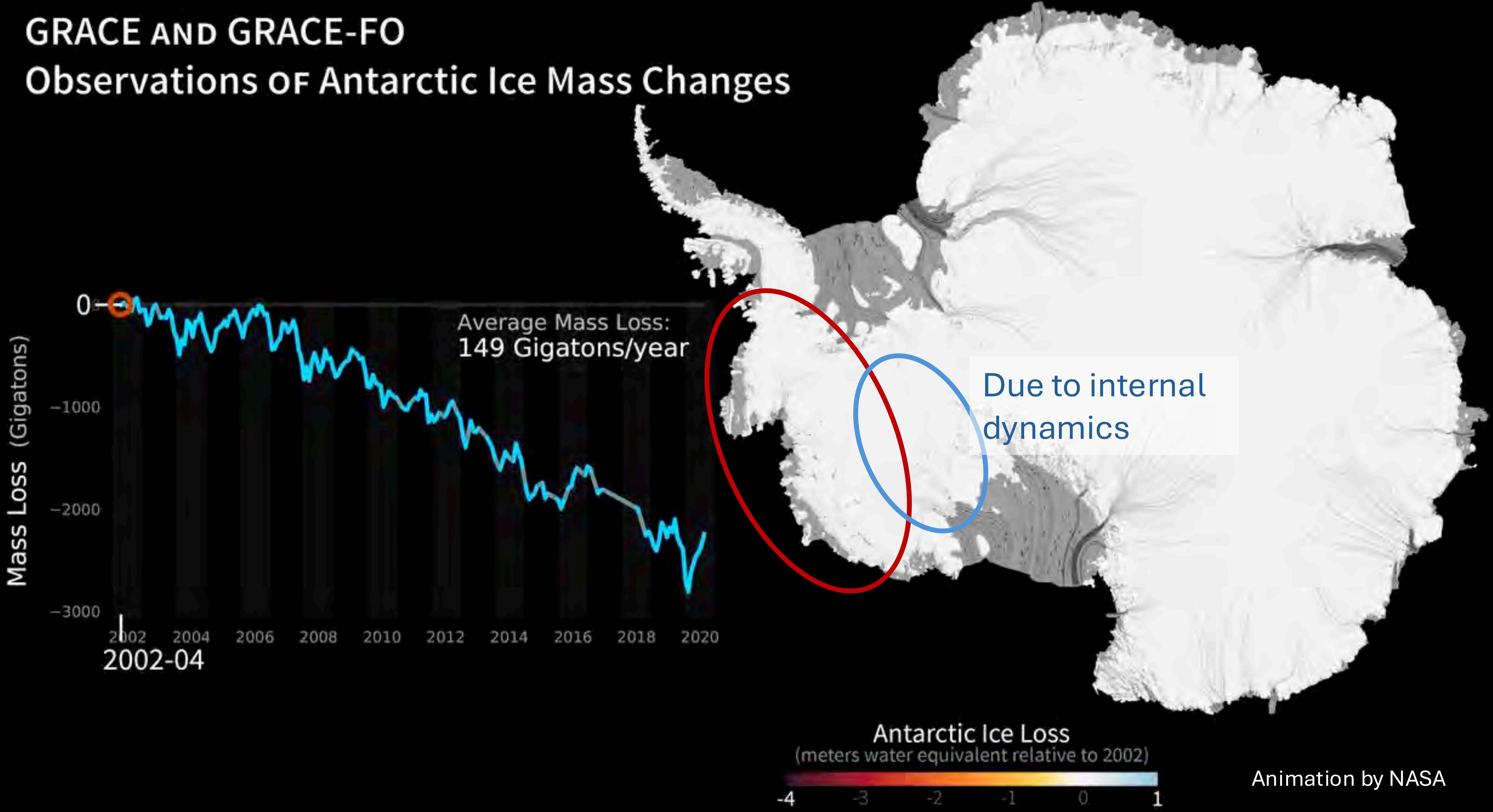
Ice sheet thickening

Surge: periodic speed-up of glaciers



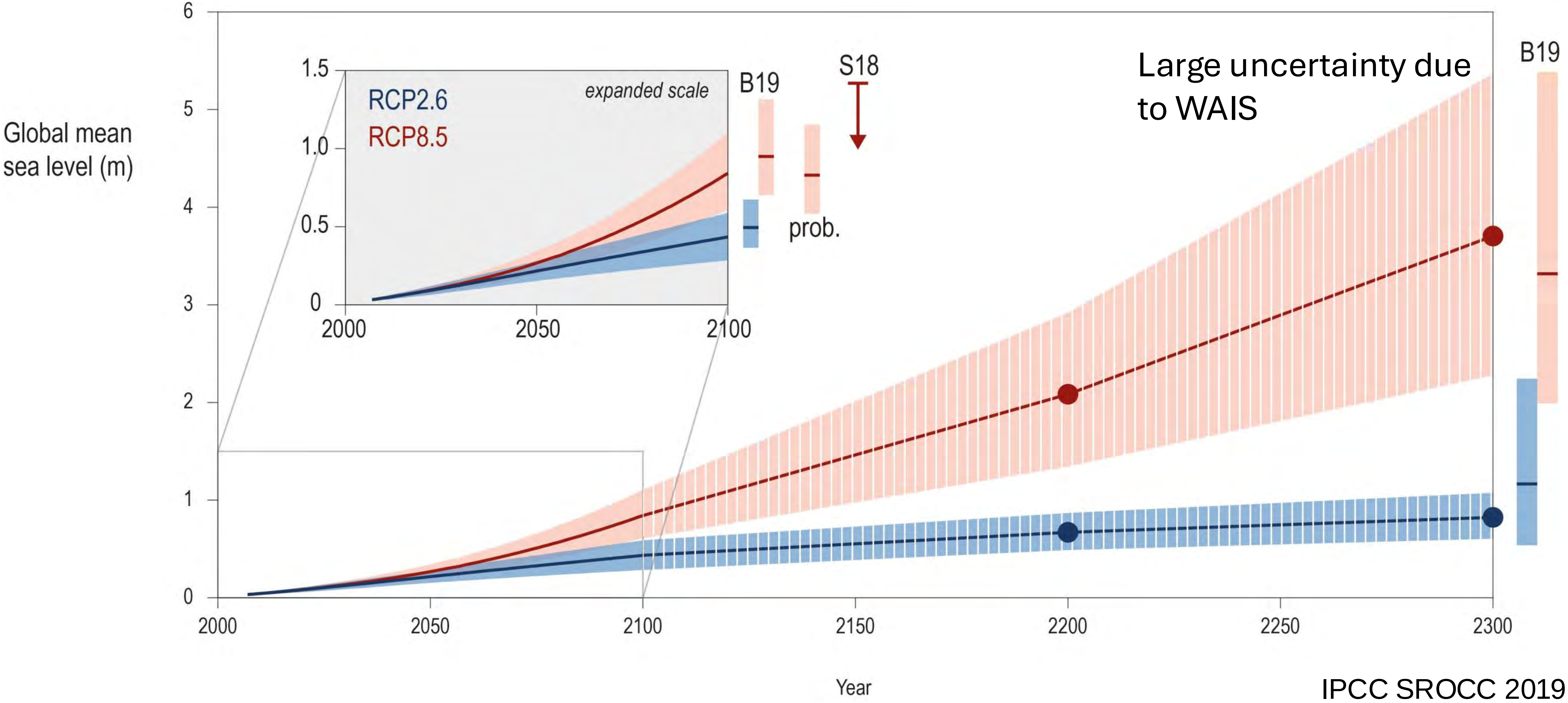
2013-2018 glacier velocity evolution of Klutlan Glacier
https://doi.org/10.5194/tc-13-795-2019

GRACE AND GRACE-FO
Observations OF Antarctic Ice Mass Changes



Animation by NASA

Projected sea level rise



Large uncertainty due to WAIS

IPCC SROCC 2019

Summary

- We study the flow and thermodynamics of ice, as well as the interaction of ice and water
- What we know reasonably well:
  - Equations for ice flow (Stokes), mass and energy balance
  - Deformation of pure ice (as a non-Newtonian fluid)
  - Resistance provided by the bed
- What we are still trying to understand:
  - Deformation of ice with impurities
  - How water moves around at glacier beds
  - How are ice sheets going to contribute to sea level rise?