The Role of Meltwater in Greenland Ice Sheet Dynamics

Lauren C. Andrews
Global Modeling and Assimilation
Earth Sciences Division, NASA GSFC

JHU Earth & Planetary Sciences
Bromery Lecture
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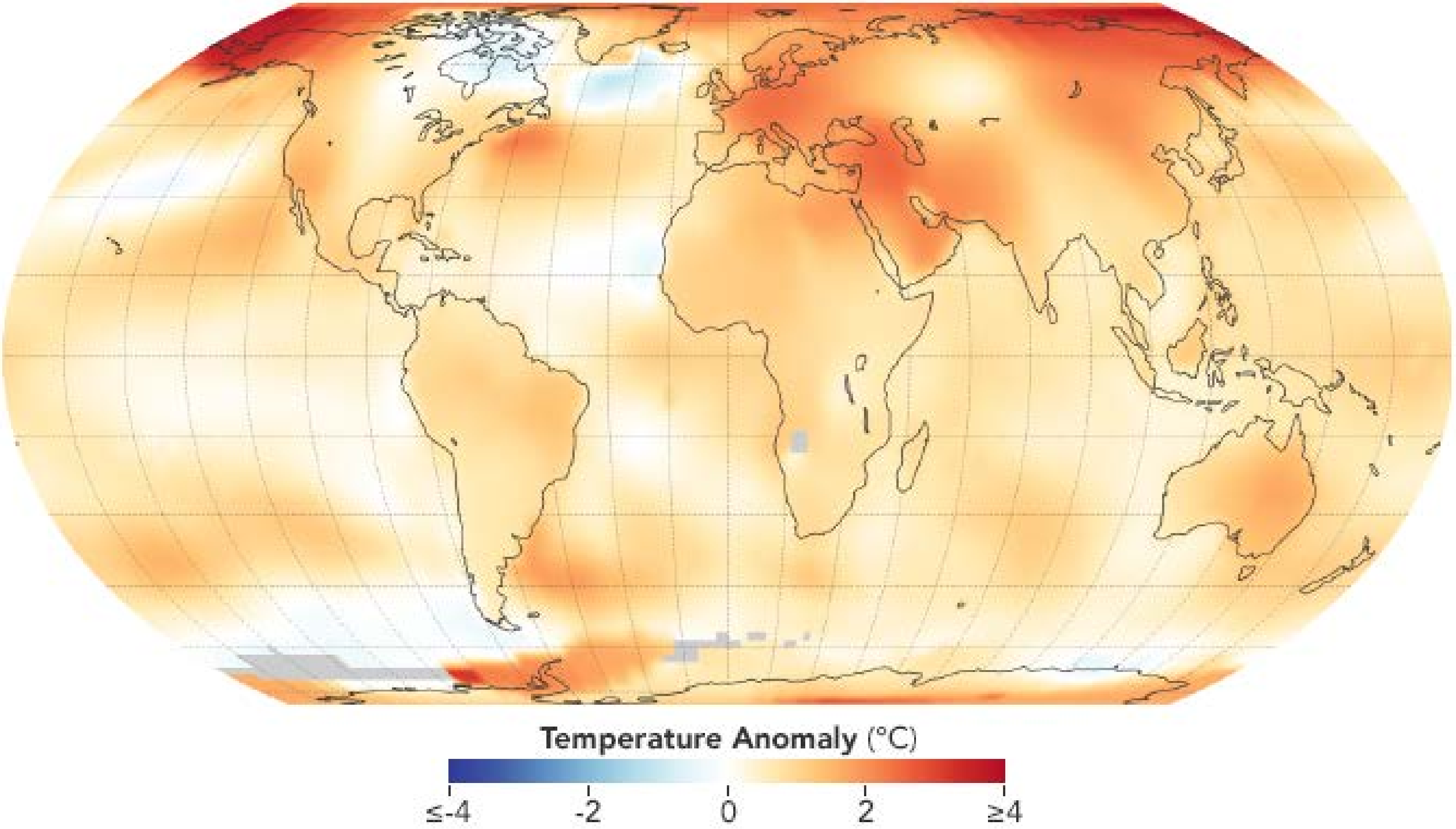
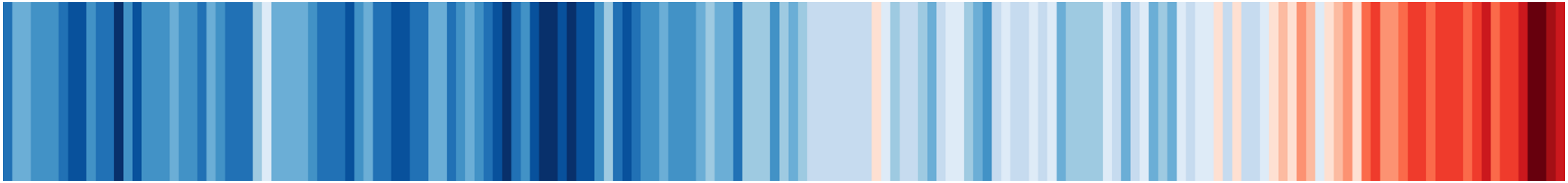
Arctic amplification



2018 anomaly relative to 1951-1980; NASA GISTEMP v4



#ShowYourStripes; Rhode et al. (2013)

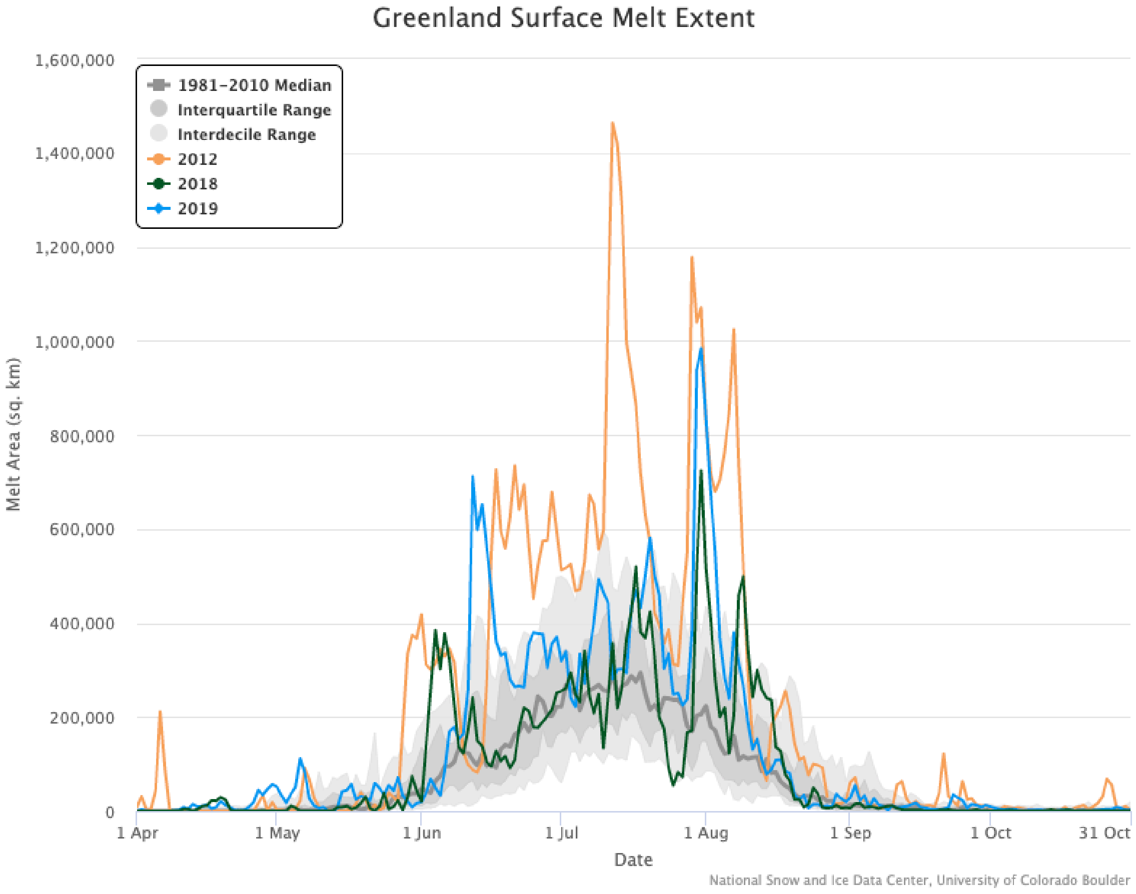
CE

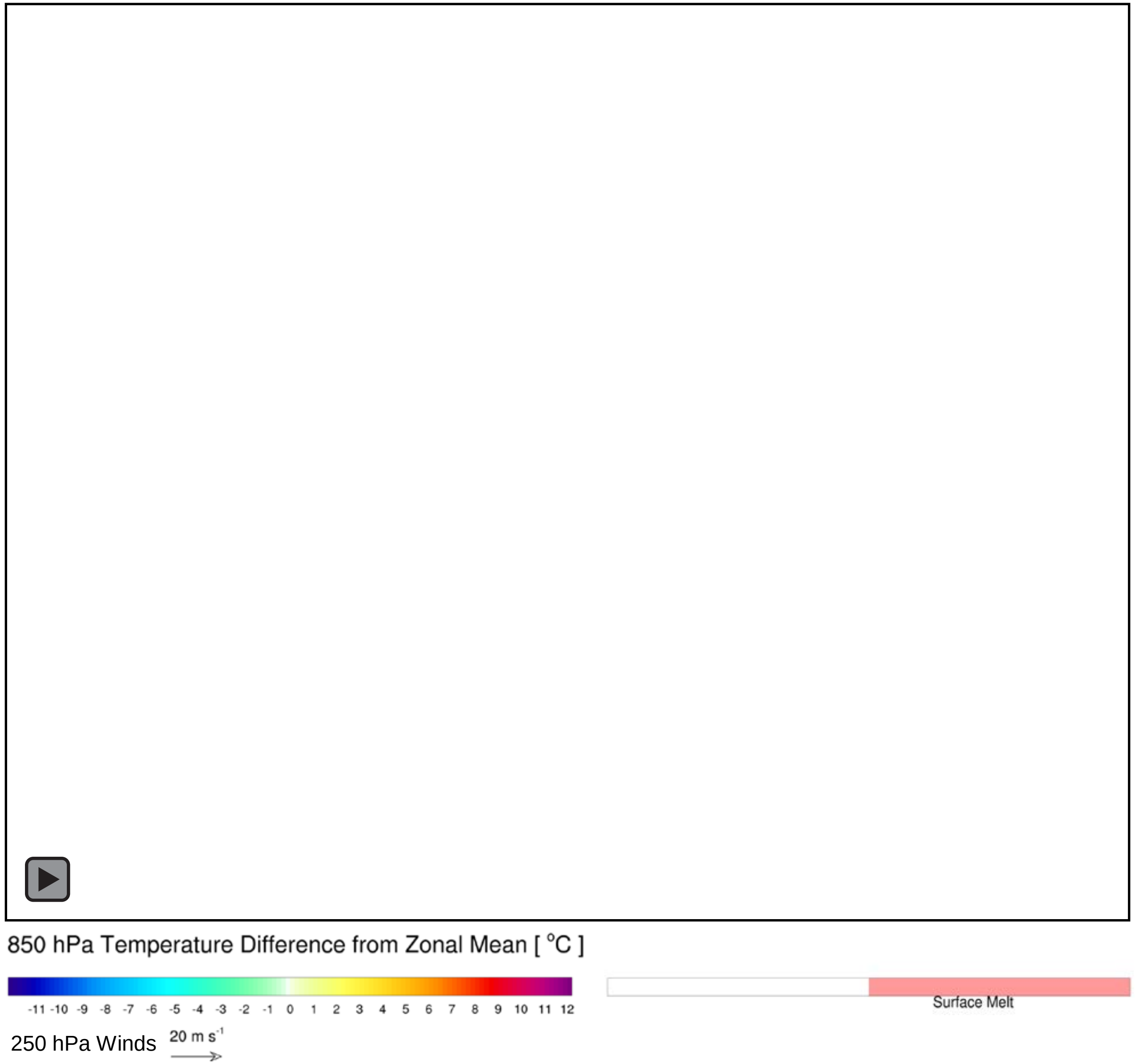
Surface & dynamic ice mass changes

- Surface → 70%
  Dynamic → 30%

- Dynamic processes are numerous and are relatively unconstrained, but are critical to determining how much of the ice sheet behaves

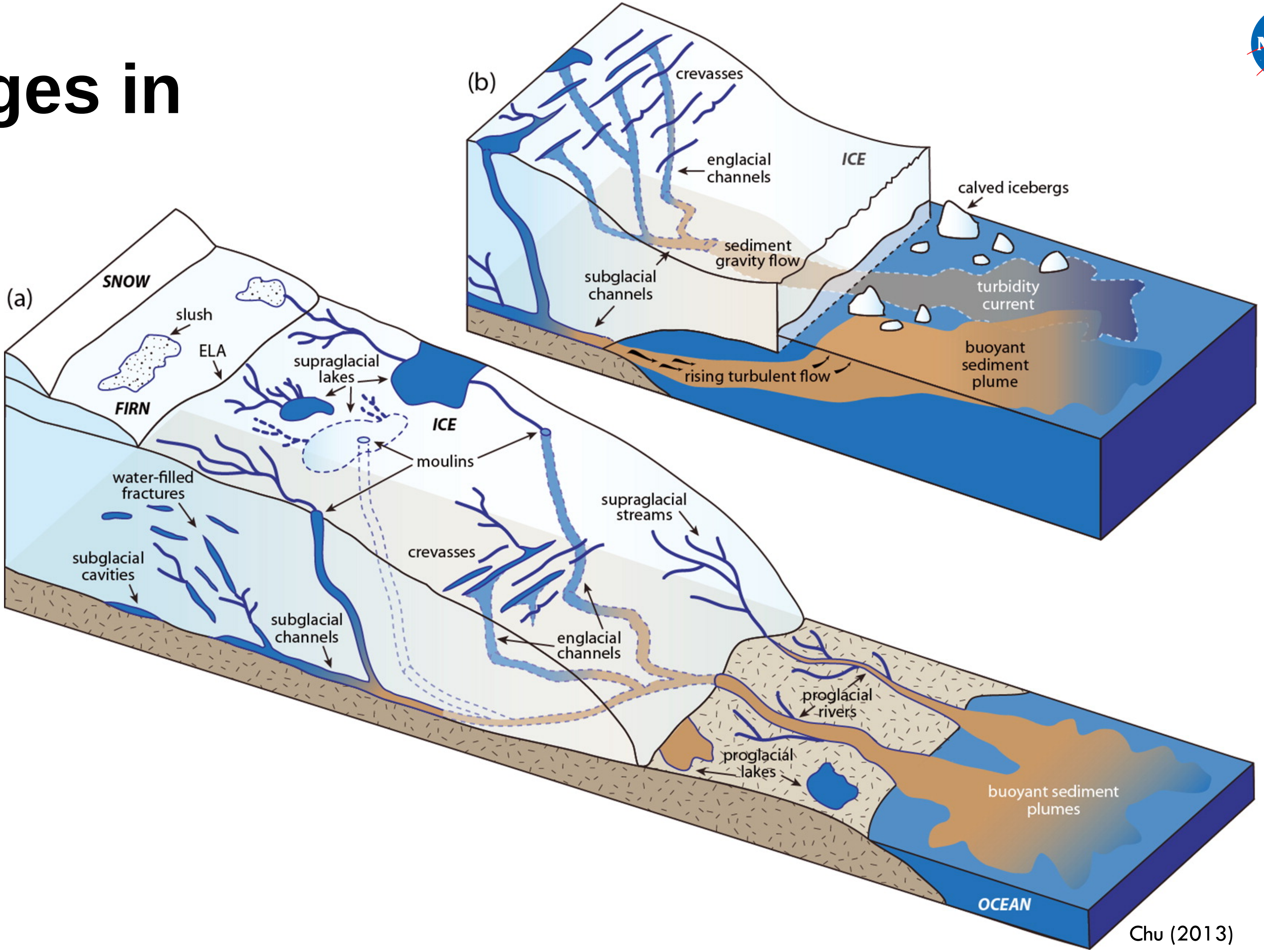
Surface melting





Andrews & Cullather (2019)

How do changes in surface melt alter ice dynamics?

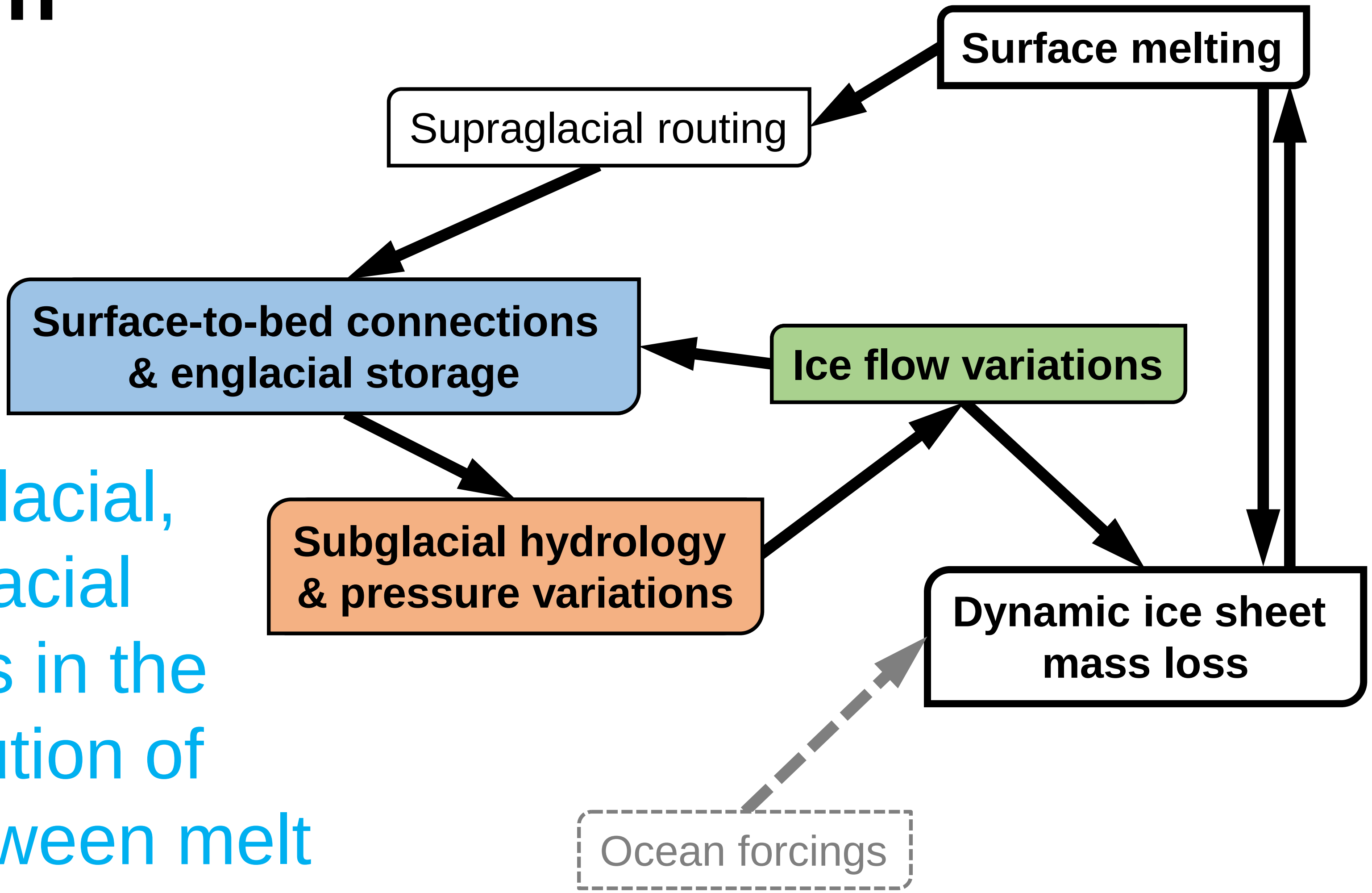


Chu (2013)

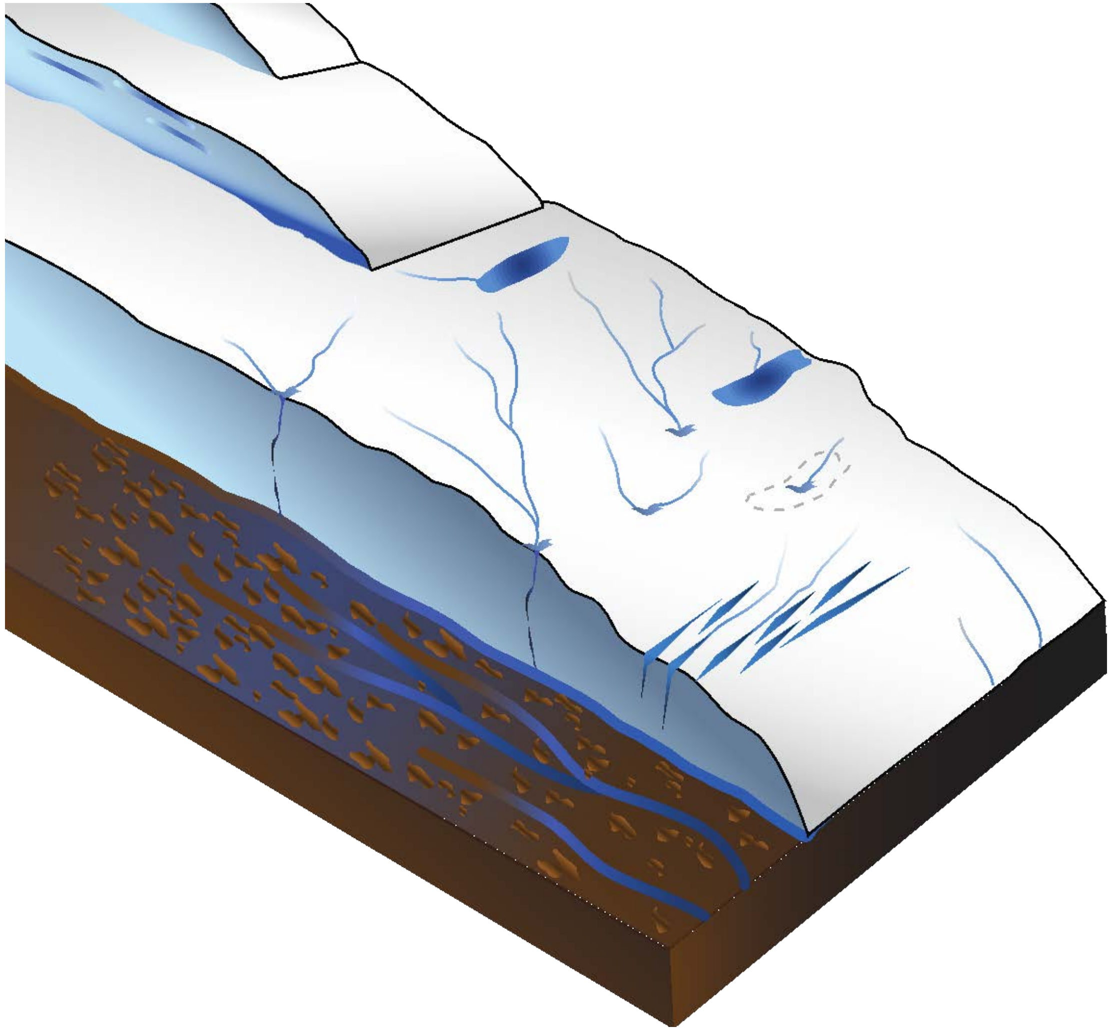
How do changes in surface melt alter ice dynamics?

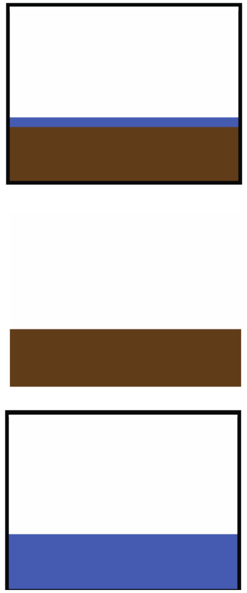
How do changes in surface melt alter ice dynamics?

Processes in the subglacial, englacial, and supraglacial systems, plus changes in the spatiotemporal distribution of melt make the link between melt and ice dynamics complex (and interesting).



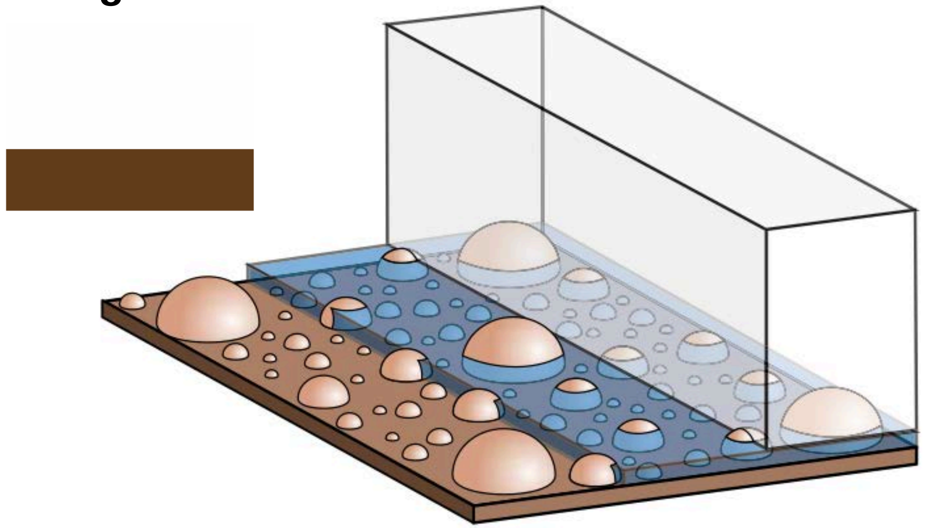
Subglacial hydrology



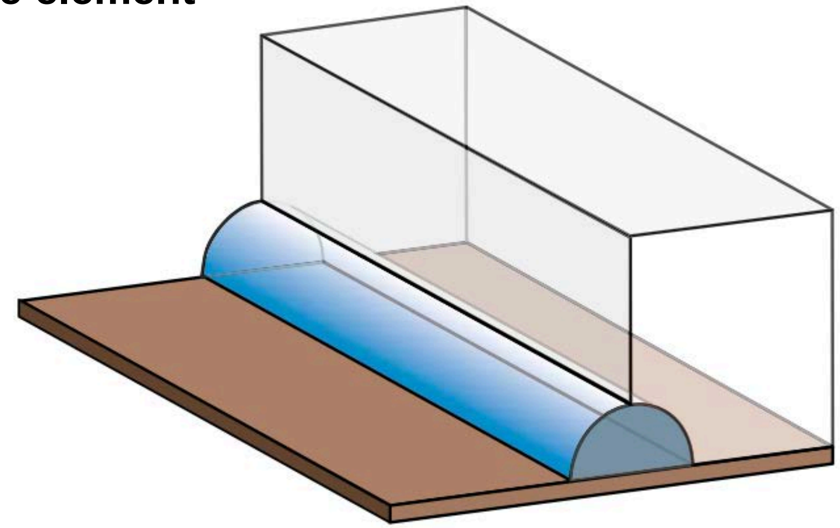


Subglacial hydrology

Idealized inefficient drainage element



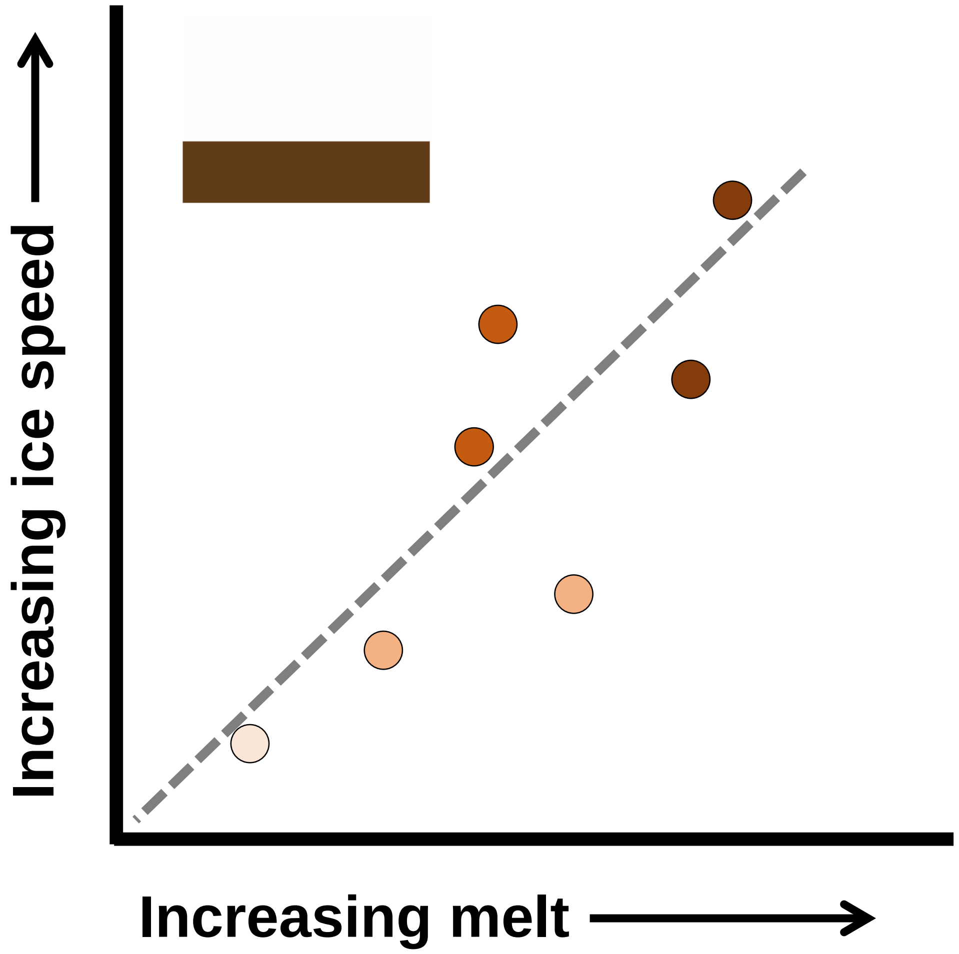
Idealized efficient drainage element

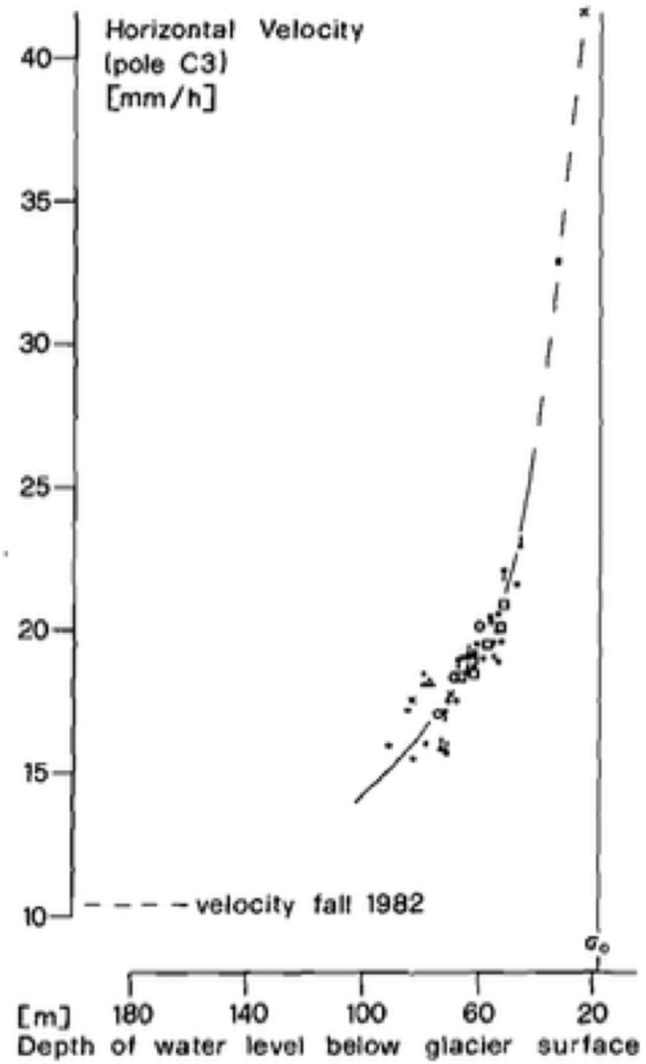


- Formed primarily due to sliding
- Slow water flow
- Operate at high pressure
- Increase in flux increases subglacial pressure & ice flow

- Formed primarily due to melting
- Fast water flow
- Operates at low pressure
- Increase in flux decreases subglacial pressure & ice flow

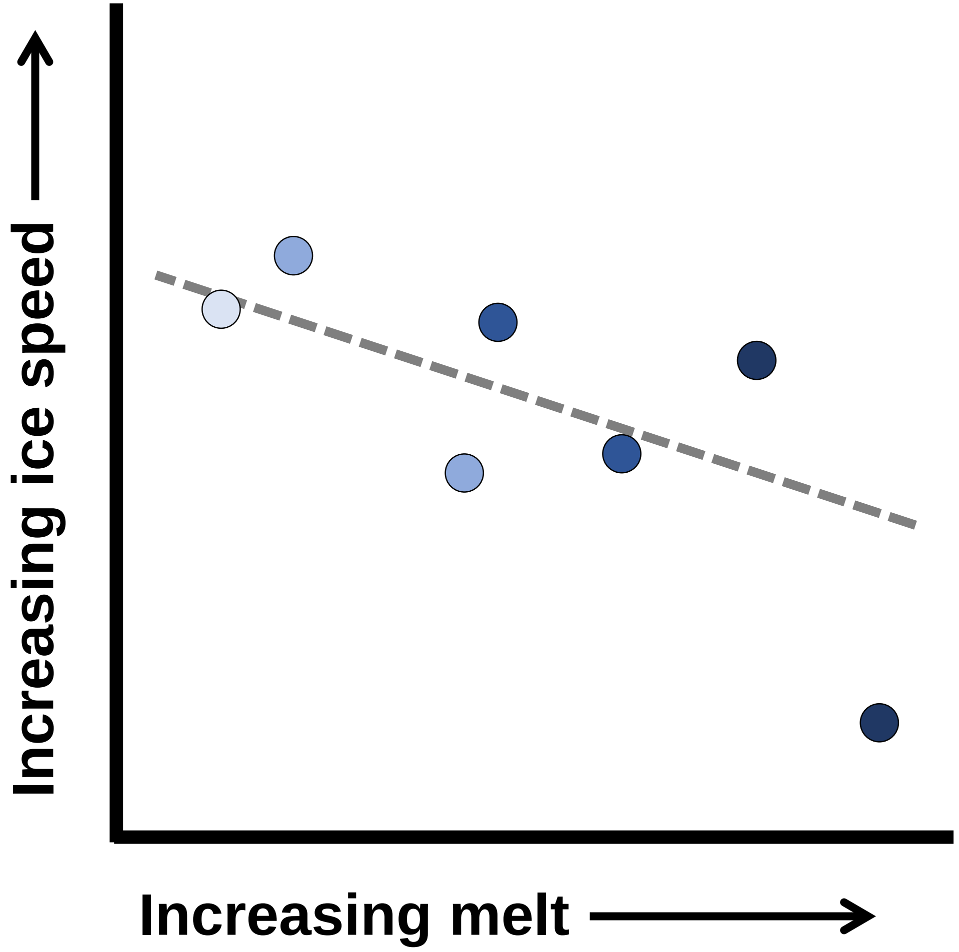
Subglacial hydrology: inefficient drainage

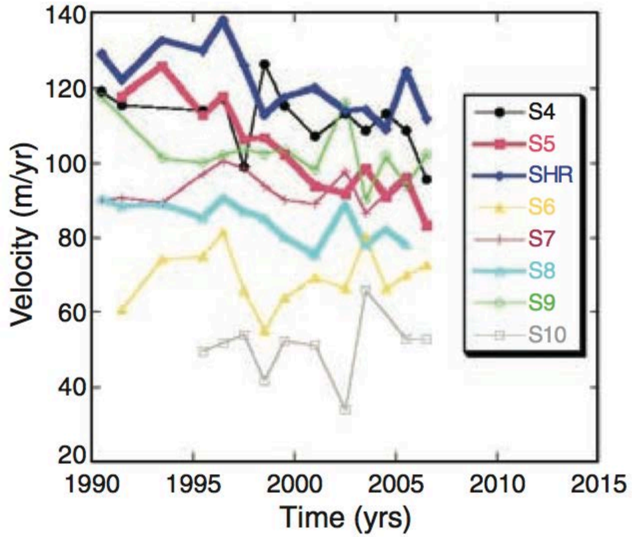


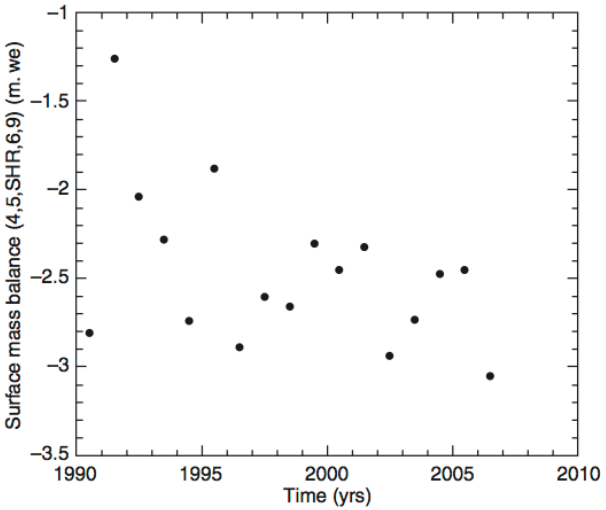


Iken & Bindschadler (1986)

Subglacial hydrology: efficient drainage

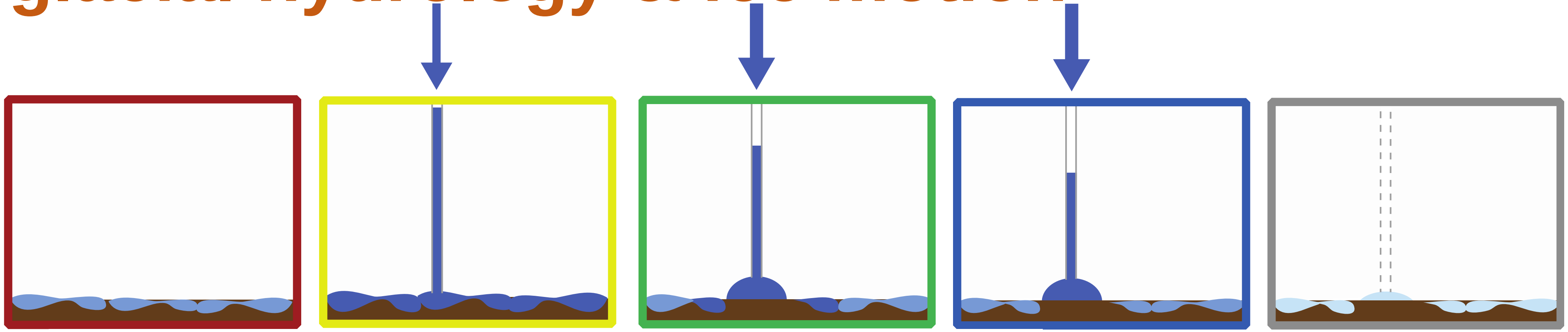


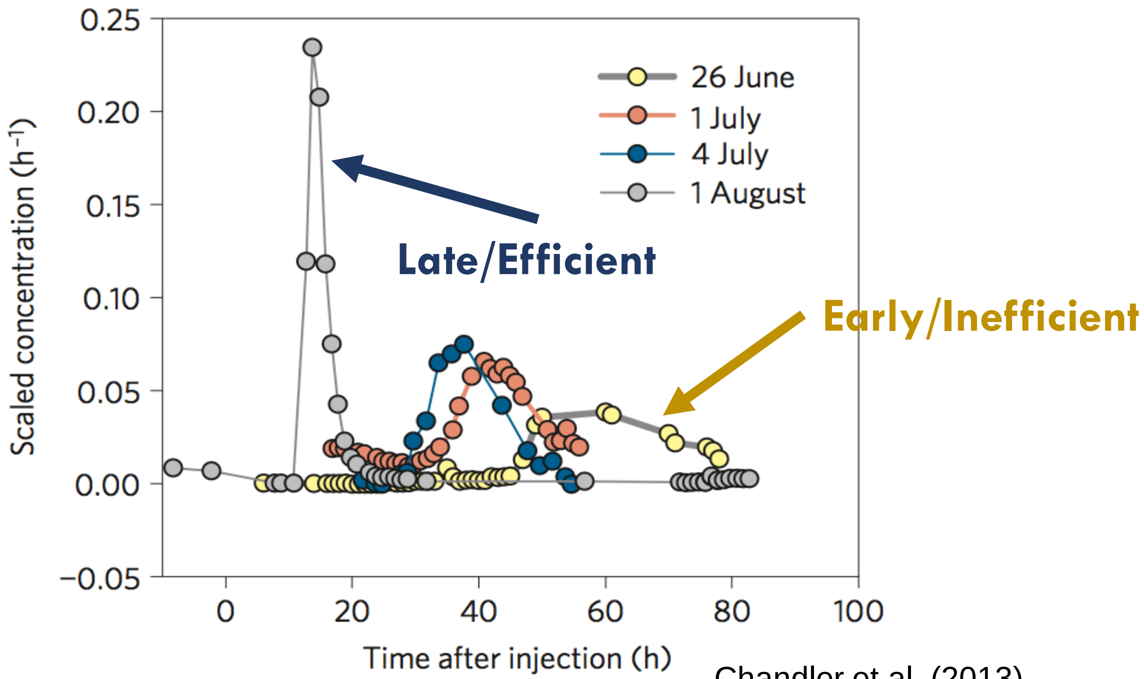




van de Wal et al. (2008)

Subglacial hydrology & ice motion

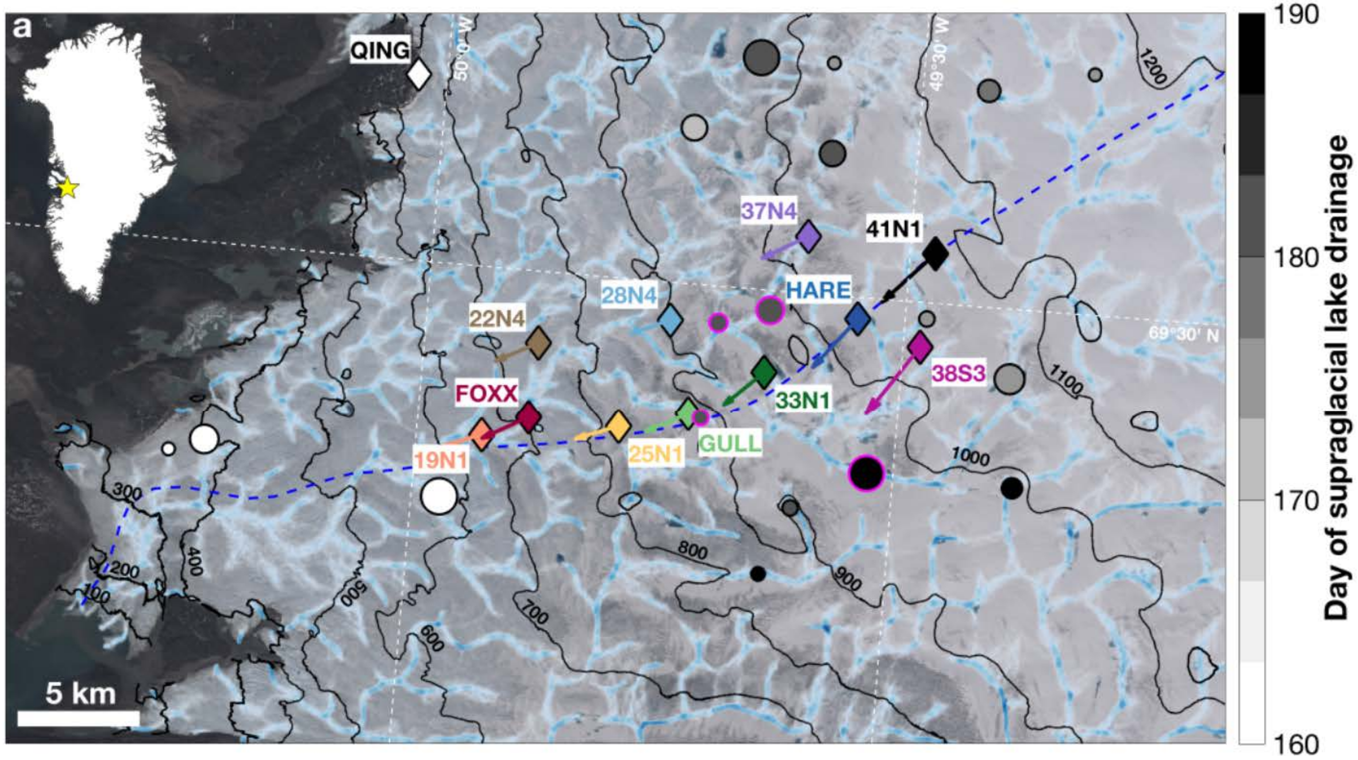


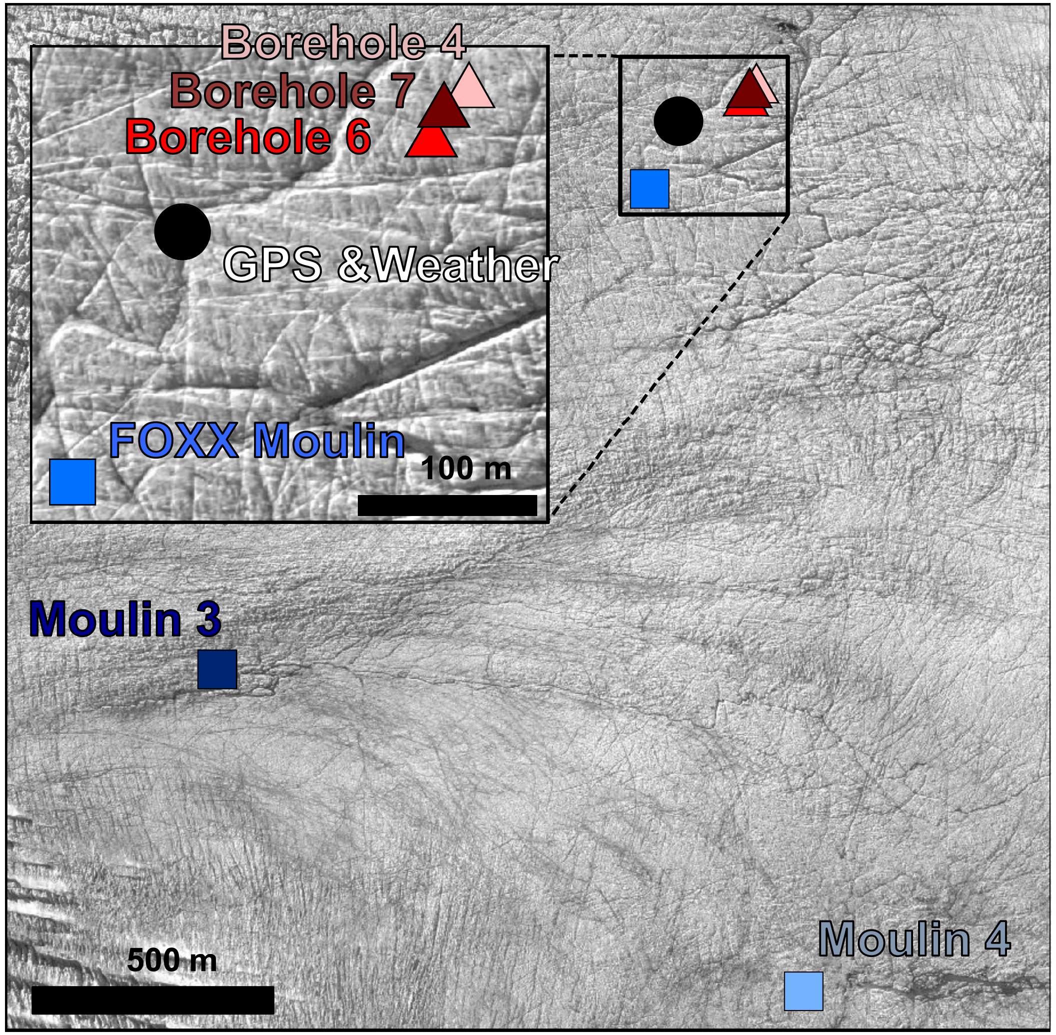


Chandler et al. (2013)

Under our current conceptualization, **an increase in efficiency** is an increase in the ability of the subglacial system to conduct available water. This should be reflected in **decreasing subglacial pressures**.

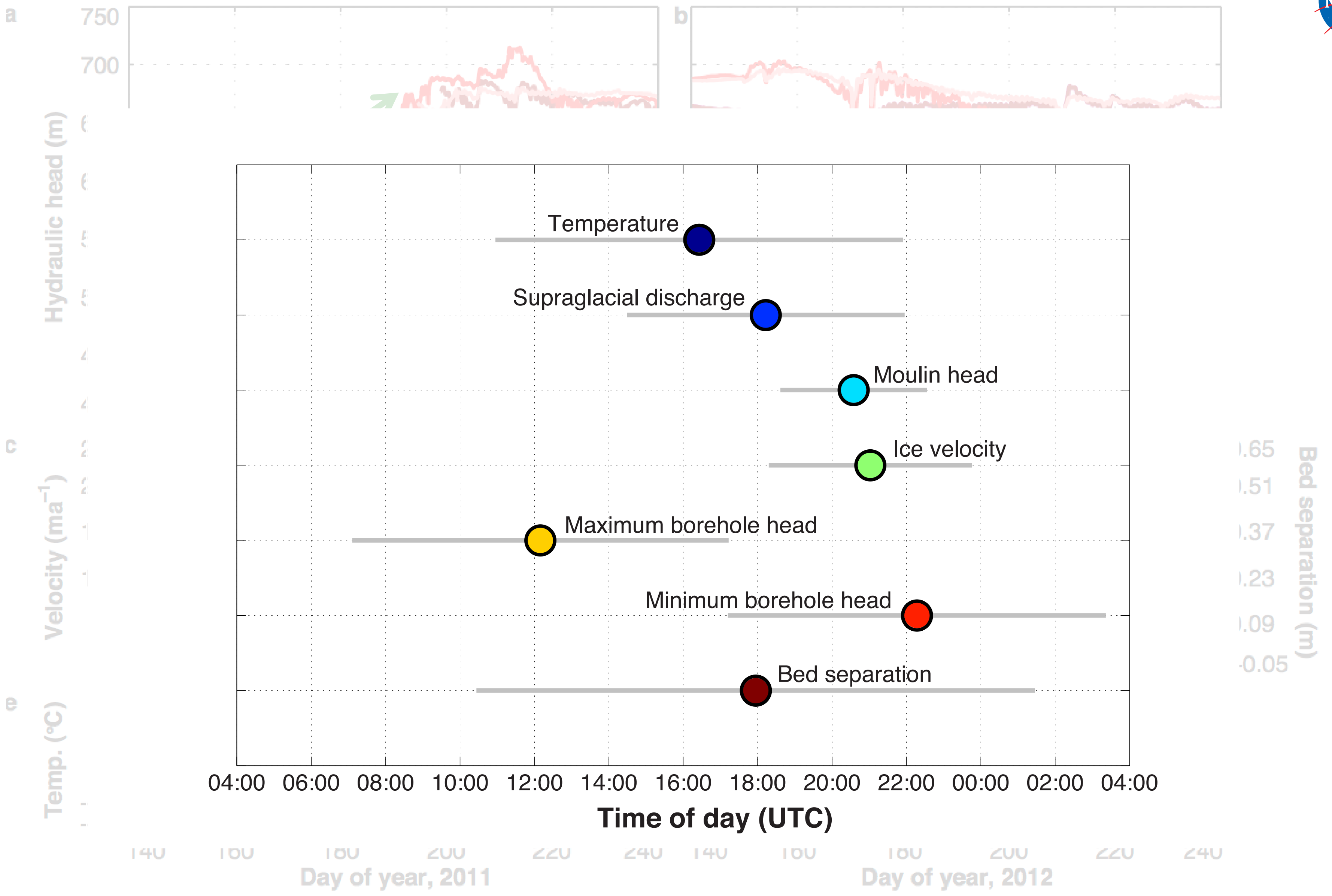
Subglacial hydrology & ice motion





Andrews et al. (2014, 2018)

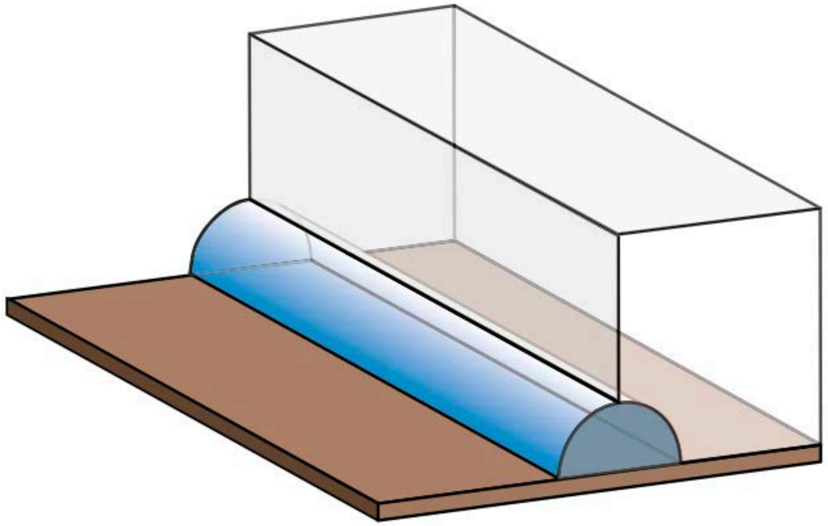
Subglacial hydrology & ice motion

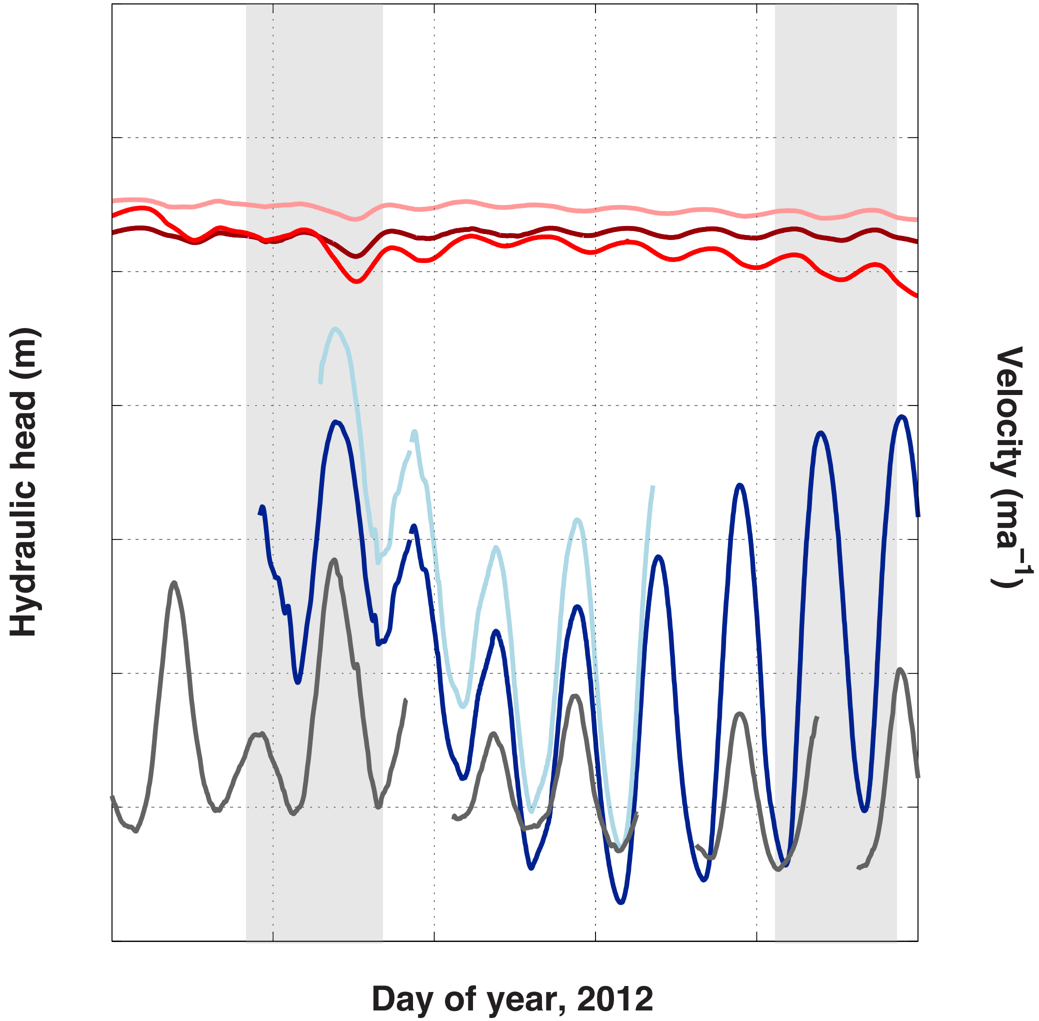


Andrews et al. (2014)

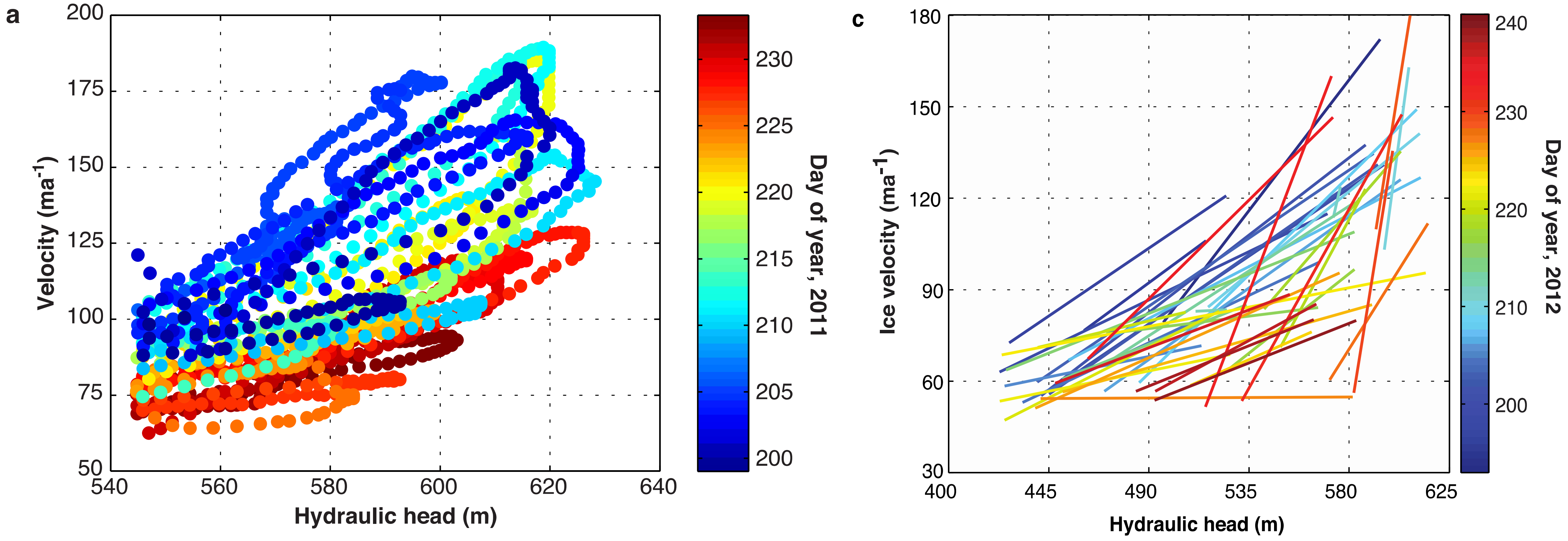
Monitoring subglacial channels

- Large diurnal variability, specifically, low diurnal minima
- Downstream similarity - a system response
- In phase with ice velocity



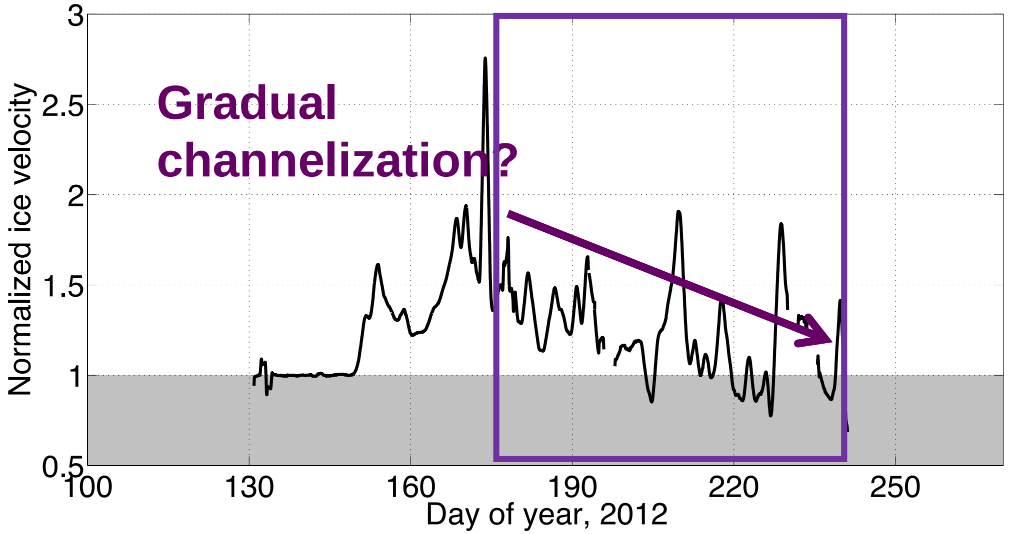


An evolving relationship between ice velocity and subglacial channel pressure

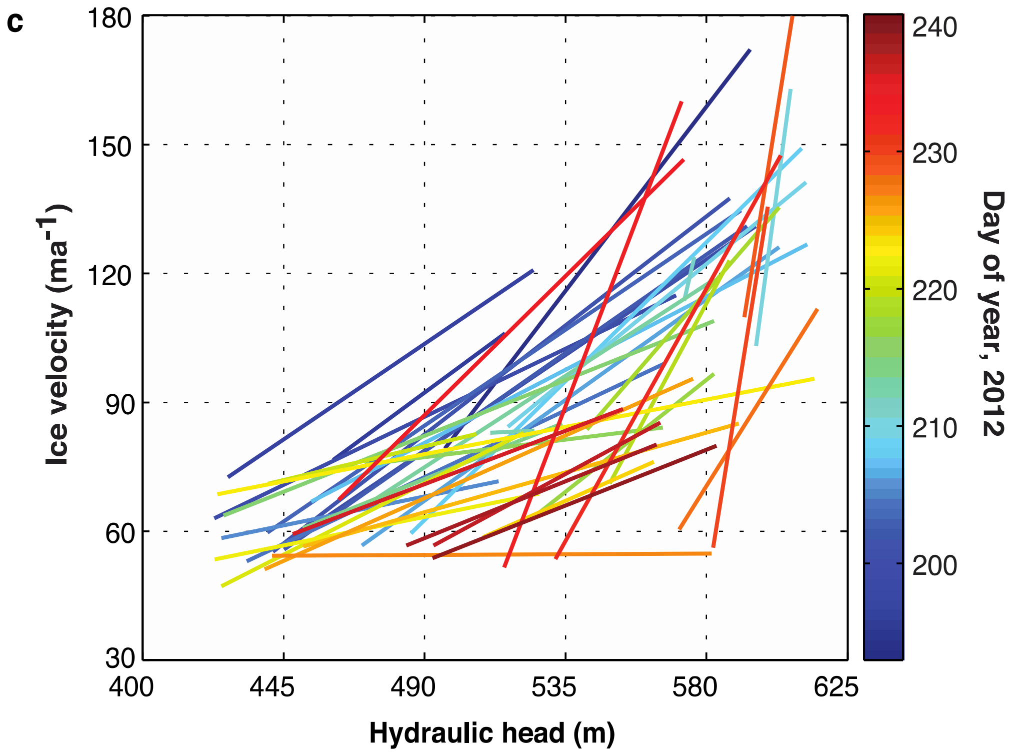


Andrews et al. (2014)

Velocity evolution without long-term increases efficiency?



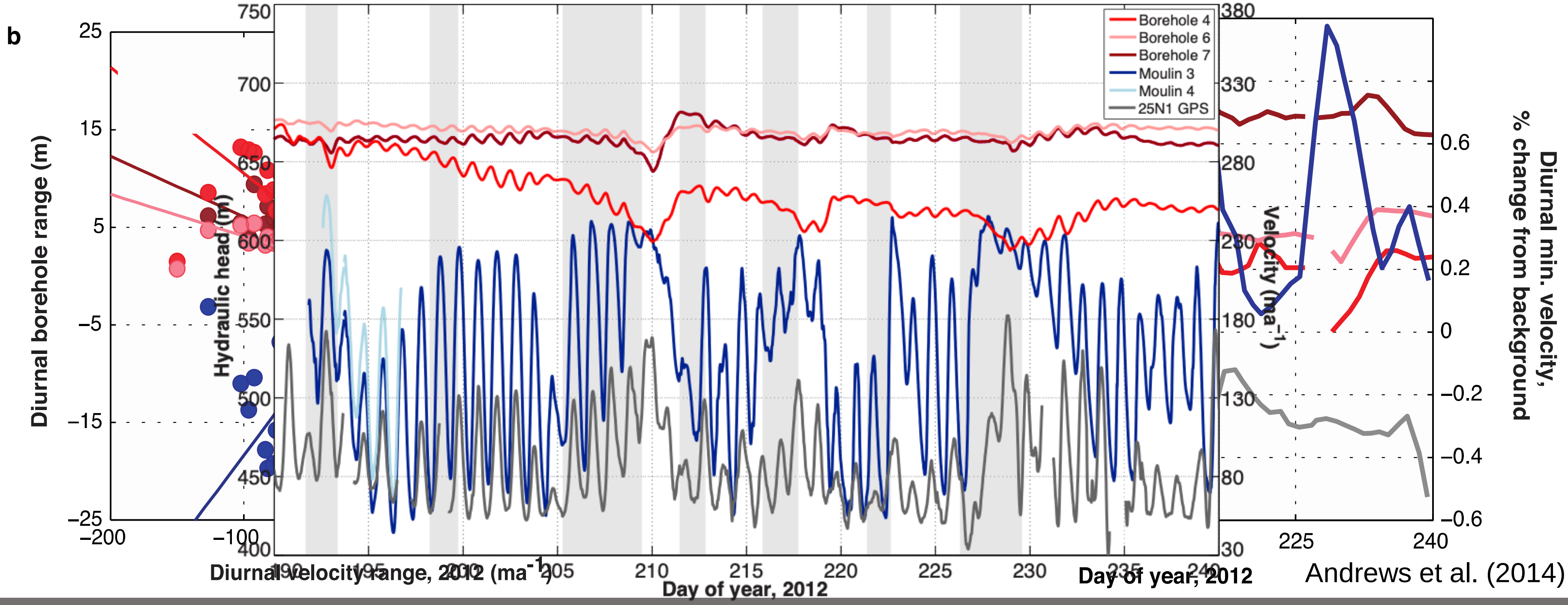
However, ice speed continues to drop, indicating evolution elsewhere in the subglacial system.



This subglacial channel is seemingly mature. We don't observe continuing increases in channel efficiency (i.e. no decreasing pressure observed in moulins).

Subglacial evolution outside channelized regions

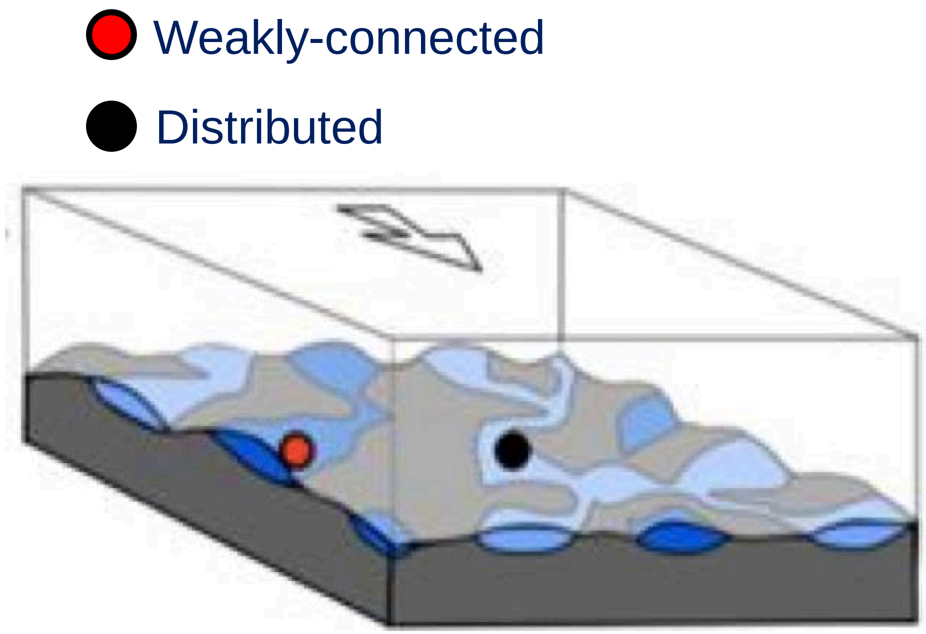
- Low amplitude diurnal changes in boreholes
- Borehole head out of phase with velocity
  - Sampled the (large) 'unconnected or weakly-connected' unchannelized system
  - Flow coupling and 'passive' cavity opening
- Long-term trends in boreholes match trends in ice velocity



Andrews et al. (2014)

Conceptualizing the weakly connected system

- Channels control daily and event (multi-day) variations in velocity
  - Moulin hydraulic head indicates the presence of stable channels during the latter half of the summer
- Late season velocity patterns are likely due to changes occurring within the isolated or weakly-connected regions of the unchannelized system.

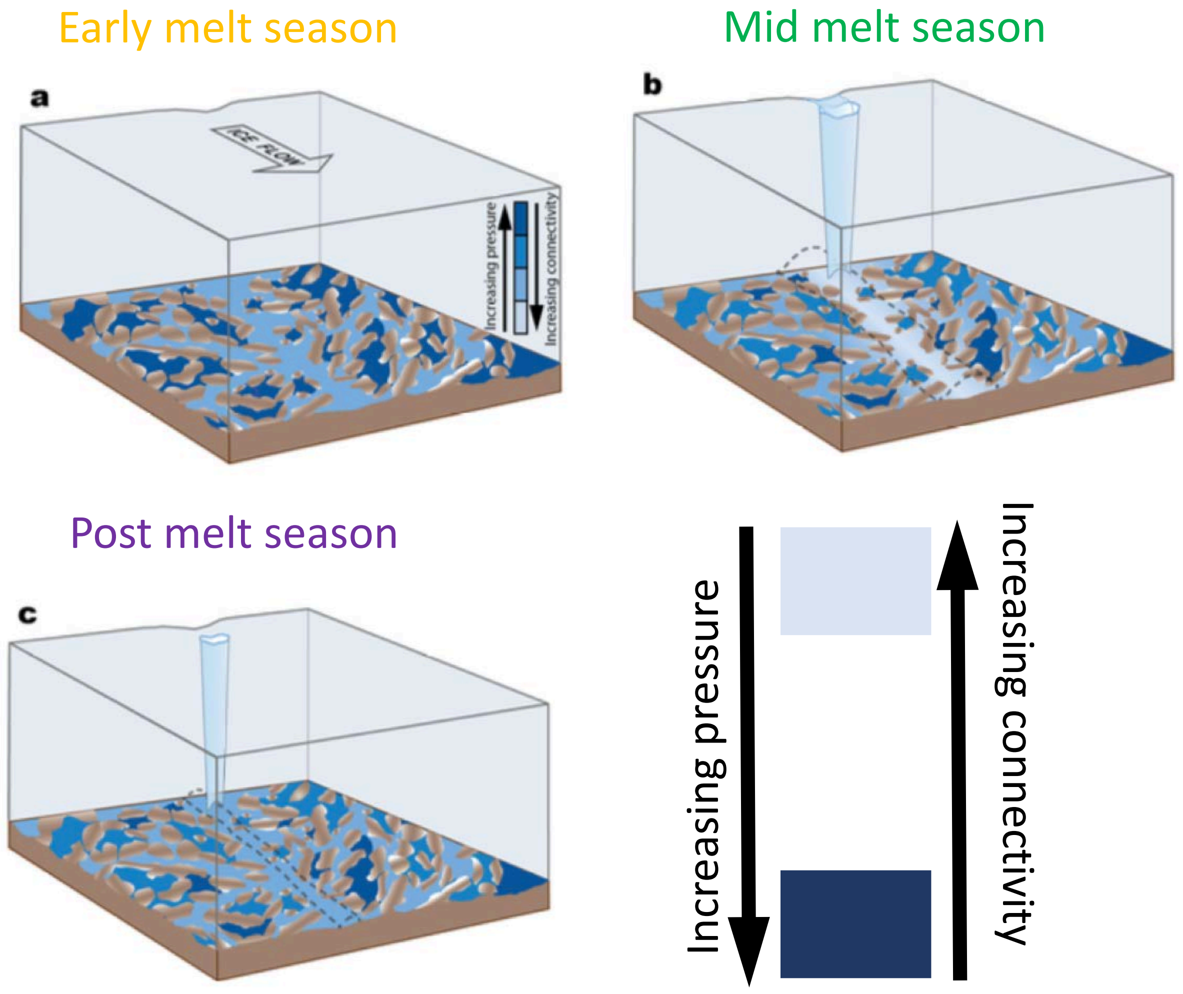


Ian Hewitt

Why could weakly connected (inactive regions) of the bed be important?

- Extensive and dynamic isolated and ephemerally connected systems under alpine glaciers (e.g., *Hodge*, 1979; *Murray & Clarke*, 1995; *Gordon et al.*, 1998)

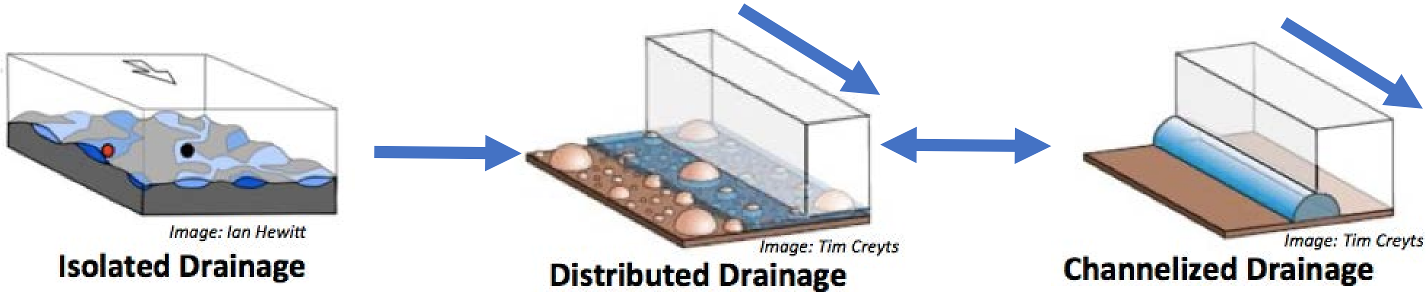
- Widespread velocities respond to the integrated basal traction over the entire bed (both **connected** and **weakly-(un)connected** regions) (*Iken & Truffer*, 1997)



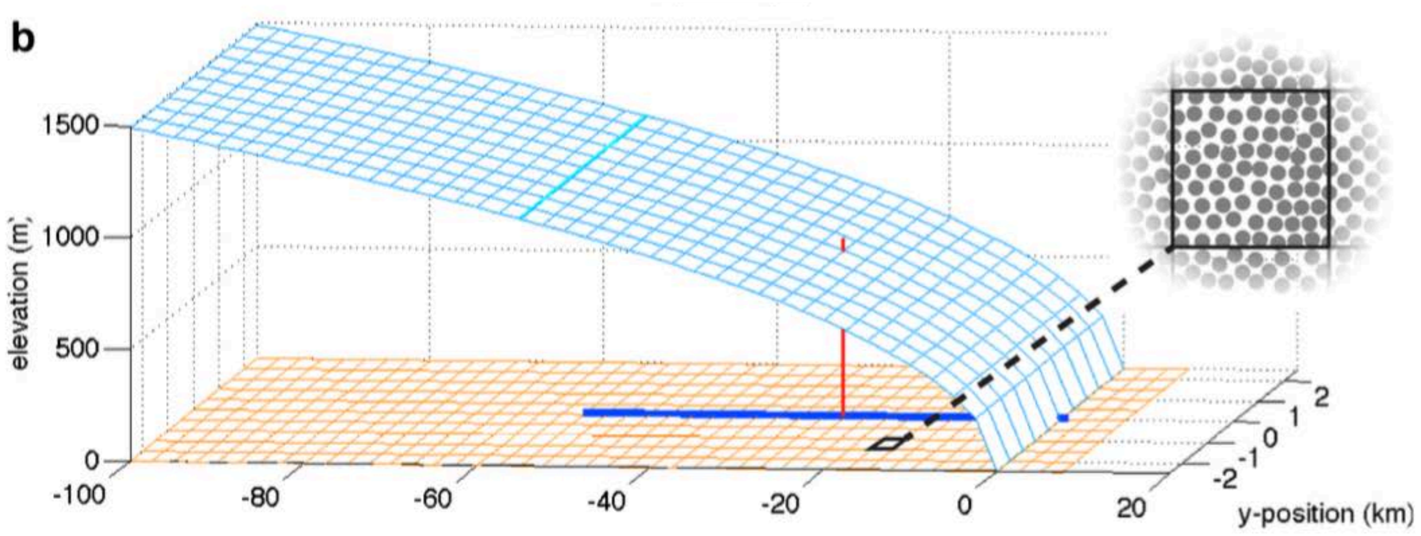
Hoffman et al. (2016)

Modeling the weakly connected system

Weakly-connected system implemented as as discontinuous reservoir that can exchange water with the surrounding drainage system in each grid cell



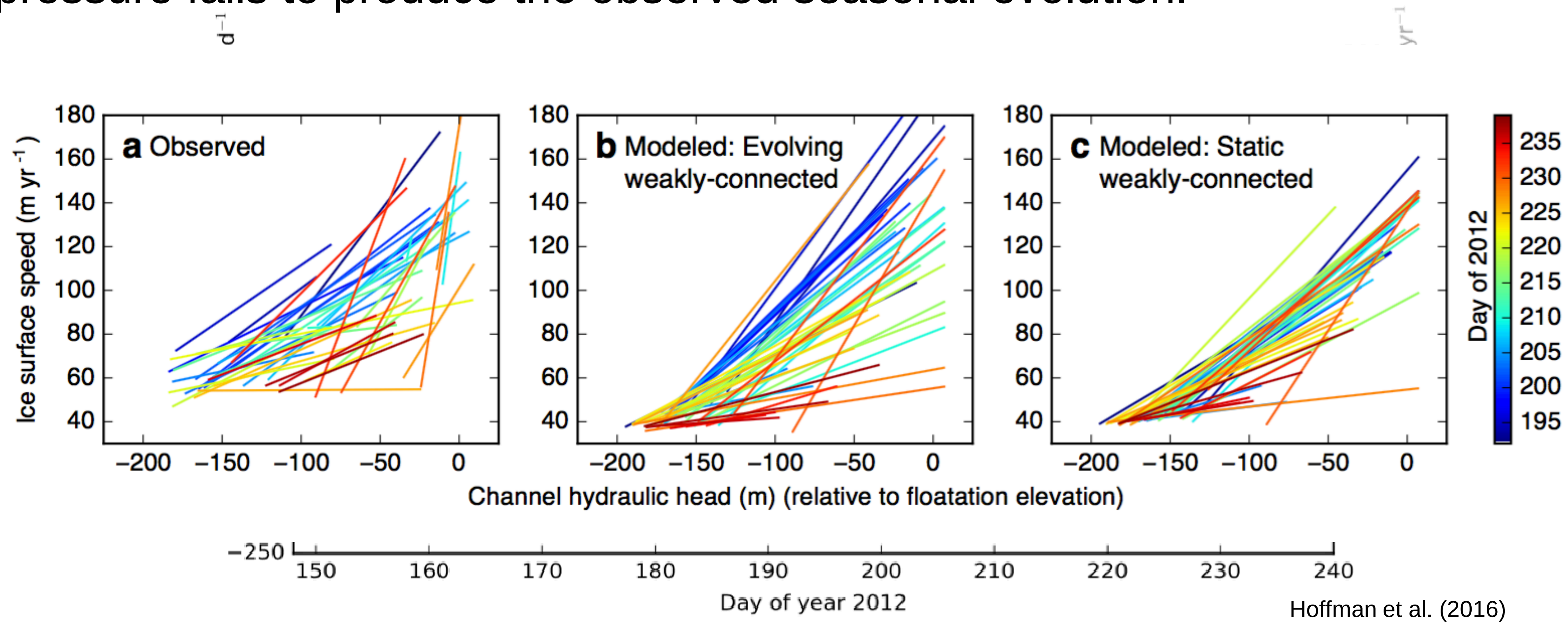
Subglacial pressure and ice velocity are coupled through a prescribed basal friction law



Hoffman et al. (2016)

Modeled and observed subglacial pressures

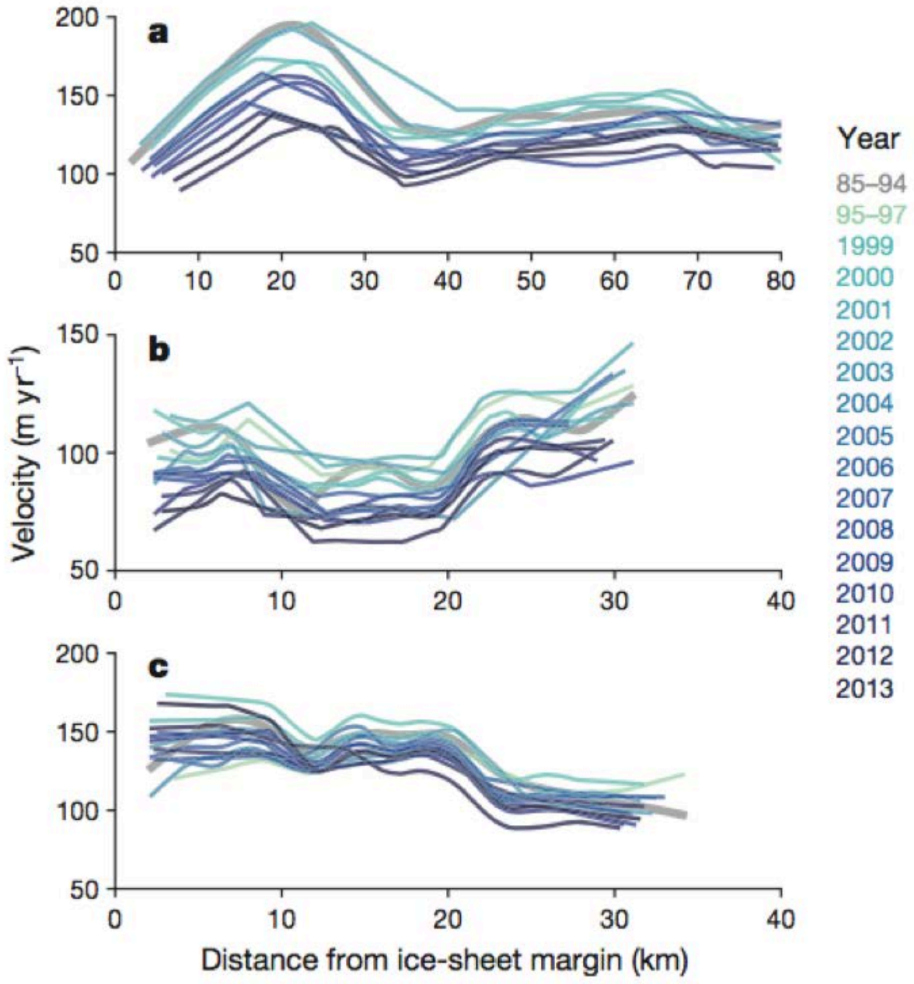
- Model reproduces the basic features of the velocity observation.
- Control simulation with prescribed, fixed weakly-connected subglacial pressure fails to produce the observed seasonal evolution.



Hoffman et al. (2016)

Why is the weakly-connected system important?

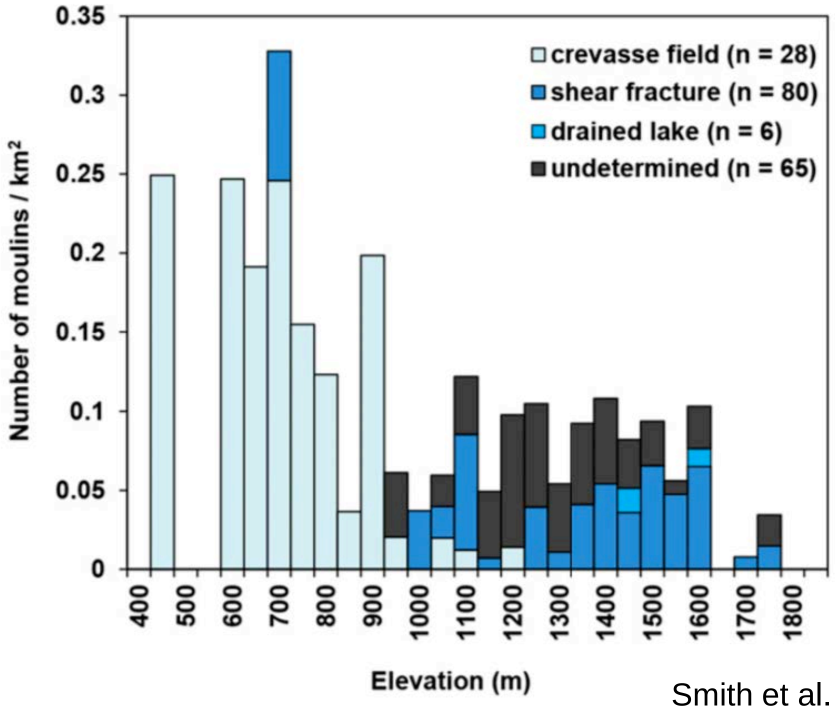
- Weakly-connected subglacial evolution previously unconsidered in subglacial hydrology models
- Necessary to explain seasonal hysteresis between moulin and ice velocity records.
- Can explain the observed winter slowdowns (*Hoffman et al.*, 2011; *Sole et al.*, 2013; *Tedstone et al.*, 2013; Tedstone et al., 2015).
- Modified parametrizations, including dynamic hydraulic conductivity better explain observations at multiple locations (Downs et al., 2018; Rada & Schoof, 2018)



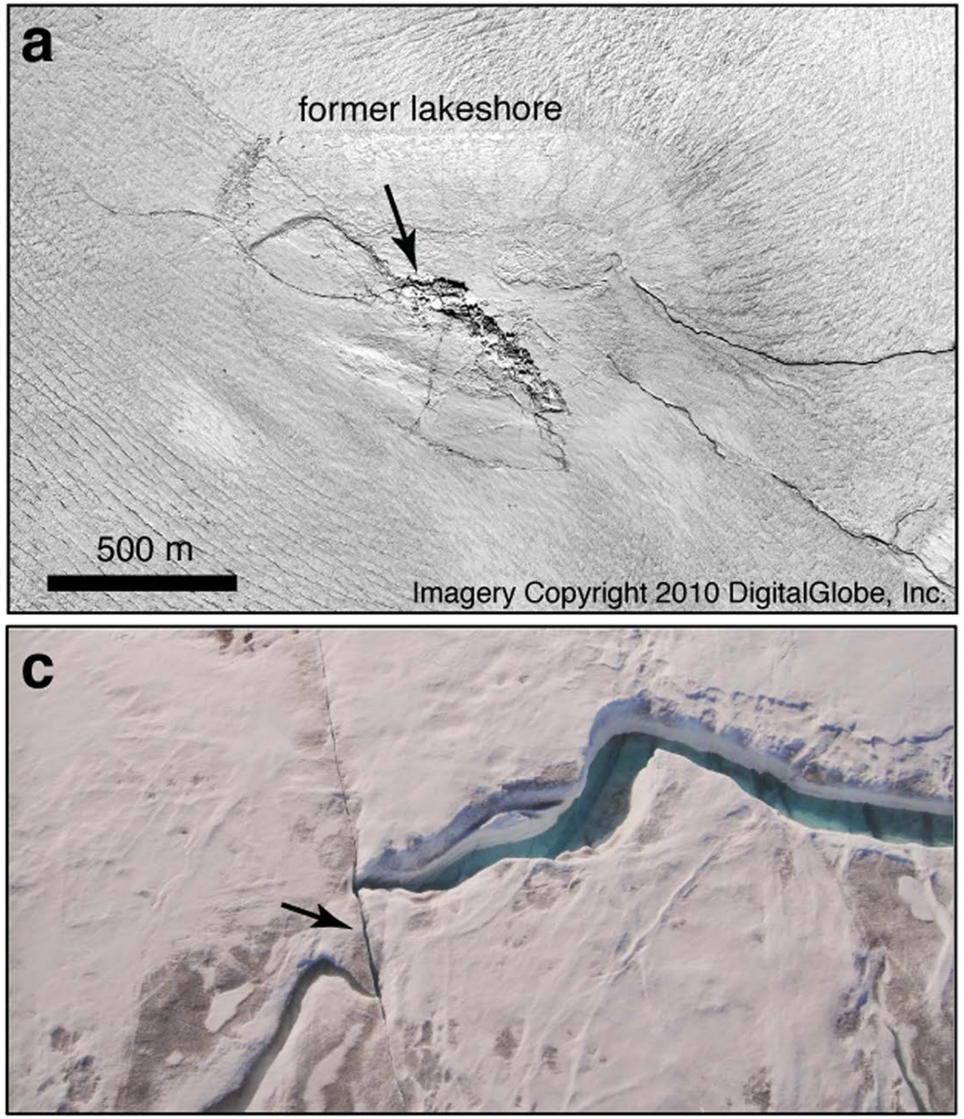
Tedstone et al. (2015)

How does meltwater get to the bed?

At higher elevations, moulins tend to form in regions of compression – counter to prevailing assumptions.



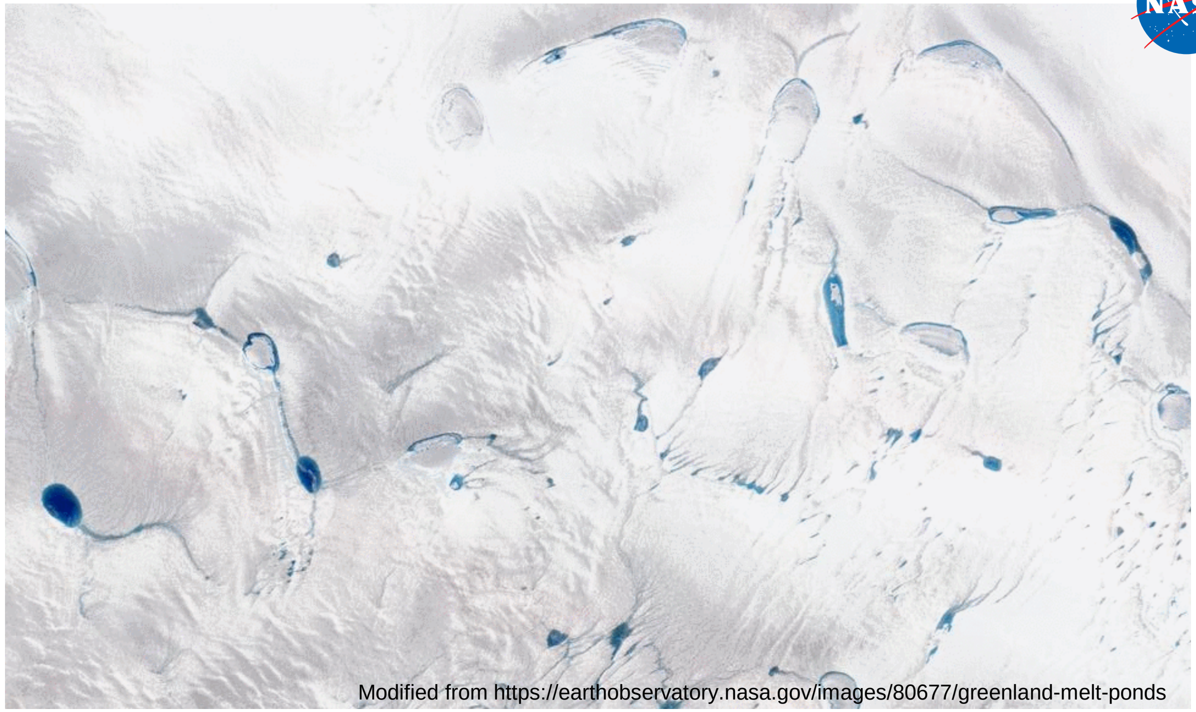
Smith et al. (2015)

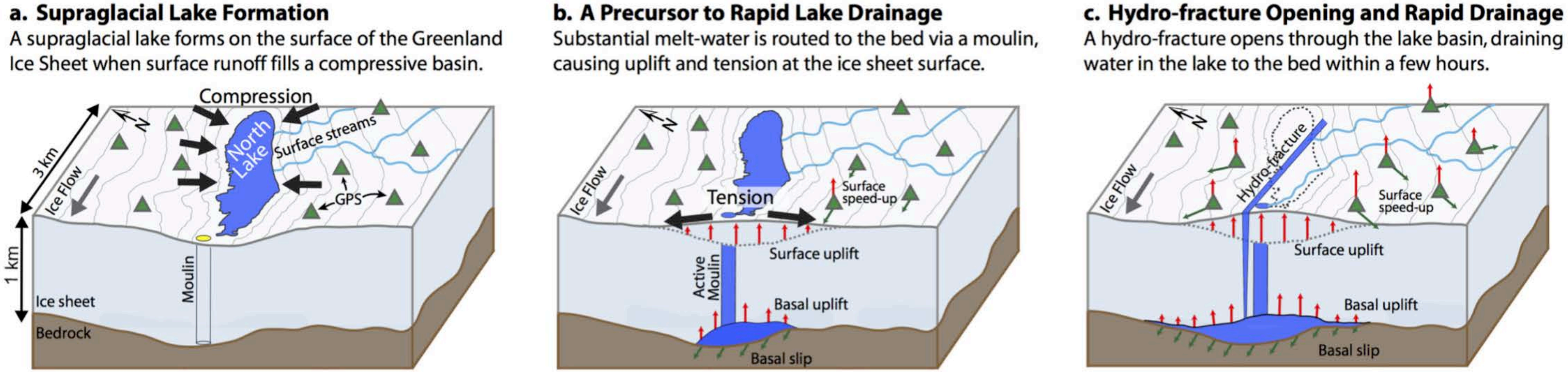


Hoffman et al. (2018)

Short perturbations may cause widespread basal connections

Lakes tend to drain in clusters and lake drainages are poorly predicted by water volume or surface characteristics, suggesting **ice flow coupling is likely important**.

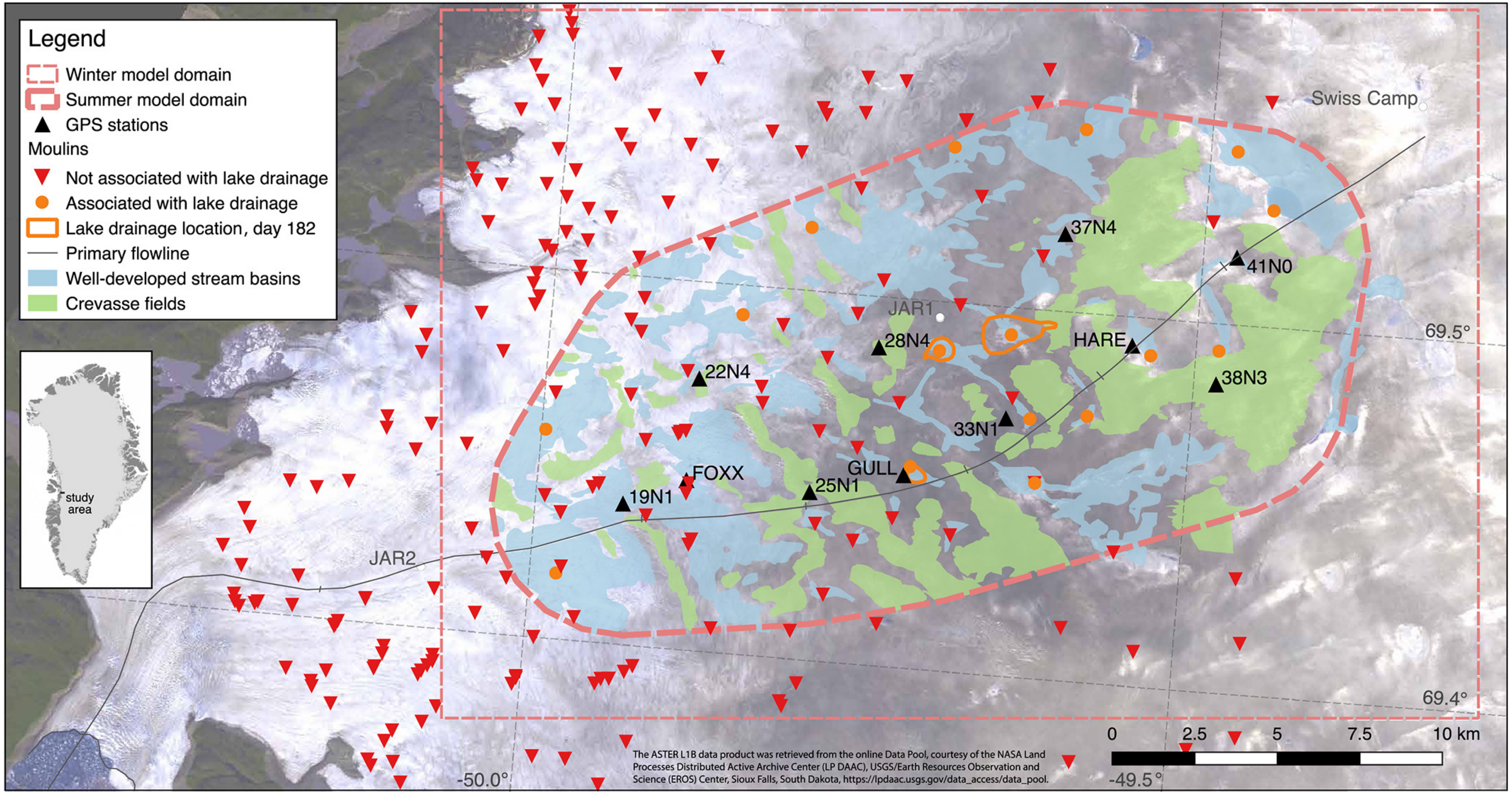


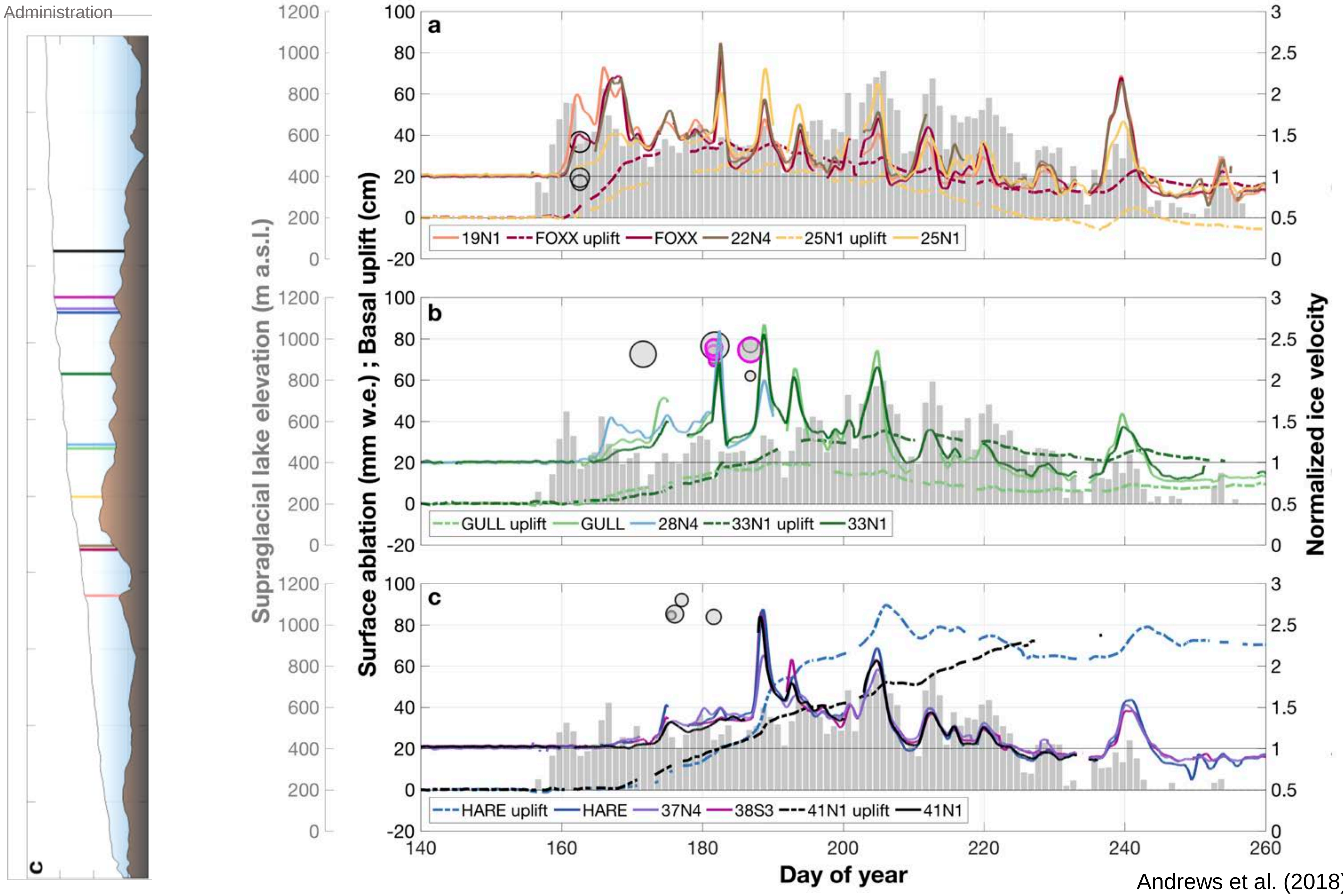


Stevens et al. (2015)

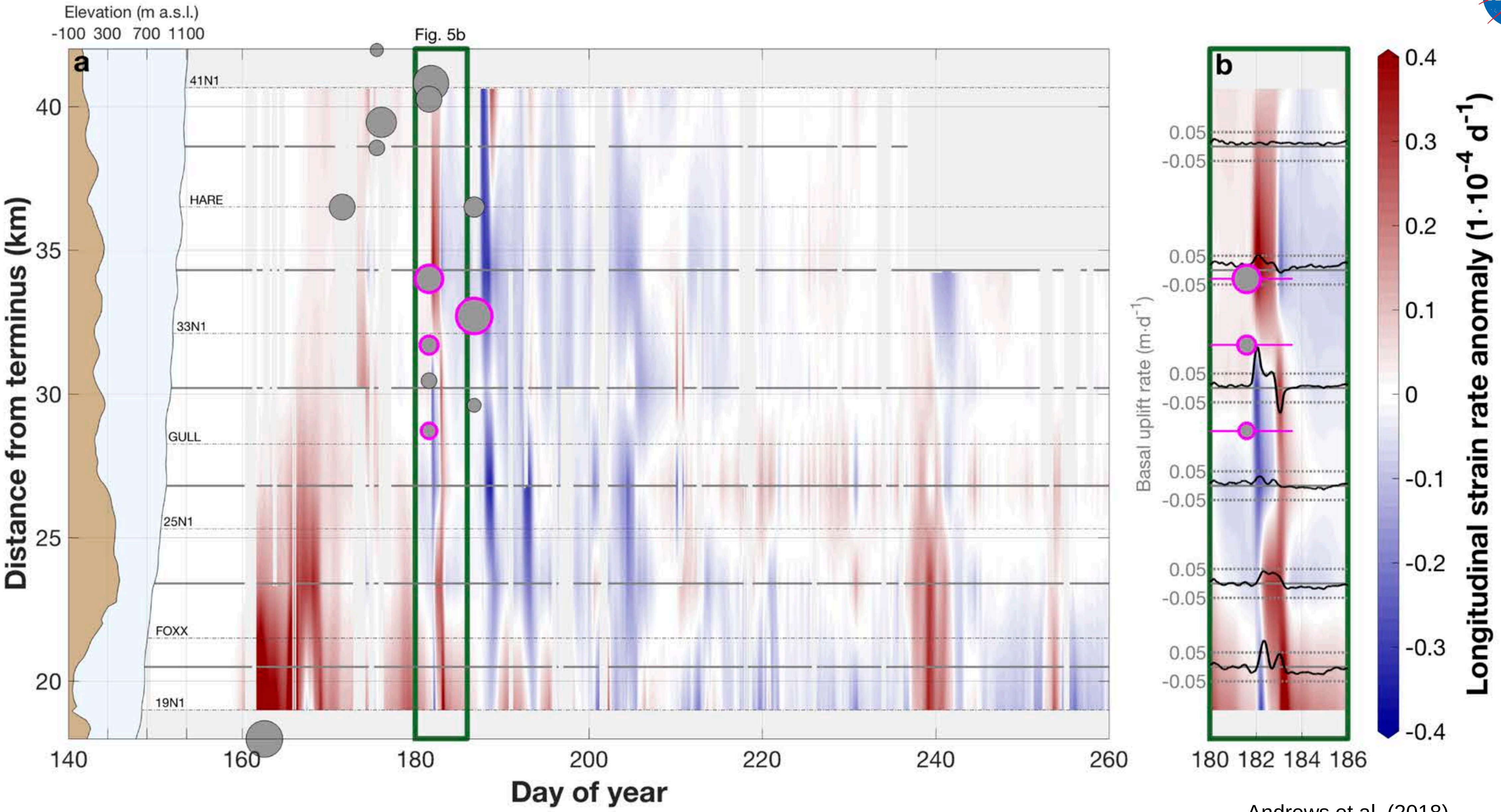
Using ice speed to model potential subglacial drainage locations

Andrews (2015); Hoffman et al. (2018)





Andrews et al. (2018)

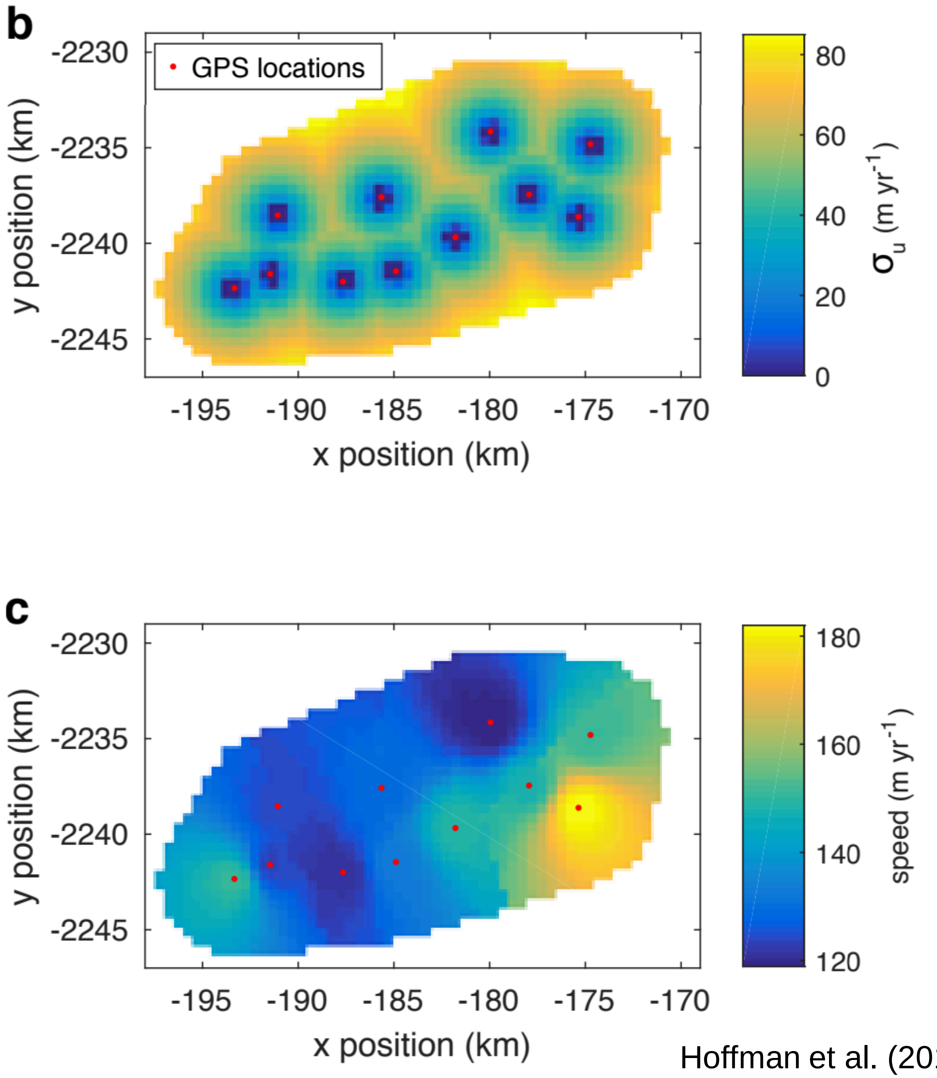


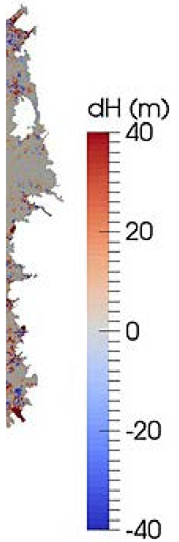
Andrews et al. (2018)

Ice dynamics model + high resolution ice velocities

- Ice flow models are often forced with ice velocities to obtain basal traction (or slipperiness).

- Instead assimilate high temporal resolution ice velocities to constrain basal traction and **ice stresses** during periods of rapid velocity change.



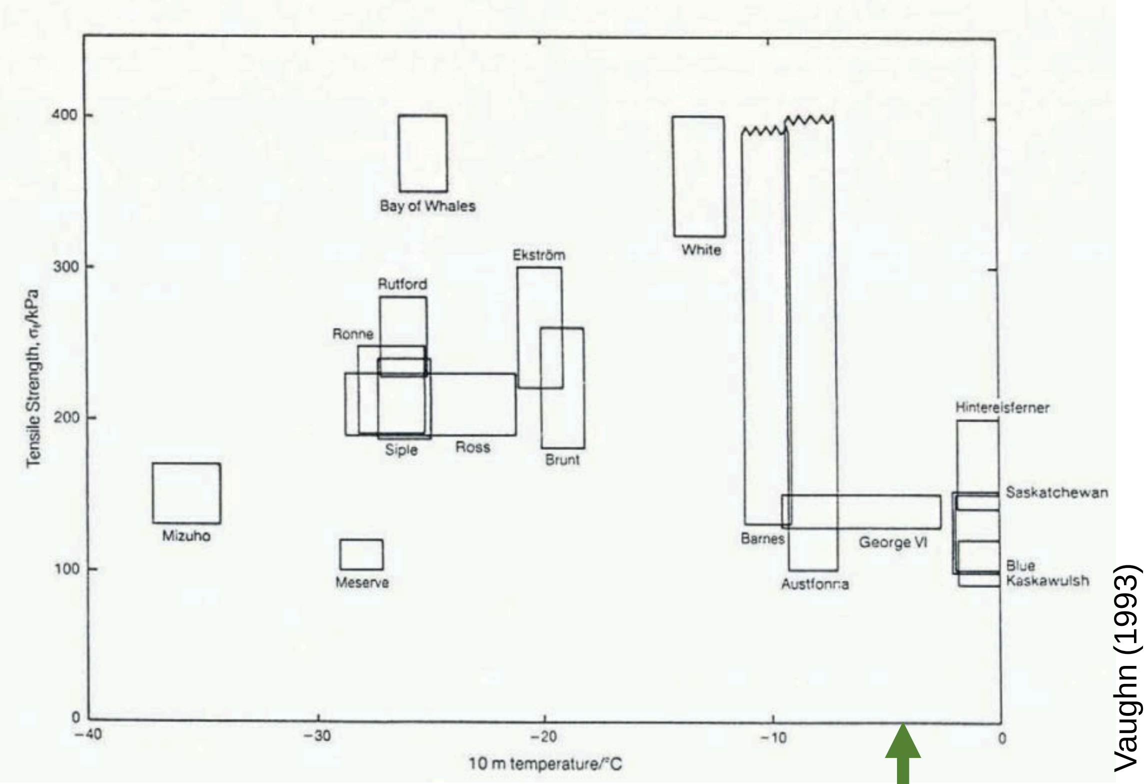


Perego et al. (2014)

Hoffman et al. (2018)

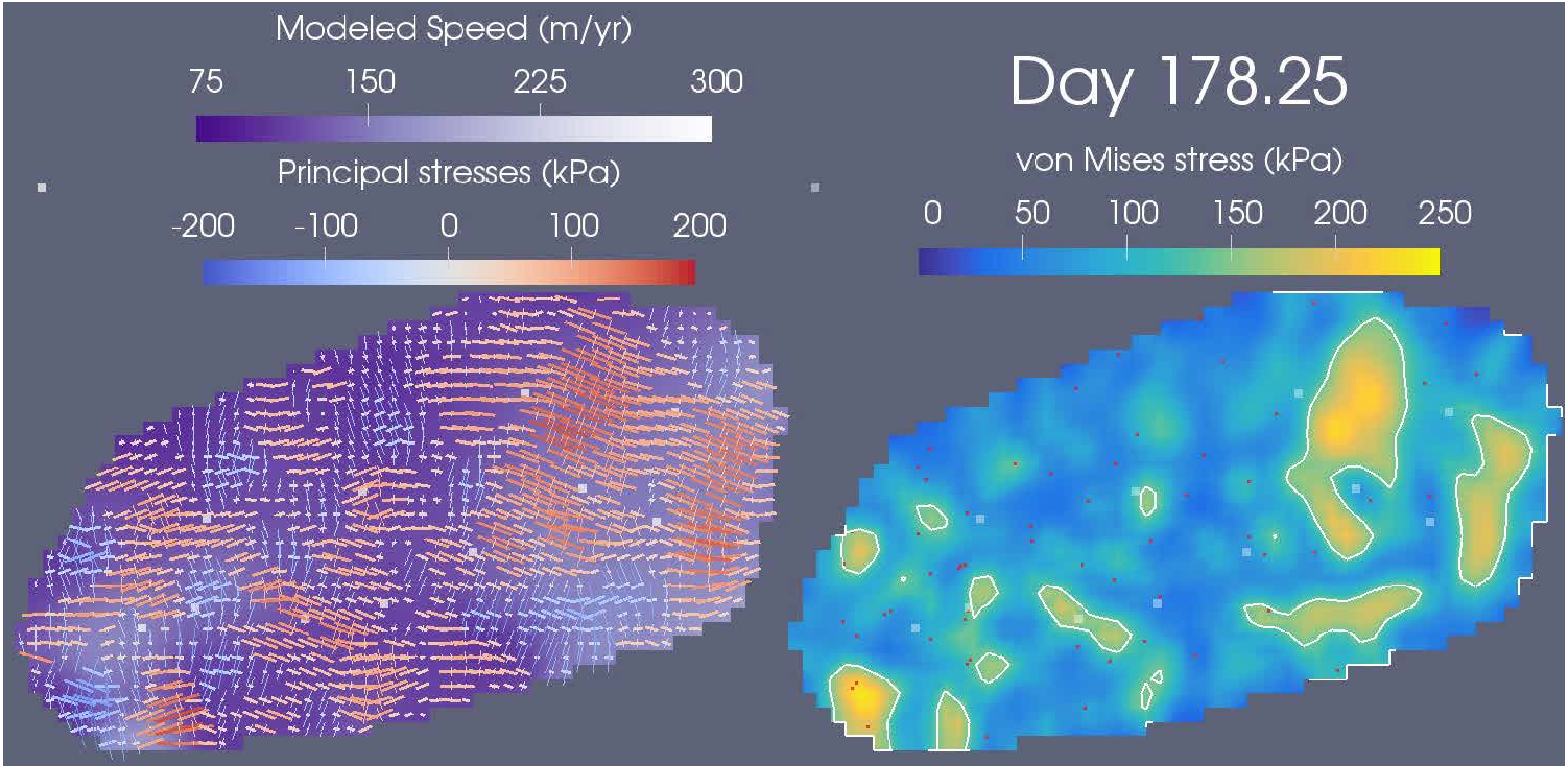
Constraints on basal traction and surface stresses

Hoffman et al. (2018)

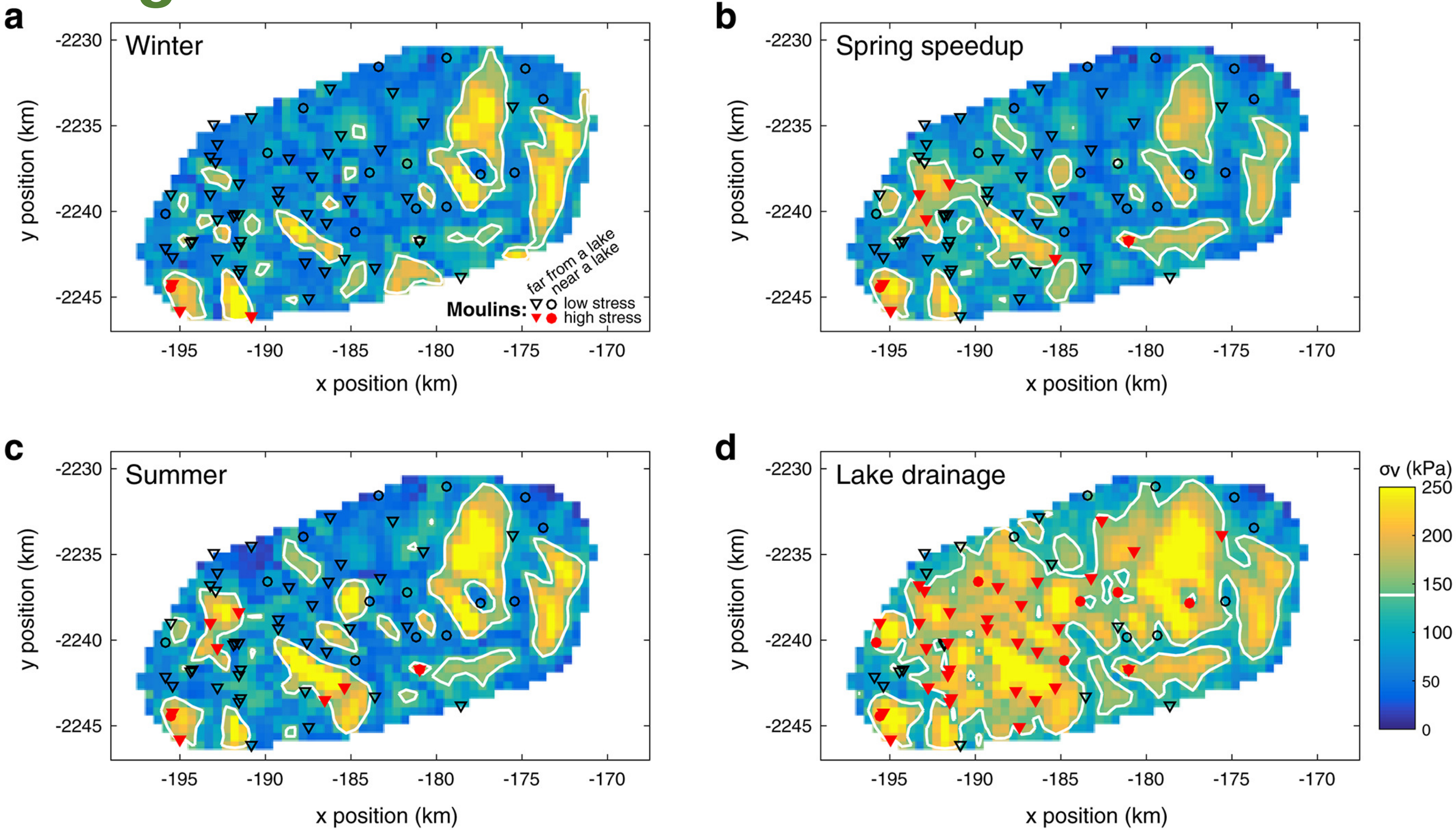


Vaughn (1993)

Ice temperatures in Greenland

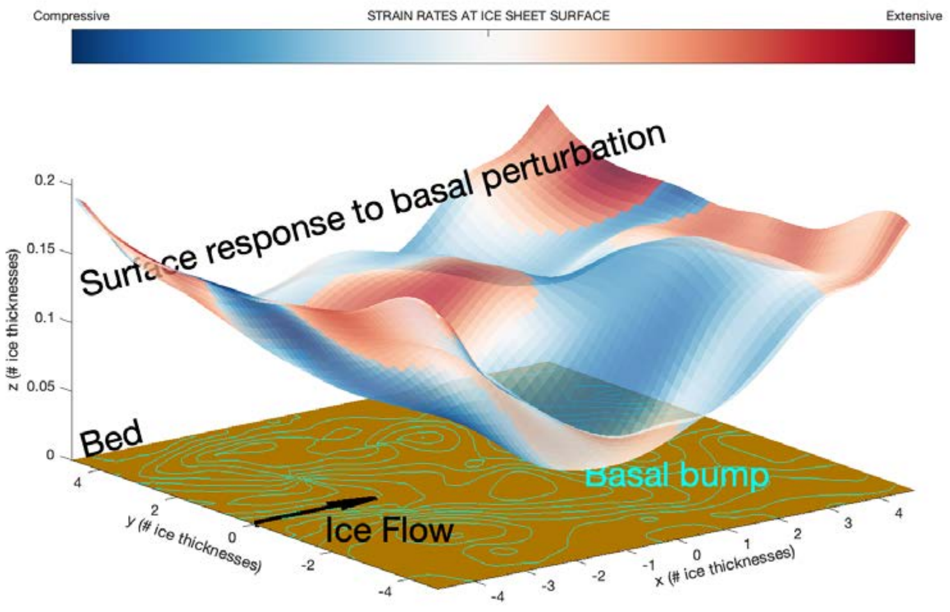

Modeled Speed (m/yr)
75
150
225
300
Principal stresses (kPa)
-200
-100
0
100
200
Day 178.25
von Mises stress (kPa)
0
50
100
150
200
250

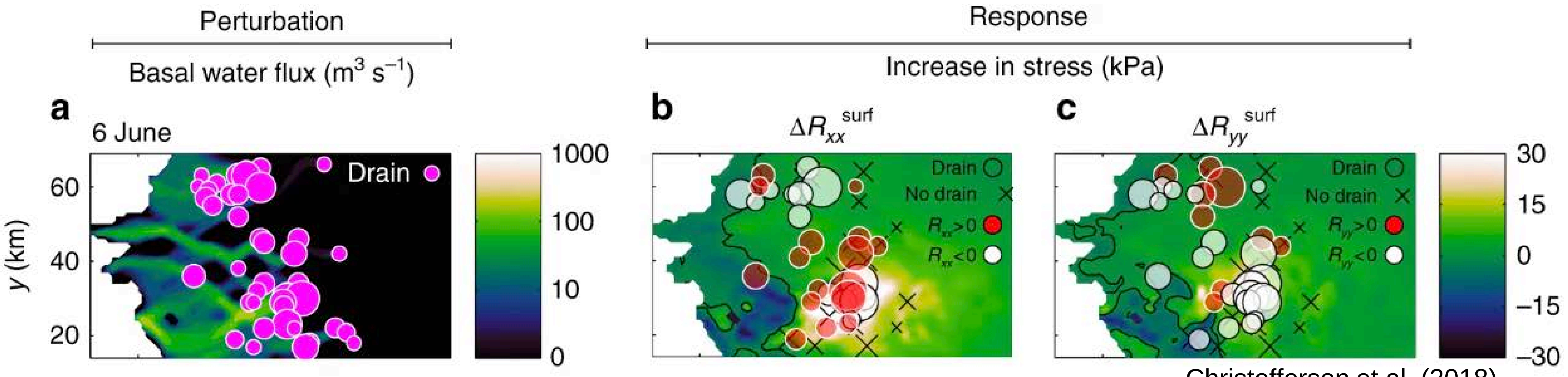
When might moulins form?



Transients matter in the glacial system

- Transient stresses driven by ice velocity perturbations likely trigger cascading lake drainage and moulin formation.
- We need to estimate the ‘sphere of influence’ of lake drainages in order to characterize how englacial connections will evolve.



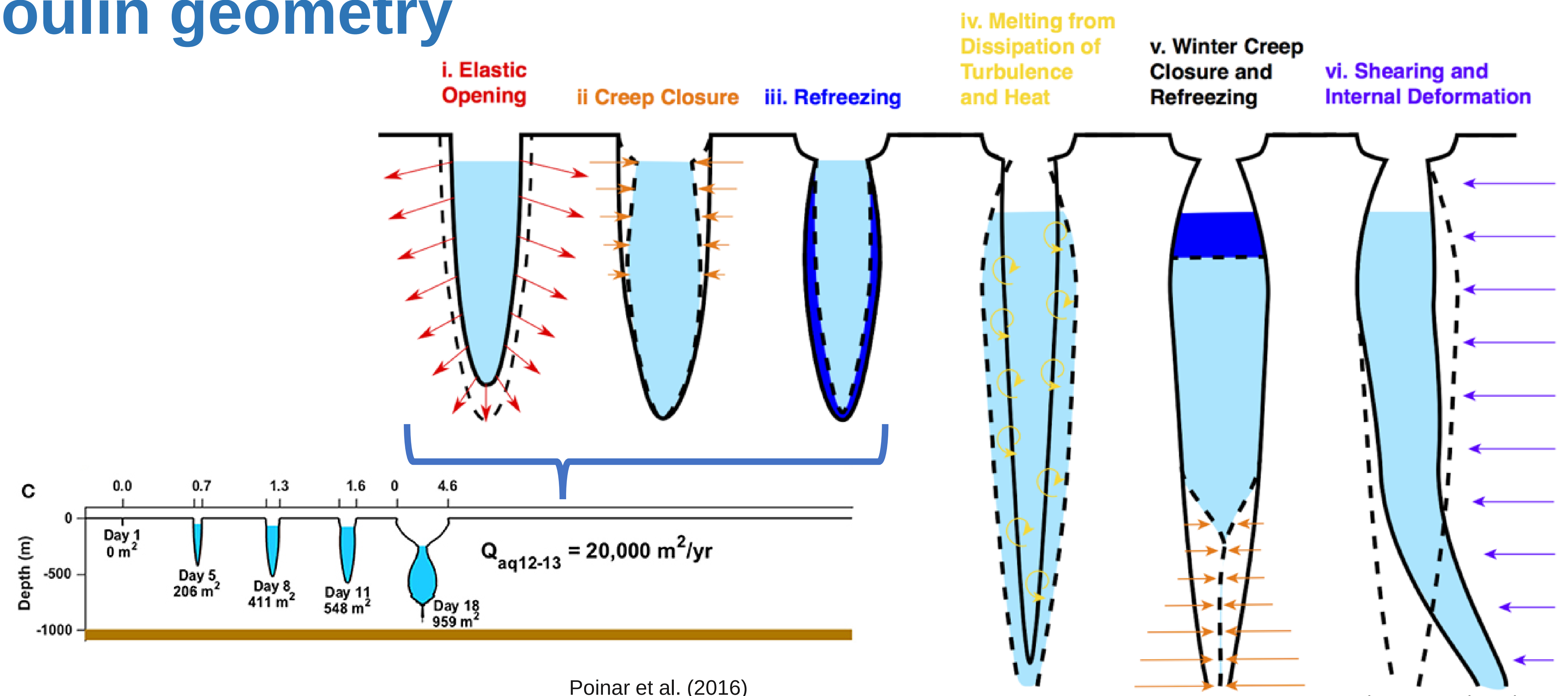


Christofferson et al. (2018)

What do moulins look like and does their shape matter?

Moulin geometry dictates subglacial pressure and variability – changes in the their shape in space and time will alter the subglacial response to surface meltwater.

Multiple non-linear processes alter moulin geometry

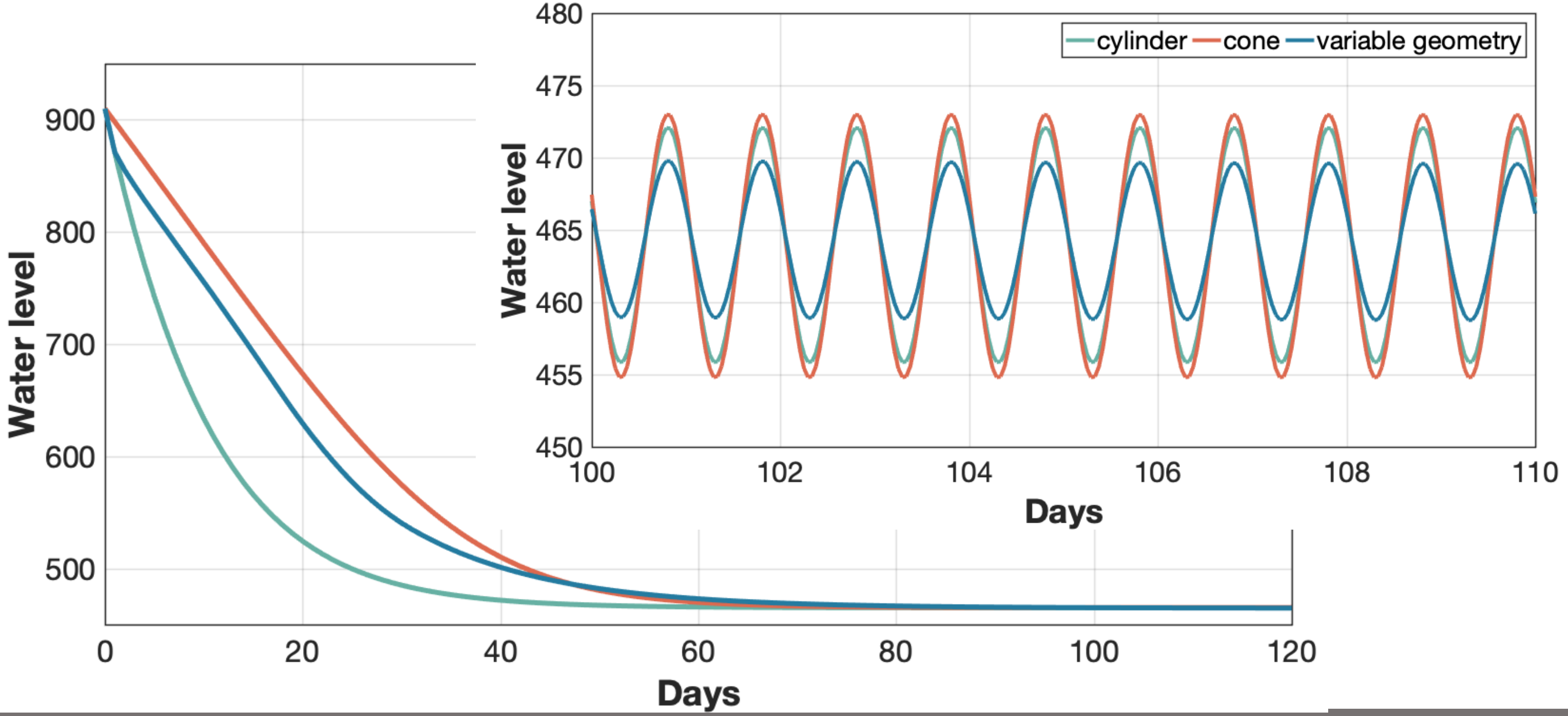


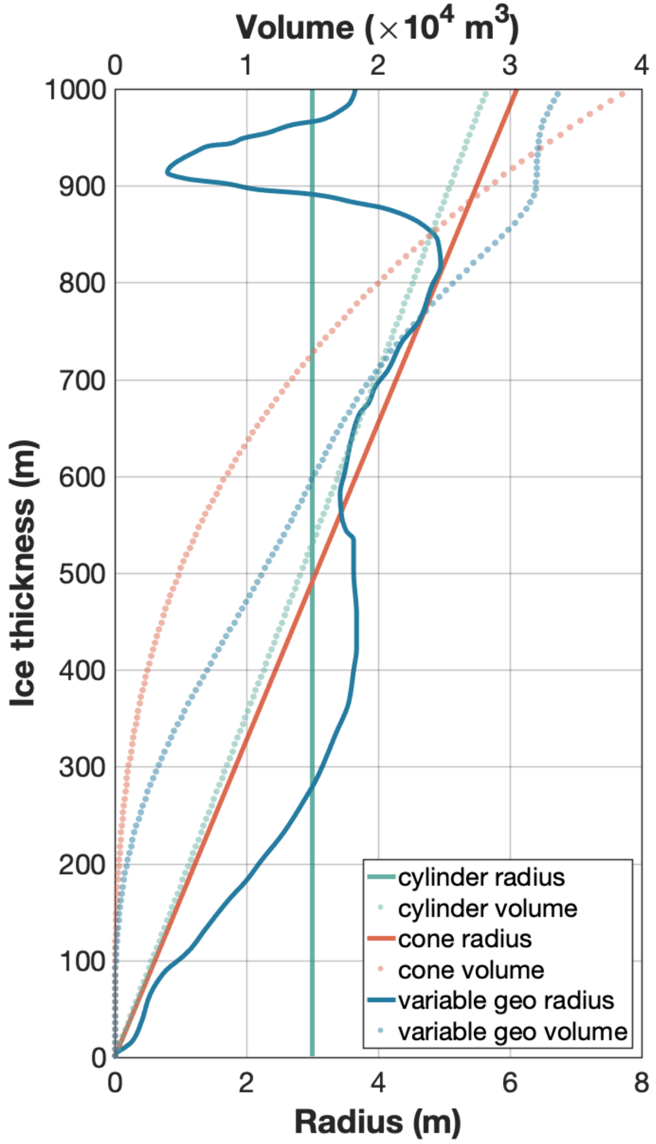
Poinar et al. (2016)

Andrews & Poinar, in prep

Moulin shape matters for subglacial pressure

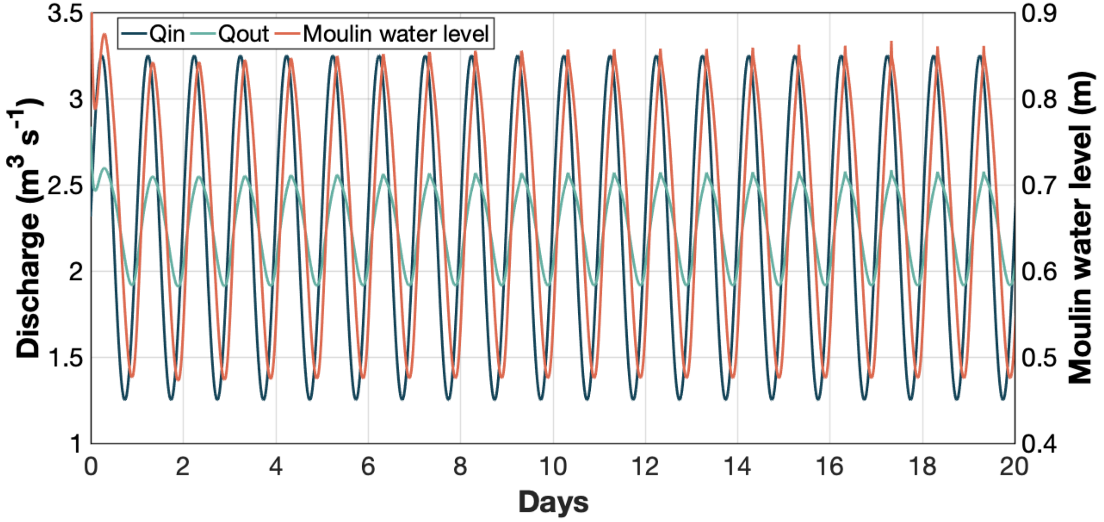
Moulin shape can alter the equilibrium response time and modify the magnitude of diurnal variability even when the mean radius is the same.

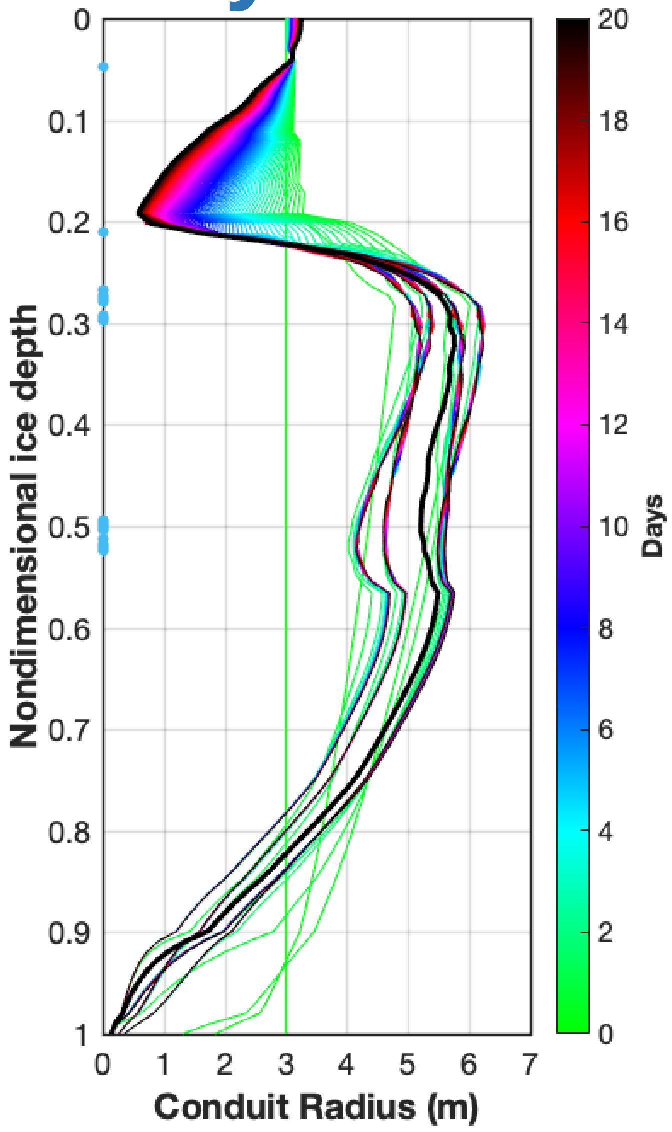


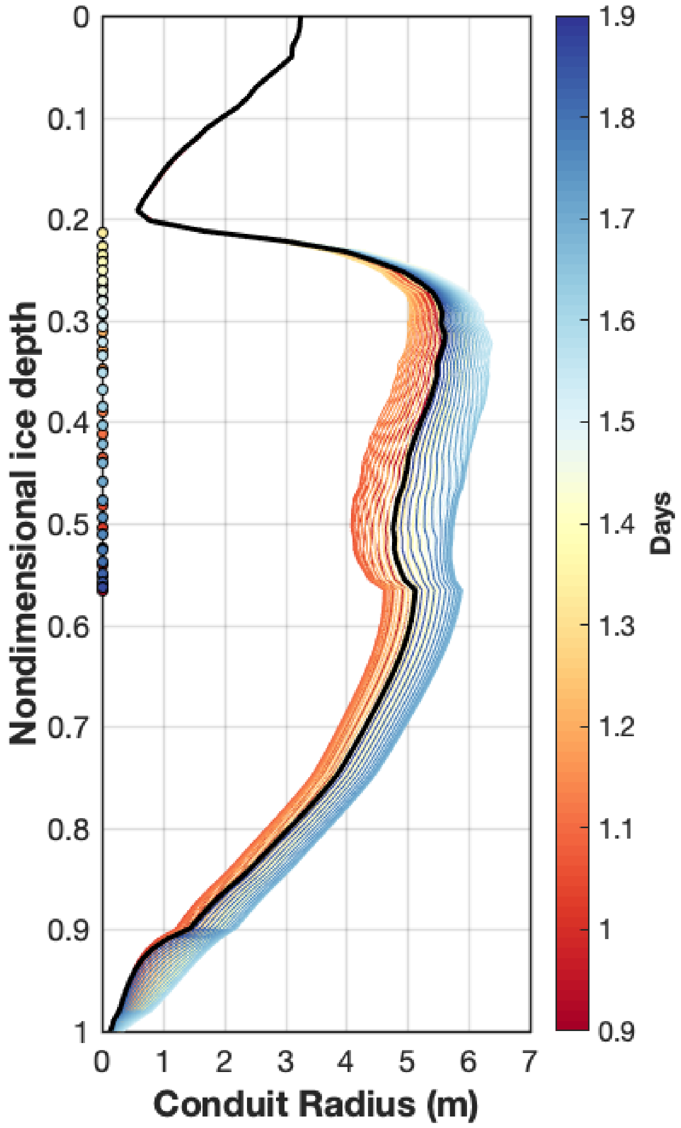


Moulin shape evolves diurnally

Moulin geometry can evolve significantly during diurnal fluctuations in melting due to changes in water level (creep closure) and melting (turbulent dissipation).



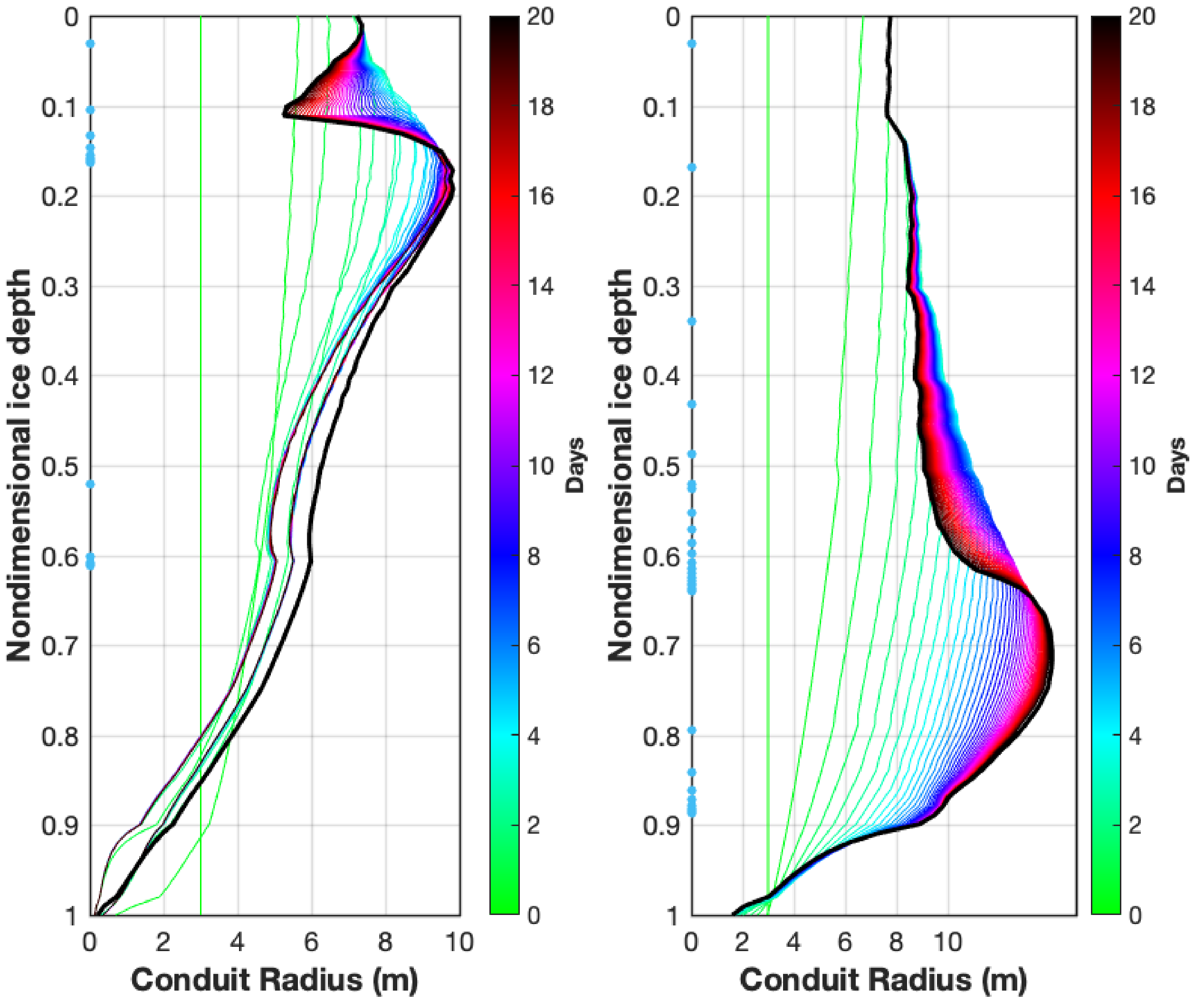




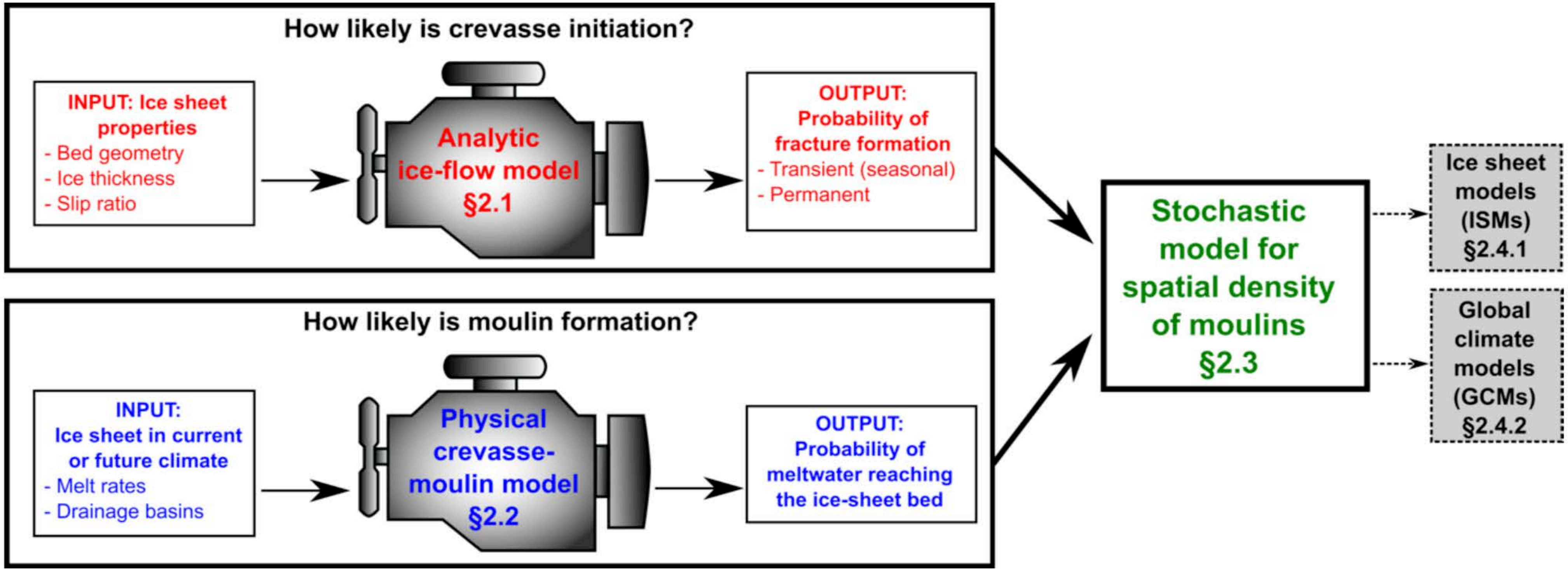
Still working out the kinks…

- Realistic ice and meltwater discharge characteristics, but potentially unrealistic geometries and water levels suggest missing model parameterizations (elastic deformation)

- Coupling to a subglacial model to more appropriately deal with changes in moulin discharge is in progress.



Understanding moulin geometry is a step toward a stochastic model



Andrews & Poinar

The link between surface melt and ice dynamics is dominated by transient behavior