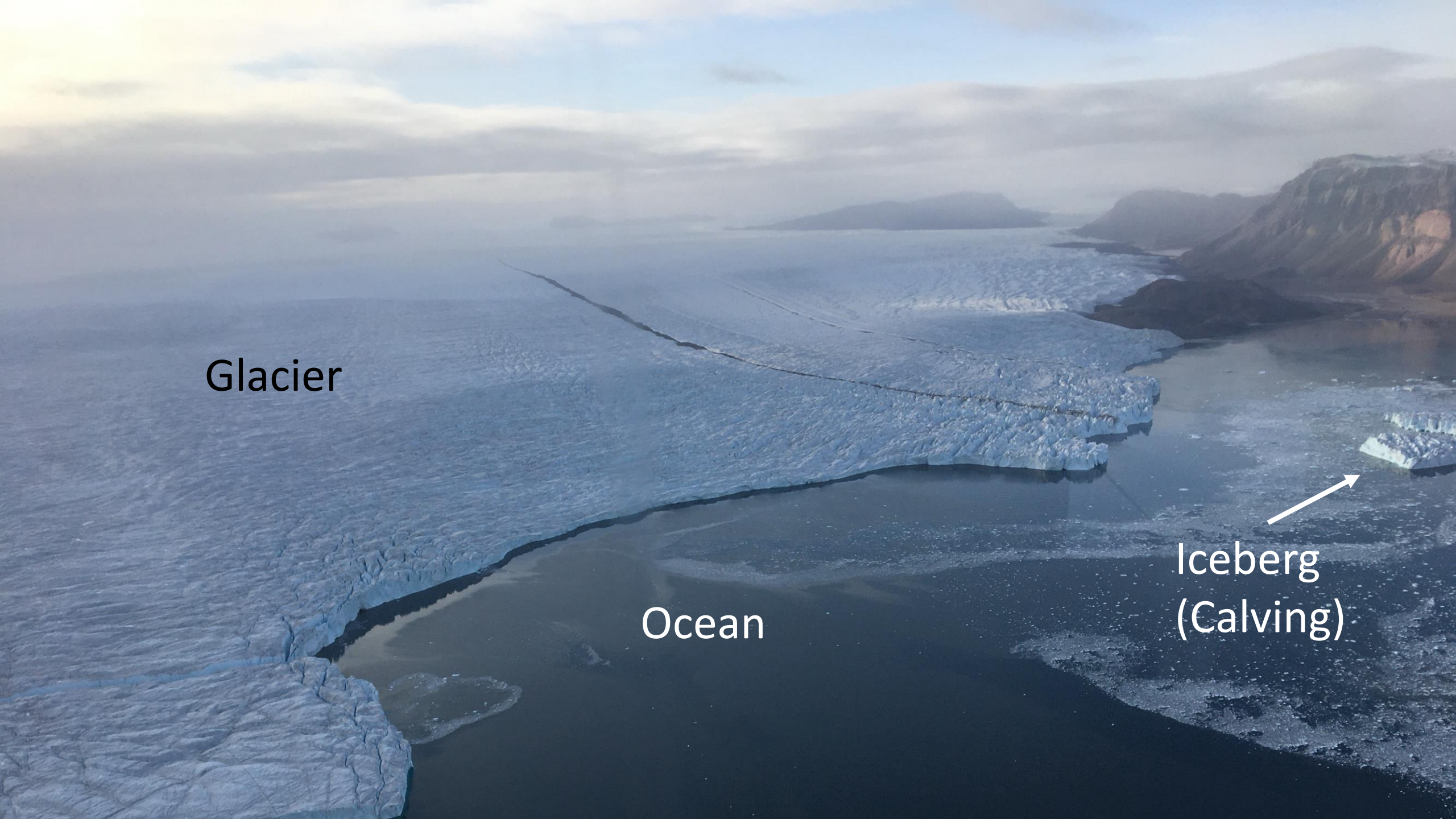
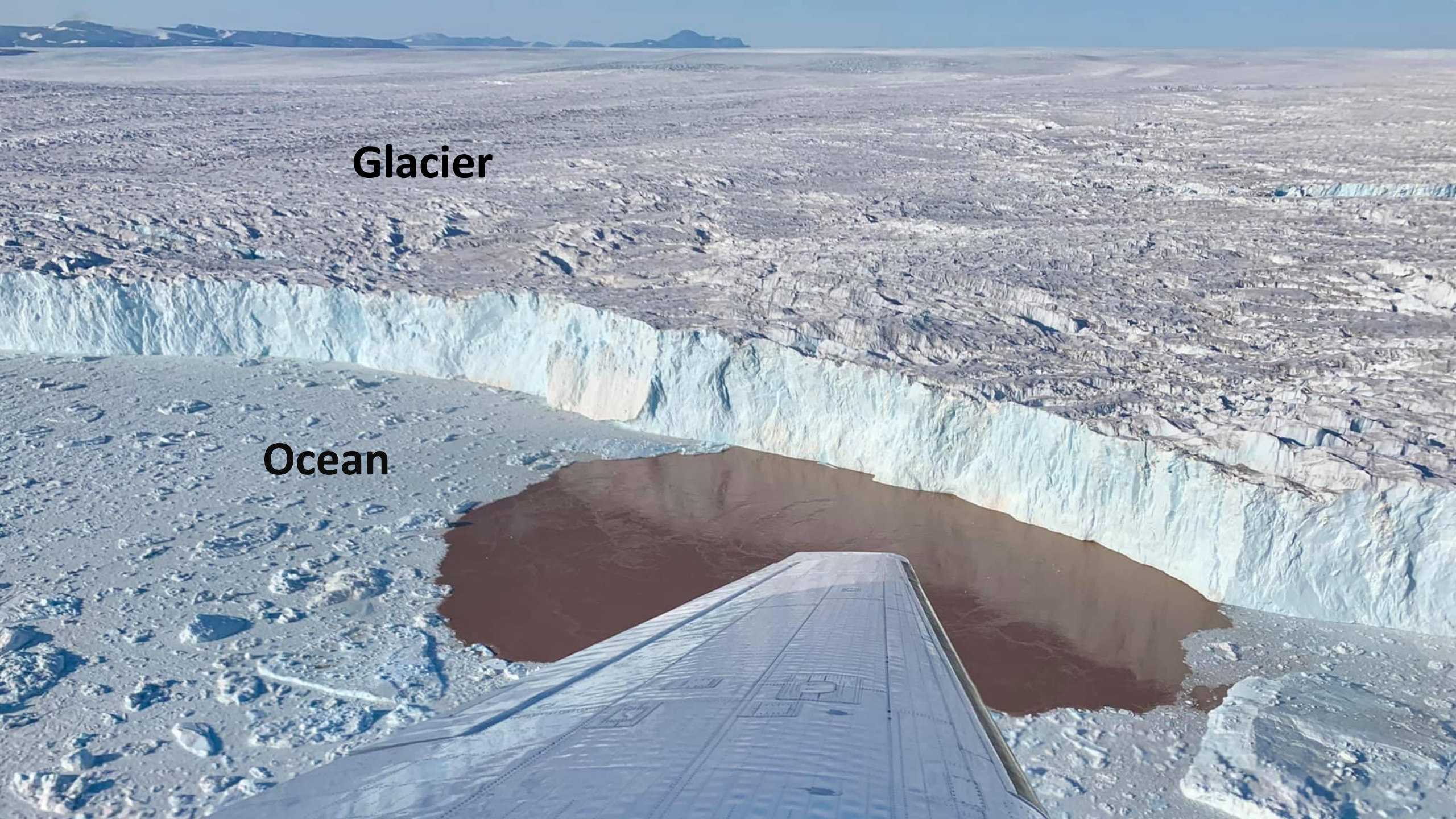
Ice Sheet - Ocean Interactions

Mike Wood

ECCO Summer School 2025


Glacier
Ocean
Iceberg
(Calving)


Rink Isbræ,
West Greenland

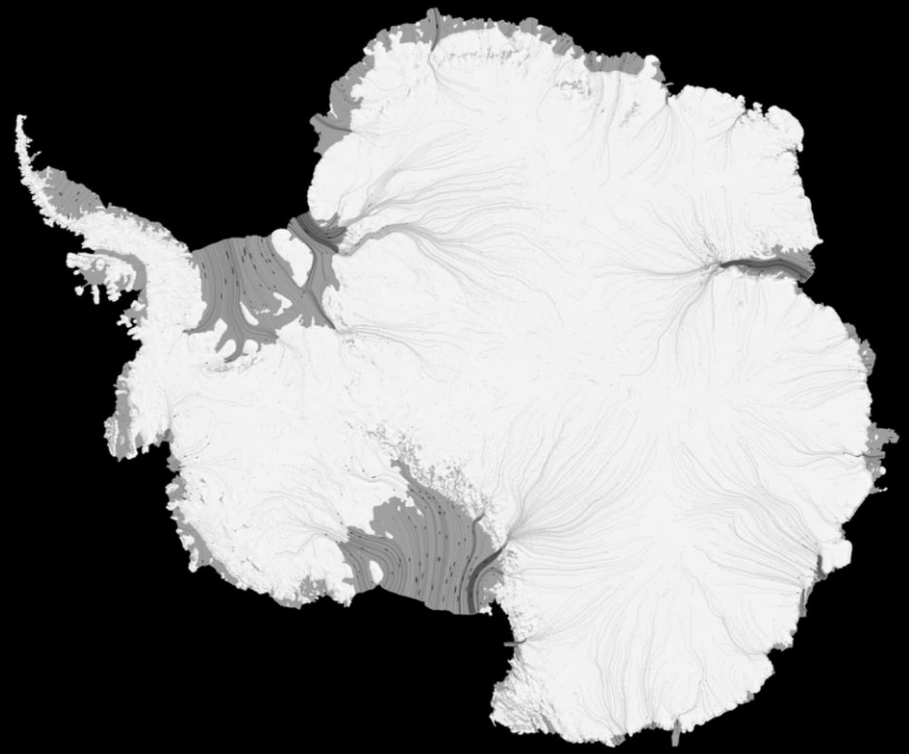

Glacier
Ocean

Learning Objectives

By the end of this presentation, I hope that you are able to:

1. Outline recent changes on the Greenland and Antarctic ice sheets
2. Describe how:
    1. ocean variability influences the ice sheets
    2. ice sheet melt influences the ocean
3. Understand how ECCO and MITgcm can (and *currently* cannot) be used to study ice ocean interactions

🤔 Questions for you



How much would sea level rise if all of Greenland's ice melted? Antarctica?

Greenland: 7.4 m
Antarctica: 66 m

How much is Greenland contributing to the 3.2 mm/yr of global sea level rise? Antarctica? (percents ok)

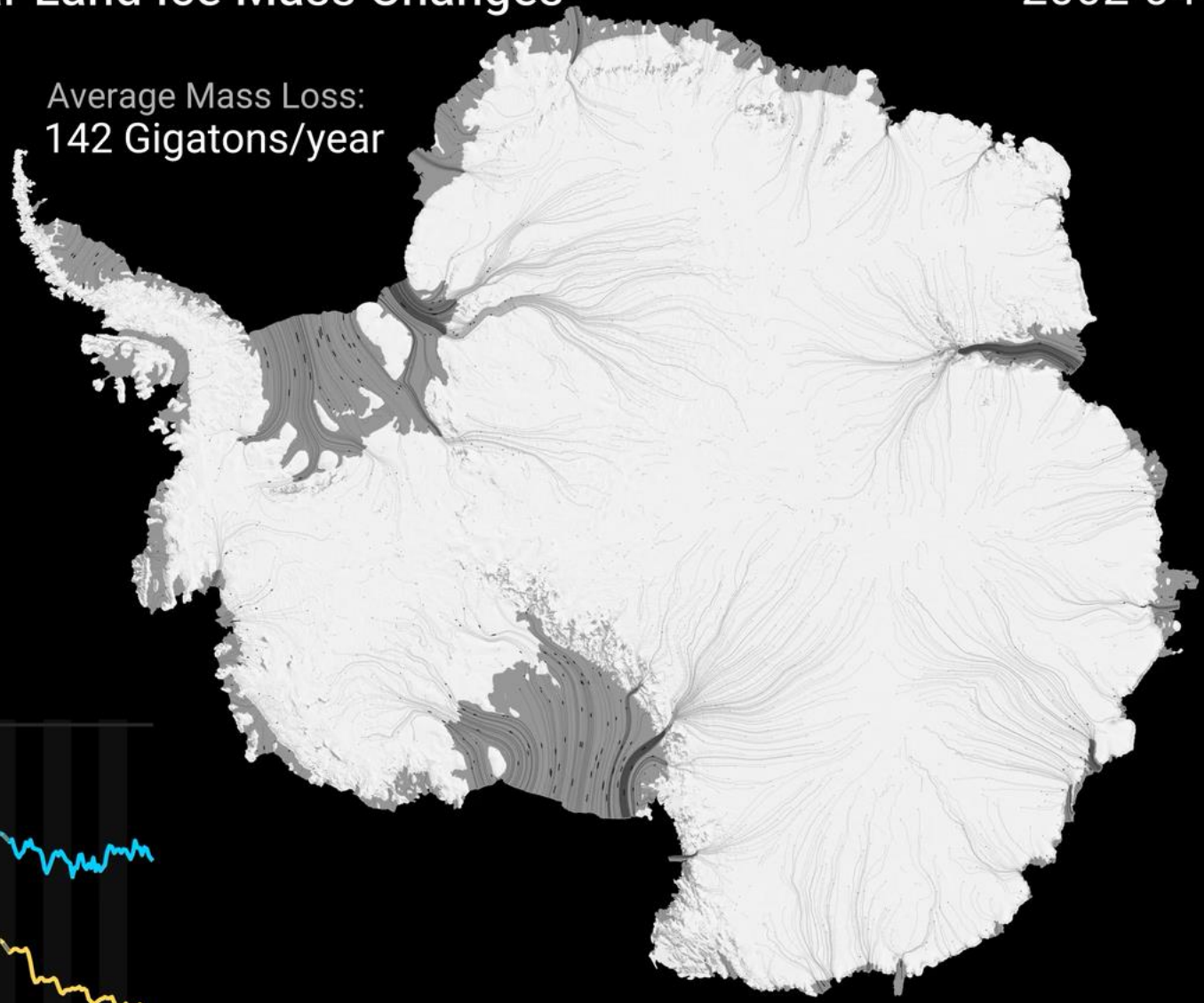
Greenland: 0.74 mm/yr (23%)
Antarctica: 0.39 mm/yr (12%)

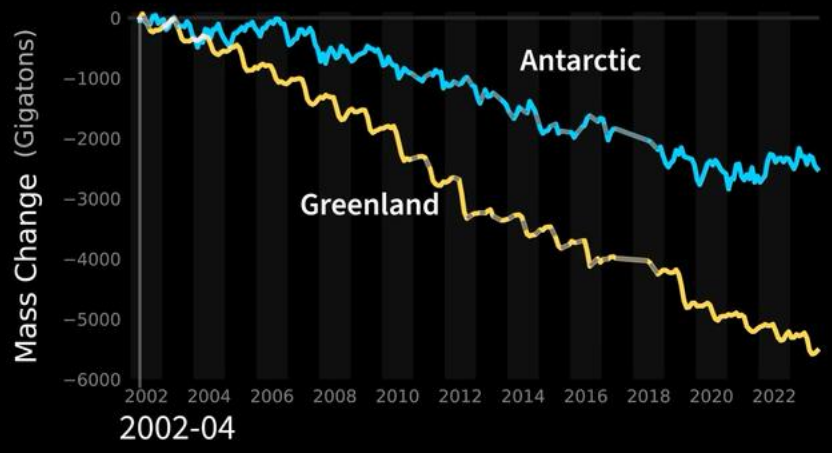
GRACE and GRACE-FO Observations of Polar Land Ice Mass Changes

2002-04

Average Mass Loss:
269 Gigatons/year

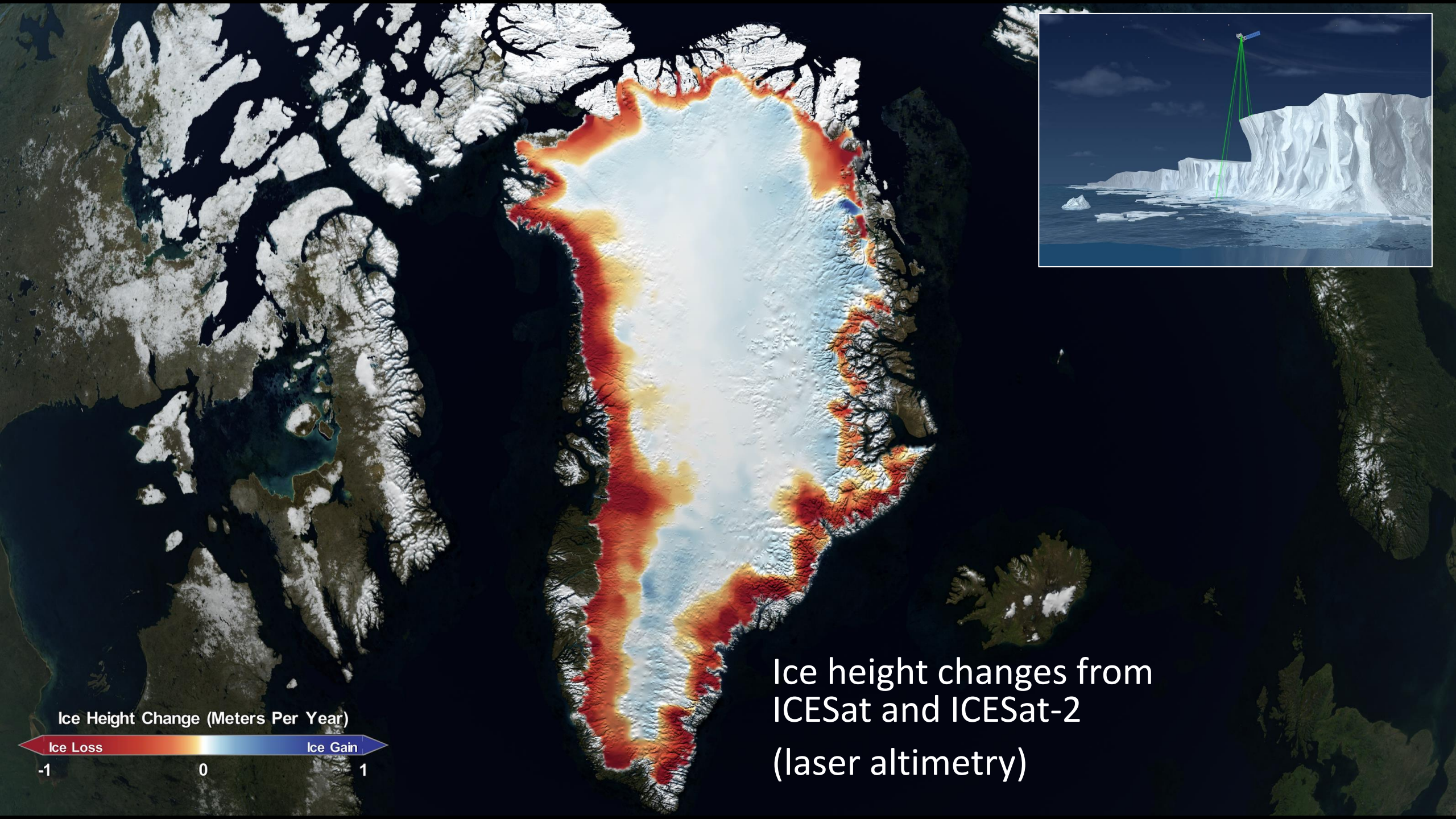
Average Mass Loss:
142 Gigatons/year





Ice Mass Change
(meters water equivalent relative to 2002)

-6 -4 -2 0 2

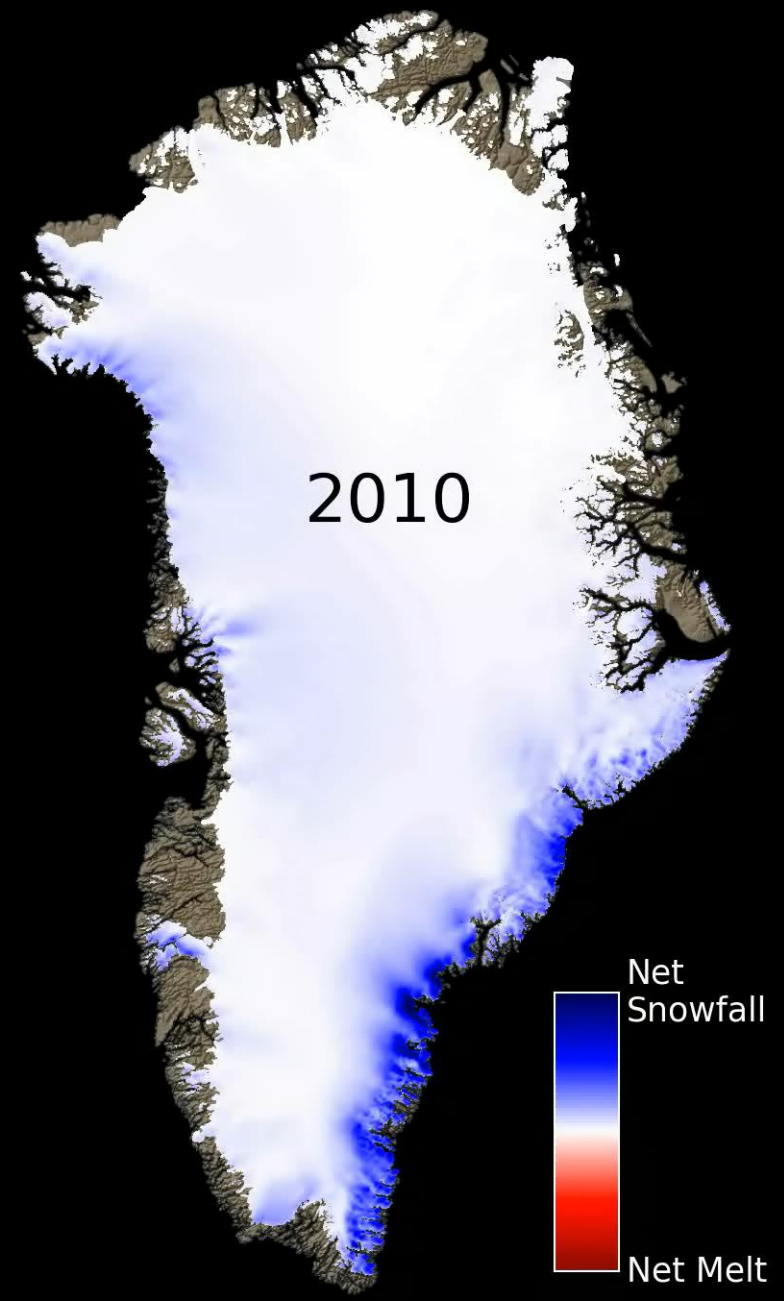


Ice height changes from ICESat and ICESat-2

(laser altimetry)

Melt from the Atmosphere

- During the winter, net snowfall results in a mass gain on the ice sheets
- During summer, there is extreme melt on the edges
- The annual mean is the Surface Mass Balance
  - Warmer air temperatures -> ice loss



Data from RACMO2.3p2, Noël et al 2019


NASA
Scientific Visualization Studio

Ocean Forcing Ice

🤔 Question for you:

What oceanographic parameters dictate ice melt rate?

Some of the major factors:

- Temperature
- Salinity

} Increase with depth at high latitudes

- Pressure
- Water Velocity

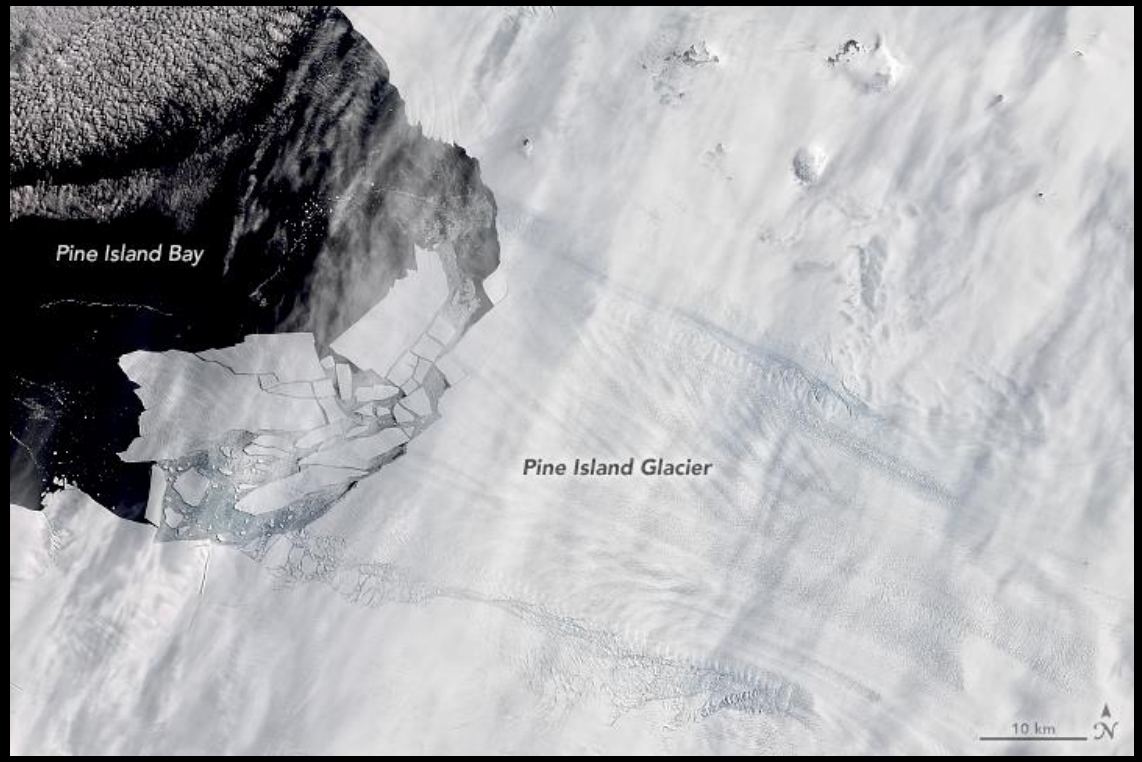
Follow-up question: What does the ice feel?

A Difference of Scales

Sermeq Kujalleq
(One of the most active glaciers in Greenland)

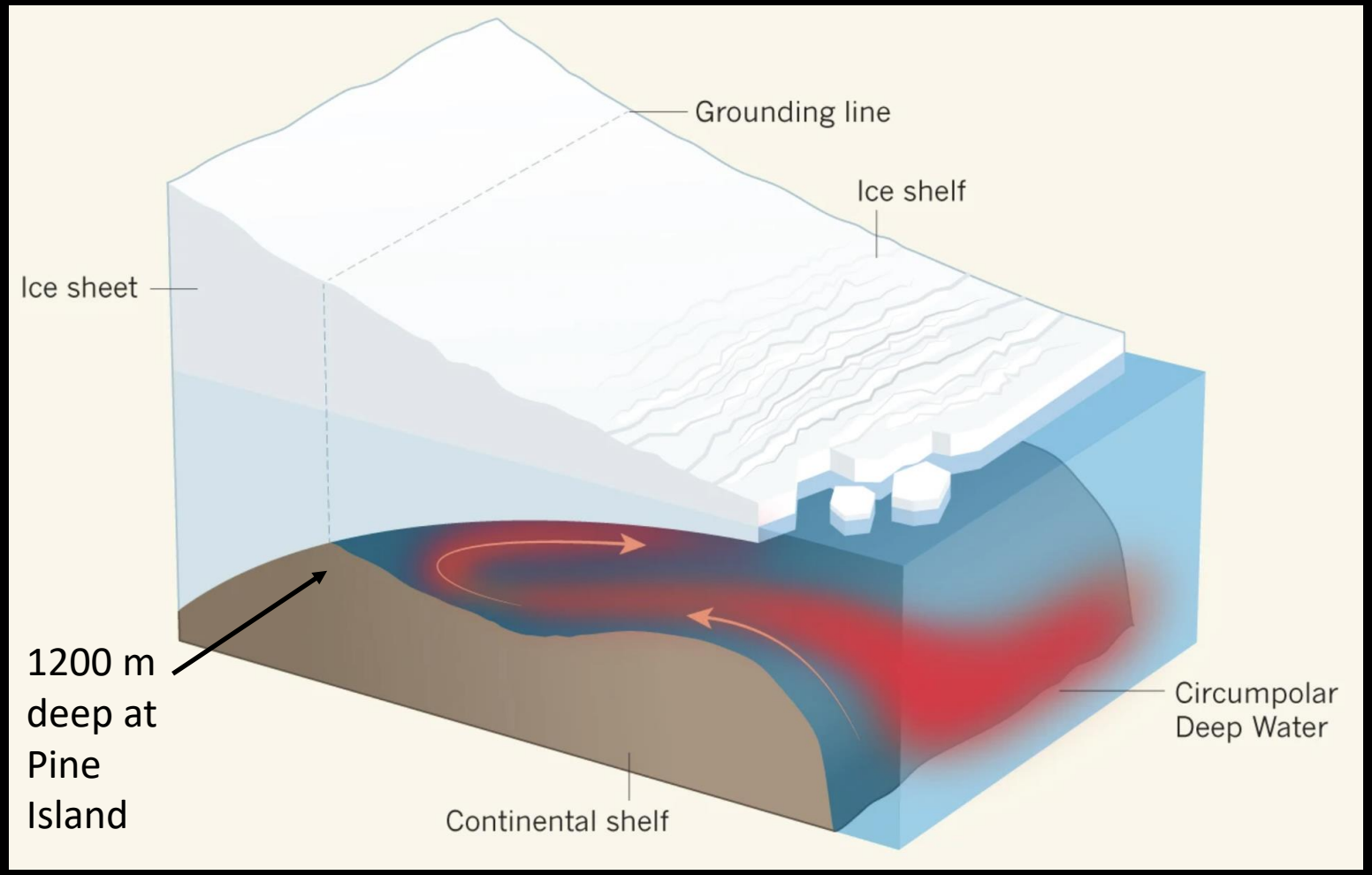
2 km

Pine Island Glacier
(One of the most active glaciers in Antarctica)



10 km

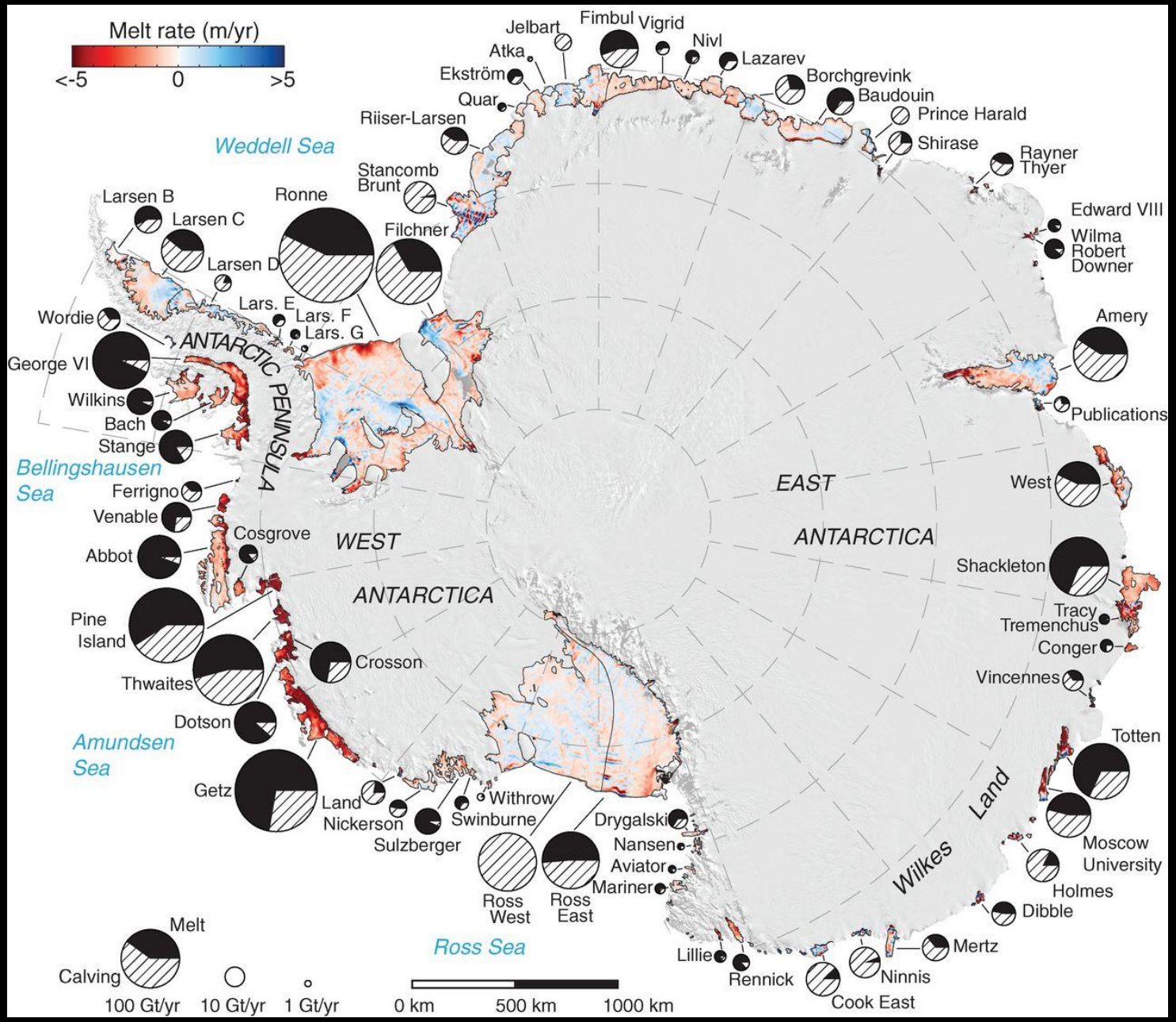
Ocean Melt in Antarctica



- Ice shelves form at the front of most glaciers in Antarctica
- Shelves are melted from below by warm Circumpolar Deep Water

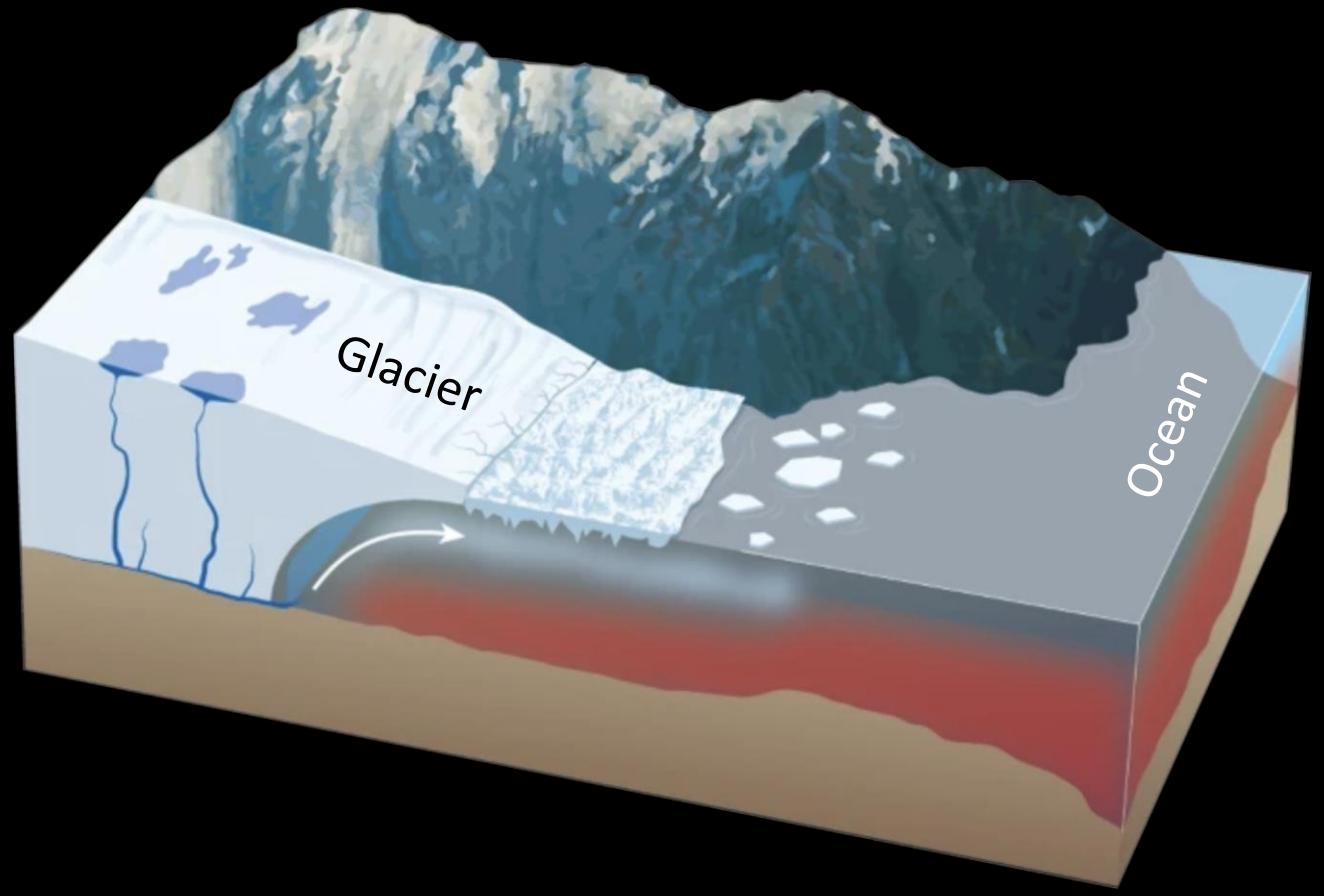
Ocean Melt in Antarctica

- A little more than half of mass loss from glaciers is due to ocean melt
- The rest of mass loss results from calving
- Collectively, this is about 2400 Gt/yr of ice discharge to the ocean

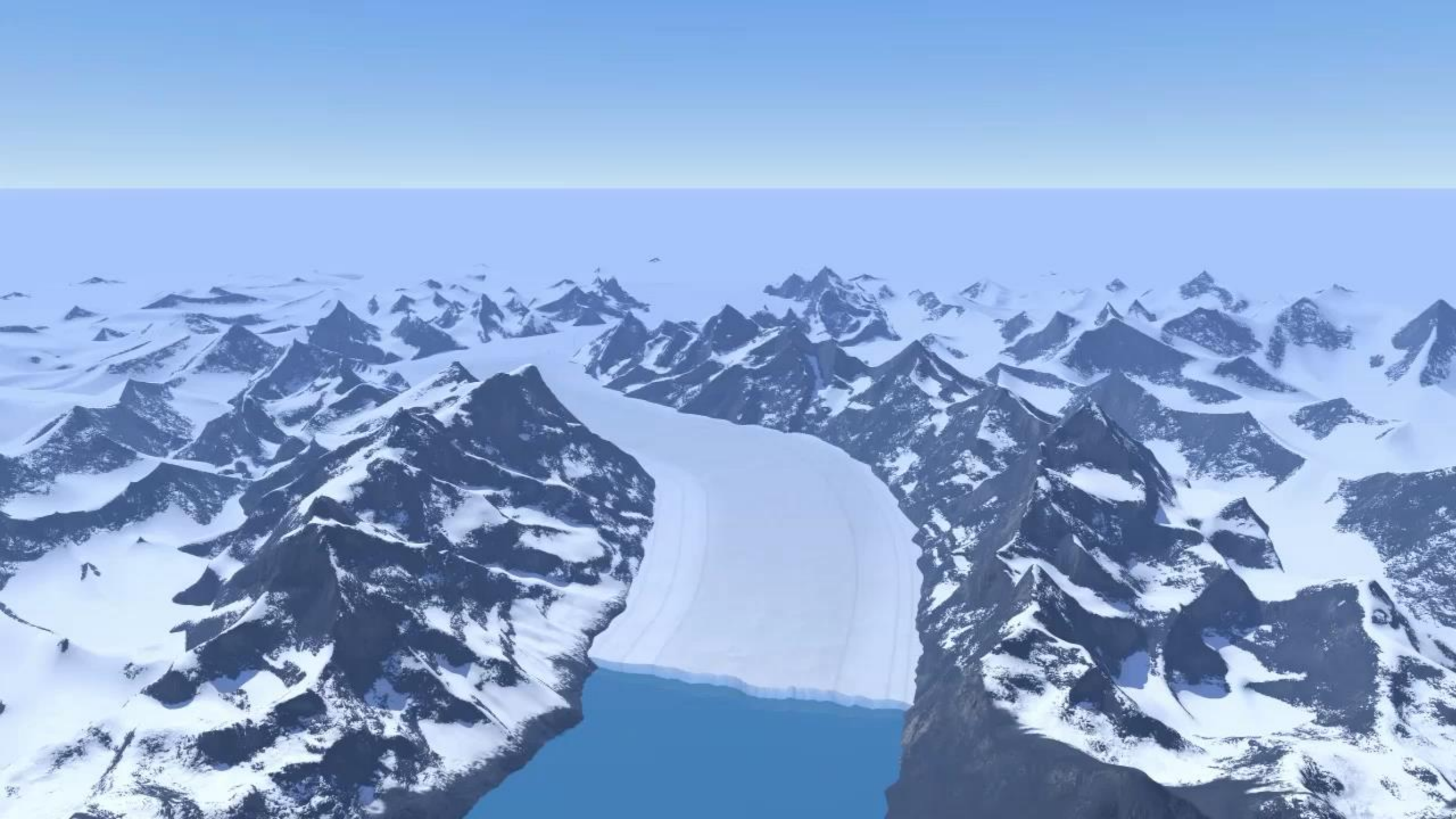


Rignot et al 2013

Ocean Melt in Greenland

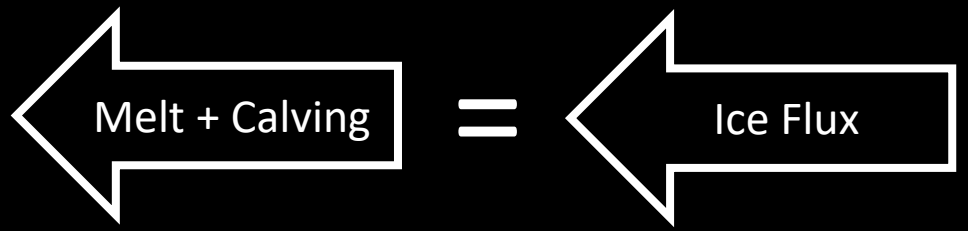


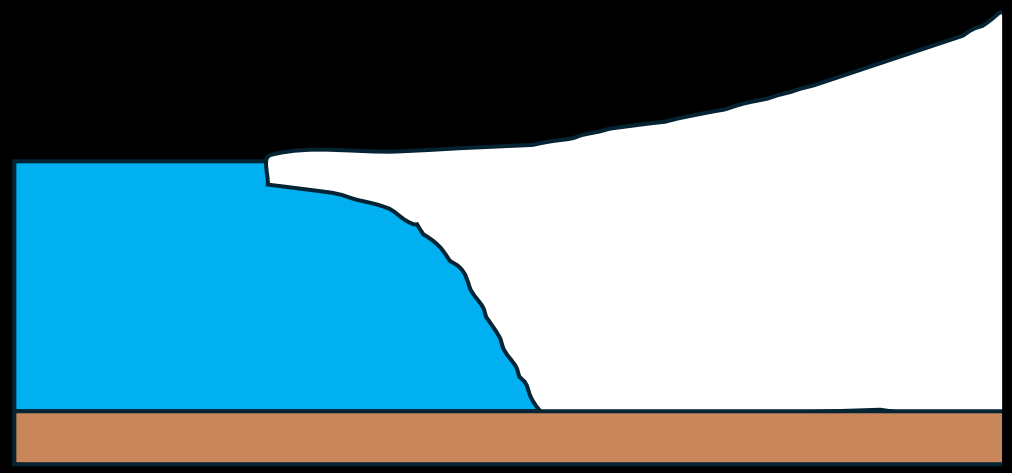
- Glacier geometry is different
  - Fronts are mostly vertical
  - Very few ice shelves
  - Grounding lines are shallower
- Glaciers also encounter warmer water at depth
- But, melt is also modulated by runoff from the ice sheet



Dynamic Glacier Changes

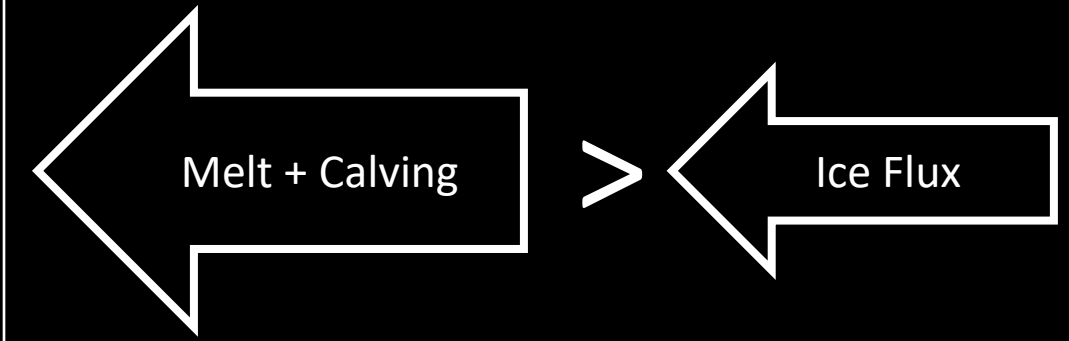
In steady state:

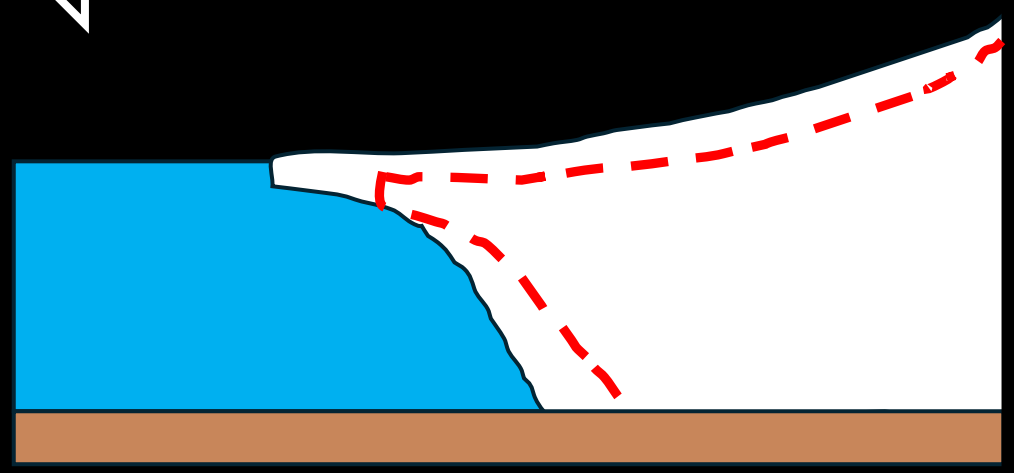




Glacier shape remains constant in steady state

Dynamic Changes:





Glaciers undergoing dynamic change
1) retreat, 2) accelerate and 3) thin

Assessing melt in Greenland

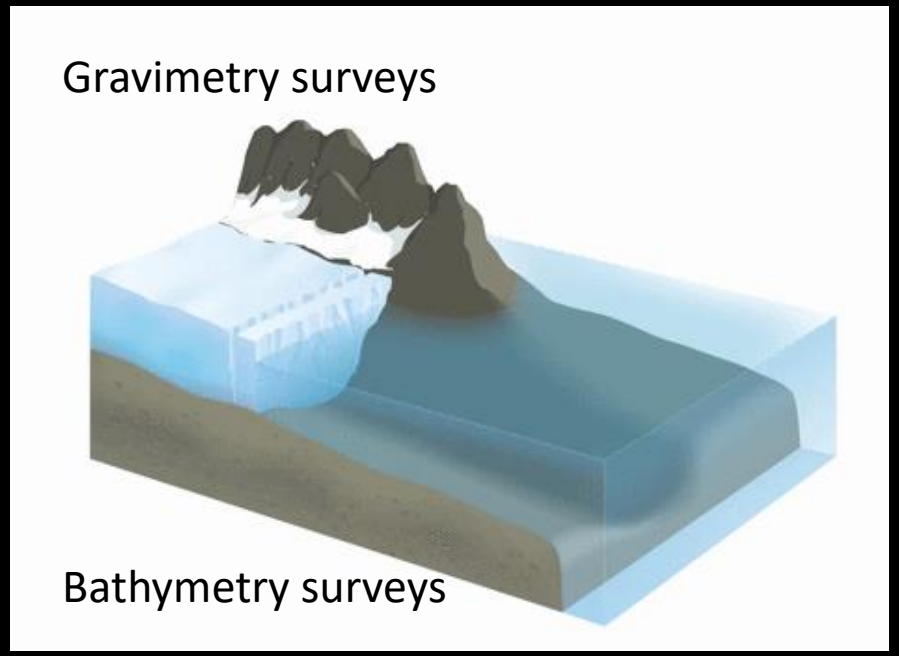
Some issues (circa 2015):

- Most fjords had no bathymetric data
  - No idea how deep the fjords were
- Most fjords had no ocean observations
  - no CTDs or moorings,
  - No ADCPs or other observations
- No observations -> no idea how to model it

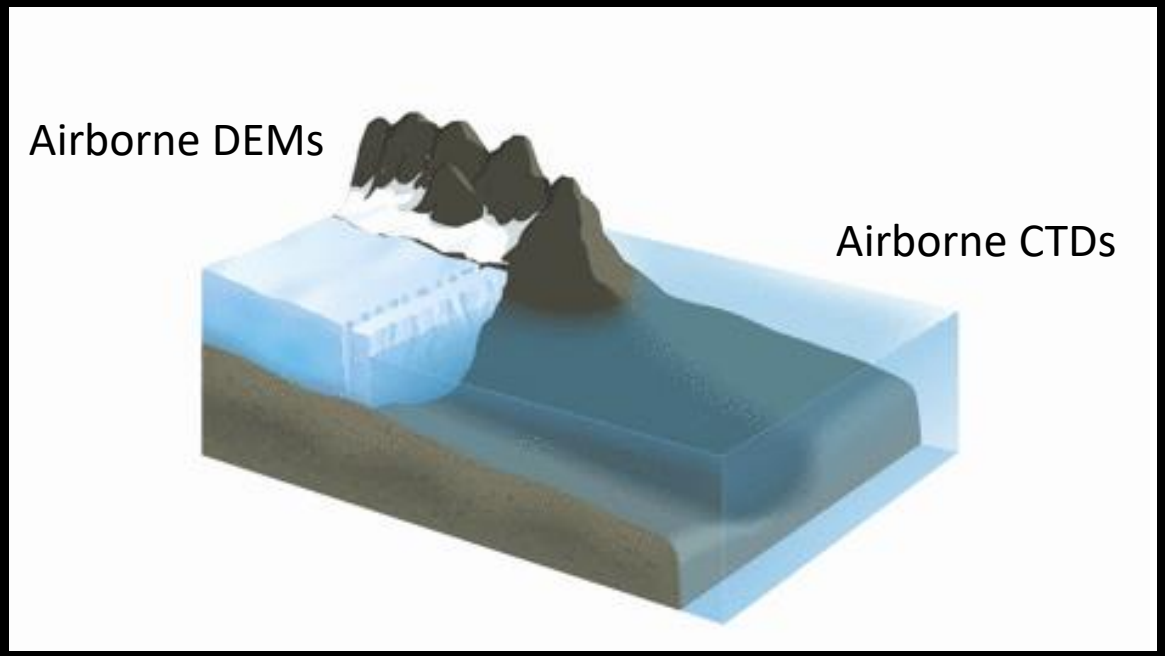
Solution:

NASA's Oceans Melting Greenland campaign

Objective: Measure the ice and ocean simultaneously for 5 years (2015-2021)



How deep is the water near glaciers?



How is the ice volume changing?

How is the temperature of the water changing?

GIF from OMG Image Archive

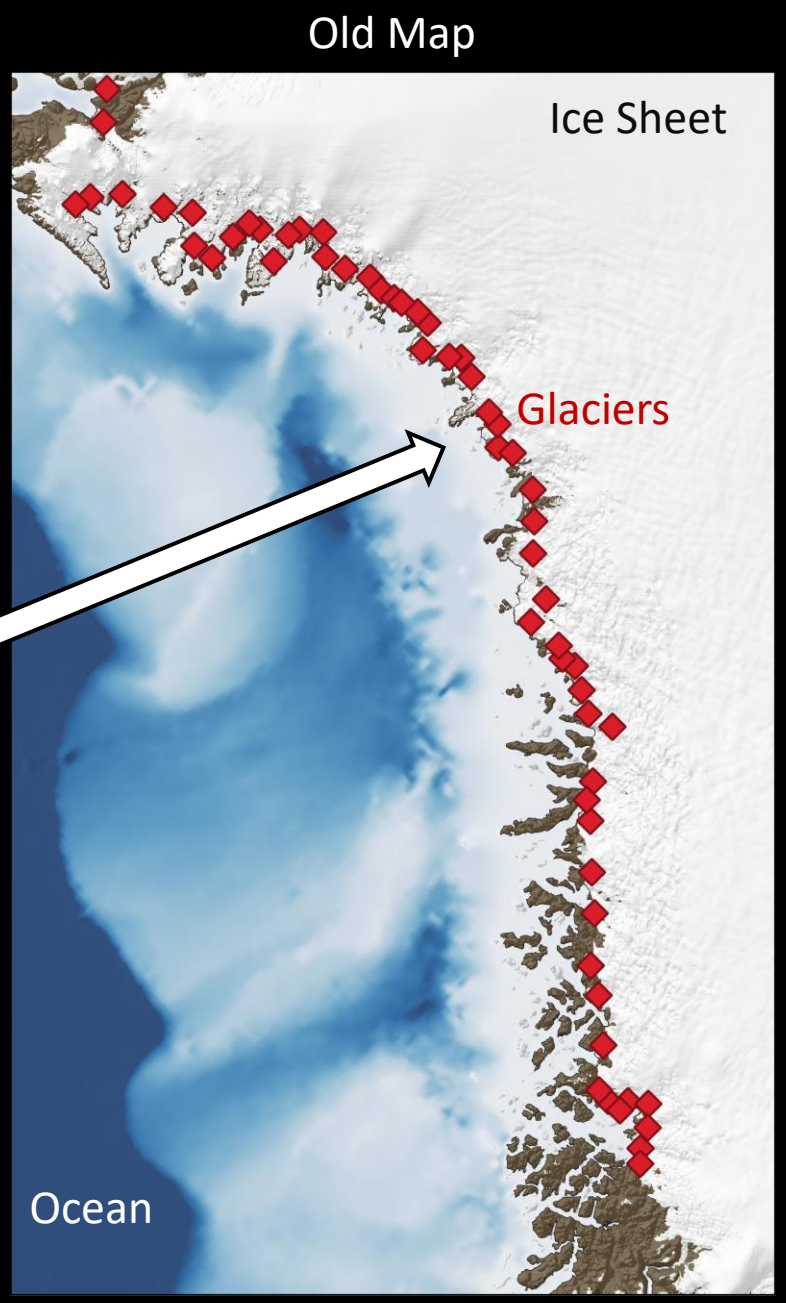
Multibeam Sonar Surveys in Greenland

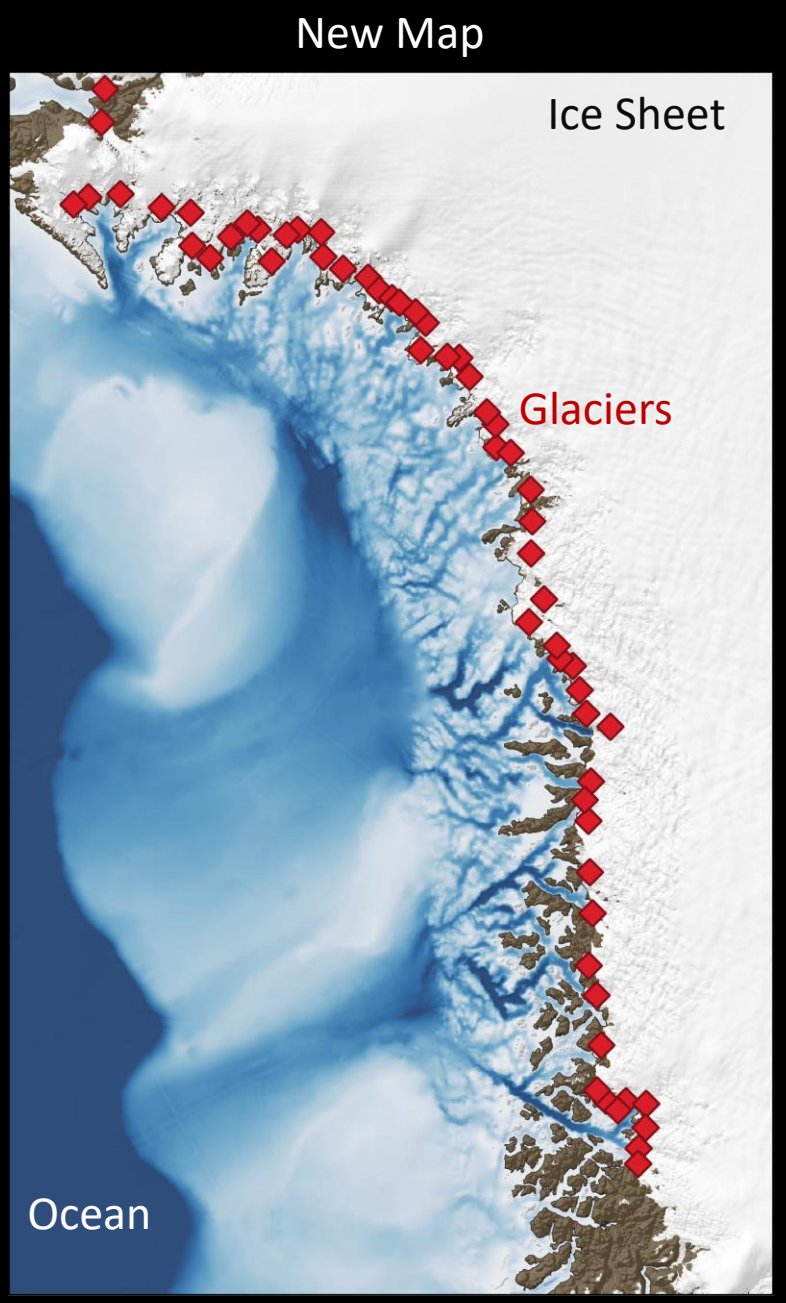
MV Cape Race, Northwest Greenland 2015

Upernavik, Greenland 2017

How deep is the ocean near the glaciers?

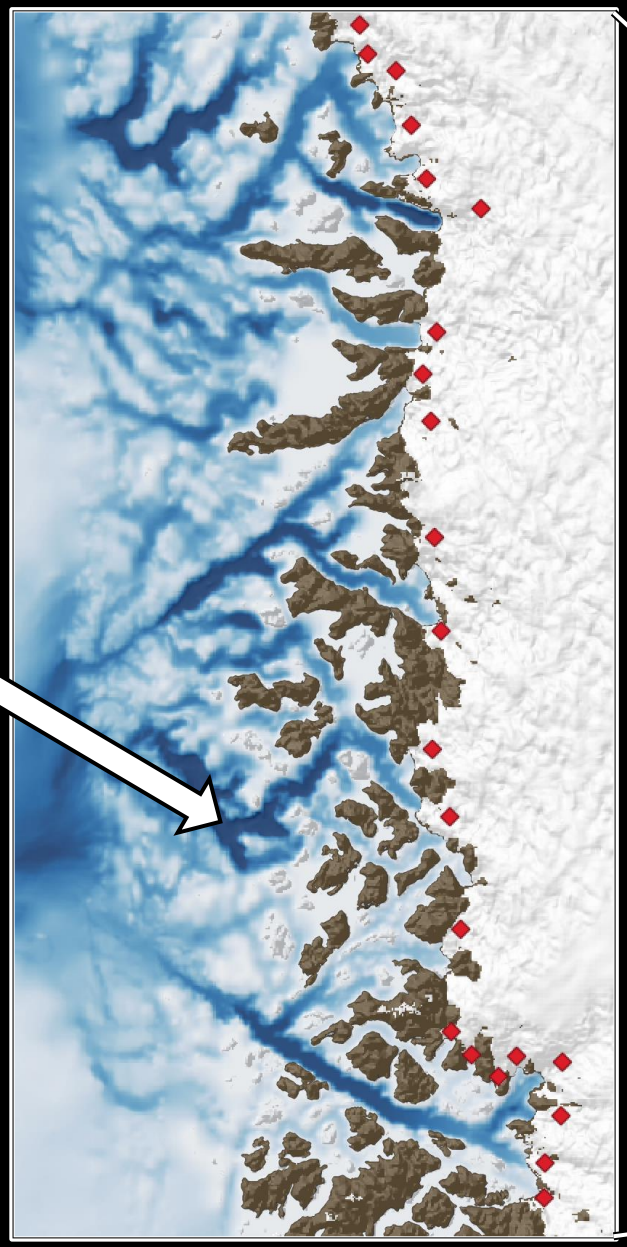
Shallow water on the coast in old map!



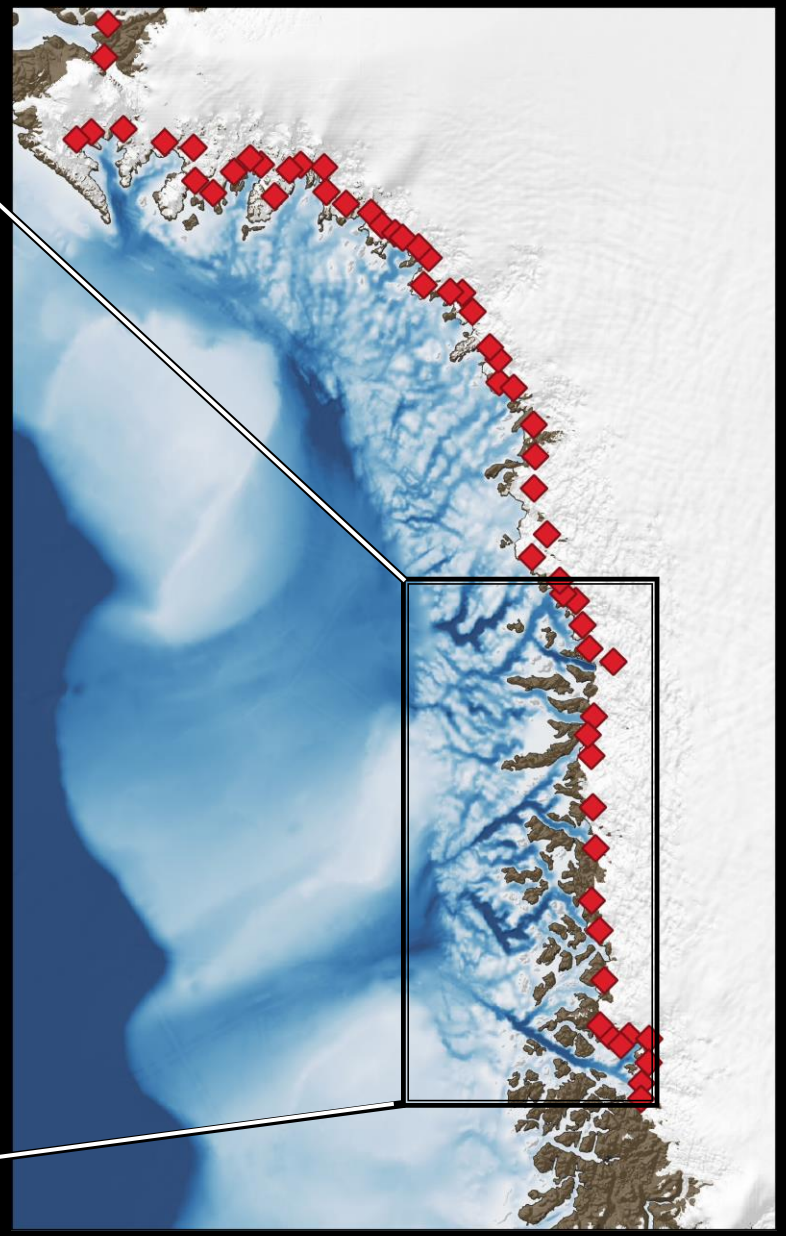


How deep is the ocean near the glaciers?

Deep channels connect ocean to glaciers



New Map



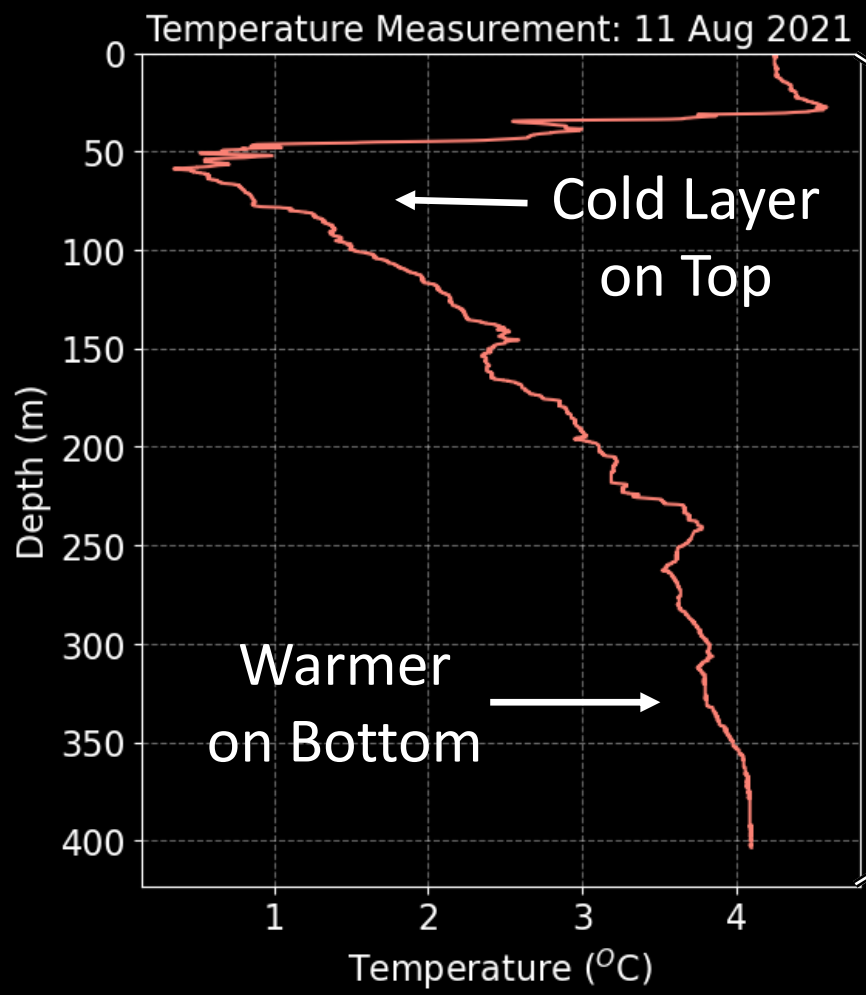
Airborne AXCTD Surveys in Greenland

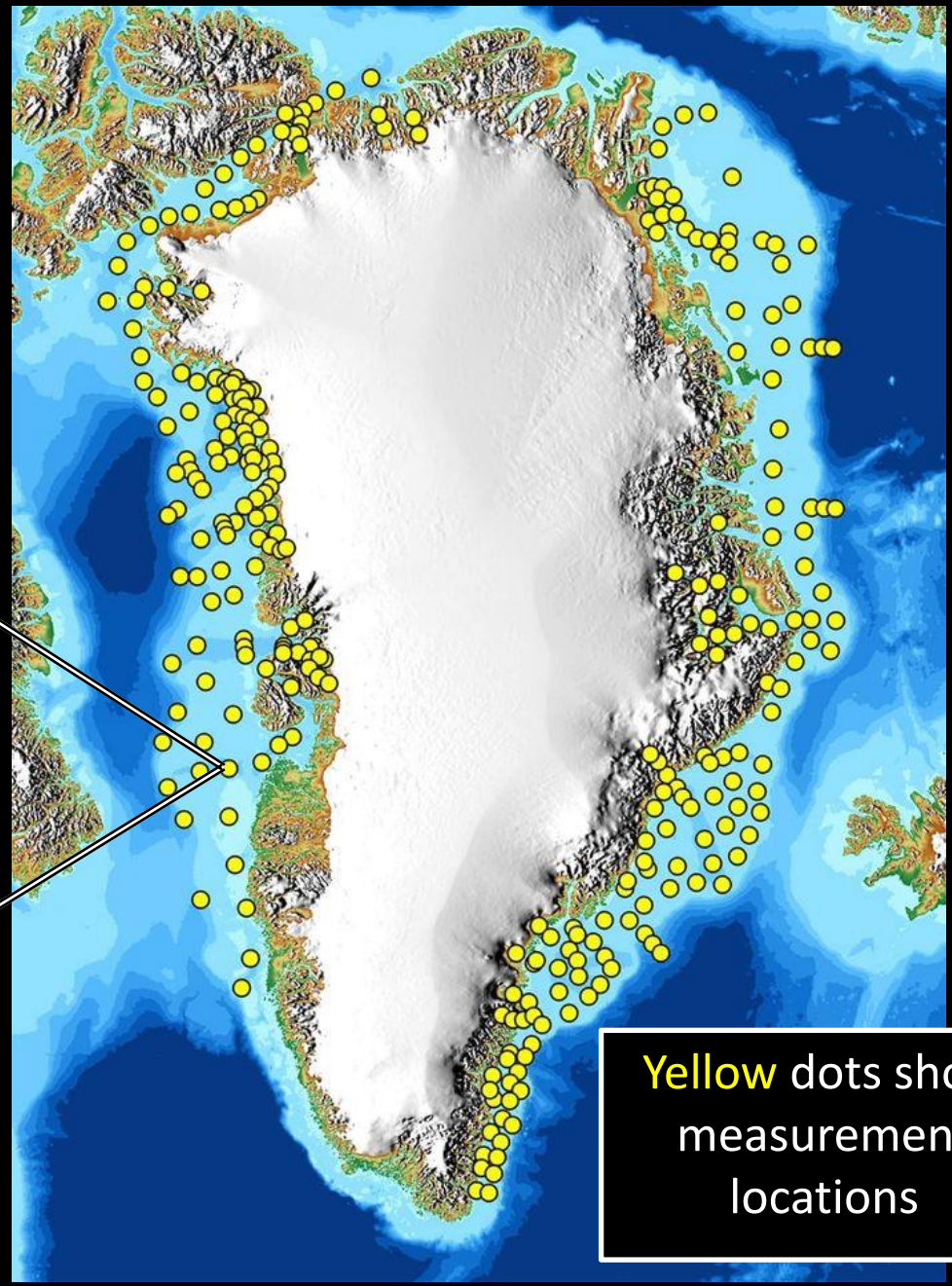
DC3 Survey Plane

Ian Deploying AXCTD

Mike Retrieving Data

How does the ocean temperature vary?



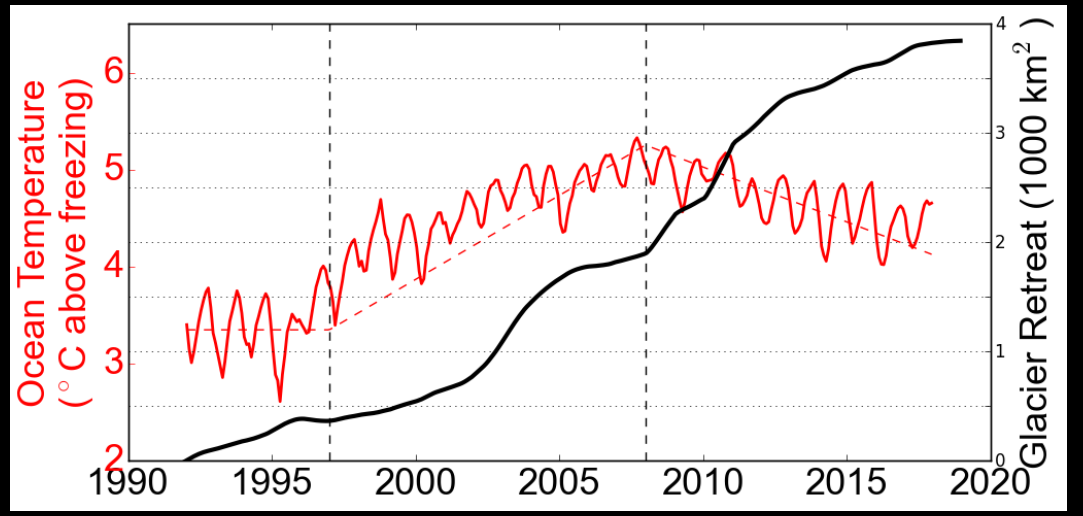


Map from Josh Willis

View of Greenland Science after OMG

- Glacier retreat is driven substantially by variations in ocean melt
  - Wood et al 2021
- Atmospheric variations also have an important role in modulating melt
  - Slater et al 2022
- Many ice models do not include an accurate representation of ocean forcing (yet)

From Wood et al 2021



Low temp,
Low Retreat

Increasing temp,
Retreat increases

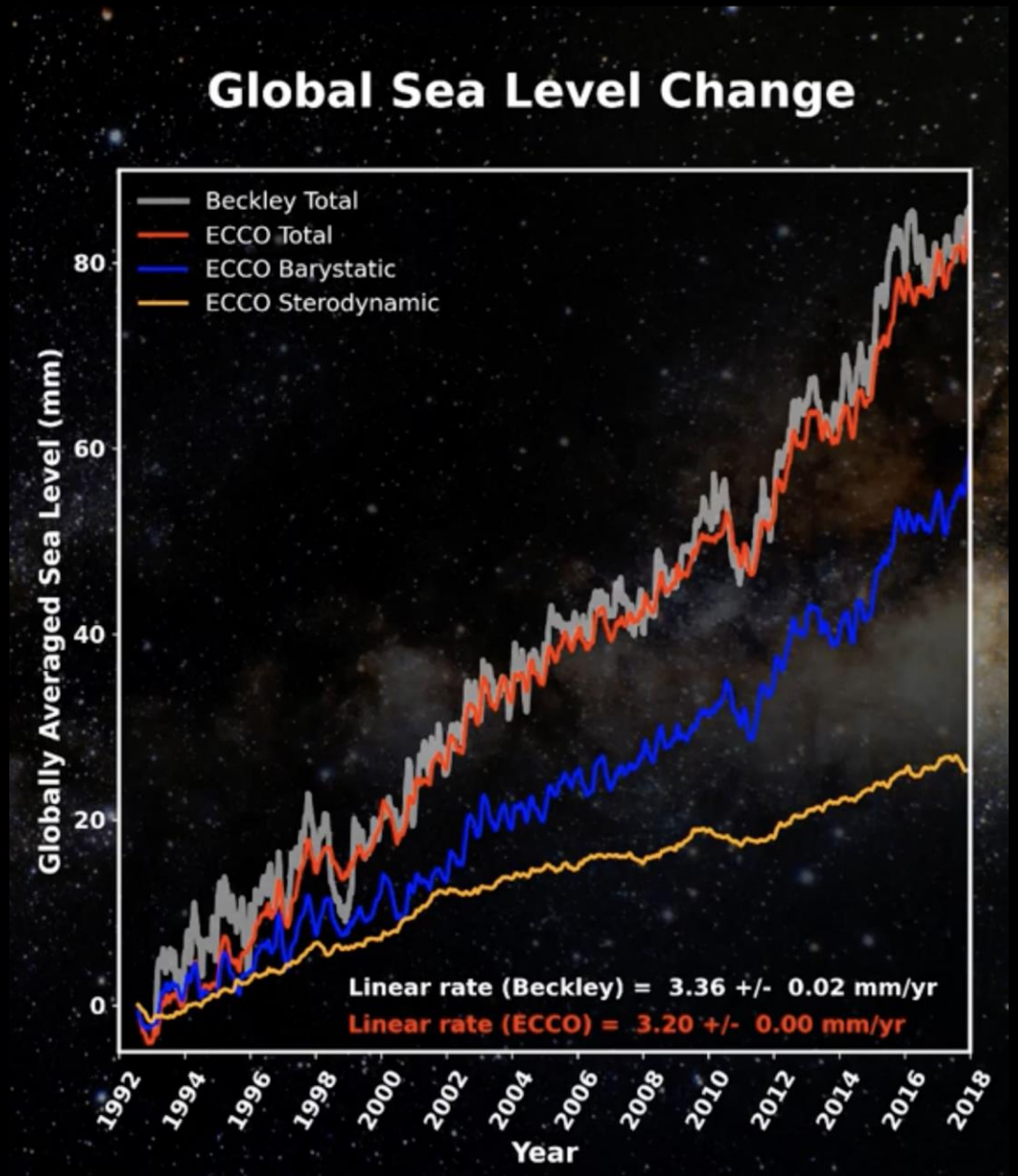
Decreasing temp,
Retreat tapers off

Ice Forcing Ocean

🤔 Question for you:

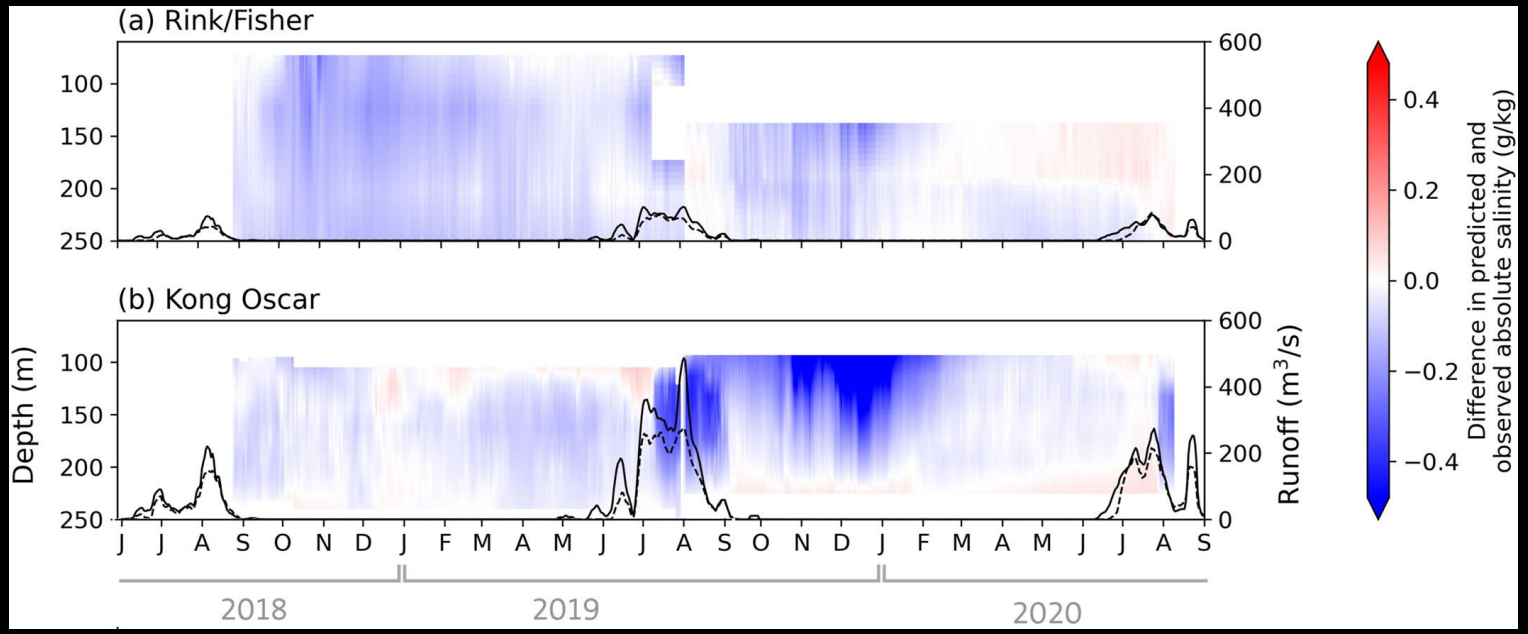
What is the barystatic contribution to sea level over the ECCO period (aka the altimetry era)?

(percents ok)



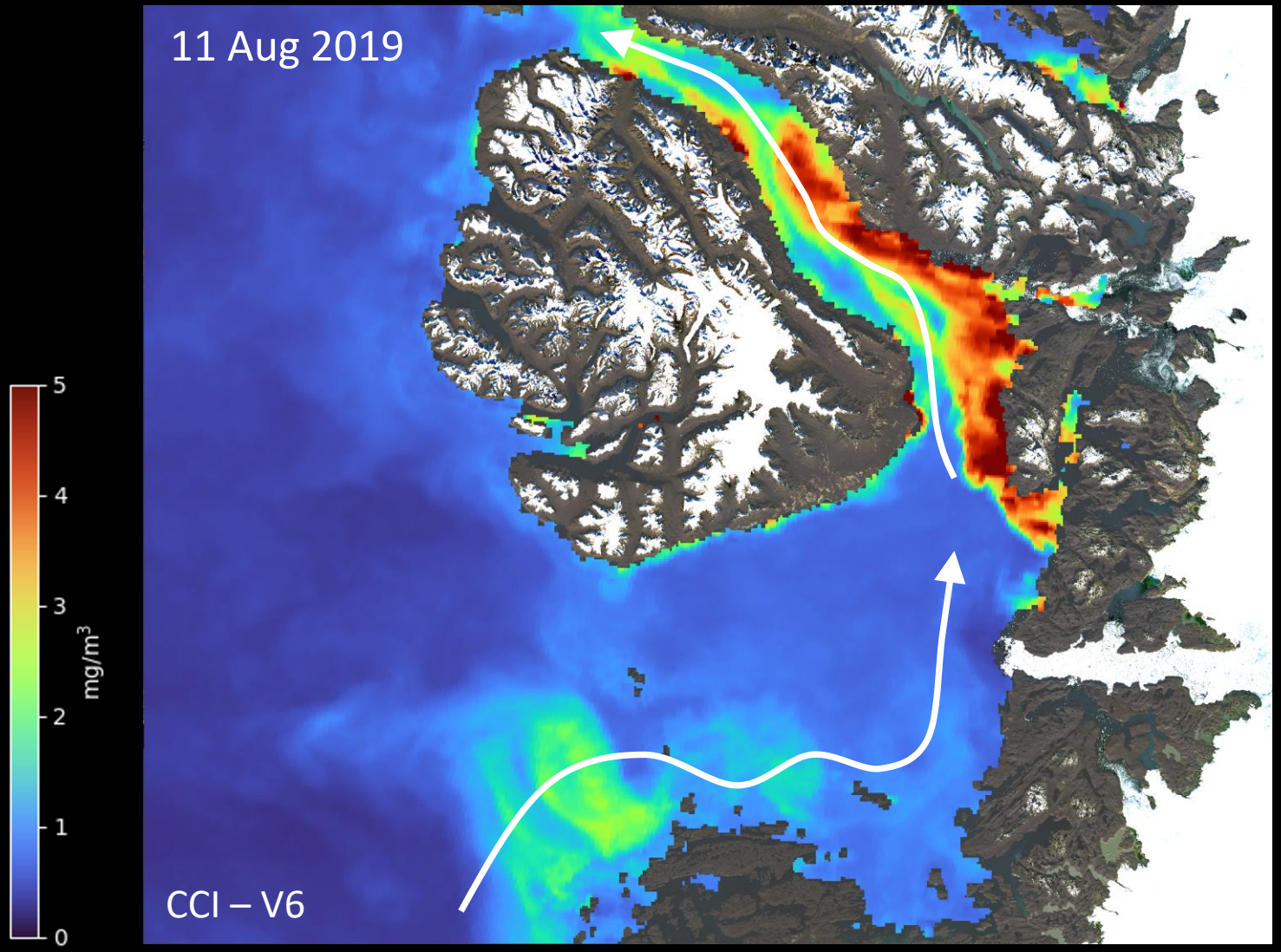
Freshwater Forcing

- Around Greenland, there are large deliveries of freshwater to the ocean
  - Decreased salinity observed in coastal waters (e.g. Zahn et al 2024)
- Potential impacts on AMOC?



Zahn et al 2024 (JGR:O)

Biogeochemical Forcing

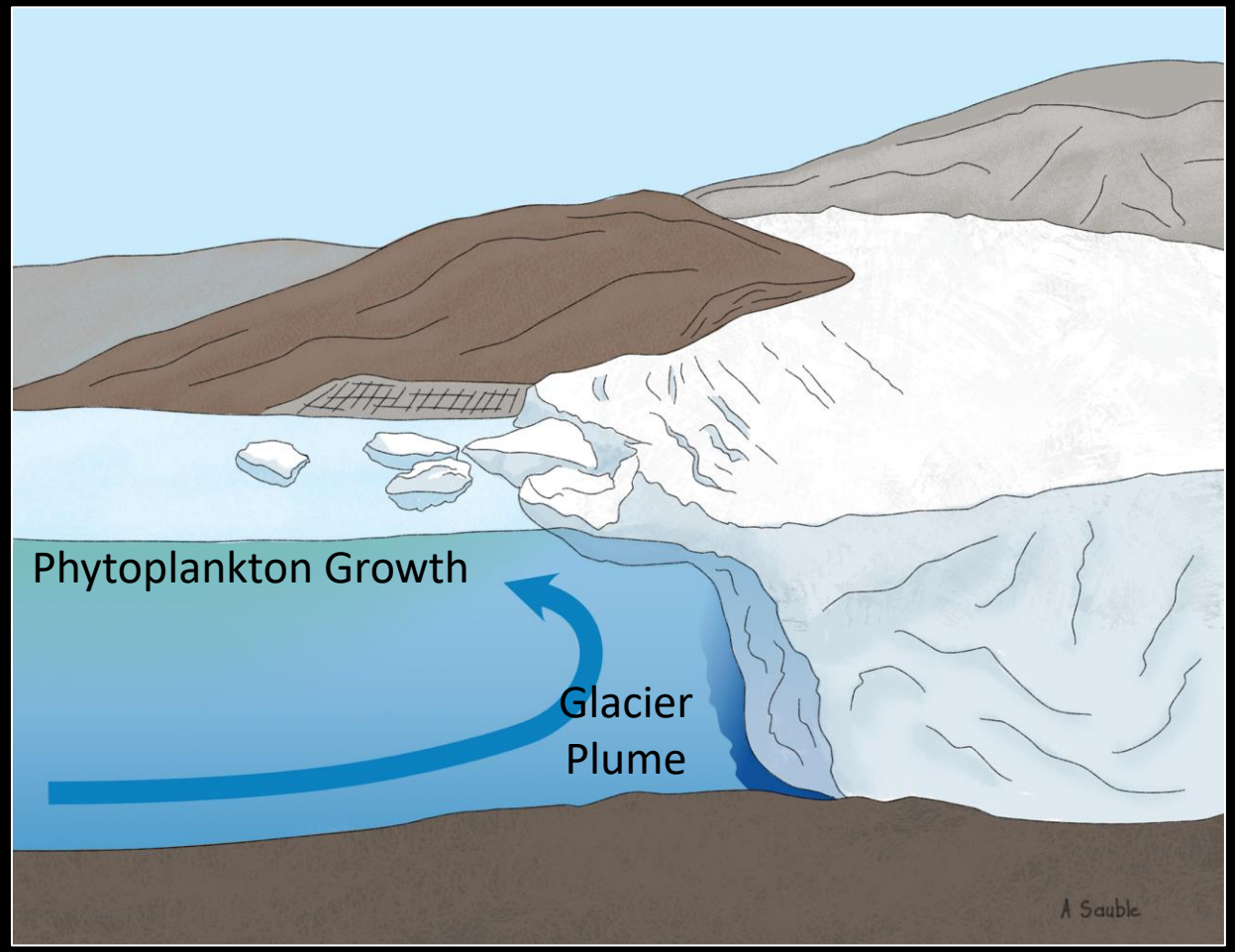


Northern part of Disko Bay (Sullorsuaq) is highly productive during the summer

Sermeq Kujalleq

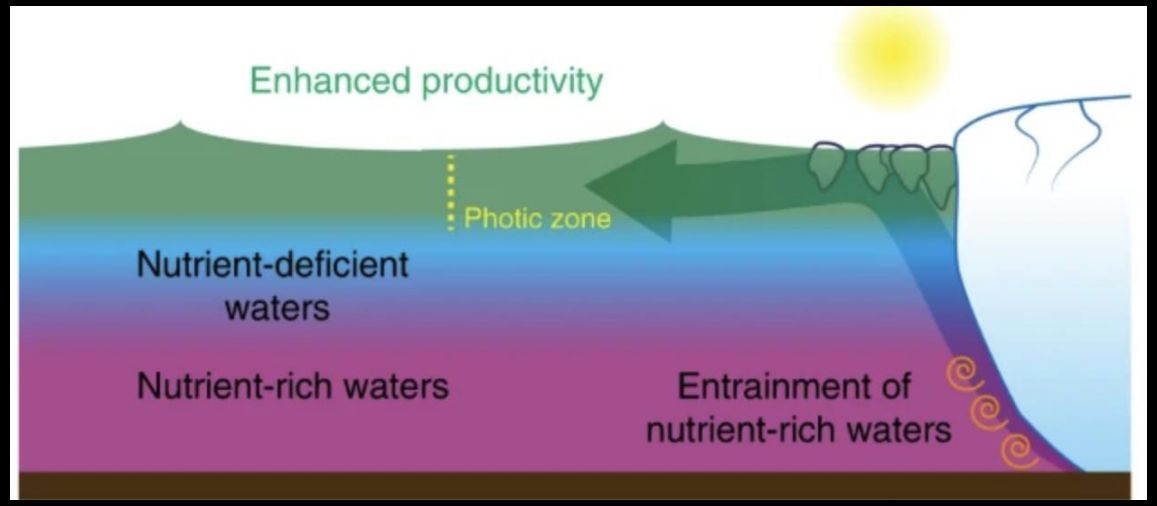
Hypothesis: Glacier-Driven Upwelling

- Runoff emerges at depth and drives >40,000 m^3/s of upwelling in the summer (Slater et al 2022)
- Emerging evidence: plumes alleviate nutrient limitations for primary productivity (e.g. Oliver et al 2023)



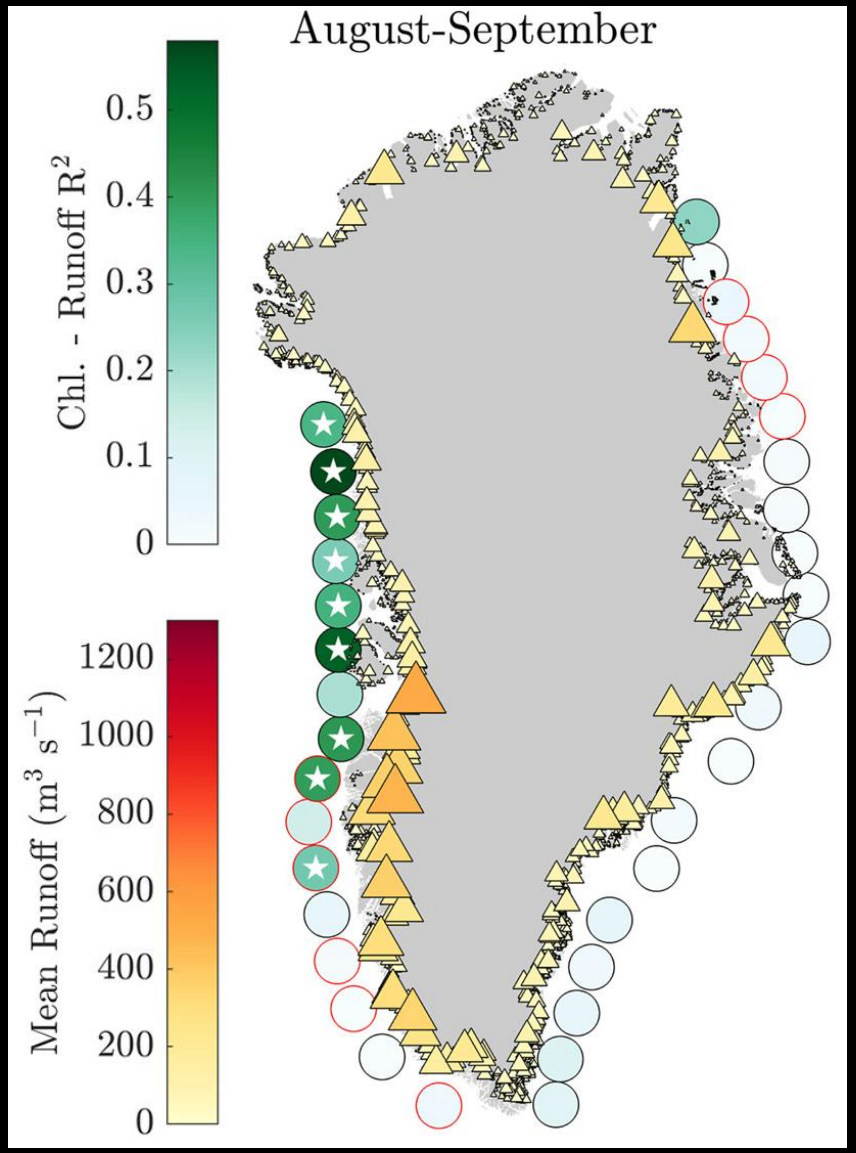
Schematic provided by science illustrator Aubrey Sauble

Glacier Plumes and Hotspots of Productivity



From Hopwood et al 2018

- Plumes drive nutrients vertically from depth to the photic zone
- Significant trends in runoff correlate with chlorophyll-a concentrations

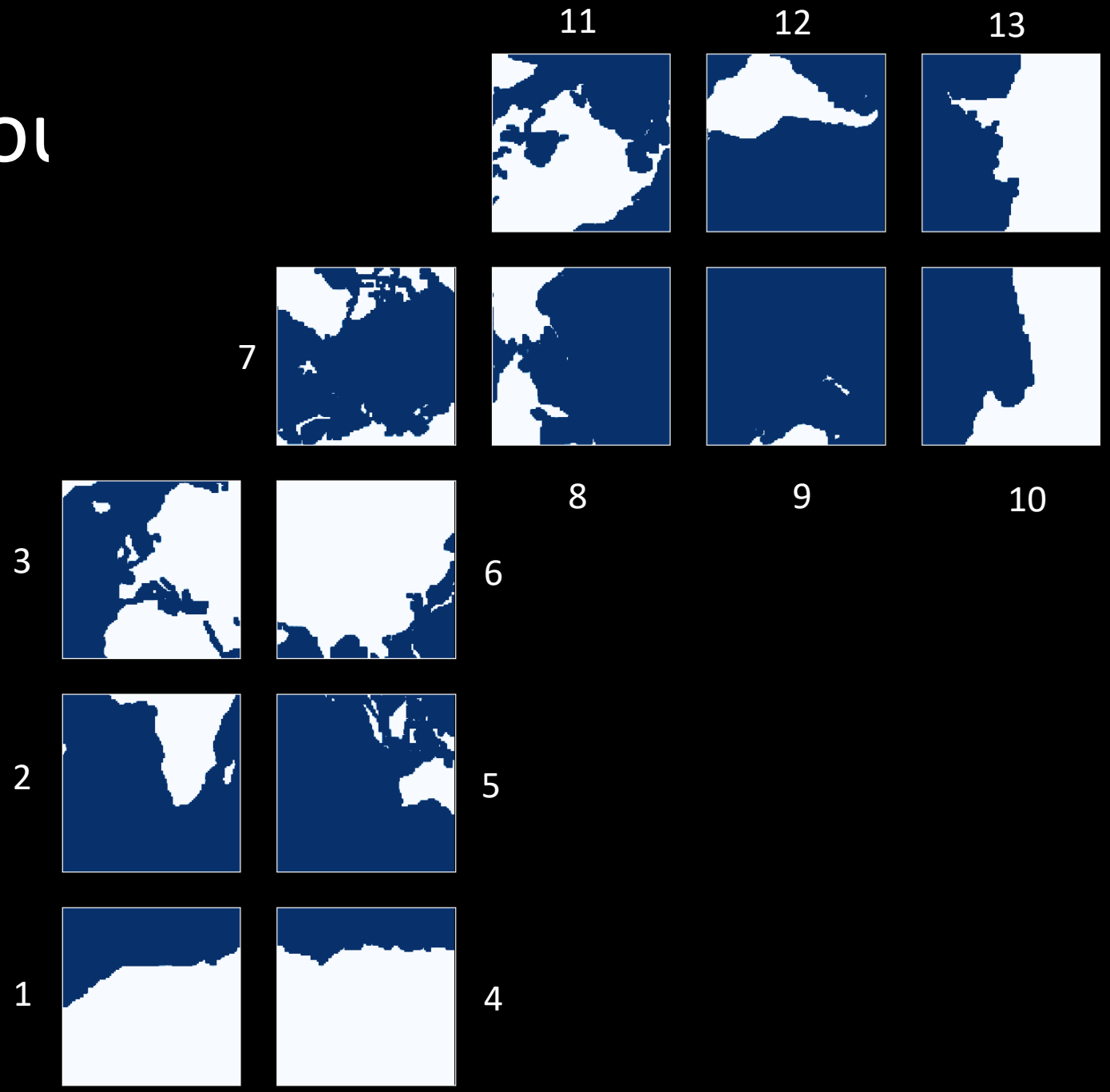


From Oliver et al 2023

ECCO, MITgcm, and the Ice Sheets

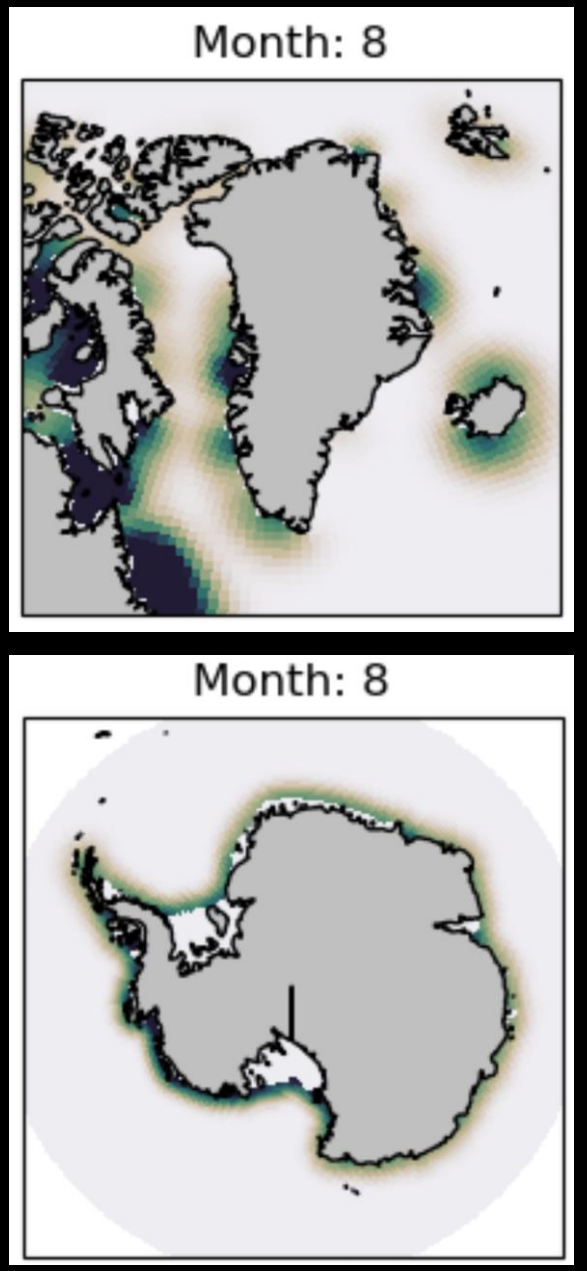
🤔 Question for you

Which ECCO tiles pertain to Greenland on the LLC Grid? Antarctica?



ECCOv4r4 and the Ice Sheets

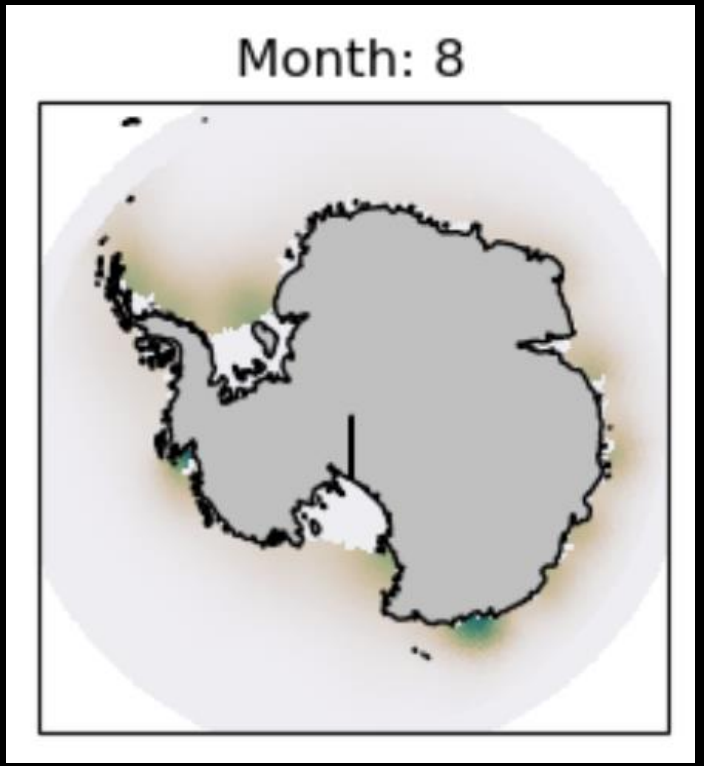
- In ECCO v4 r4, there is no direct interaction with the ice
- Runoff fields in the model are used to account for seasonal addition of fresh water
  - Runoff is from monthly climatology
  - Runoff at the surface only
- No icebergs or glacier melt



August Runoff
Climatology in ECCOv4r4

ECCOv4r5 and the Ice Sheets

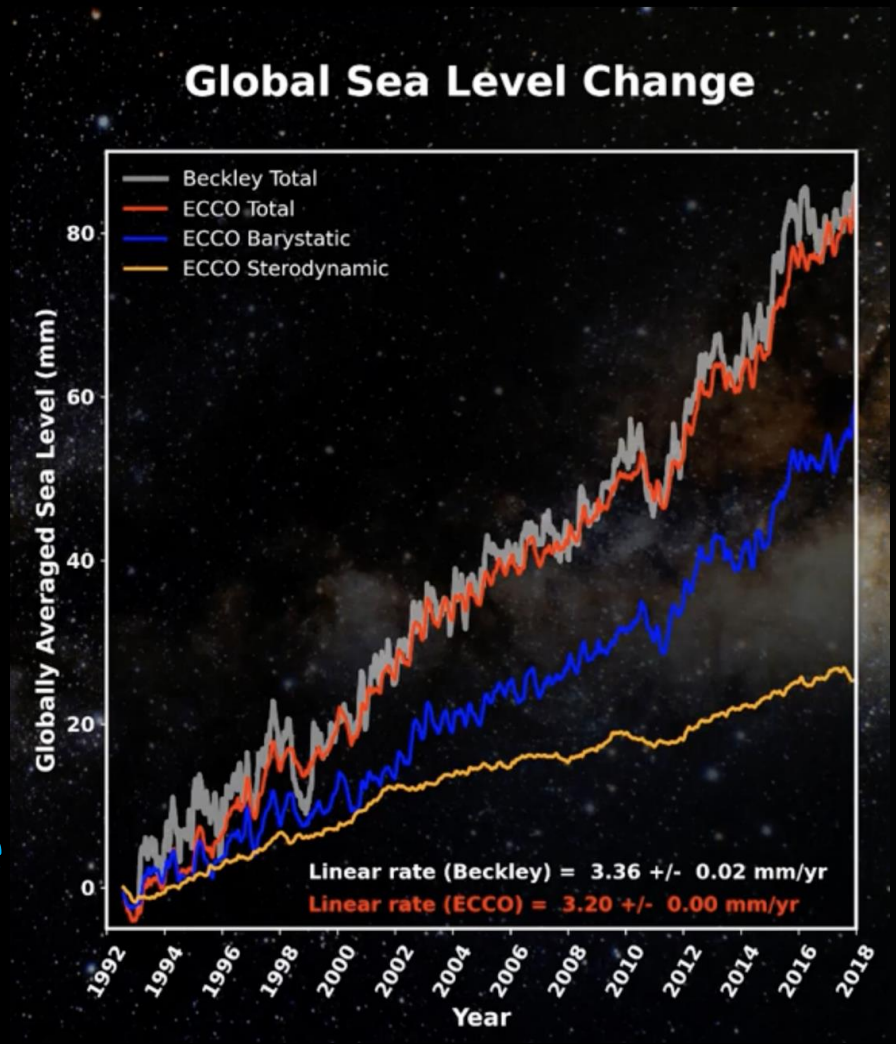
- In ECCO v4 r5, there is freshwater runoff from icebergs around Antarctica
- Also, basal melting is computed with a parameterization of ice melt
- Runoff is used for Greenland as before
  - Not possible to do the same thing as in Antarctica due to ice geometry, resolution, and other issues



August Runoff + Icebergs Climatology in ECCOv4r5

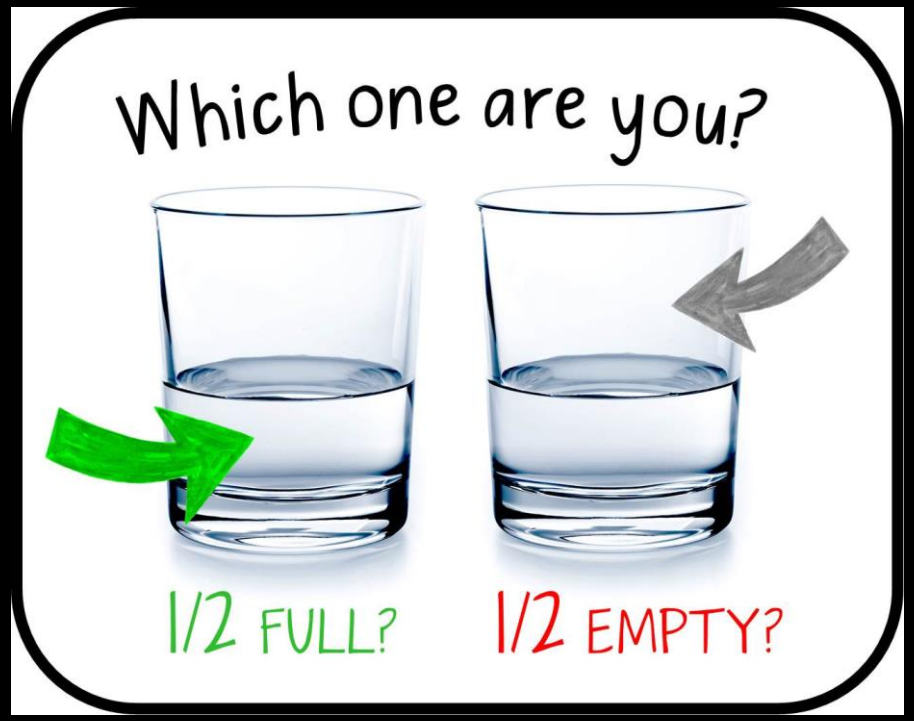
How does ECCO get sea level right?

- It's the precip/evap control parameters
  - One improvement to ECCO is to add Greenland ice sheet runoff + icebergs
- Hard part: this is not only discharged into the surface
  - Not exactly clear how to add this
- Also, icebergs carry mass away and distribute it in other locations
- In short – the Greenland ice sheet and the ocean don't talk!



Glass half empty?

- Analyze state output
- Investigate budgets
- Interrogate model
- Exploit adjoint



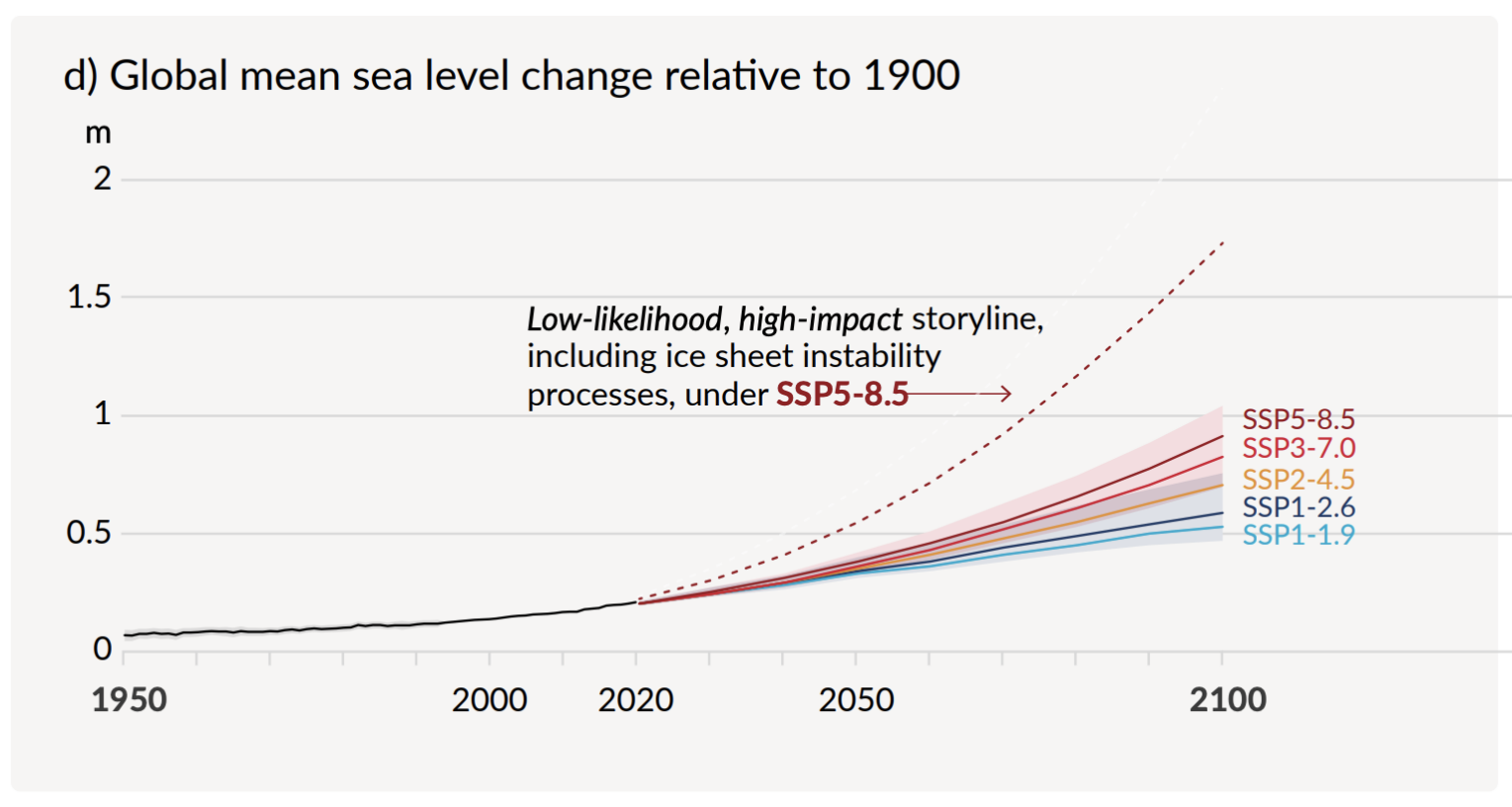
- Improve model
- Add more observations
- Extend analysis period
- Refine optimization

Glass half empty?

- Analyze state output
- Investigate budgets
- Interrogate model
- Exploit adjoint

- Contribute to the ECCO model
- Explore unresolved processes
- Consider implications for other global-scale modeling efforts

How much will sea level rise in the future?



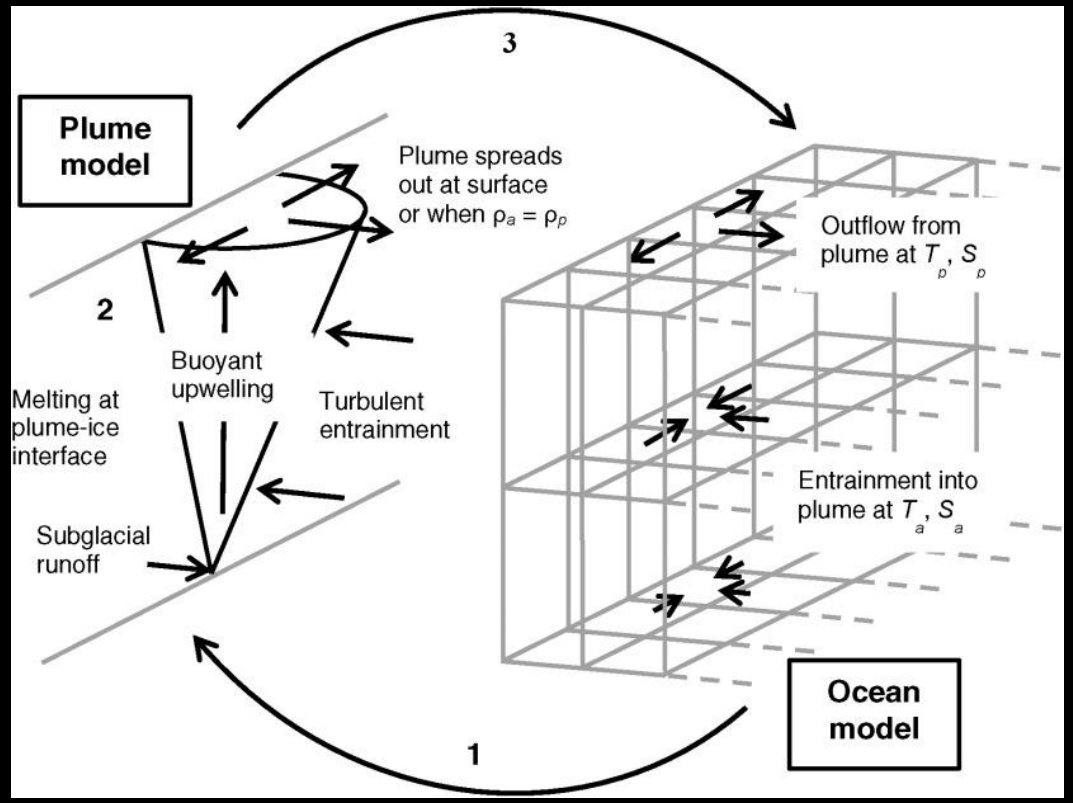
IPCC AR6 Summary for Policy Makers

"… the largest gap in our knowledge is about the physical understanding and implementation of the calving process, i.e. the interaction of the ice sheet with the ocean."

- Goelzer et al 2020 (Contribution to IPCC AR6)

MITgcm: Iceplume

- The plume is implemented with the MITgcm package *iceplume* (Cowton et al 2015)
- *iceplume* solves for circulation resulting from subglacial discharge and parameterized melt
- Subglacial discharge provided to model can be computed from surface mass balance models (Noel et al 2019, Mankoff et al 2020)

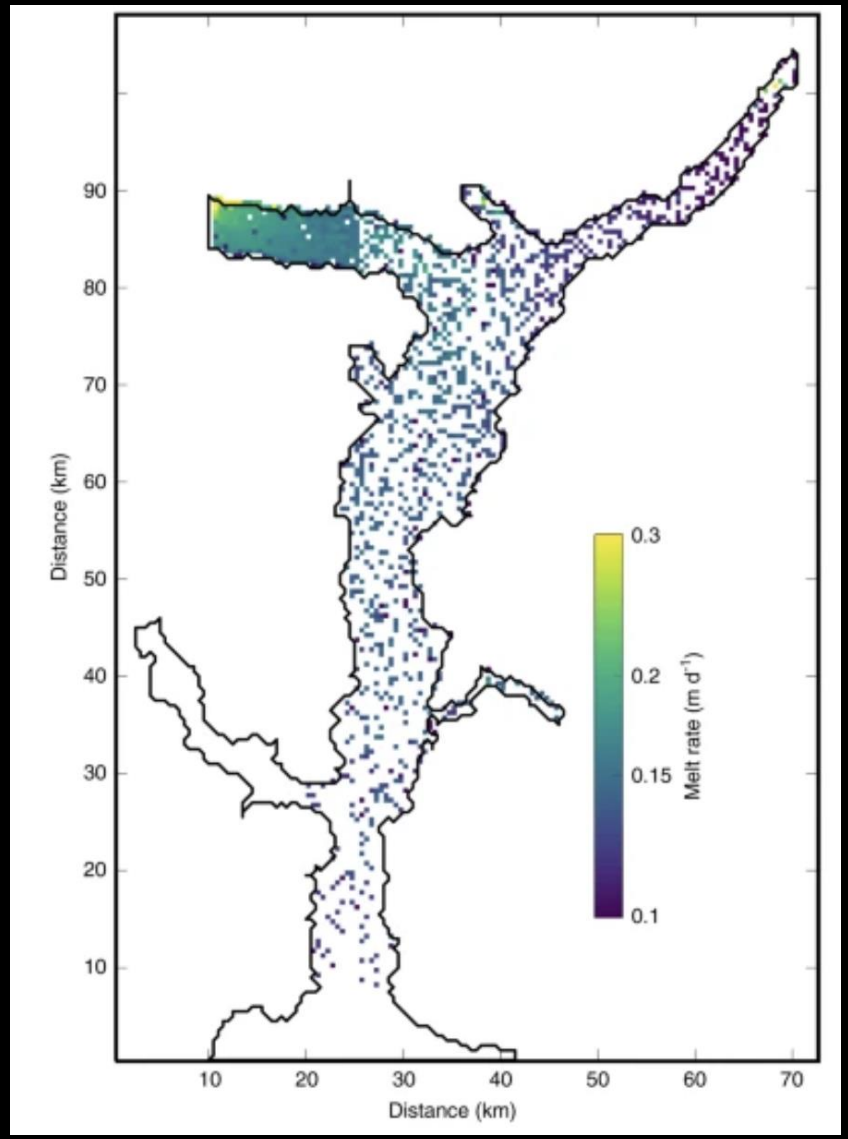


Cowton et al 2015, Figure 1

Cowton et al 2015, Schulz, Nguyen, Pillar et al 2022

MITgcm: Iceberg (Davison)

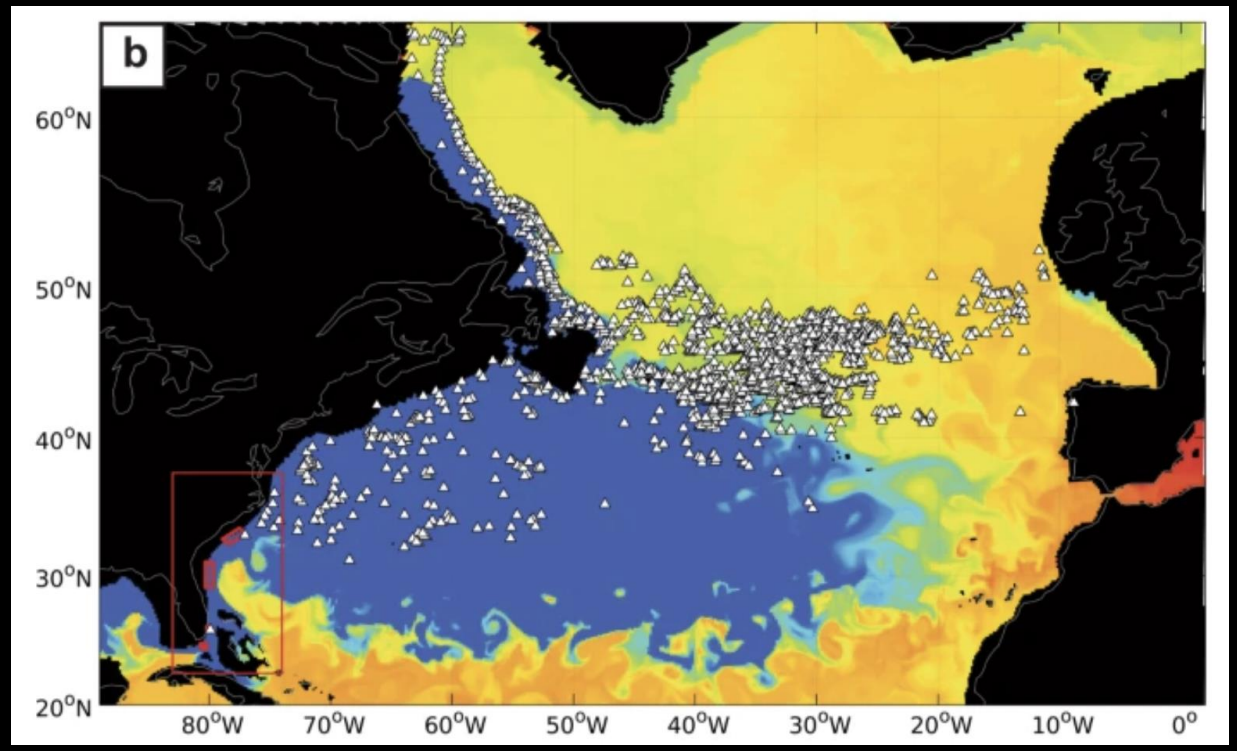
- Iceberg package
  - Pros:
    - Iceberg melt is introduced vertically
    - Iceberg size is specified a priori
    - Suitable for fjord-scale simulations
  - Cons
    - Icebergs don’t move
    - Icebergs don’t change size
    - Not suitable for large-scale simulations



Davison et al 2020

MITgcm: Iceberg (Condron)

- Iceberg package (aka MITberg)
  - Pros:
    - Icebergs are dynamic in time
      - Removed from domain when they melt
    - Suitable for large-scale simulations
  - Cons
    - Icebergs melt at surface only
    - Icebergs are given a prescribed geometry by model
    - Icebergs are introduced stochastically

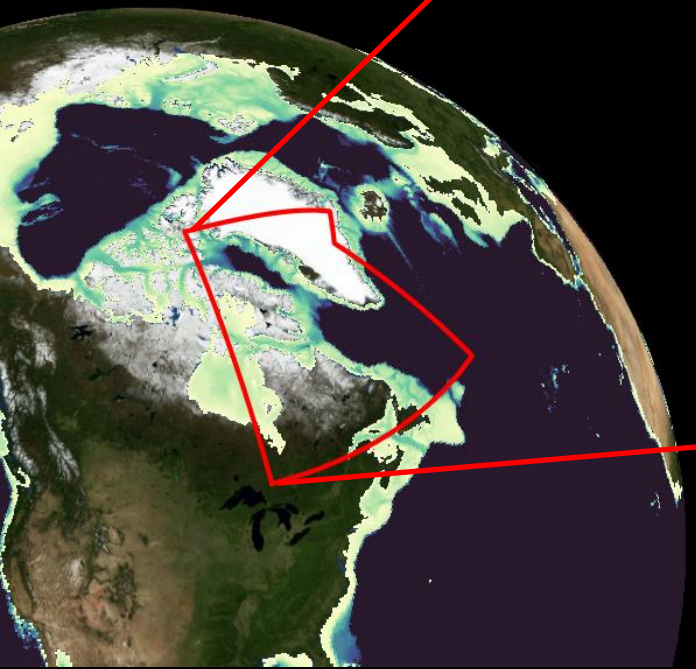


Condron et al 2021

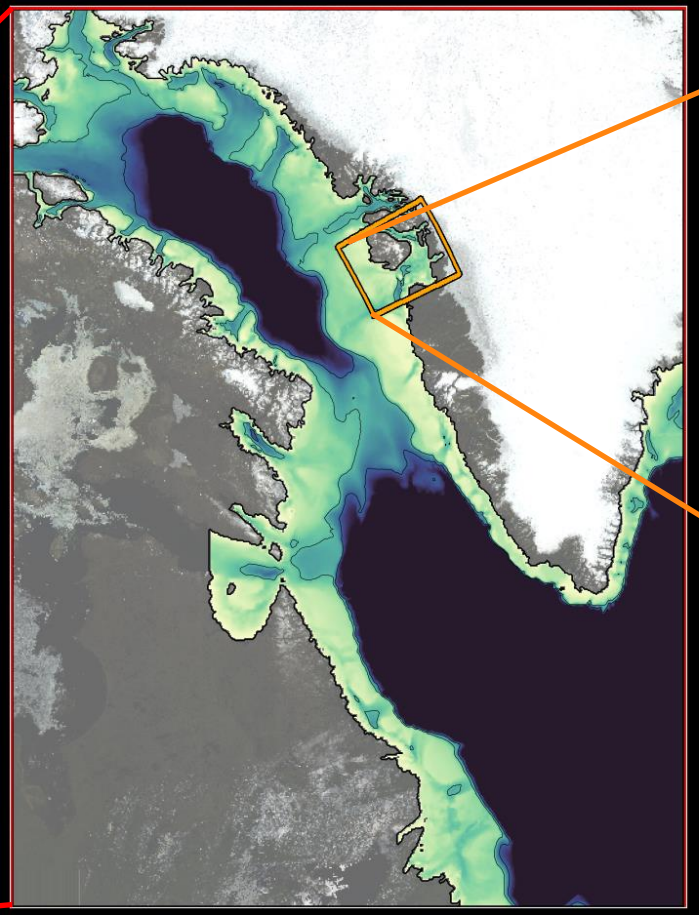
Some Regional Work I’ve Been Up To

Downscaled MITgcm Model Framework

1. Start with ECCO (1992-2021) (~15 km)



2. Downscale into a regional model (L1, 3-4 km)



1992-2021

3. Downscale into a fjord scale model (L2, 500 m)

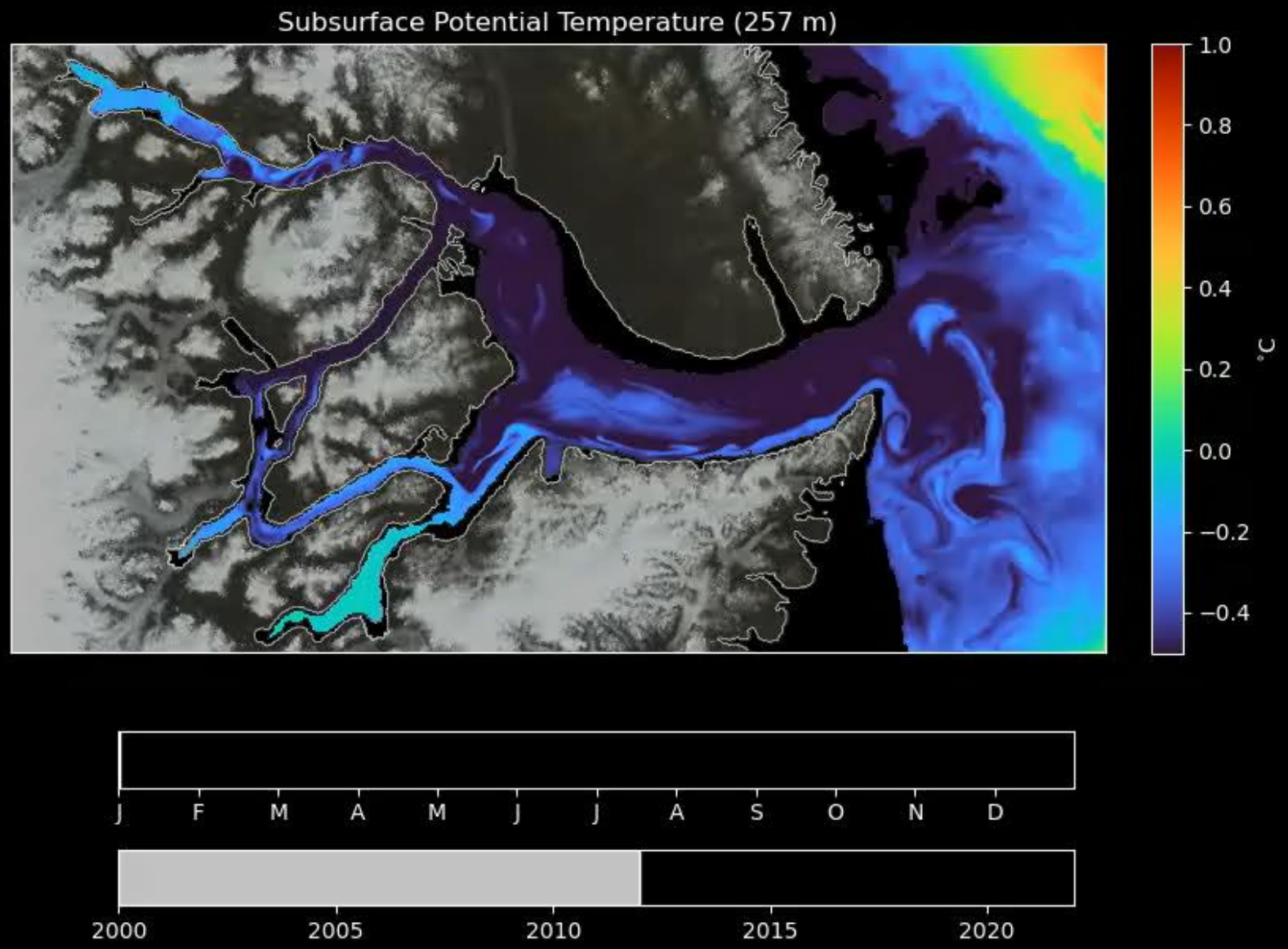
Boundary, external, and initial conditions are inherited from the “parent” model

Case Study: Greenland Fjords

- Parent Models:
  - ECCOv5 and
  - L1 (LLC1080) East Greenland
- Resolution: 500m
- Time Duration:

  22 Years (2000-2021)

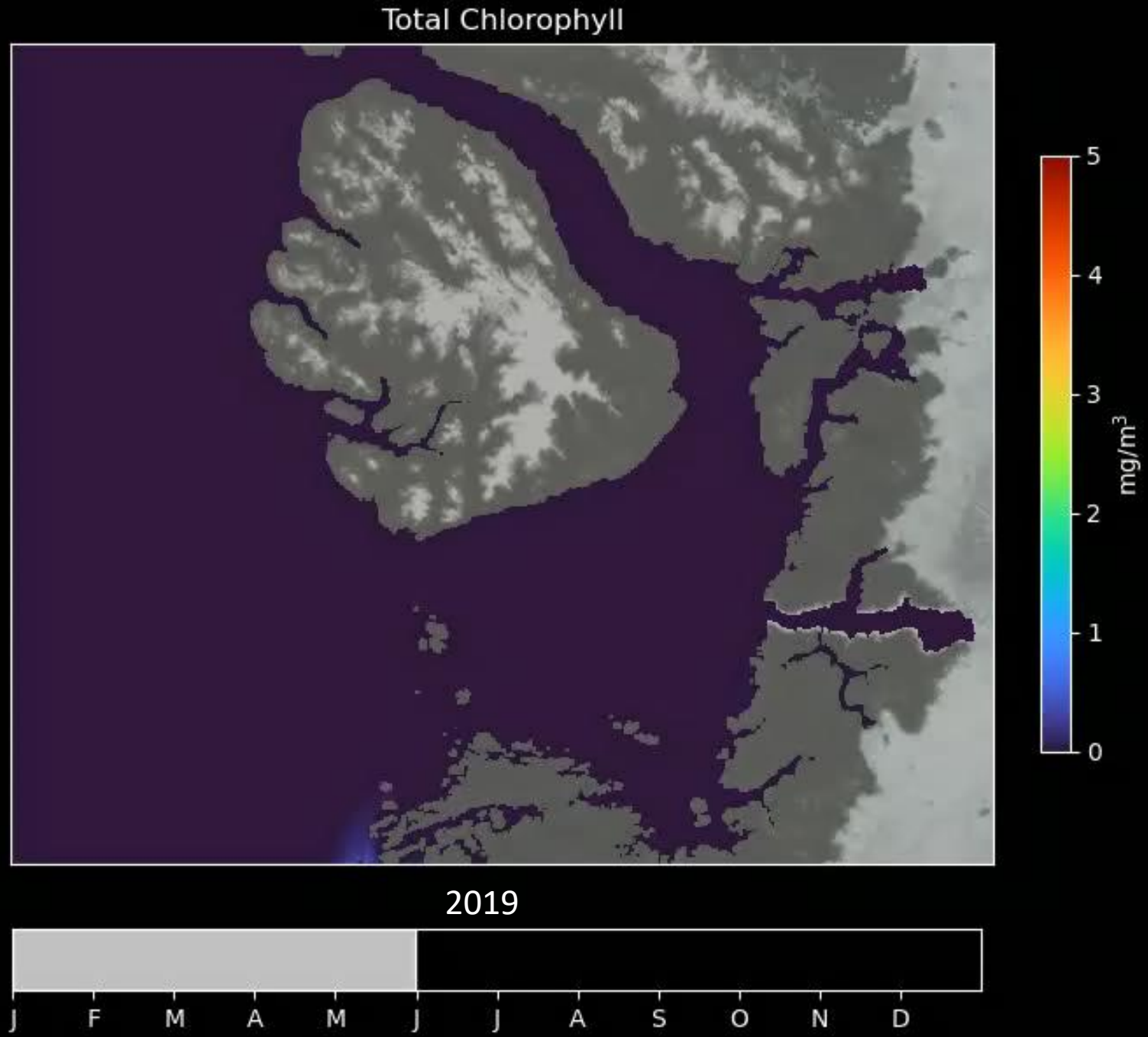
  Ice front melt is driven by iceplume package



Ice front melt from Schultz et al (UT Austin)

Chlorophyll-a: The effect of the plume

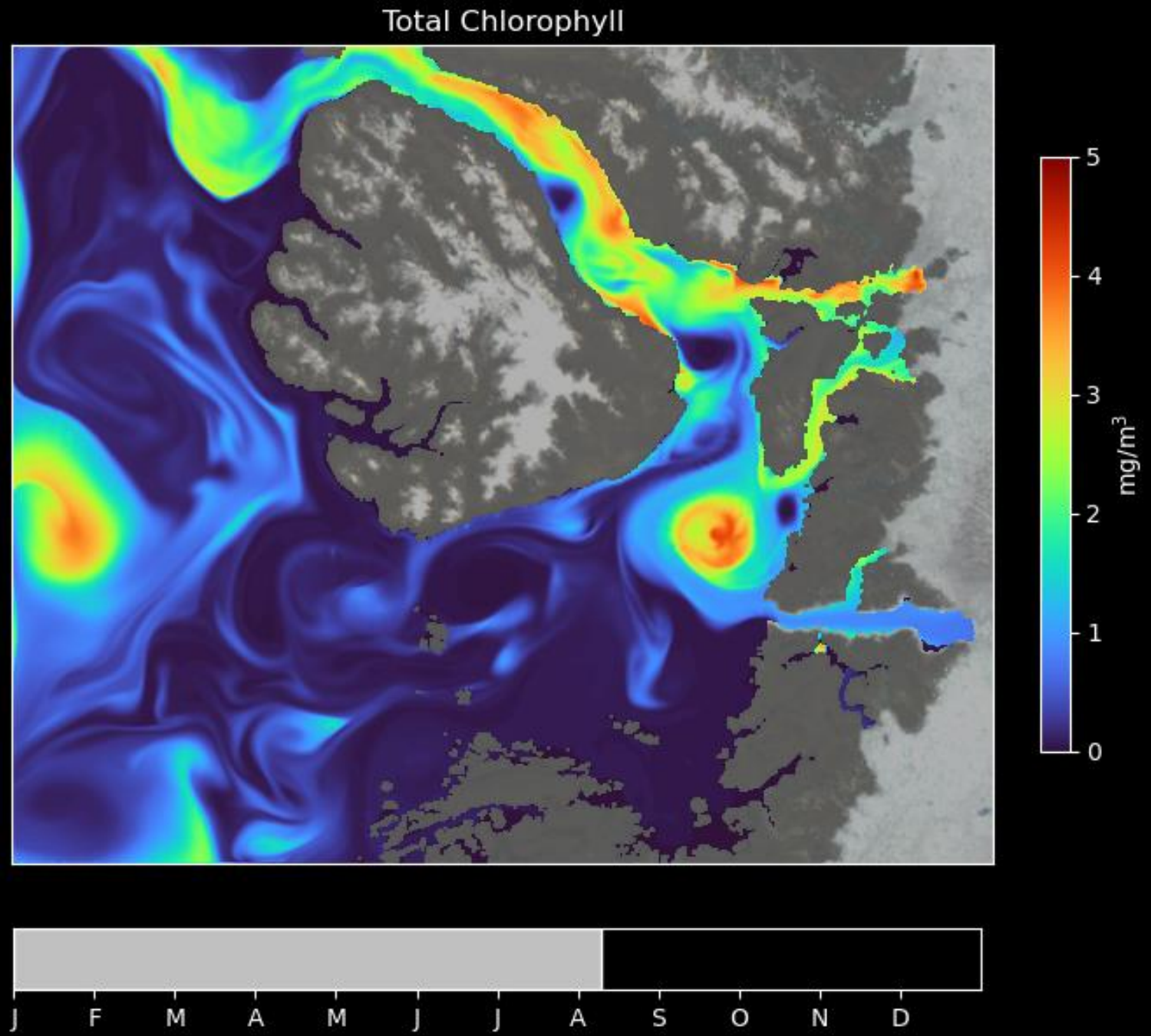
- With nutrients from plume-driven upwelling, chlorophyll-a accumulates and peaks downstream
- Peak chlorophyll-a concentrations correspond to peak periods of subglacial discharge



Model Depth: 20 m

Chlorophyll-a: The effect of the plume

- With subglacial discharge, chlorophyll-a field is spatially consistent with observations

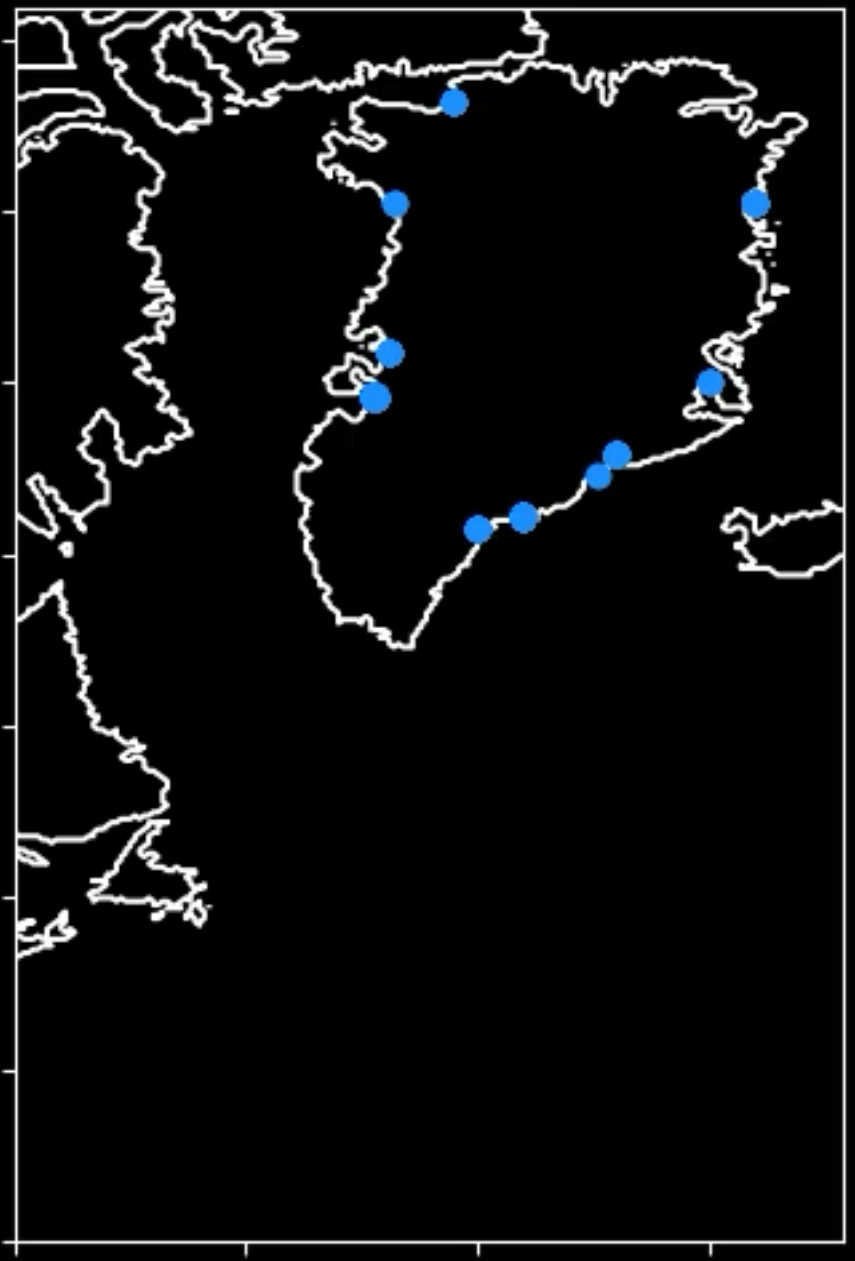


Model Depth: 20 m

Iceberg Modeling

Question: How can we get Lagrangian icebergs that melt with depth?

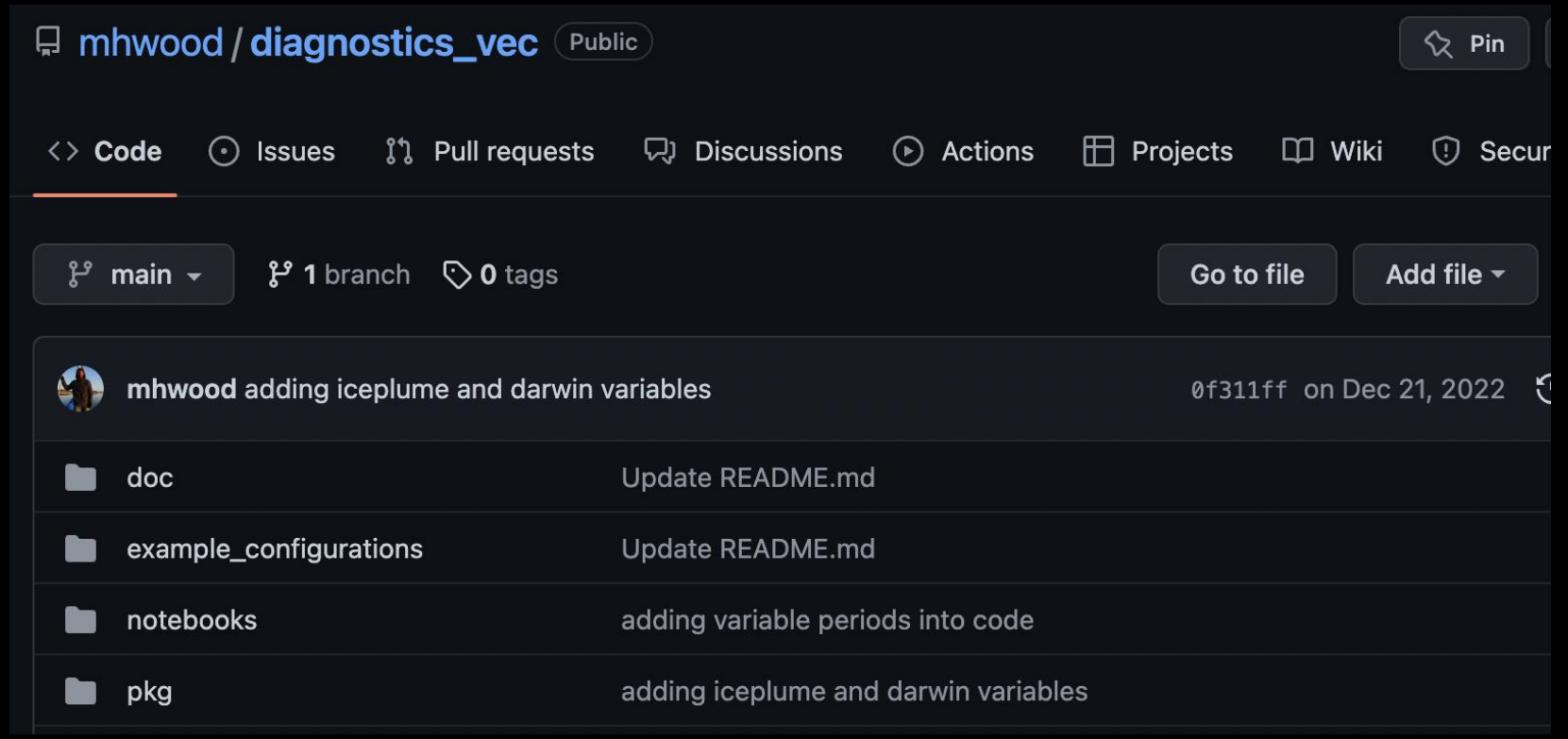
- Leverage numerical schemes from Condron et al
- Implement melt parameterizations from other packages



Iceberg test run in Greenland

diagnostics_vec

- New package for MITgcm (PR not yet submitted)
- Diagnostics only where you want em! (just provide a mask!)
- Available at github.com/mhwood/diagnostics_vec



Questions?
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