Causes of recent Greenland Ice Sheet mass loss

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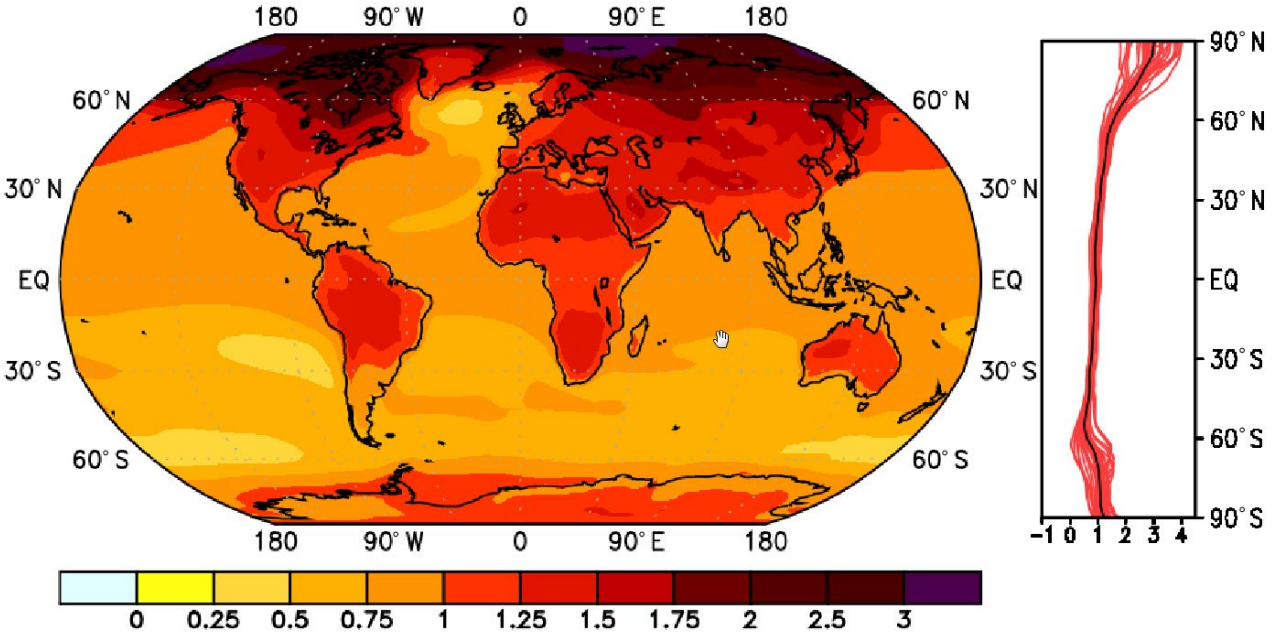
Why do polar regions play a significant role in global climate?

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

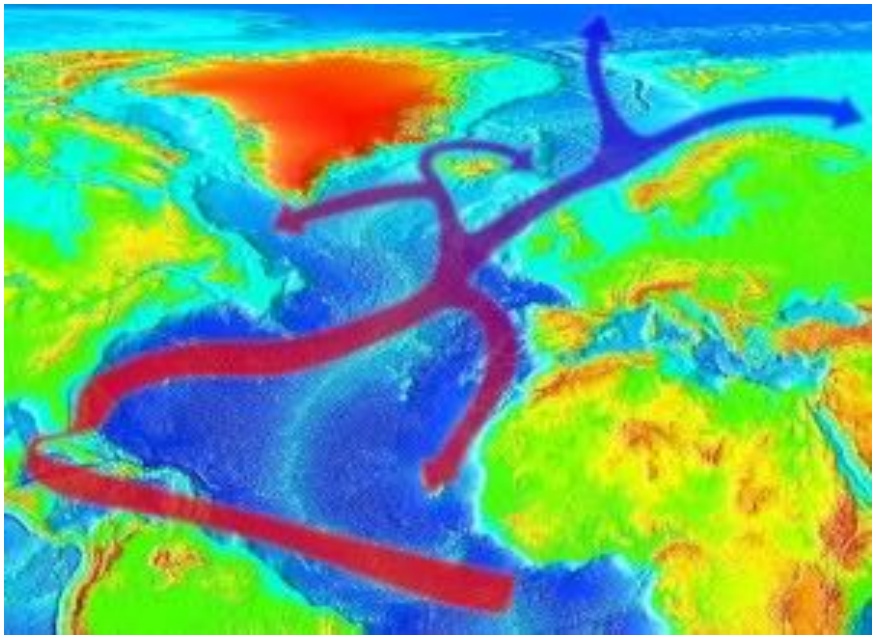
Polar amplification

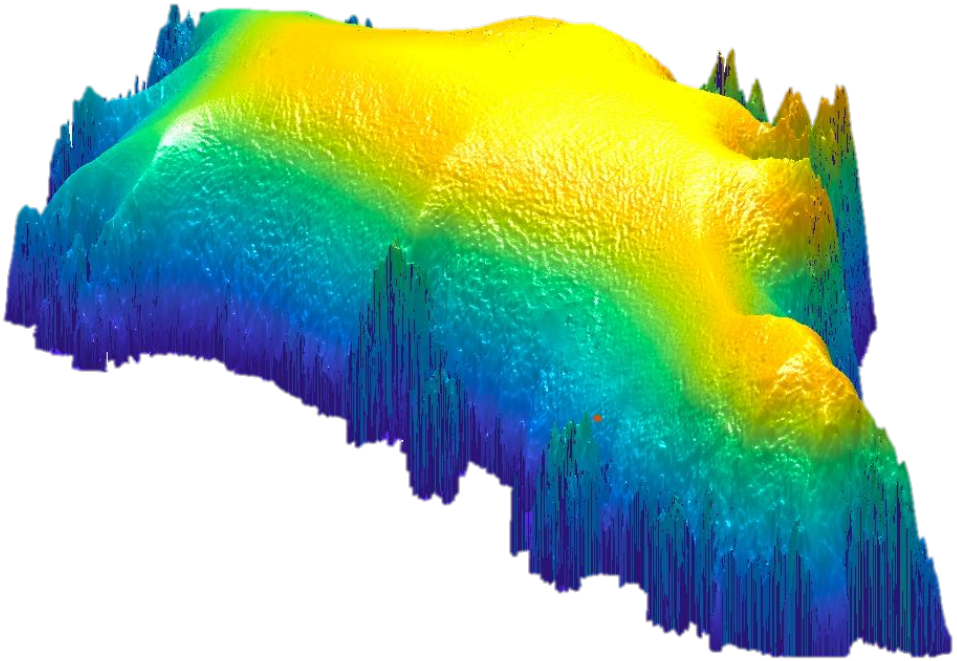
- High-latitude regions warm faster than the global average
  - Arctic: 2.5 °C
  - Antarctic: 1.5 °C
  - Global: 1.1 °C
- Factors: *Ice-albedo feedback, permafrost-carbon feedback,* **changes in atmospheric and oceanic circulation**



Freshwater Inputs from Land and Ice Sheets

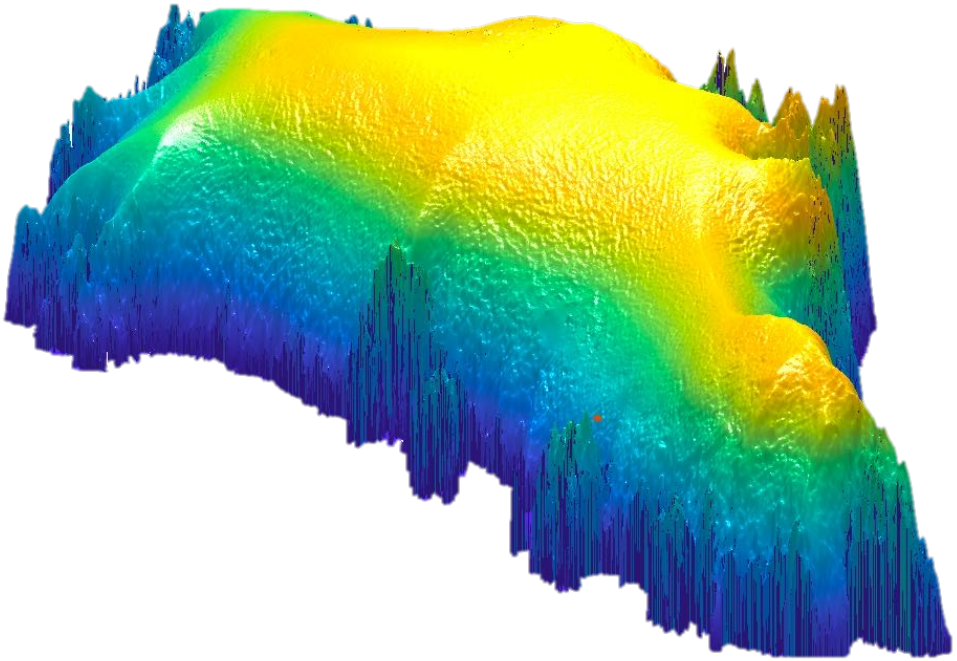
- Freshwater inputs from melting ice sheets and land runoff impact ocean salinity, circulation, and temperature.
- These changes can have far-reaching effects on global climate, marine ecosystems, and sea levels.





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)

- 2nd 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)


Nigeria
Abuja
Kano
Djibouti
Ethiopia
South Sudan
Central African Republic
Cameroon
Port Harcourt
Yaounde
Douala
Bangui
Juba
Equatorial Guinea
São Tomé and Príncipe
Libreville
Gabon
Republic of the Congo
Democratic Republic of the Congo
Uganda
Kampala
Kenya
Nakuru
Nairobi
Rwanda
Burundi
Arusha
Mombasa
Kinshasa
Tanzania
Dar es Salaam
Luanda
Angola
Zambia
Malawi
Lusaka
Harare
Mozambique
Zimbabwe


KEPULAUAN MELAYU
Timor Sea
Darwin
Port Moresby
Solomon Sea
NORTHERN TERRITORY
Townsville
Mackay
Coral Sea
QUEENSLAND
Alice Springs
Australia
WESTERN AUSTRALIA
SOUTH AUSTRALIA
Brisbane
Gold Coast
NEW SOUTH WALES
Newcastle
Sydney
Canberra
Adelaide
Great Australian Bight
VICTORIA
Melbourne
TASMANIA
Hobart
Perth
Bunbury


QUEBEC
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
OREGON
IDAHO
SOUTH DAKOTA
WISCONSIN
MICHIGAN
WYOMING
NEBRASKA
IOWA
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ILLINOIS
INDIANA
OHIO
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NEVADA
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KANSAS
MISSOURI
United States
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Las Vegas
Los Angeles
San Diego
ARIZONA
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LOUISIANA
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Mexico
Mexico City
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Dominican Republic
Puerto Rico
Guatemala
Honduras
Caribbean Sea


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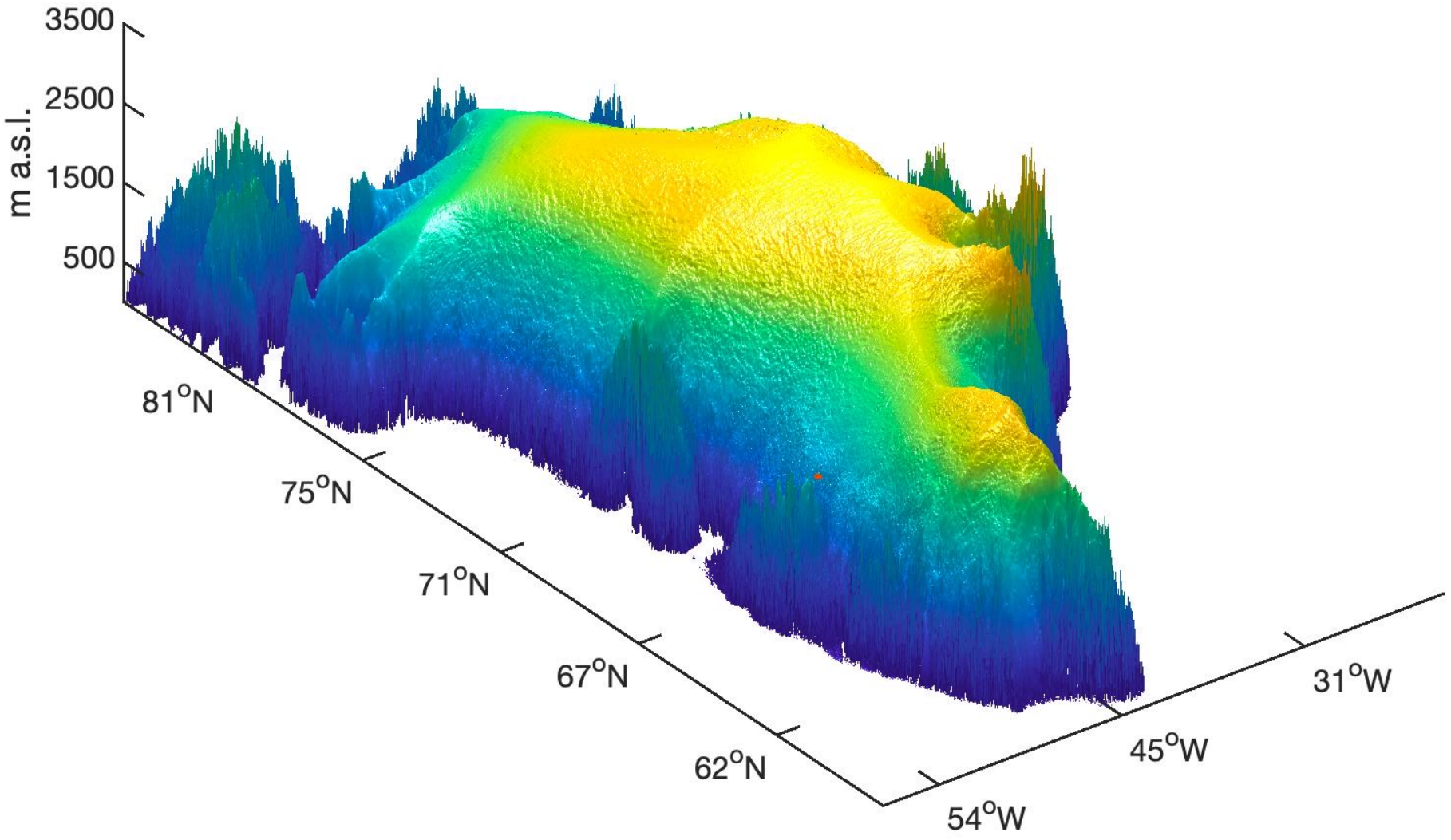
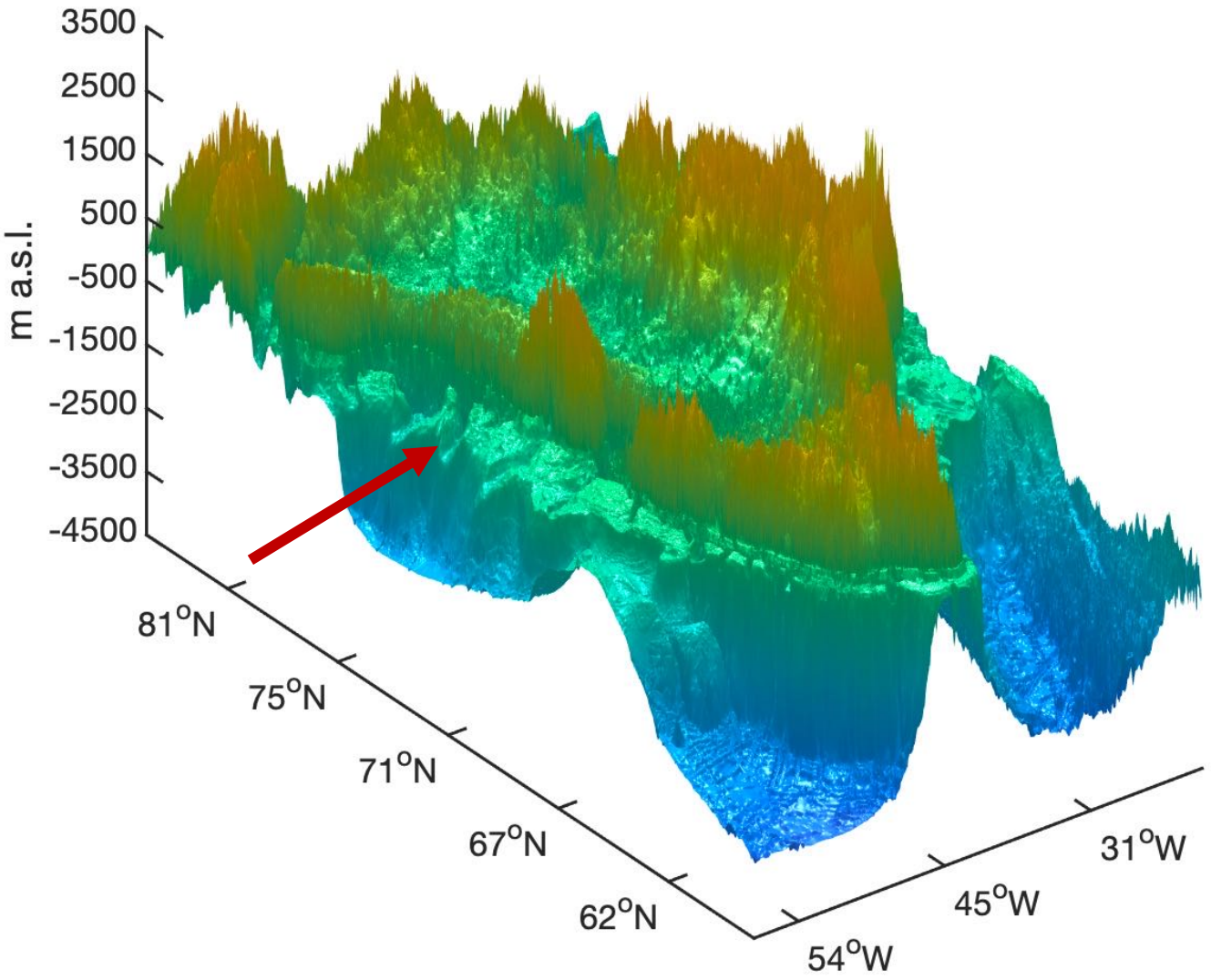
HIMACHAL PRADESH
Lahore
Chandigarh
TIBET
Pakistan
PUNJAB
UTTARAKHAND
HARYANA
New Delhi
UTTAR PRADESH
Nepal
Kathmandu
SIKKIM
Bhutan
Jaipur
RAJASTHAN
Lucknow
Karachi
BIHAR
ASSAM
MEGHALAYA
Bangladesh
India
MADHYA PRADESH
JHARKHAND
GUJARAT
Ahmedabad
WEST BENGAL
TRIPURA
MIZORAM
Surat
CHHATTISGARH
Chhindwara
ODISHA
MAHARASHTRA
Mumbai
TELANGANA
Hyderabad
GOA
KARNATAKA
ANDHRA PRADESH
Bengaluru
Chennai
Bay of Bengal
Mysuru
TAMIL NADU
Kochi
KERALA
Sri Lanka
Colombo

Ice Sheet Surface Topography

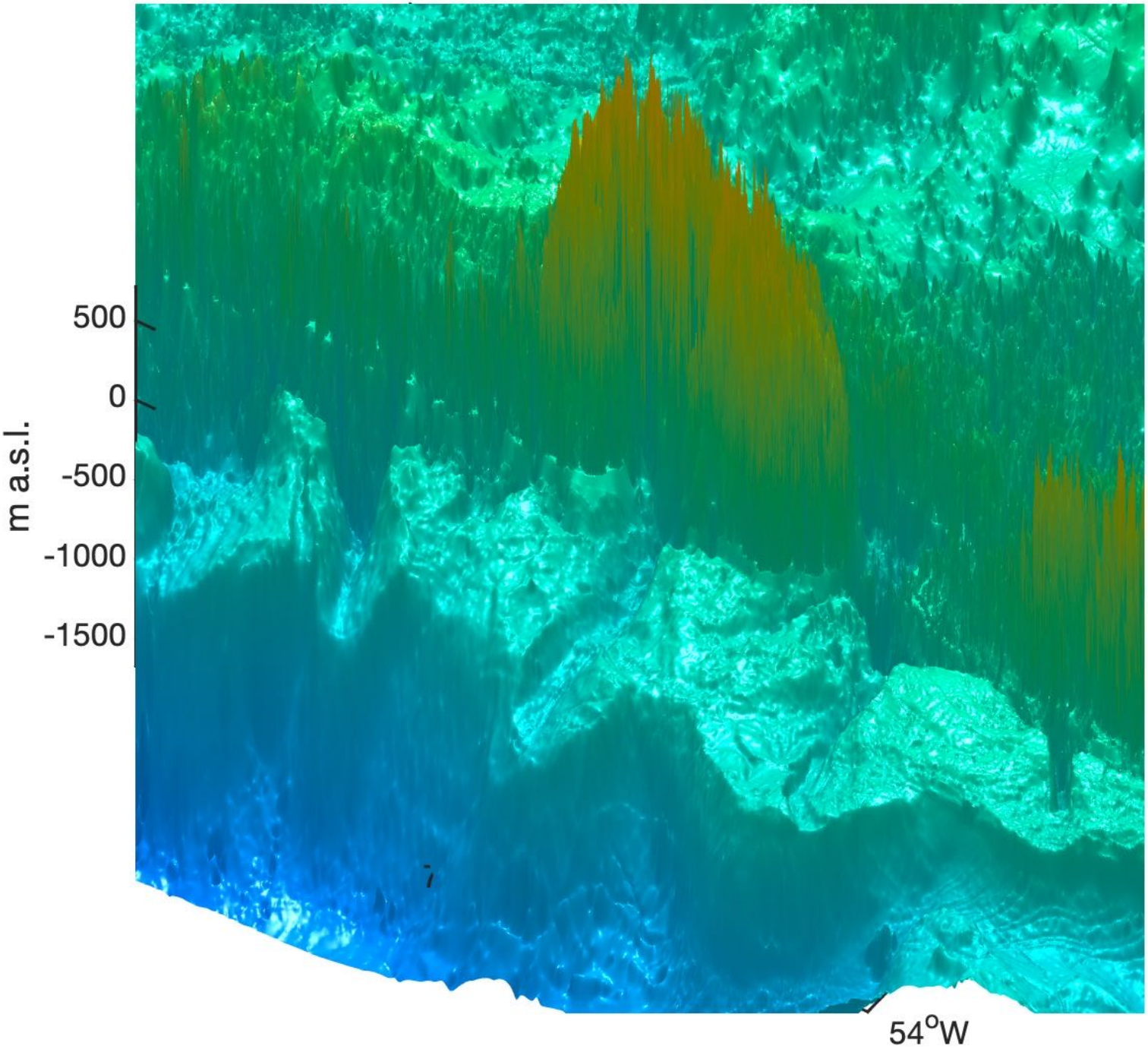


BedMachine v3: Morlighem et al. 2017

“X-Ray vision” Ice Sheet Bed Topography



BedMachine v3: Morlighem et al. 2017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-500
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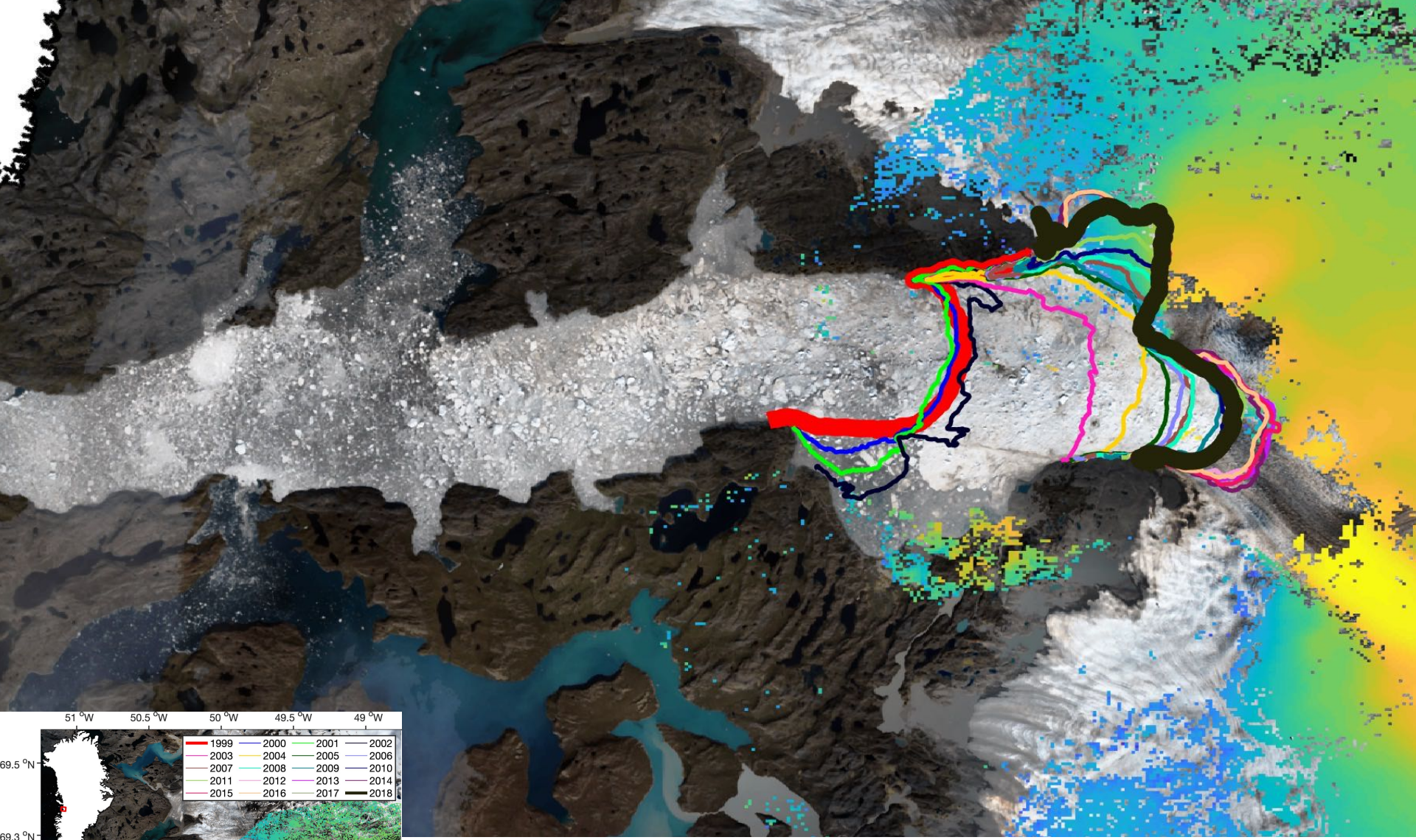
-1500
m a.s.l.
54°W


51 °W
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49 °W
69.5 °N
69.3 °N
69.1 °N
69 °N
1999 2000 2001 2002
2003 2004 2005 2006
2007 2008 2009 2010
2011 2012 2013 2014
2015 2016 2017 2018
20 km
1
10
100
1000
10000
Annual average ice surface velocity [m yr-1]

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?**

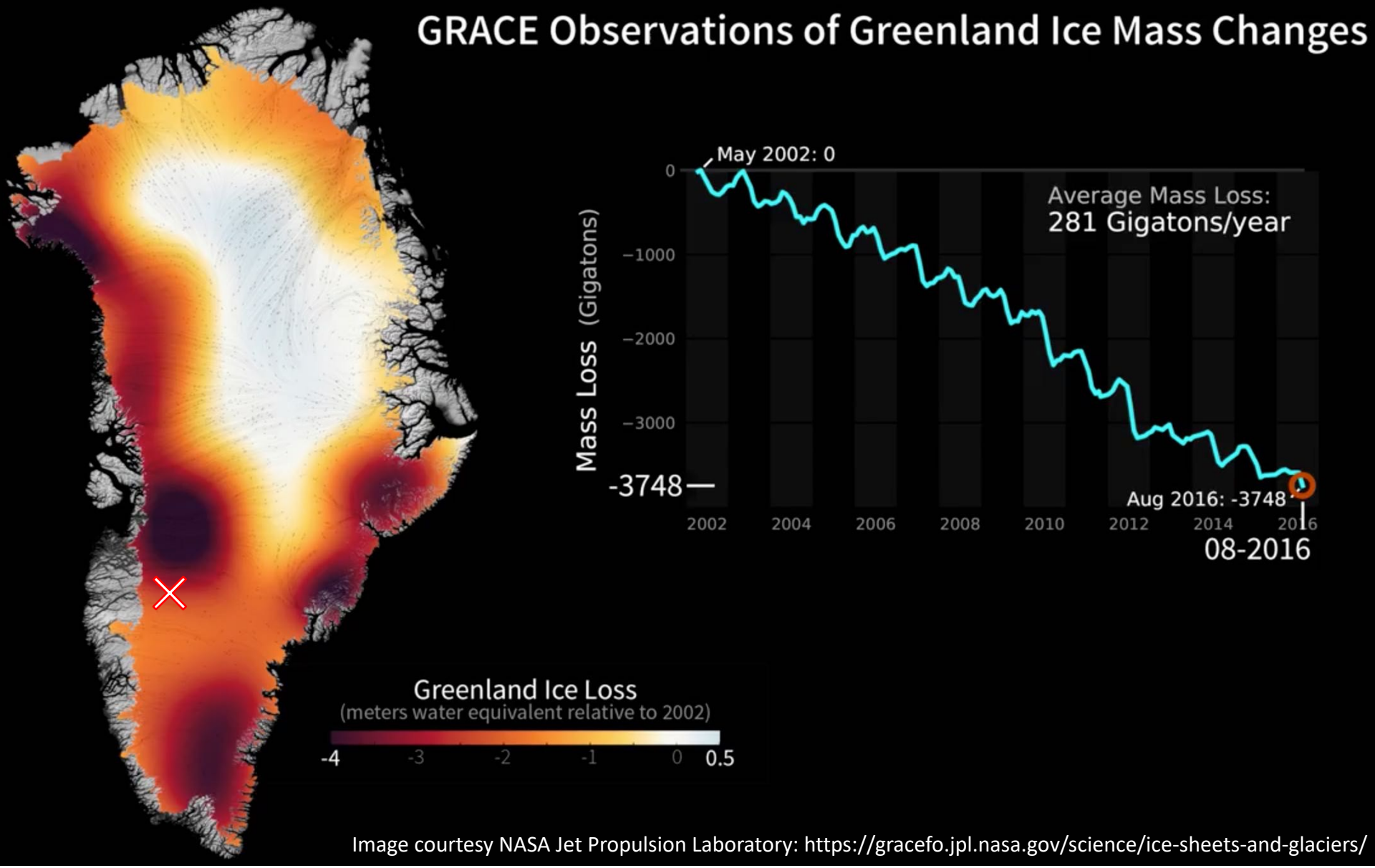
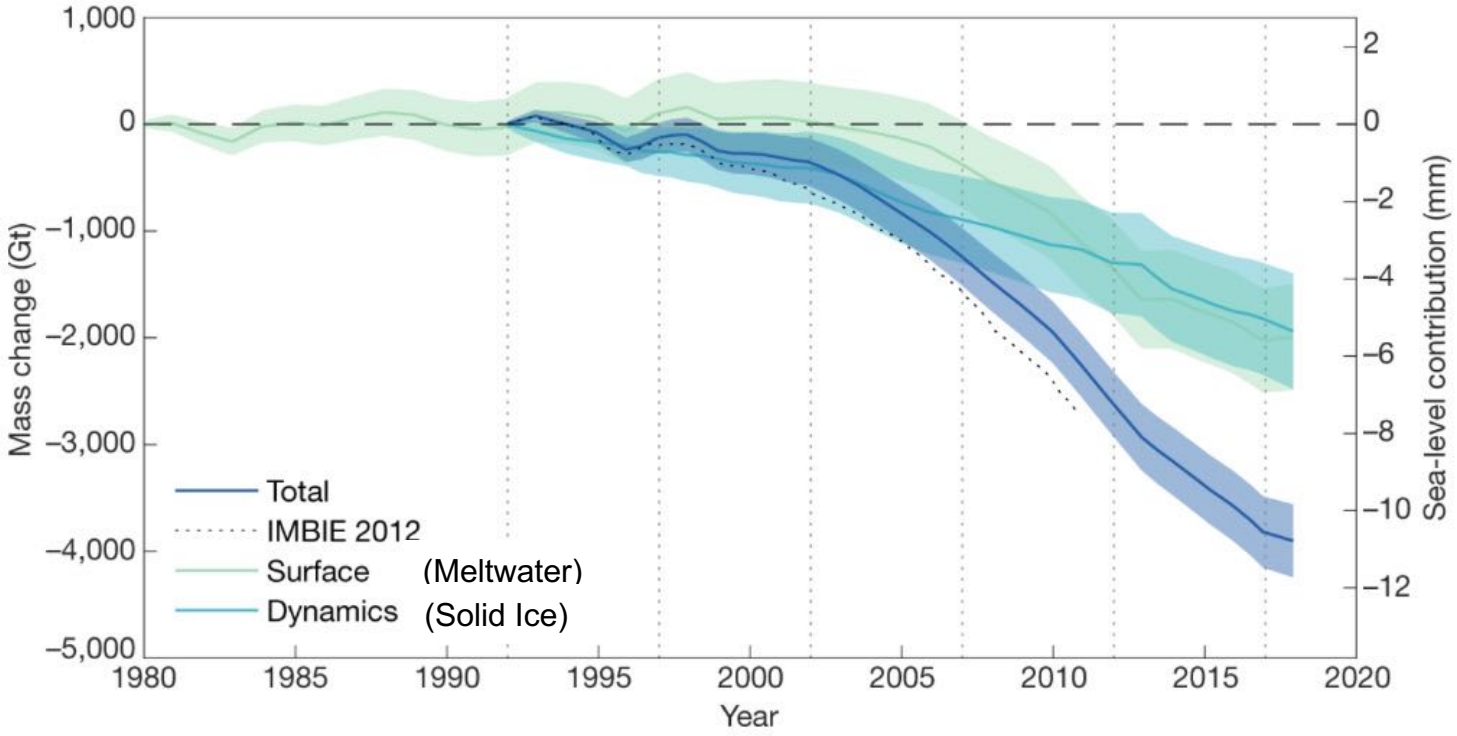


Image courtesy NASA Jet Propulsion Laboratory: https://gracefo.jpl.nasa.gov/science/ice-sheets-and-glaciers/

Theme: total mass loss <u>observed</u> by GRACE

~ 1 mm global sea level rise <u>per year</u>

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



MB = SMB - D

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

nature

Article | Published: 10 December 2019

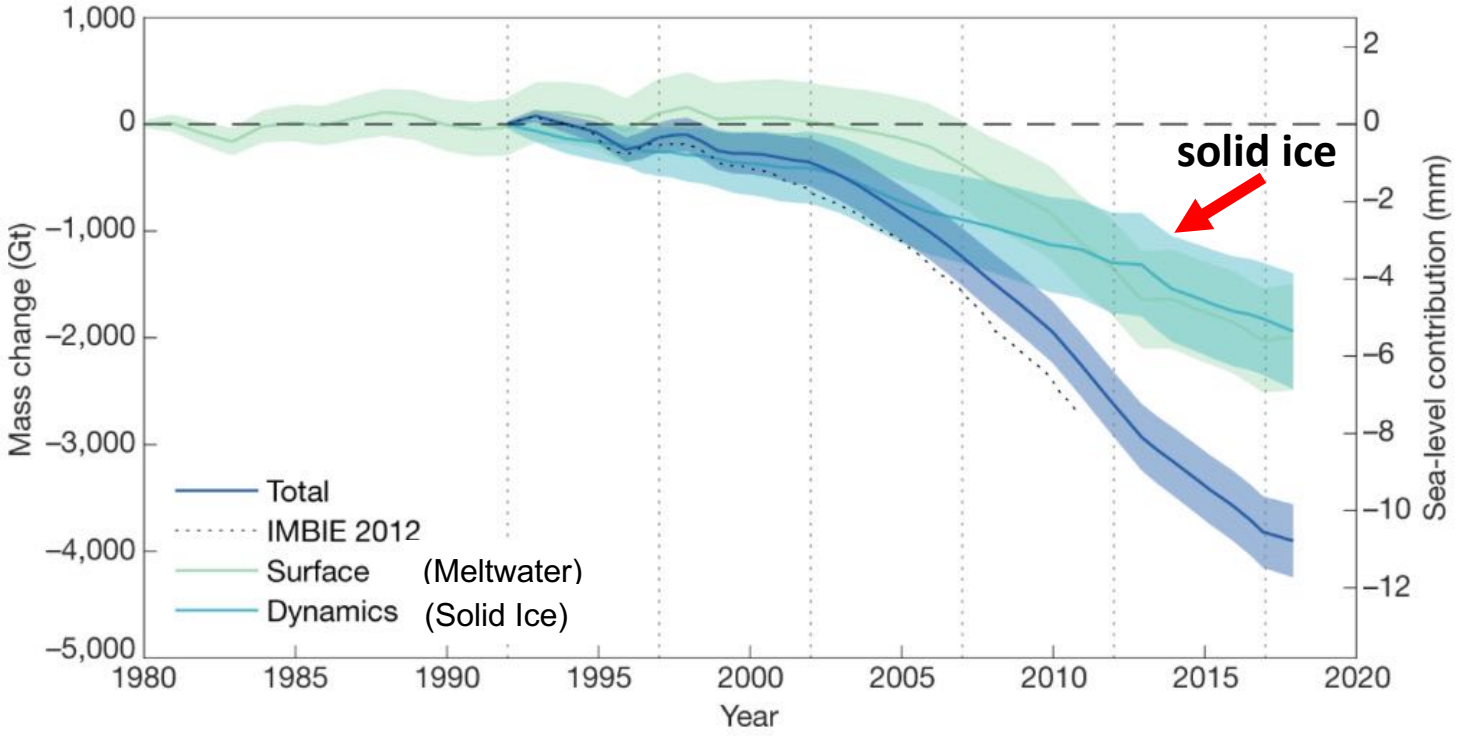
Mass balance of the Greenland Ice Sheet from 1992 to 2018

The IMBIE Team

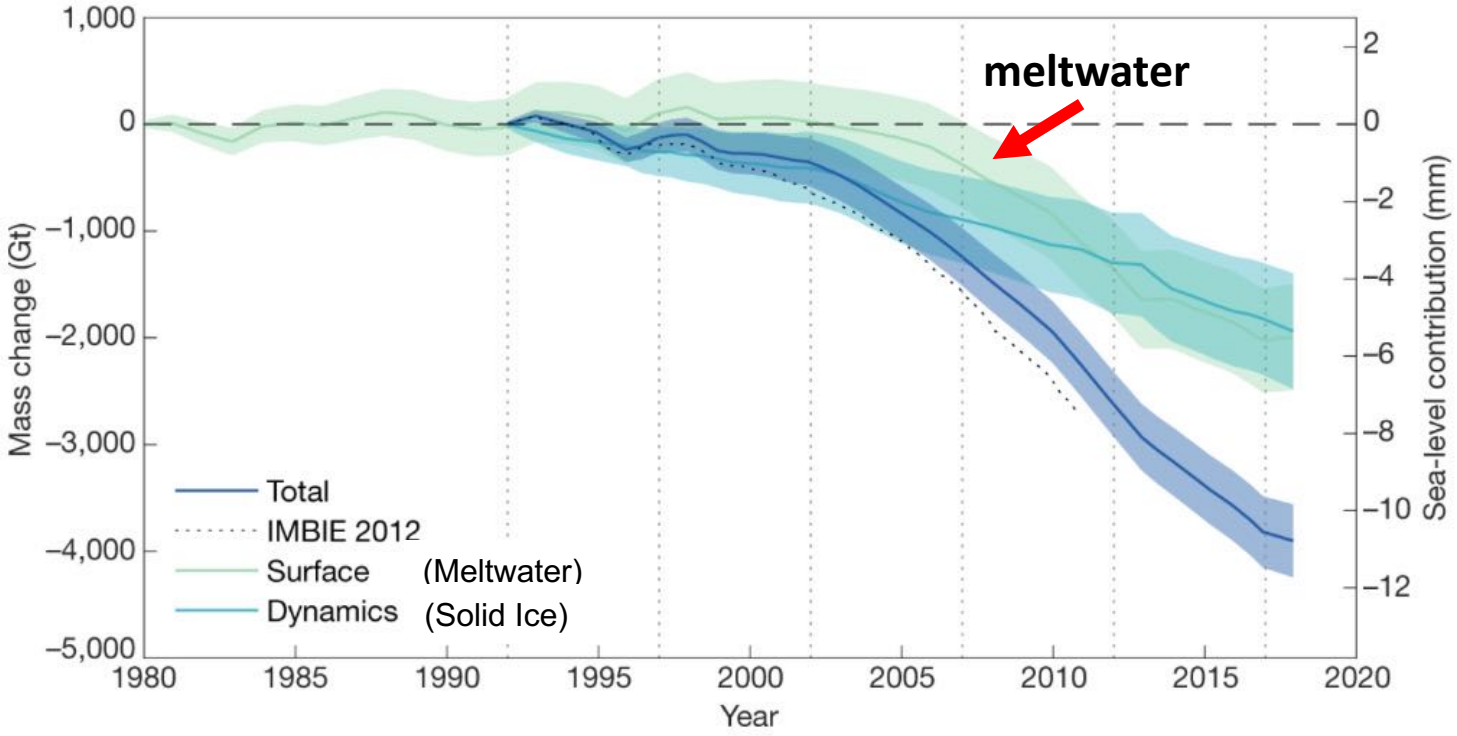
Nature **579**, 233–239(2020) | Cite this article

Theme: solid ice discharge vs surface mass balance

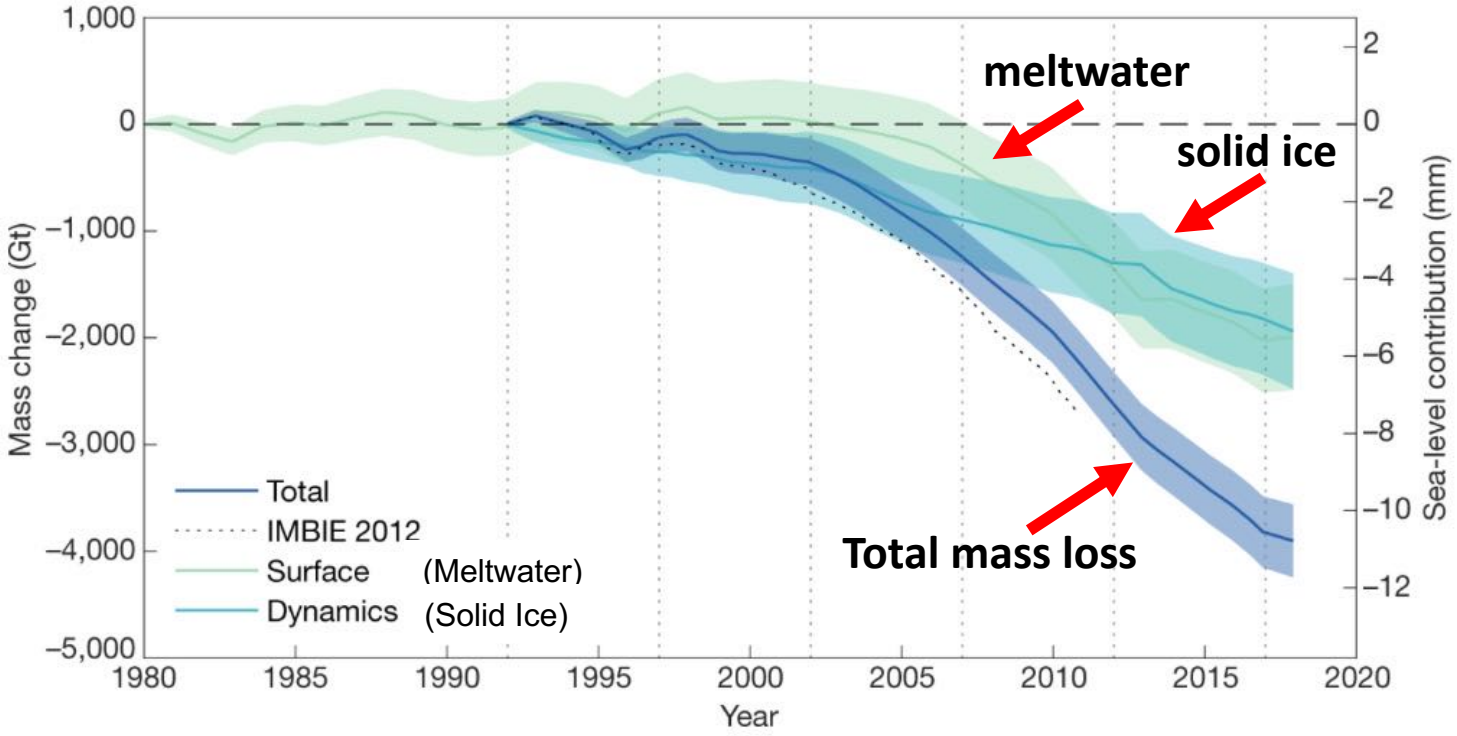
Greenland is losing mass from solid ice **and** meltwater runoff



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

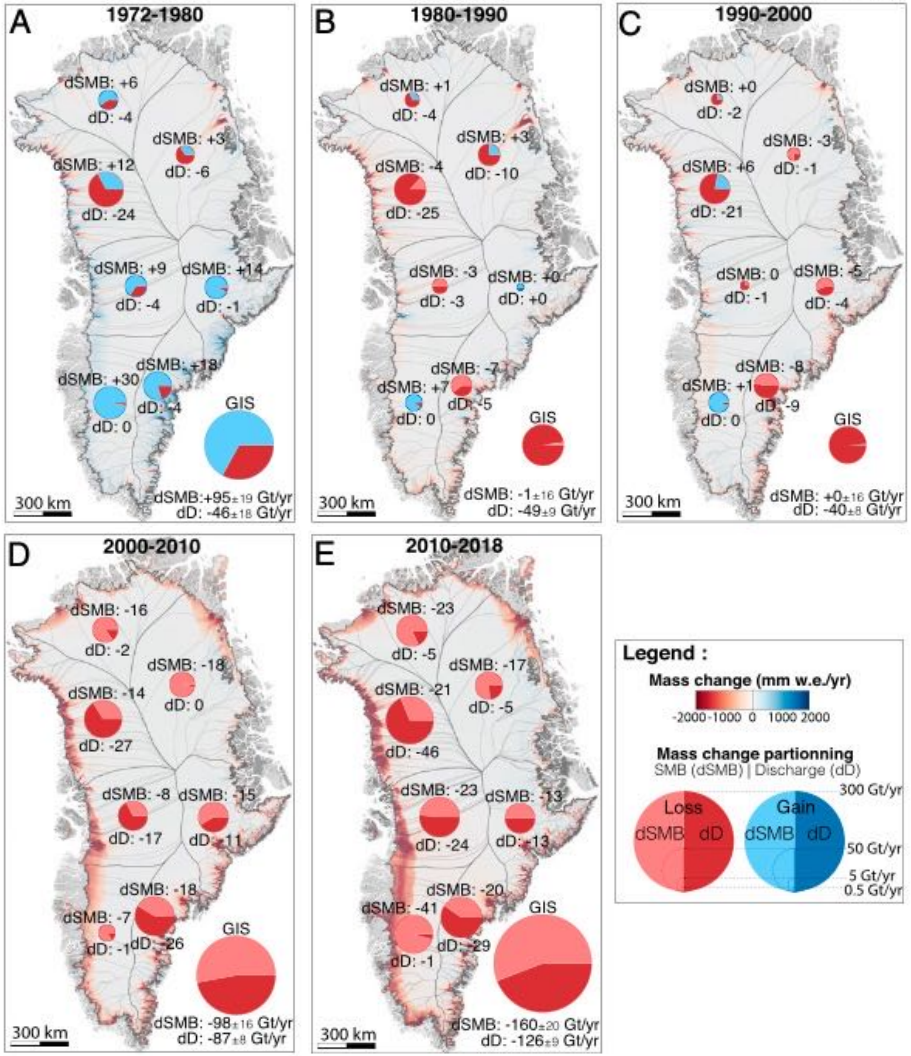


Greenland is losing mass from solid ice **and** meltwater runoff



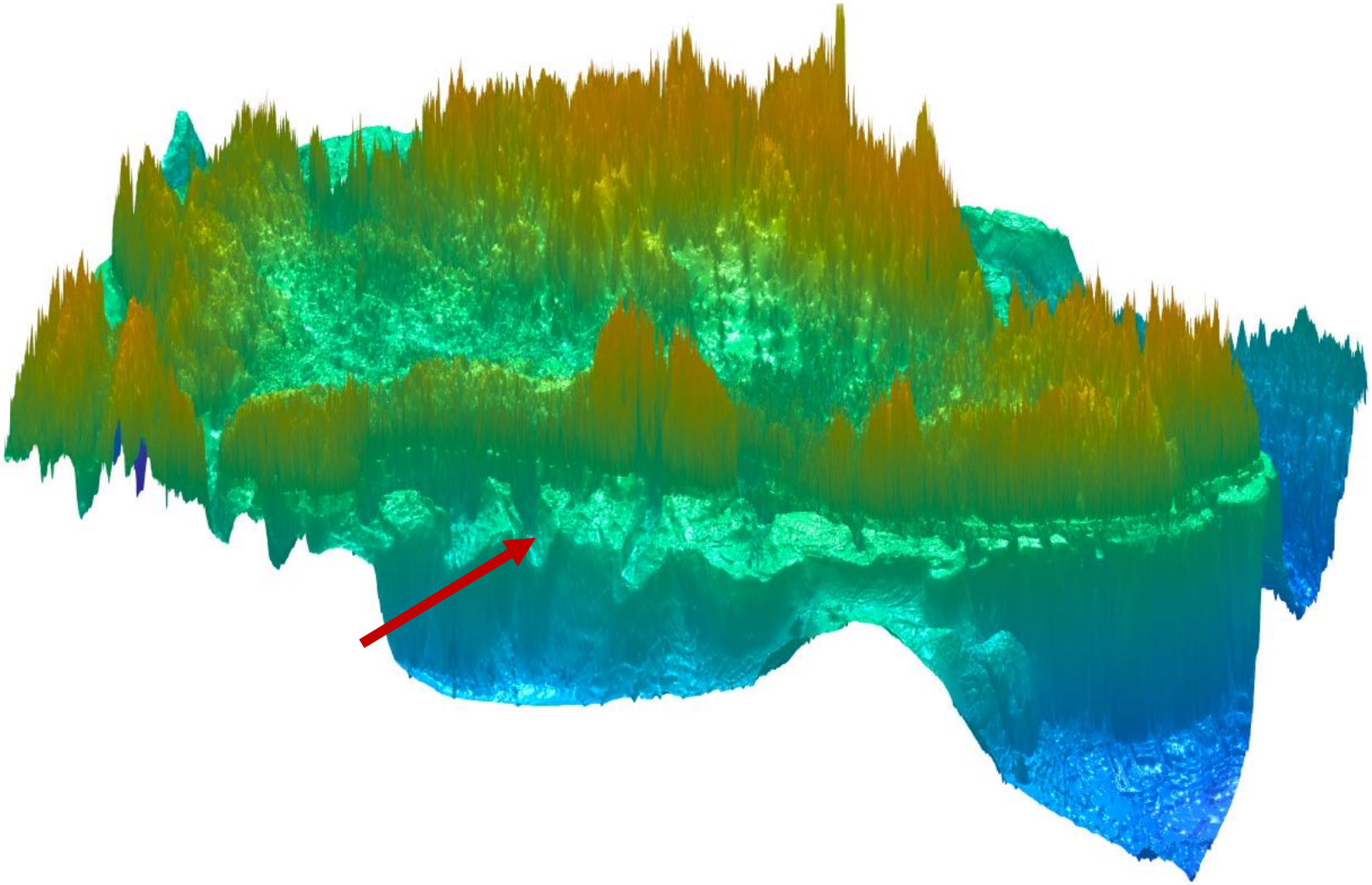
(Second largest contributor to global sea level-rise after thermal expansion of oceans)

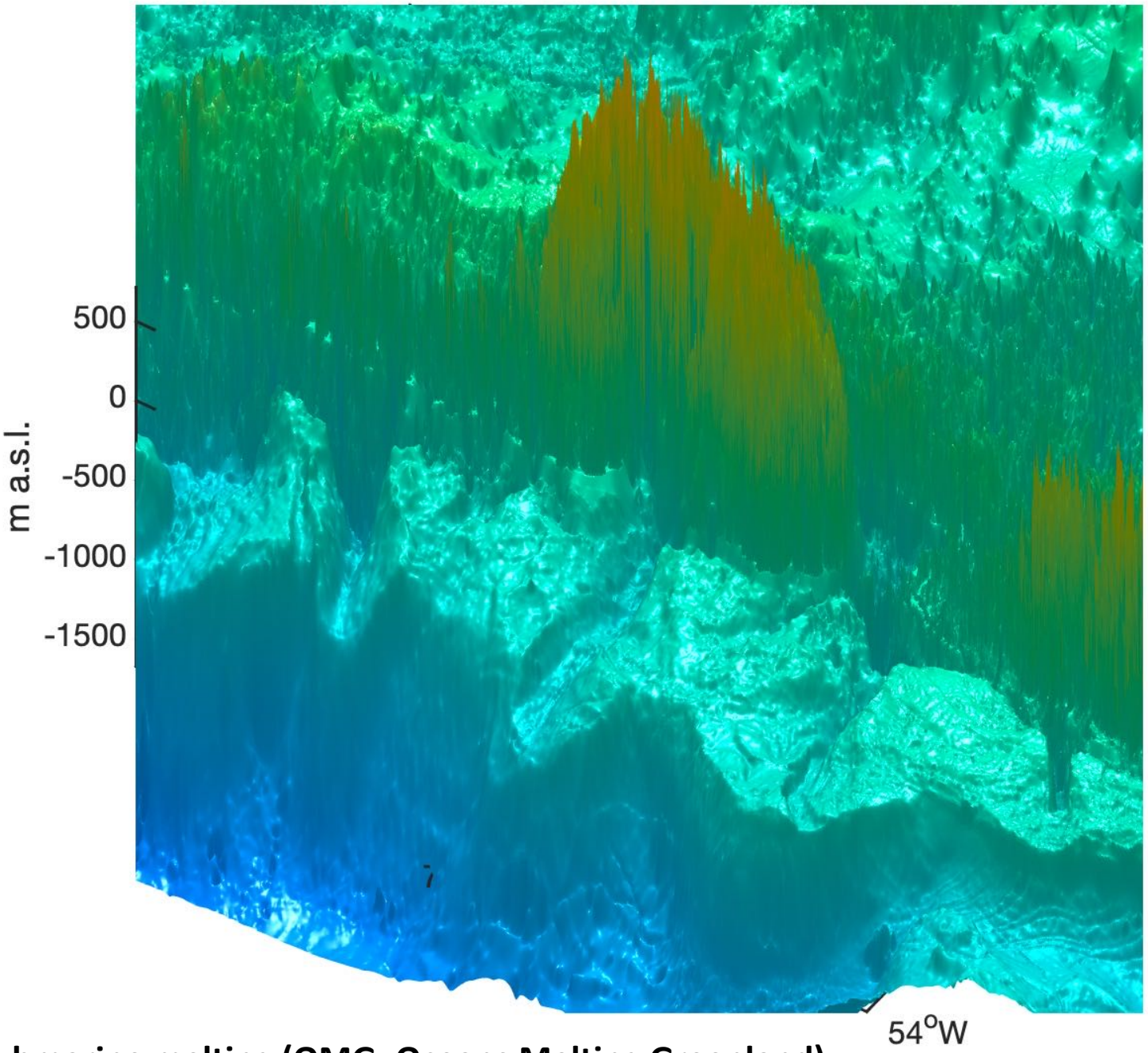
Solid Ice Discharge and Surface Mass Balance



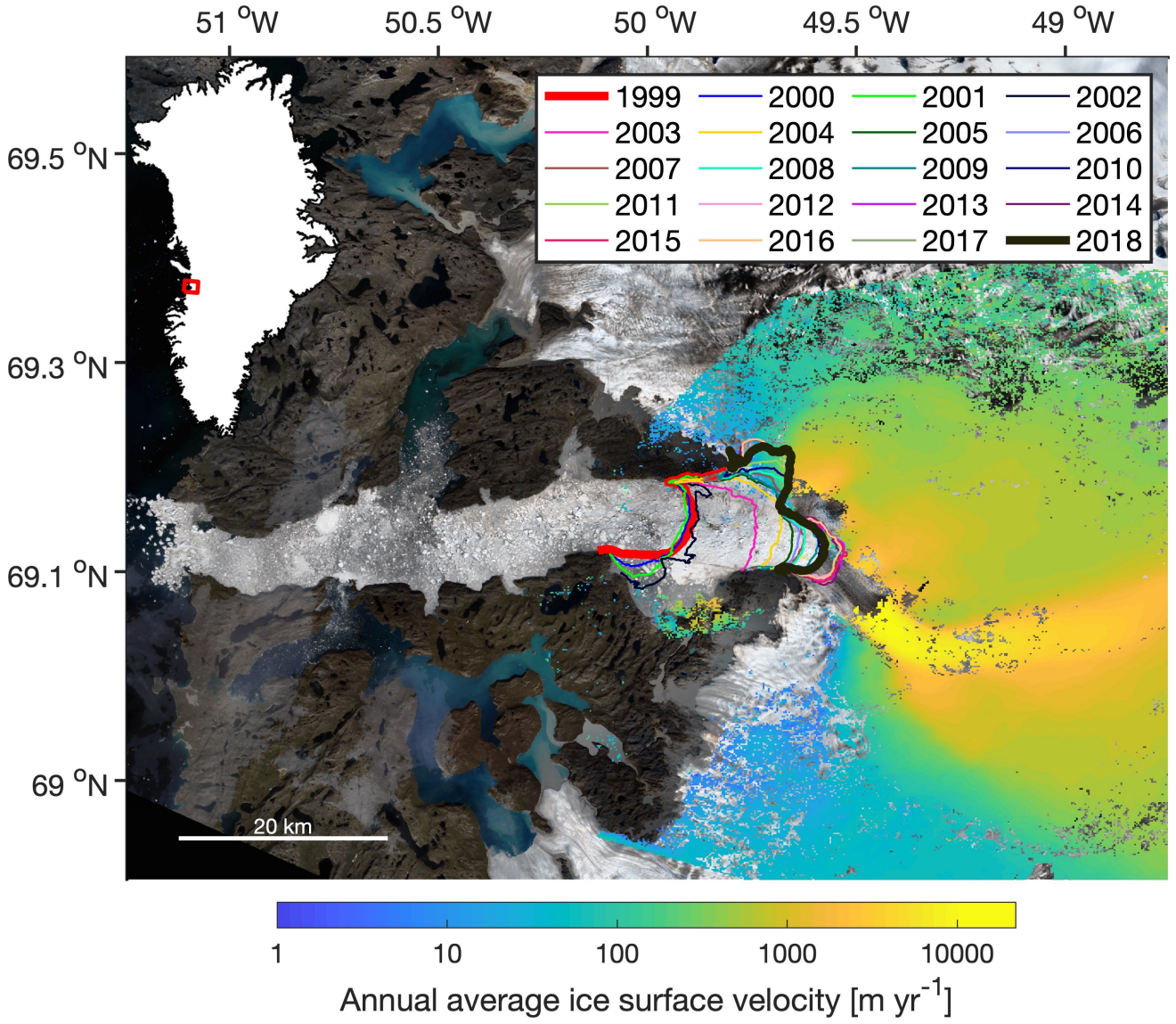
Mouginot et al. (2019) *PNAS*

Outlet Glacier Fjord Bathymetry





Theme: submarine melting (OMG: Oceans Melting Greenland)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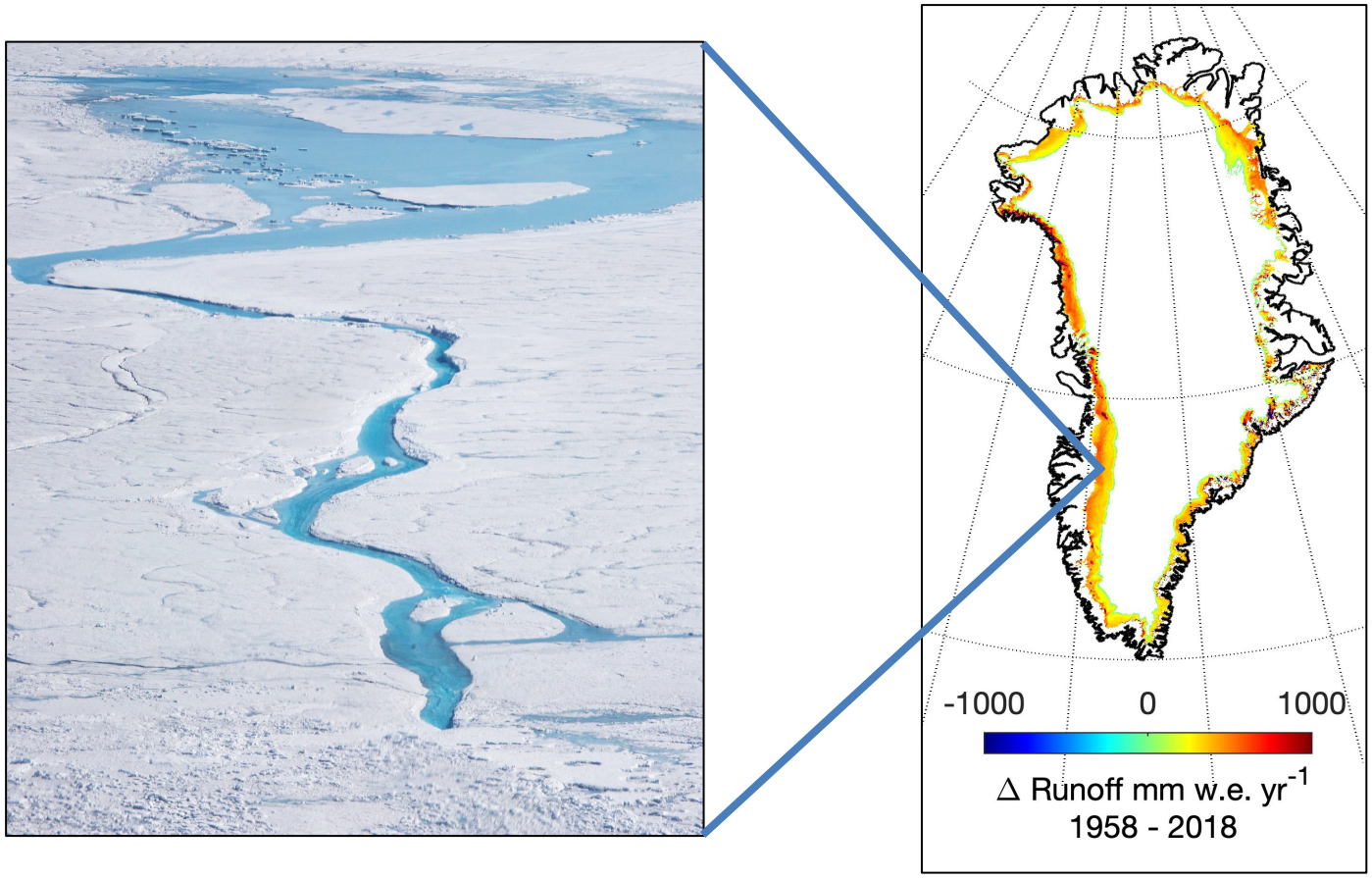
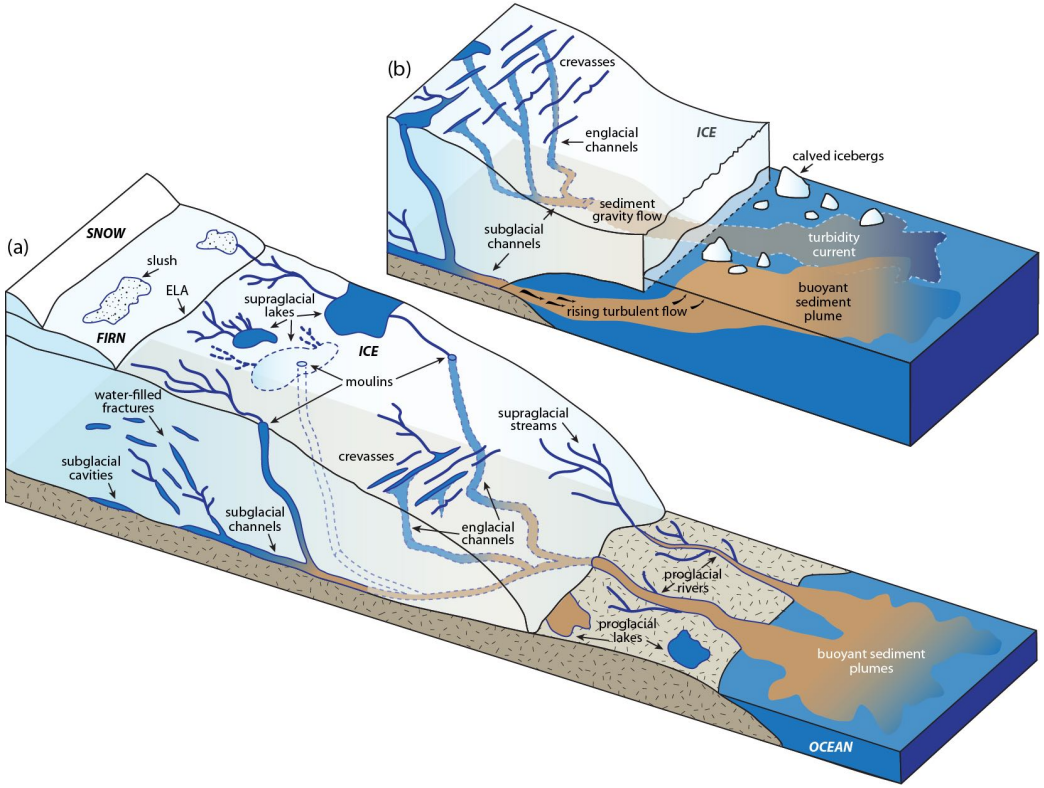
Annual average ice surface velocity [m yr-1]

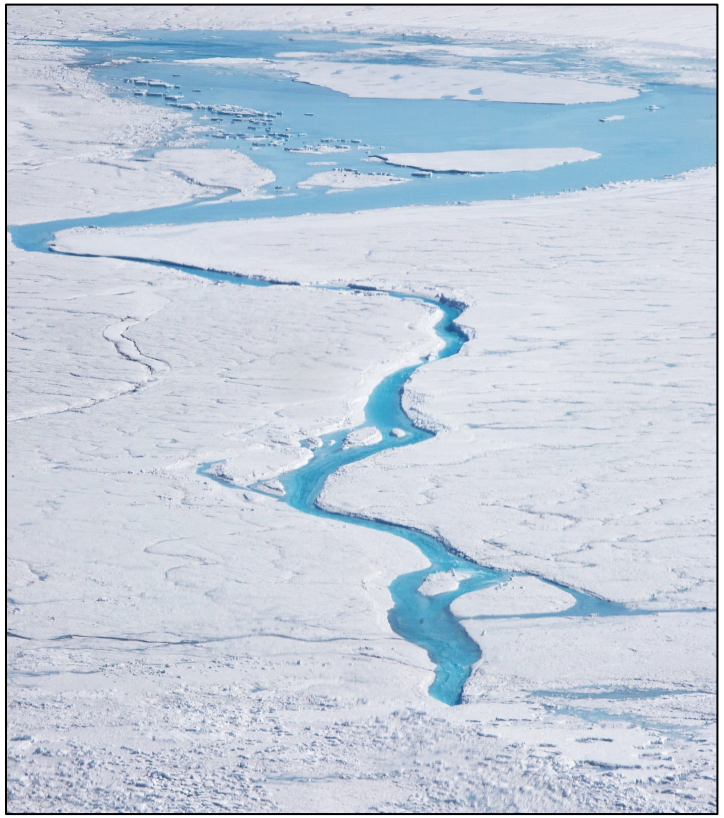
Melting bare ice in Greenland's ablation zone



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

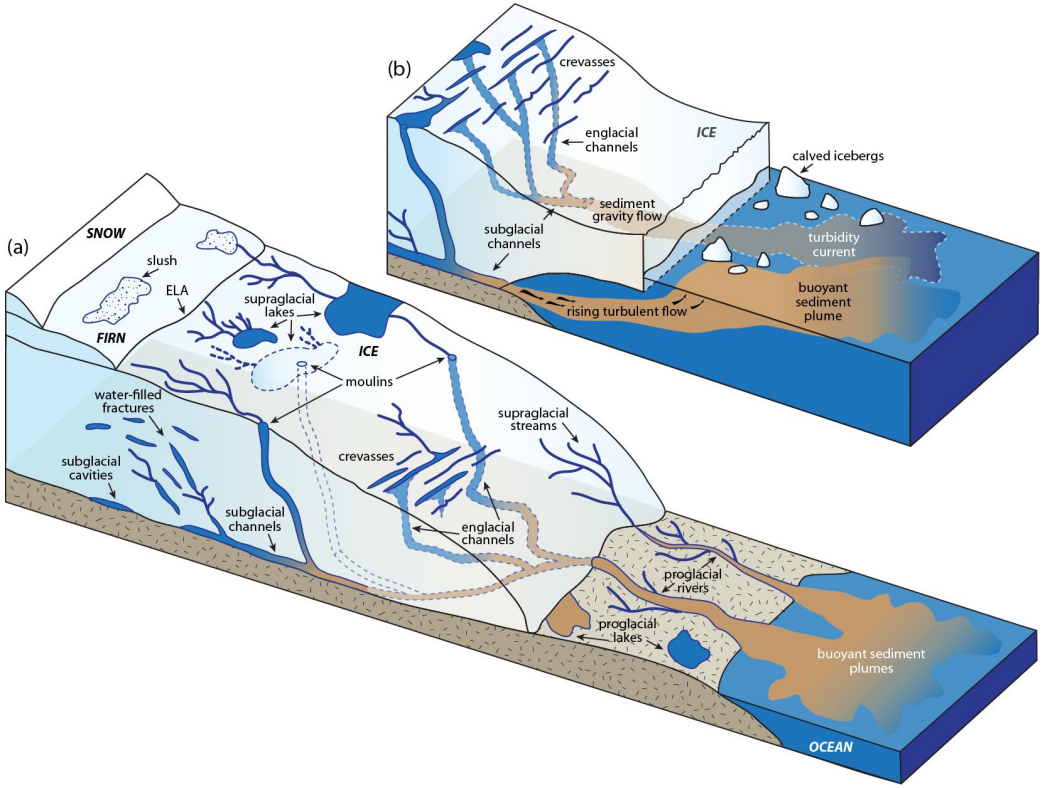
Greenland Ice Sheet surface hydrology





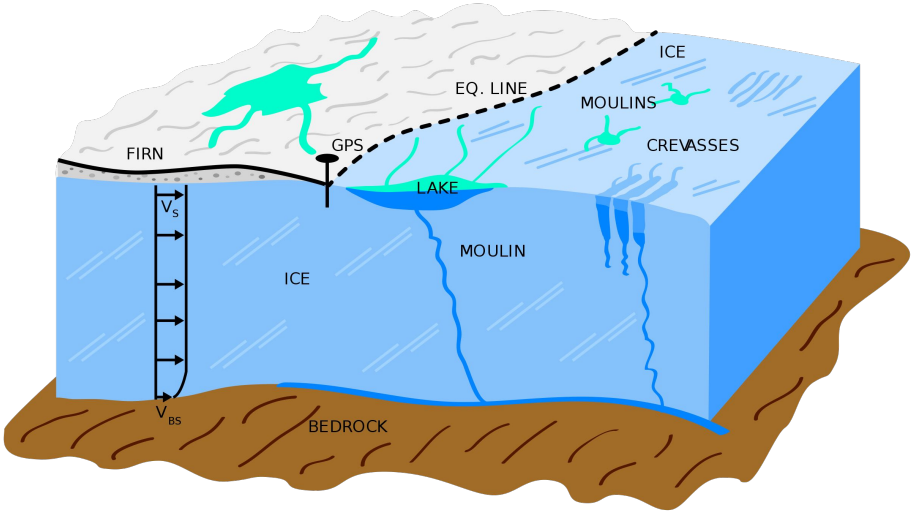
Vena Chu (2014), *Prog. Phys. Geog.*

Greenland Ice Sheet surface hydrology



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

Meltwater lubrication–ice acceleration: positive feedback?

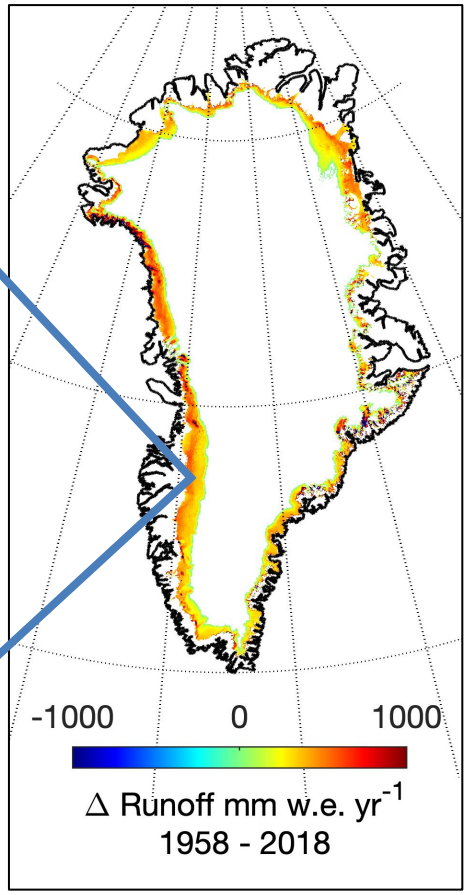


Zwally et al. 2002, *Science*

Theme: Meltwater runoff–solid ice discharge positive feedback

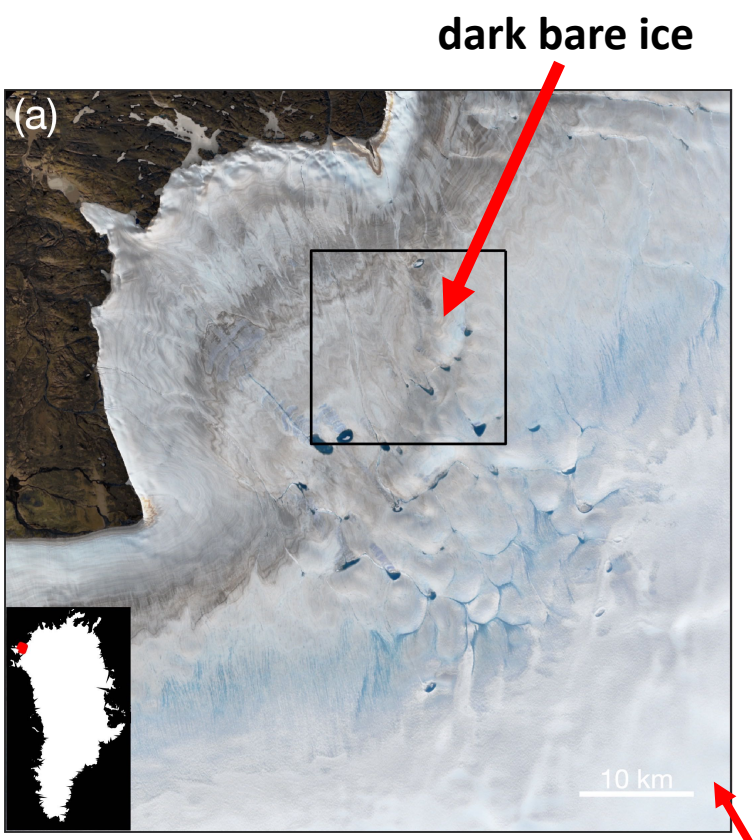
Melting bare ice in Greenland's ablation zone

bare glacier ice

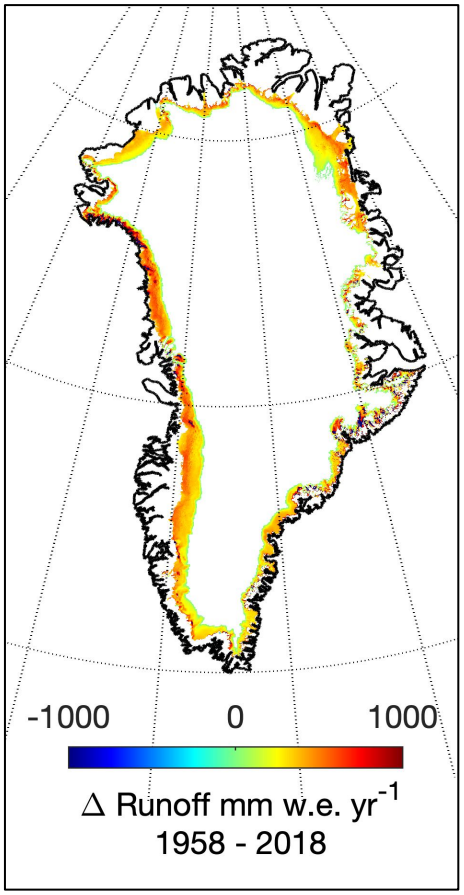


Theme: Bare ice exposure and bare ice albedo

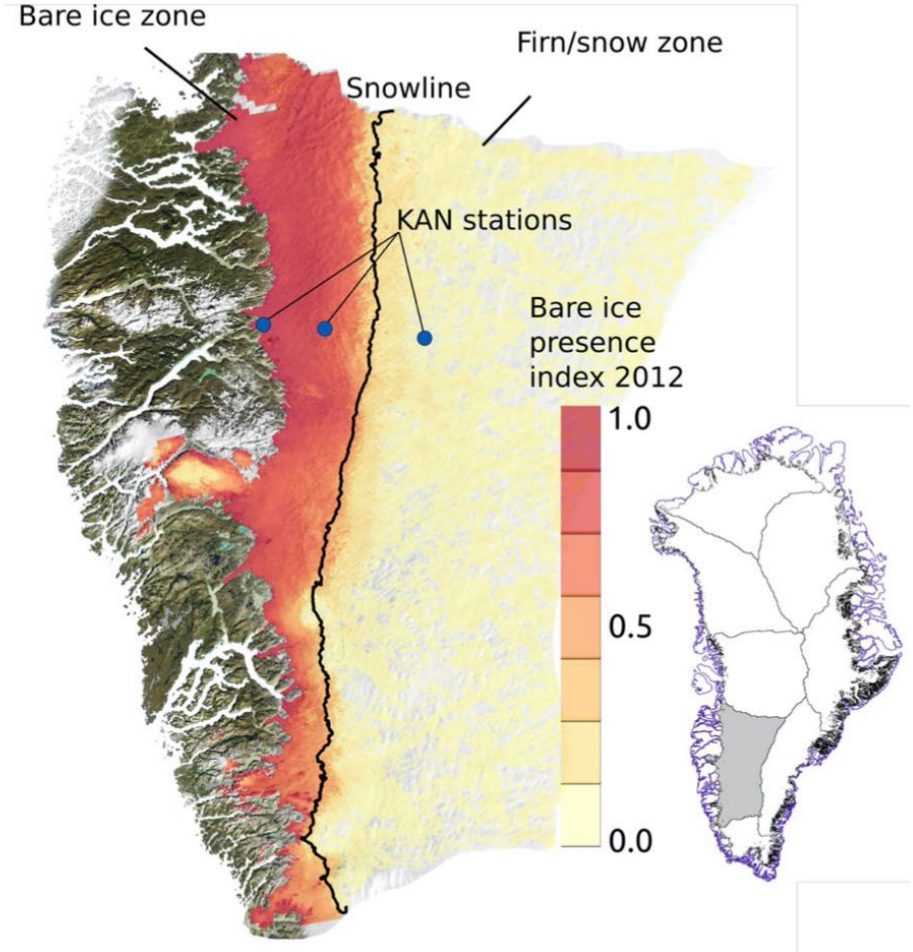
~85% of Greenland's meltwater comes from melting bare ice

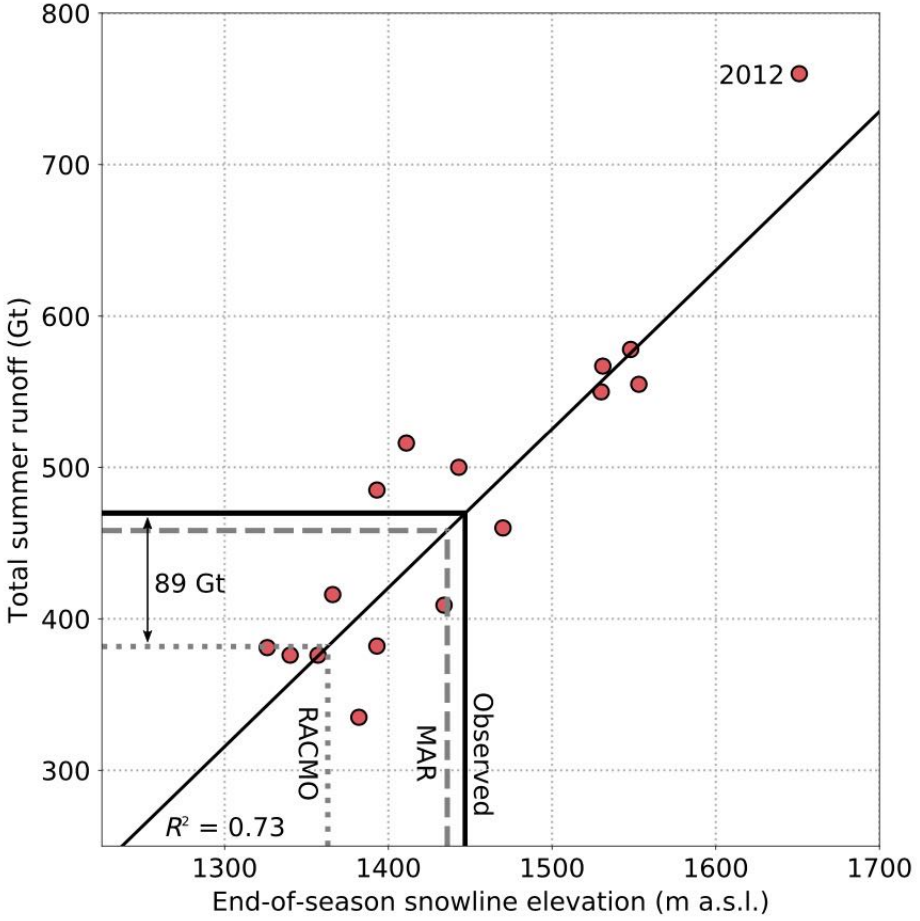


Cooper and Smith (2019) *Remote Sensing*



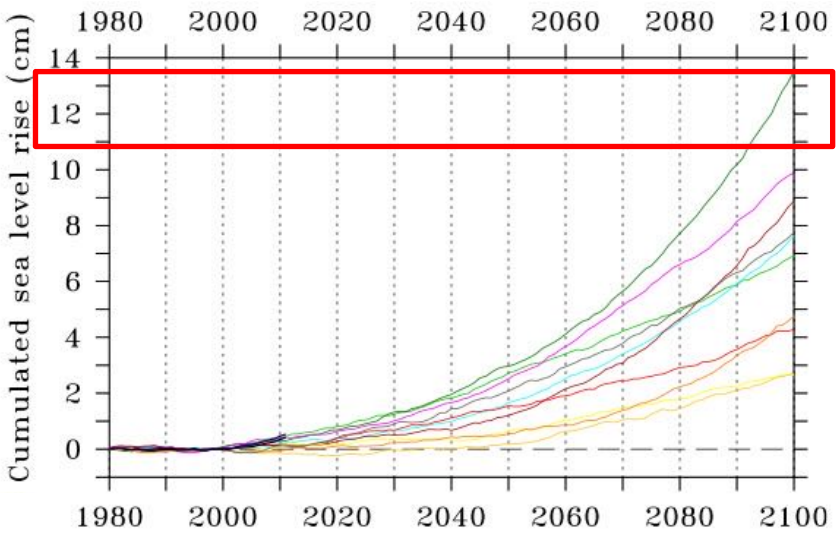
Bare ice exposure and meltwater runoff



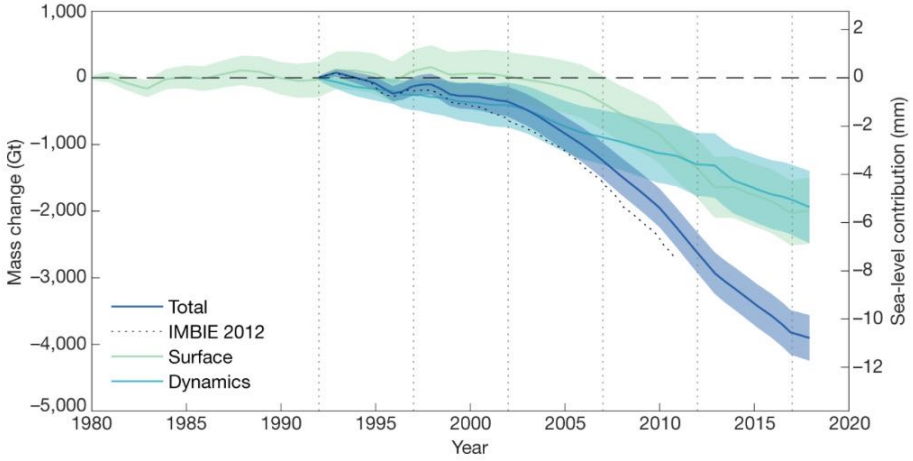


Ryan et al. 2019, *Nature Communications*

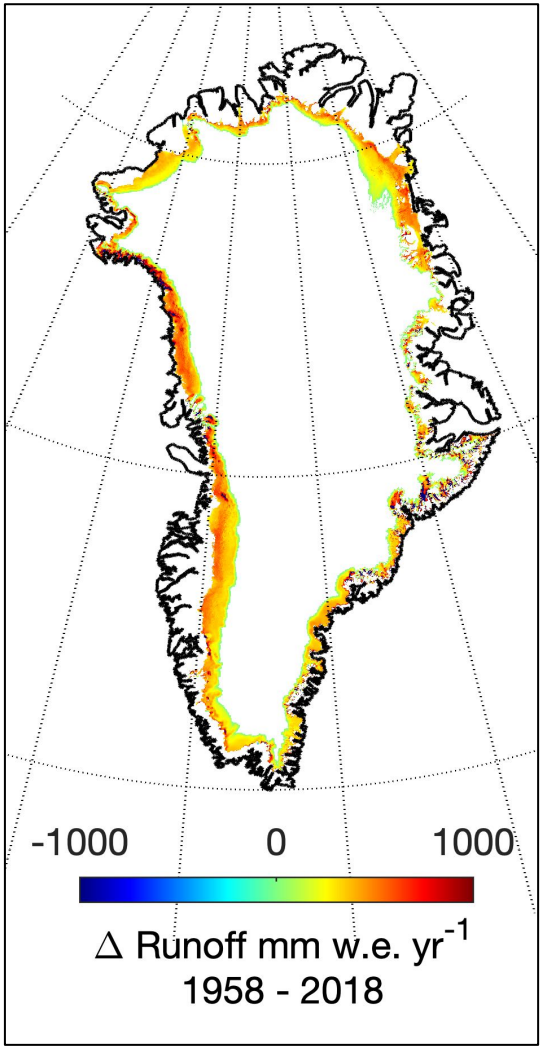
Climate models are tools to predict future sea levels



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



The IMBIE team (2020)

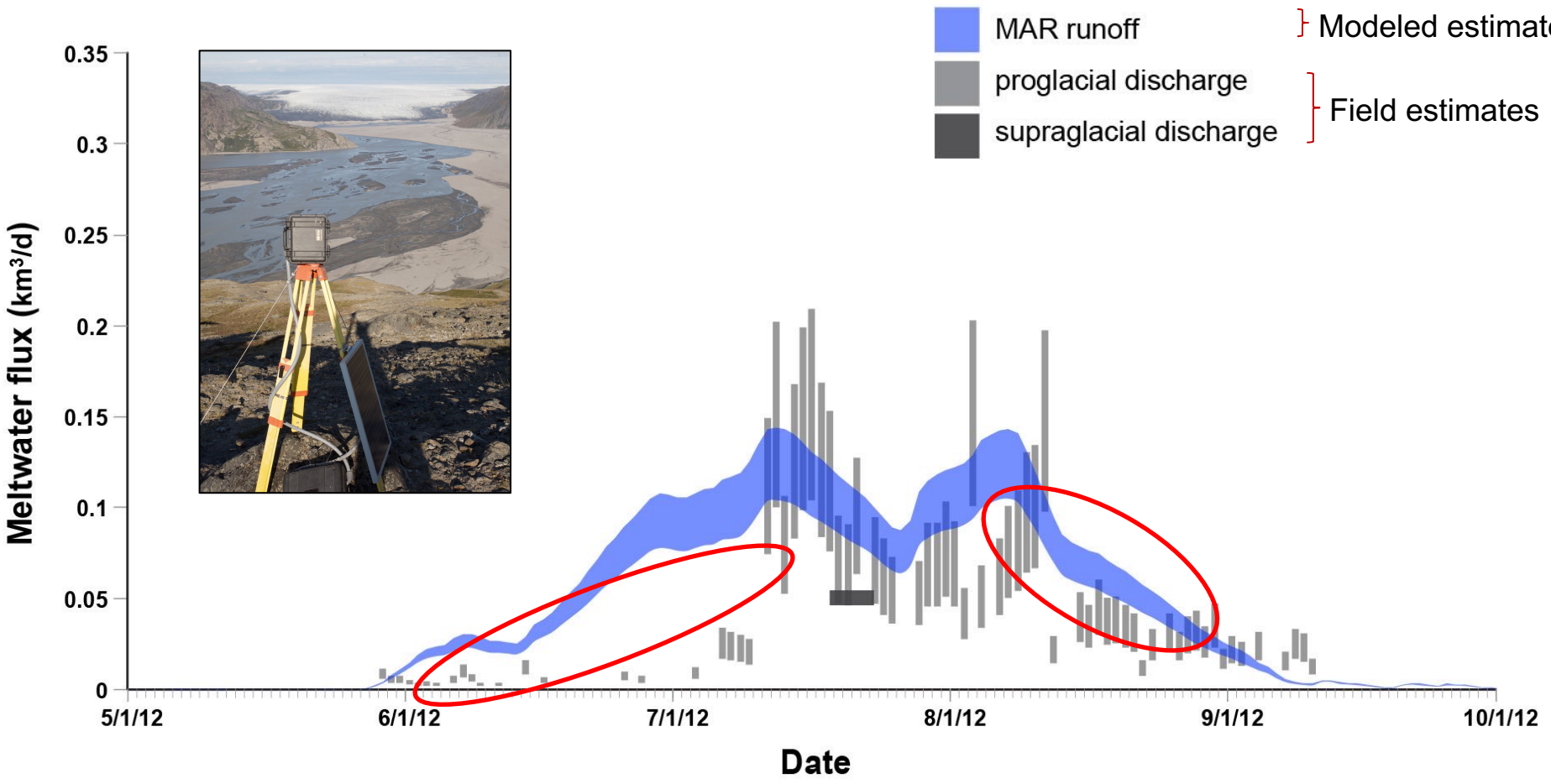


RACMO 2.3 data courtesy Brice Noel

How do climate models predict ice sheet meltwater runoff?

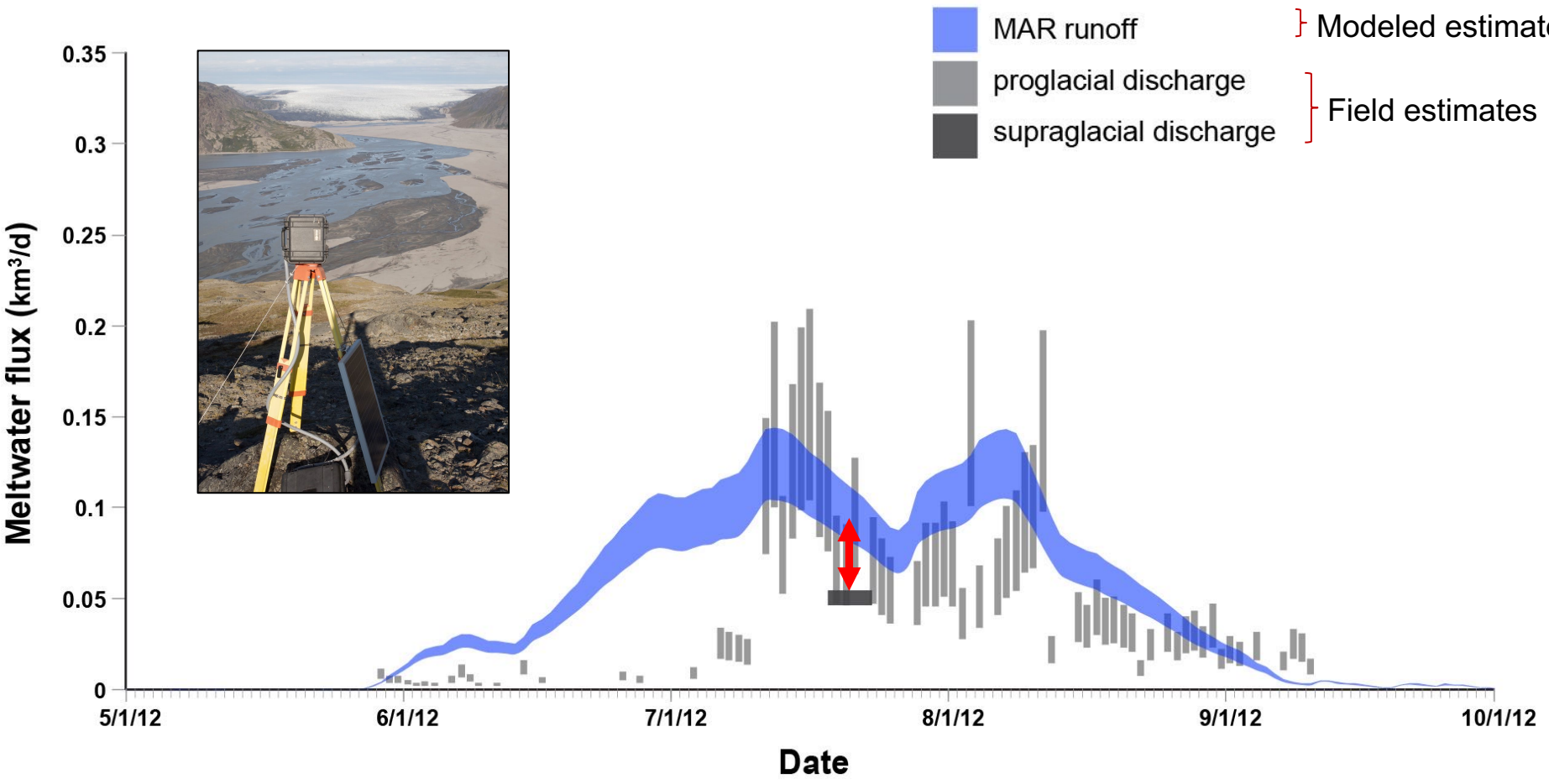
Smith et al. 2015, *PNAS*

How do climate models predict ice sheet meltwater runoff?



Modified from Smith et al. 2015, *PNAS*

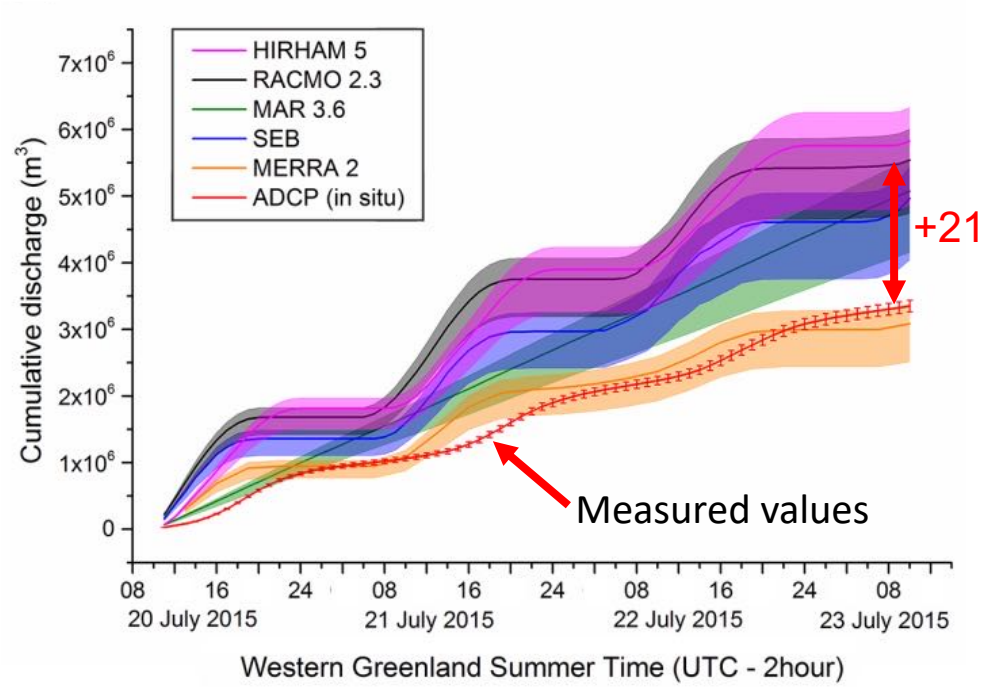
How do climate models predict ice sheet meltwater runoff?



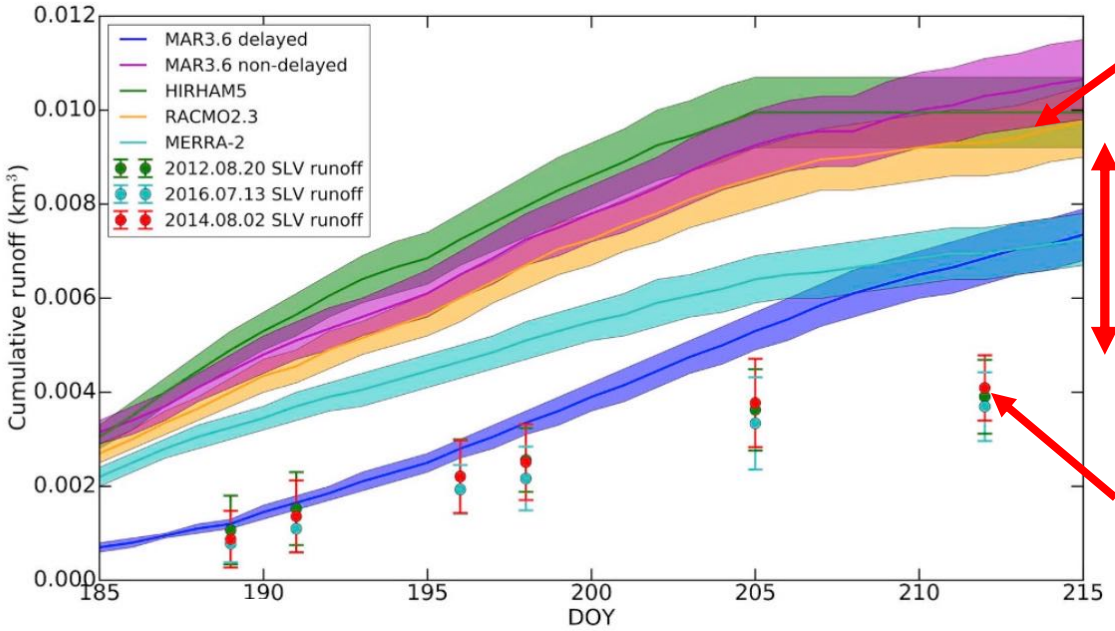
Modified from Smith et al. 2015, *PNAS*

Measuring ice sheet meltwater runoff

Smith et al. (2017) *PNAS*



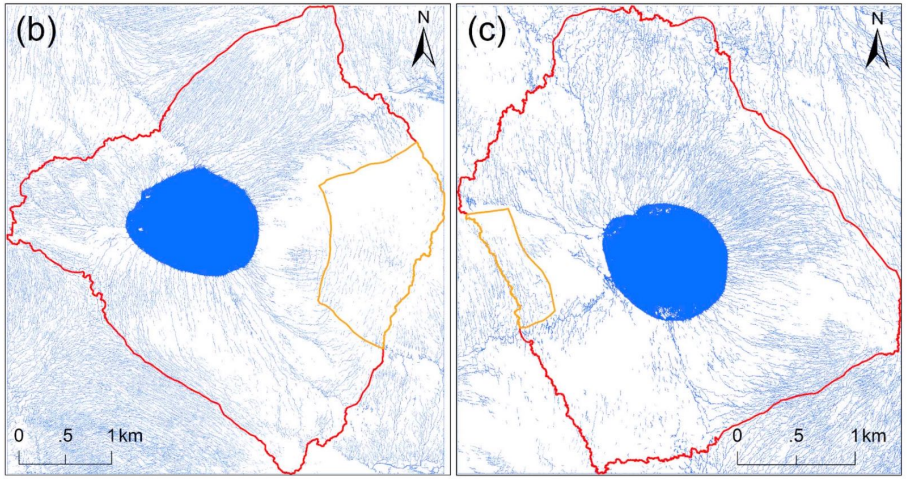
Do Climate Models Overpredict Ice Sheet Meltwater Runoff?



Model predictions

+40–55% overestimation

Satellite observations

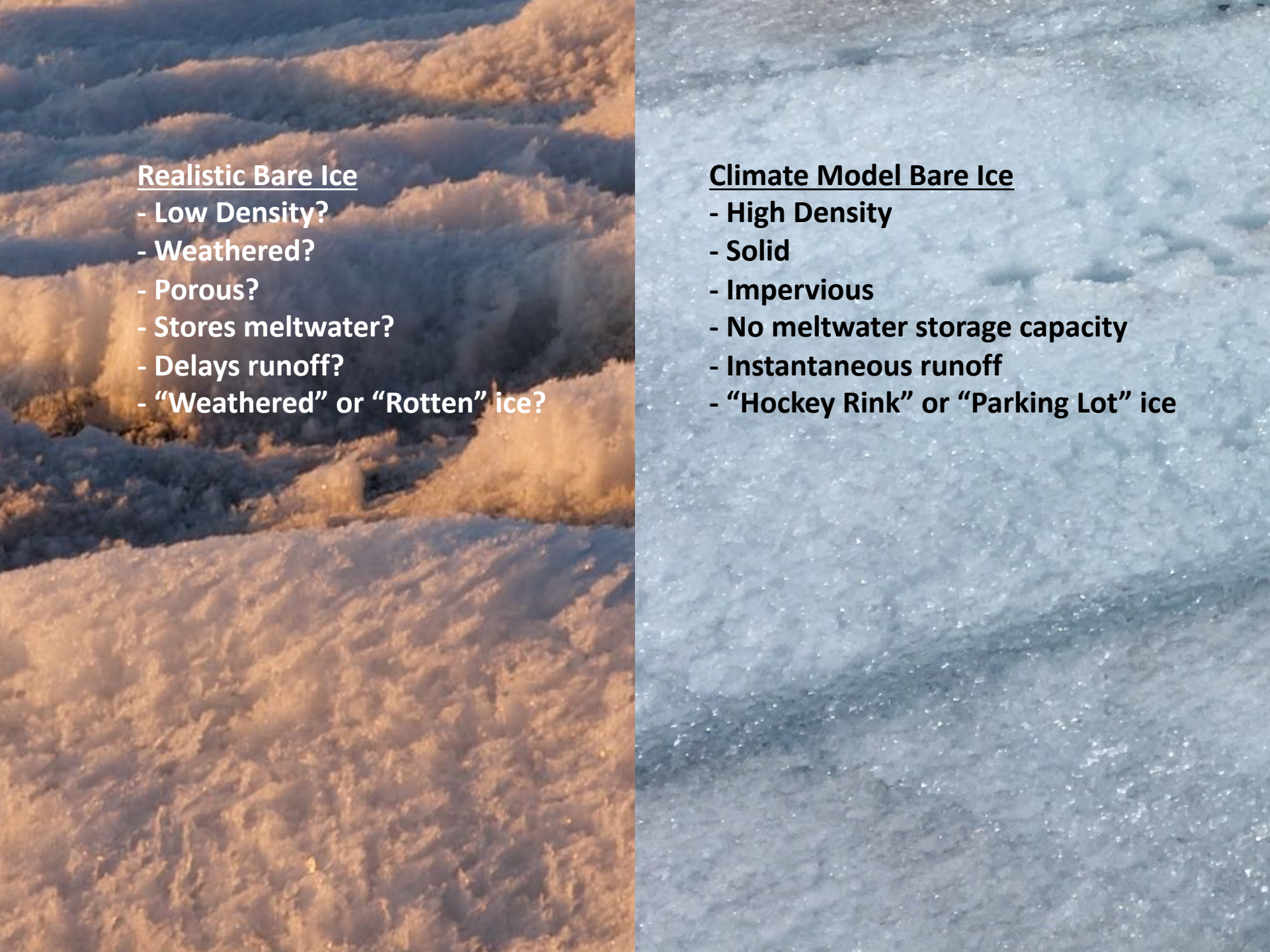


Yang et al. (2019)
Remote Sensing Environment


“Rotten ice”

Climate Model Bare Ice

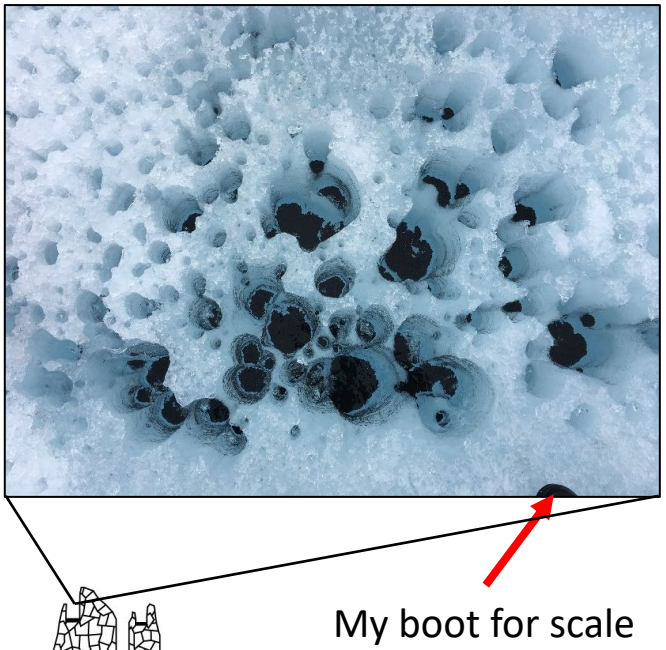
- **High Density**
- **Solid**
- **Impervious**
- **No meltwater storage capacity**
- **Instantaneous runoff**
- **“Hockey Rink” or “Parking Lot” ice**

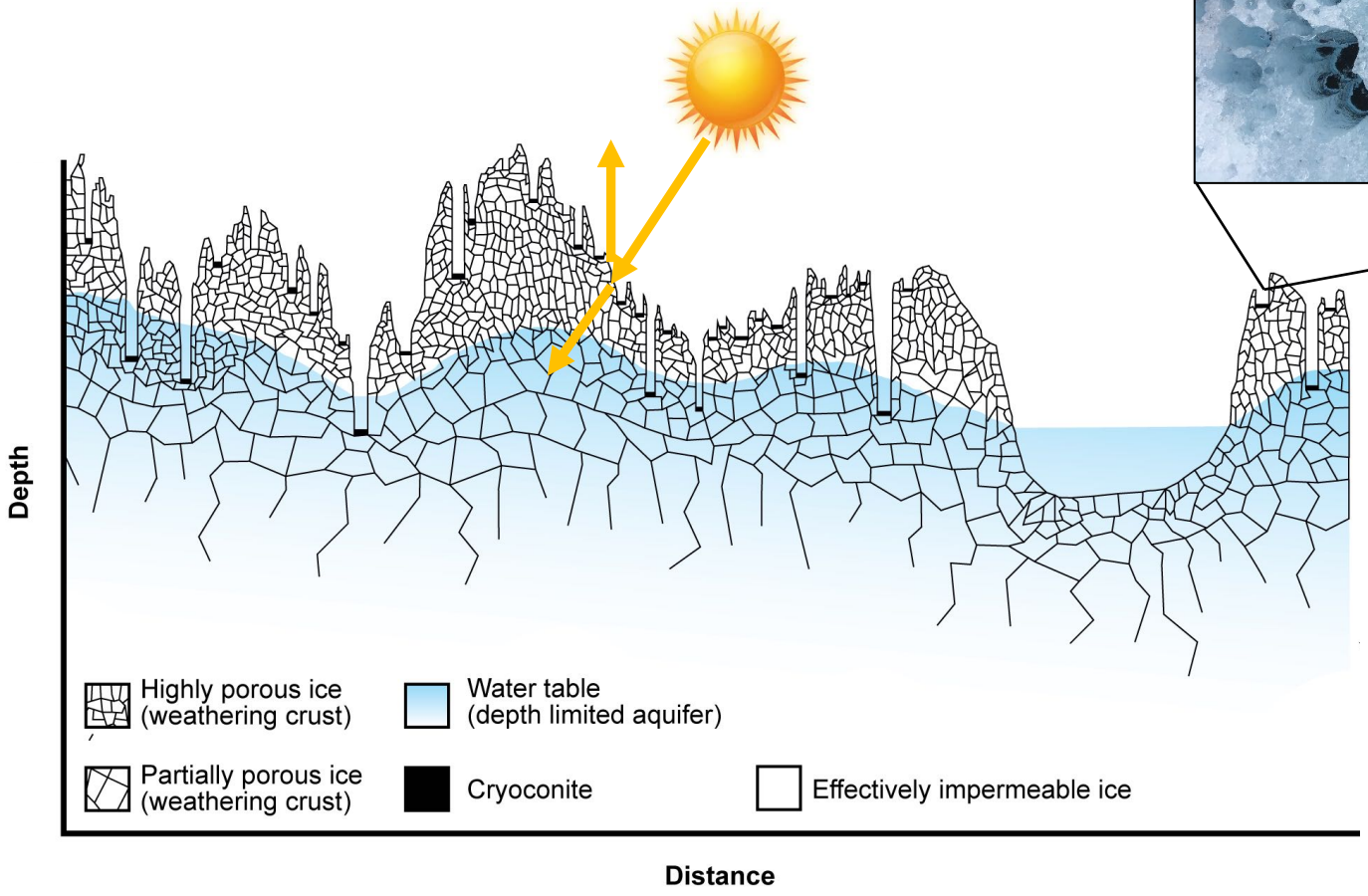


Realistic Bare Ice
- Low Density?
- Weathered?
- Porous?
- Stores meltwater?
- Delays runoff?
- “Weathered” or “Rotten” ice?

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

The Greenland Ice Sheet critical zone

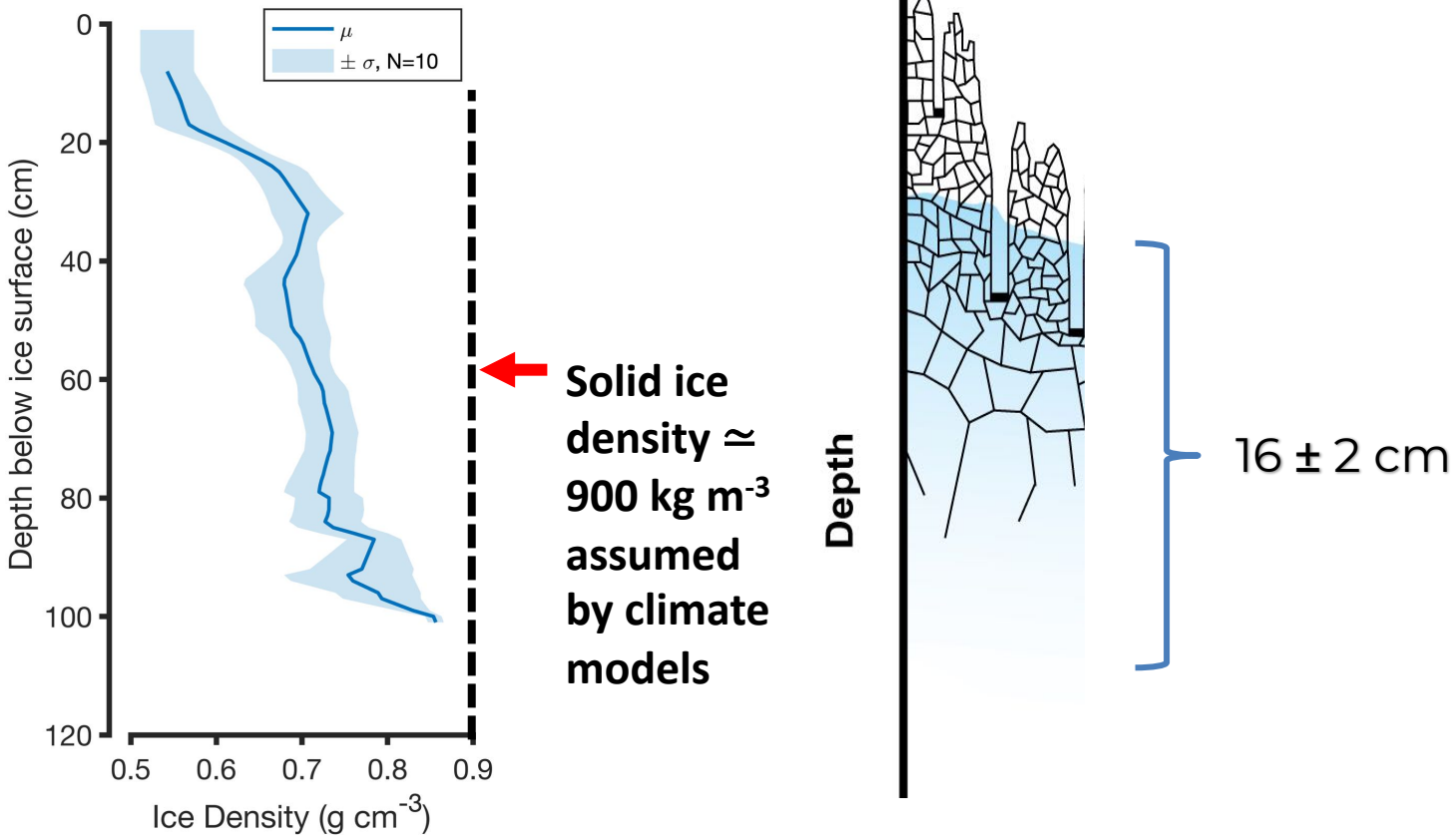




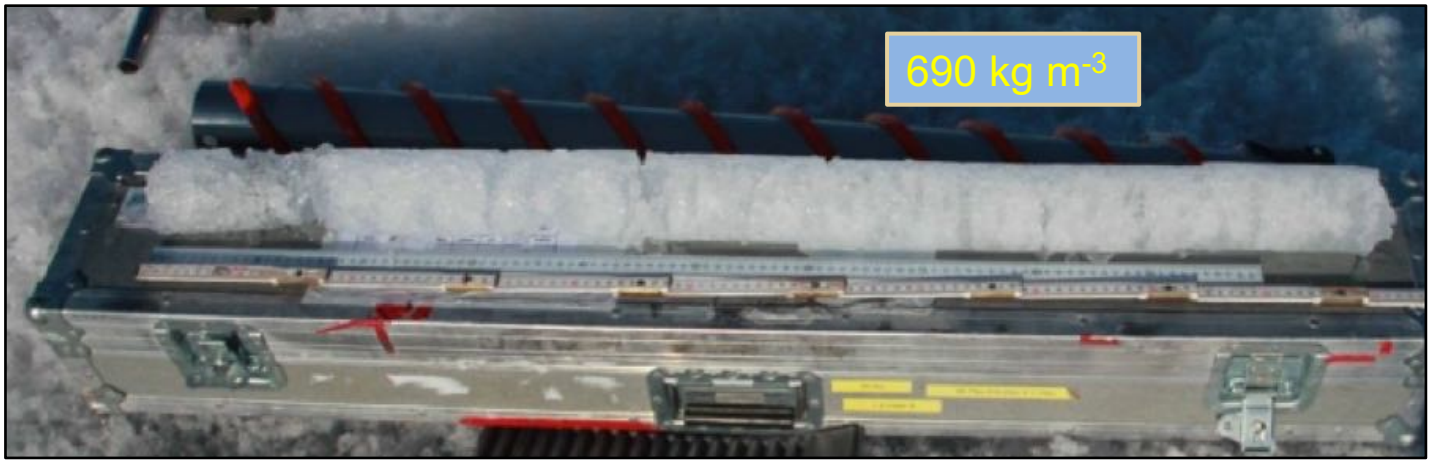
Cooper et al. (2018) *The Cryosphere*


ADCP

Field Measurements of Ice Density and Water Storage

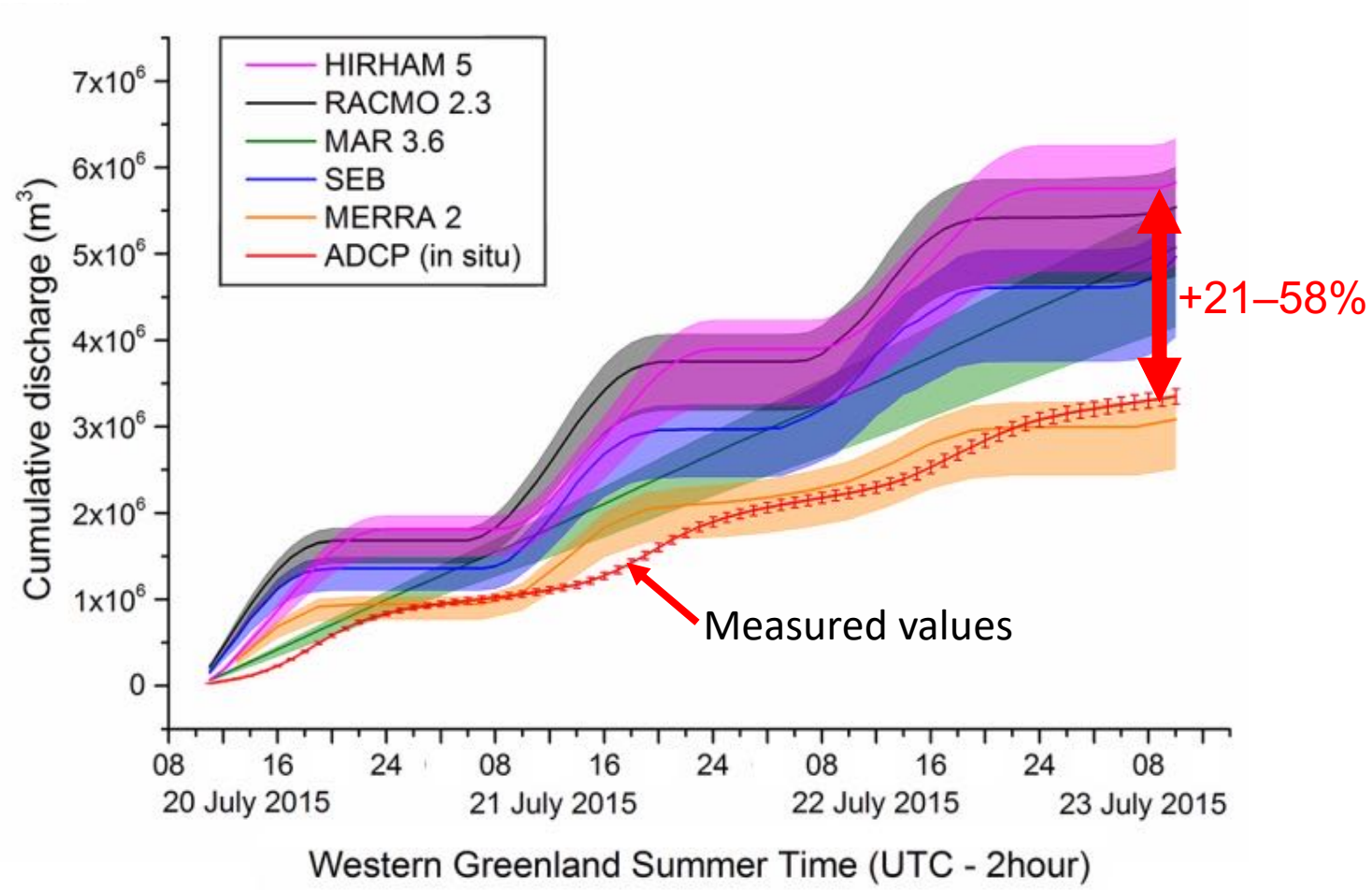


Evidence of sub-surface melting in bare ice



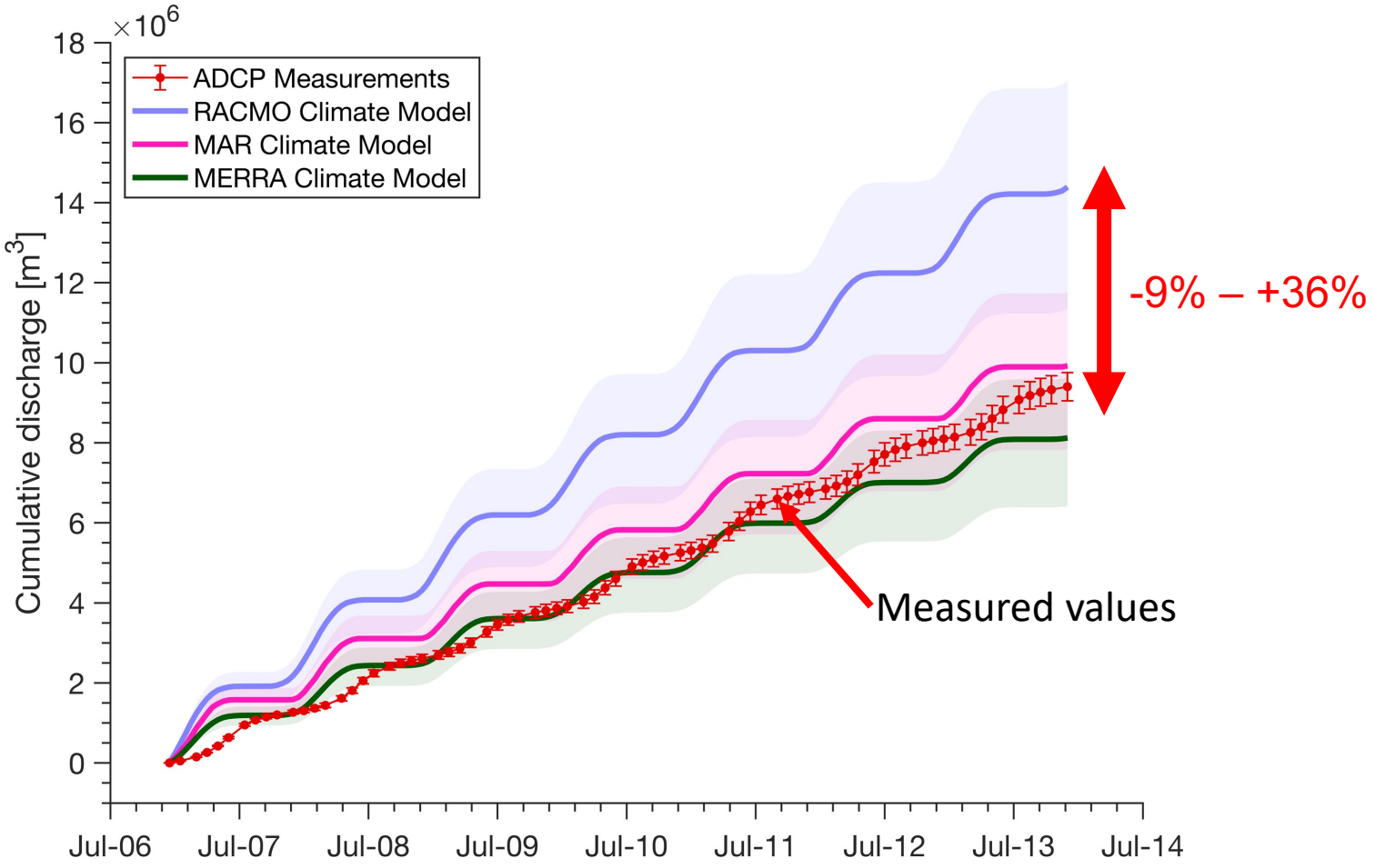
Solid ice counter example ~900 kg m^{-3}

Do Climate Models Overpredict Ice Sheet Meltwater Runoff?

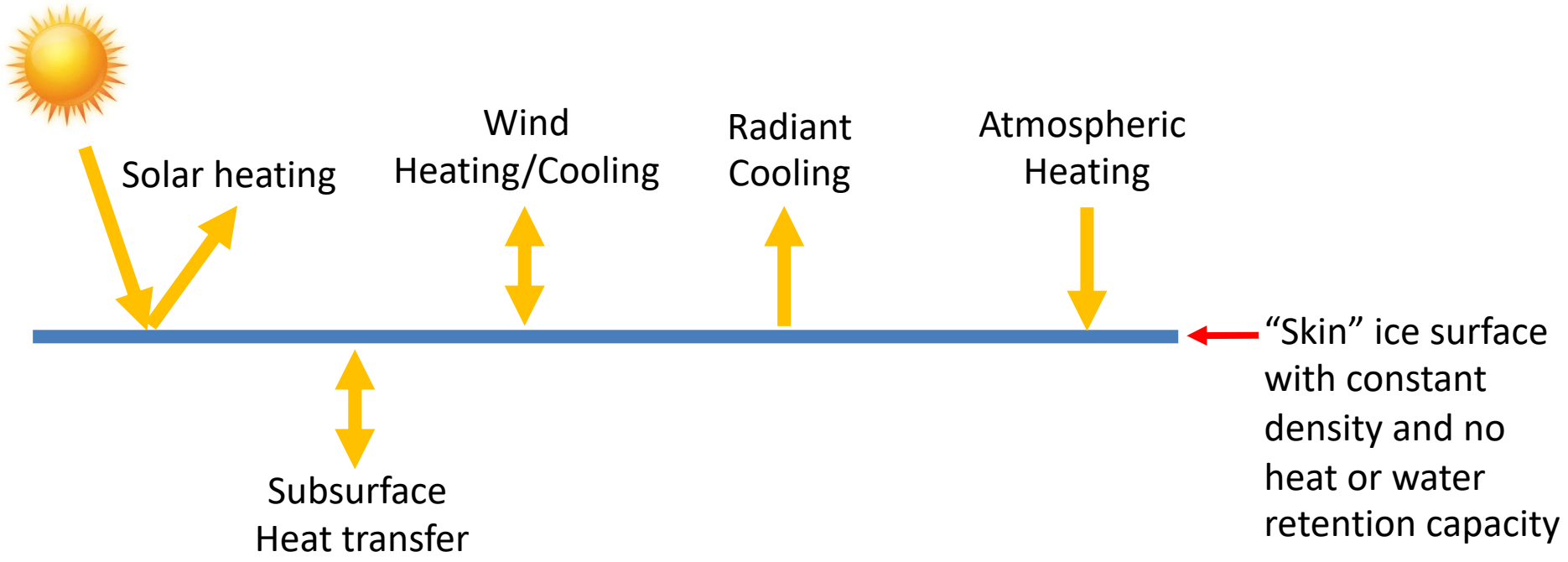


Smith et al. (2017) *PNAS*

Do Climate Models Overpredict Ice Sheet Meltwater Runoff?



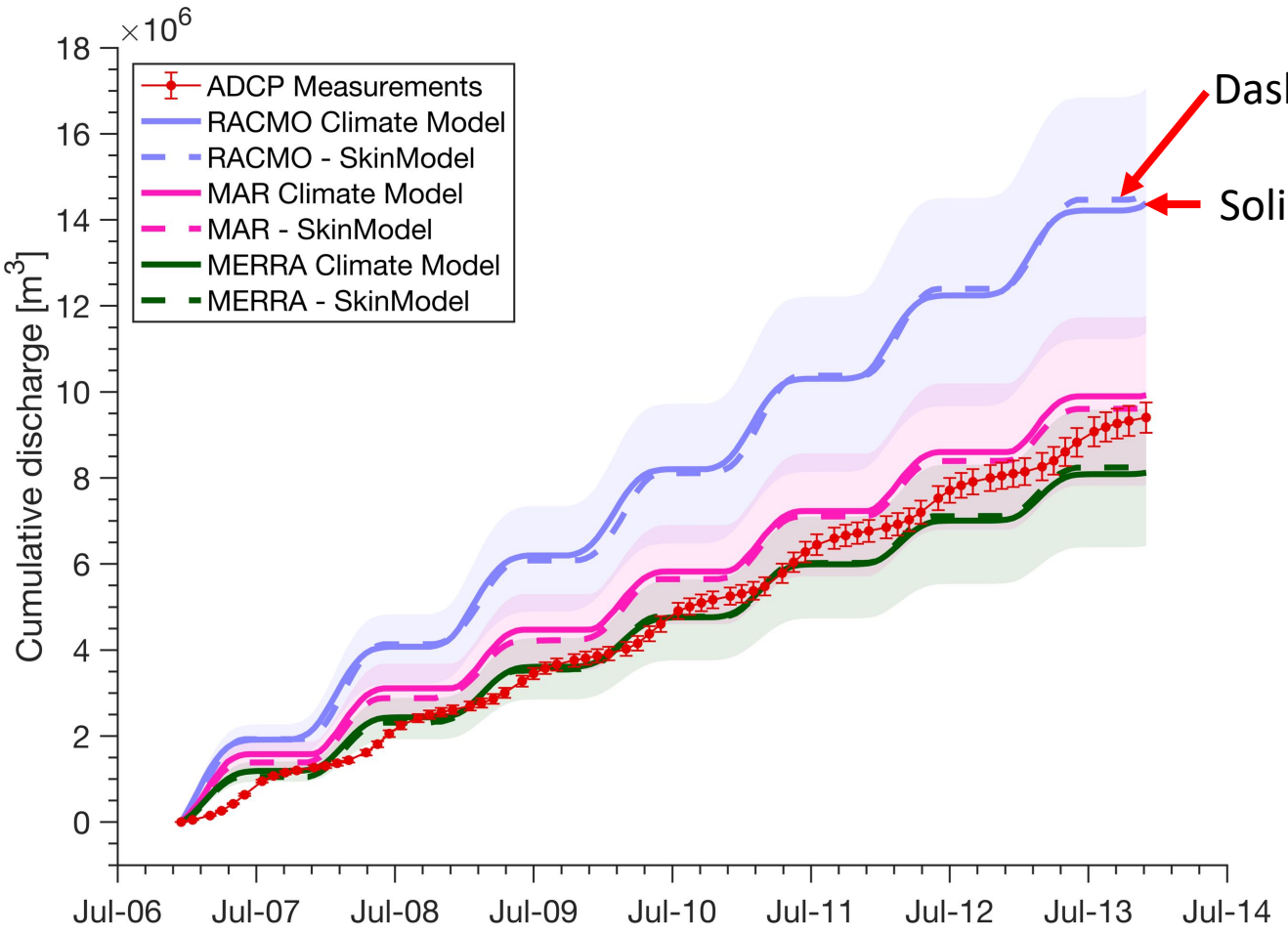
Skin Model: a numerical model of ice sheet meltwater runoff



$$C_{\mathrm{v}} \frac{\partial T_{\mathrm{i}}}{\partial t} = \frac{\partial}{\partial z}\left[k_{\mathrm{i}} \frac{\partial T_{\mathrm{i}}}{\partial z} \right]$$

$$Q_{\mathrm{si}}(1-\alpha) + Q_{\mathrm{li}} - \epsilon\sigma T_{\mathrm{sfc}}^{4} + Q_{\mathrm{h}} + Q_{\mathrm{e}} + Q_{\mathrm{c}} = Q_{\mathrm{m}}$$

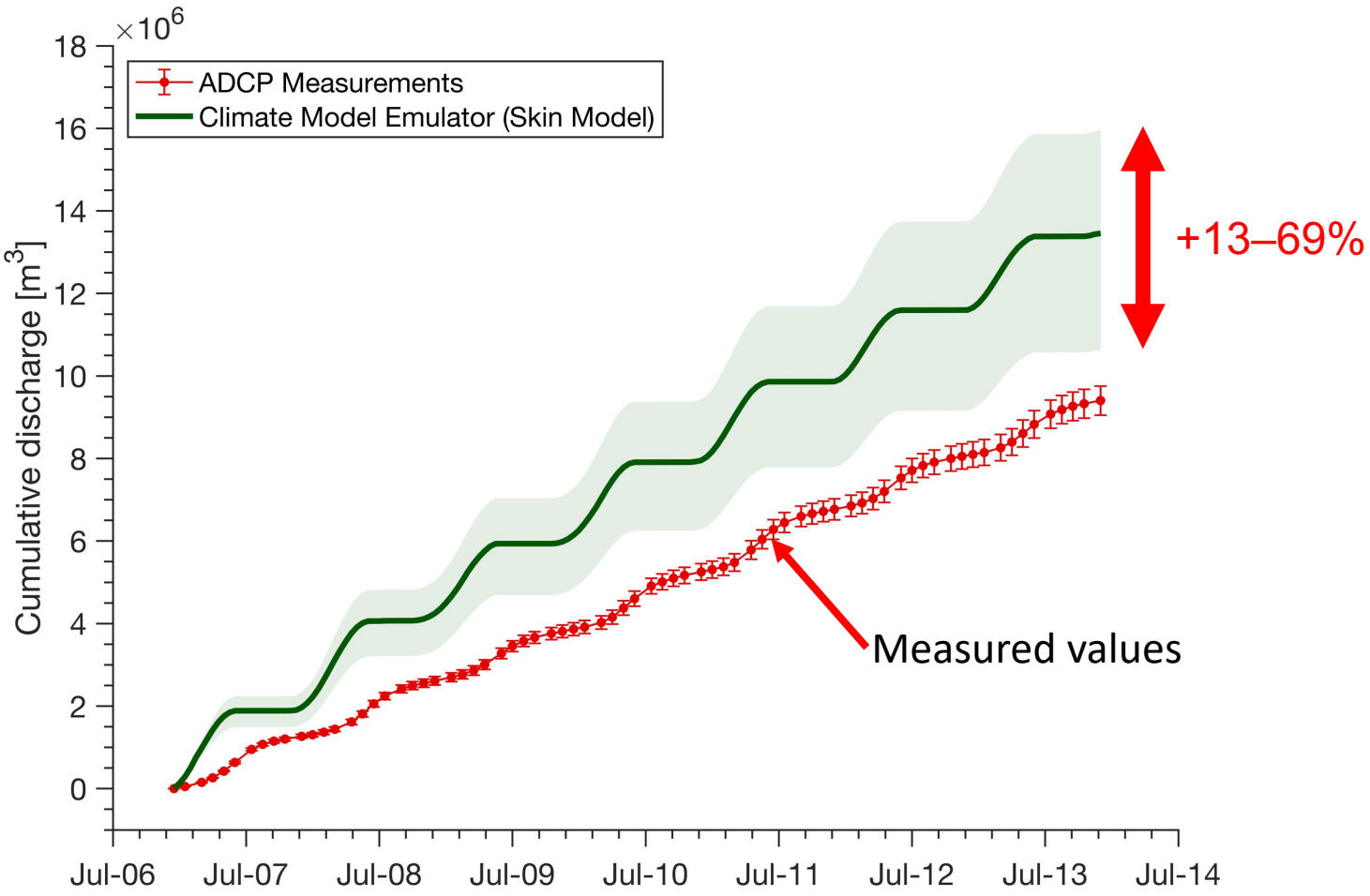
Emulating climate model predictions of ice sheet meltwater runoff



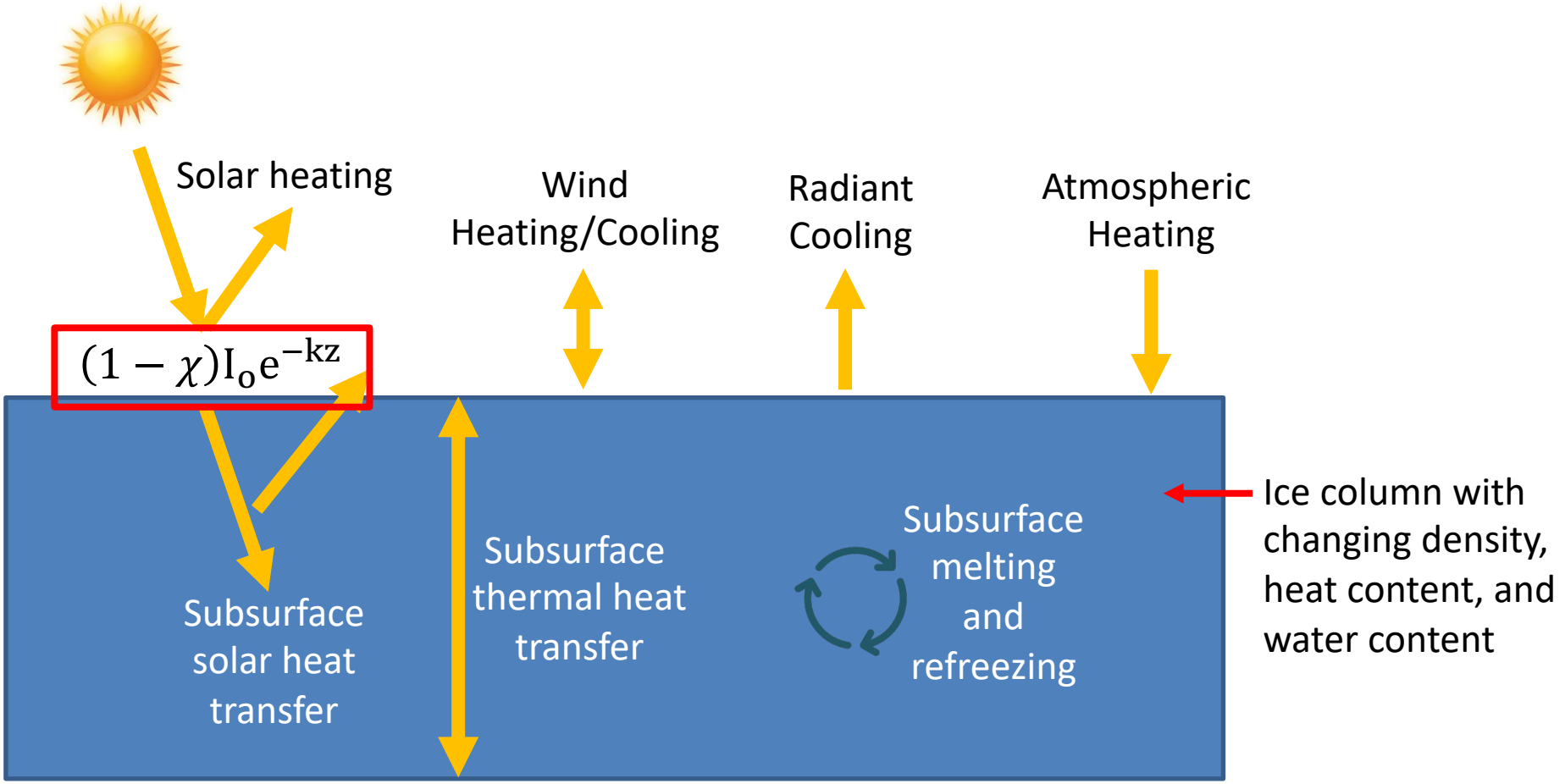
Dashed lines = Skin Model

Solid lines = Climate Models

Explaining climate model predictions of ice sheet meltwater runoff



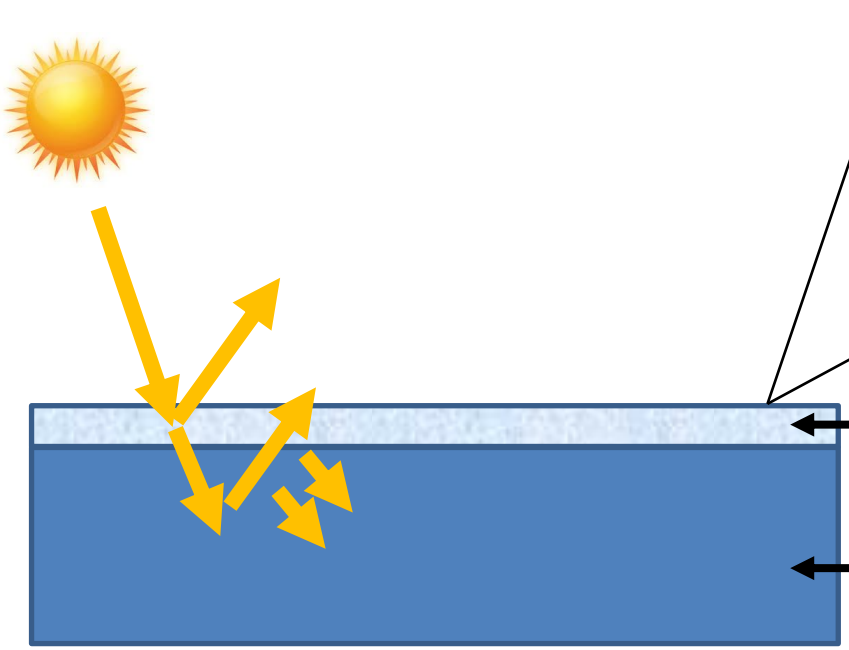
Ice Model: a numerical model of ice sheet meltwater runoff

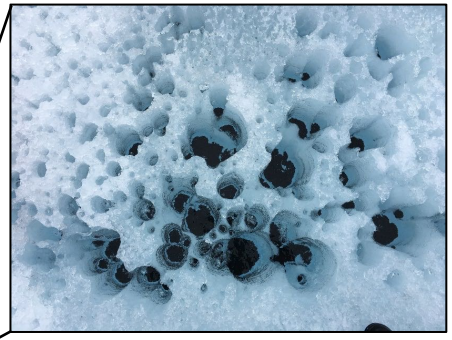


$$C_\mathrm{v}\frac{\partial T_\mathrm{i}}{\partial t}-\rho_\mathrm{i}L_\mathrm{f}\frac{\partial \theta_\mathrm{i}}{\partial t}=\frac{\partial}{\partial z}\left[(k_\mathrm{i}+k_\mathrm{v})\frac{\partial T_\mathrm{i}}{\partial z}\right]-\frac{\partial \mathrm{q}}{\partial z}-C_\mathrm{v}v_\mathrm{i}\frac{\partial T_\mathrm{i}}{\partial z}$$

- 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

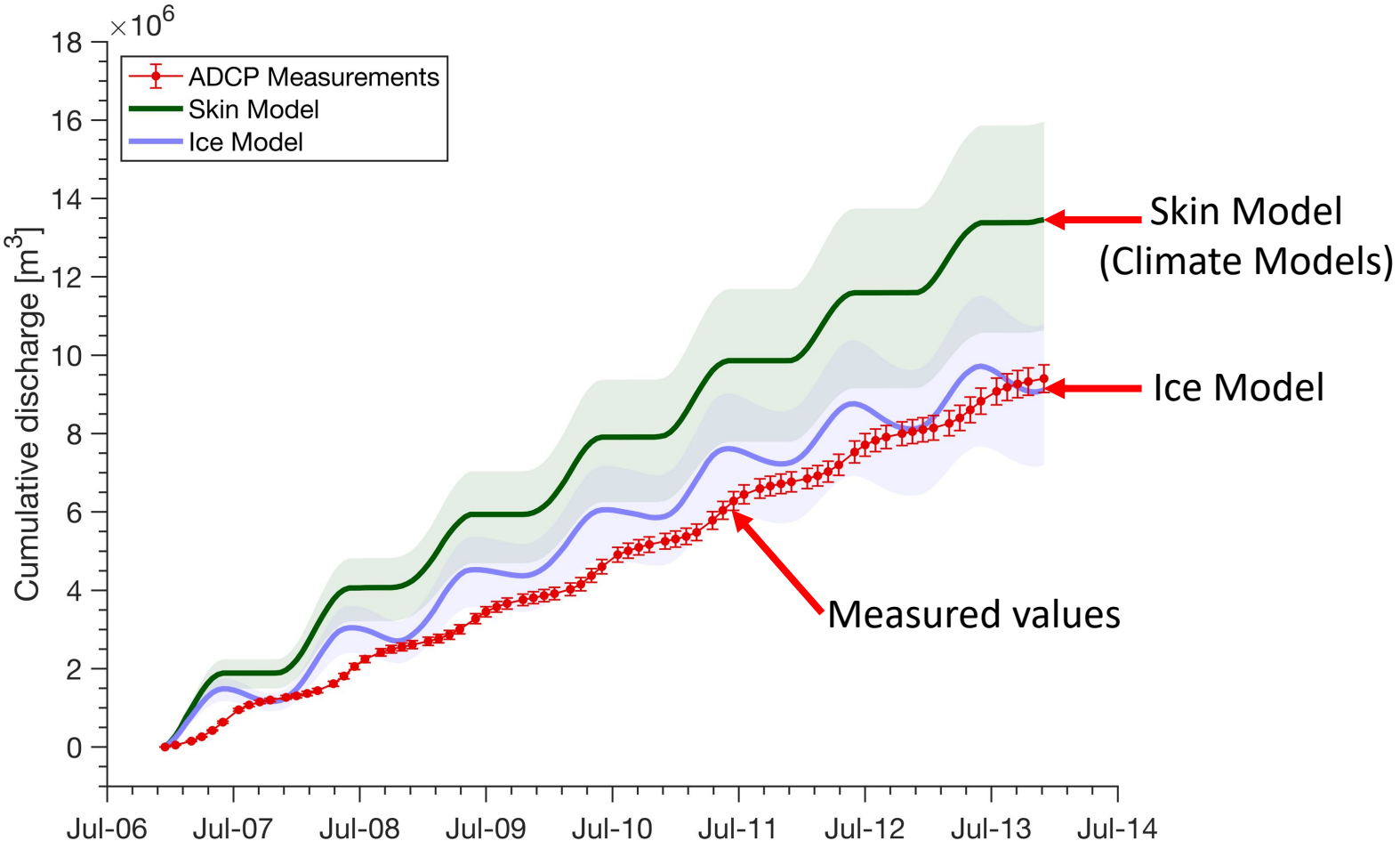




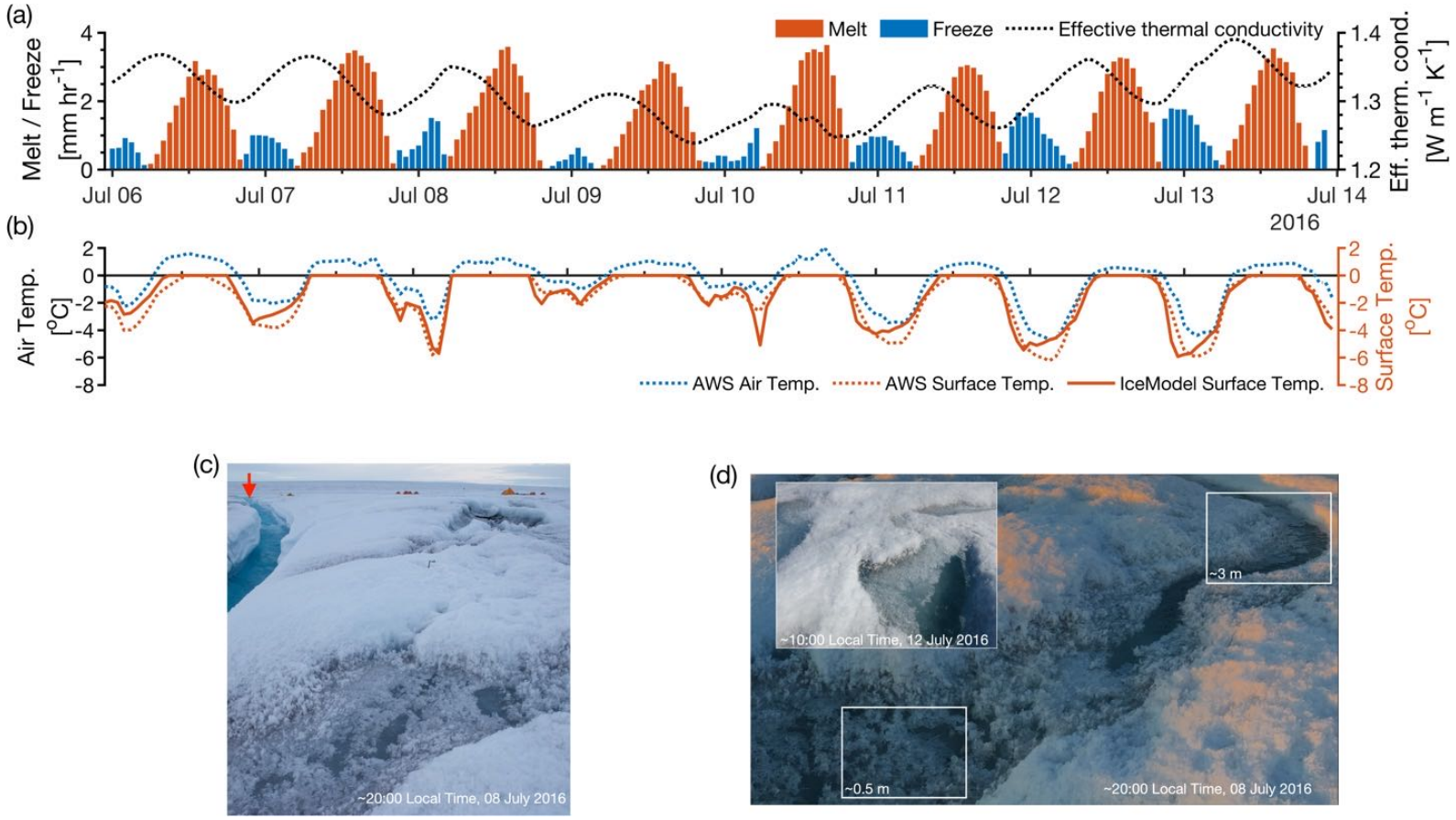
Rotten ice near the surface is highly reflective and contains cryoconite that absorbs light

Light that penetrates deeper provides heat that melts the ice from within

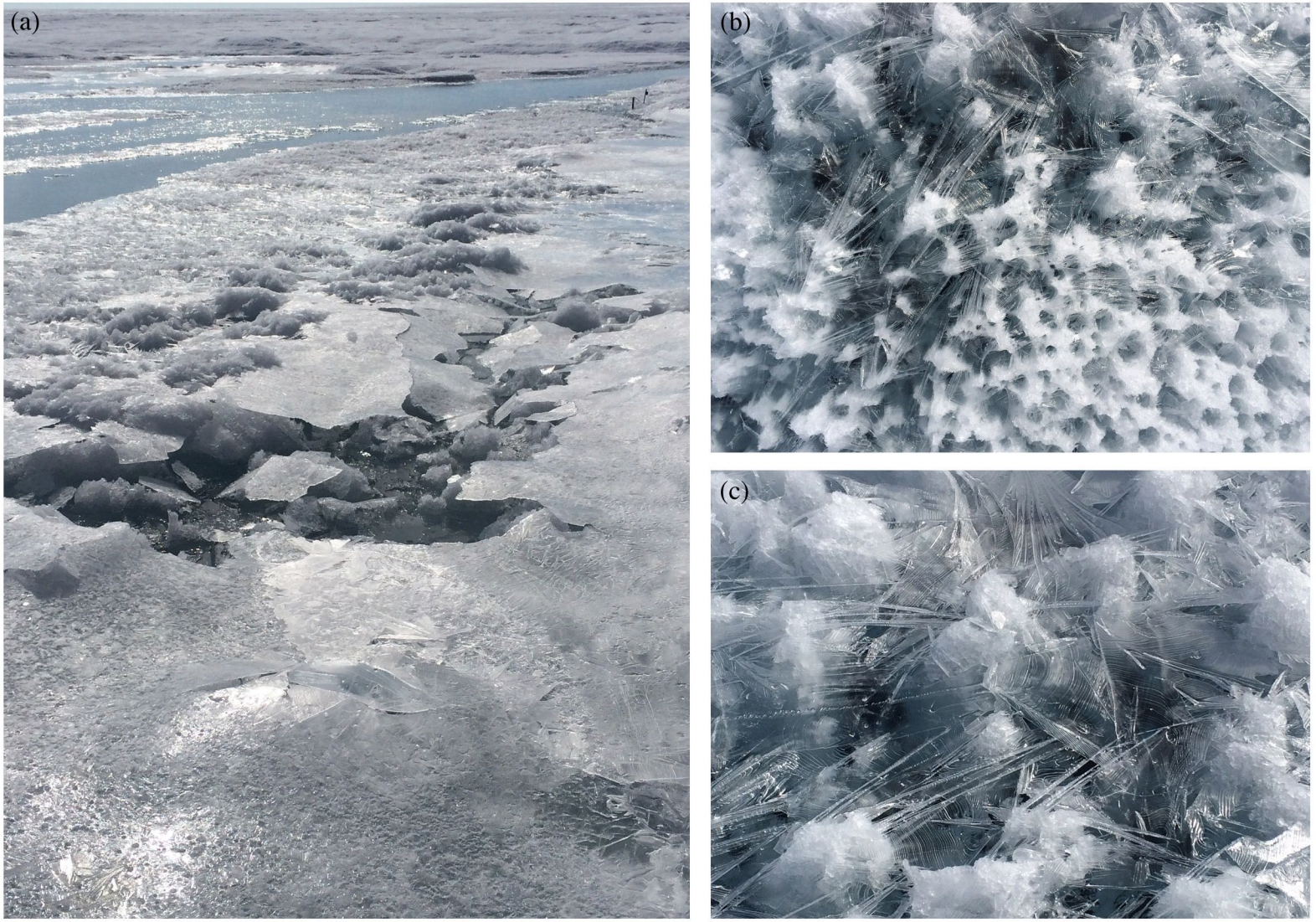
Explaining climate model predictions of ice sheet meltwater runoff



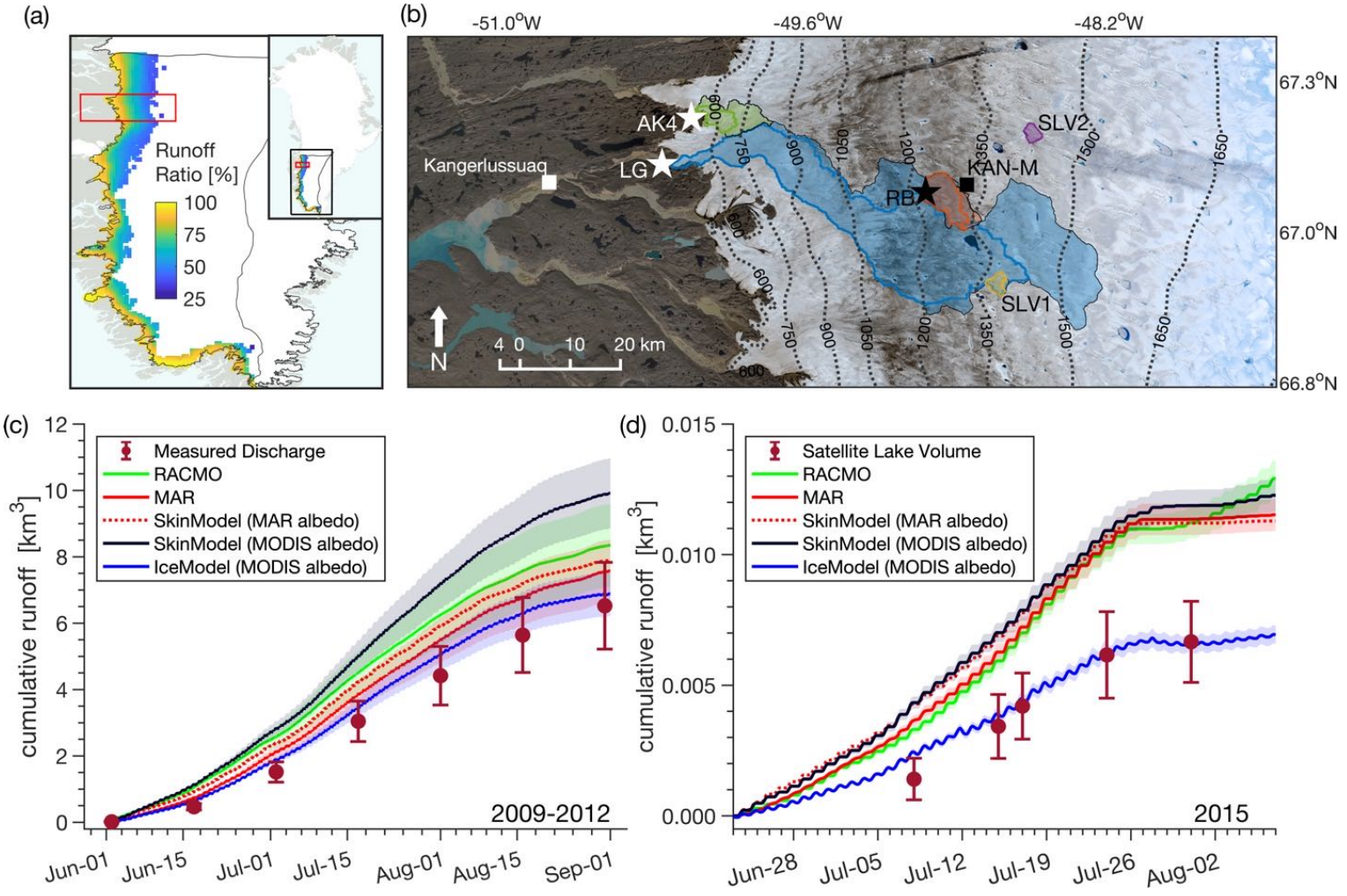
Meltwater refreezing in bare ice: a buffer on mass loss?



Refreezing explains climate model overprediction of runoff

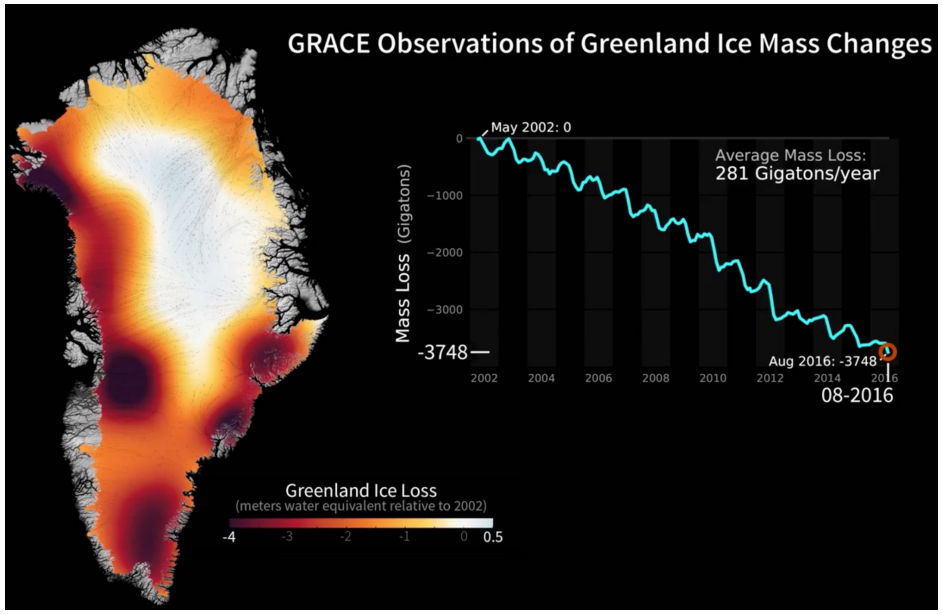


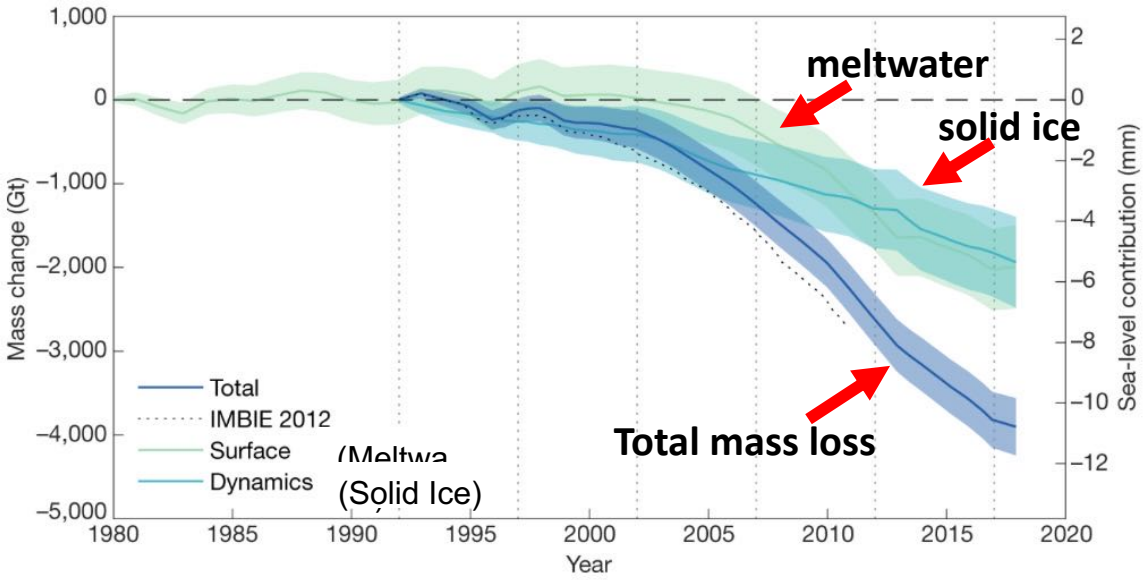
Refreezing explains climate model overprediction of runoff



Cooper et al. 2021, *(In Revision)*

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






Thank you!
(questions?)

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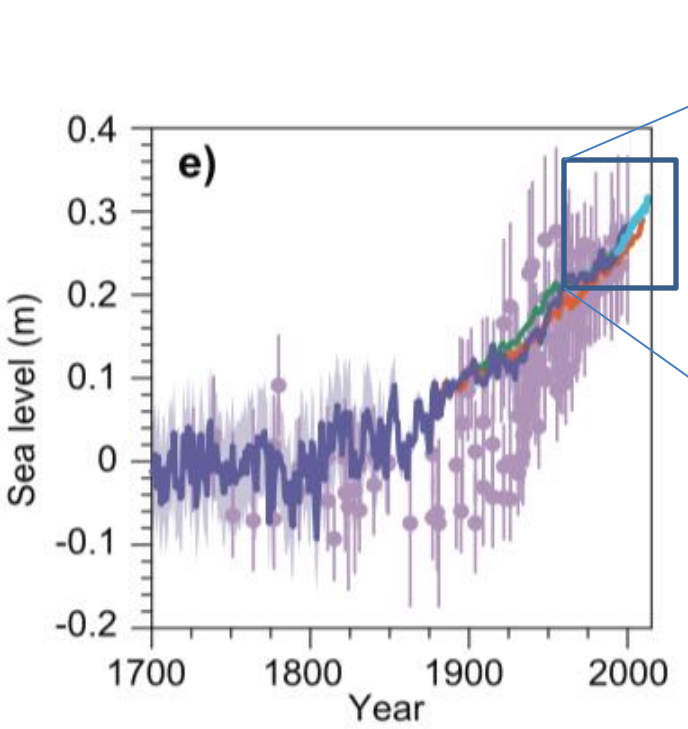
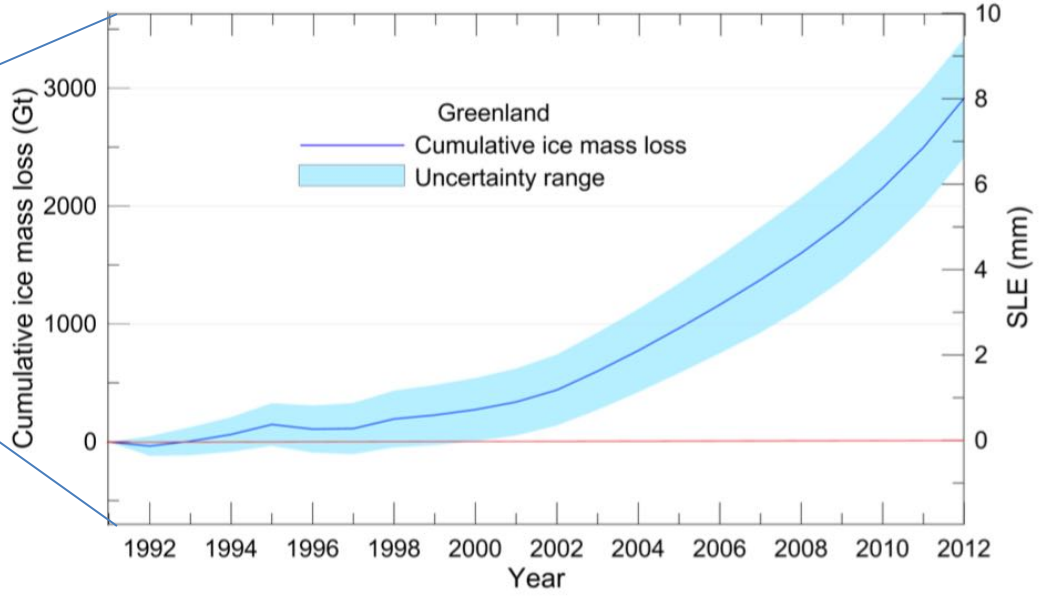
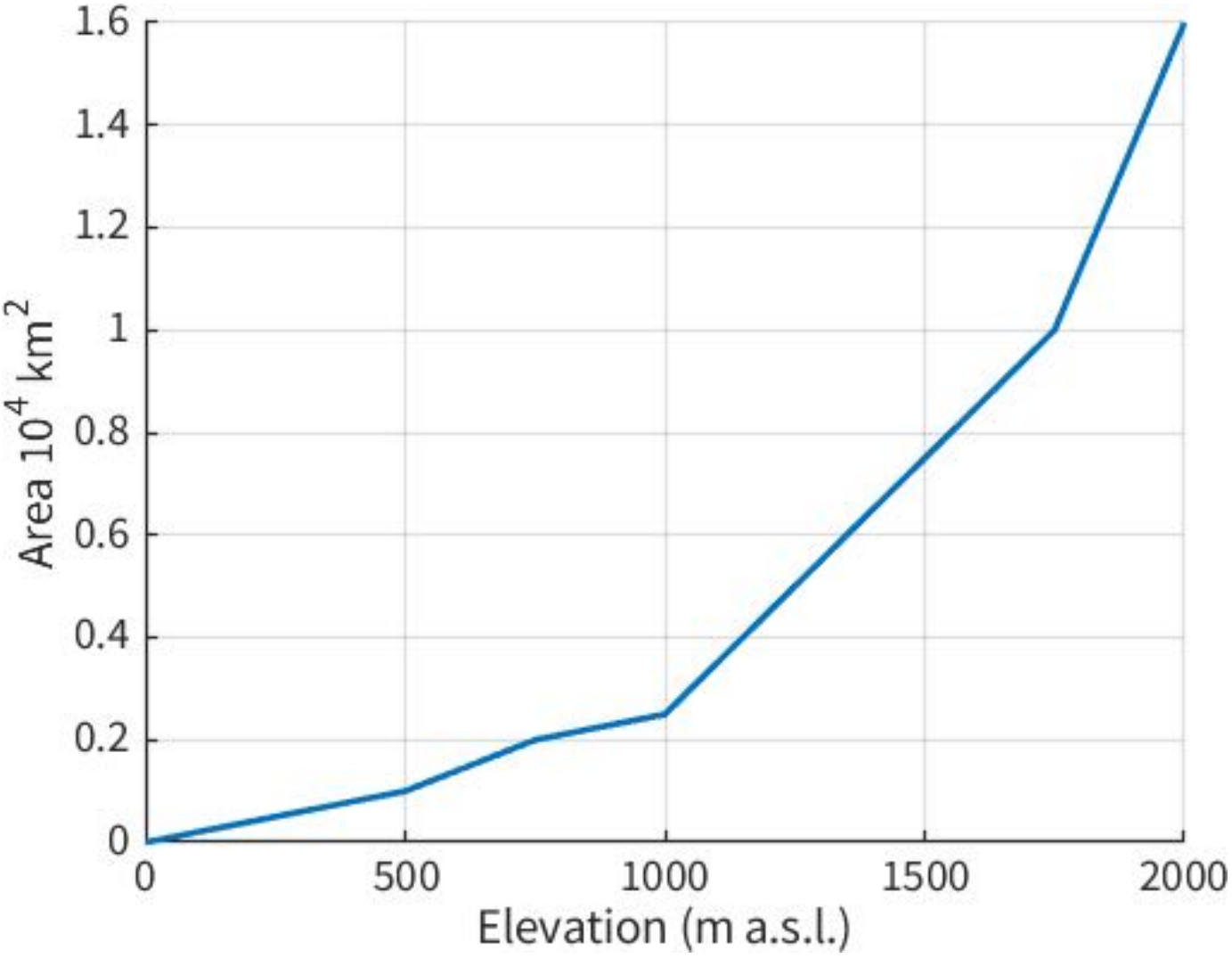


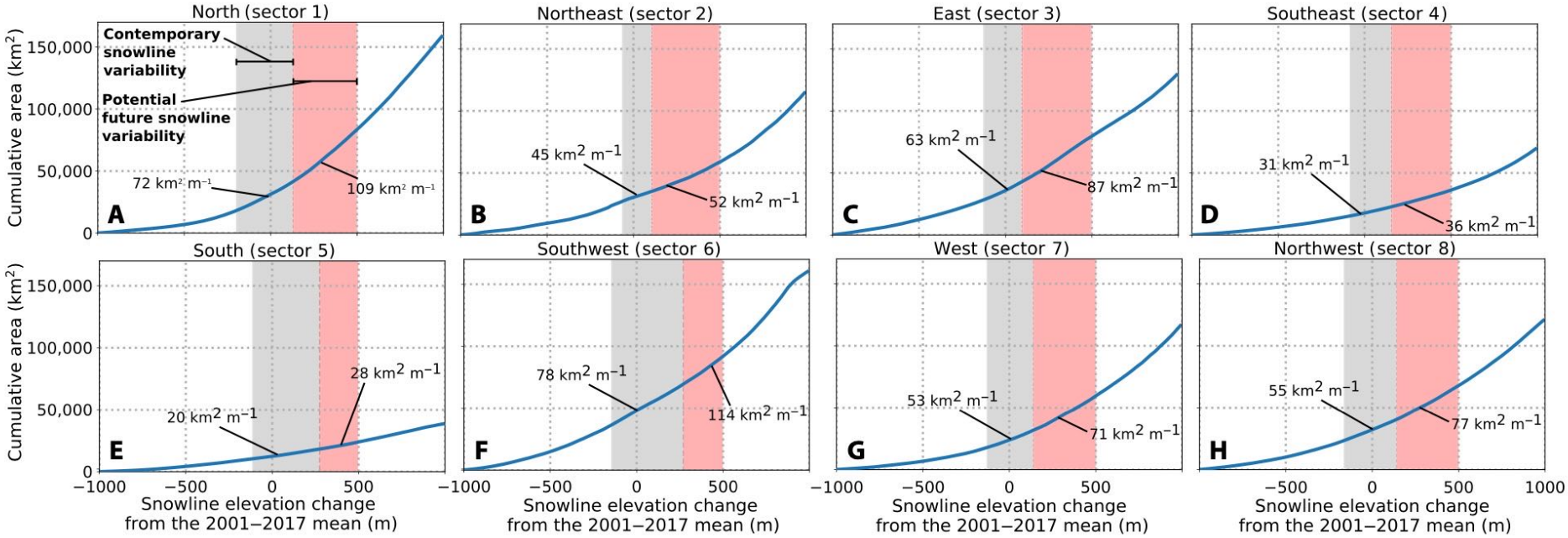


Church et al. (2013)

Ice Sheet Hypsometry

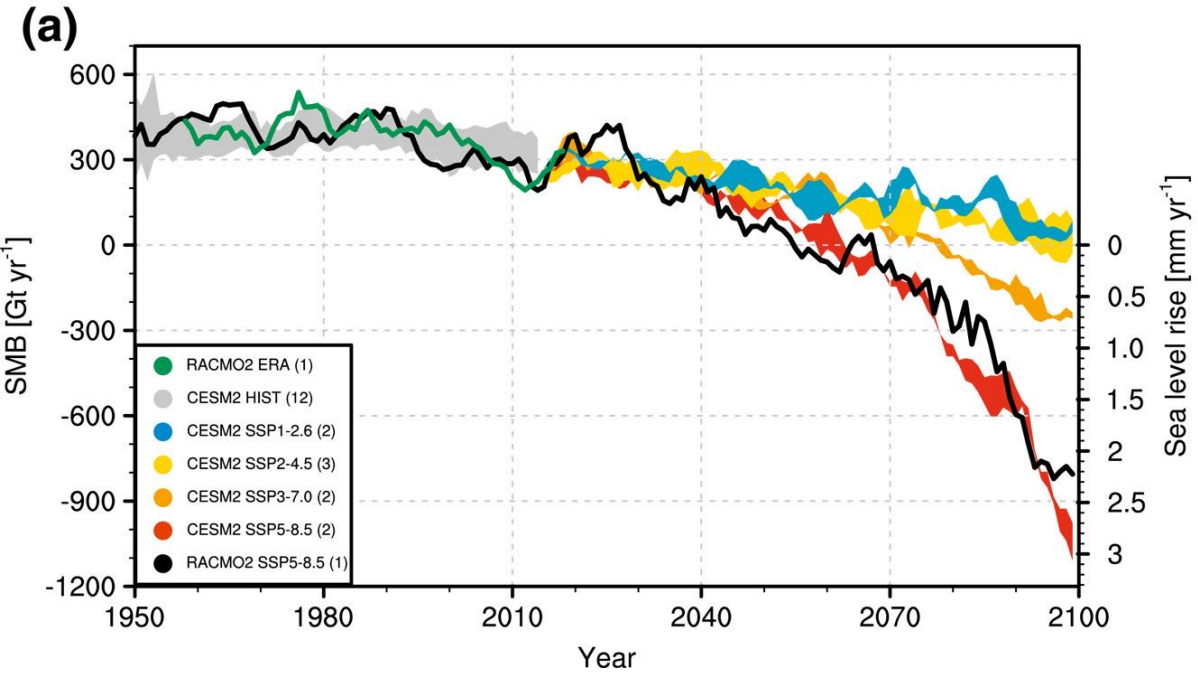


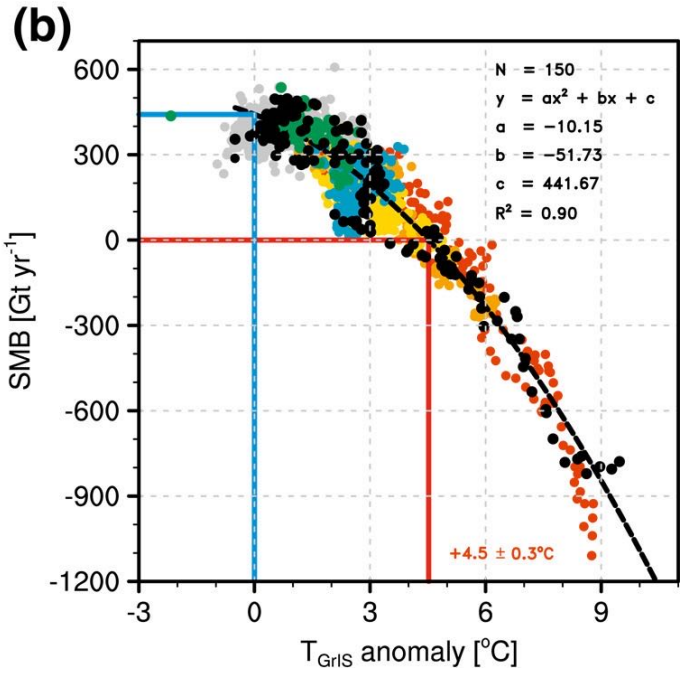
Is a tipping point ahead?



Ryan et al. 2019, *Nature Communications*

Irreversible mass loss due to negative SMB



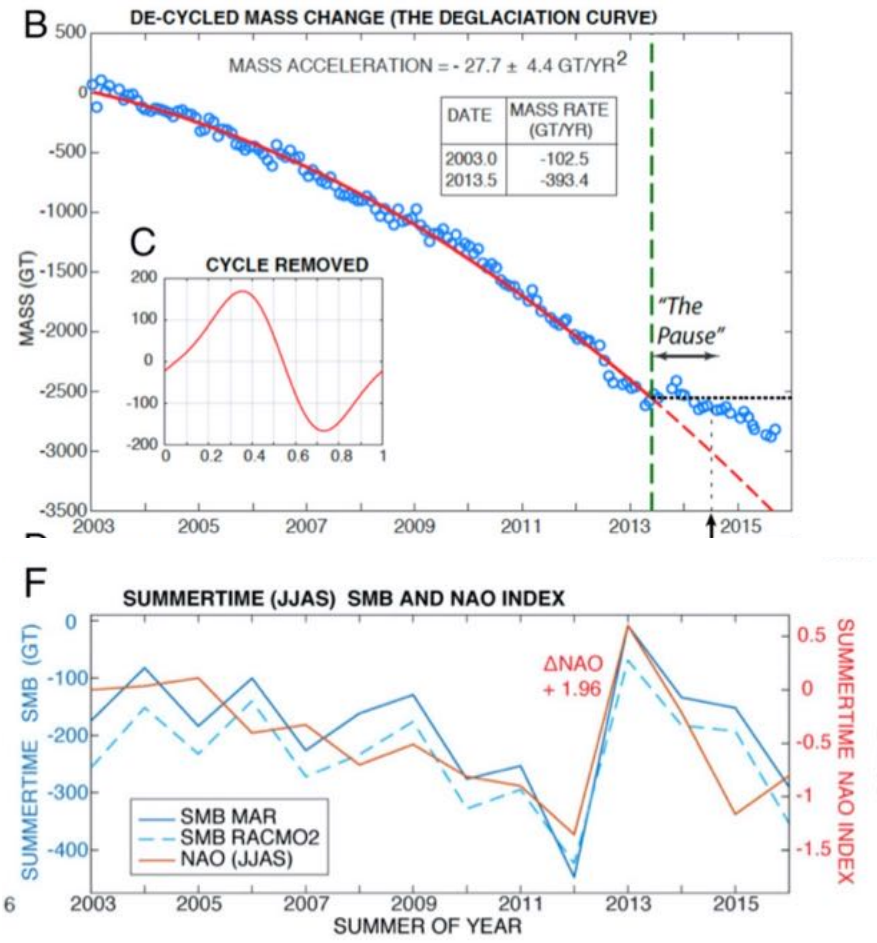


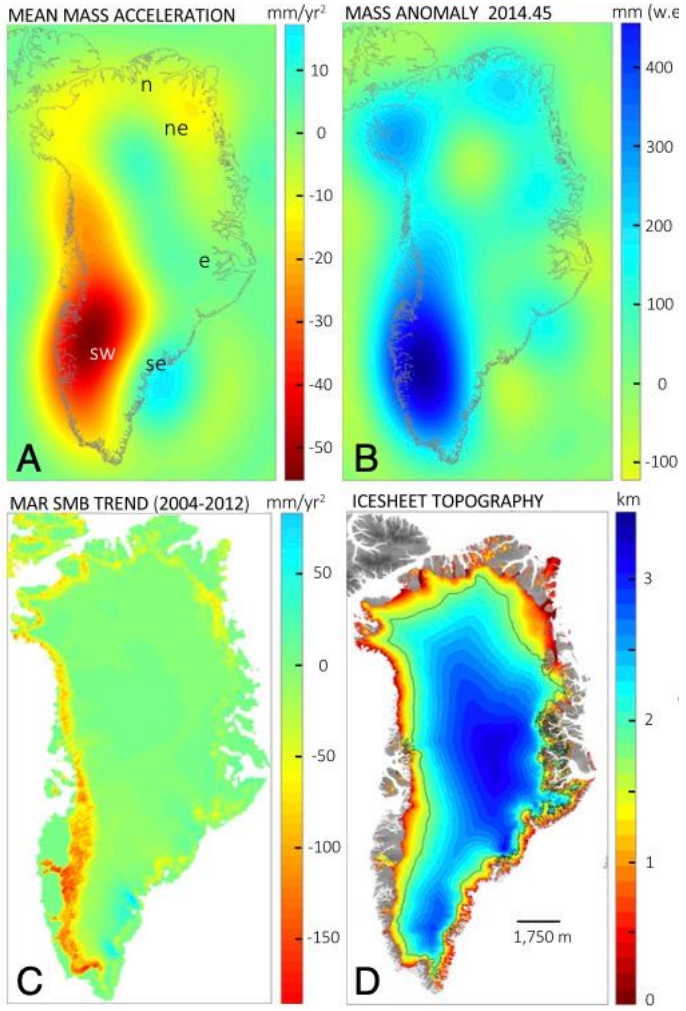
Noel et al. 2021, *GRL*

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

Theme: irreversible tipping points

Regional atmospheric circulation and surface melt

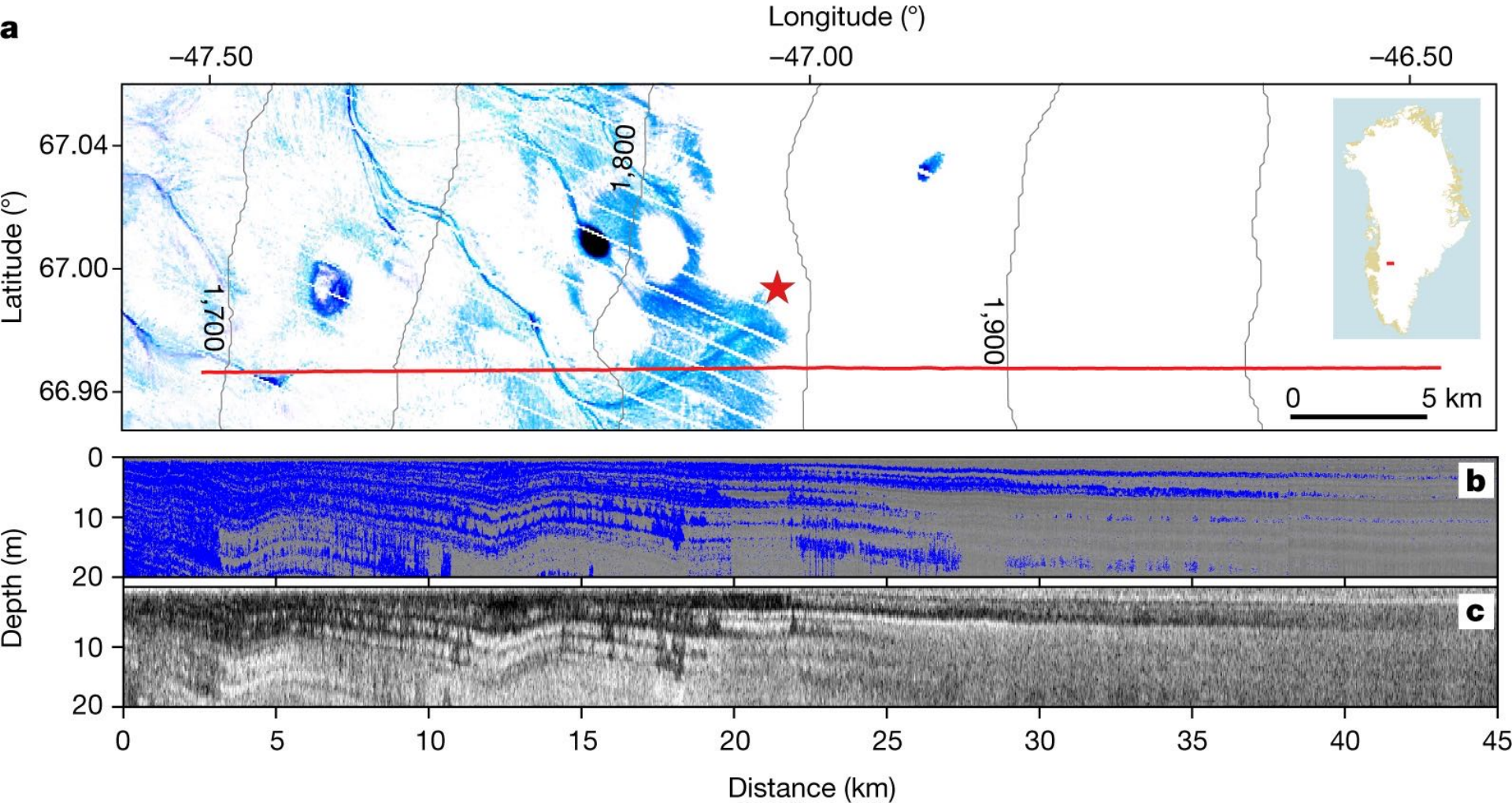




Bevis et al. 2019, *PNAS*

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

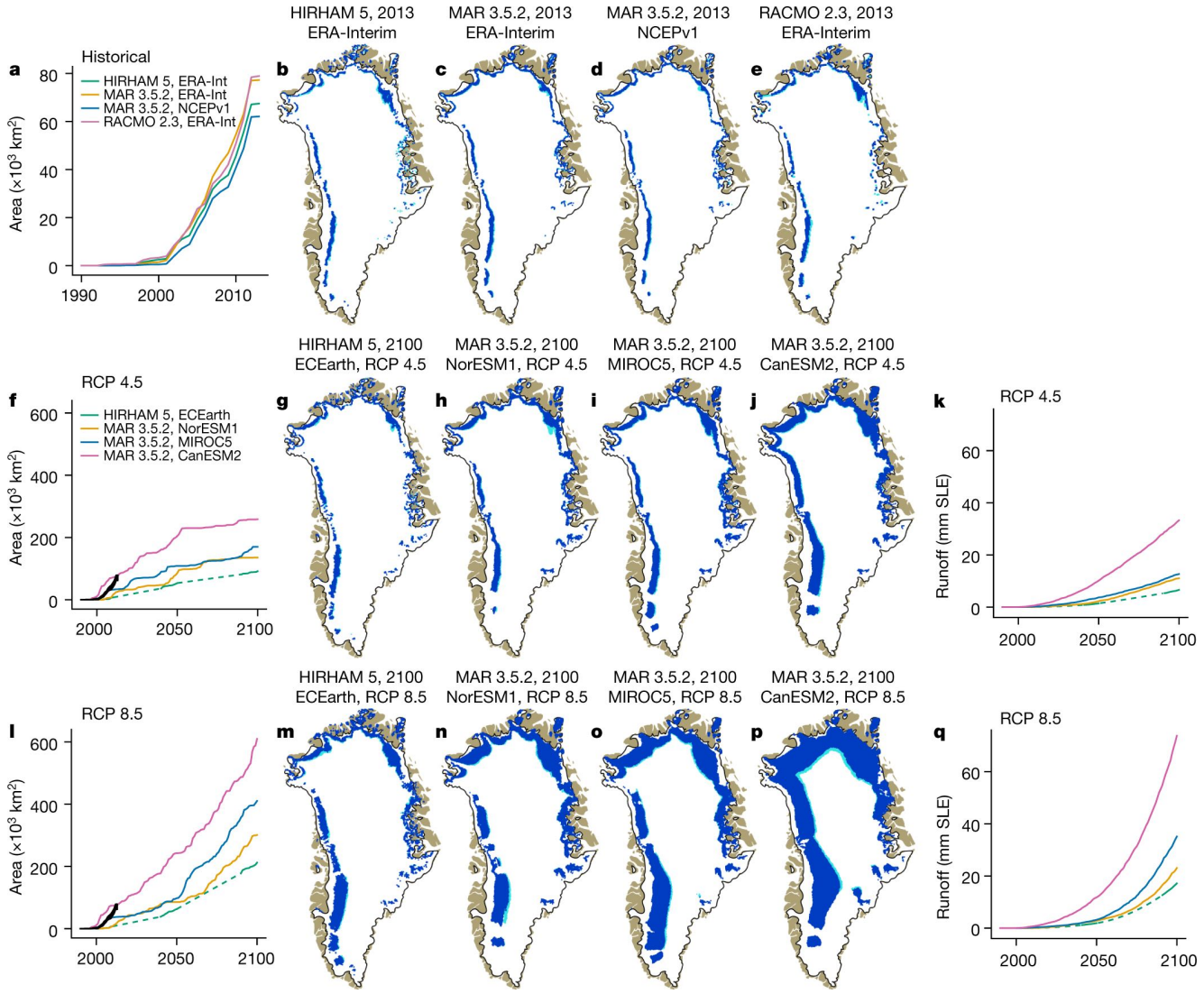
Meltwater runoff over low-permeability ice slabs in southwest Greenland



MacFerrin et al. 2019, *Nature*

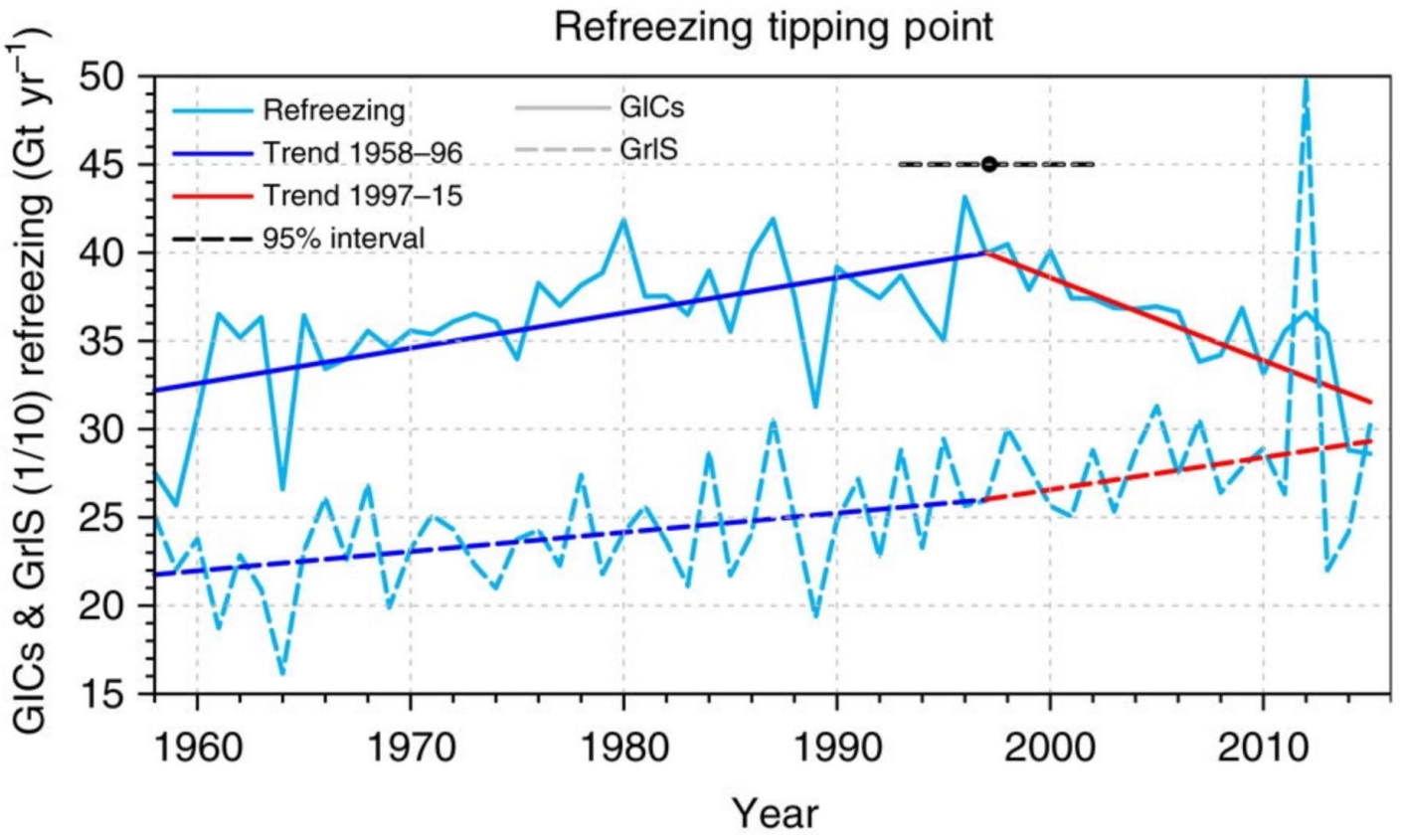
Theme: Meltwater refreezing in firn

Meltwater runoff over low-permeability ice slabs in southwest Greenland



MacFerrin et al. 2019, *Nature*

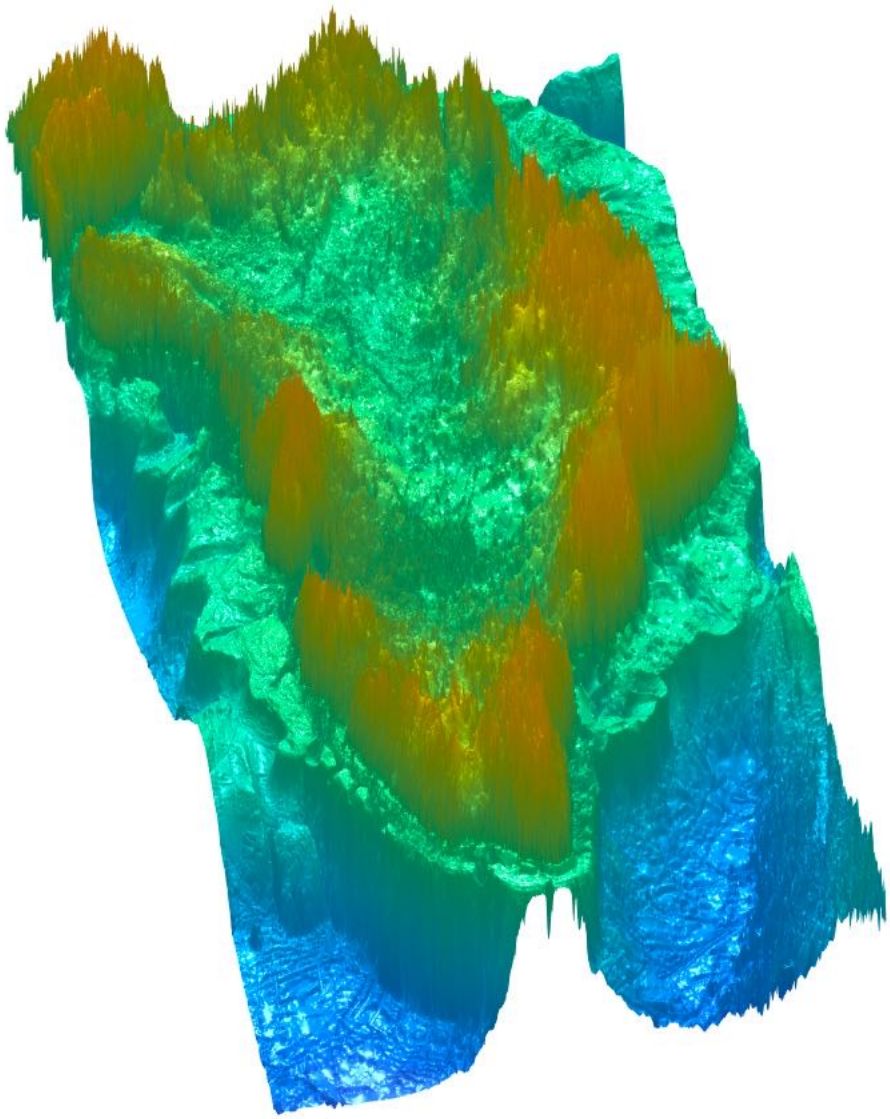
Is a tipping point ahead?

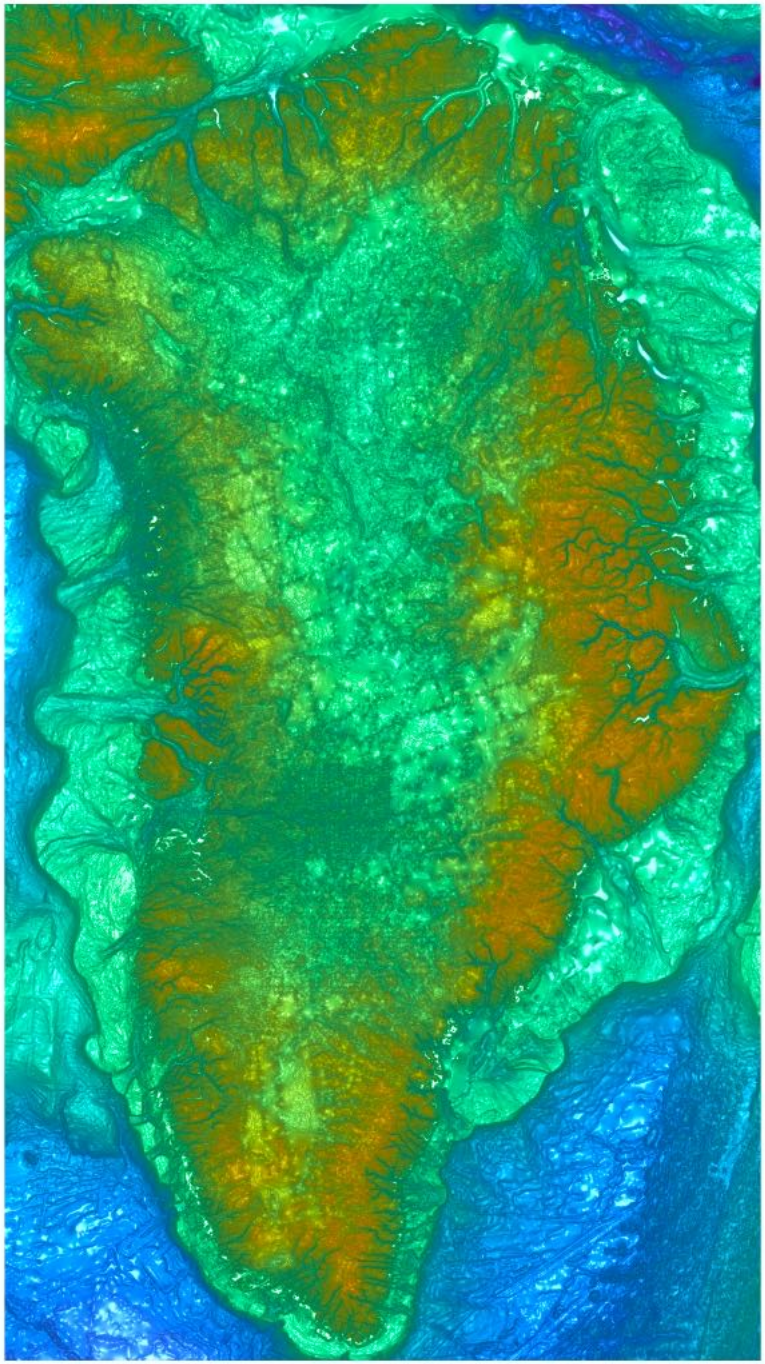


Noel et al. 2019, *Nature Communications*

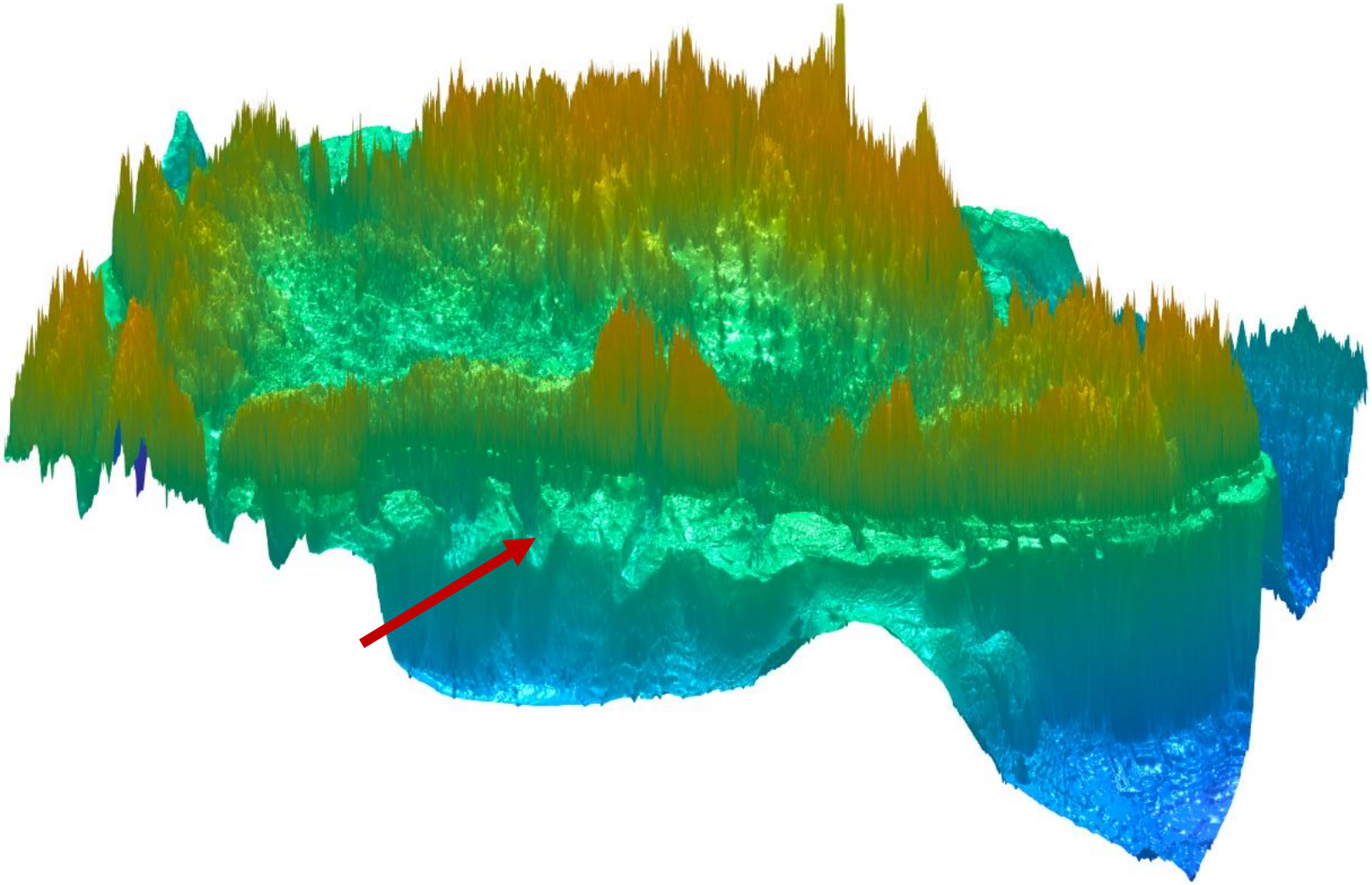
Theme: Meltwater refreezing in firn leading to irreversible mass loss

“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*