

# Causes of recent Greenland Ice Sheet mass loss



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**15 April 2024**

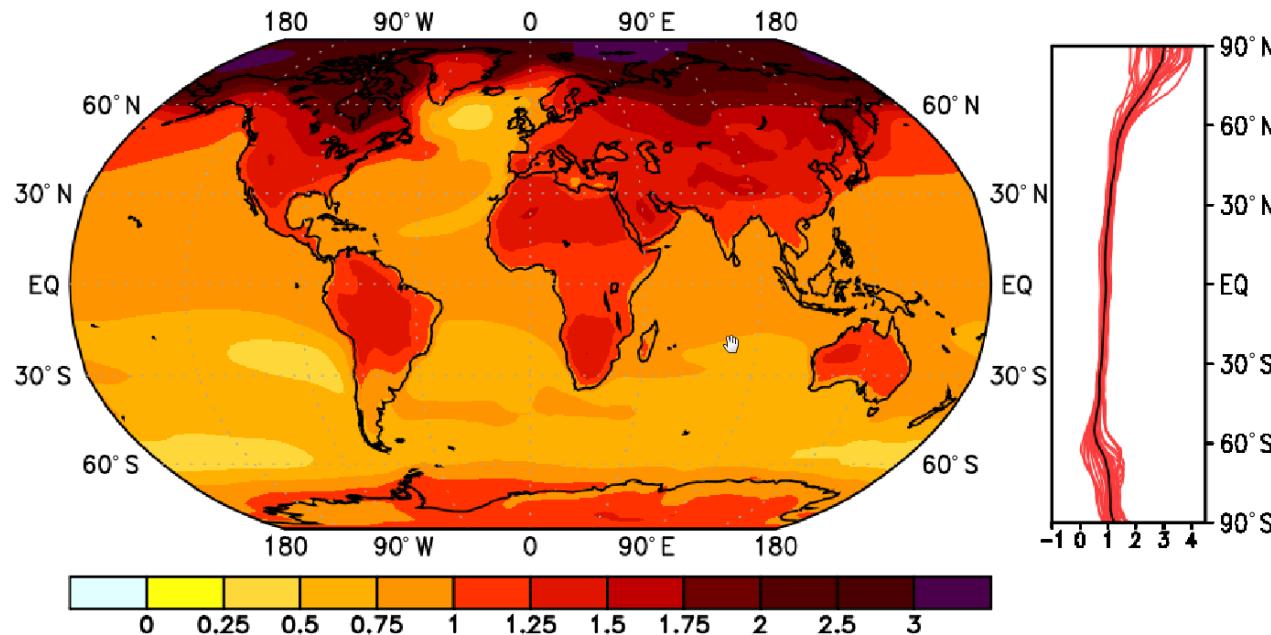
# Why do polar regions play a significant role in global climate?

- *The high albedo of snow and ice*
- *The large amount of carbon stored in permafrost*
- **The large amount of freshwater stored in glaciers**



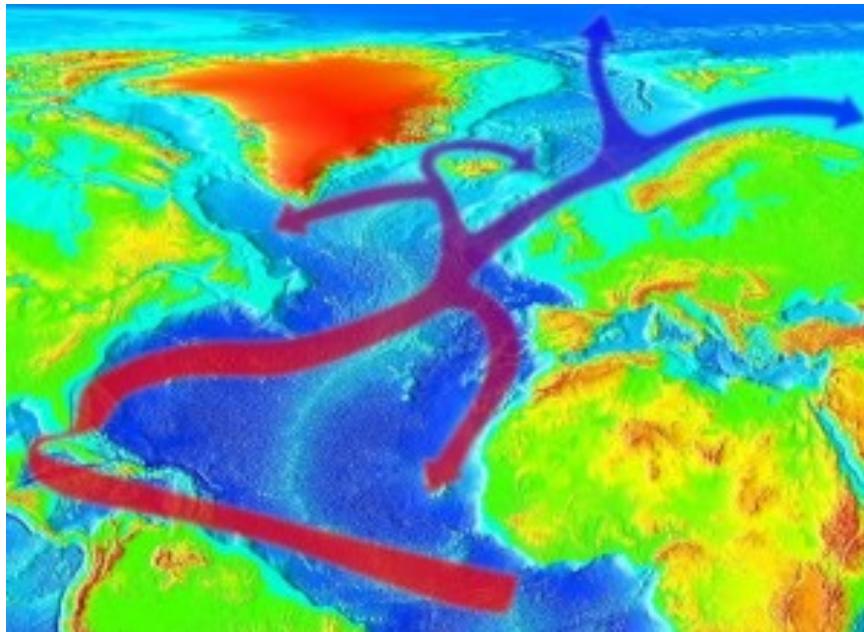
# Polar amplification

- High-latitude regions warm faster than the global average
  - Arctic: 2.5 °C
  - Antarctic: 1.5 °C
  - Global: 1.1 °C
- Factors: *Ice-albedo feedback, permafrost-carbon feedback, changes in atmospheric and oceanic circulation*

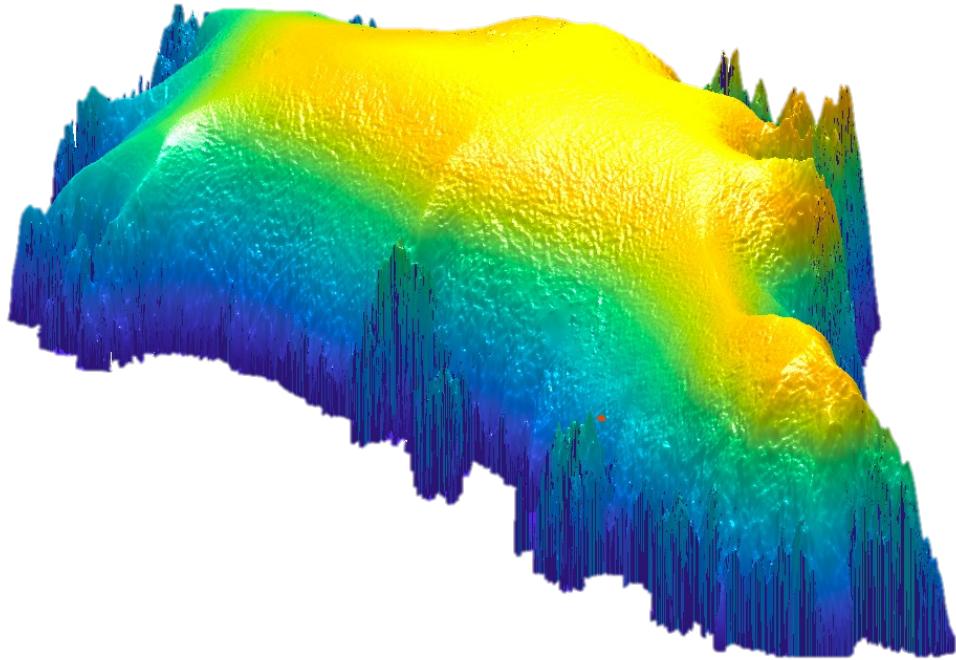


# Freshwater Inputs from Land and Ice Sheets

- Freshwater inputs from melting ice sheets and land runoff impact ocean salinity, circulation, and temperature.
- These changes can have far-reaching effects on global climate, marine ecosystems, and sea levels.

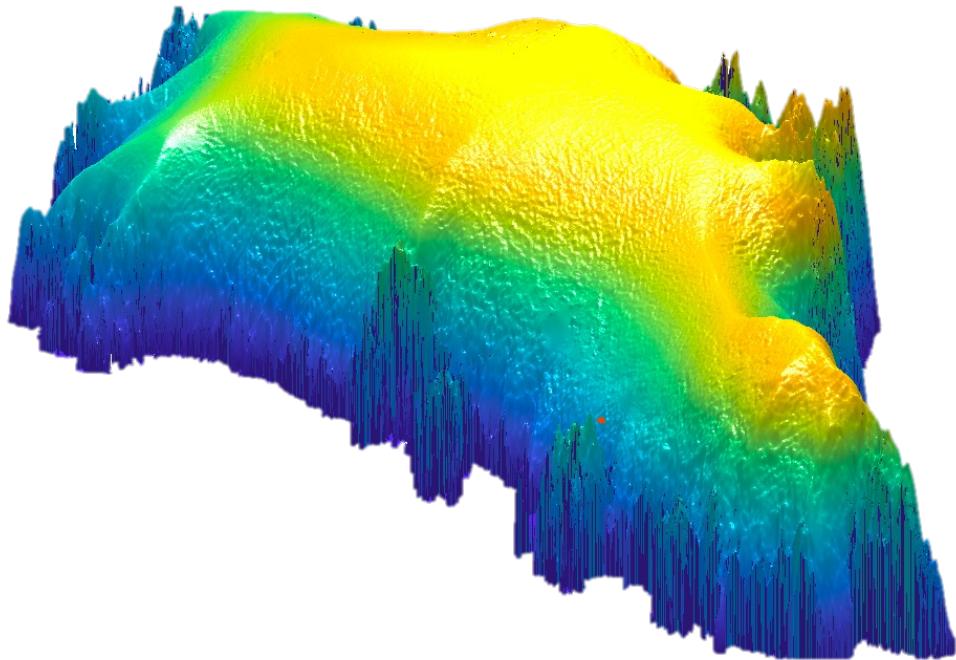


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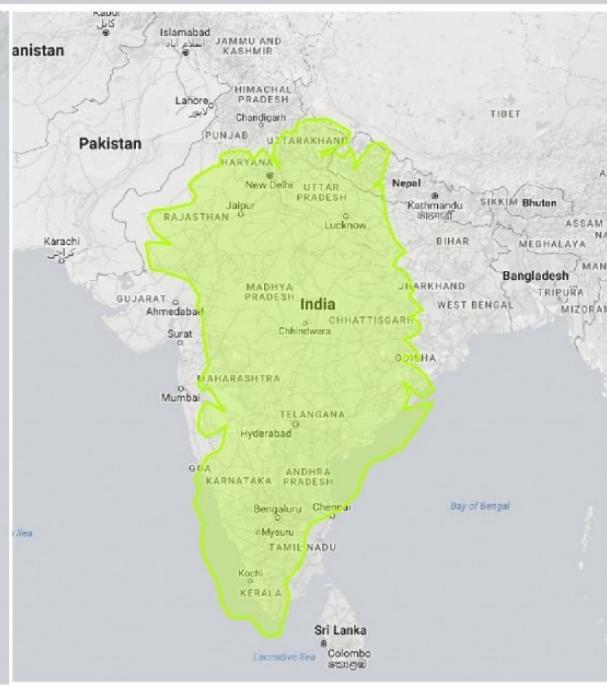
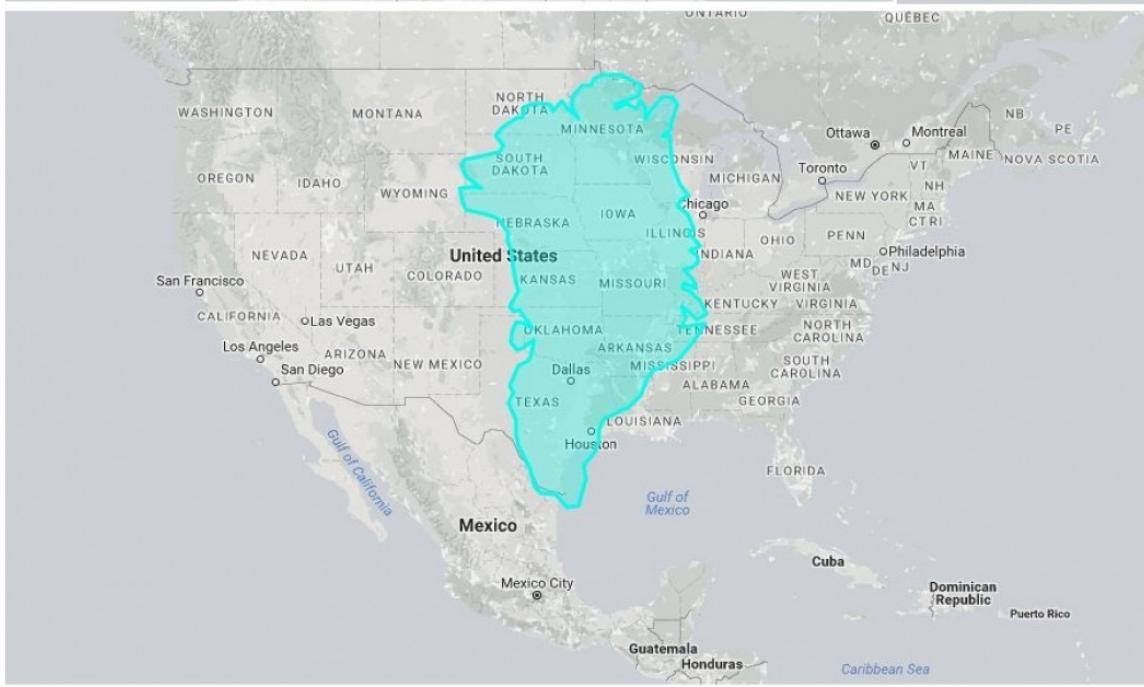
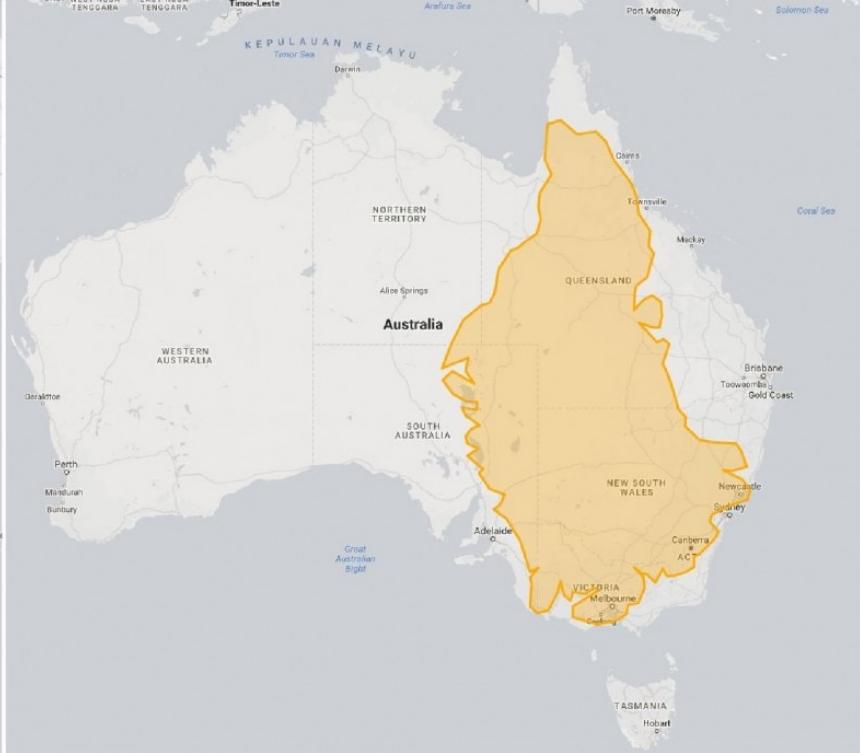
# Kalaallit Nunaat (Greenland)

- Populated since ~2500 BC
- ~90% (58,000) Greenlandic Inuit, rest Danish/European
- Autonomous territory of Denmark since 1953
- Self-governed since 2008
- Maintain right to full independence, but yet to exercise

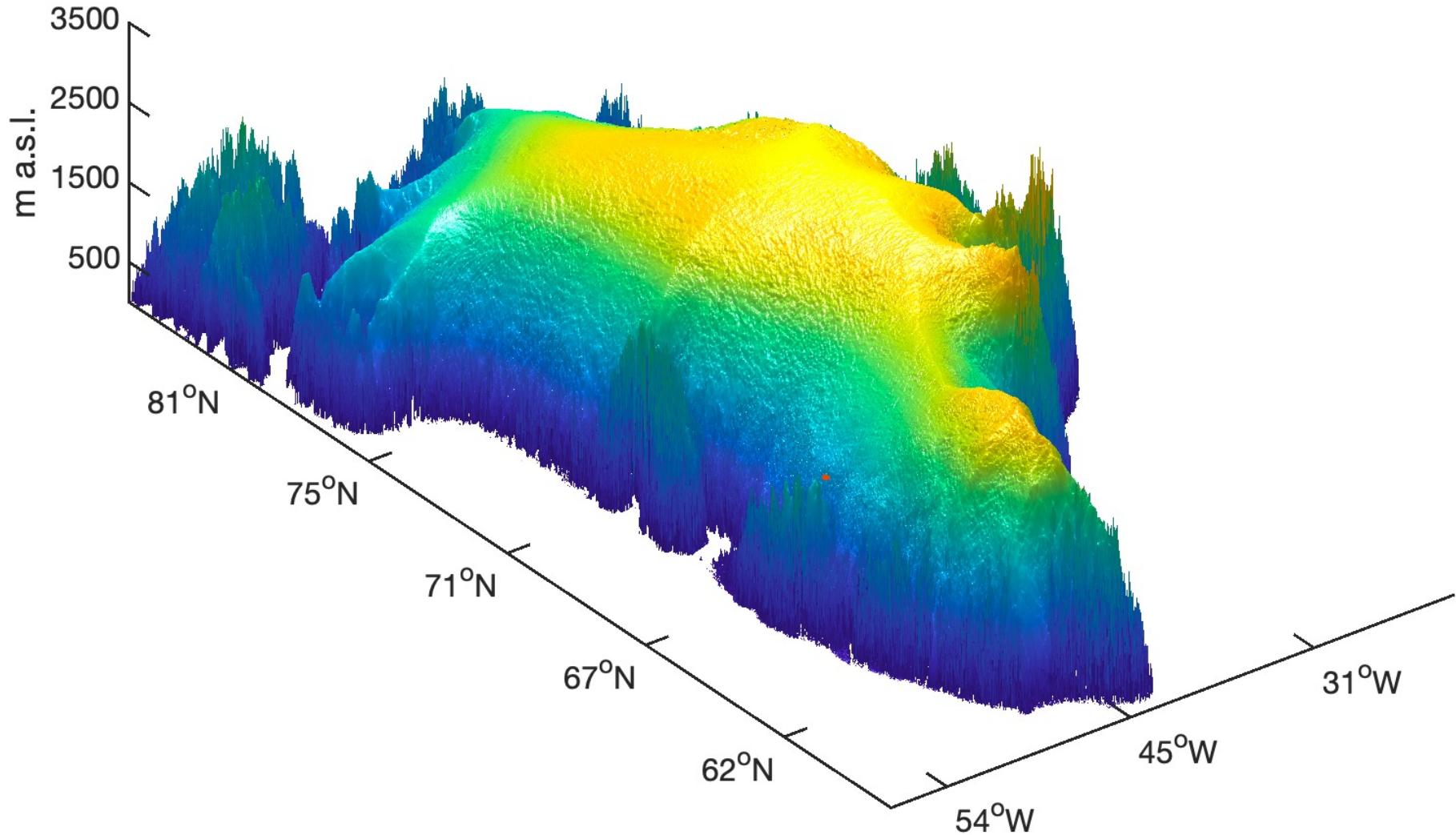


# Kalaallit Nunaat (Greenland)

- 2<sup>nd</sup> largest island on Earth
- Largest island that is not a continent
- ~3000 km (1800 mi) N-S, 1300 km (800 mi) E-W
- ~3 km (1.9 mi) max ice thickness
- ~7.2 m (23.6 ft) sea level-rise equivalent
- Lowest temperature recorded in N. Hemisphere: -93°F (-70°C)

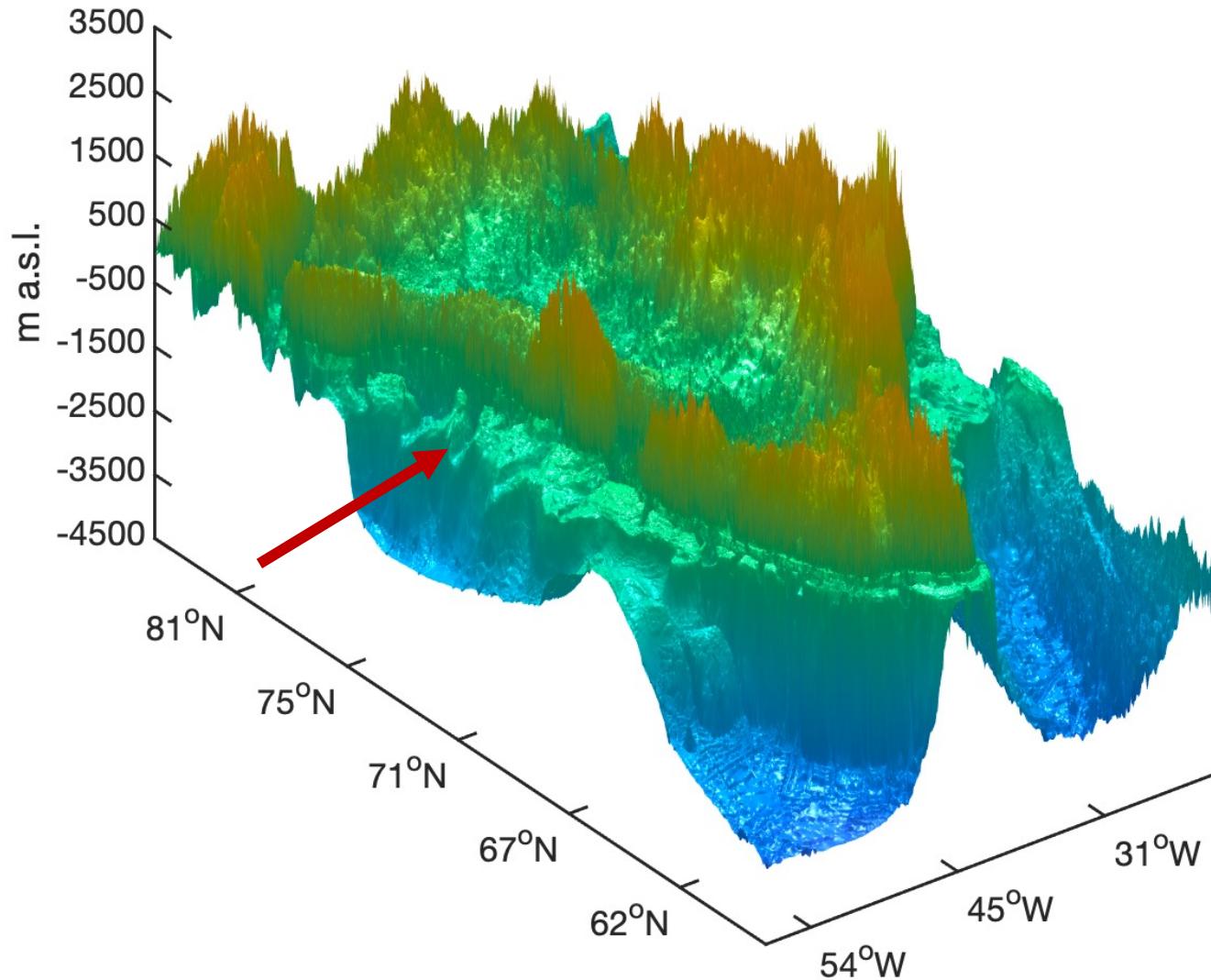


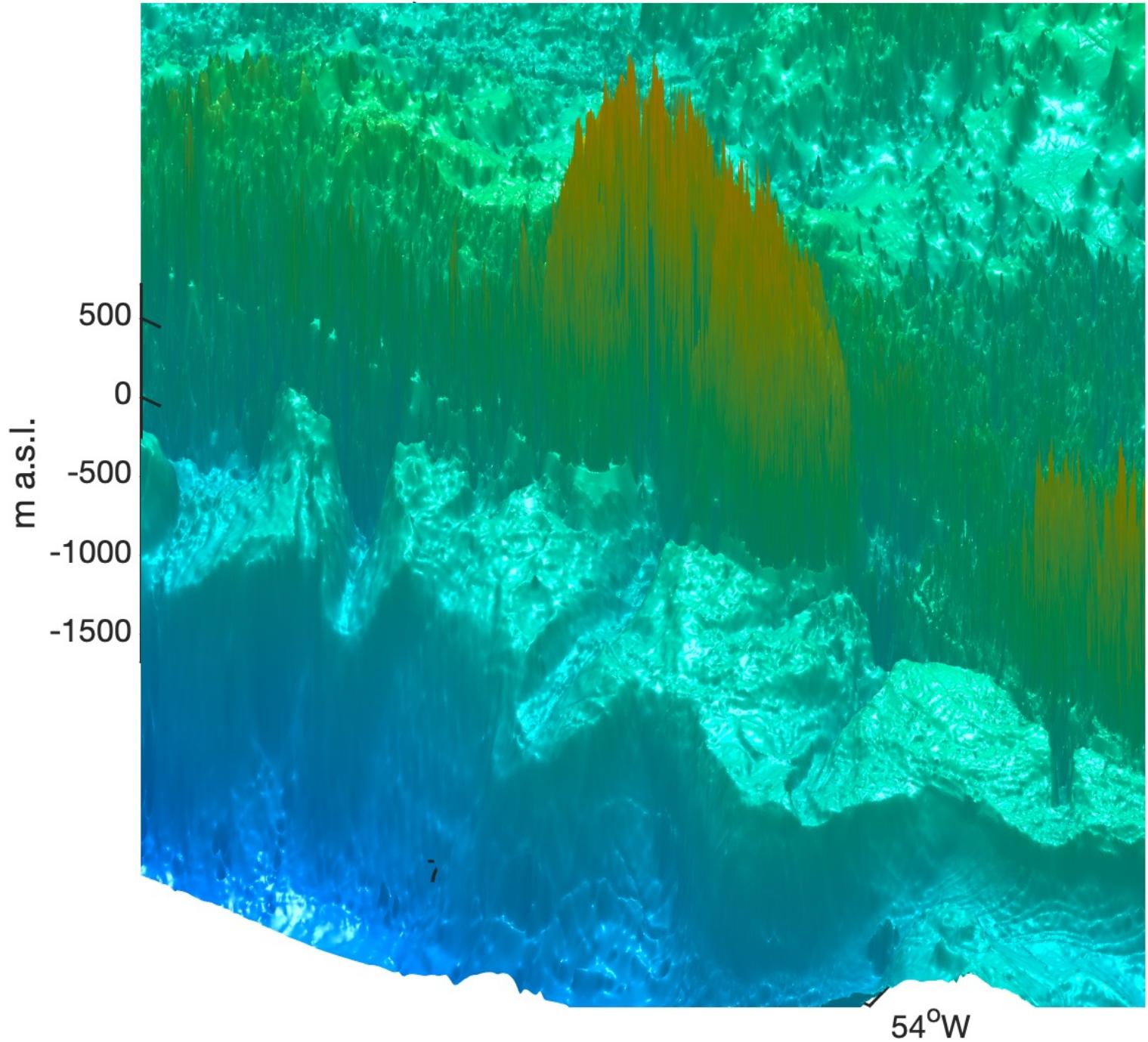
# Ice Sheet Surface Topography

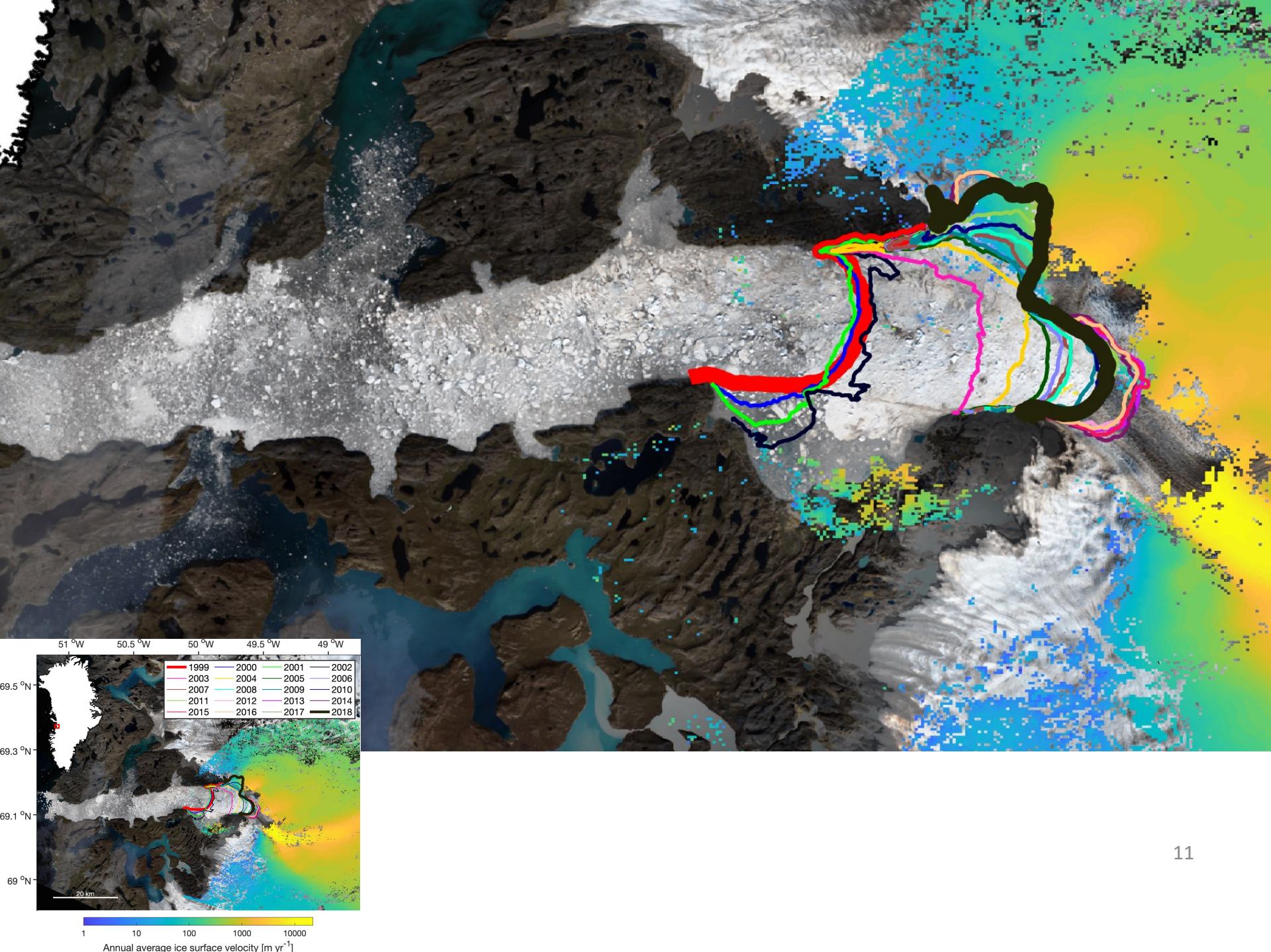


BedMachine v3: Morlighem et al. 2017

# “X-Ray vision” Ice Sheet Bed Topography









# Major Themes in Ice Sheet Mass Balance

- Total mass loss is **observed** by GRACE (and independently pseudo-observed by satellite altimetry + modeling)
  - Total mass balance = surface mass balance – solid ice discharge
- Relative amounts of ice discharge versus surface mass balance (SMB)
- Submarine melting (ocean water melting ice shelves, thermal forcing)
- Meltwater runoff as the main driver of negative SMB (and future mass loss)
- Solid ice-meltwater runoff feedbacks
- Less snowfall = higher bare ice exposure (with lower **albedo** than snow)
- High pressure blocking enhancement of surface warming (negative NAO)
- Meltwater refreezing in firn
- **Irreversible tipping points?**

# GRACE Observations of Greenland Ice Mass Changes

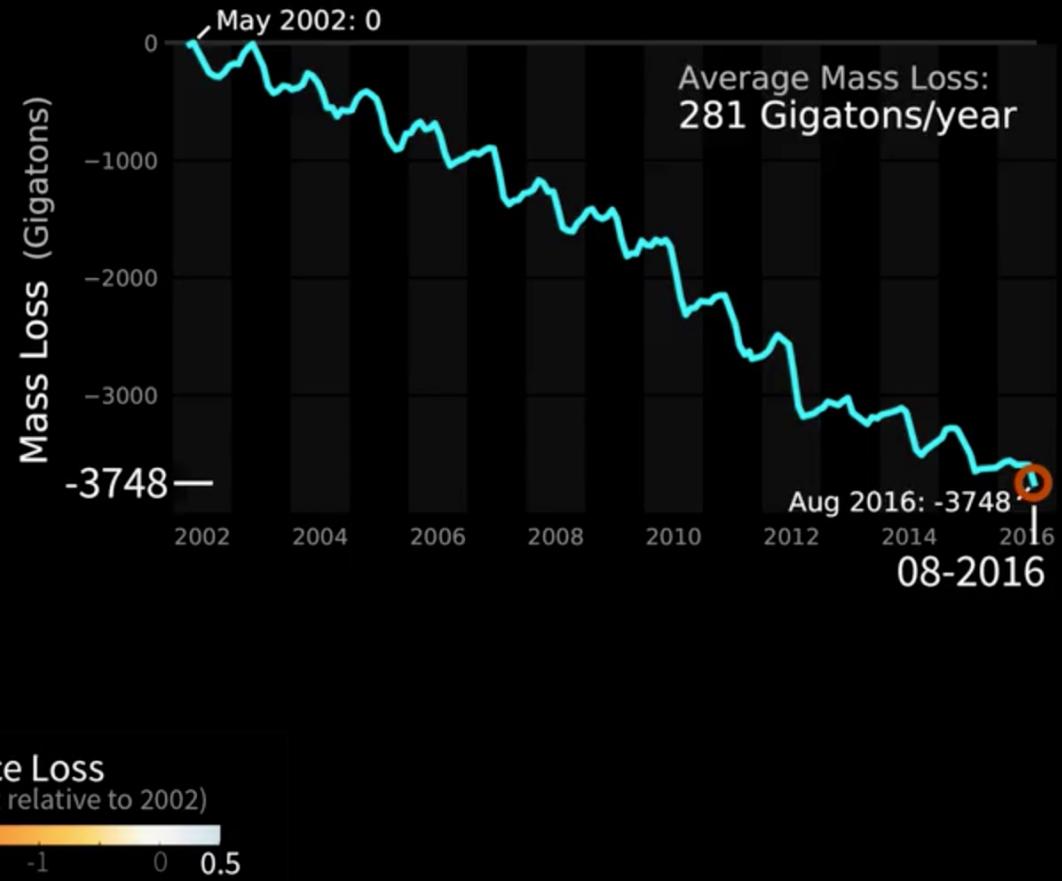
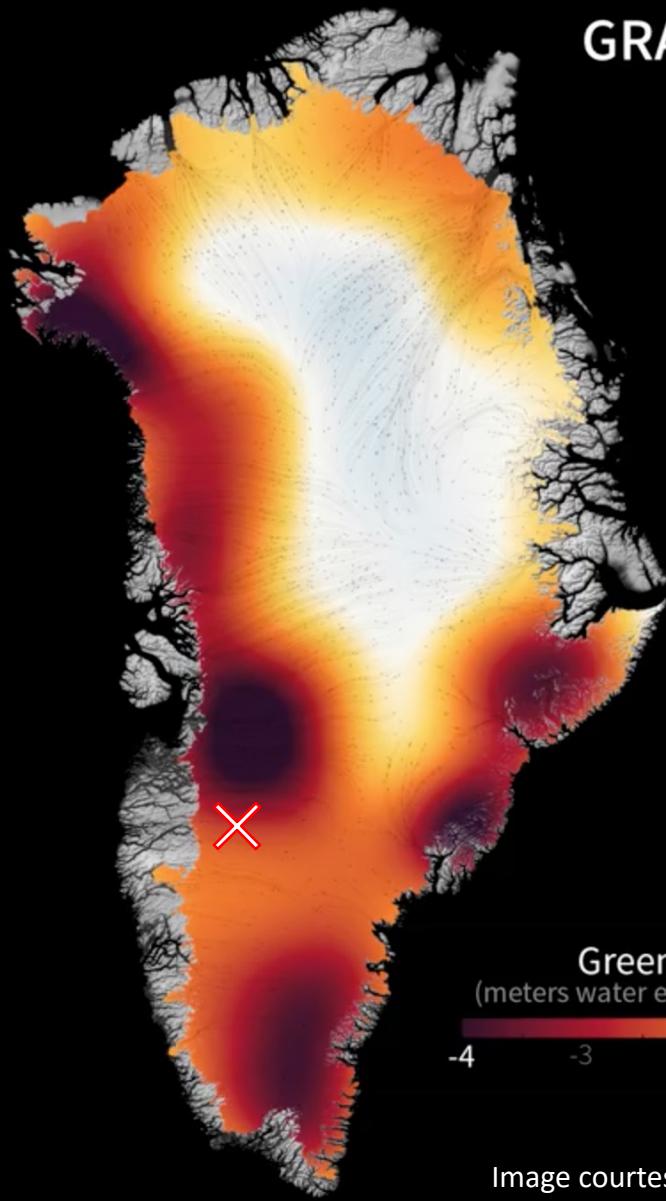
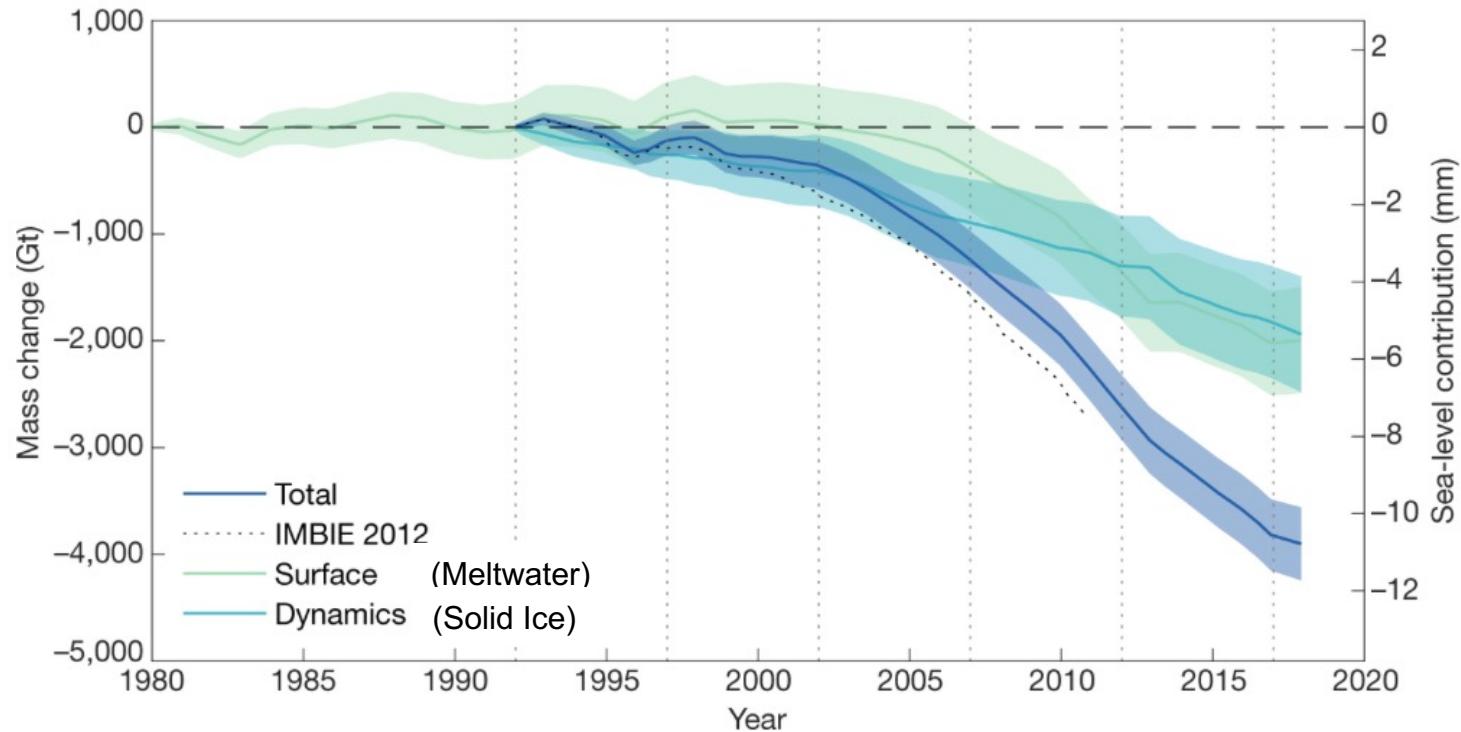


Image courtesy NASA Jet Propulsion Laboratory: <https://gracefo.jpl.nasa.gov/science/ice-sheets-and-glaciers/>

# Greenland is losing mass from solid ice **and** meltwater runoff



nature

$$MB = SMB - D$$

(Mass Balance = Surface Mass Balance – Solid Ice Discharge)

Article | Published: 10 December 2019

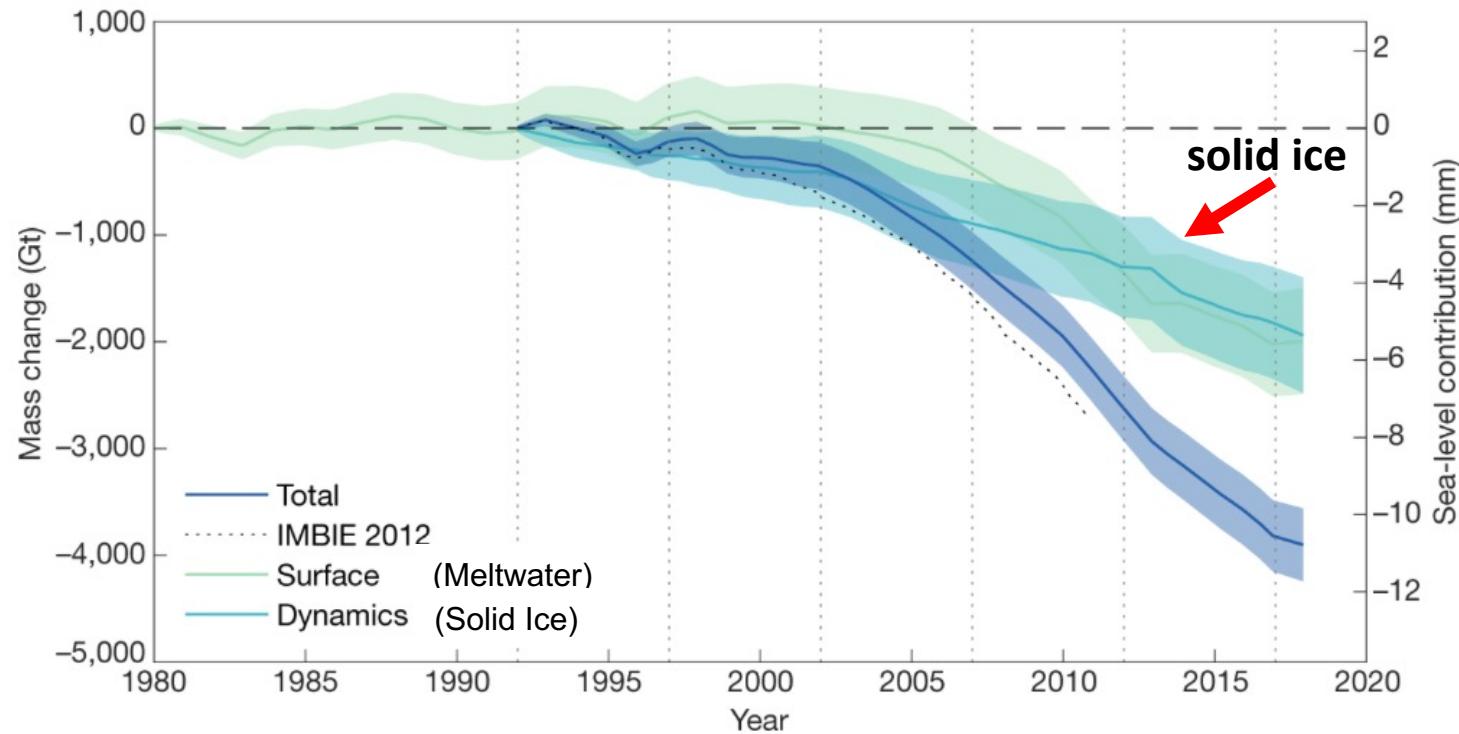
Mass balance of the Greenland Ice Sheet  
from 1992 to 2018

The IMBIE Team

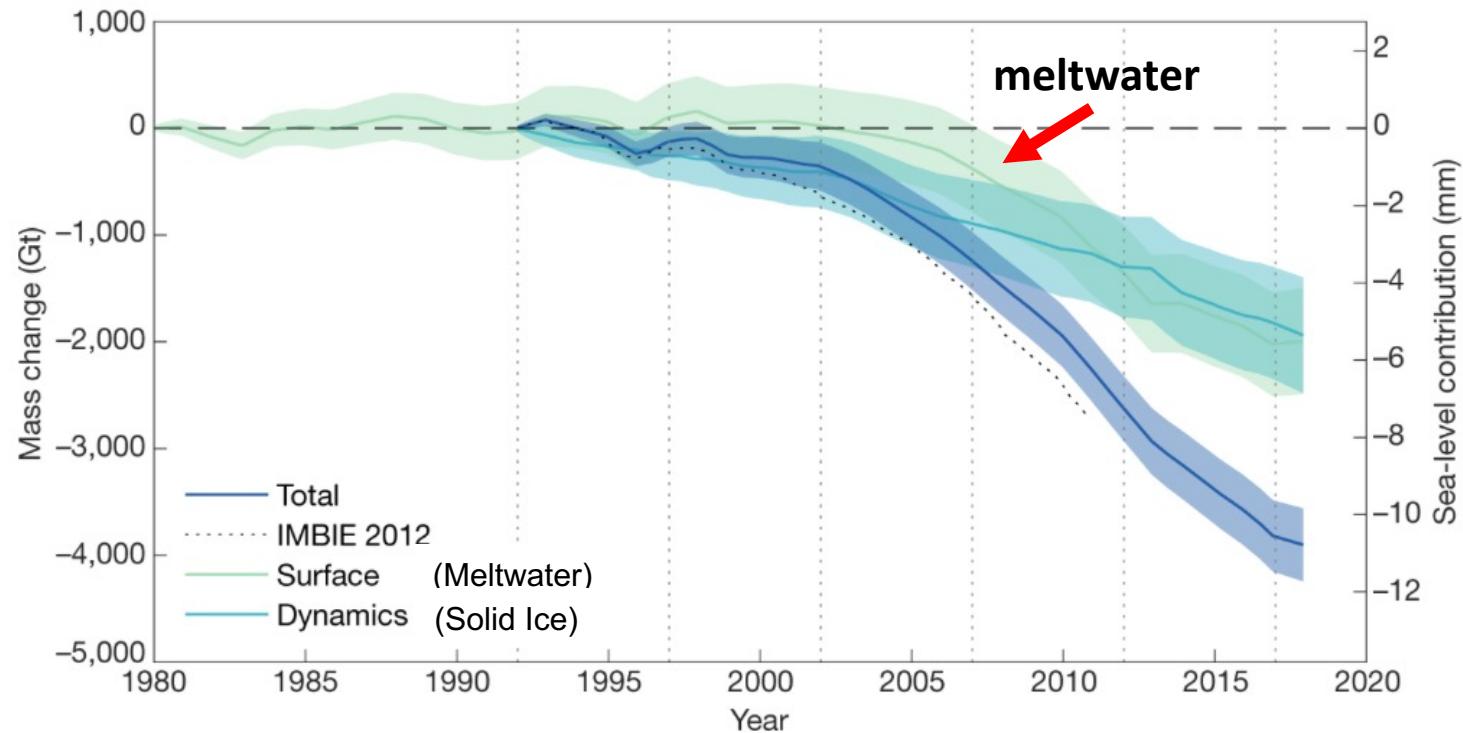
Nature 579, 233–239(2020) | Cite this article

Theme: solid ice discharge vs surface mass balance

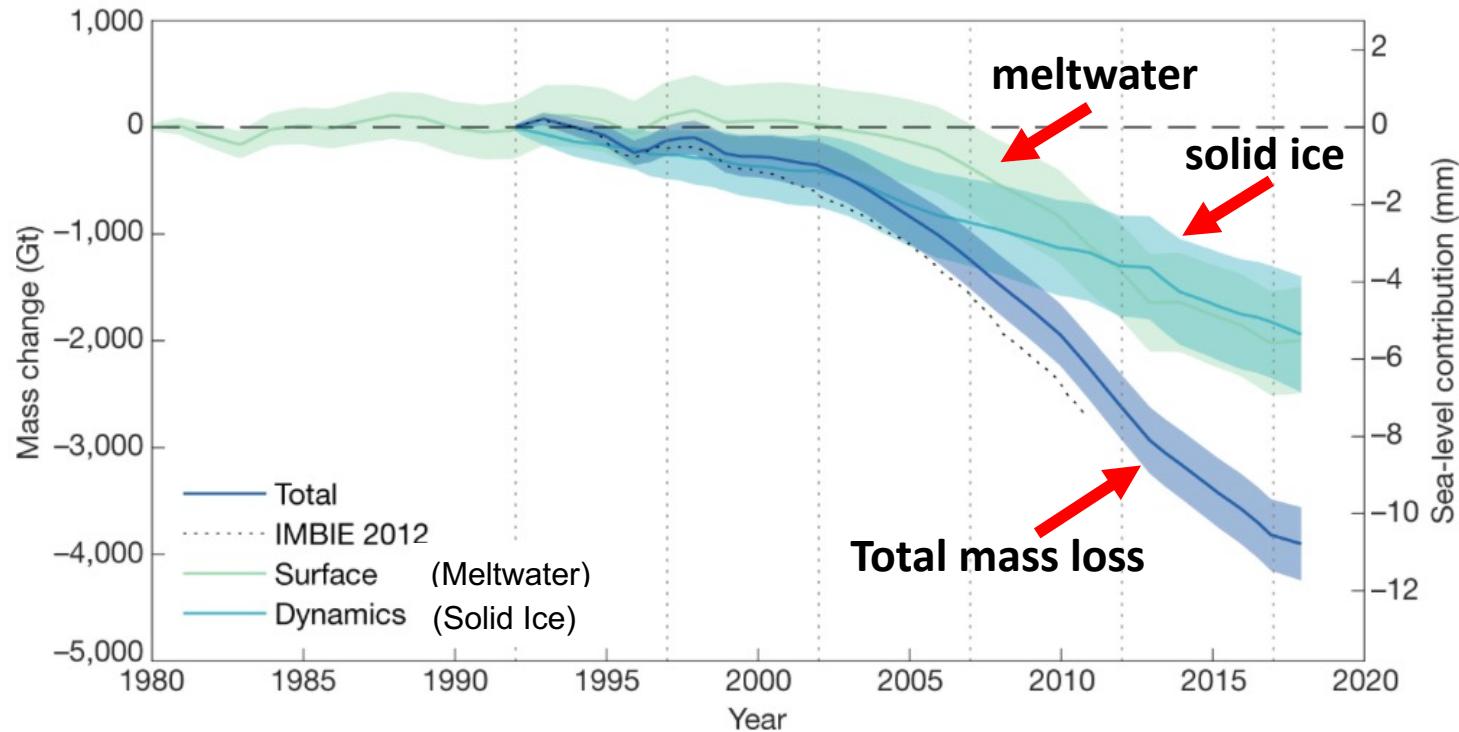
# Greenland is losing mass from solid ice **and** meltwater runoff



# Greenland is losing mass from solid ice **and** meltwater runoff

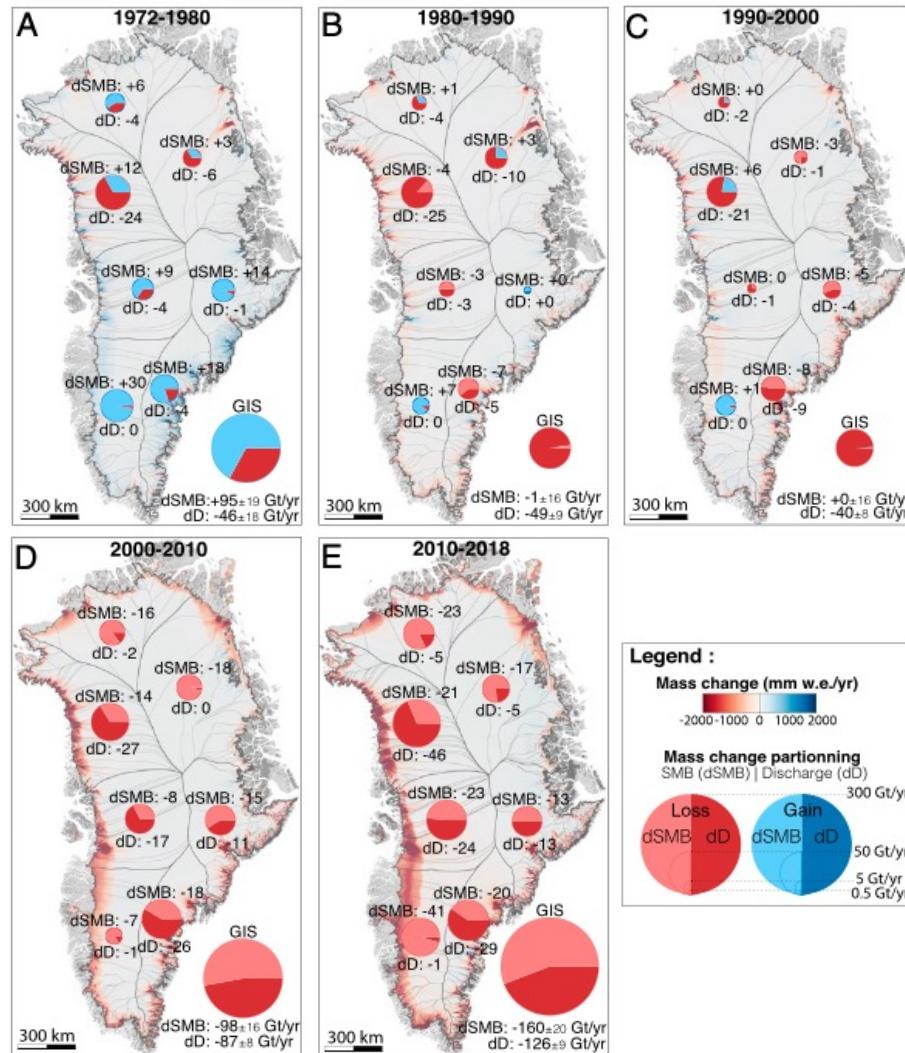


# Greenland is losing mass from solid ice **and** meltwater runoff

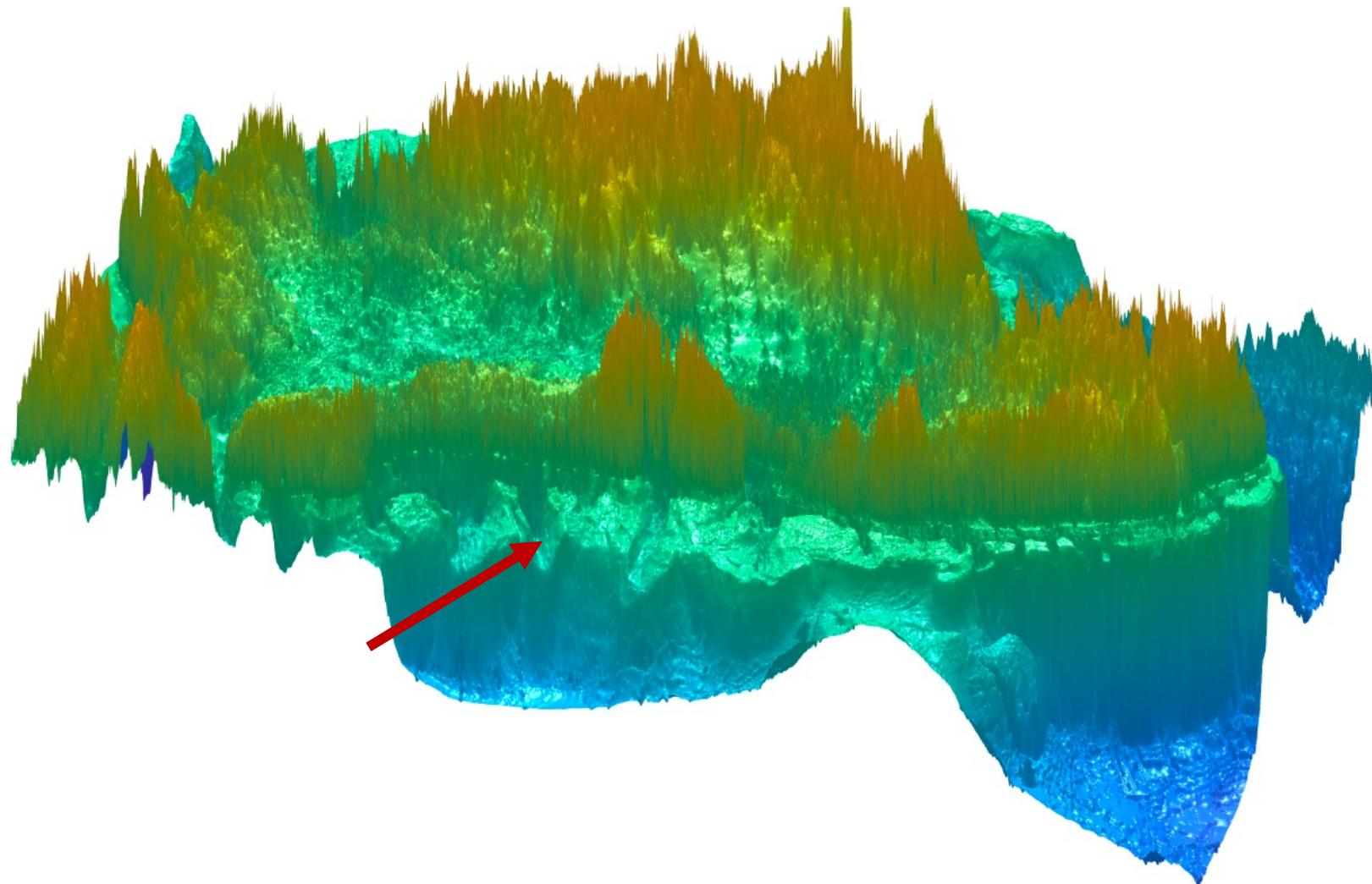


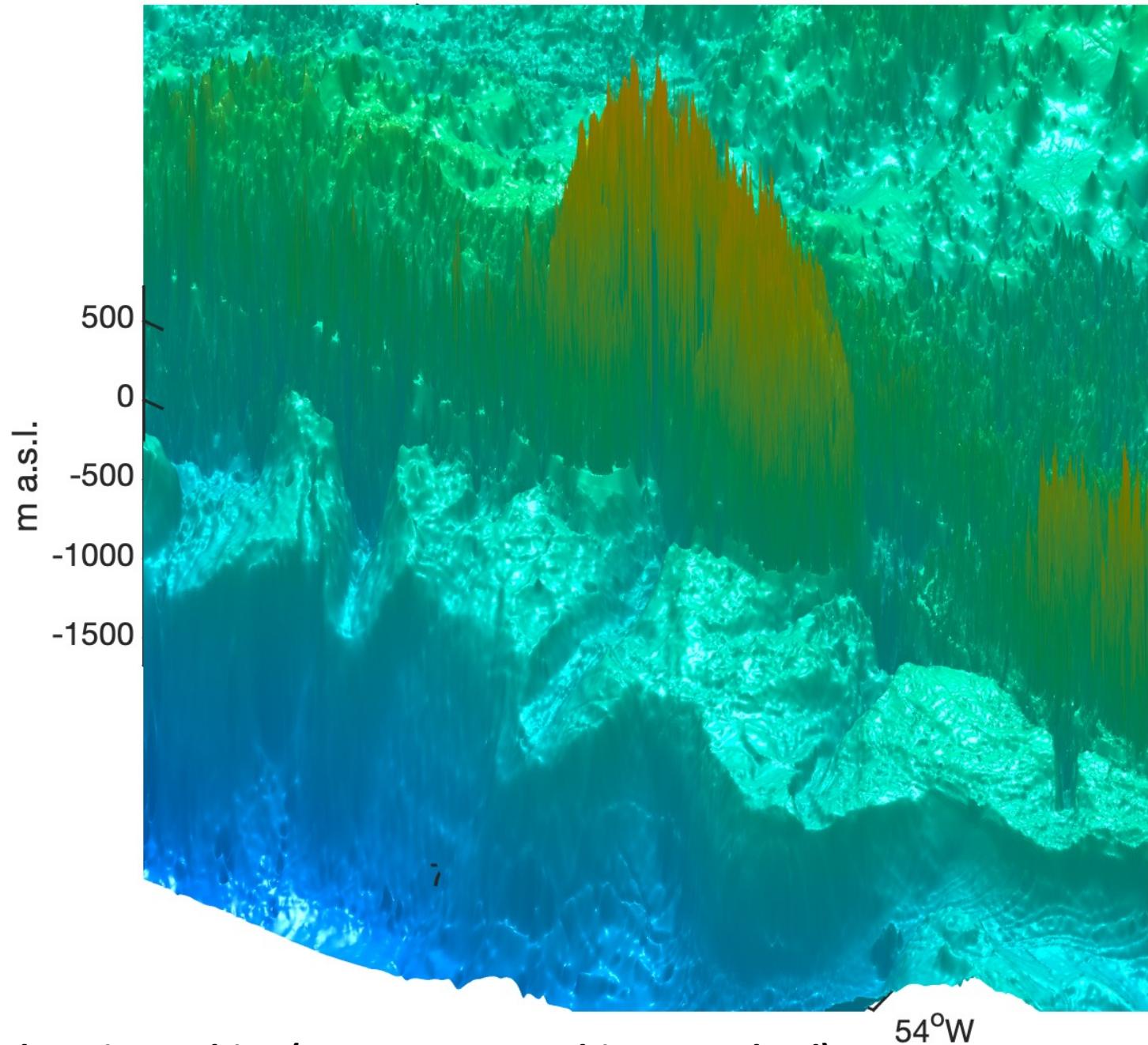
(Second largest contributor to global sea level-rise after thermal expansion of oceans)

# Solid Ice Discharge and Surface Mass Balance

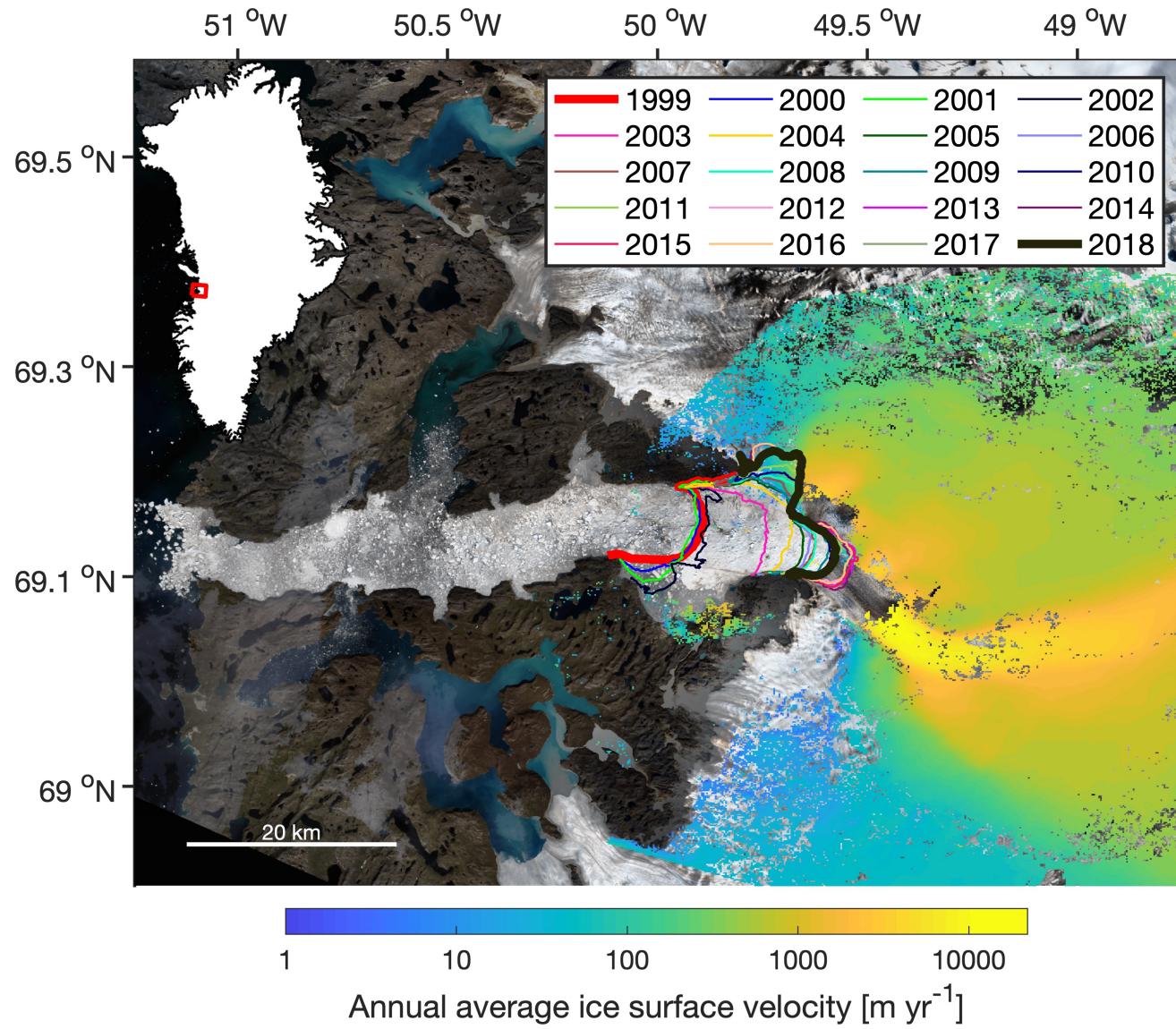


# Outlet Glacier Fjord Bathymetry

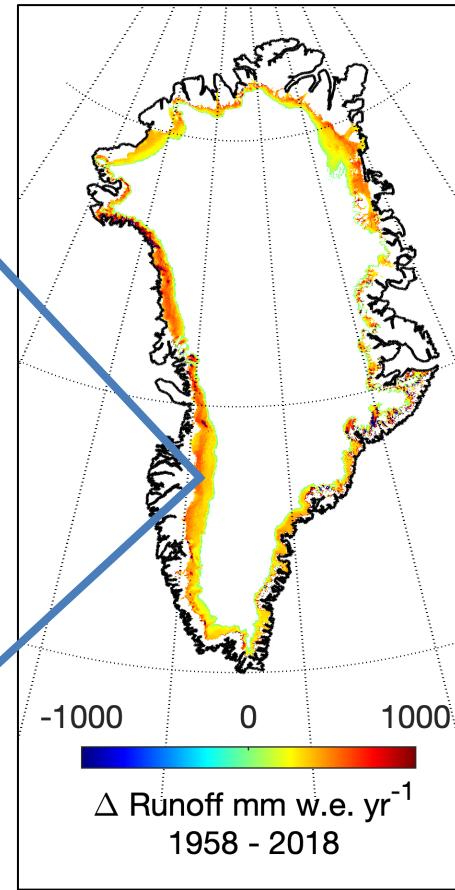
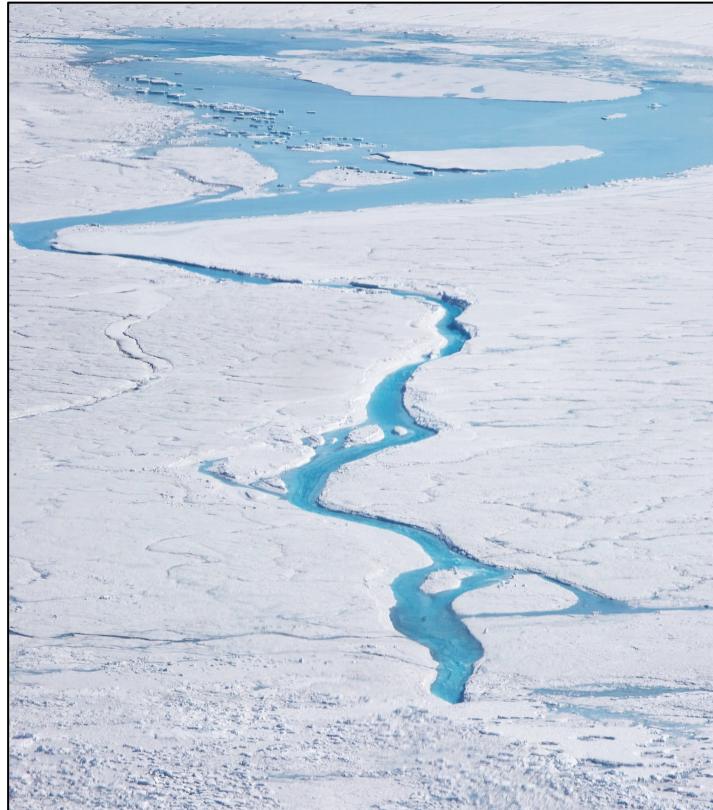




Theme: submarine melting (OMG: Oceans Melting Greenland)

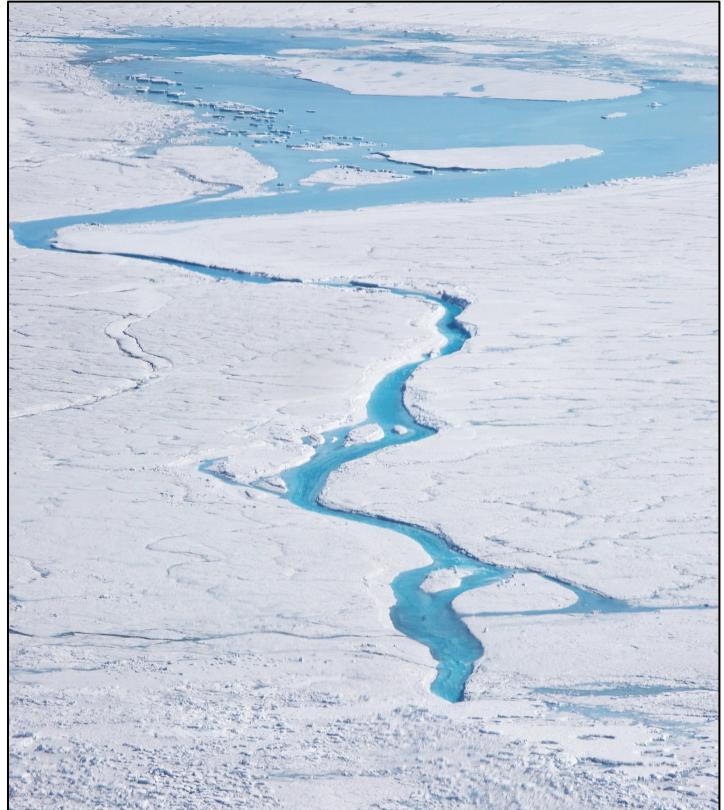
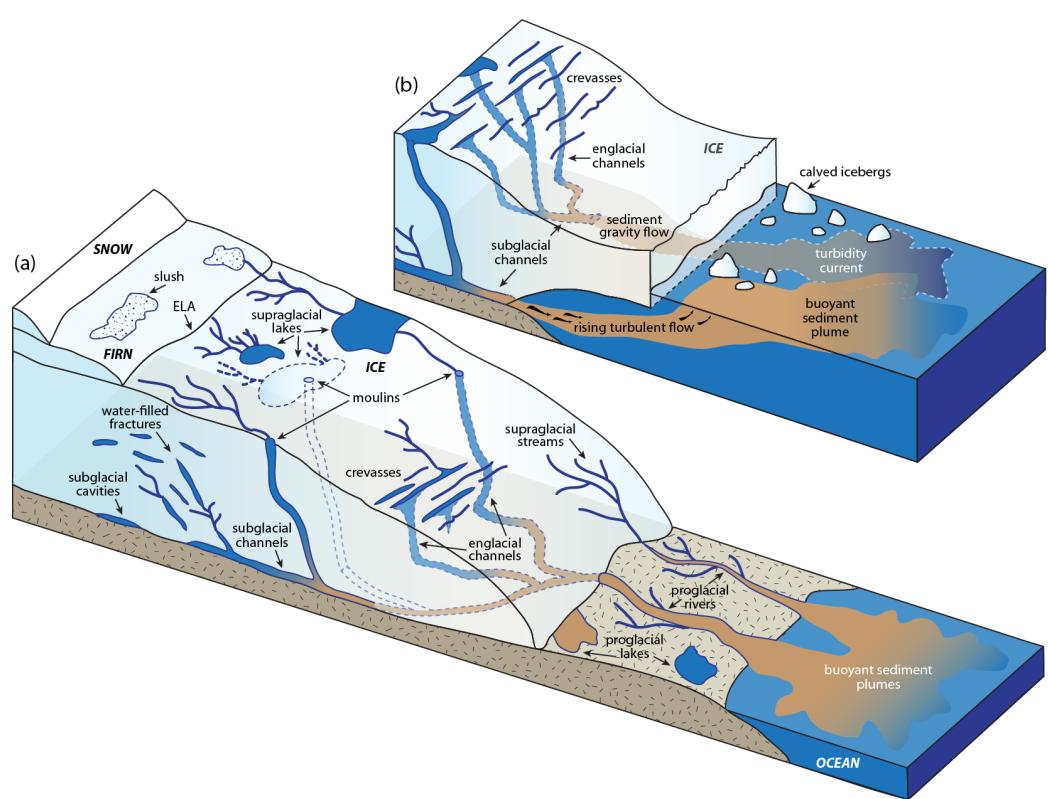


# Melting bare ice in Greenland's ablation zone



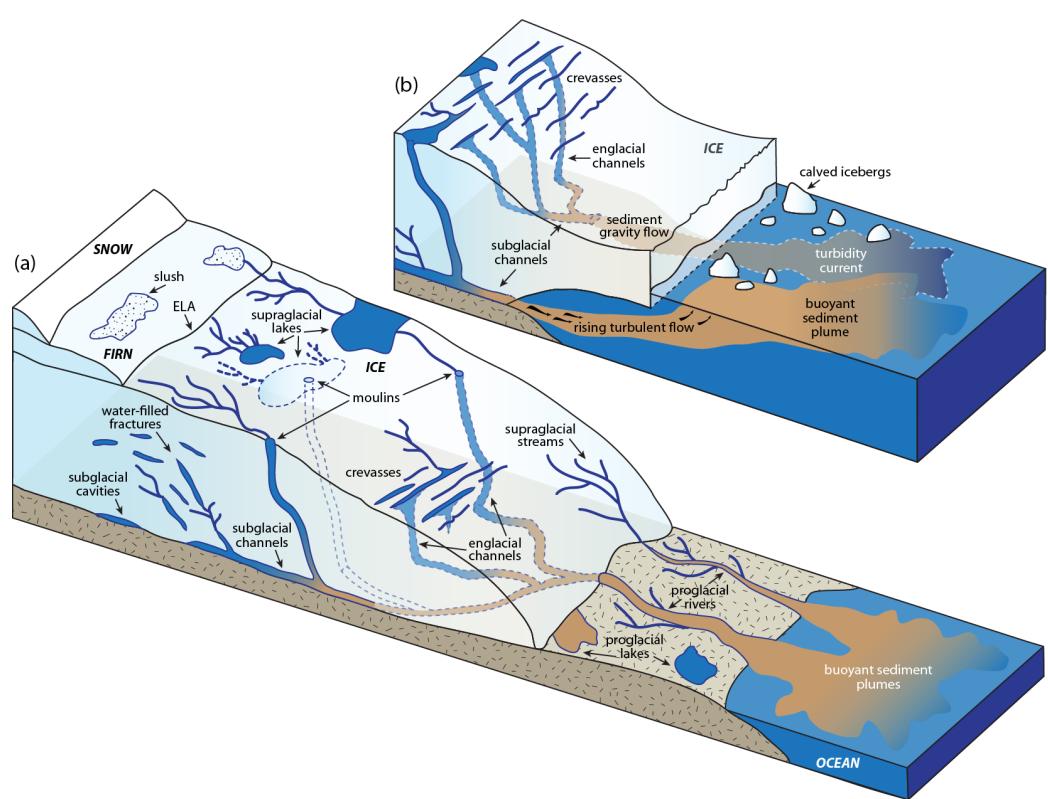
Theme: Meltwater runoff as the main driver of negative SMB (and future mass loss)

# Greenland Ice Sheet surface hydrology



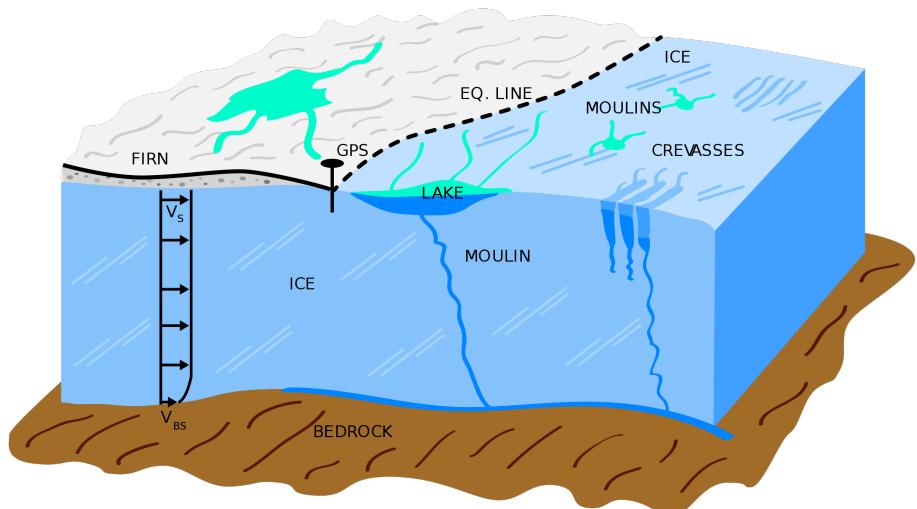
Vena Chu (2014), *Prog. Phys. Geog.*

# Greenland Ice Sheet surface hydrology



Vena Chu (2014), *Prog. Phys. Geog.*

# Meltwater lubrication–ice acceleration: positive feedback?



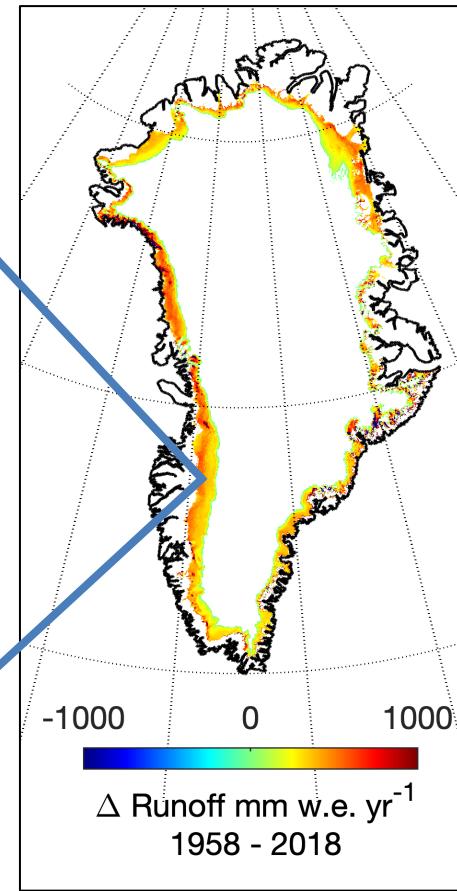
Zwally et al. 2002, *Science*

**Theme: Meltwater runoff–solid ice discharge positive feedback**

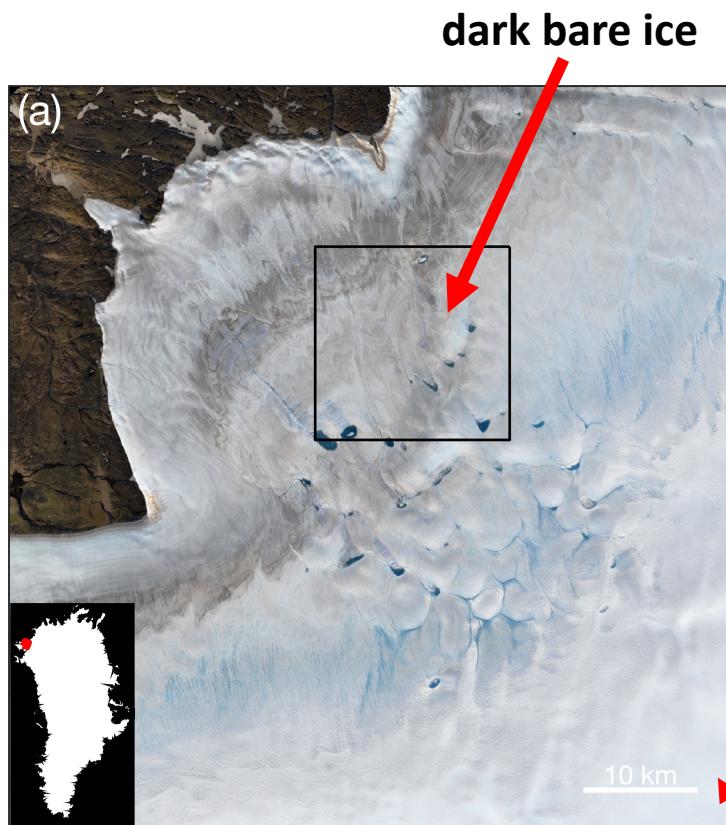
# Melting bare ice in Greenland's ablation zone



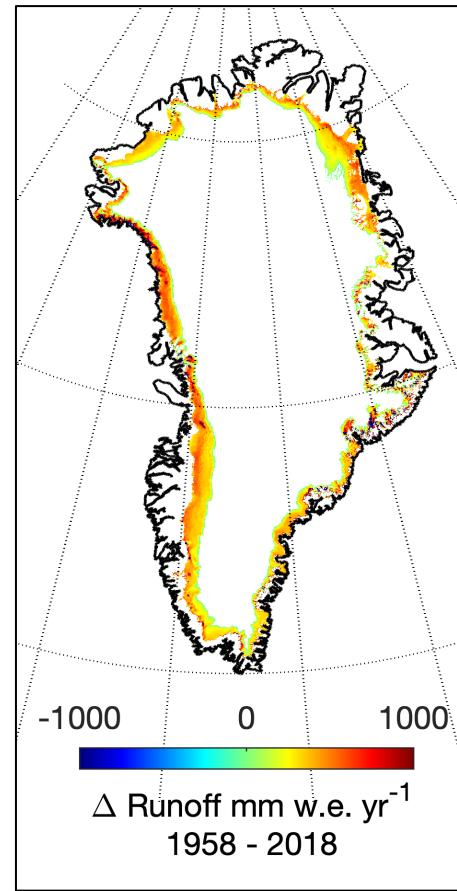
bare glacier ice



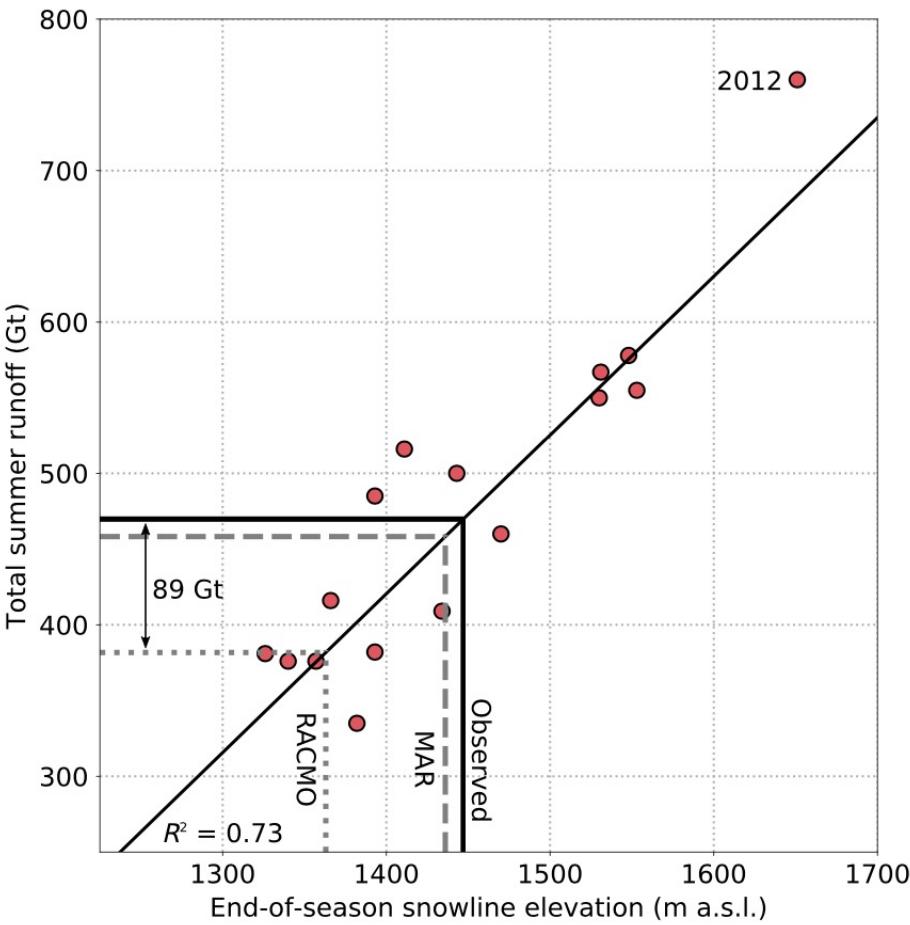
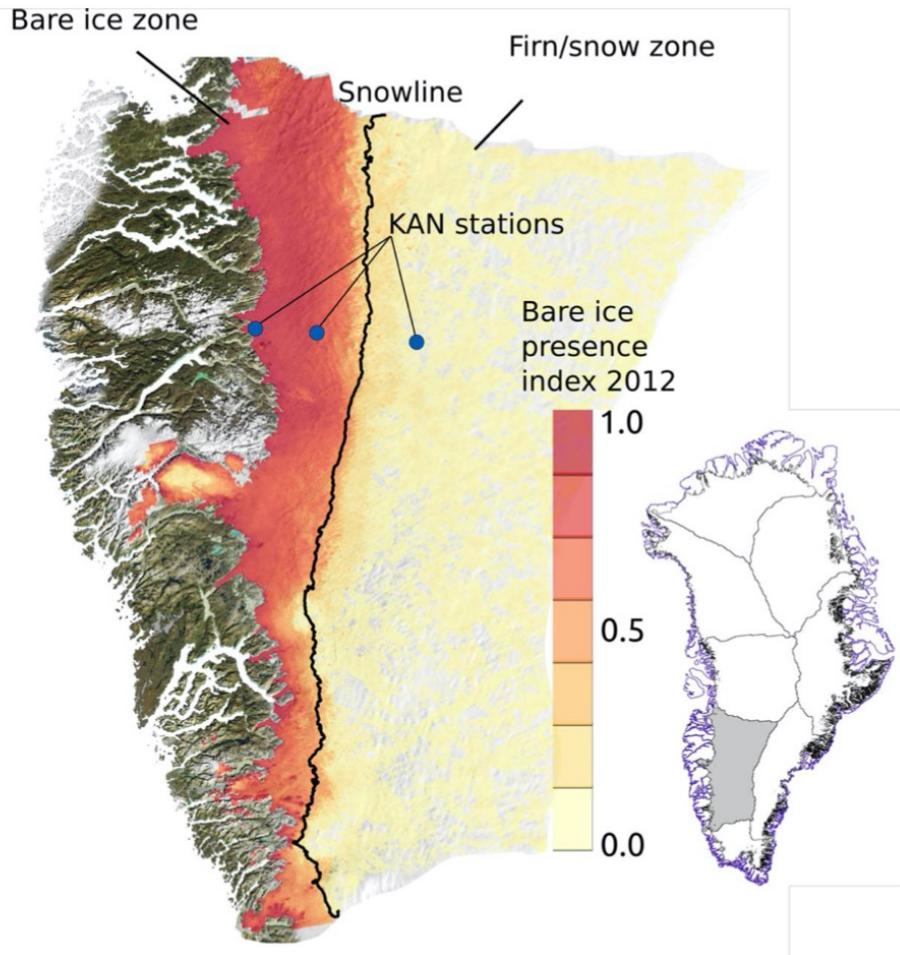
~85% of Greenland's meltwater comes from melting bare ice



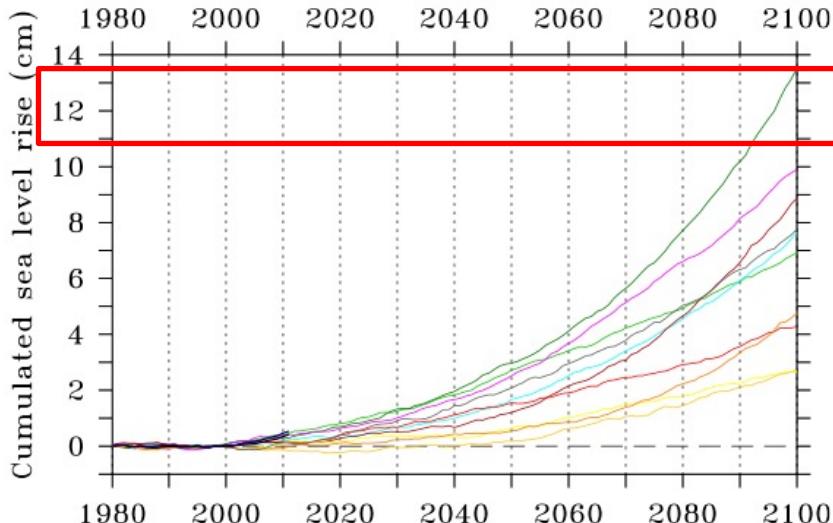
Cooper and Smith (2019) *Remote Sensing*



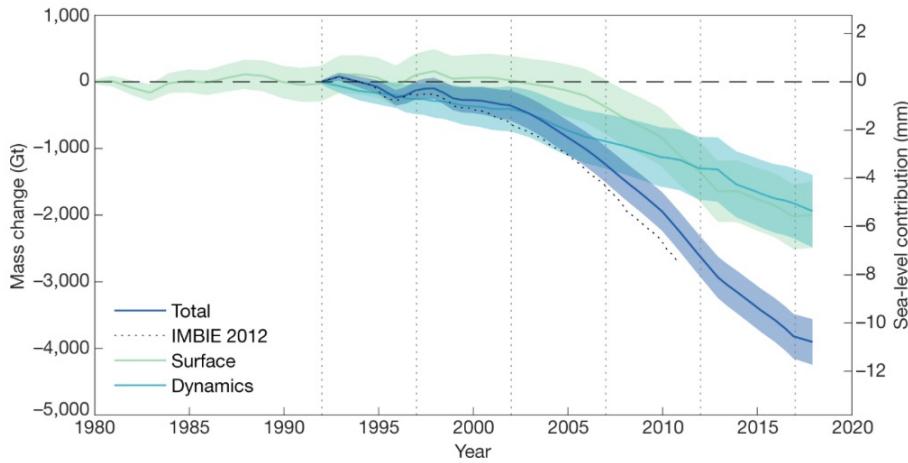
# Bare ice exposure and meltwater runoff



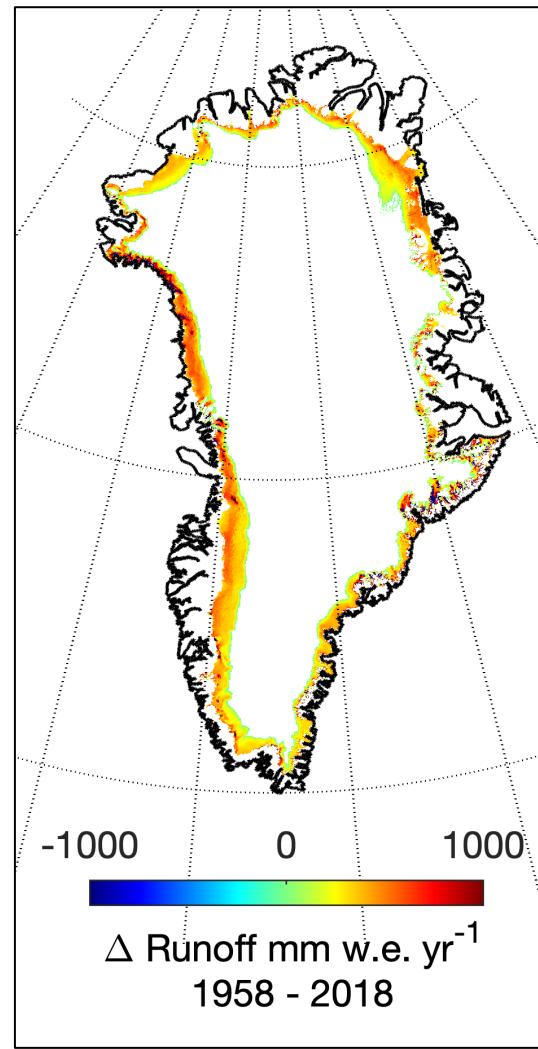
# Climate models are tools to predict future sea levels



Fettweis et al. (2013), *The Cryosphere*

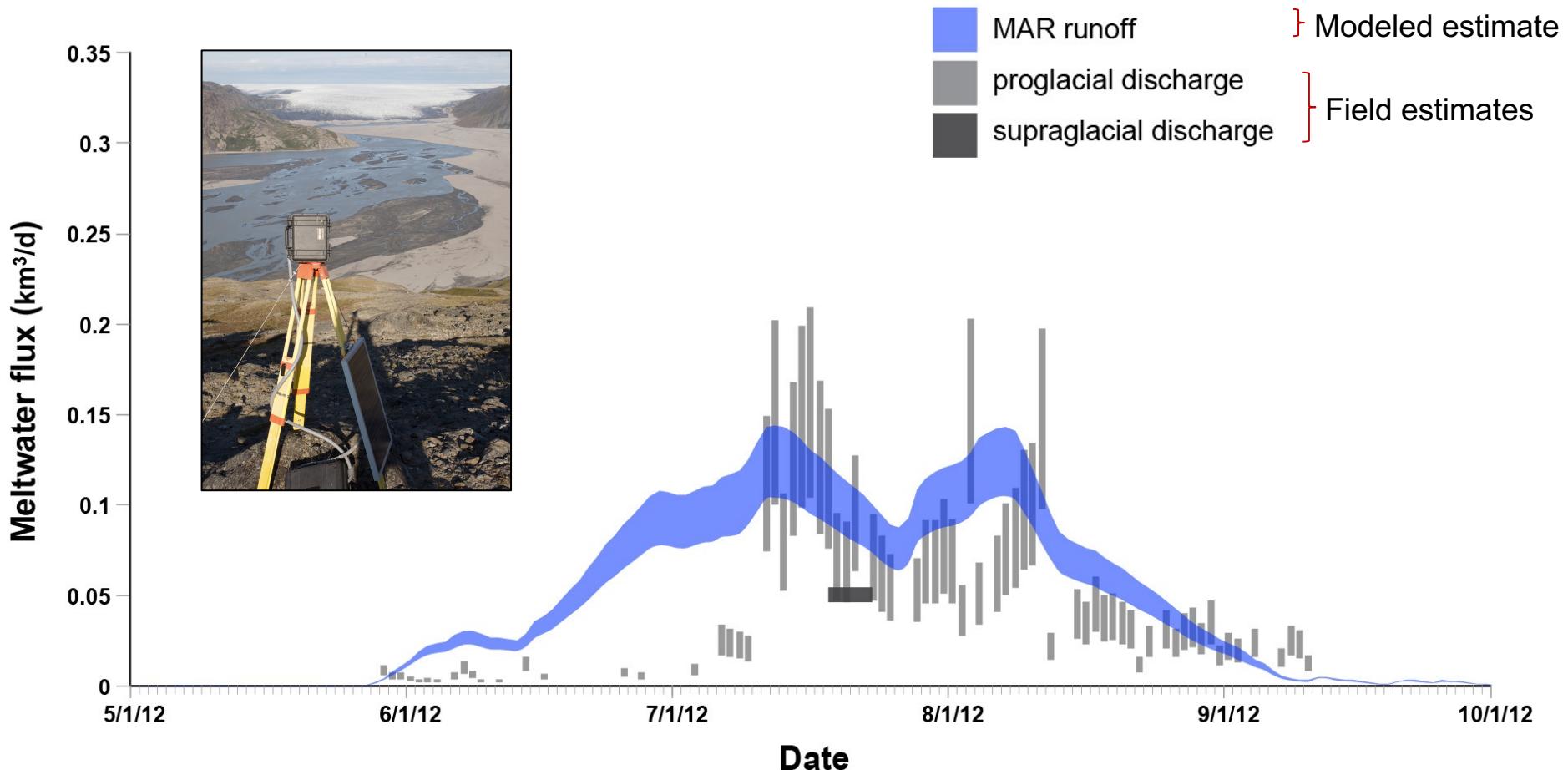


The IMBIE team (2020)



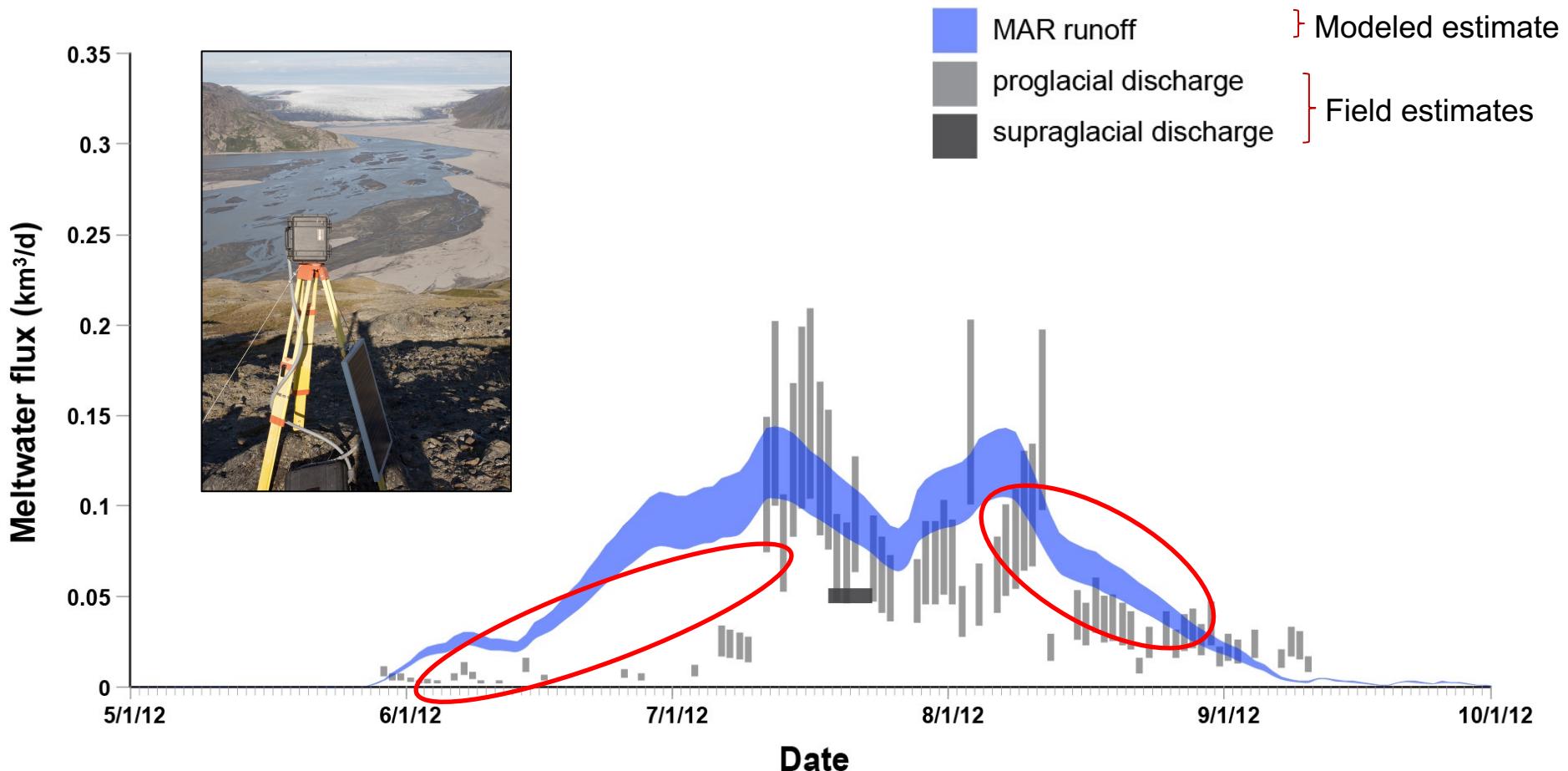
RACMO 2.3 data courtesy Brice Noel

# How do climate models predict ice sheet meltwater runoff?



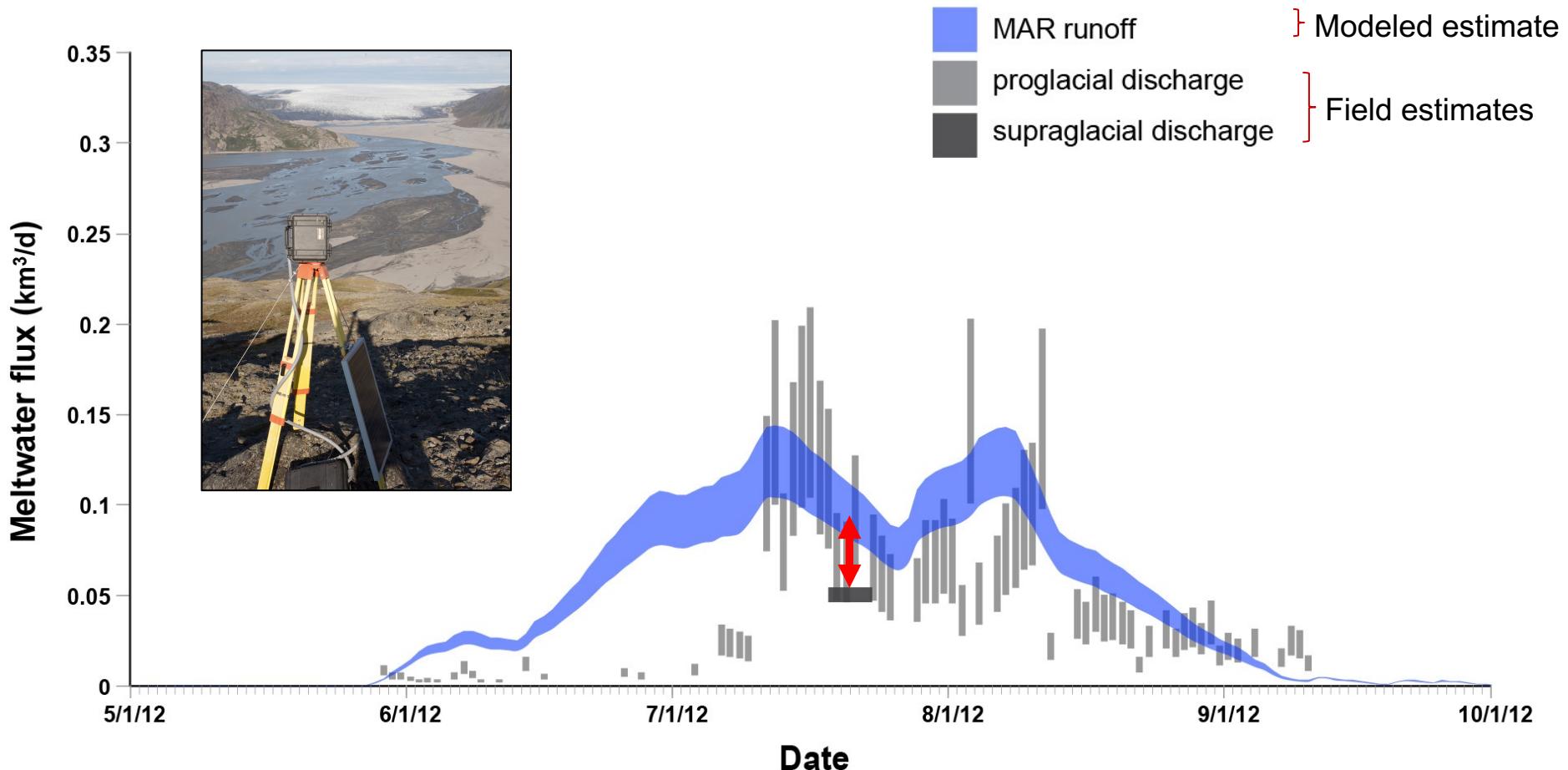
Smith et al. 2015, PNAS

# How do climate models predict ice sheet meltwater runoff?



Modified from Smith et al. 2015, PNAS

# How do climate models predict ice sheet meltwater runoff?



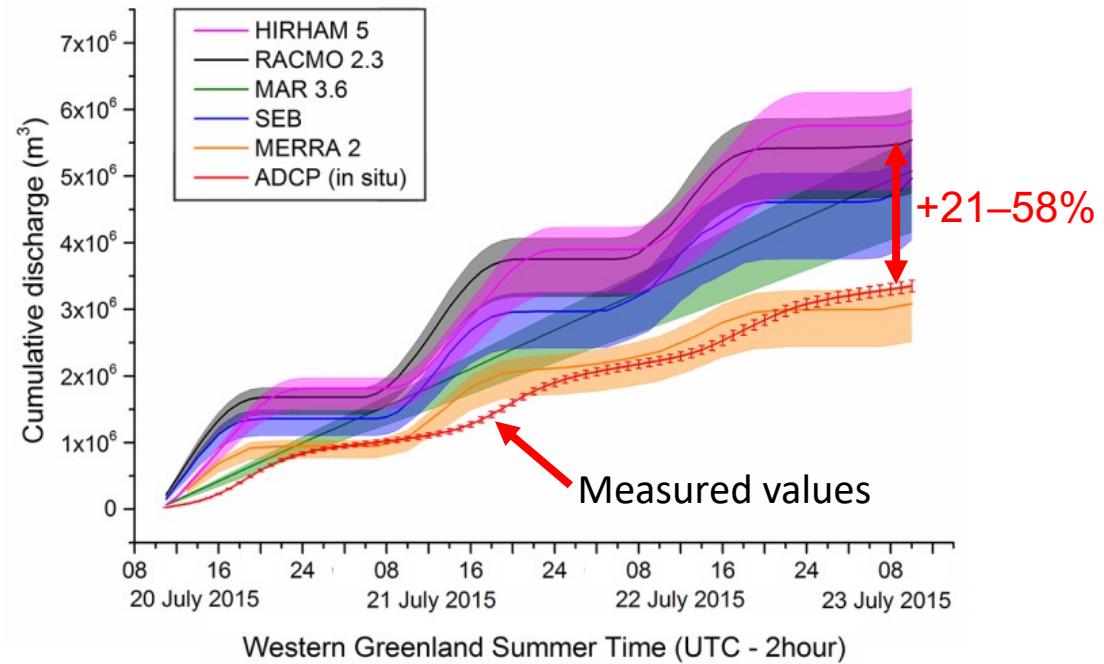
Modified from Smith et al. 2015, PNAS



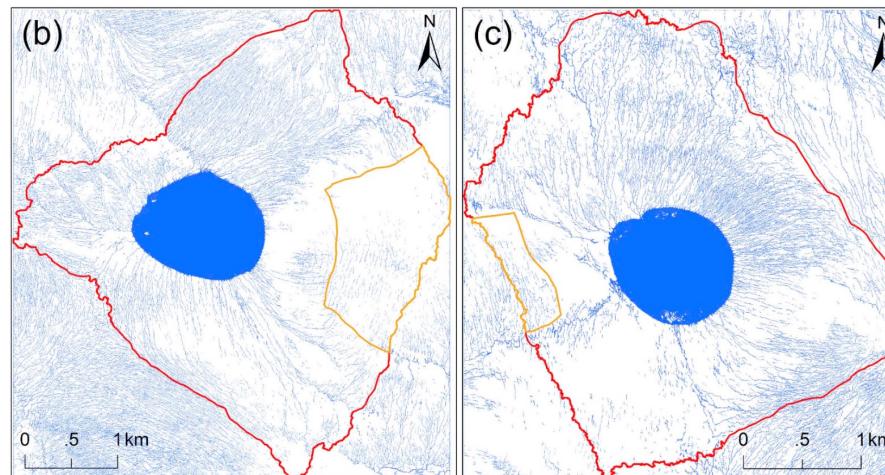
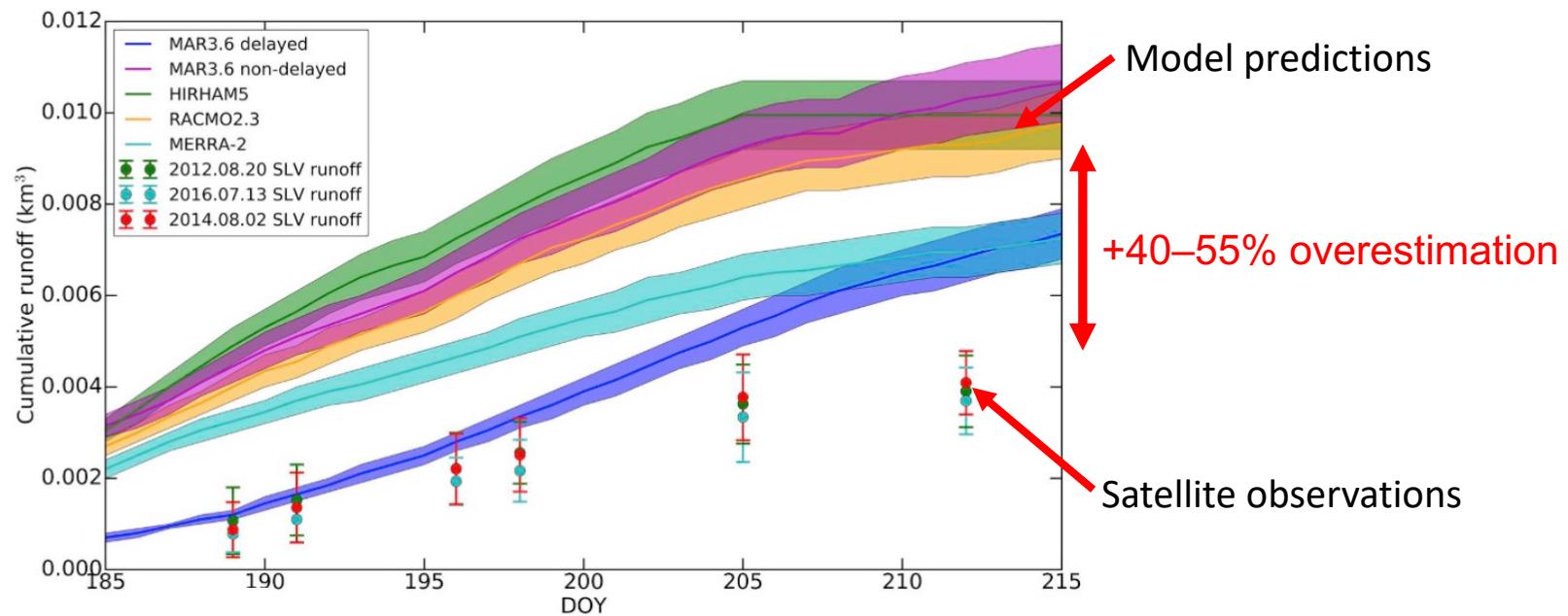
# Measuring ice sheet meltwater runoff



Smith et al. (2017) PNAS



# Do Climate Models Overpredict Ice Sheet Meltwater Runoff?



Yang et al. (2019)  
*Remote Sensing Environment*



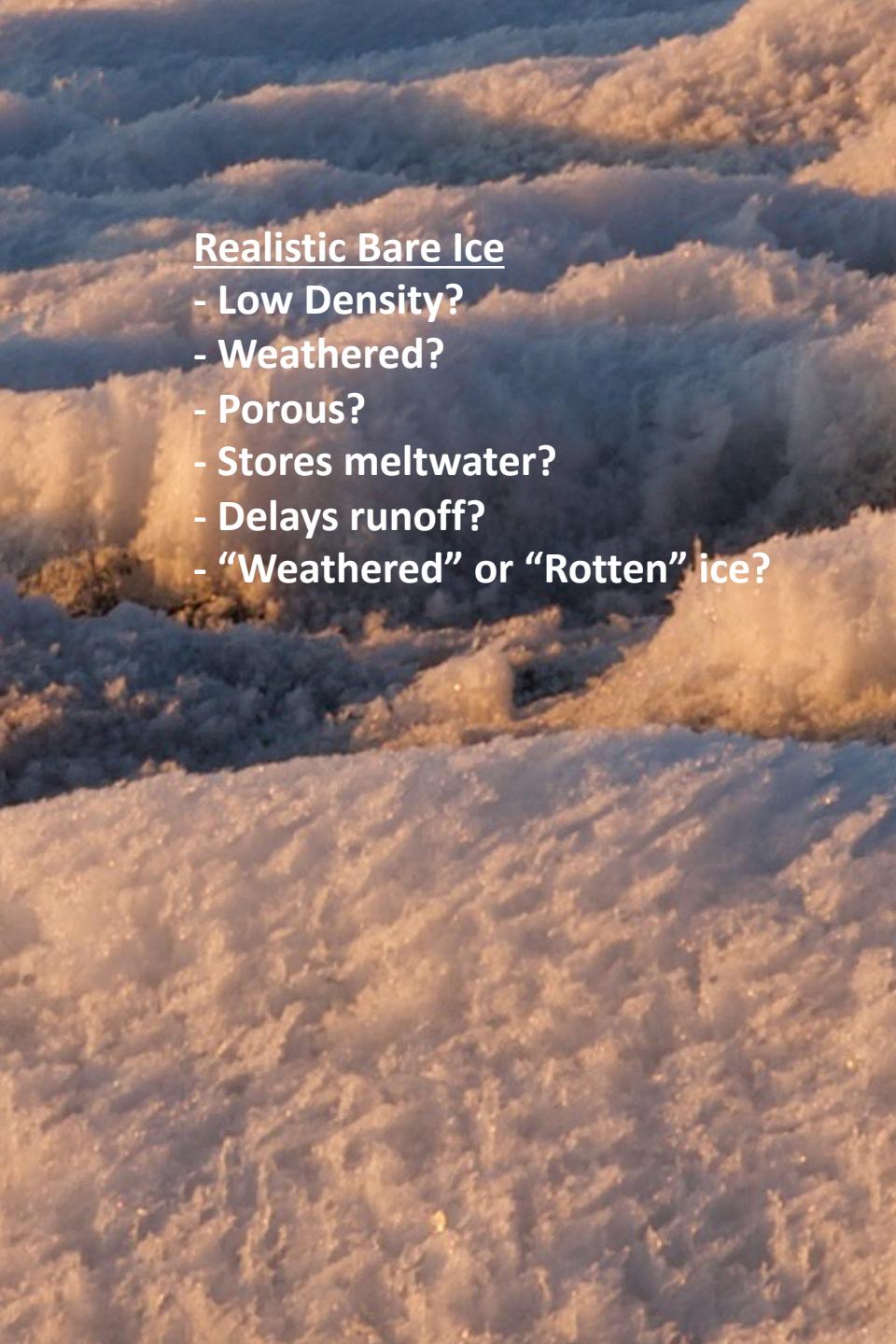
“Rotten ice”





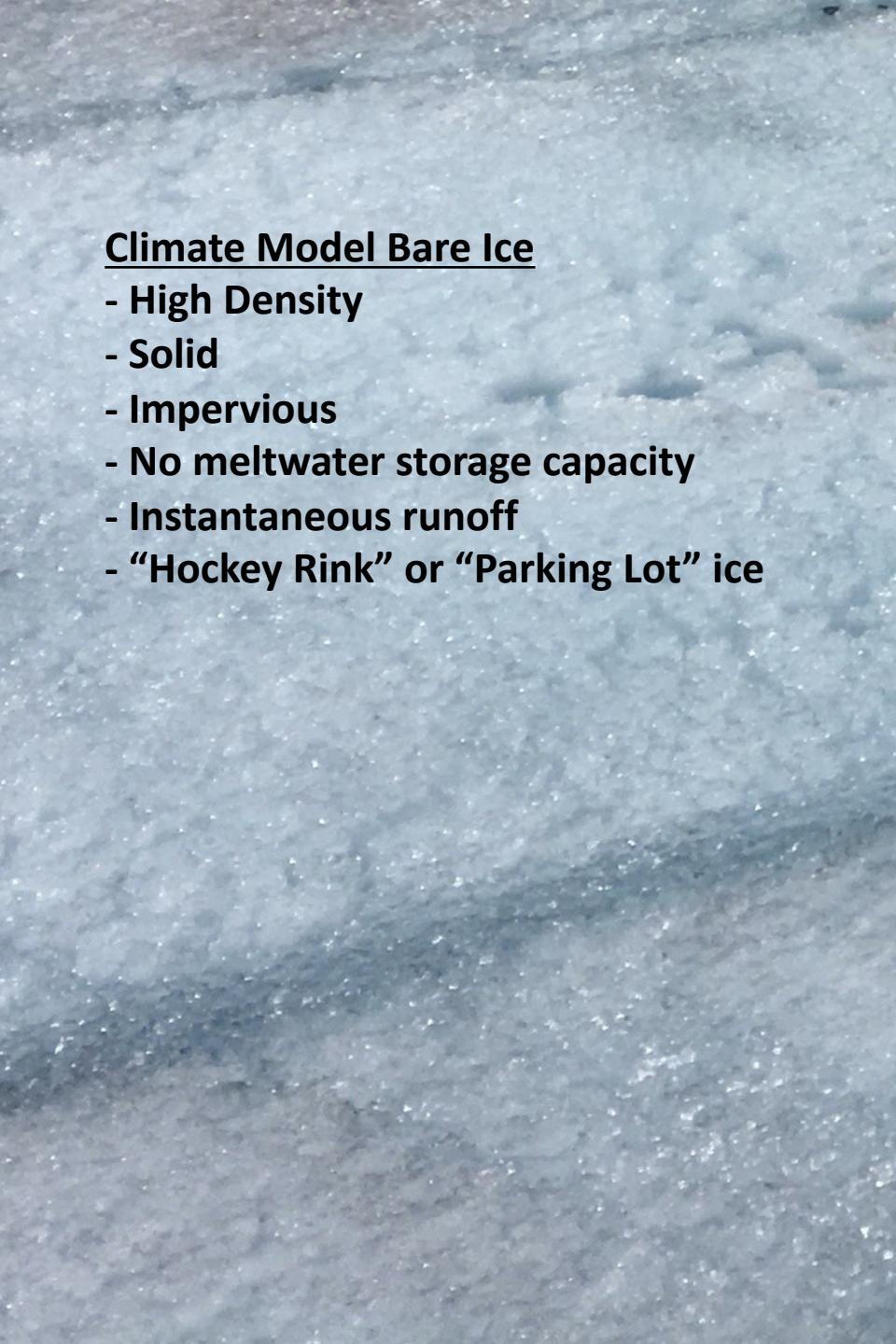
### Climate Model Bare Ice

- High Density
- Solid
- Impervious
- No meltwater storage capacity
- Instantaneous runoff
- “Hockey Rink” or “Parking Lot” ice



### Realistic Bare Ice

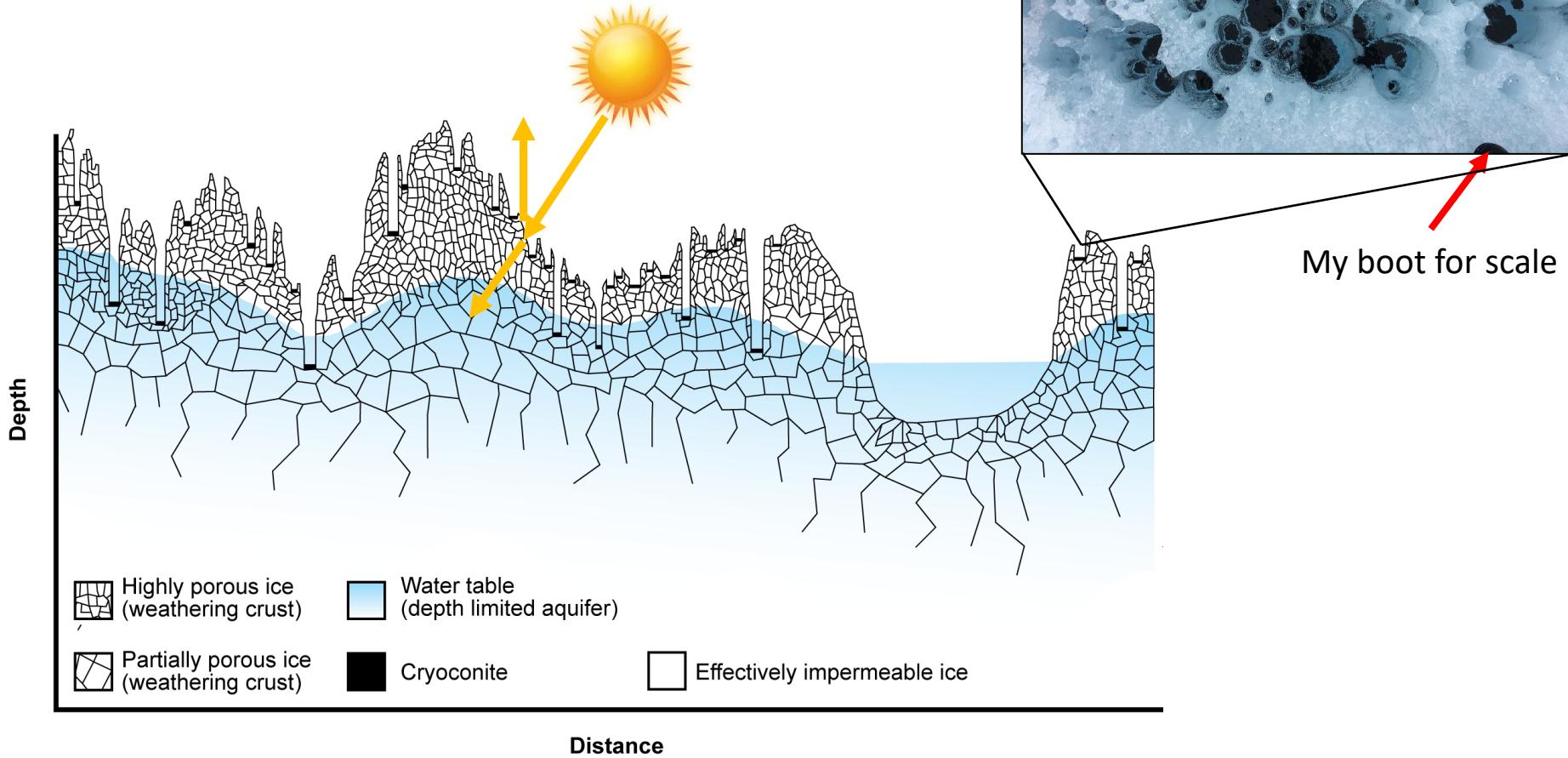
- Low Density?
- Weathered?
- Porous?
- Stores meltwater?
- Delays runoff?
- “Weathered” or “Rotten” ice?



### Climate Model Bare Ice

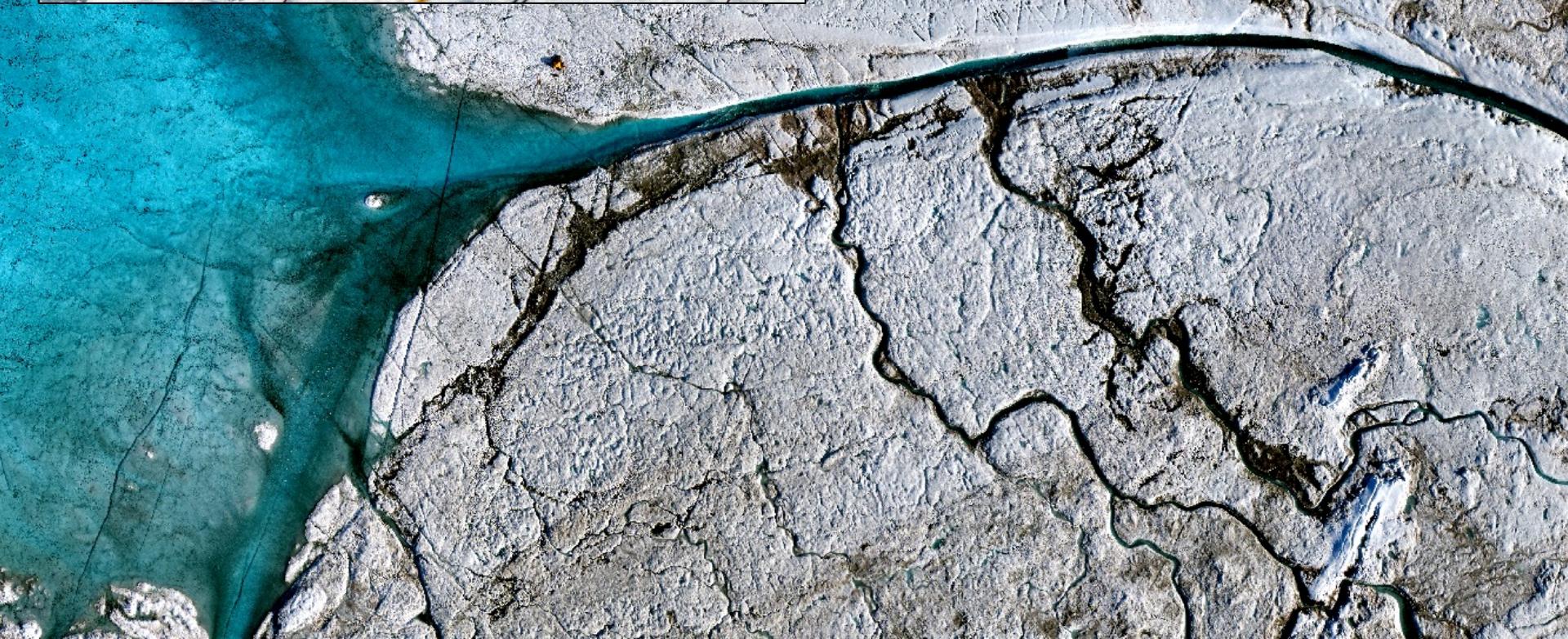
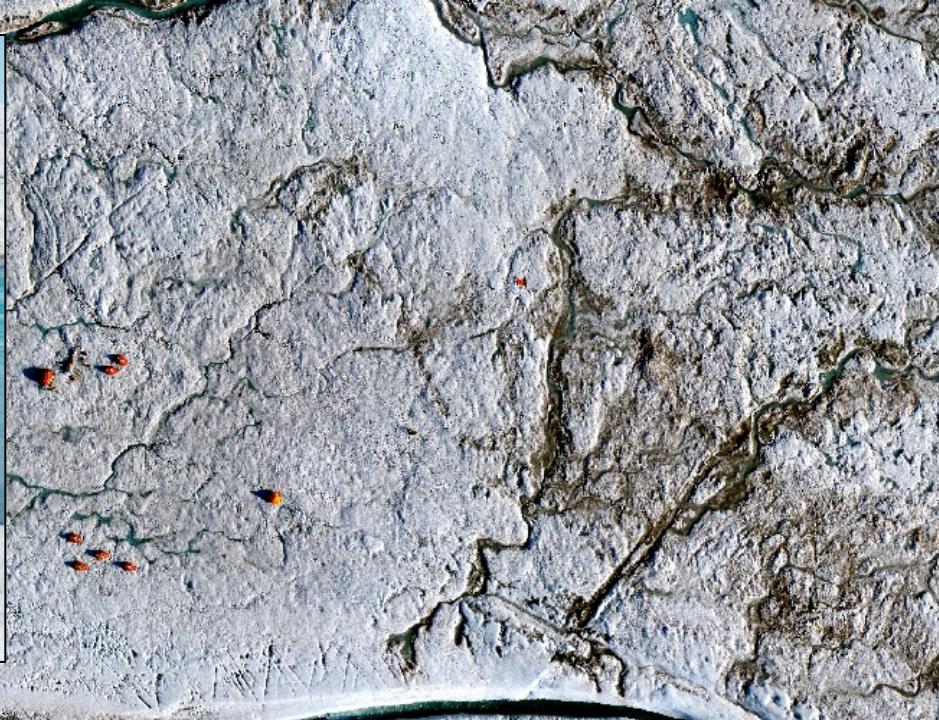
- High Density
- Solid
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# The Greenland Ice Sheet critical zone

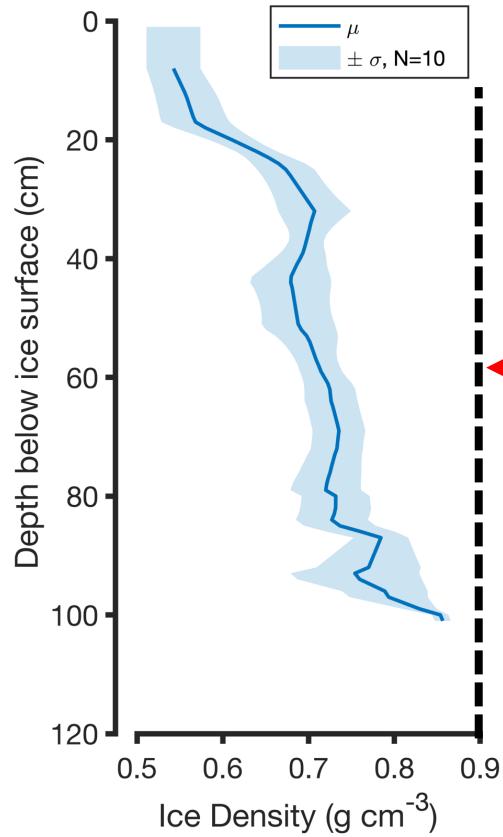


Cooper et al. (2018) *The Cryosphere*

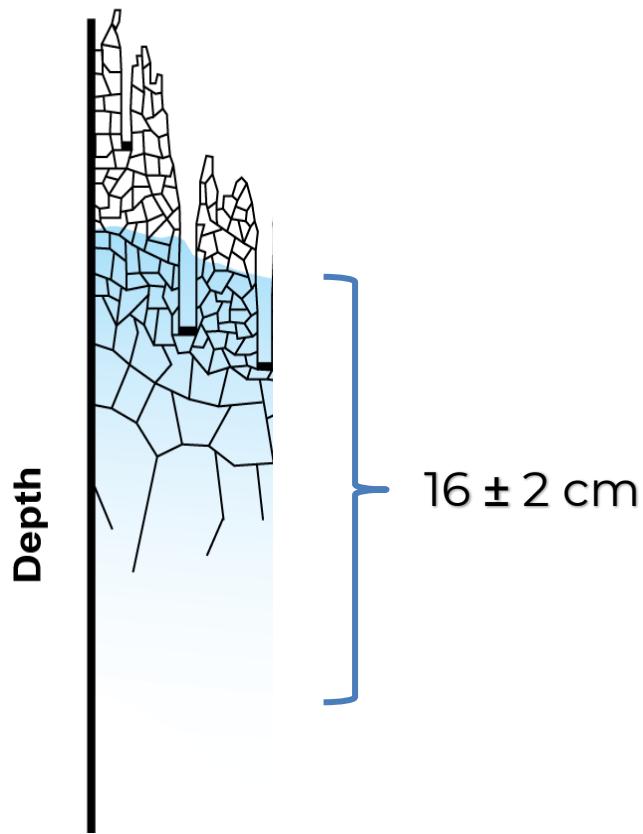




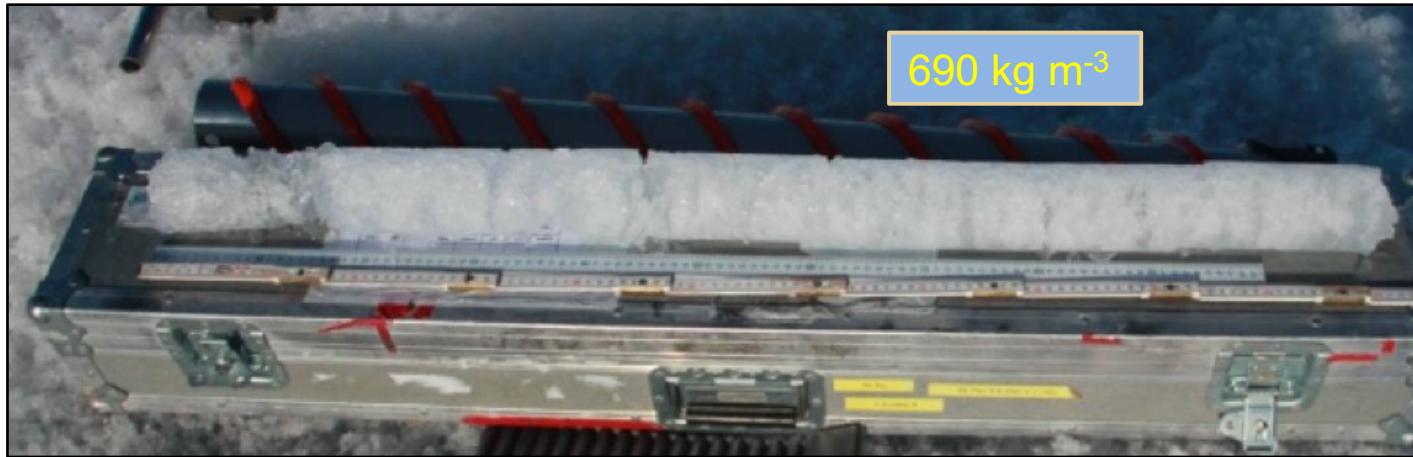
# Field Measurements of Ice Density and Water Storage



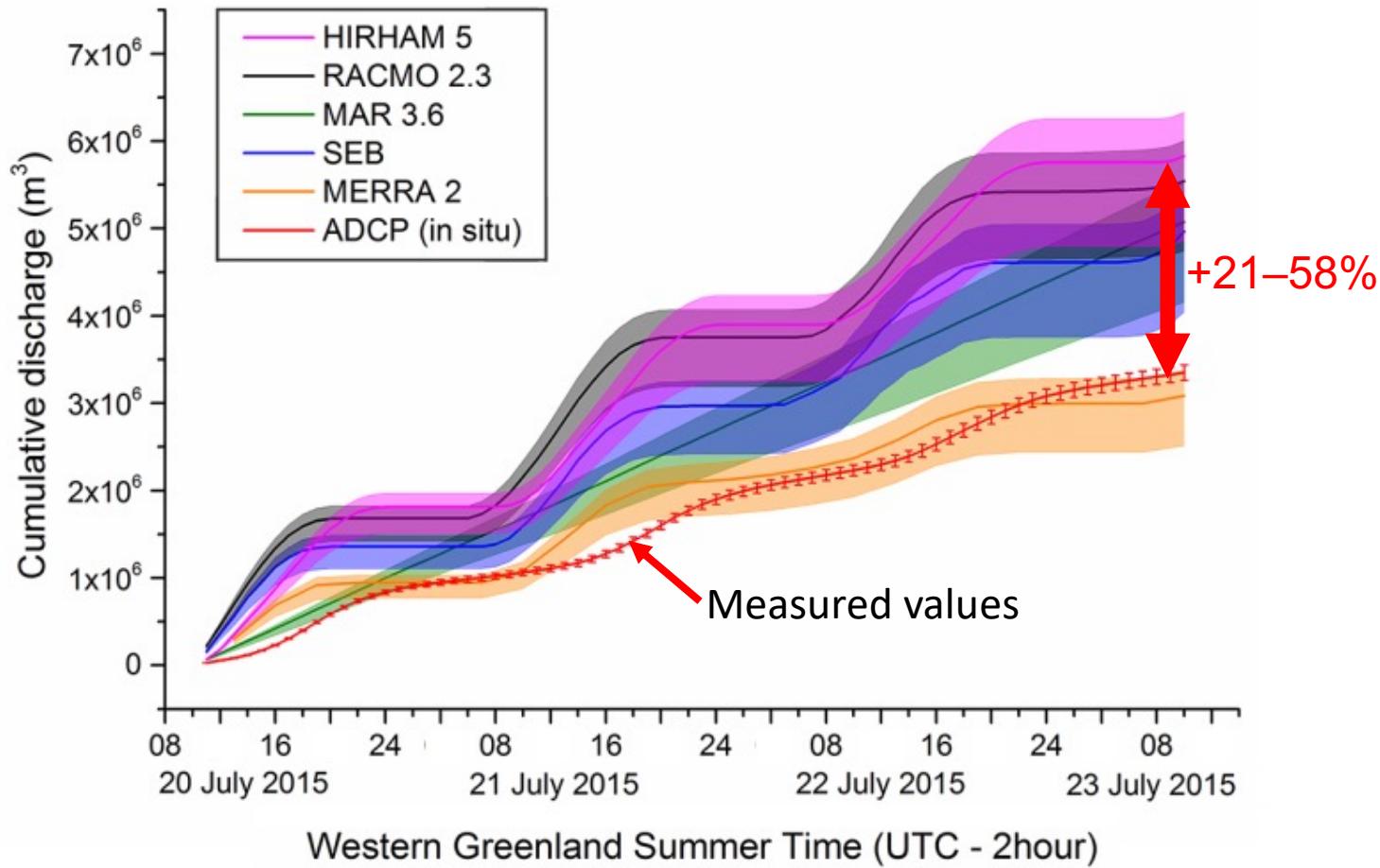
Solid ice density  $\approx 900 \text{ kg m}^{-3}$  assumed by climate models



# Evidence of sub-surface melting in bare ice

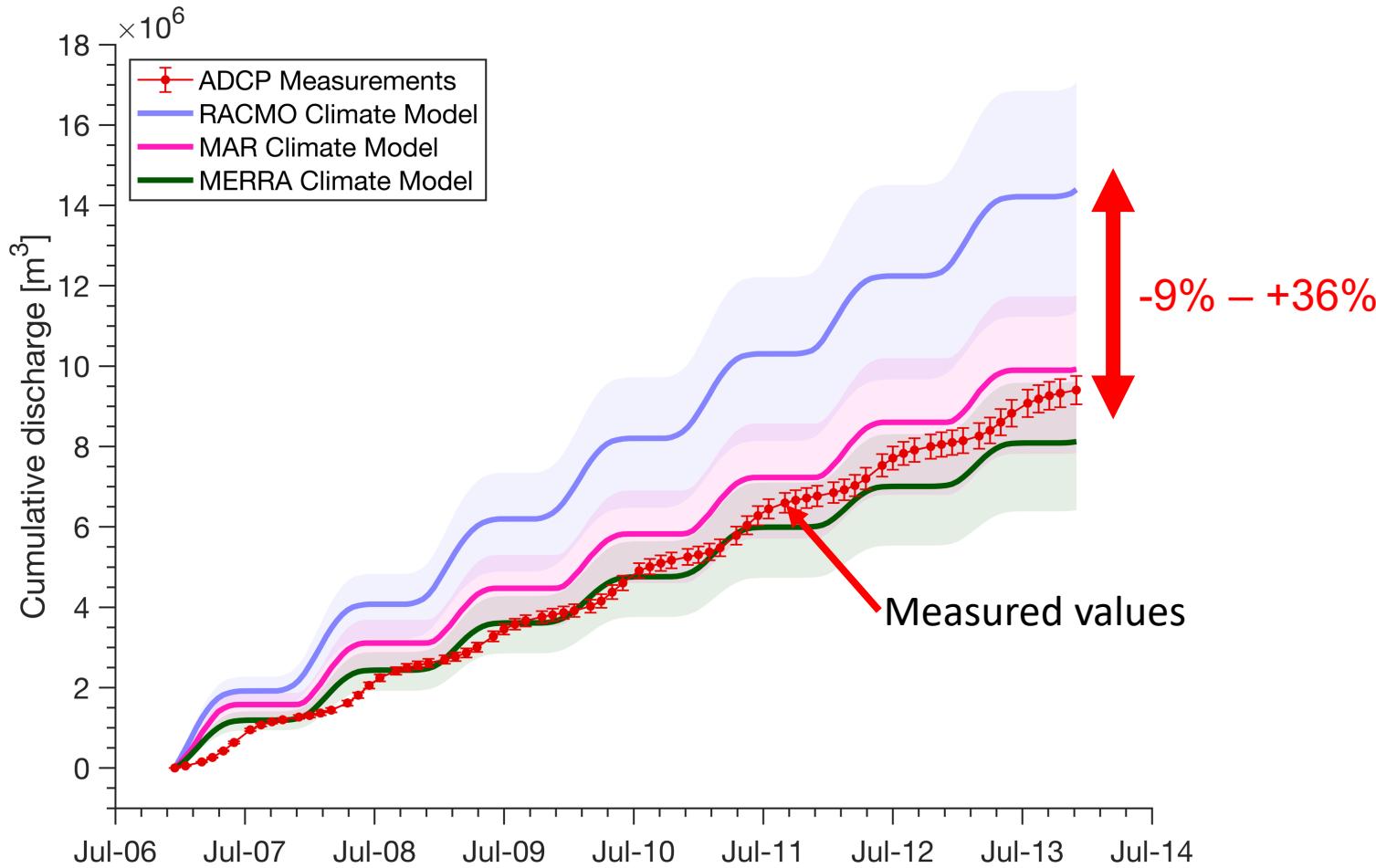


# Do Climate Models Overpredict Ice Sheet Meltwater Runoff?

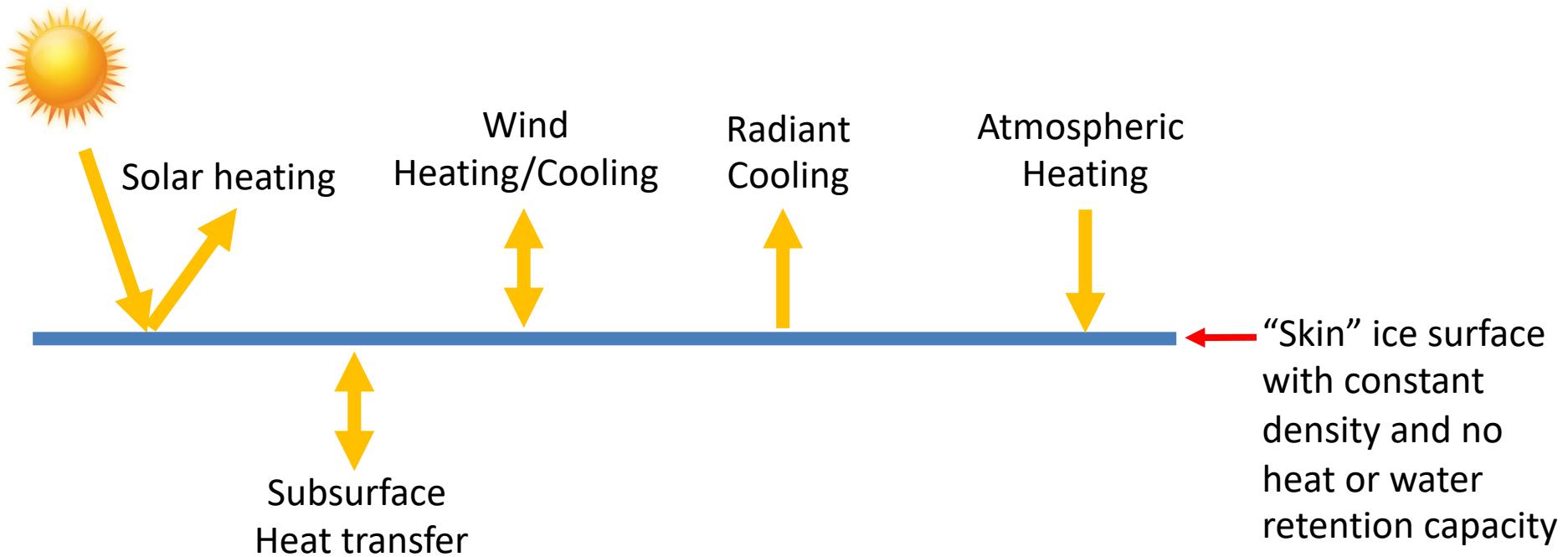


Smith et al. (2017) PNAS

# Do Climate Models Overpredict Ice Sheet Meltwater Runoff?



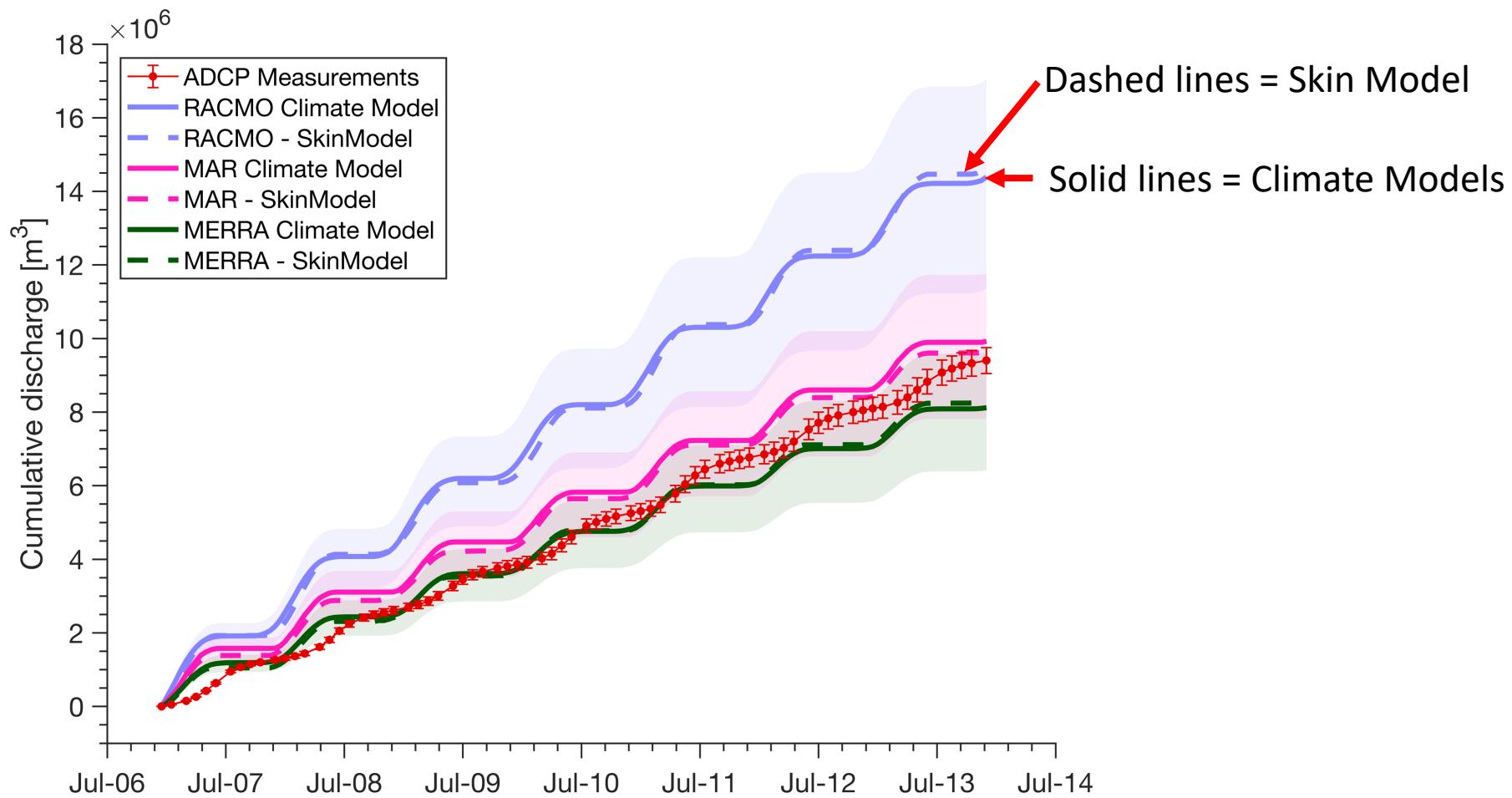
# Skin Model: a numerical model of ice sheet meltwater runoff



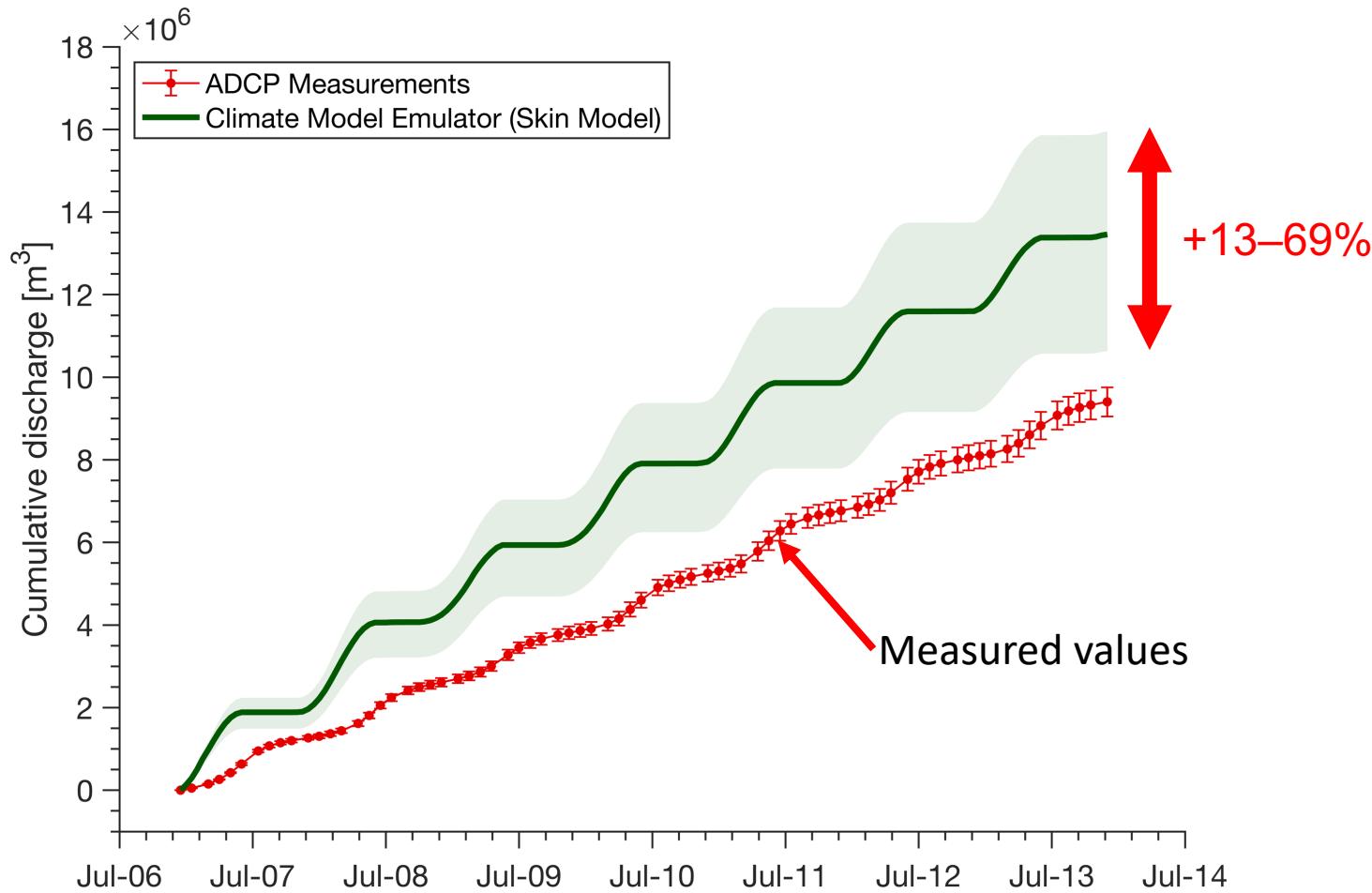
$$C_v \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial z} \left[ k_i \frac{\partial T_i}{\partial z} \right]$$

$$Q_{si}(1 - \alpha) + Q_{li} - \epsilon \sigma T_{sfc}^4 + Q_h + Q_e + Q_c = Q_m$$

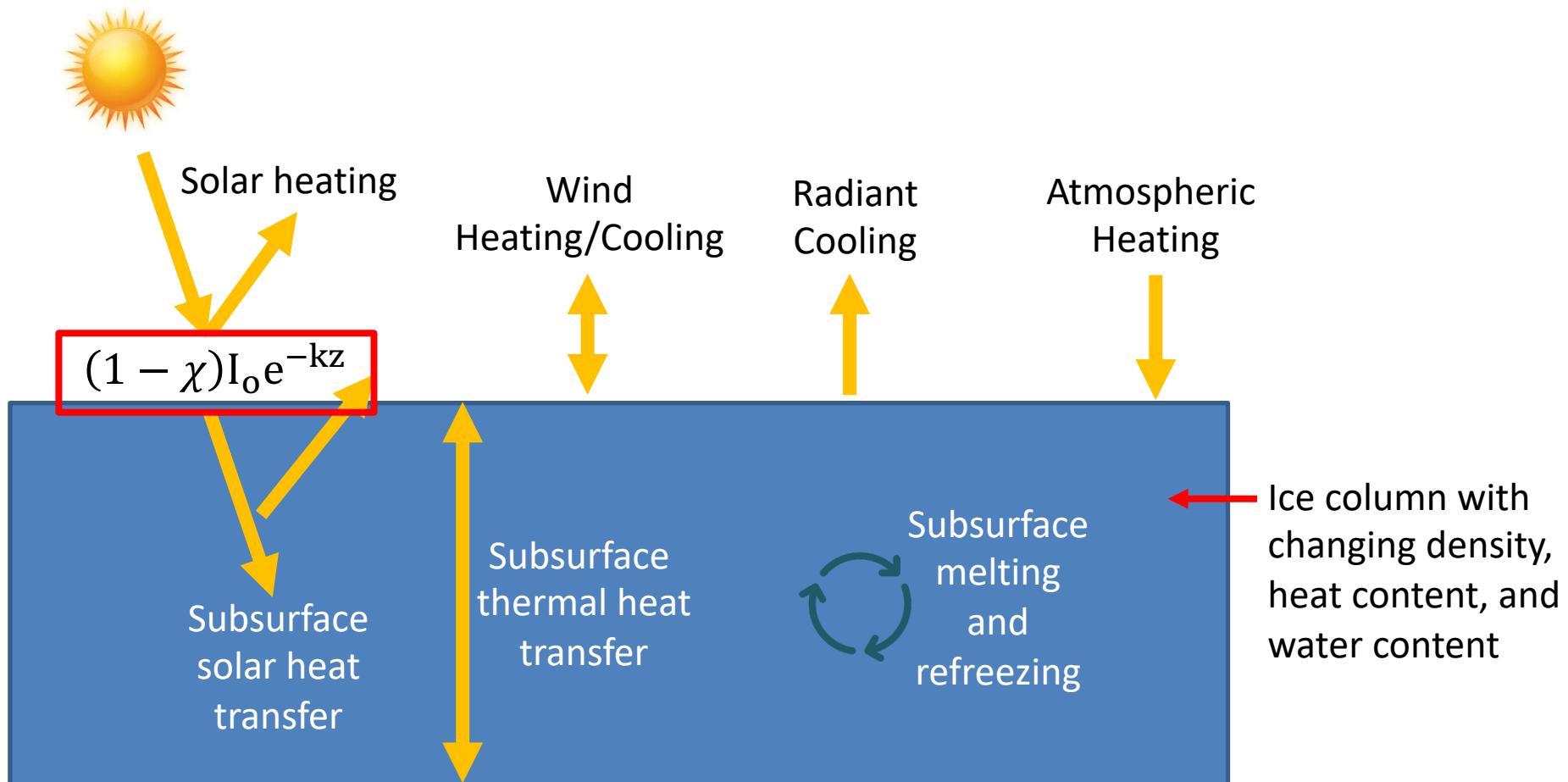
# Emulating climate model predictions of ice sheet meltwater runoff



# Explaining climate model predictions of ice sheet meltwater runoff



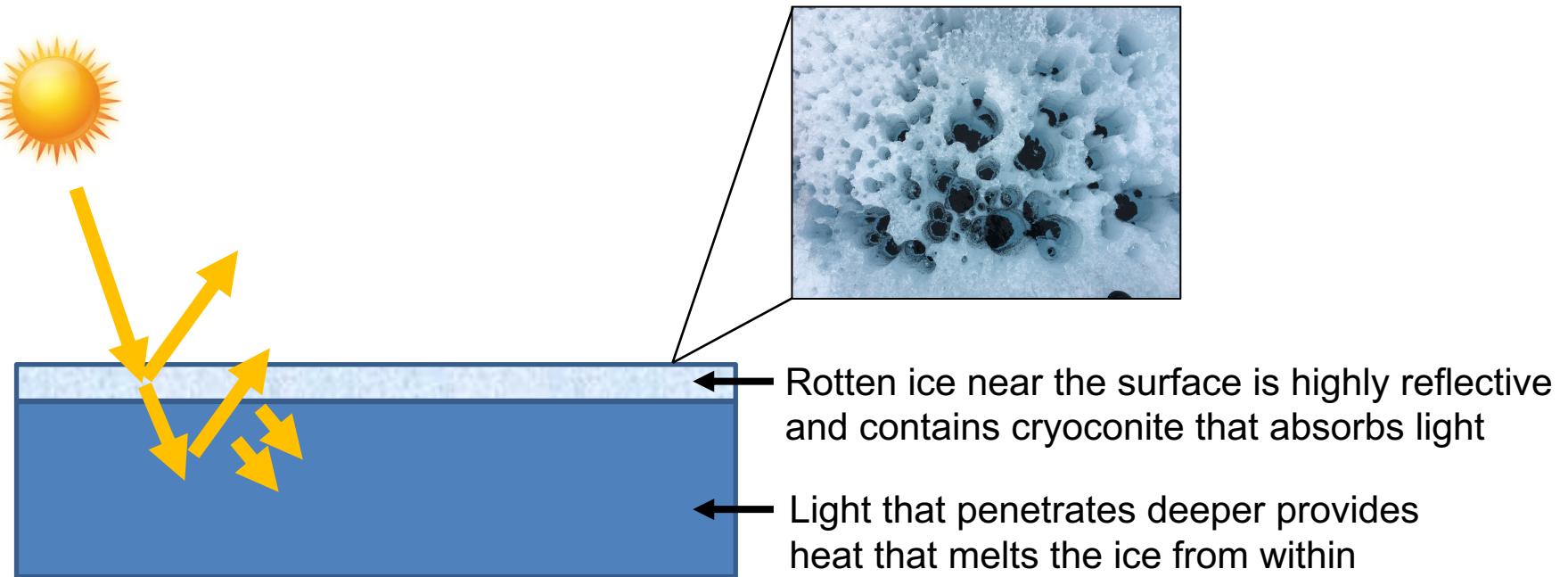
# Ice Model: a numerical model of ice sheet meltwater runoff



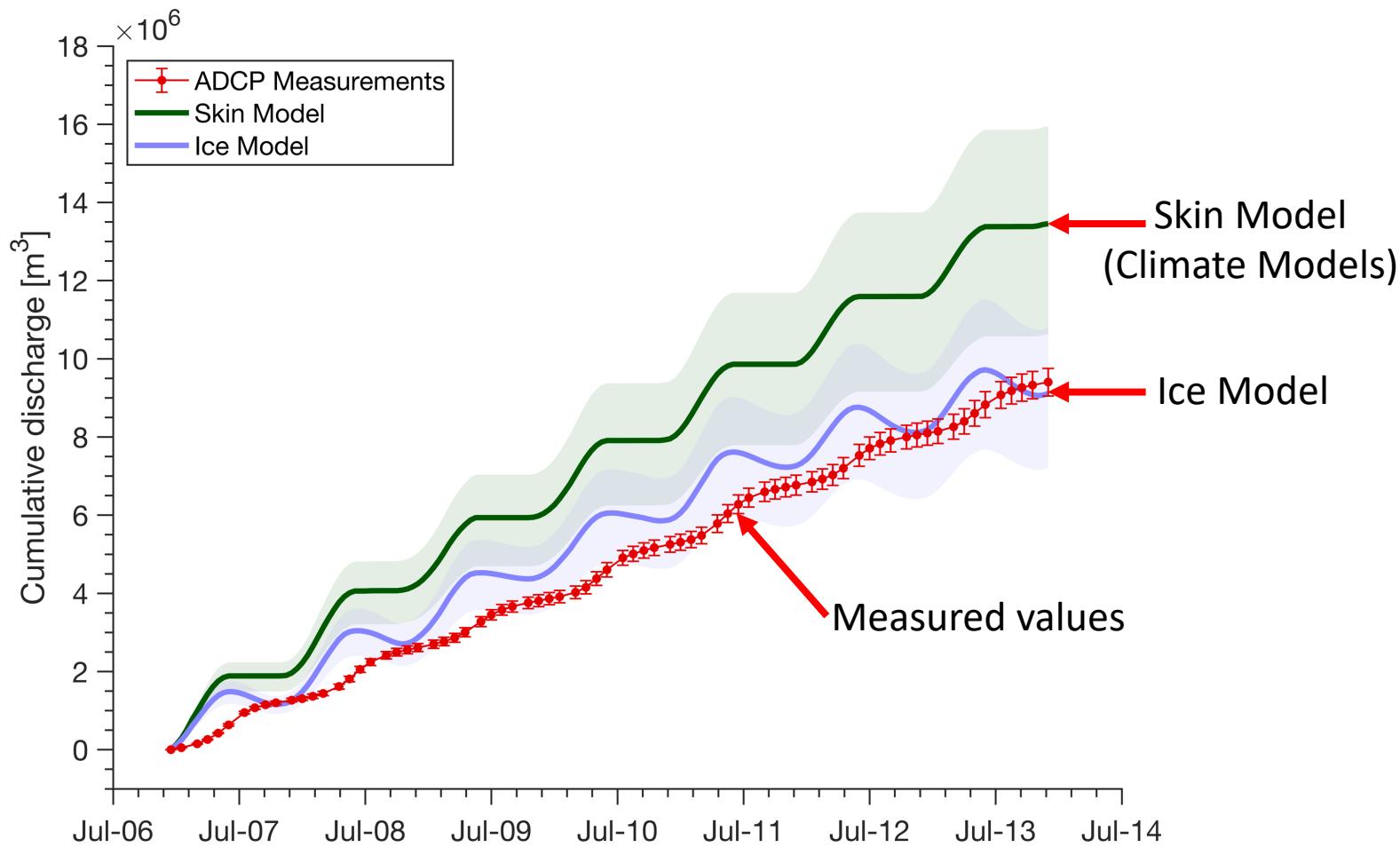
$$C_v \frac{\partial T_i}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z} \left[ (k_i + k_v) \frac{\partial T_i}{\partial z} \right] - \frac{\partial q}{\partial z} - C_v v_i \frac{\partial T_i}{\partial z}$$

- Enthalpy method thermodynamics
- 112-band spectral radiative heat transfer
- Water vapor diffusion
- Adaptive time-stepping, mesh refinement

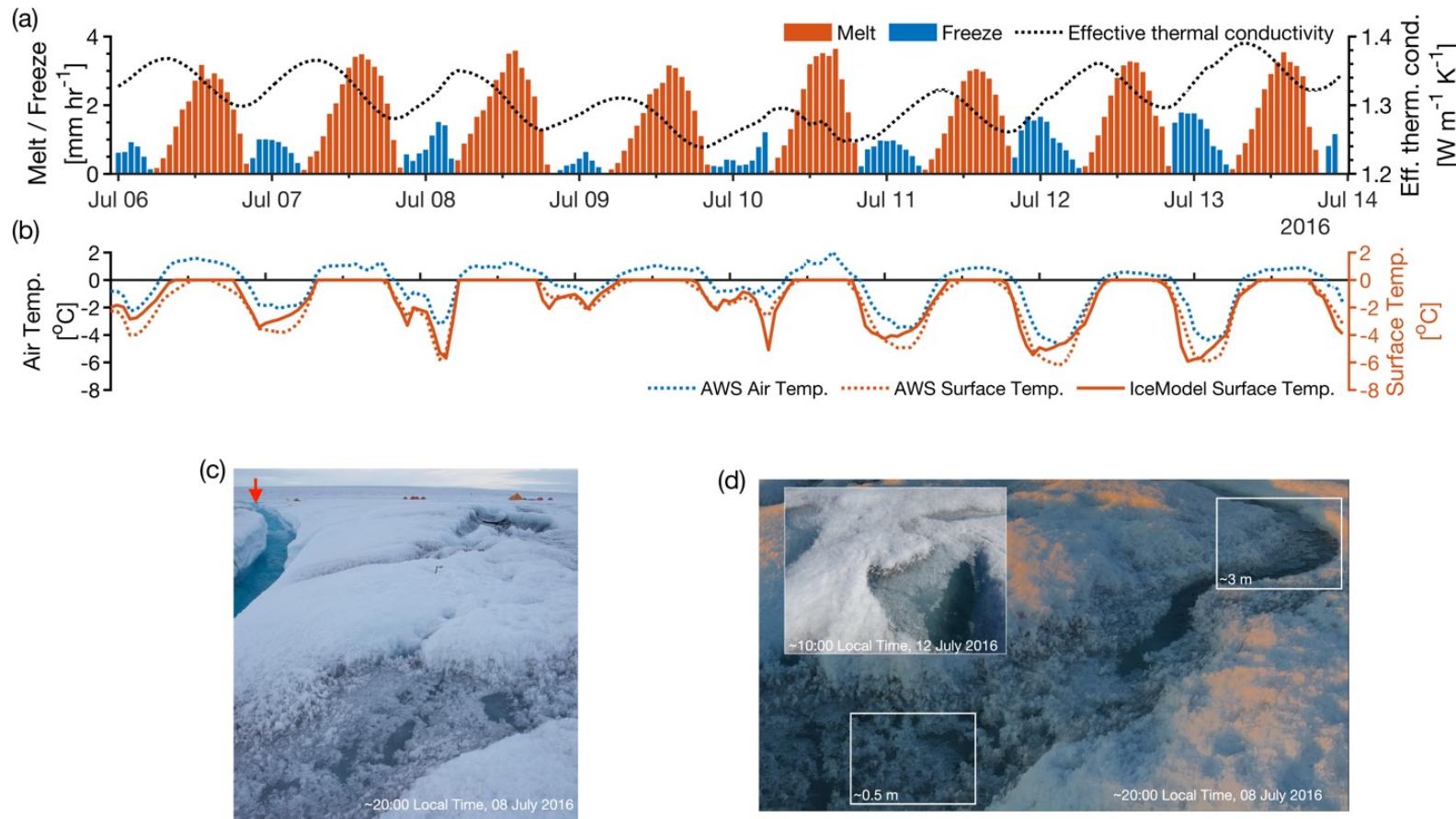
# Developing a model of light transmission into glacier ice



# Explaining climate model predictions of ice sheet meltwater runoff



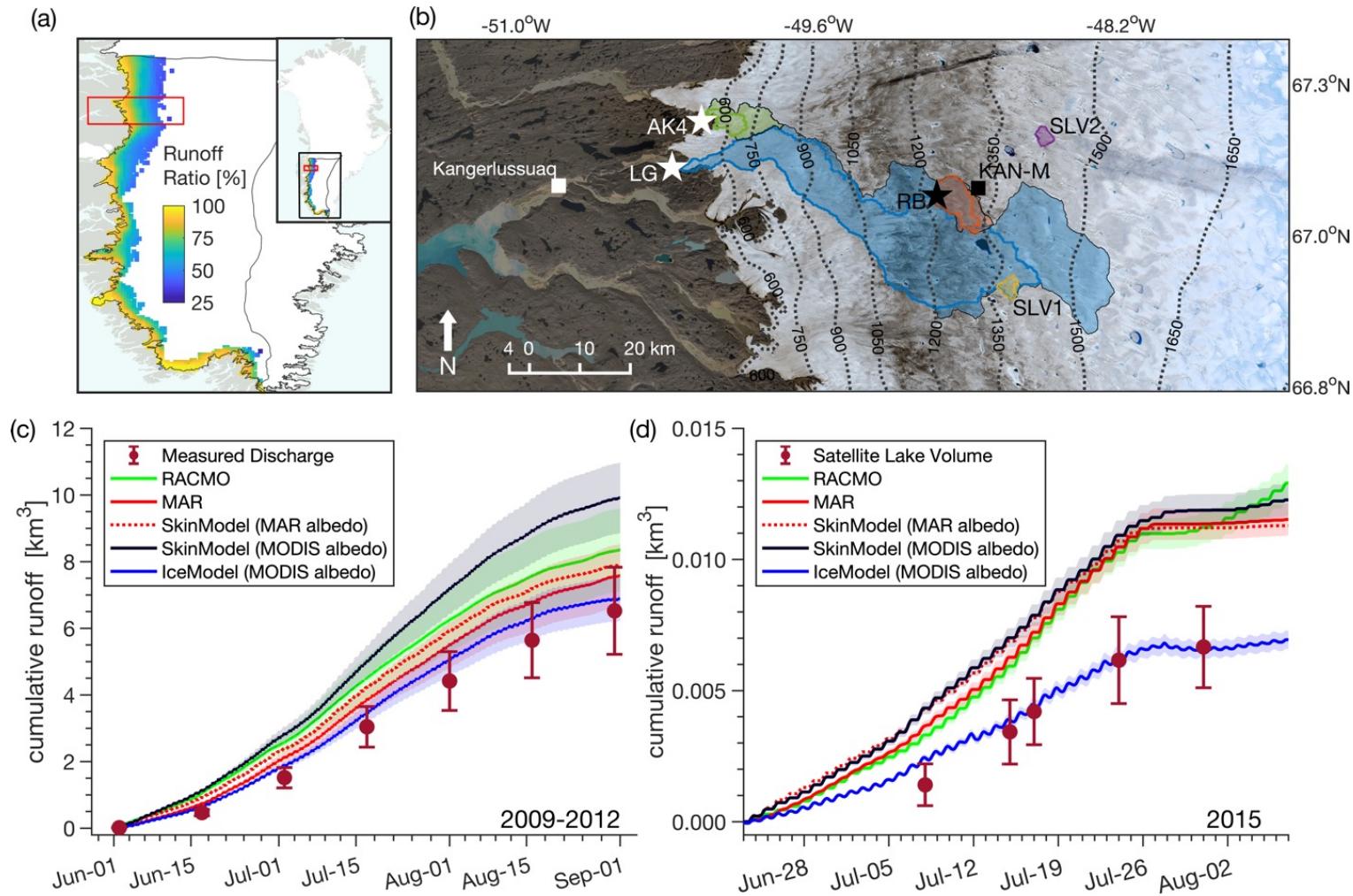
# Meltwater refreezing in bare ice: a buffer on mass loss?



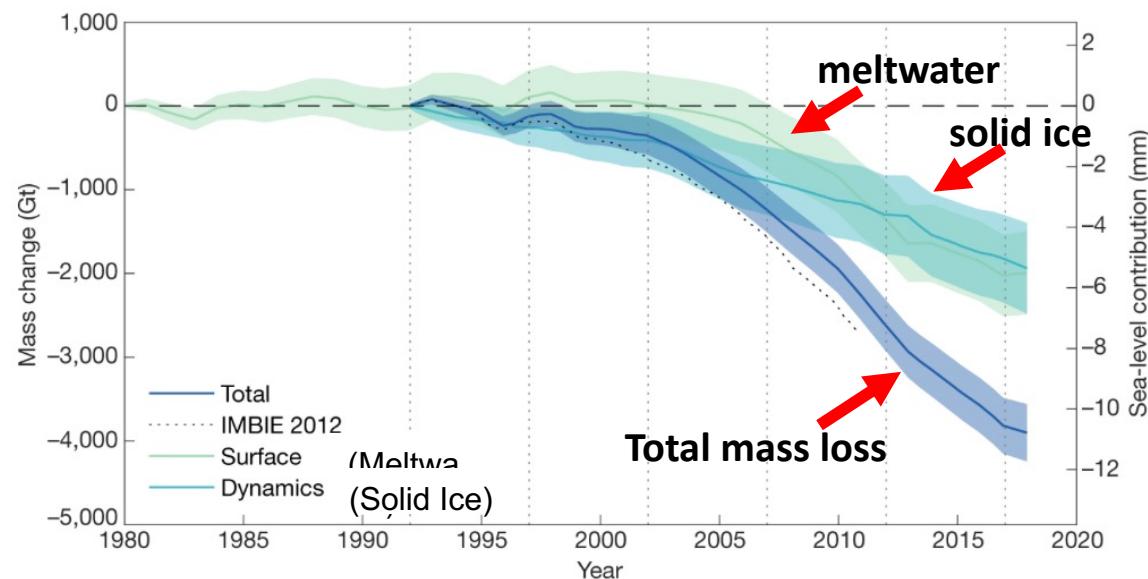
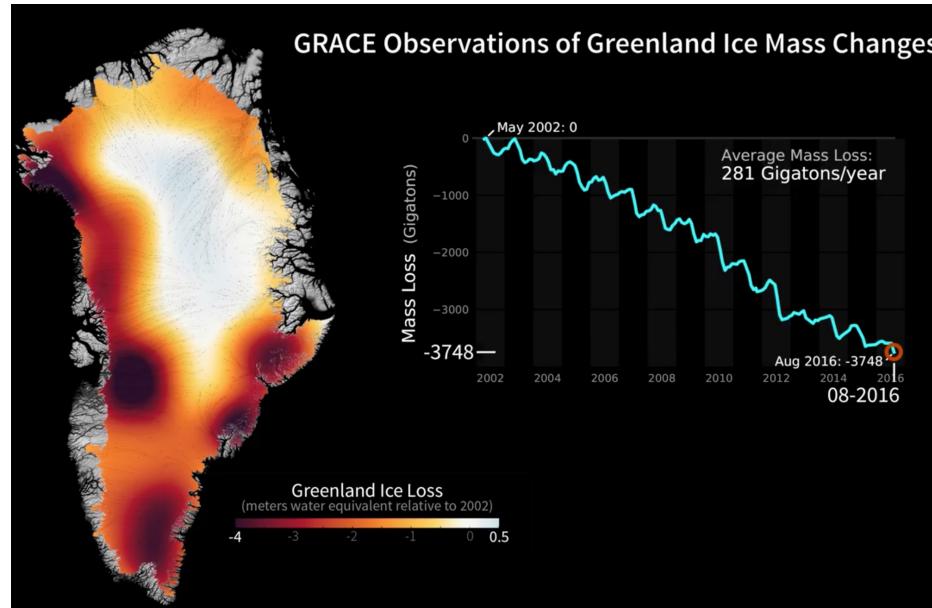
# Refreezing explains climate model overprediction of runoff



# Refreezing explains climate model overprediction of runoff



# We know the ice sheets are losing mass – can models explain why?



**Thank you!**  
**(questions?)**



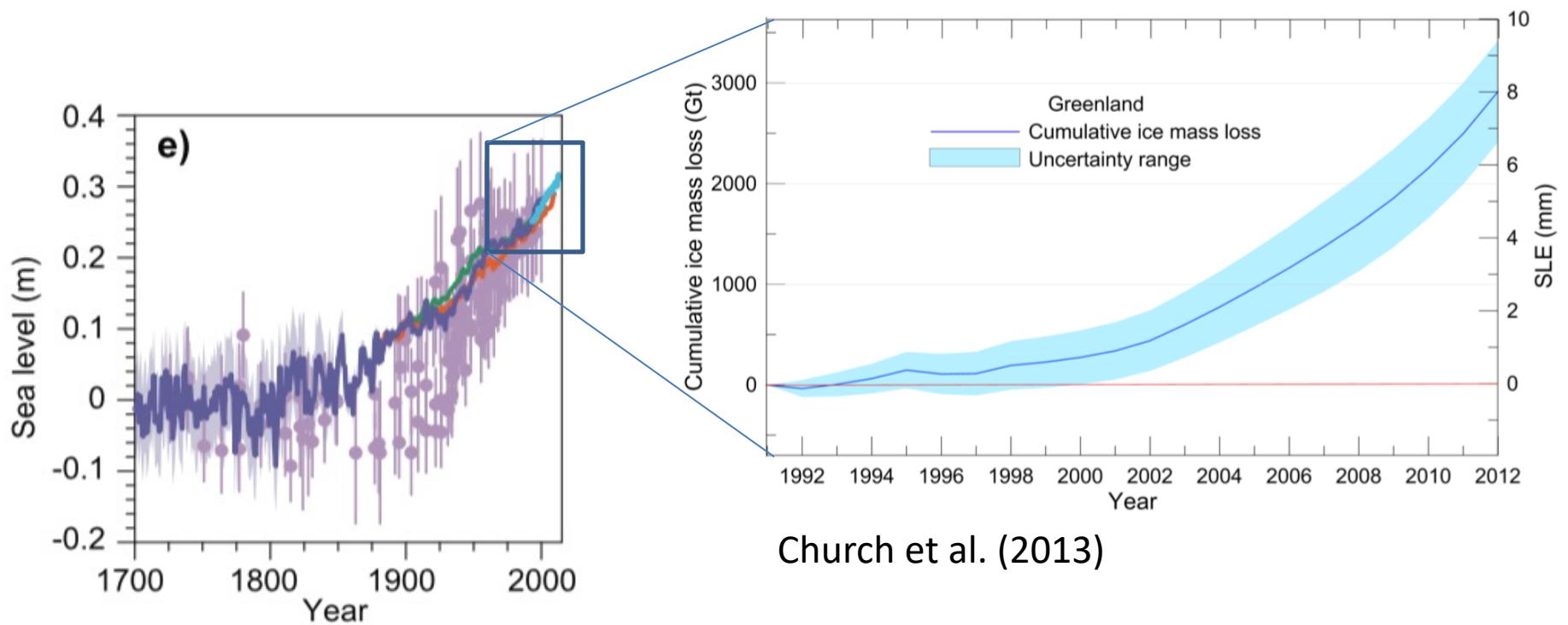
## References

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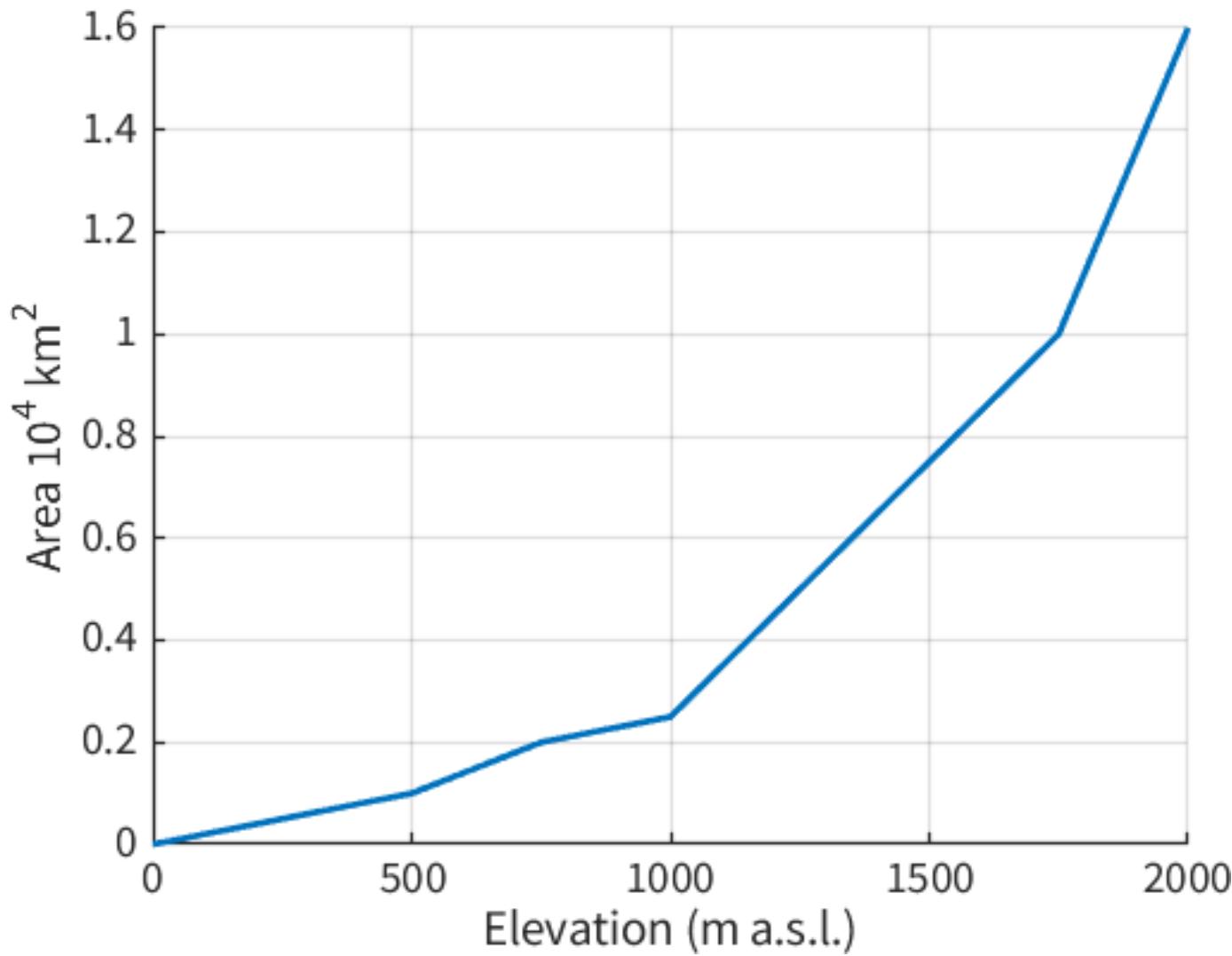




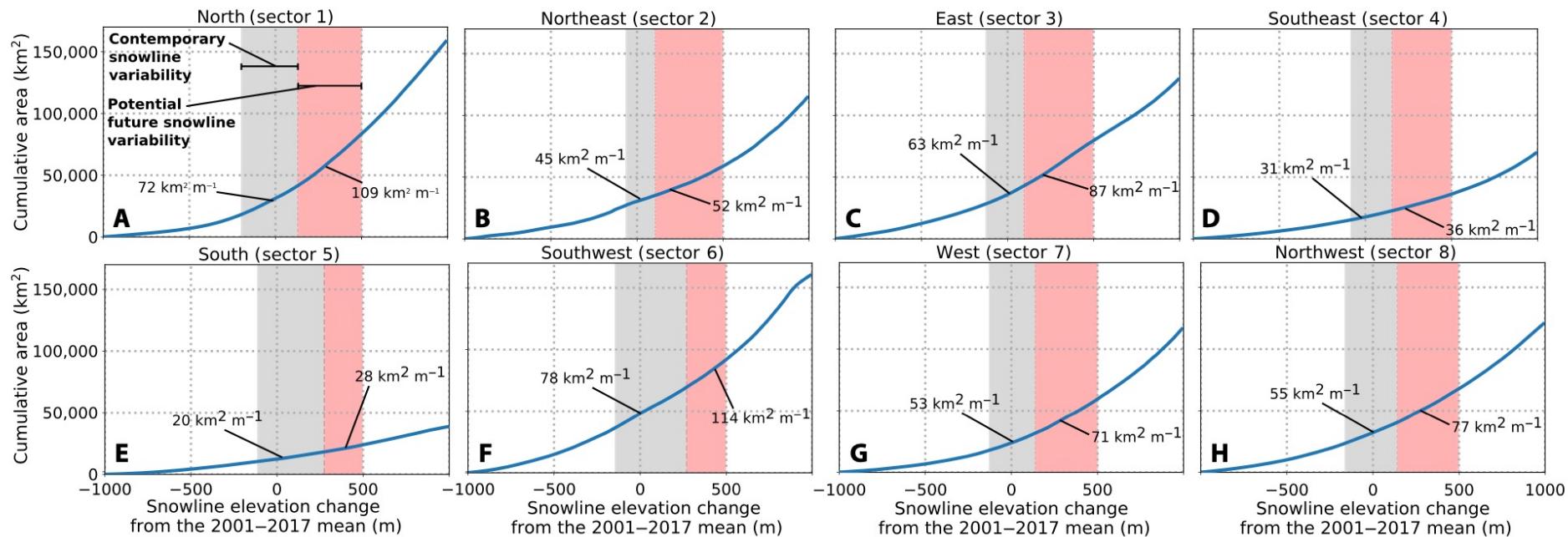




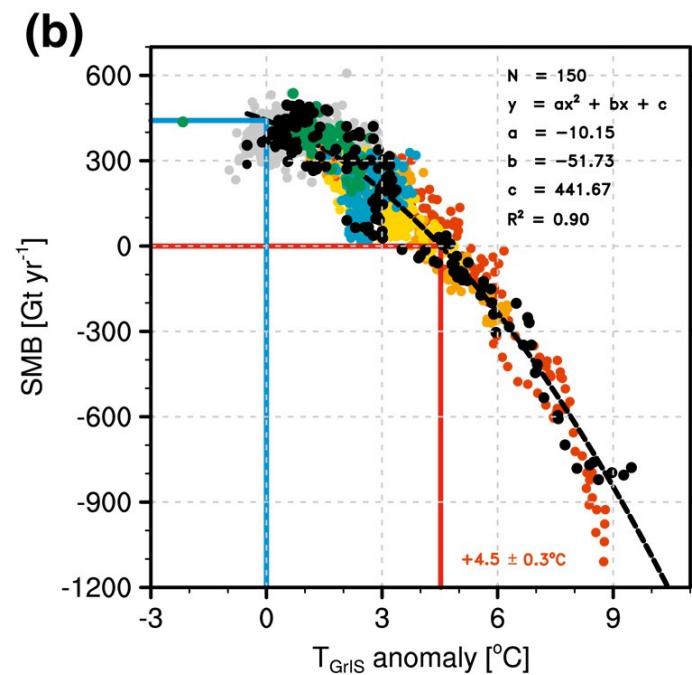
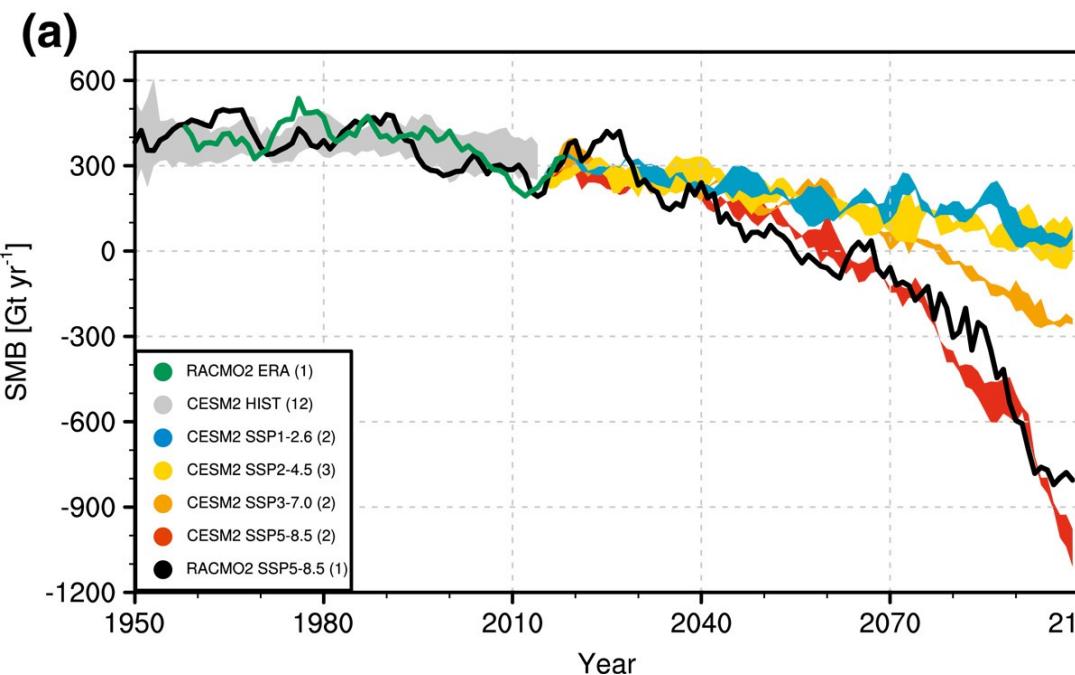
# Ice Sheet Hypsometry



# Is a tipping point ahead?



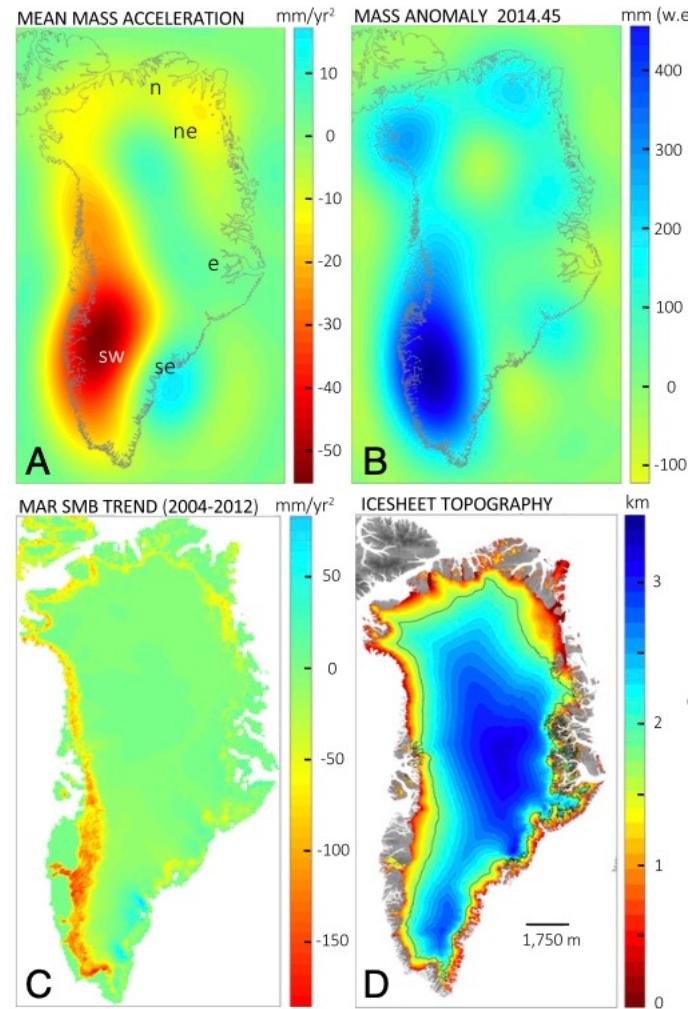
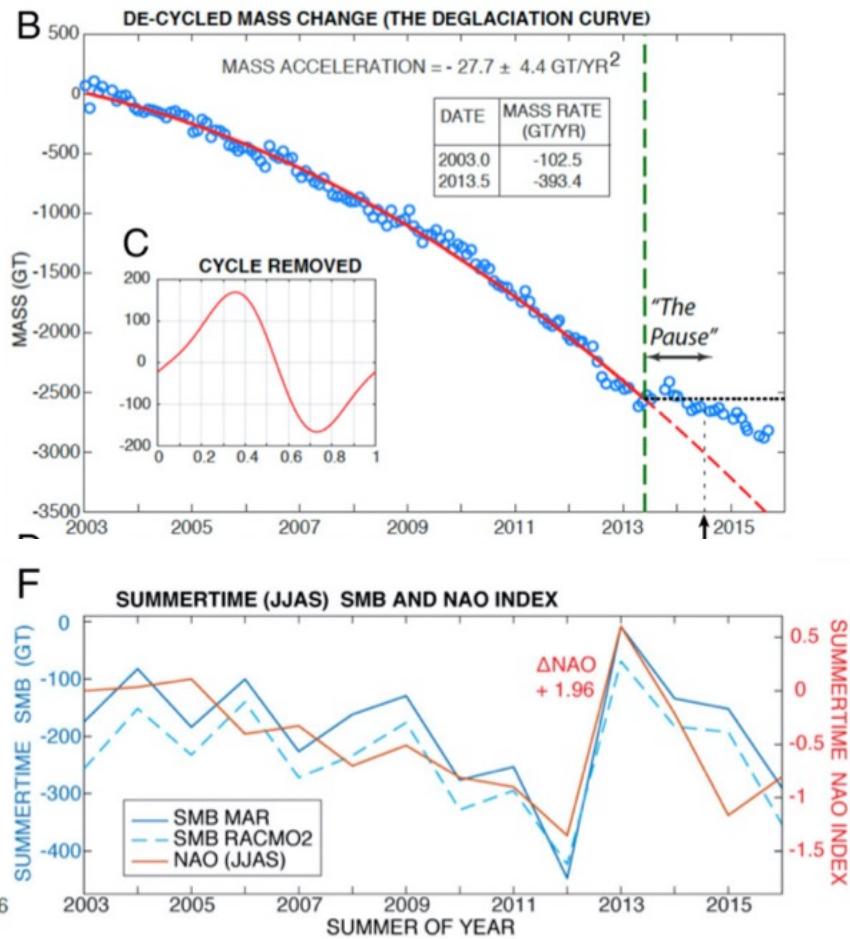
# Irreversible mass loss due to negative SMB



Noel et al. 2021, *GRL*

Tipping point = 4.5°C Greenland atmospheric warming  
(2.7°C global warming)

# Regional atmospheric circulation and surface melt

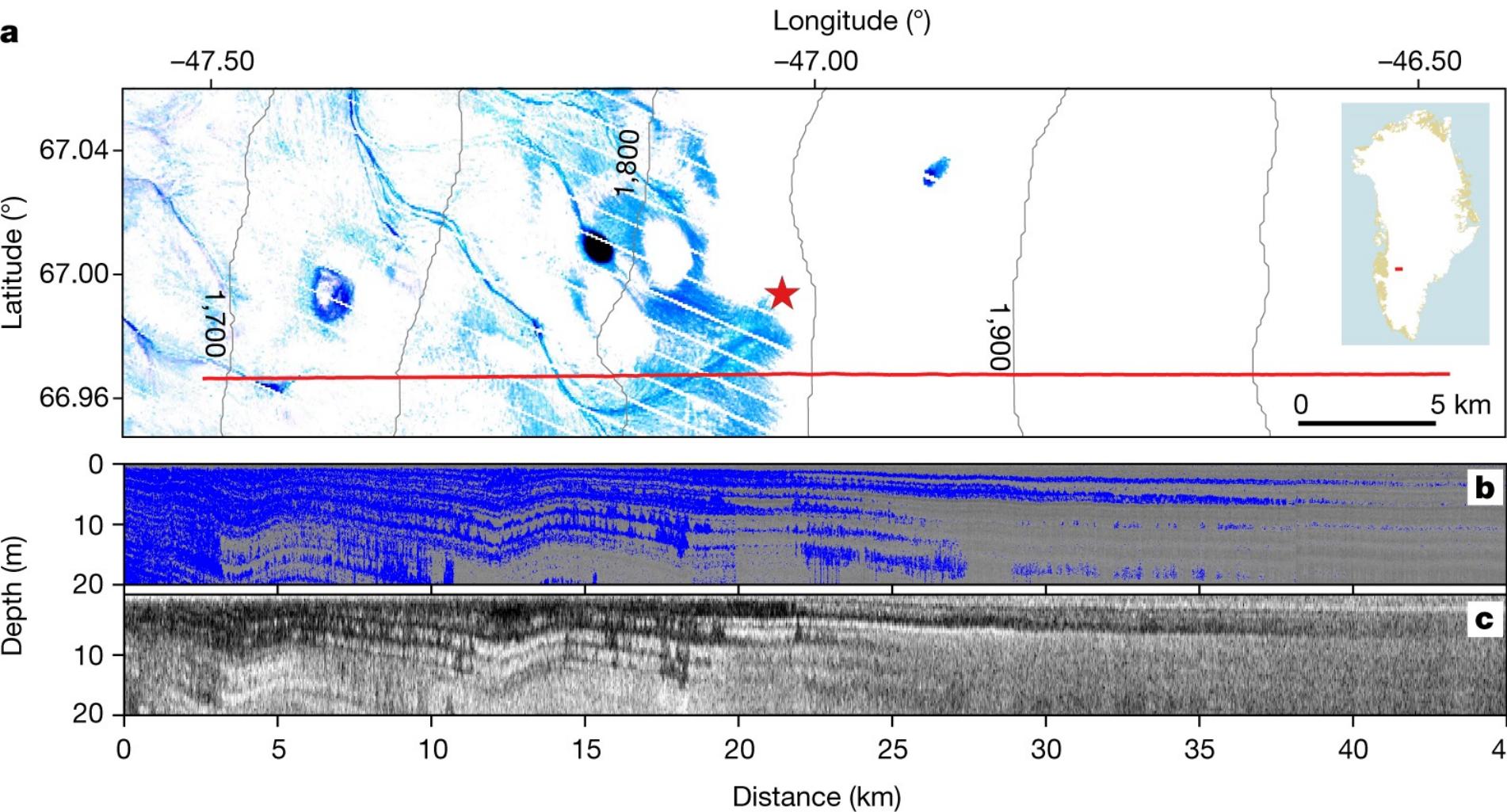


Bevis et al. 2019, PNAS

Theme: High pressure blocking enhancement of surface warming (negative NAO)

# Meltwater runoff over low-permeability ice slabs in southwest Greenland

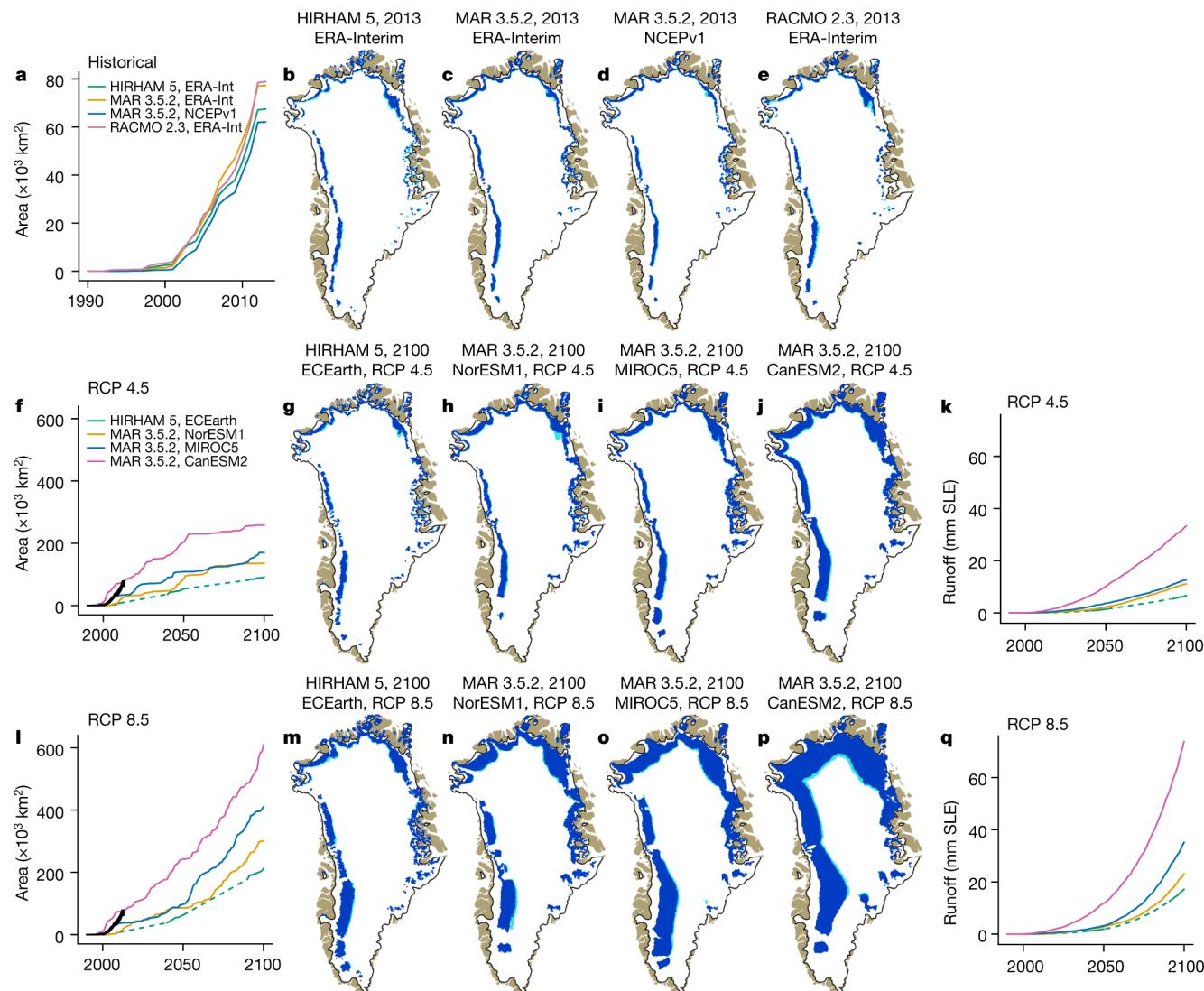
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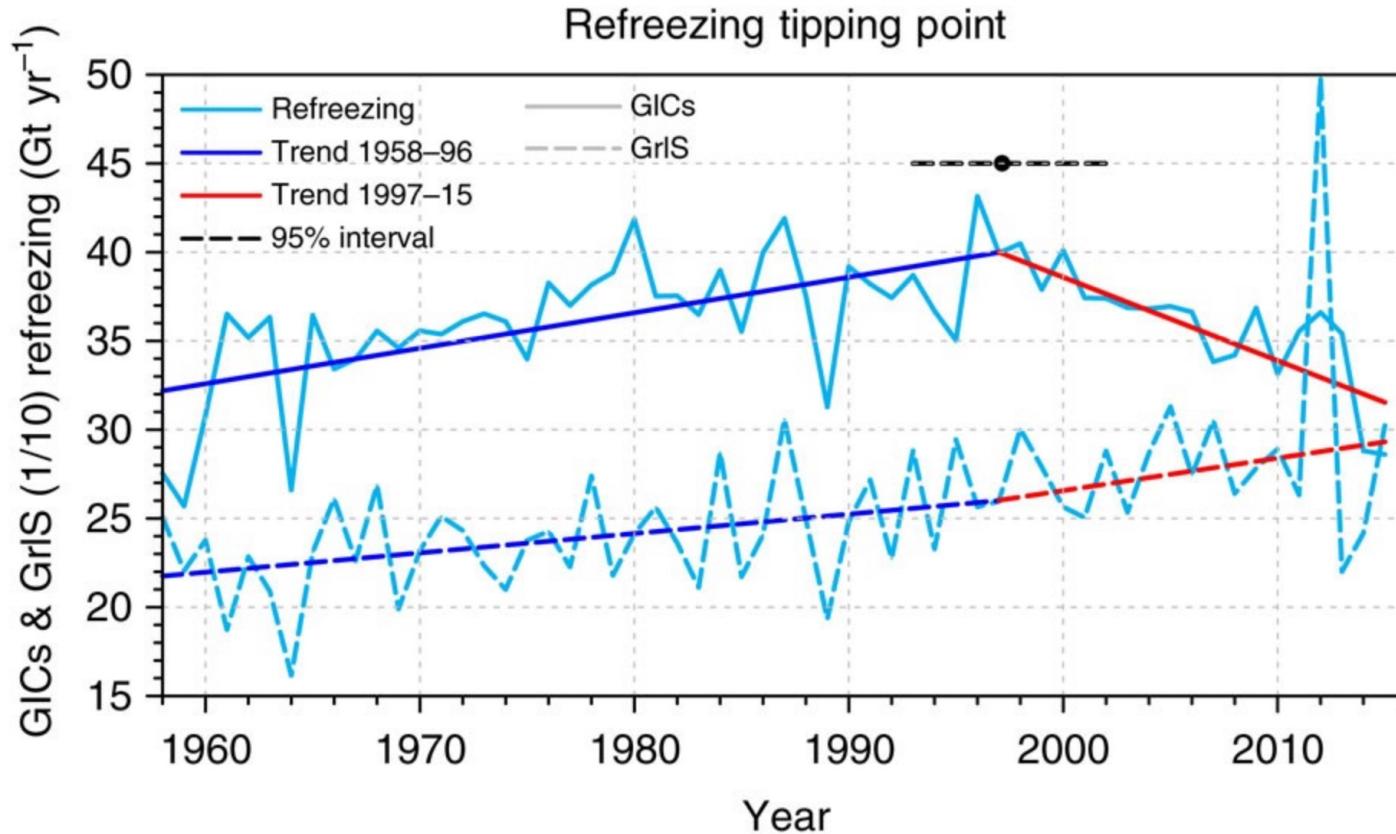
MacFerrin et al. 2019, *Nature*

Theme: Meltwater refreezing in firn

# Meltwater runoff over low-permeability ice slabs in southwest Greenland

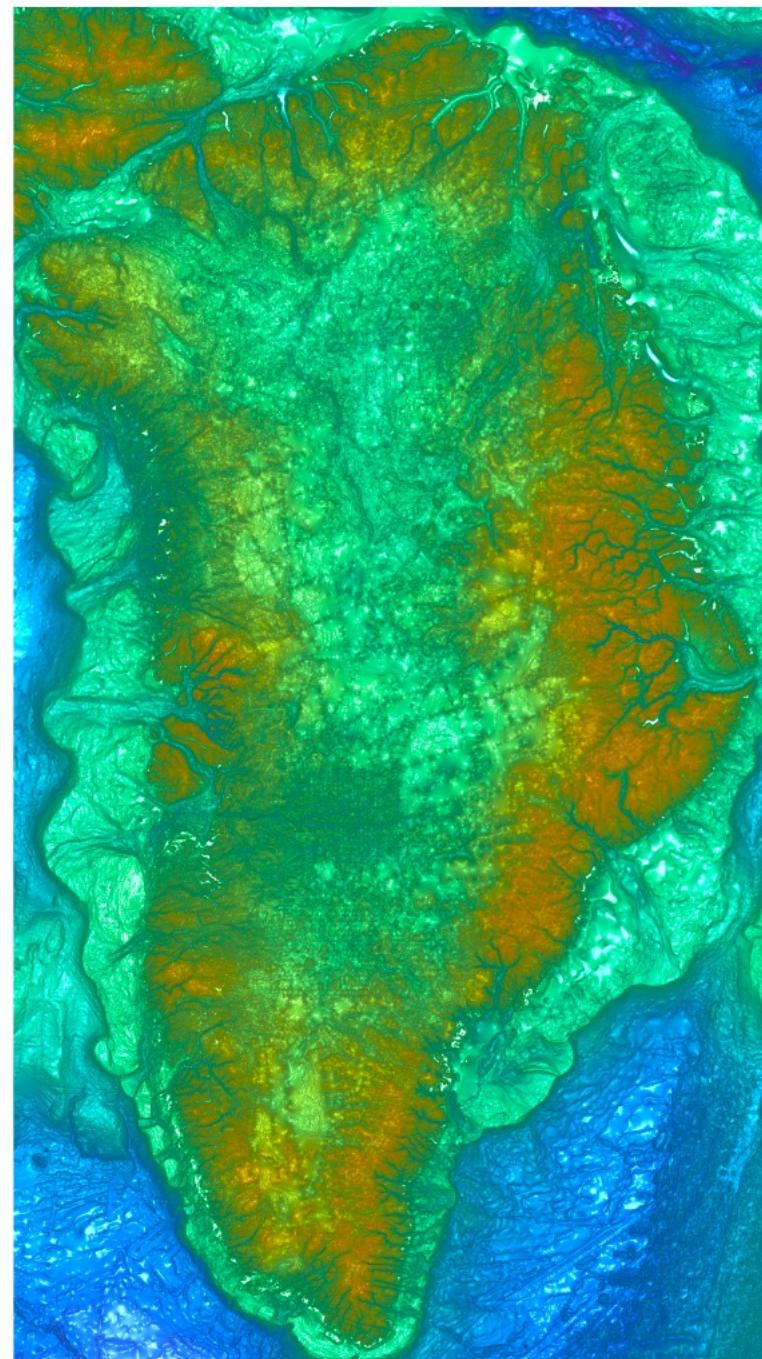
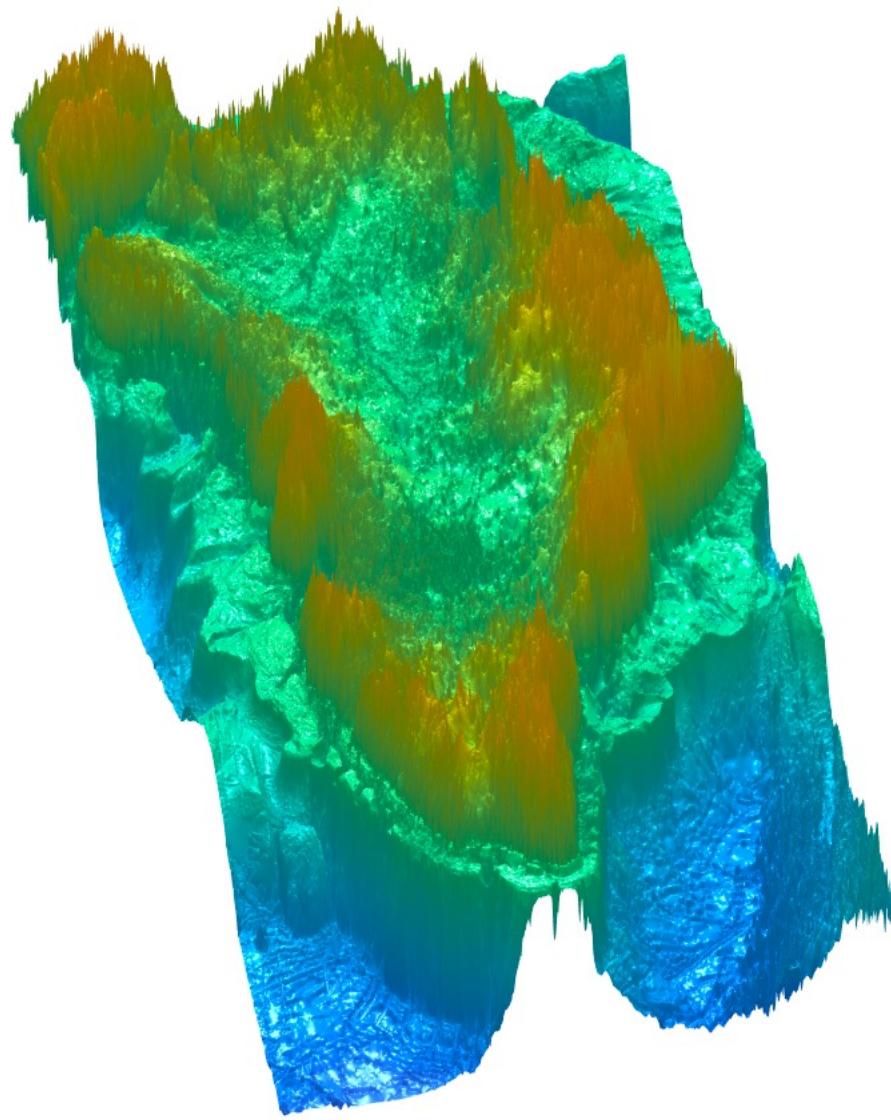


# Is a tipping point ahead?

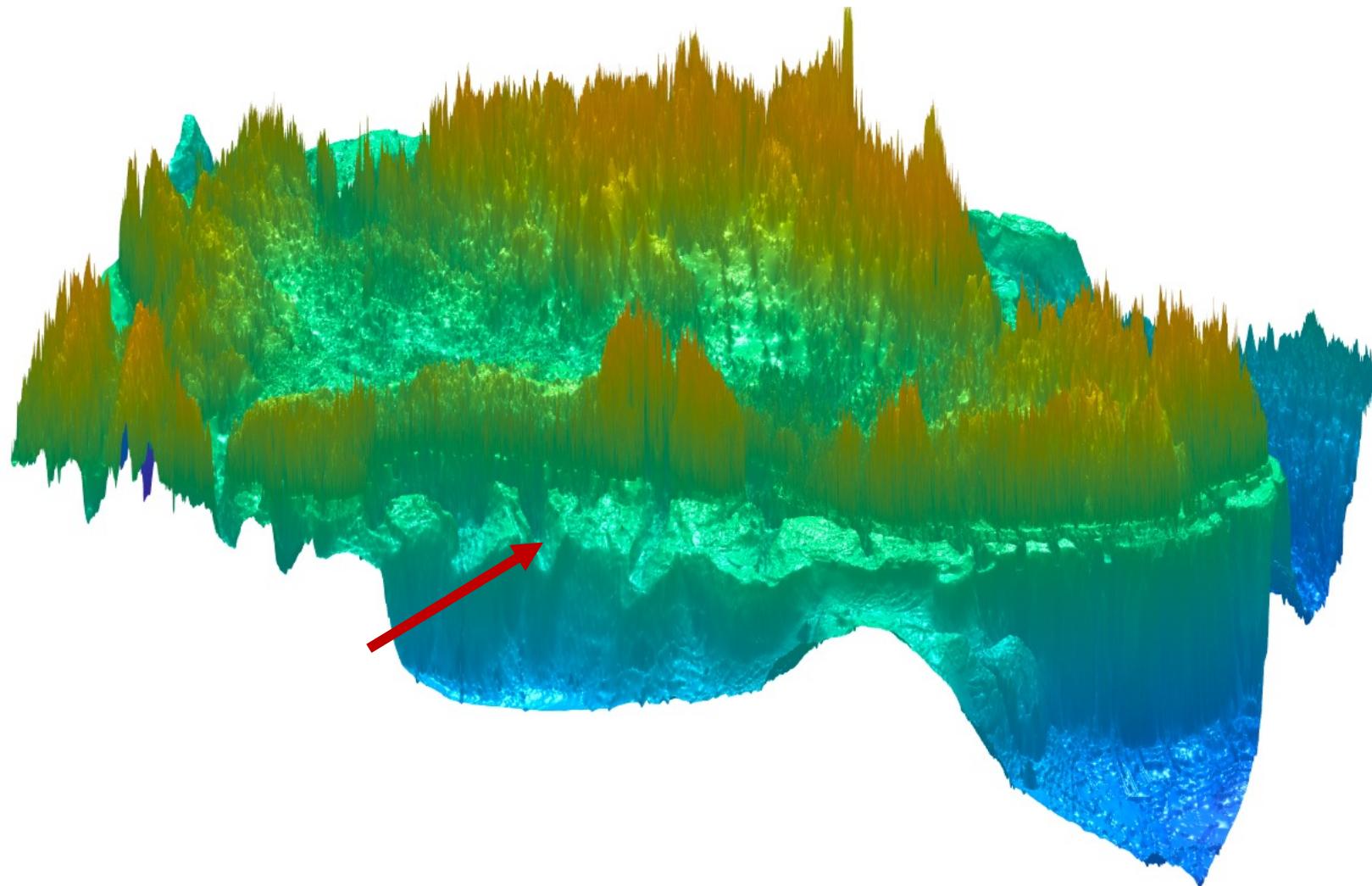


Noel et al. 2019, *Nature Communications*

## “X-Ray vision” of Ice Sheet Bed



# Outlet Glacier Fjord Bathymetry



# Lecture notes available on github

- [\*https://github.com/mgcooper/GCEE6320-Spring-2023-slides.git\*](https://github.com/mgcooper/GCEE6320-Spring-2023-slides.git)

