Ice sheet surface representation in an Earth system model

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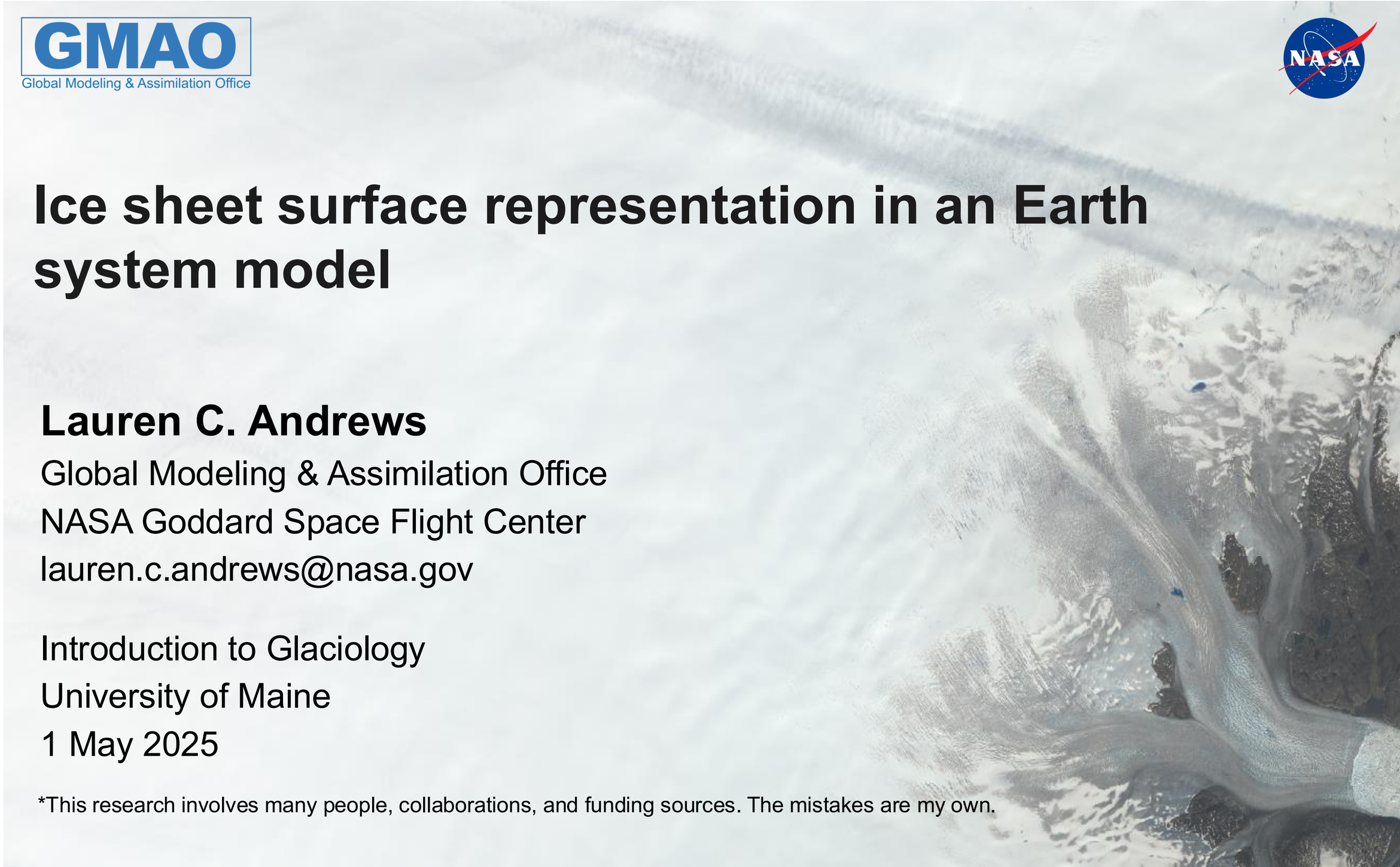
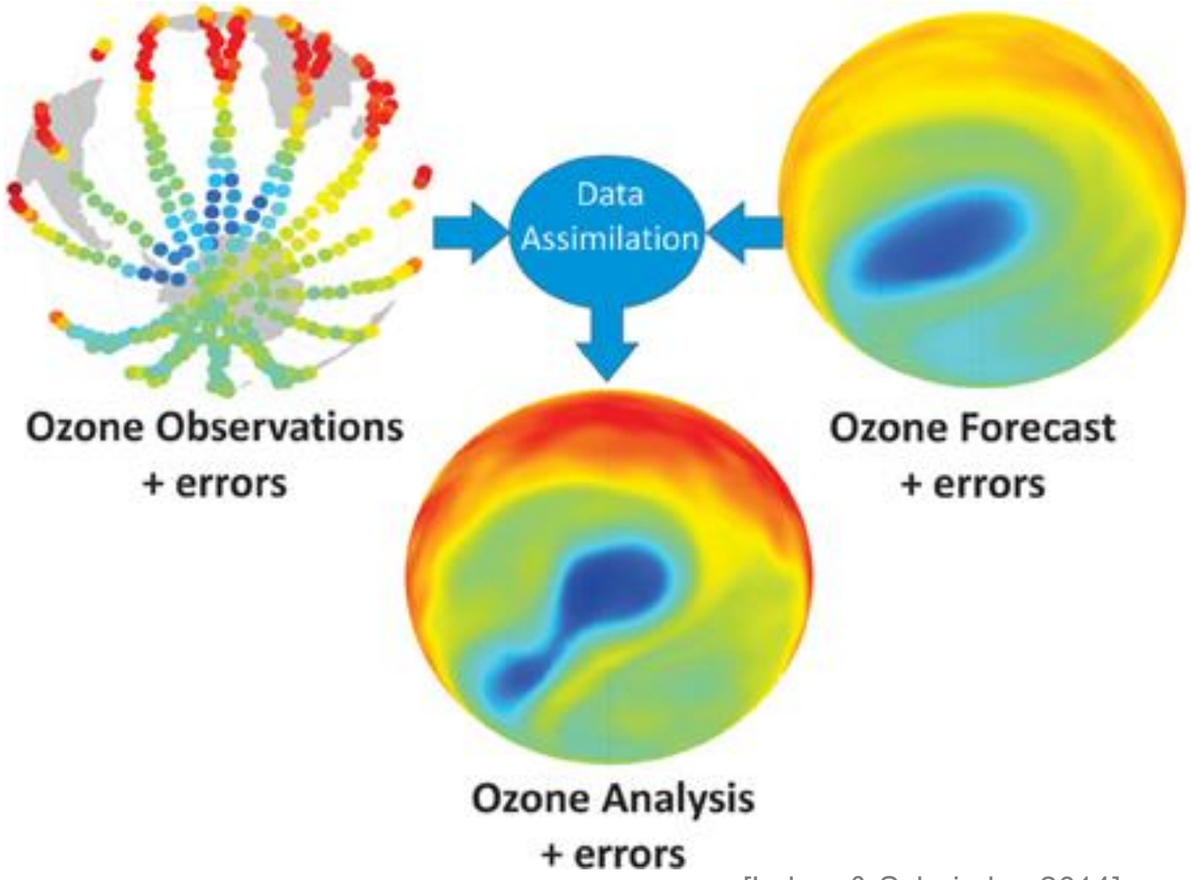
Introduction to Glaciology
University of Maine
1 May 2025

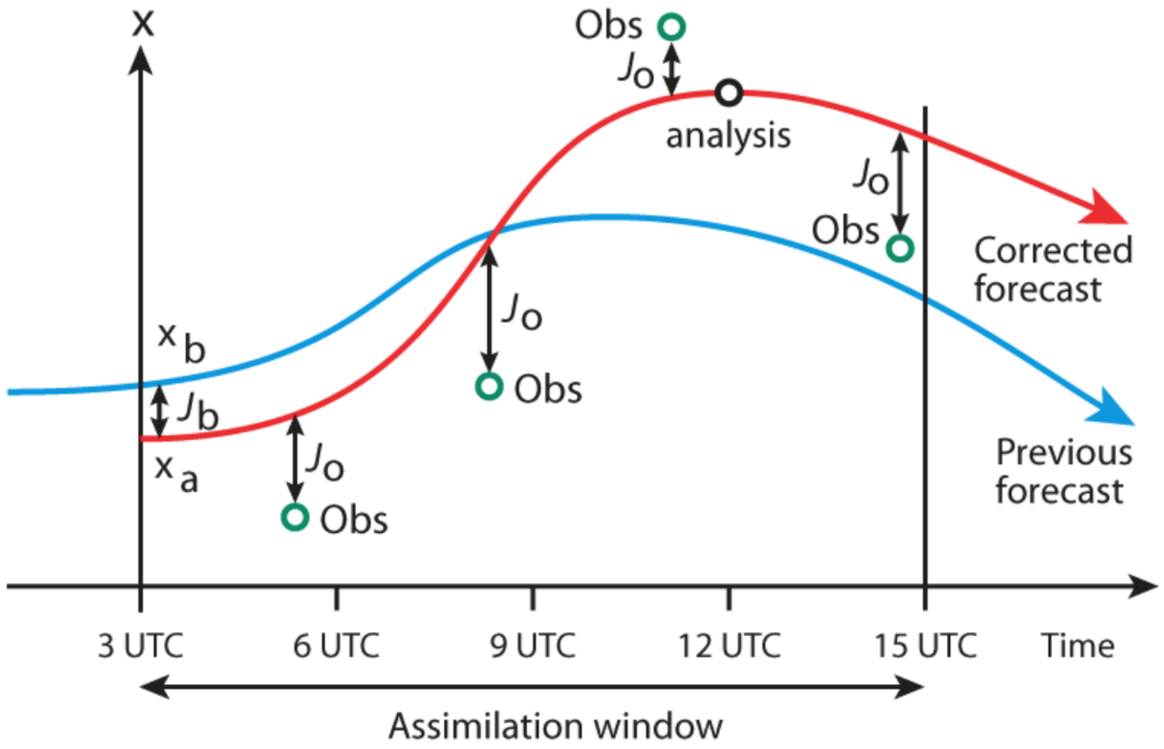
*This research involves many people, collaborations, and funding sources. The mistakes are my own.



What do we do in the GMAO?



[Lahoz & Schnieder, 2014]



[ECMWF, 2022]

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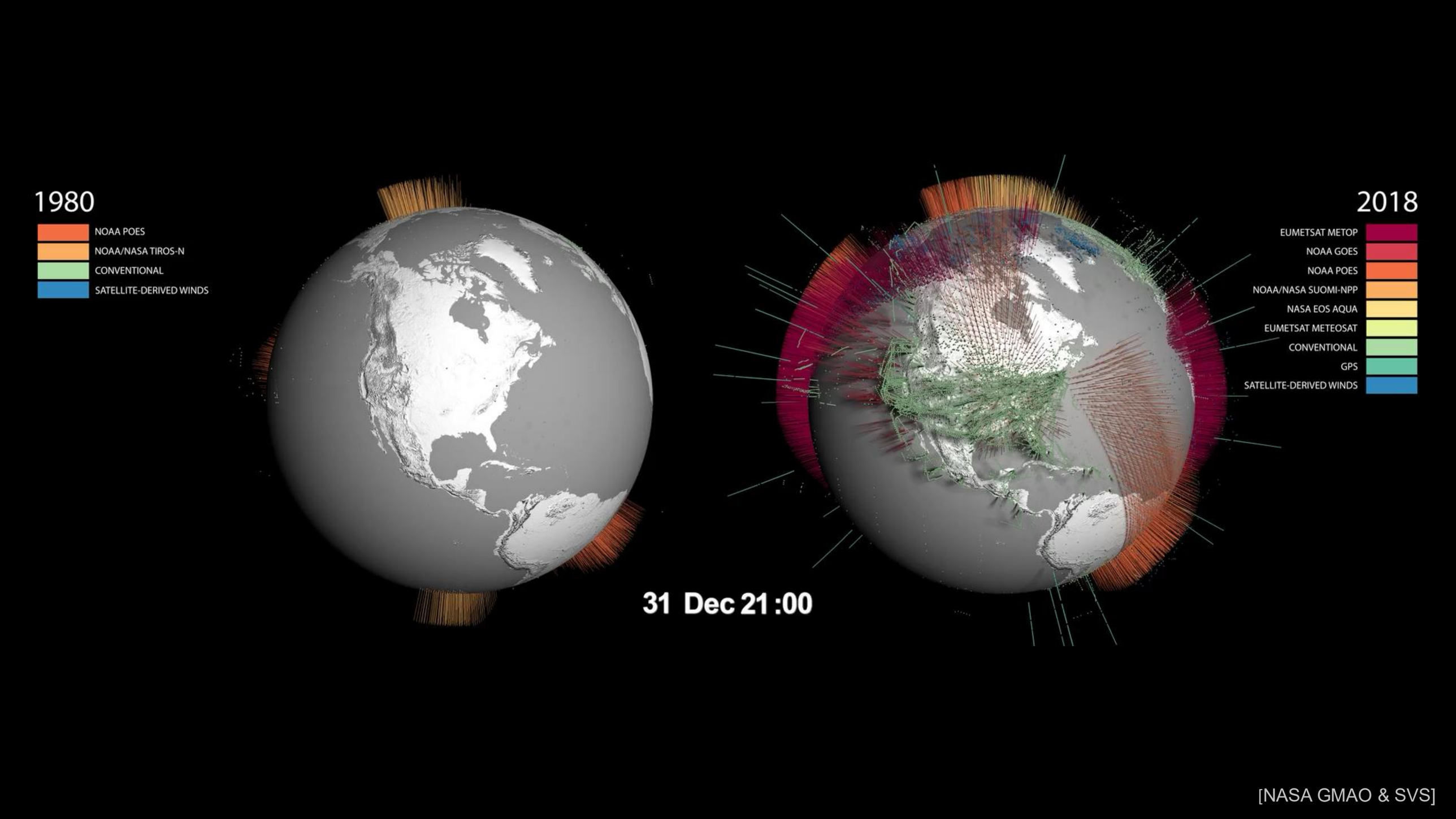
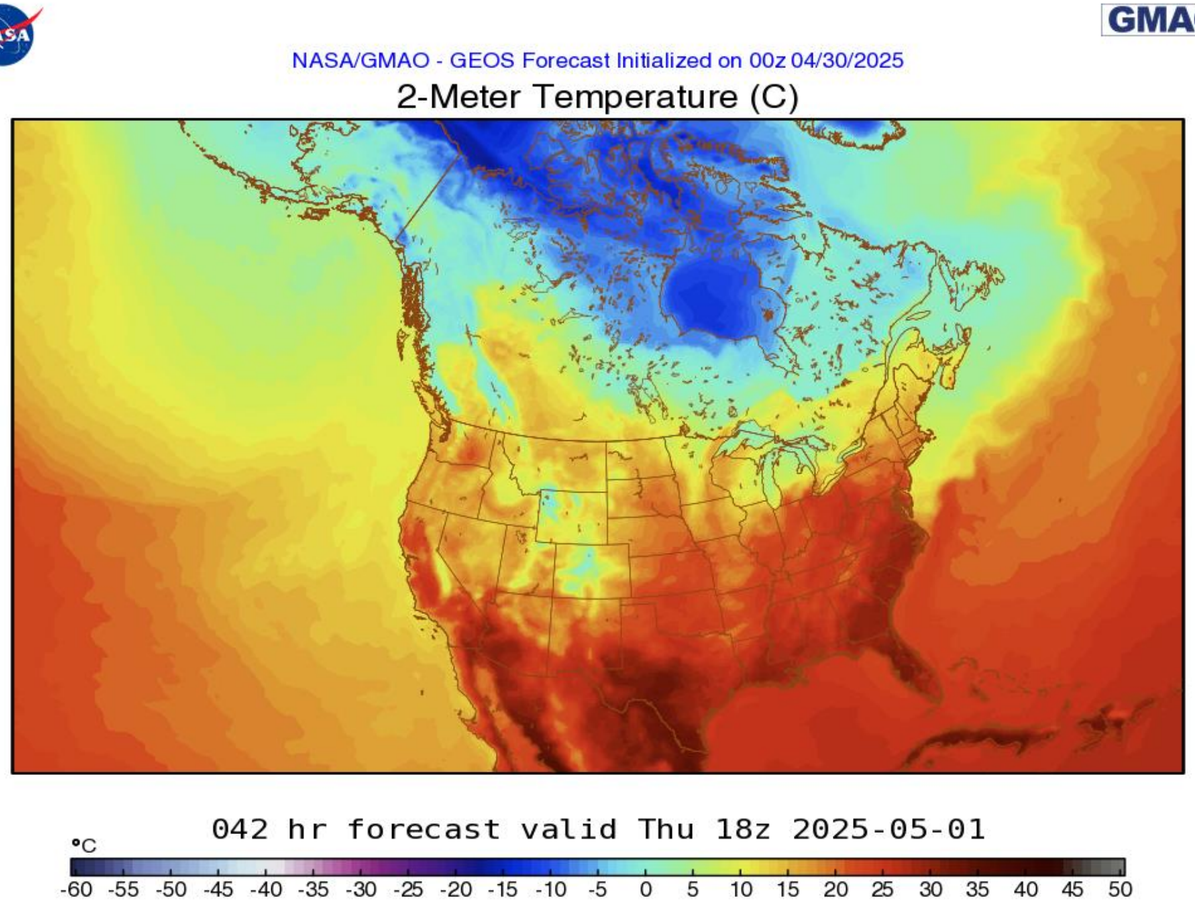
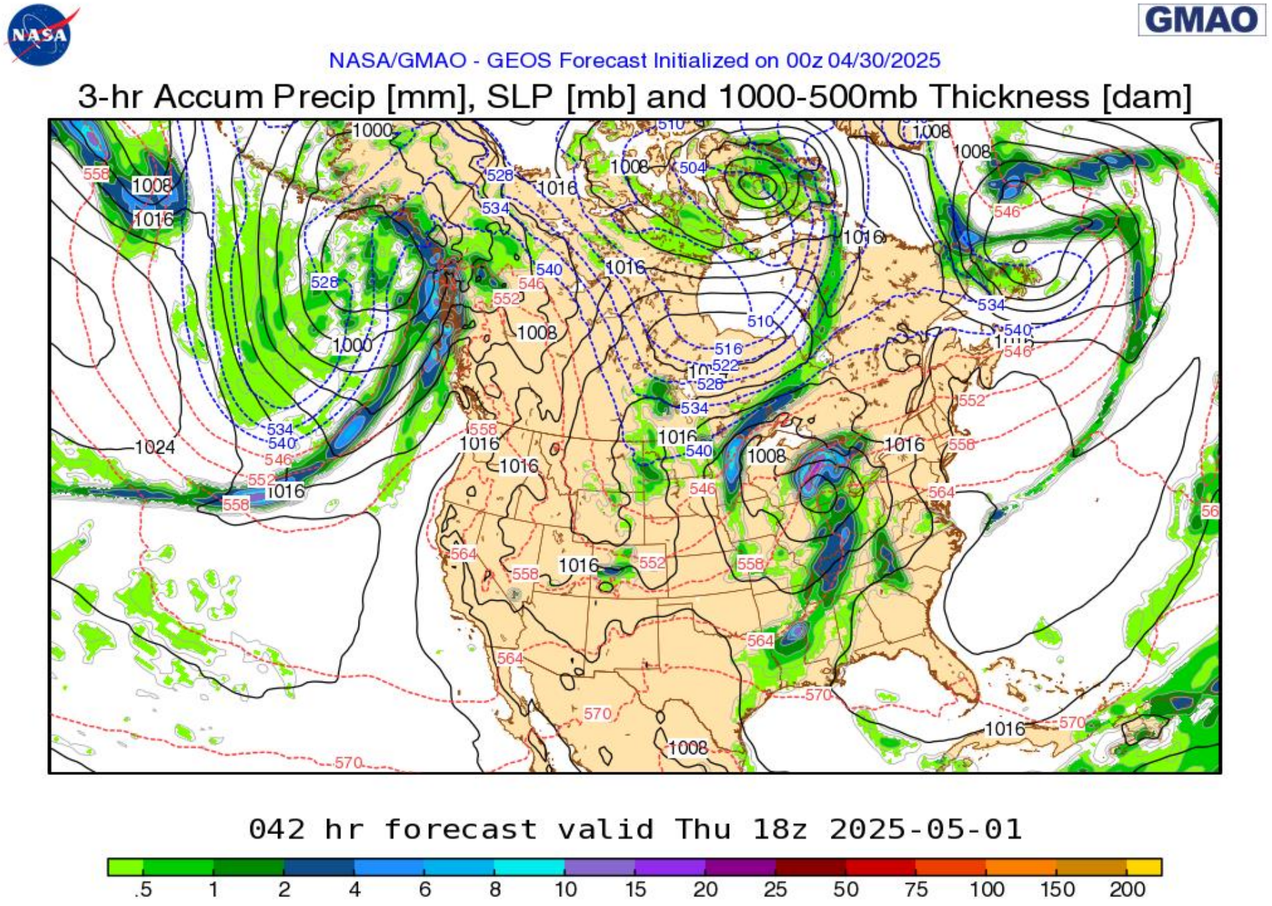


[NASA GMAO & SVS]

What do we do in the GMAO?





https://fluid.nccs.nasa.gov/

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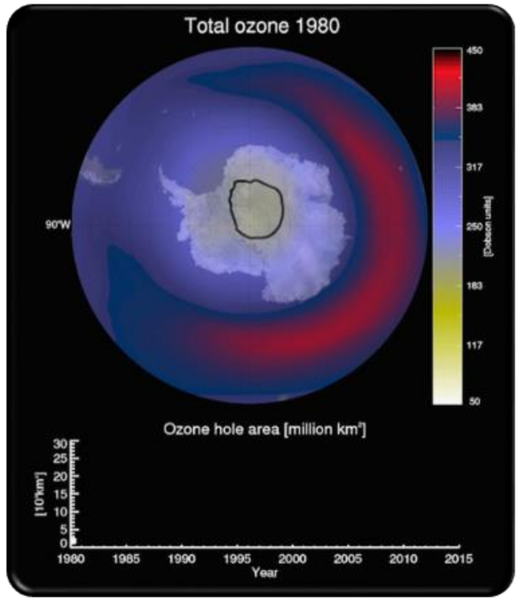
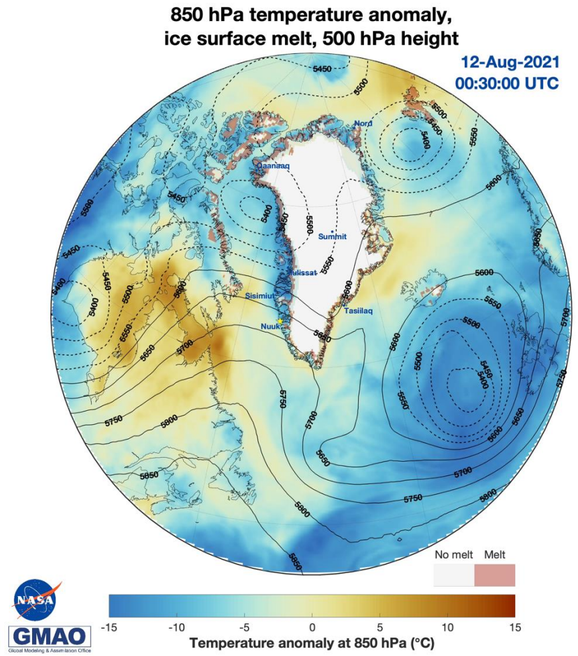
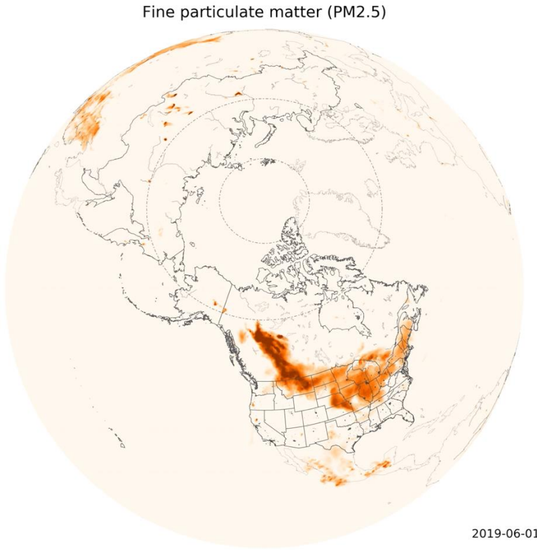
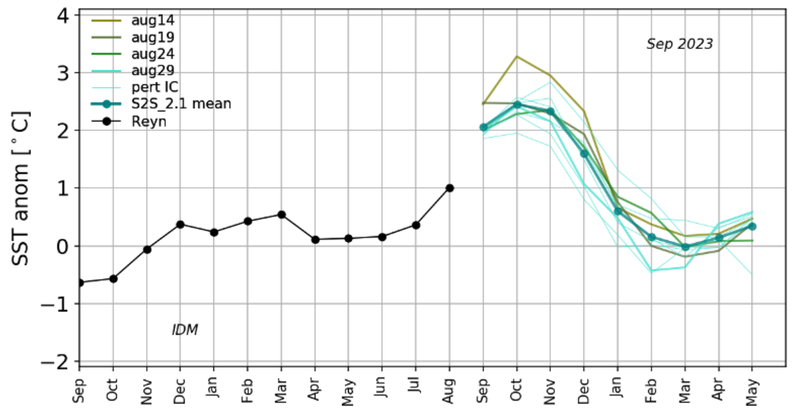
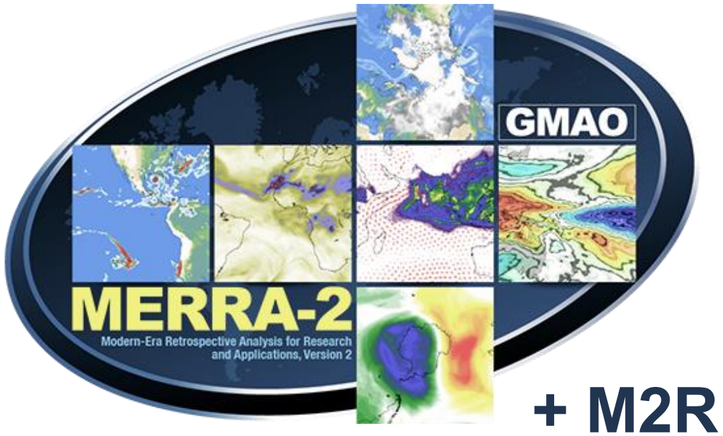
What do we do in the GMAO?











GEOS-IT, MERRA-21C **M21C-Polar** **MERRA-3**

+ M2R12K

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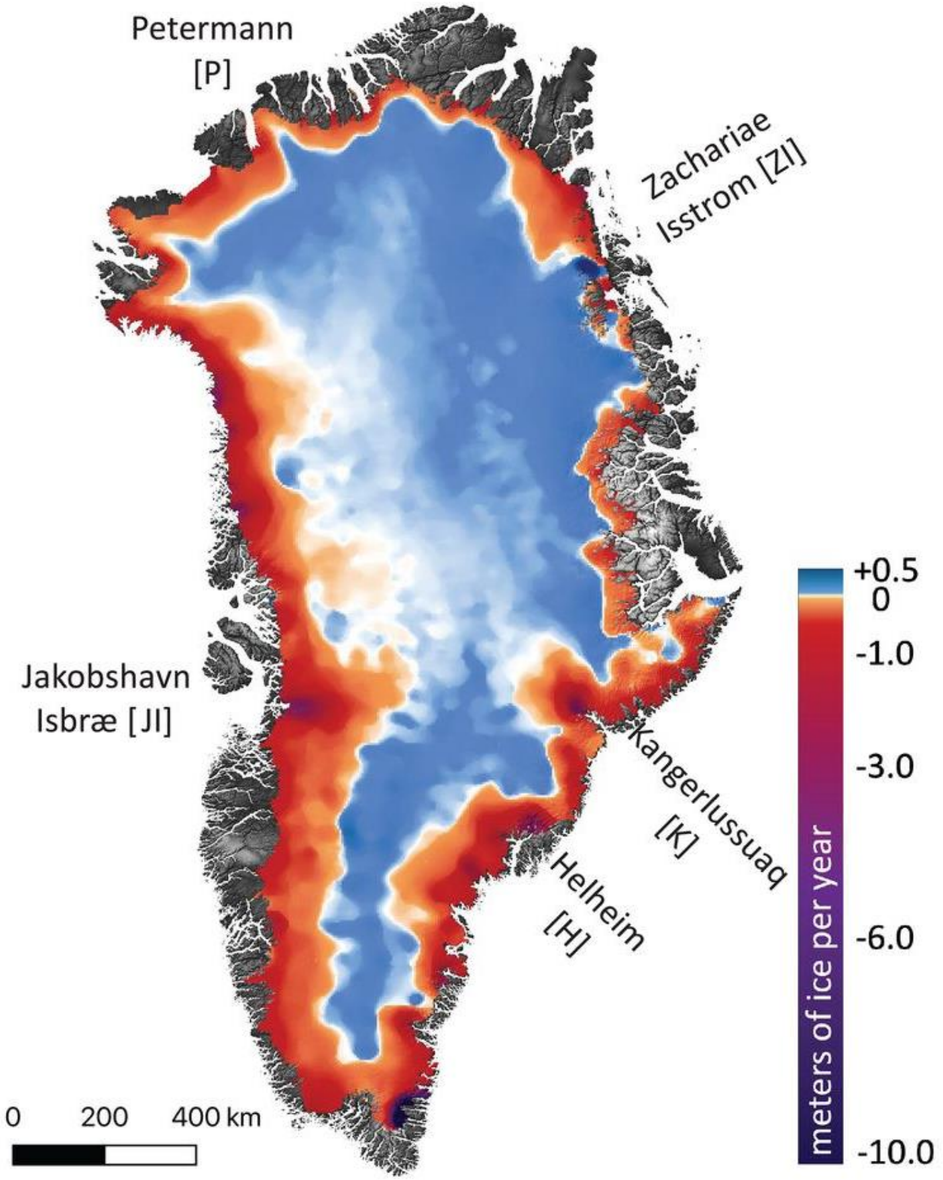
Who uses our products?

- **ESMs ↔ process studies and models**
- Reanalyses provide atmospheric forcing for many cryospheric process studies.
- The ability of reanalyses to represent atmospheric and near surface conditions directly impact snow, firn, and dynamical processes.
- Known biases and limitations.



[Smith et al., 2020]

From surface processes to dynamics

Ice sheet surface processes

How does GEOS represent ice surfaces?

How are we improving ice surface processes to better support the cryospheric community?

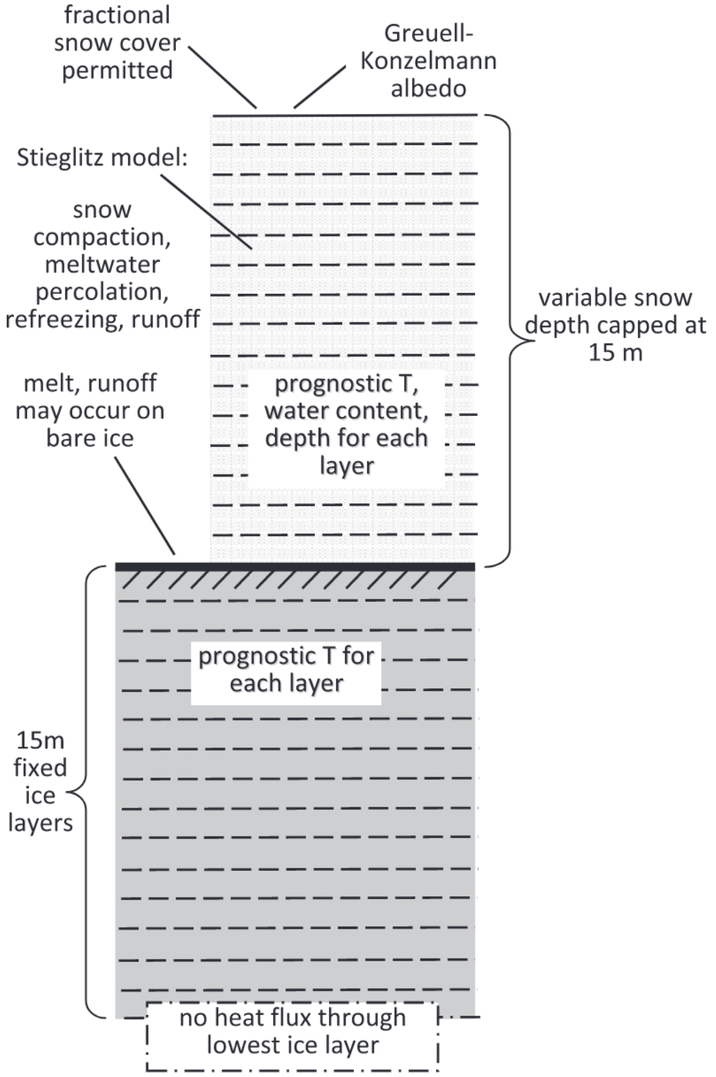
Ice sheet dynamics

Supraglacial to englacial dynamics: Moulin evolution and the influence of surface meltwater runoff [Andrews et al., 2022; Trunz et al., 2023].

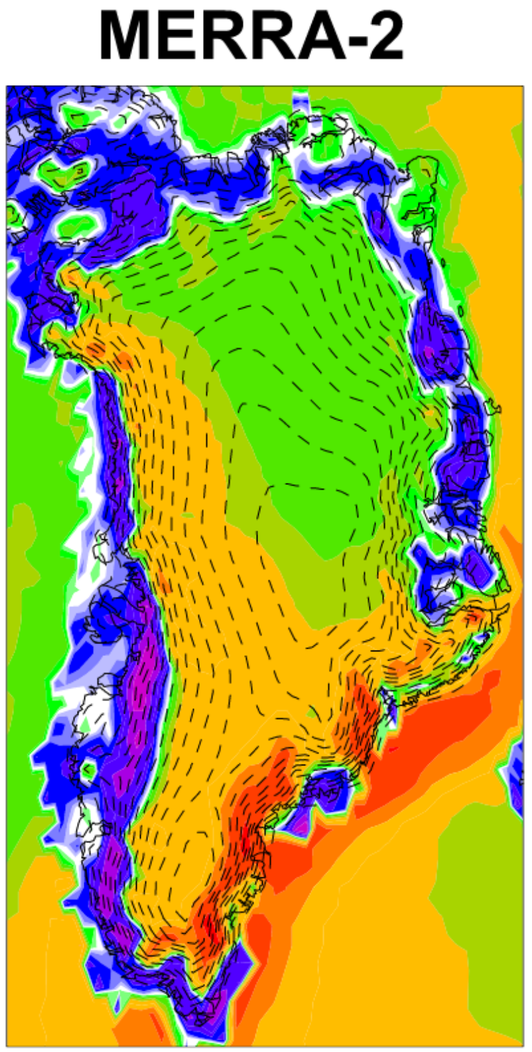
Linking the surface to dynamics through meltwater storage [Smith et al., 2021].

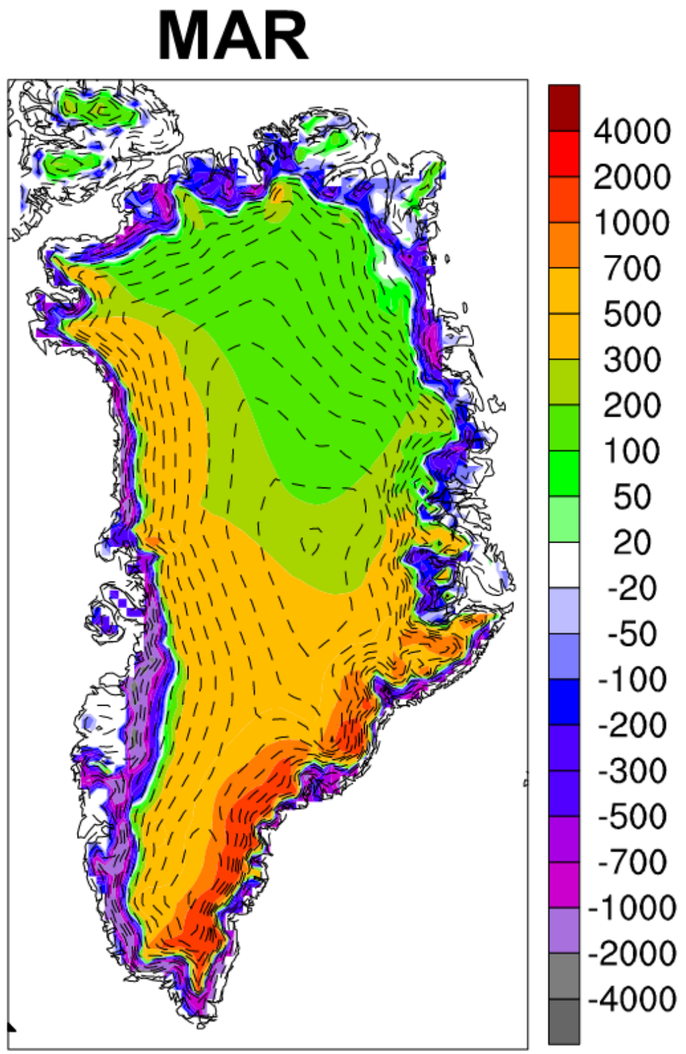
The role of surface and basal melt on seasonal in outlet glacier behavior [Andrews et al., in prep].

Surface mass balance and surface representation



[Cullather et al., 2014]



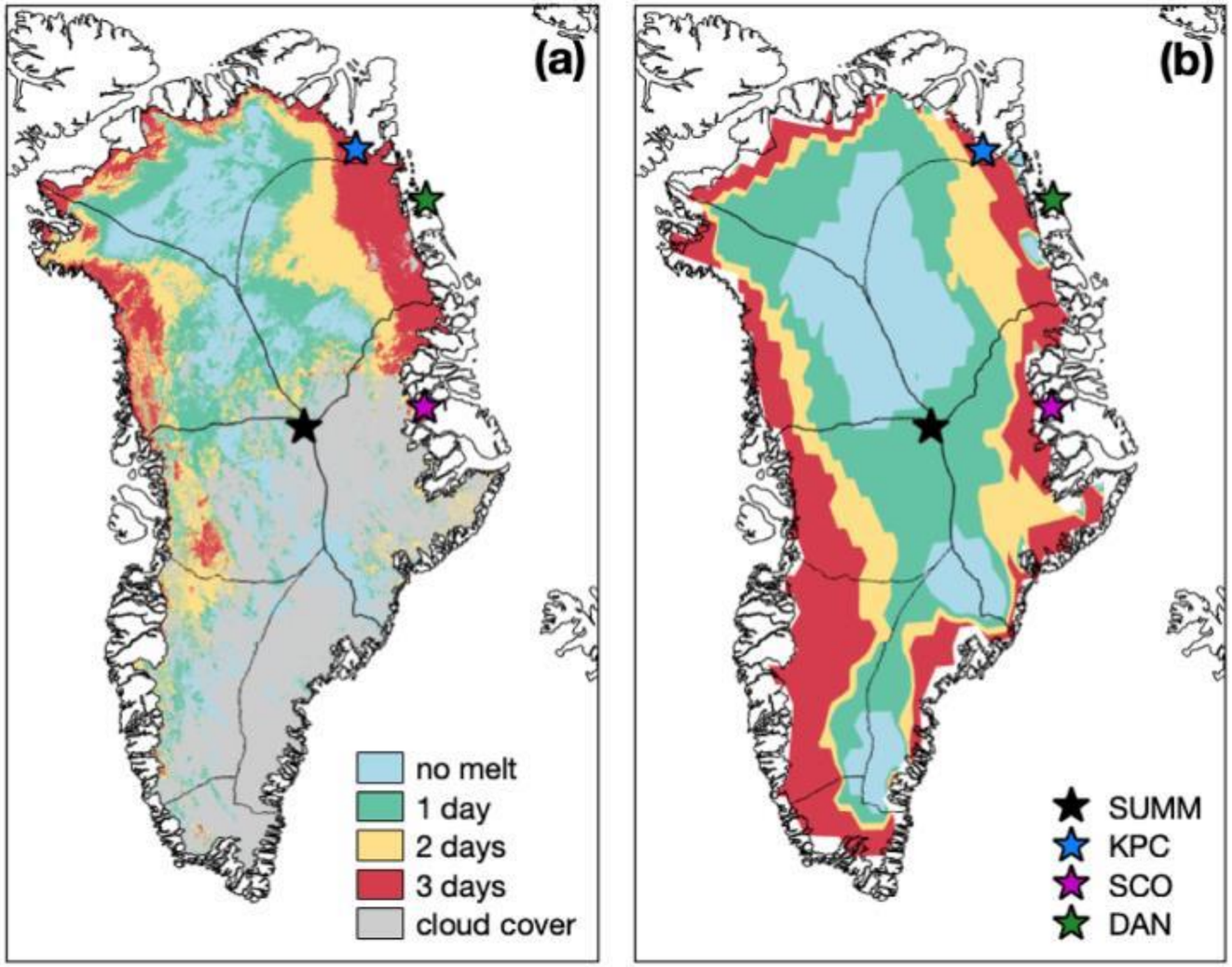


Surface mass balance (mm yr^{-1} w. e., 2000-18)

Surface mass balance and surface representation

- Despite coarse resolution, MERRA-2 can reasonably reproduce surface melt extent -- even during melt events like that in July 2019.

- There are limitations, including how surface temperature is calculated.



[Cullather et al., 2020]

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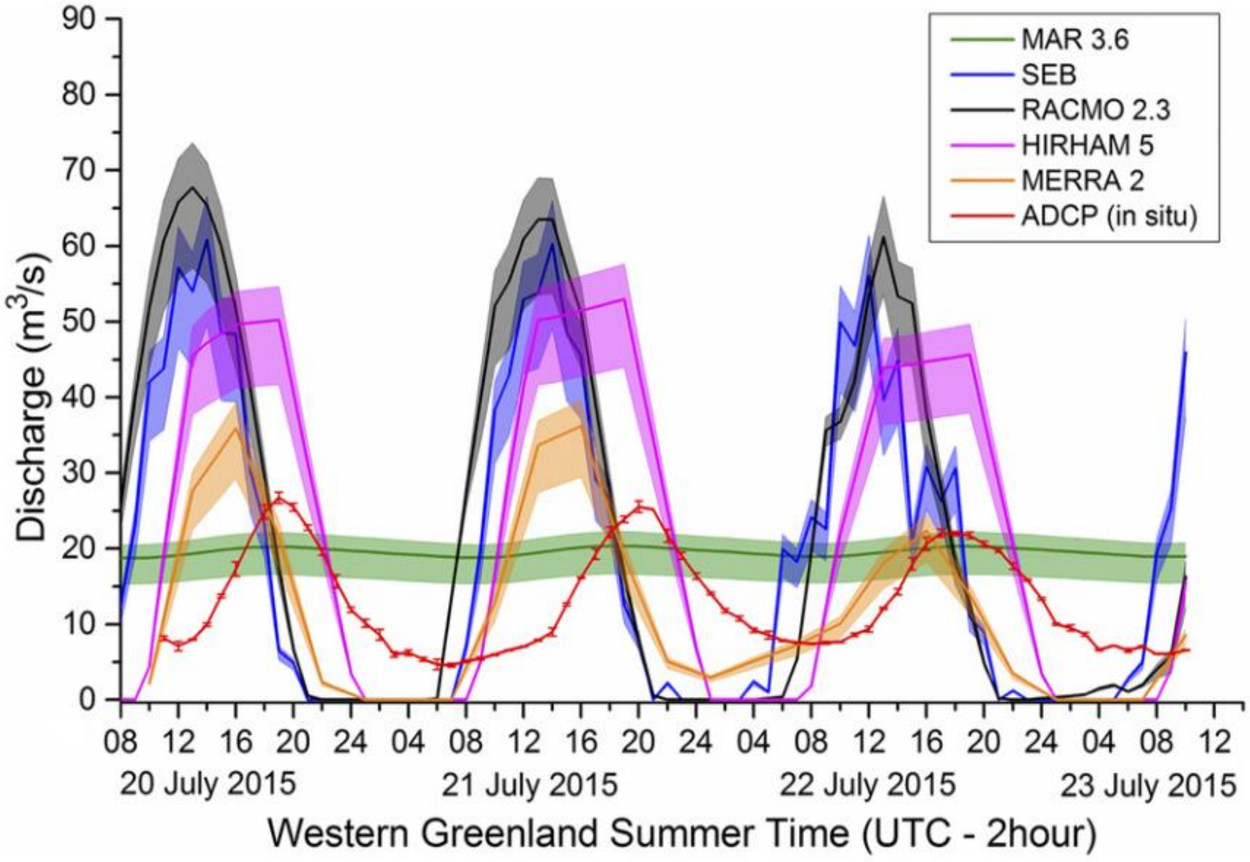
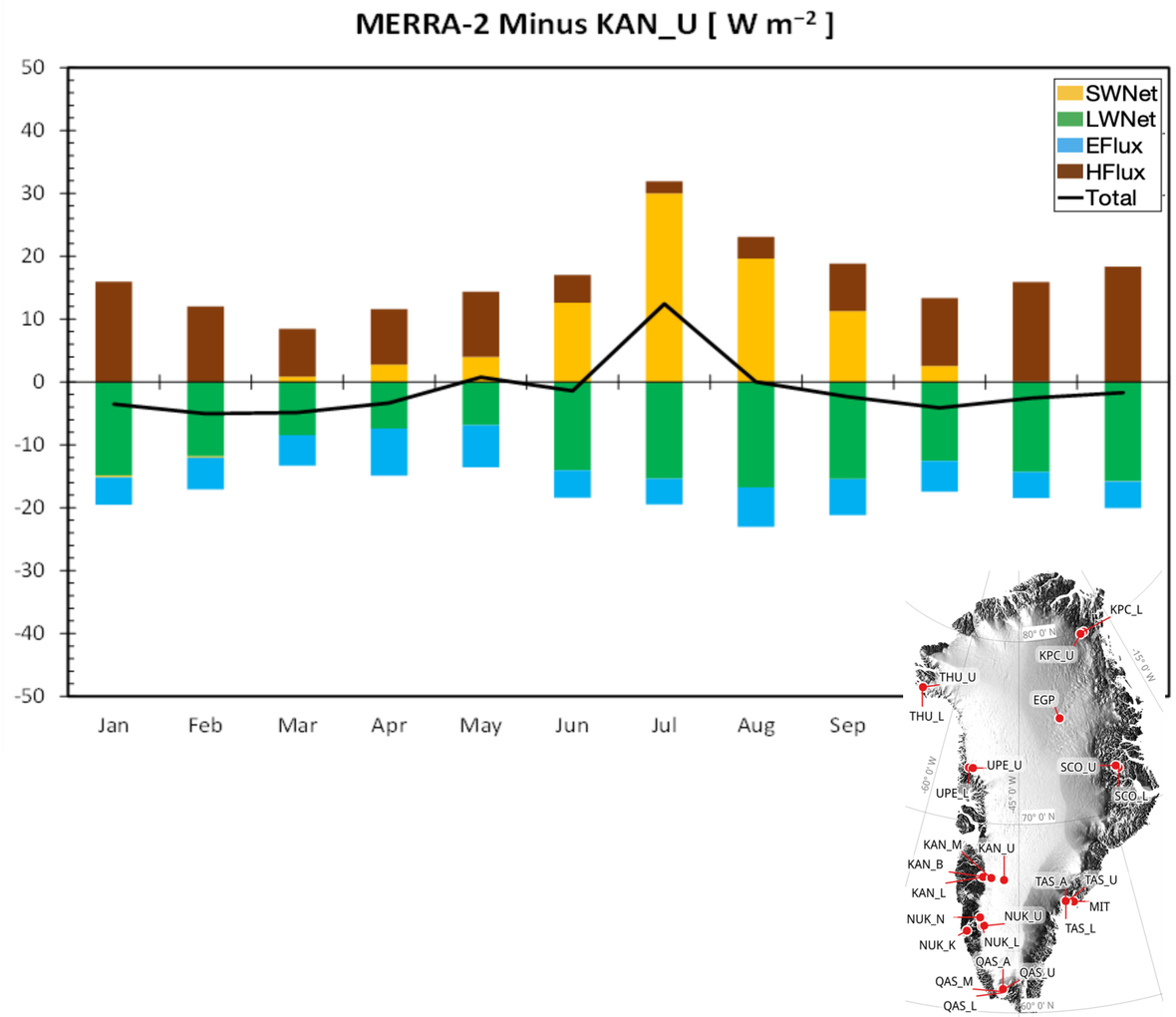
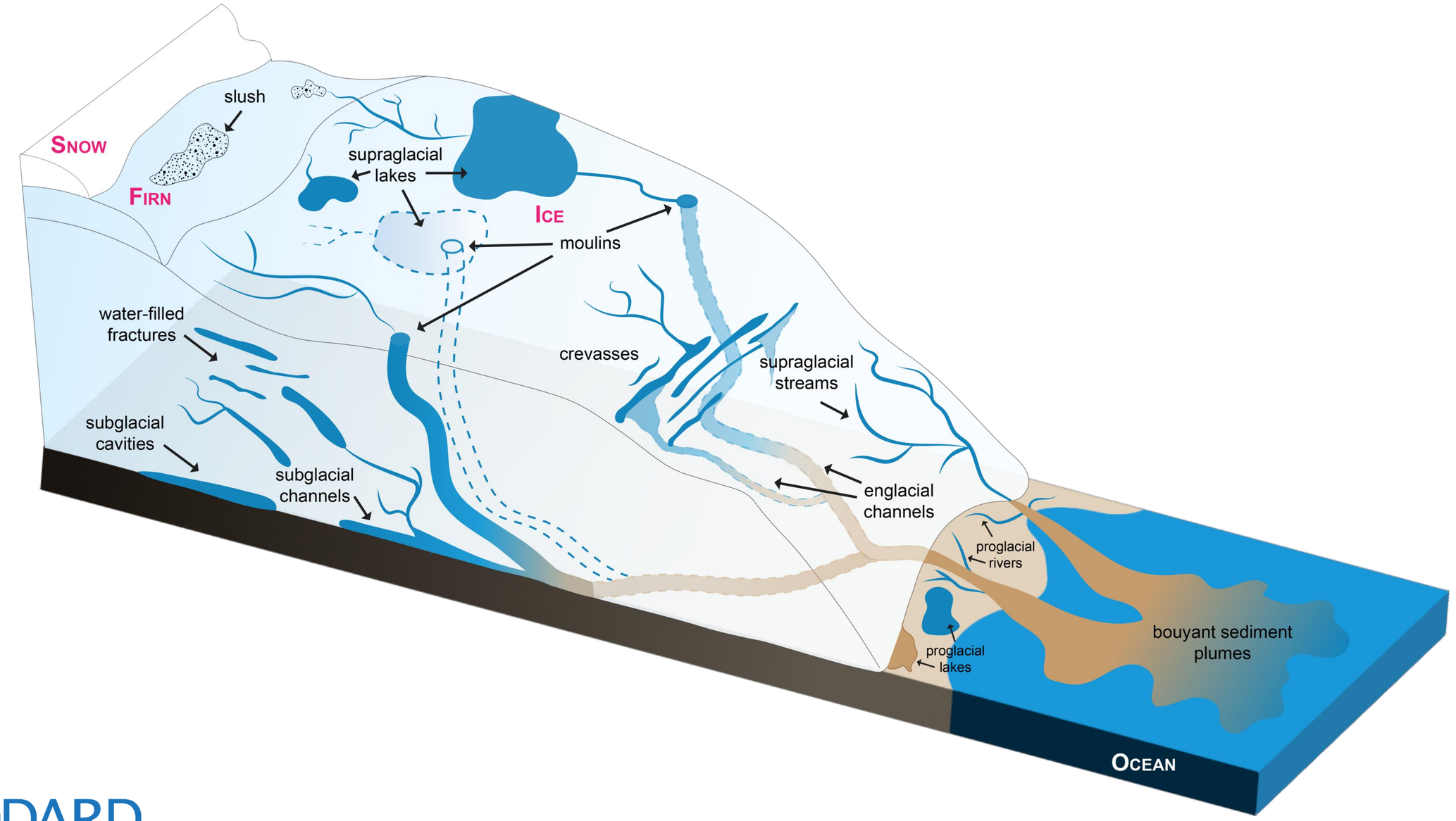
Surface mass balance and surface representation



[Smith et al., 2017]

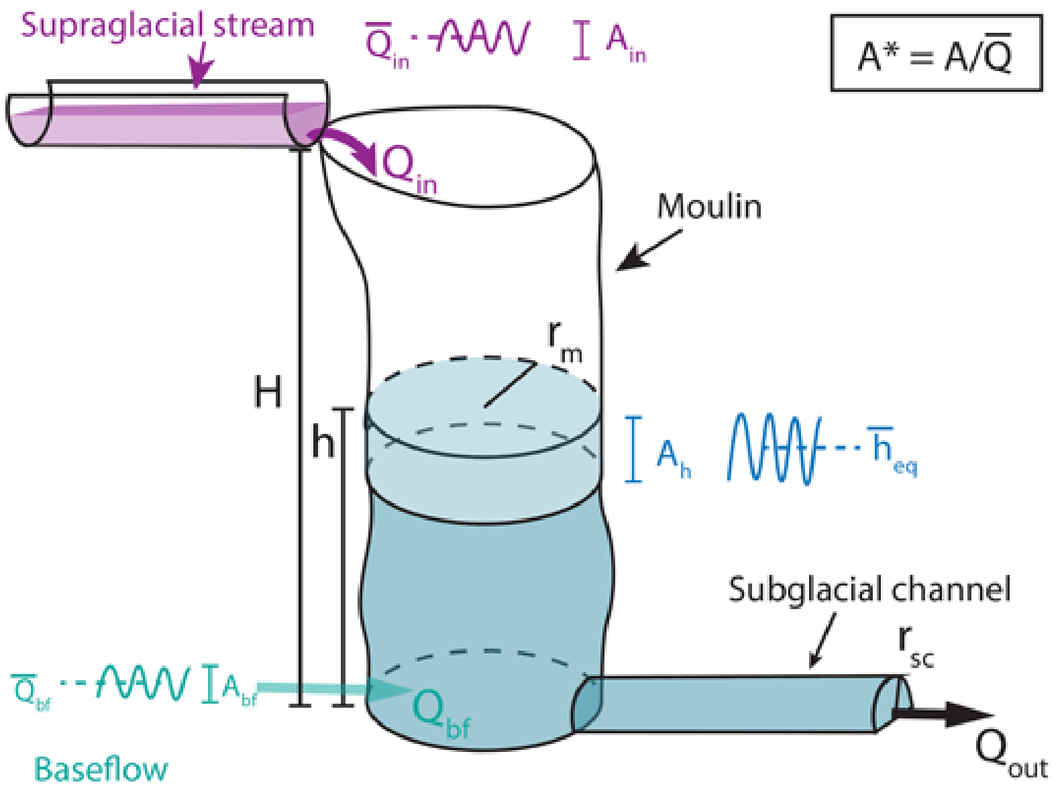


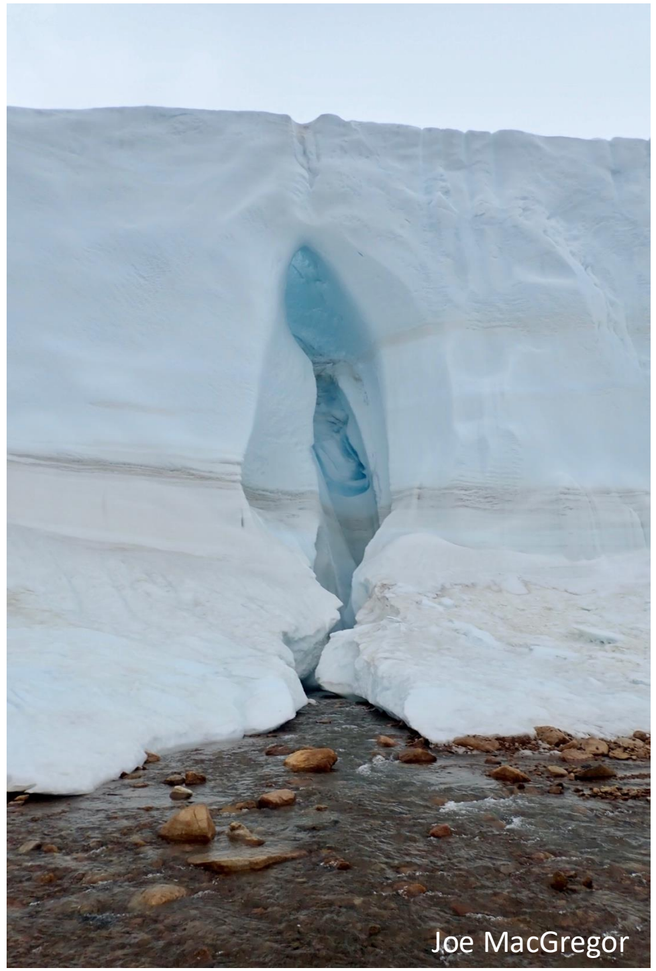
Glacial hydrology



[Modified from Chu, 2014]

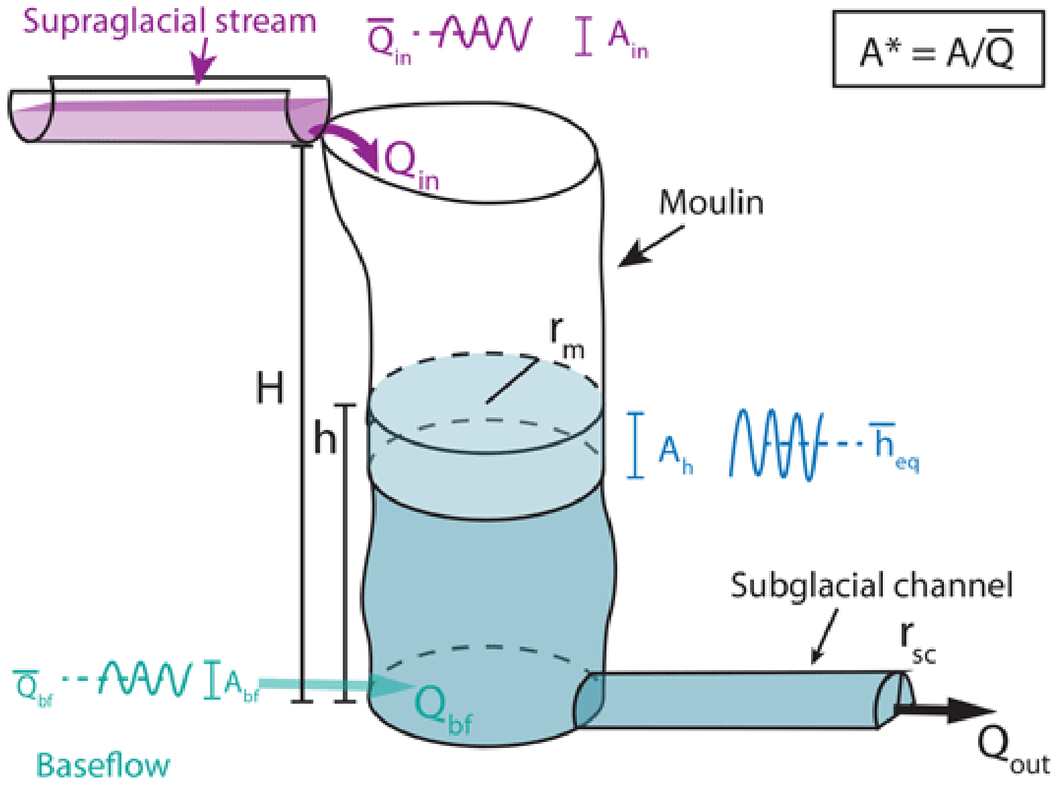
Supraglacial to englacial dynamics

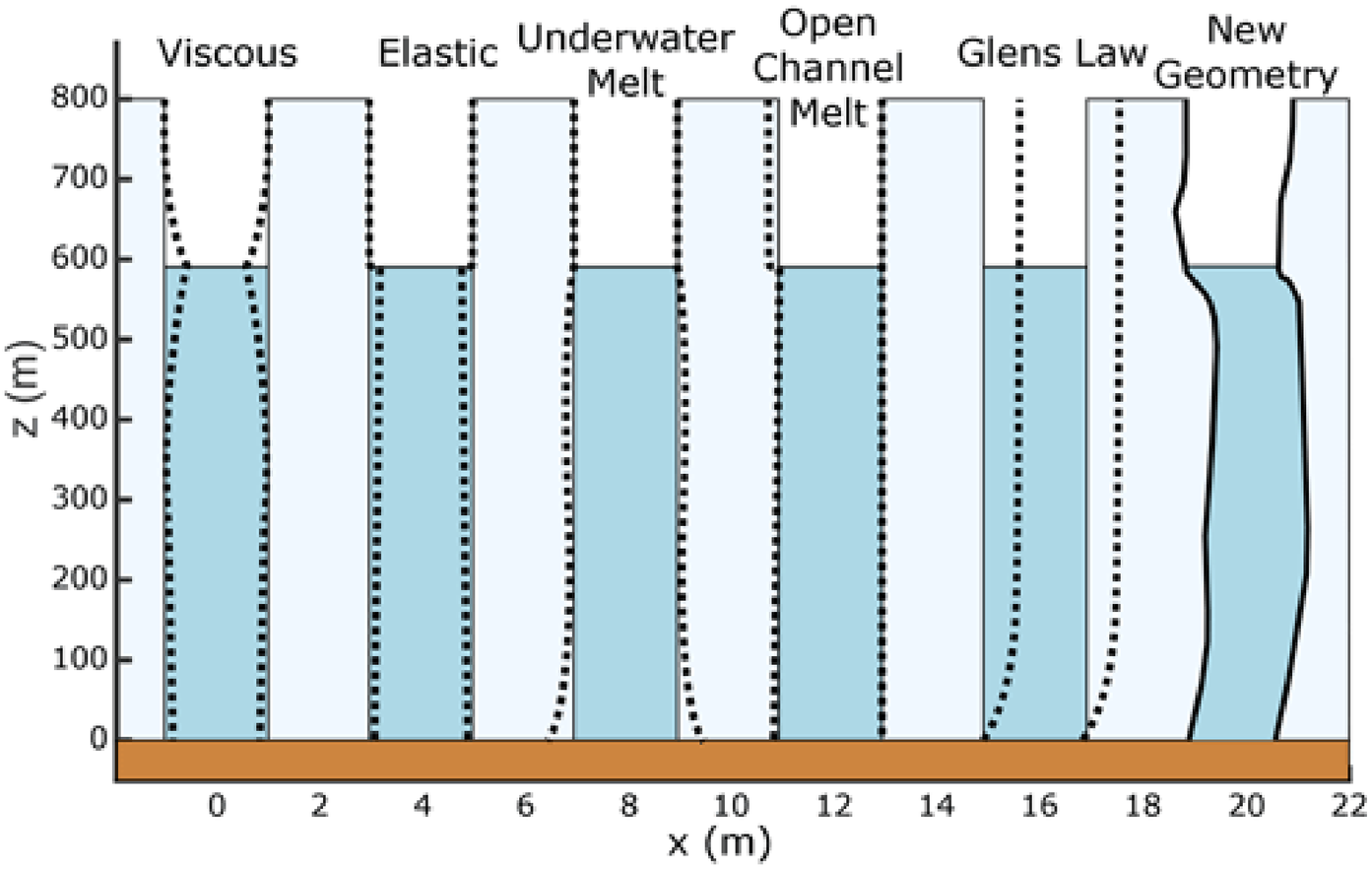




[Andrews et al., 2022; Trunz et al., 2023]

Supraglacial to englacial dynamics





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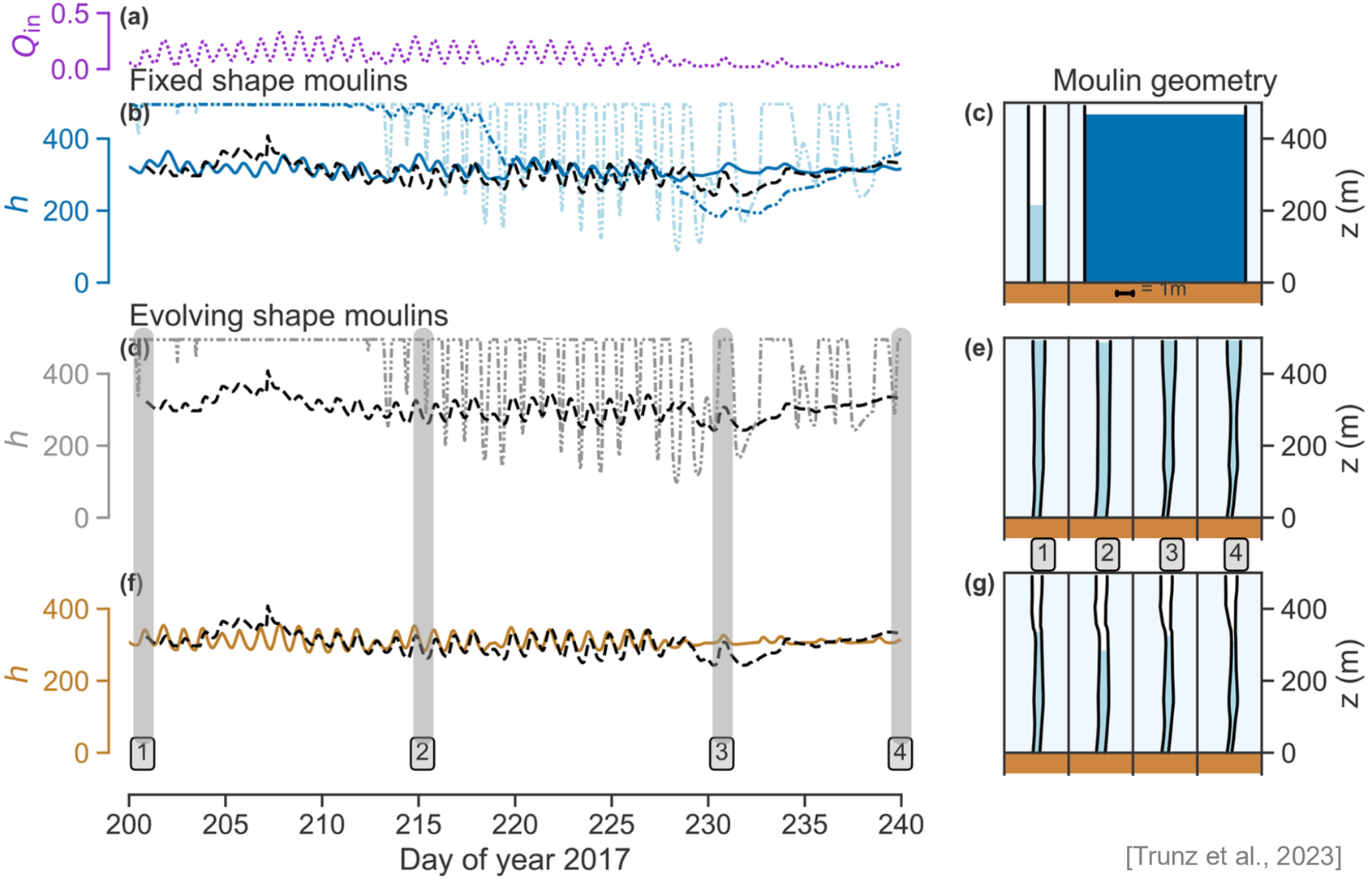
Supraglacial to englacial dynamics

- Moulins tend to be modeled as cylinders.
- It's much easier to model moulin water levels with an evolving moulin, particularly in the early melt season.
- Interconnectivity between moulins is required.



[Trunz et al., 2023]

Q_{in}: Meltwater input (m^3s^{-1})
h: Measured moulin head (m from bed)
h: Sim Fa (fixed, r=0.5 m)
h: Sim Fb (fixed, r=5 m)
h: Sim Fc (fixed, r=5 m, baseflow=1 m^3s^{-1}))
h: Sim EMa (evolving, no baseflow)
h: Sim EMb (evolving, baseflow=2 m^3s^{-1})

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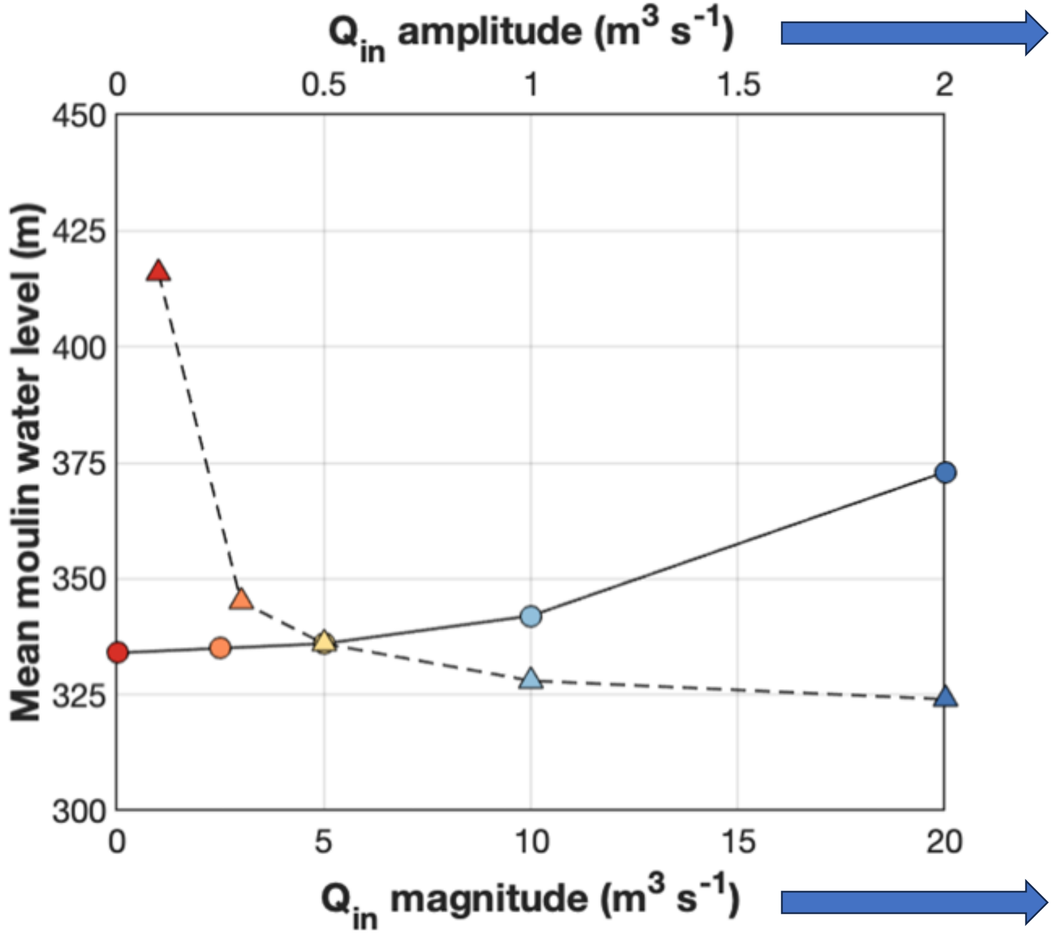
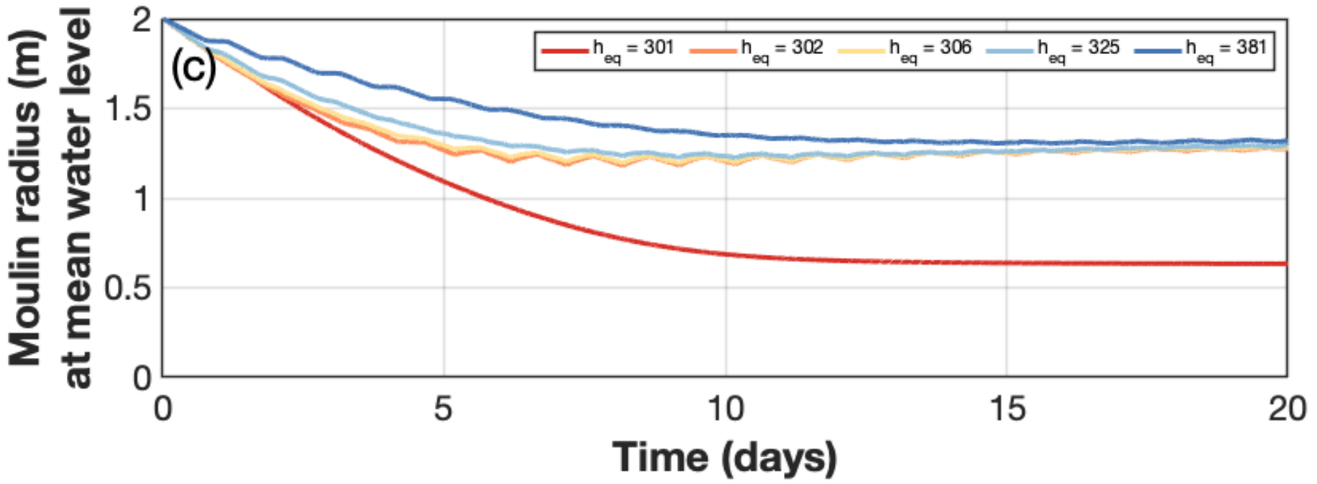
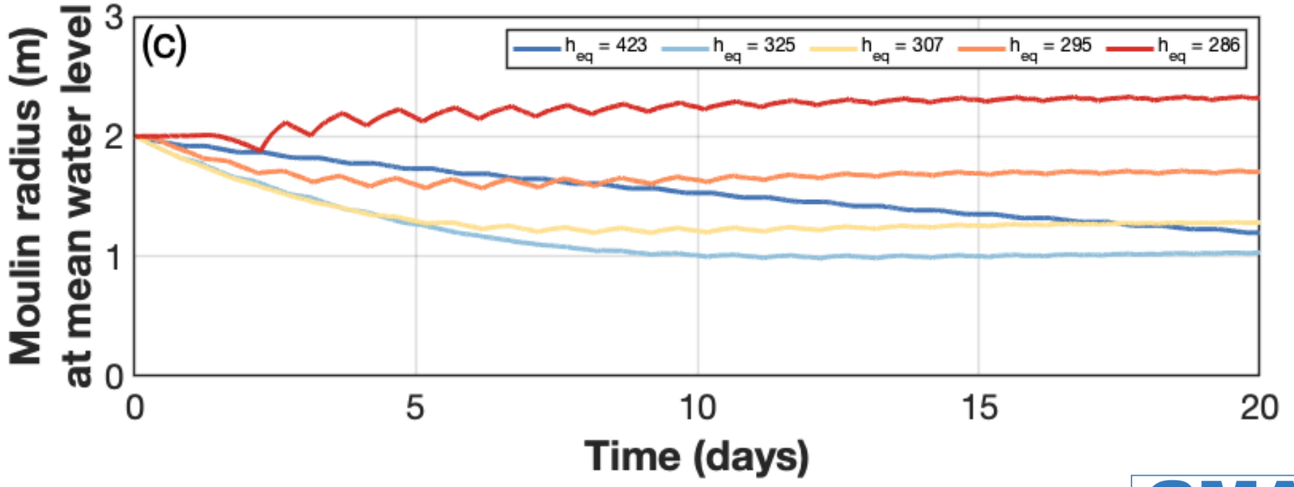
Supraglacial to englacial dynamics







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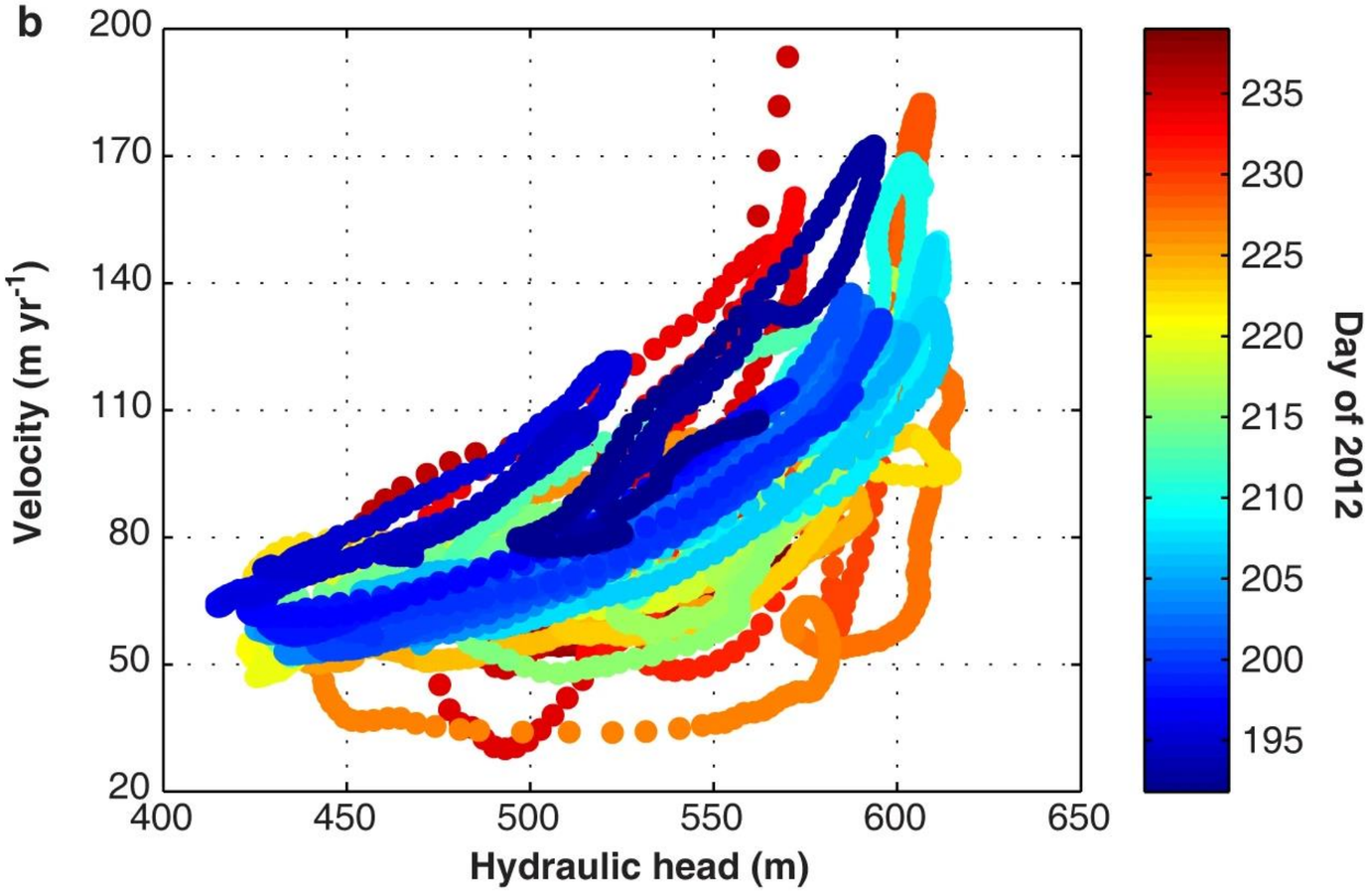
Supraglacial to englacial dynamics

Ice velocity is driven by subglacial pressure, but why/how?



[Andrews et al., 2014]

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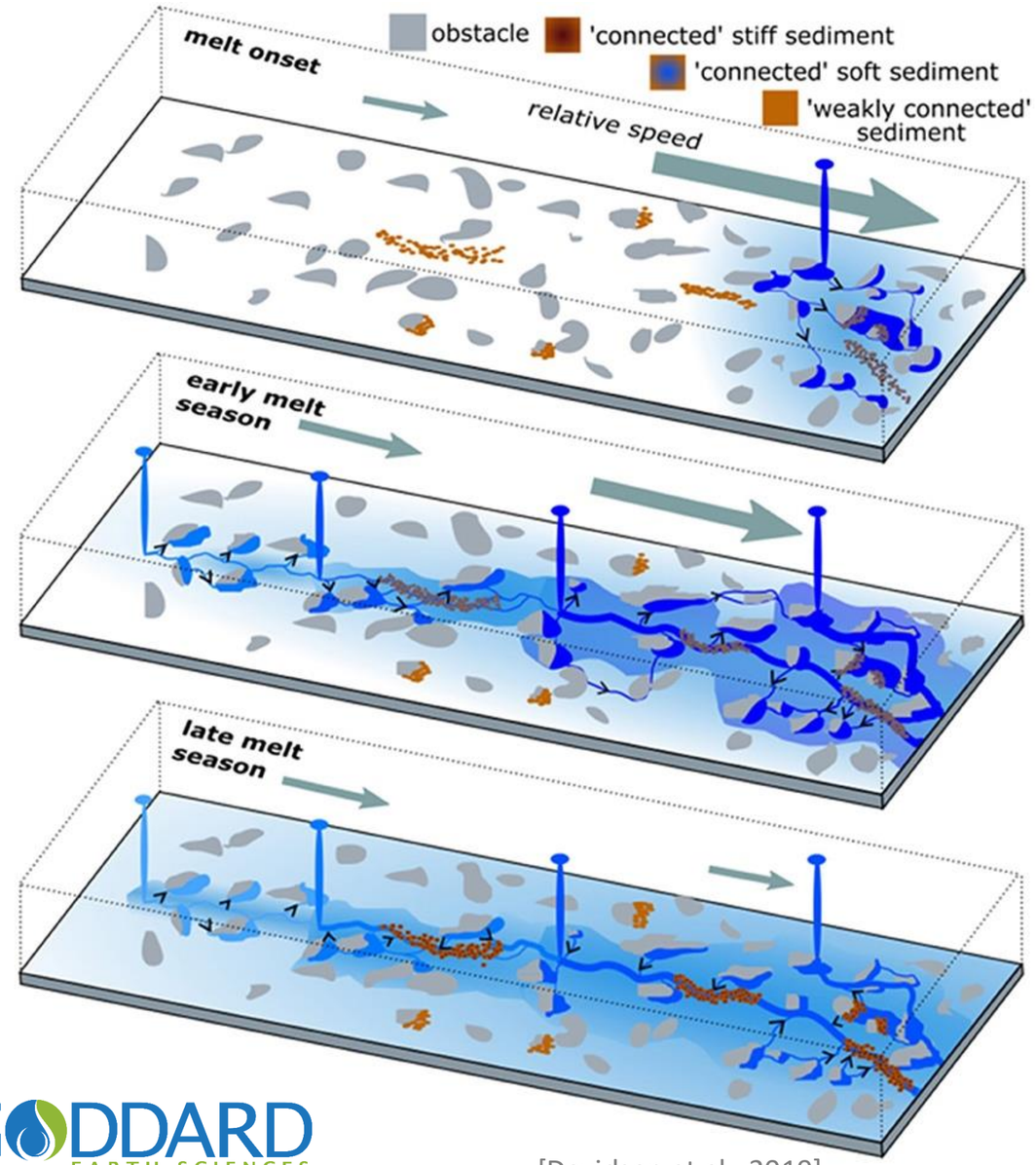
From supraglacial runoff to subglacial storage



[Davidson et al., 2019]

[Iken et al., 1983: The Uplift of Unteraagletscher at the beginning of the melt season – a consequence of water storage at the bed?]

Horizontal velocity ~ pressure
~ △storage ~ vertical velocity

Measurable?? **Sort of measurable**

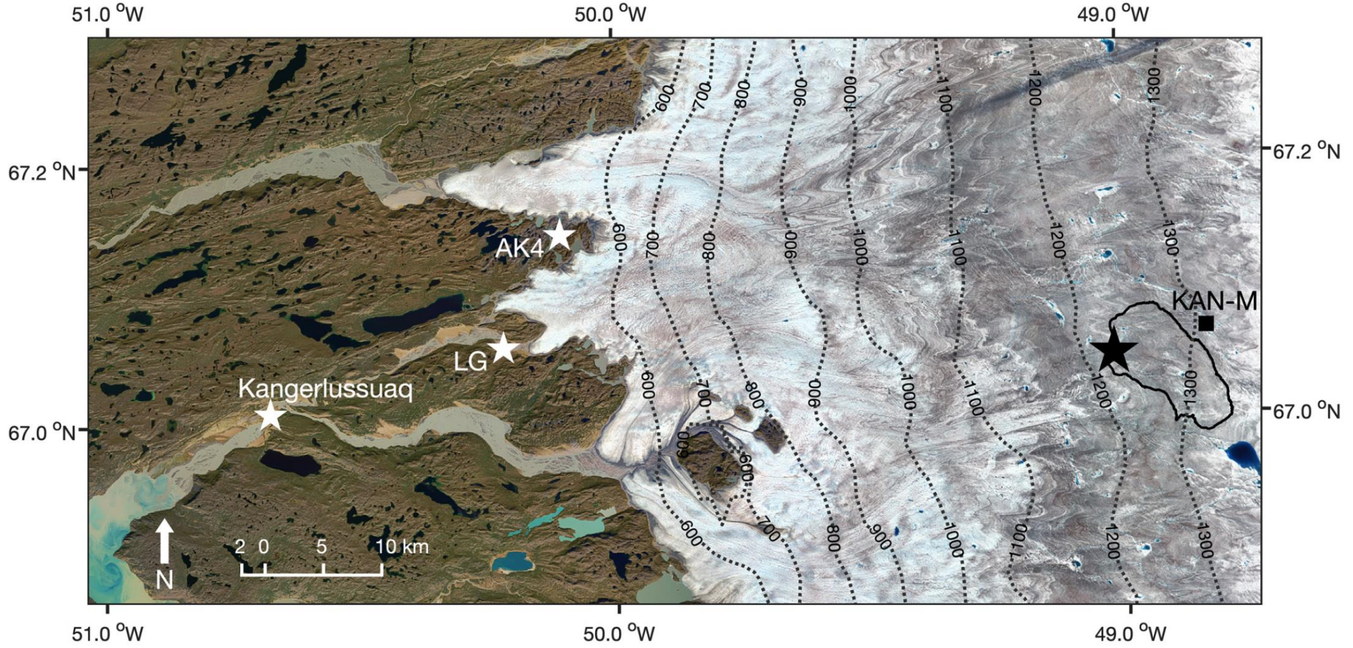
From supraglacial runoff to subglacial storage

Horizontal velocity ~ pressure

~ △storage ~ vertical velocity

Measurable??

Sort of measurable



[Smith et al., 2021]

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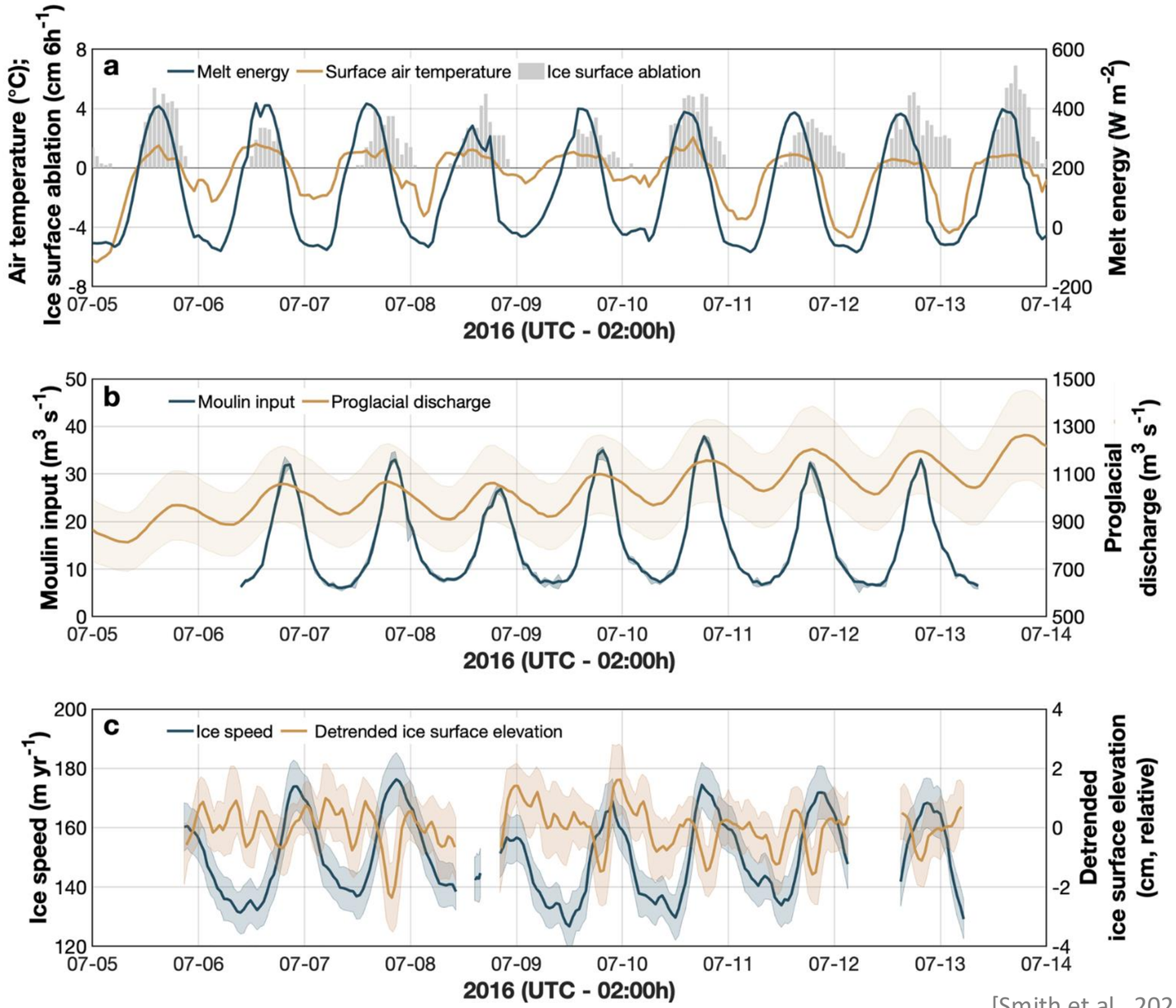
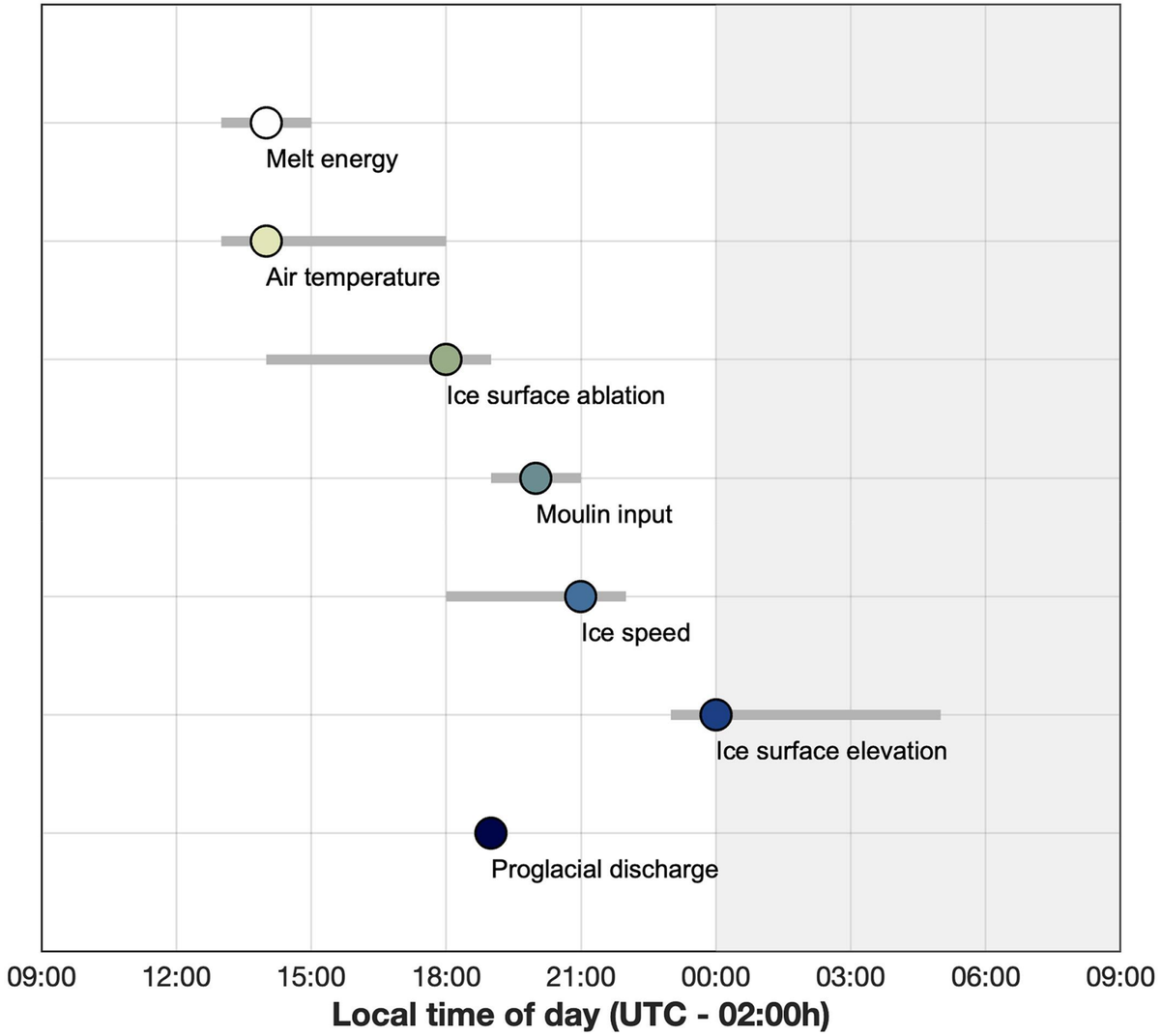
From supraglacial runoff to subglacial storage



[Smith et al., 2021]

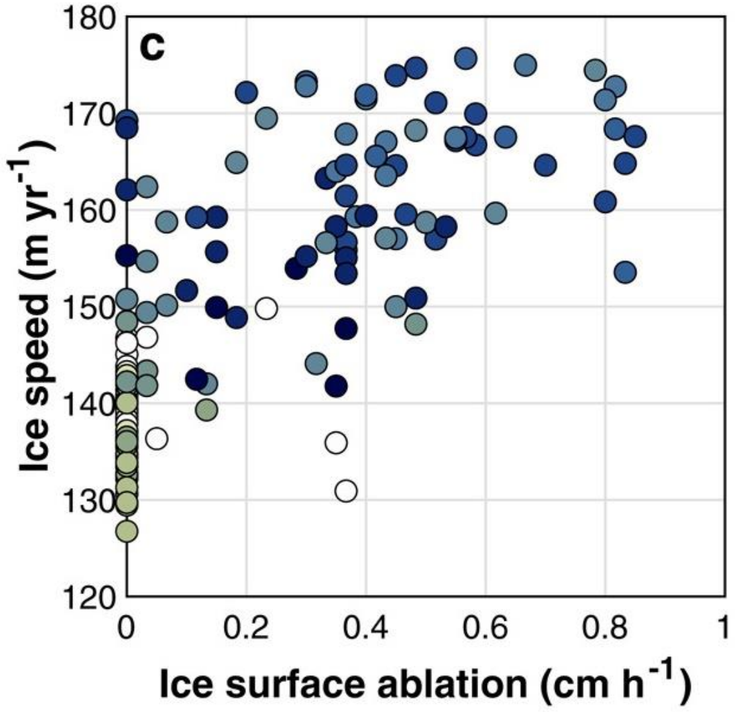
From supraglacial runoff to subglacial storage

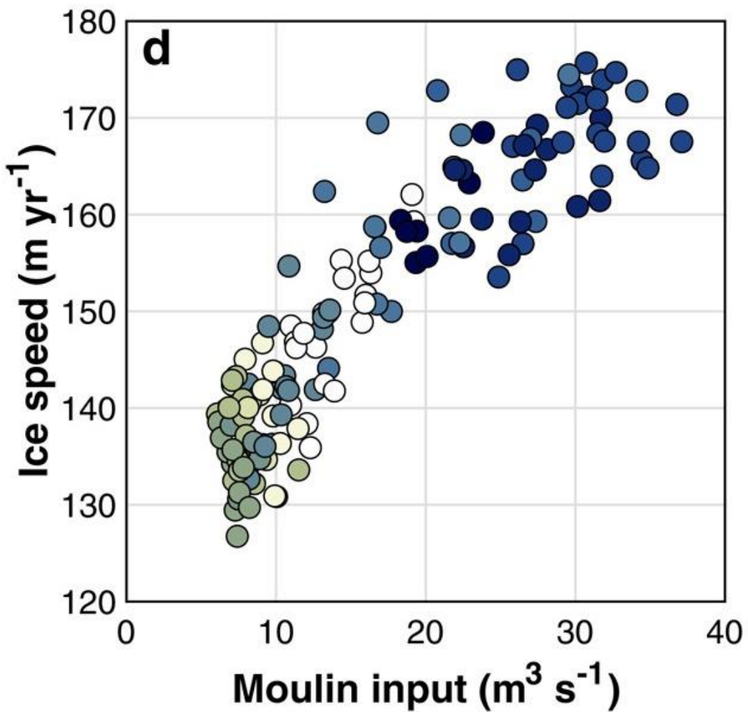


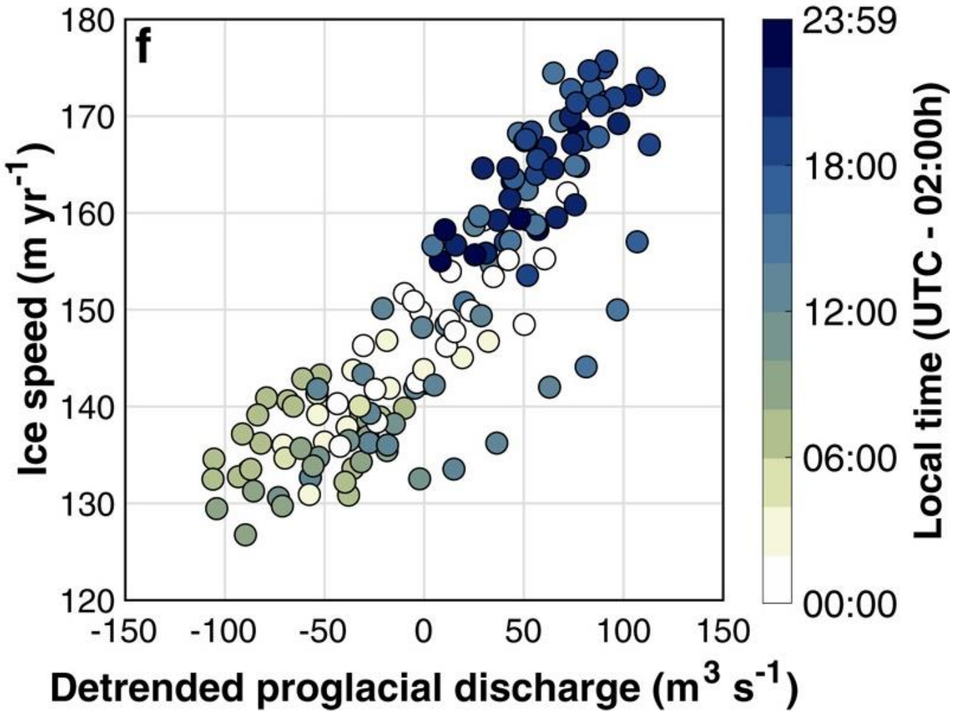
[Smith et al., 2021; See Andrews, 2015 for another version]

From supraglacial runoff to subglacial storage

- Ablation is essentially what most reanalyses/models provide over bare ice.
- Moulin input considers surface routing & is a reasonable proxy for moulin water level.
- The strongest lagged correlation between speed and proglacial discharge is -2h.







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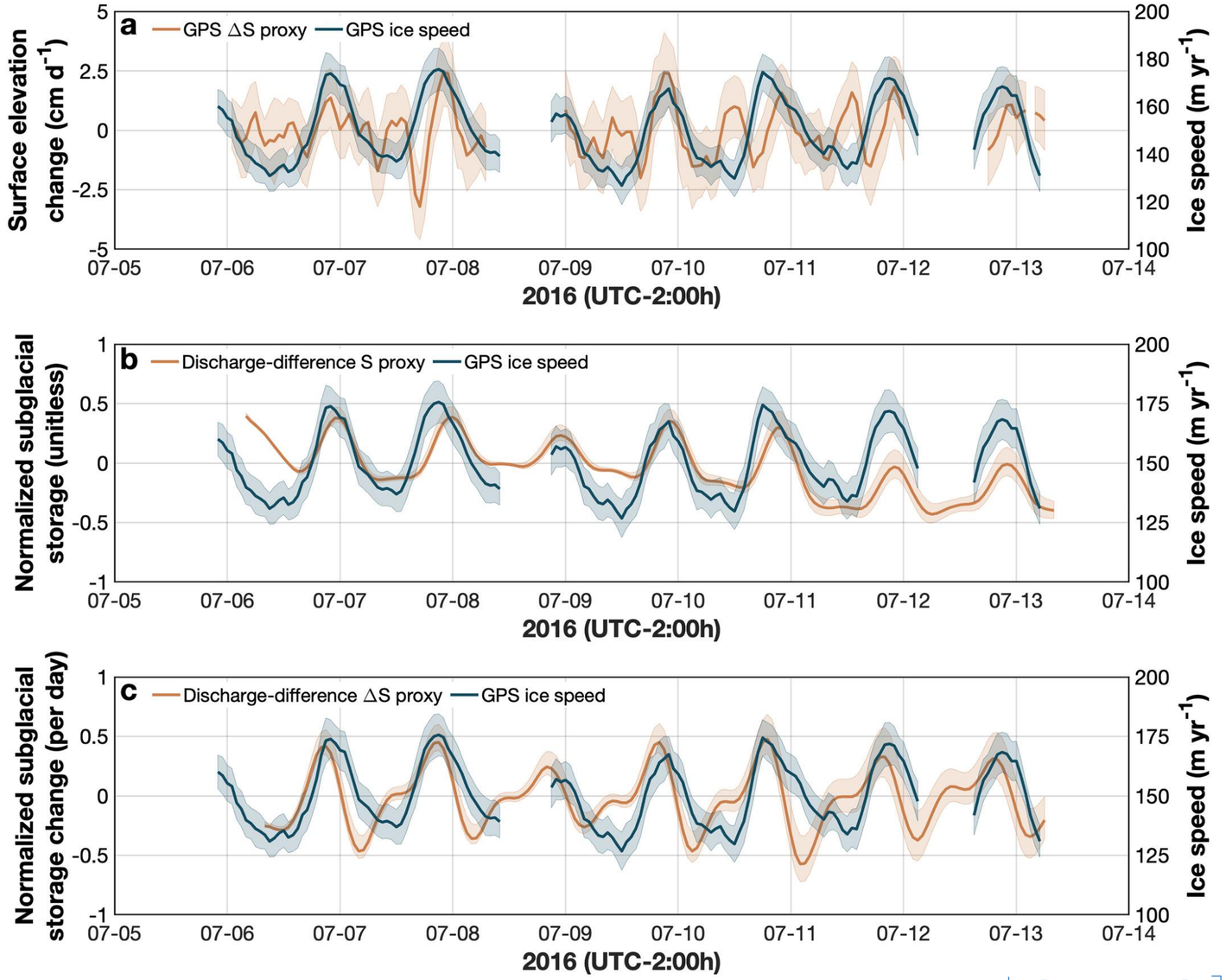
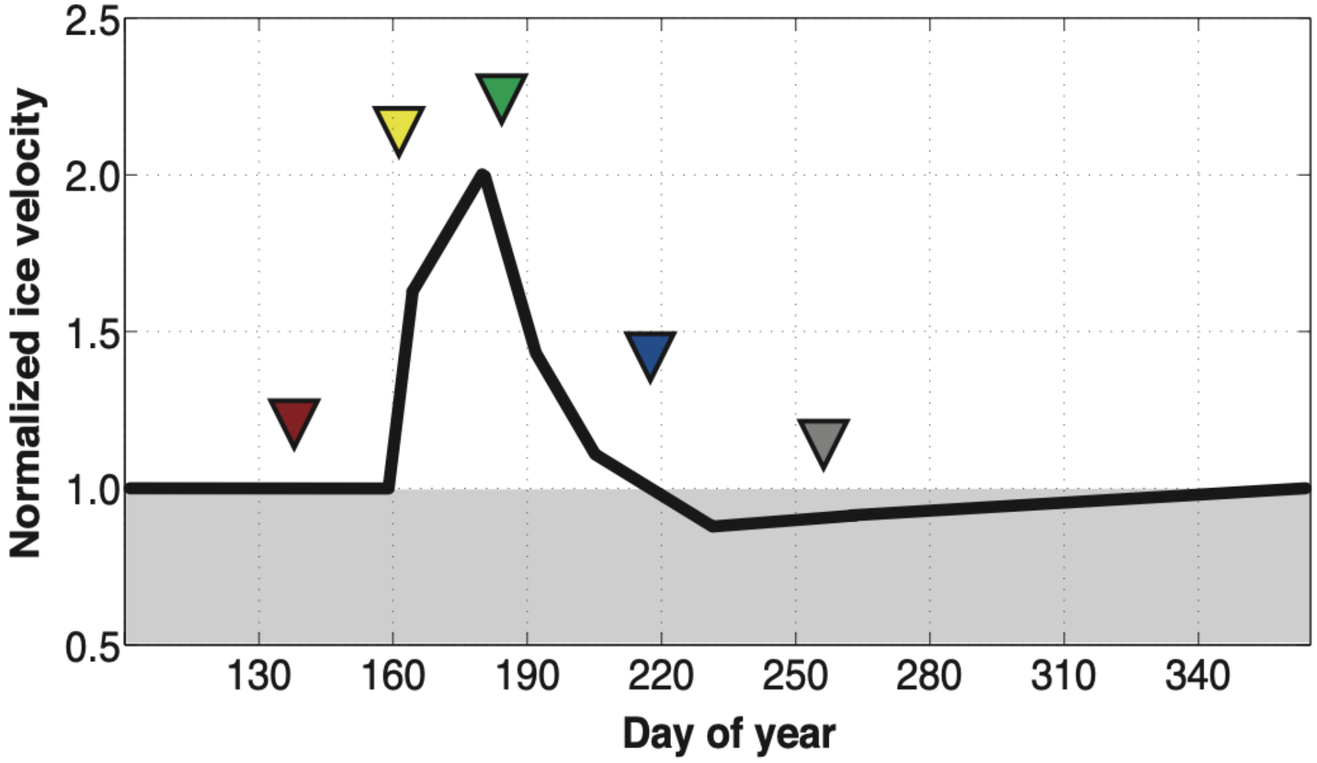
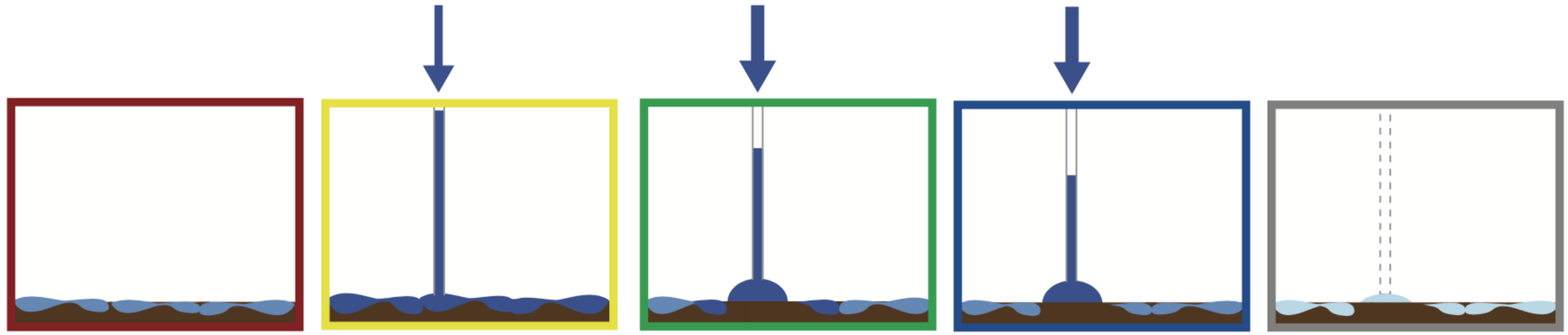
From supraglacial runoff to subglacial storage

- Surface elevation change (e.g., vertical velocity is noisy).
- Normalized ‘subglacial storage’ exhibits a clear trend not present in the ice velocities.
- ‘Normalized subglacial storage change’ has multiple ‘expected’ characteristics.
- Interpret with caution. Scaling up is only possible with high quality estimates of surface and proglacial runoff.



Interaction between surface melt and basal melt





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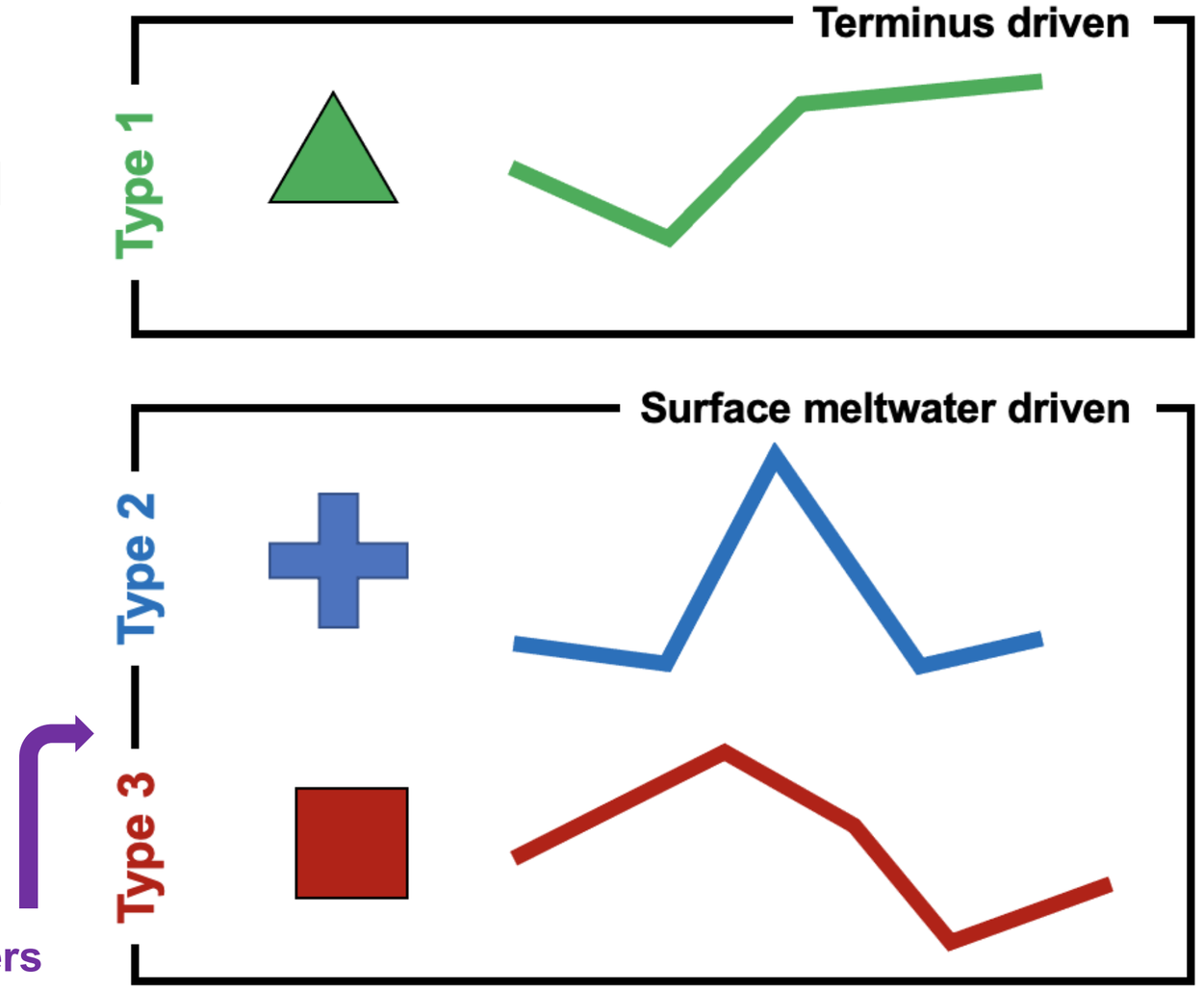
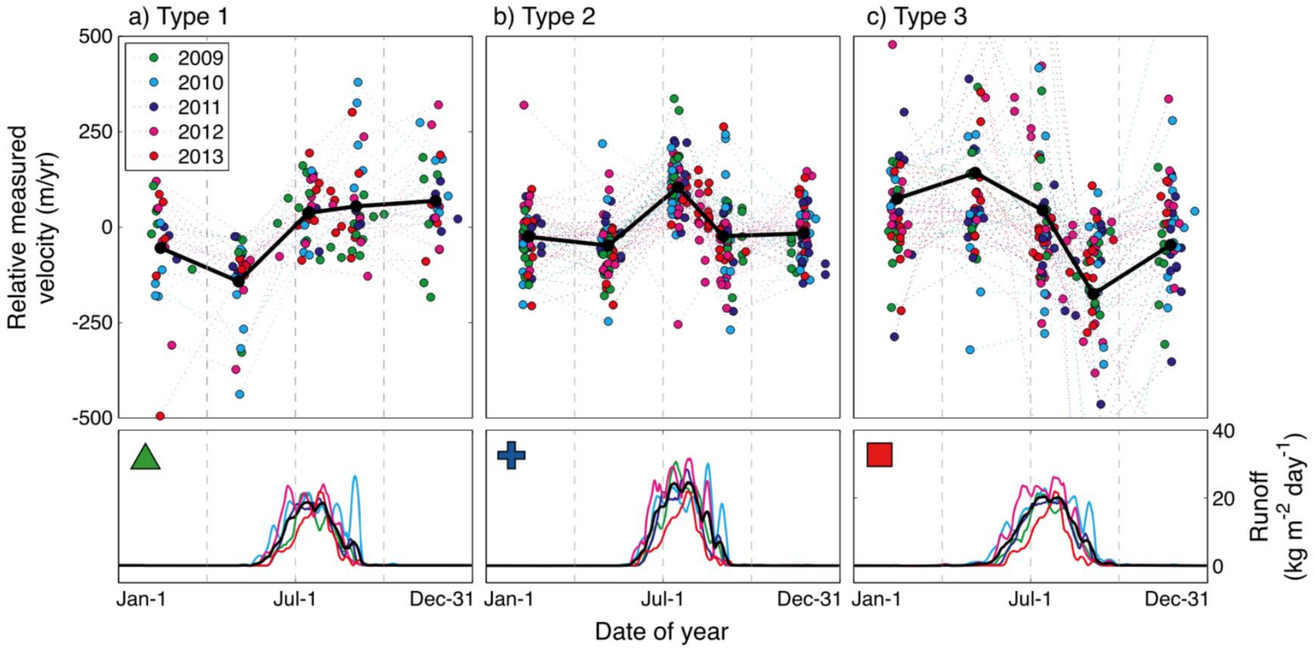
Interaction between surface melt and basal melt

- We like to characterize the seasonal variability in outlet glacier speed based on the form of the annual velocity signal.
- The ‘glacier type’ does not map easily surface meltwater characteristics. Why not?
- Does basally generated meltwater impact seasonal velocity change?

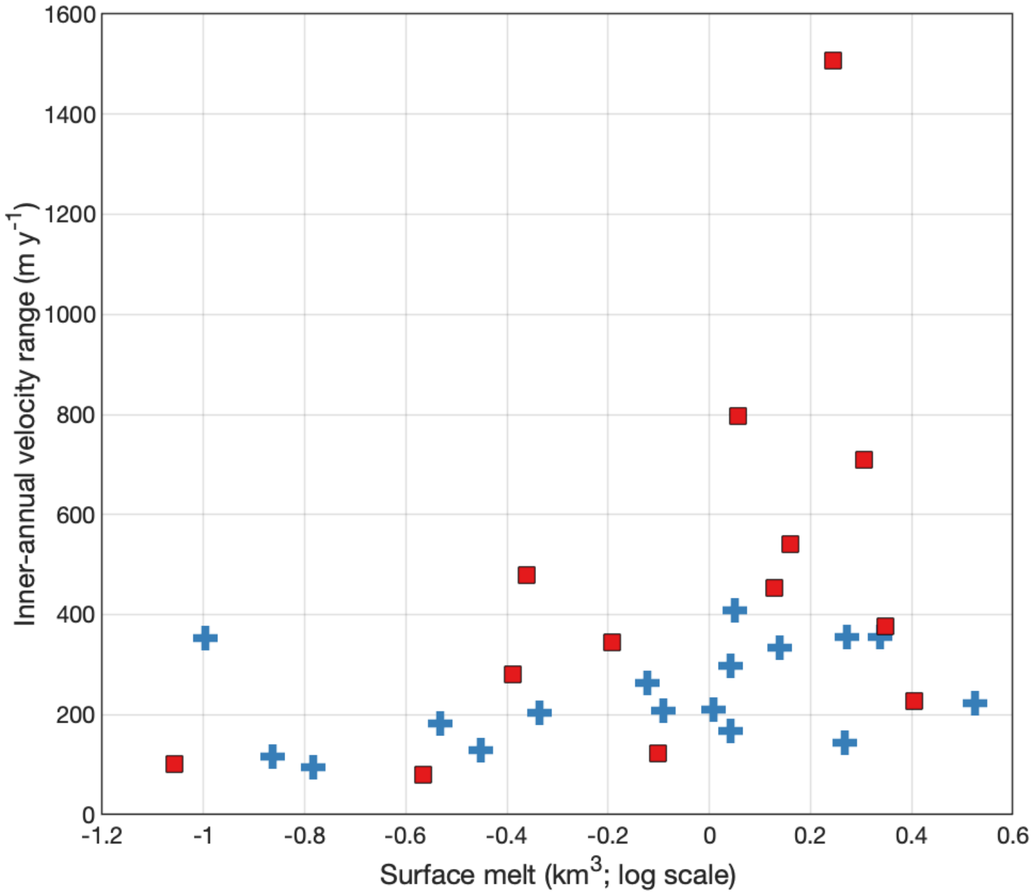


I’m mostly interested in these glaciers

Interaction between surface melt and basal melt



[Moon et al., 2014; expanded by Vijay et al., 2021]



If cumulative surface melt explained glacier type, we would expect clustering of glacier type based on surface melt volume.

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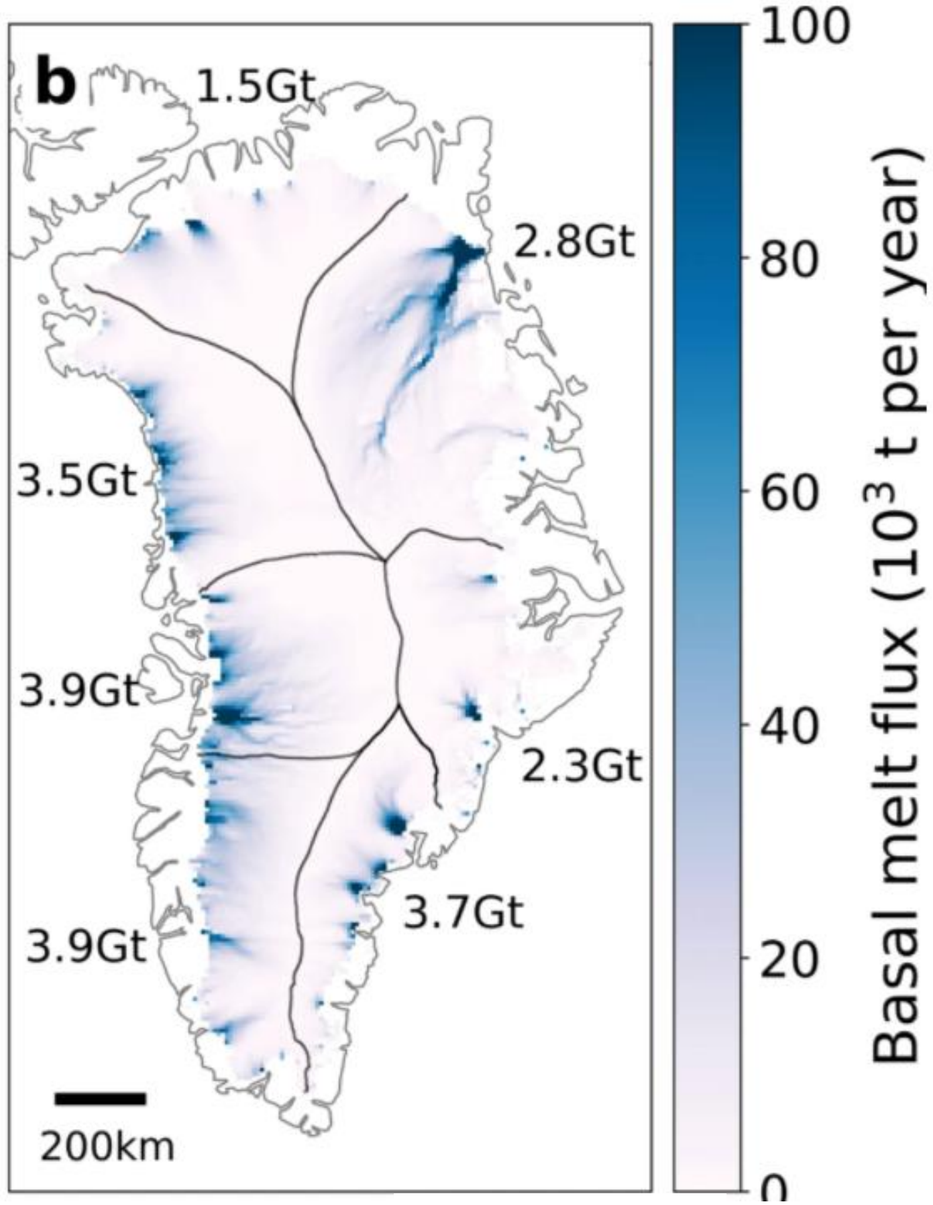
Interaction between surface melt and basal melt

If glacier type isn't easily mappable to characteristics of surface meltwater availability, what could it be?

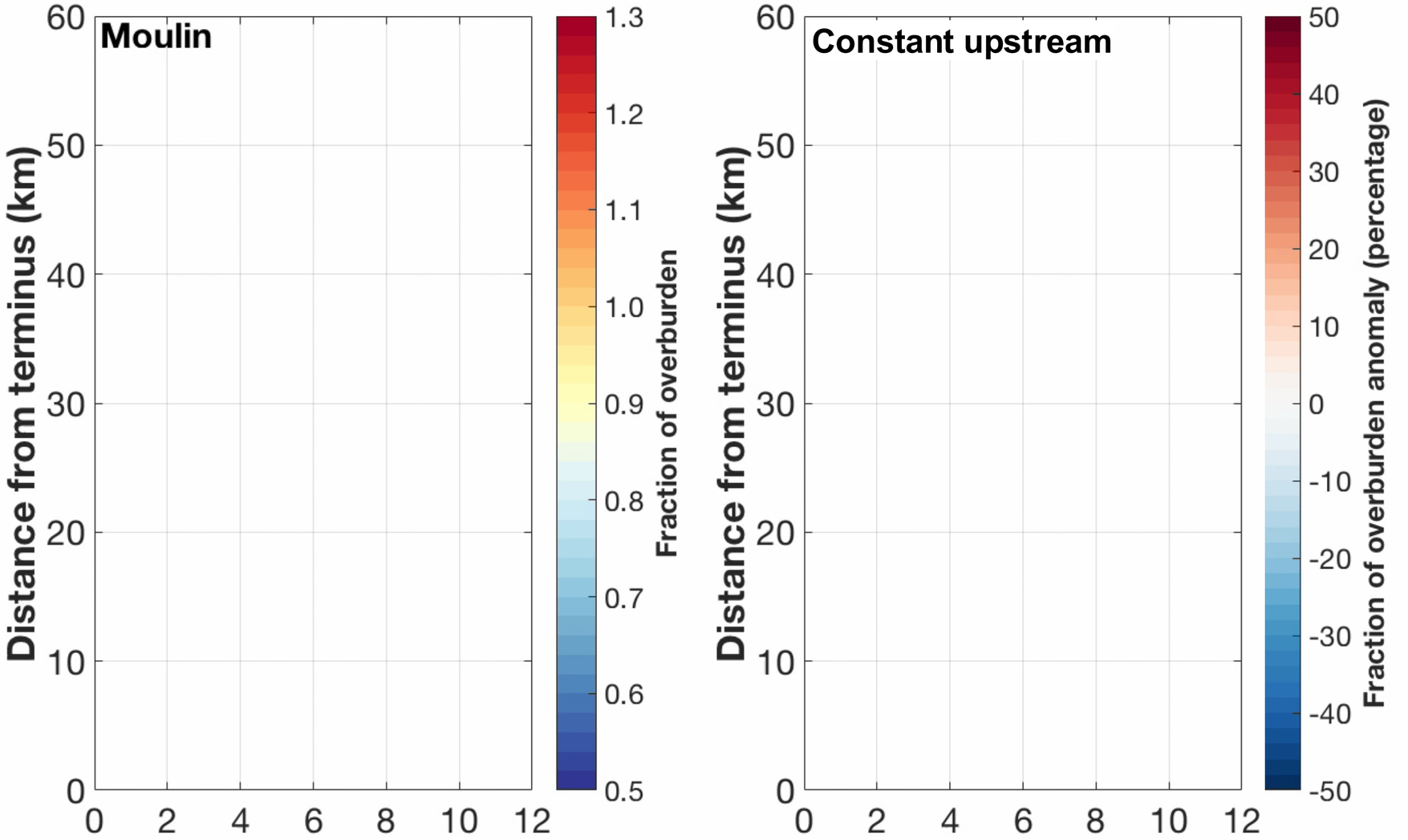
The combination of surface and basal meltwater availability.



[Karlsson et al., 2021]

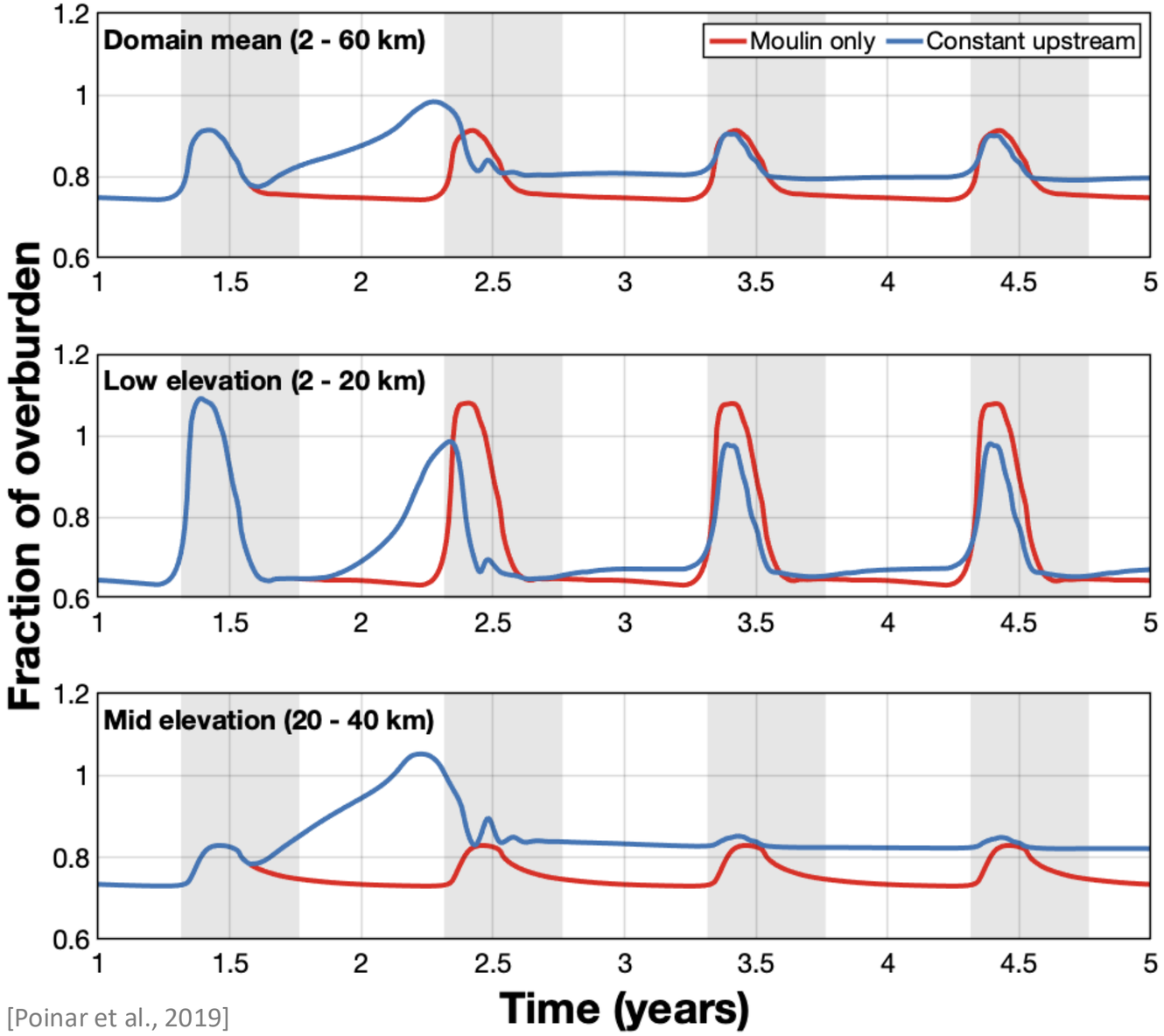
Interaction between surface melt and basal melt

Basally supplied meltwater affects the seasonality of subglacial pressures.



[Predecessor to Poinar et al., 2019]

Interaction between surface melt and basal melt



[Poinar et al., 2019]

The addition of a small constant supply of meltwater at high elevations allows more channels to persist during winter months

This results in more rapid channel growth during the melt season and lower pressures near the terminus.

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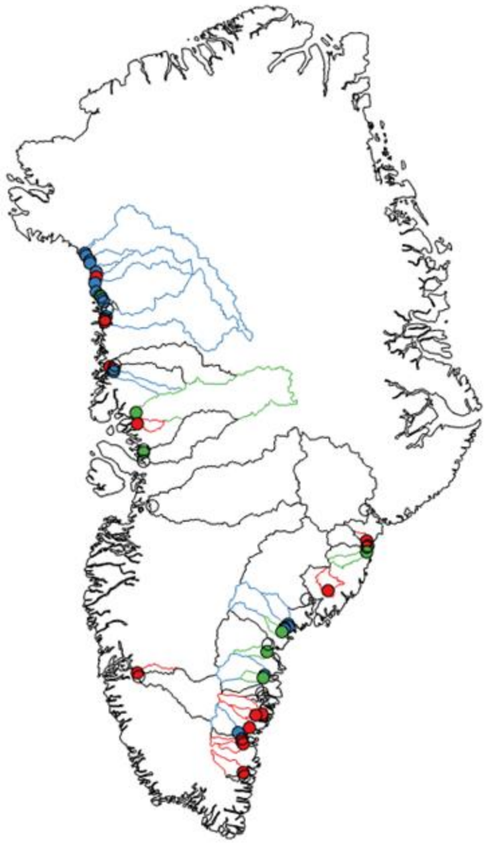
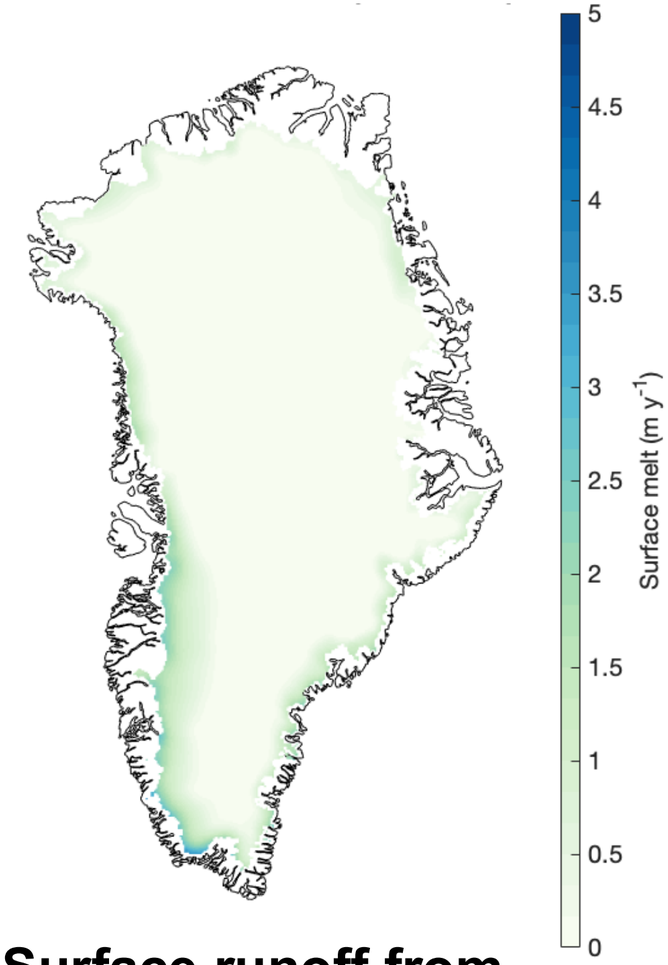
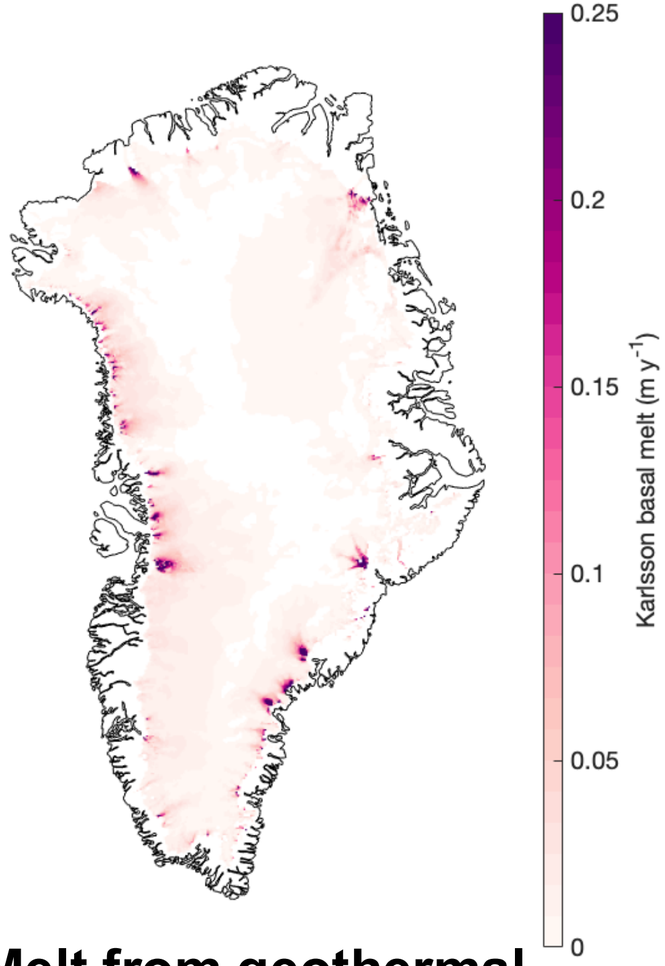
Interaction between surface melt and basal melt

Type 1
Type 2
Type 3







- Moon et al. (2014) glacier types & velocity information
  - DEM delineated basins
- Surface runoff from M2R12K (high-resolution replay of MERRA-2)
- Melt from geothermal and frictional sources (Karlsson et al., 2021)

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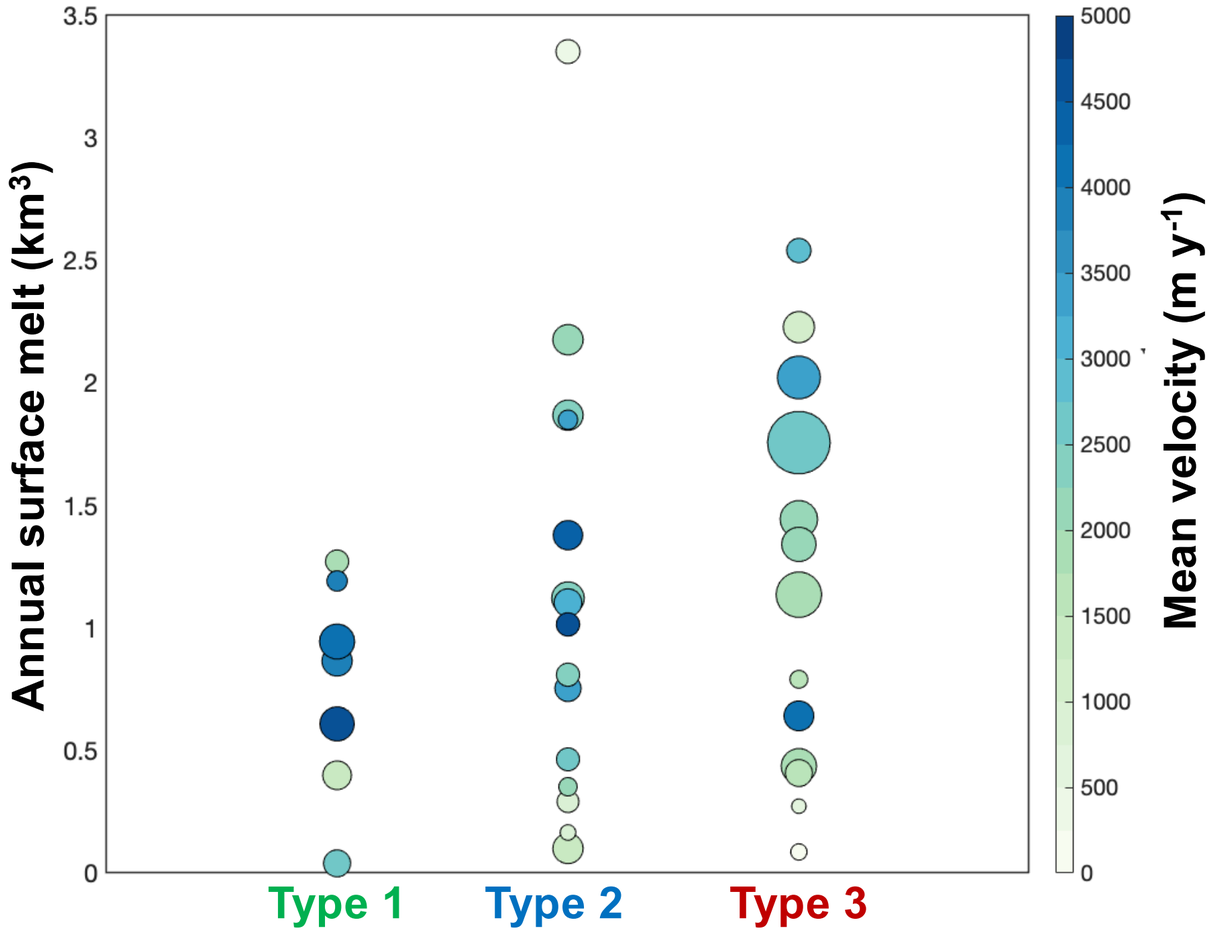
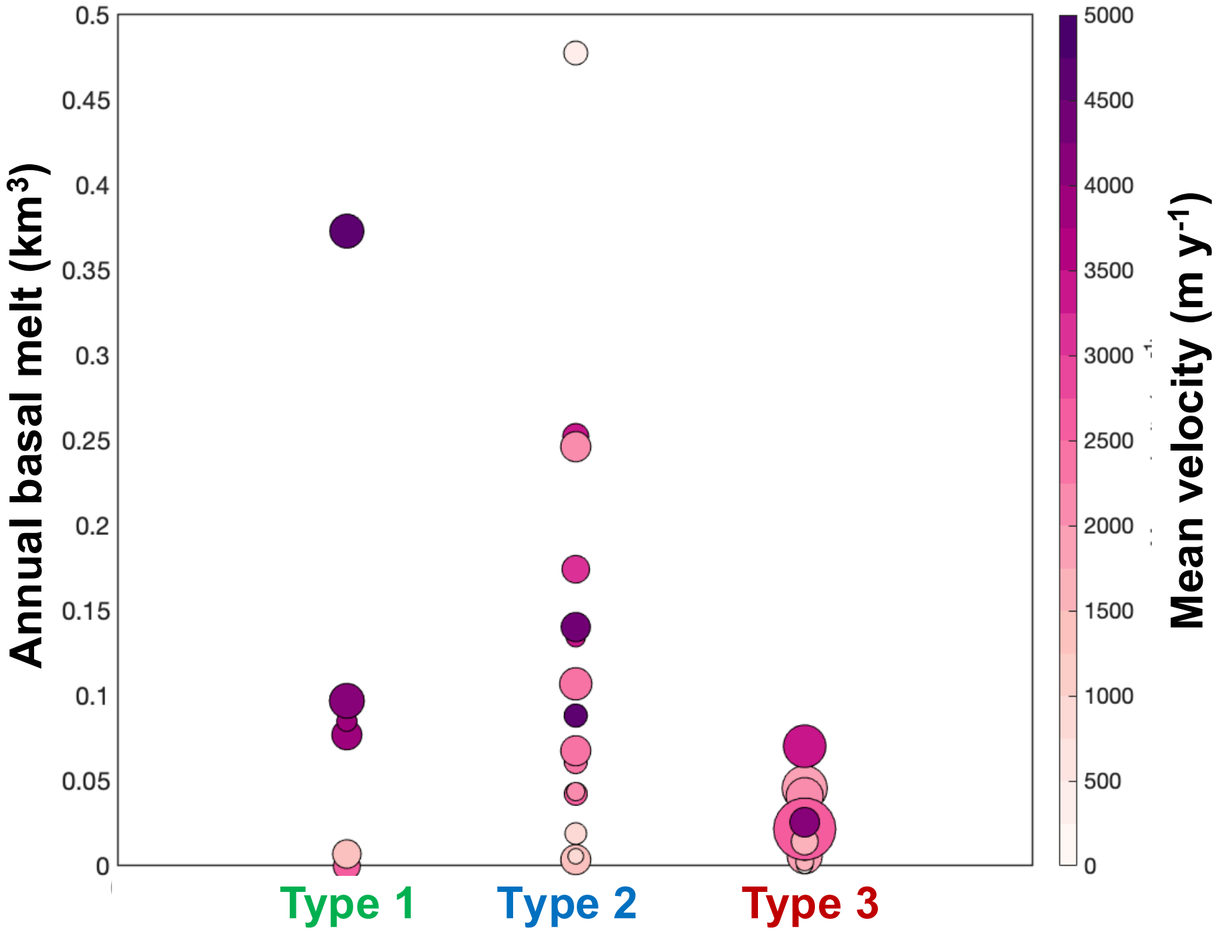
Interaction between surface melt and basal melt





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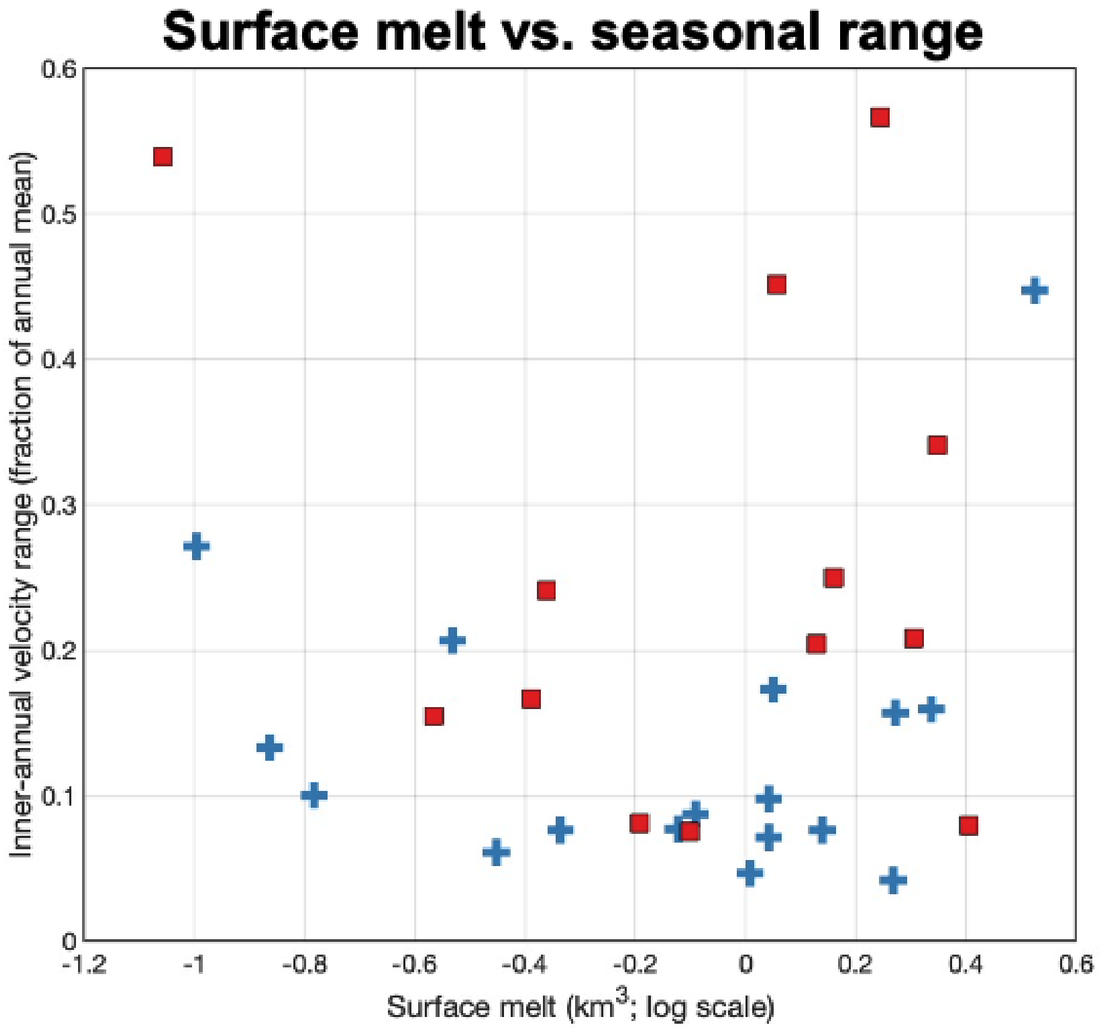
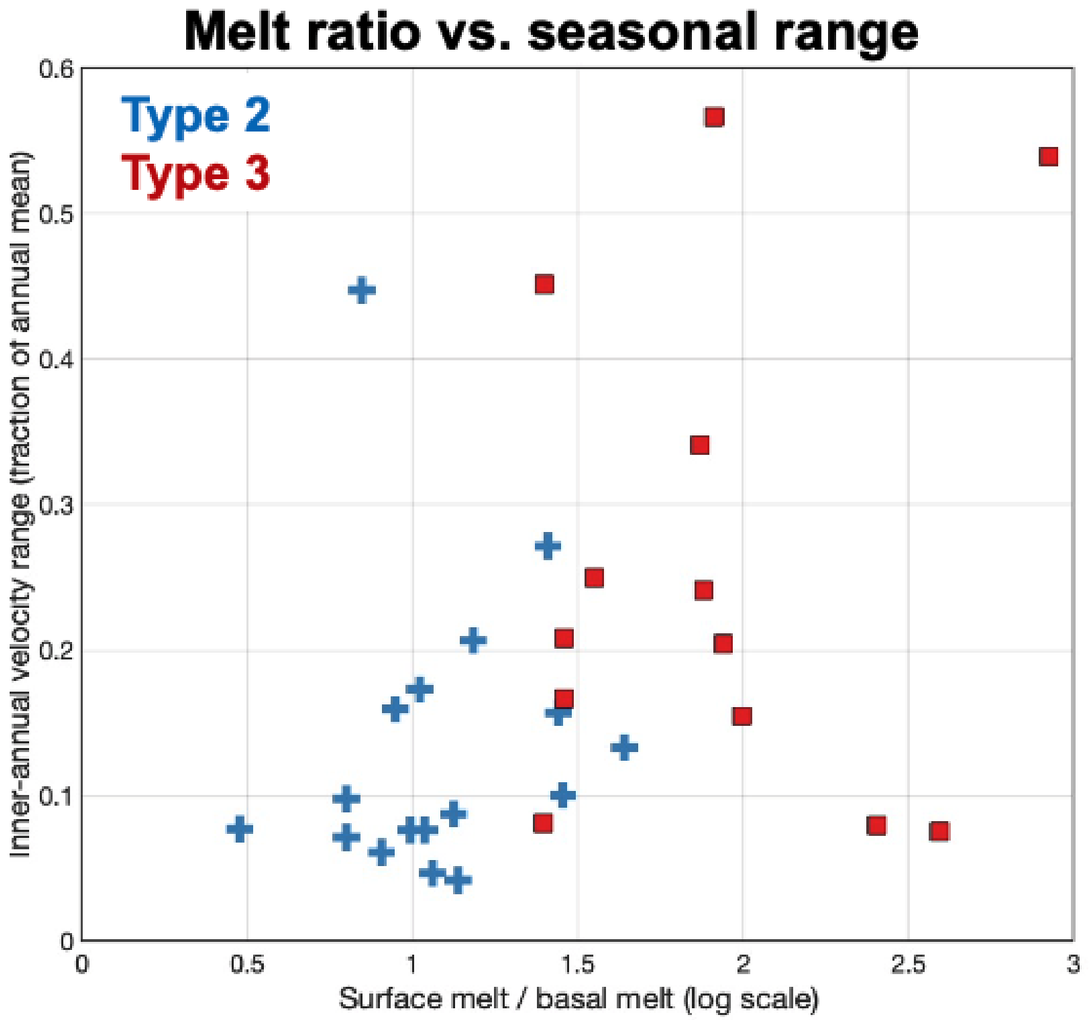
Interaction between surface melt and basal melt





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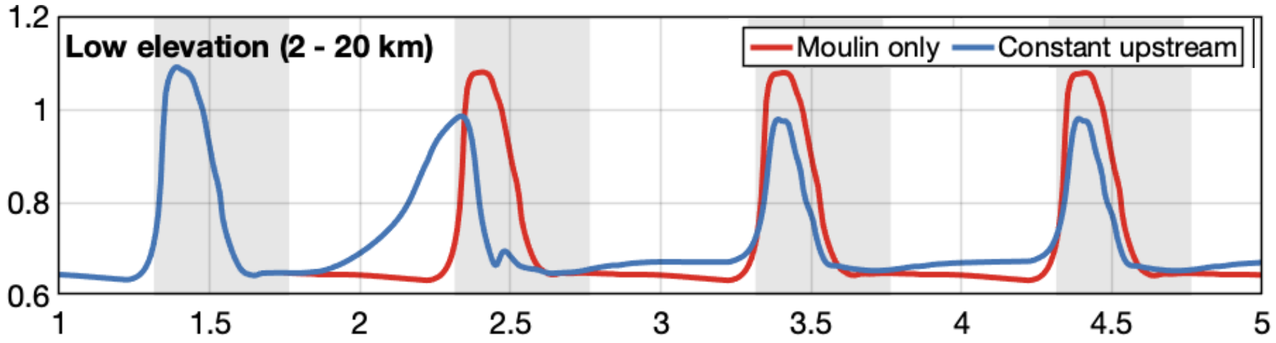
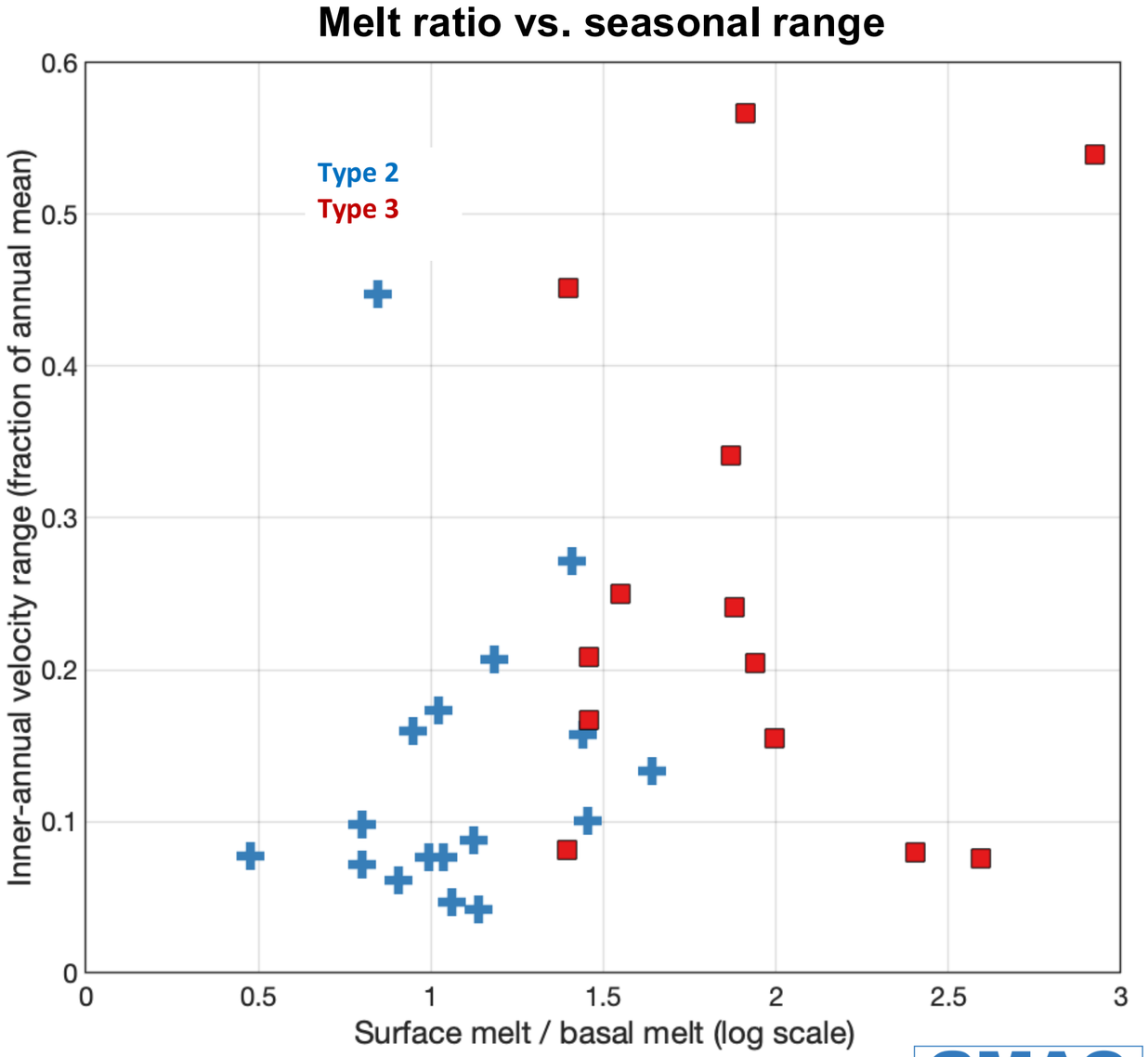
Interaction between surface melt and basal melt

Type 2 glaciers tend to have less seasonal variability due to more cumulative basal melt.

Type 3 glaciers tend to exhibit more seasonal variability because they generally have less basal melt.





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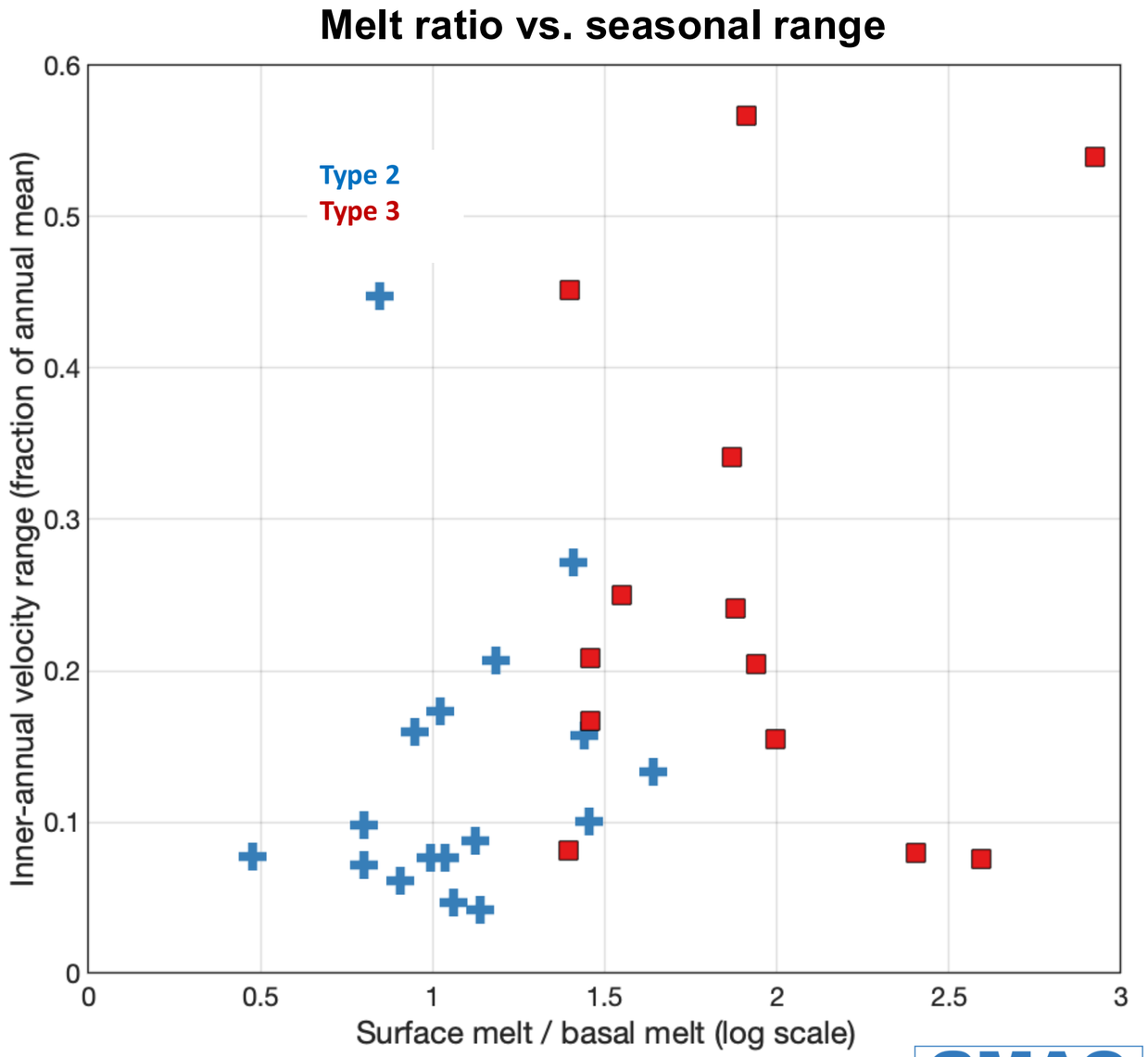
Interaction between surface melt and basal melt

Caveats and thoughts

- This analysis lacks subtlety.
- The observed relationship relies on persistent glacier behavior.

There are confounding factors and processes that can modify the observed relationship.

1. Poor estimation of surface runoff.
2. No representation on subglacial storage, subglacial hydrology or groundwater storage.



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From surface processes to dynamics

Ice sheet surface processes

How does GEOS represent ice surfaces?

How are we improving ice surface processes to better support the cryospheric community?

Ice sheet dynamics

Supraglacial to englacial dynamics: Moulin evolution and the influence of surface meltwater runoff [Andrews et al., 2022; Trunz et al., 2023].

Linking the surface to dynamics through meltwater storage [Smith et al., 2021].

The role of surface and basal melt on seasonal in outlet glacier behavior [Andrews, ????].

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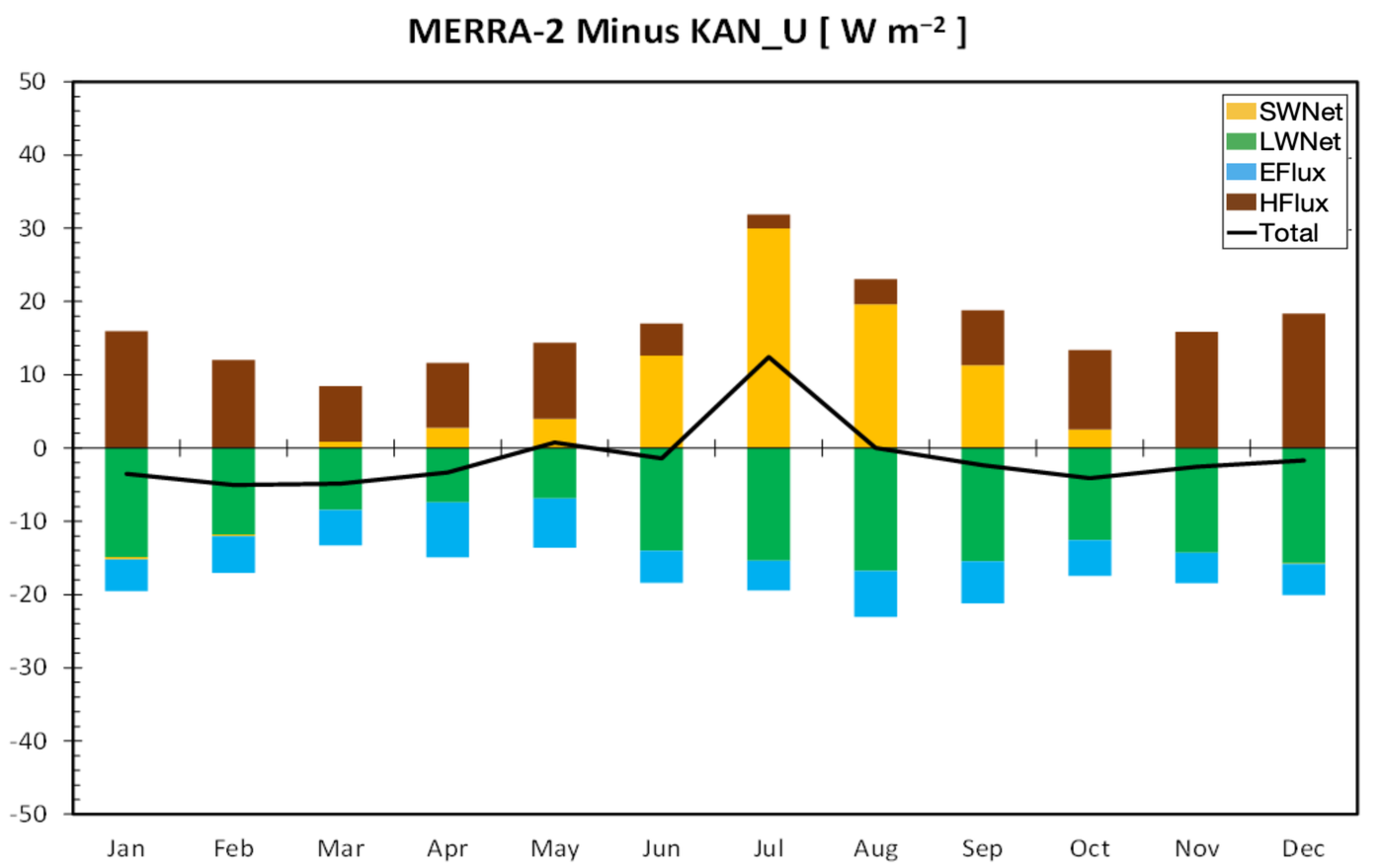
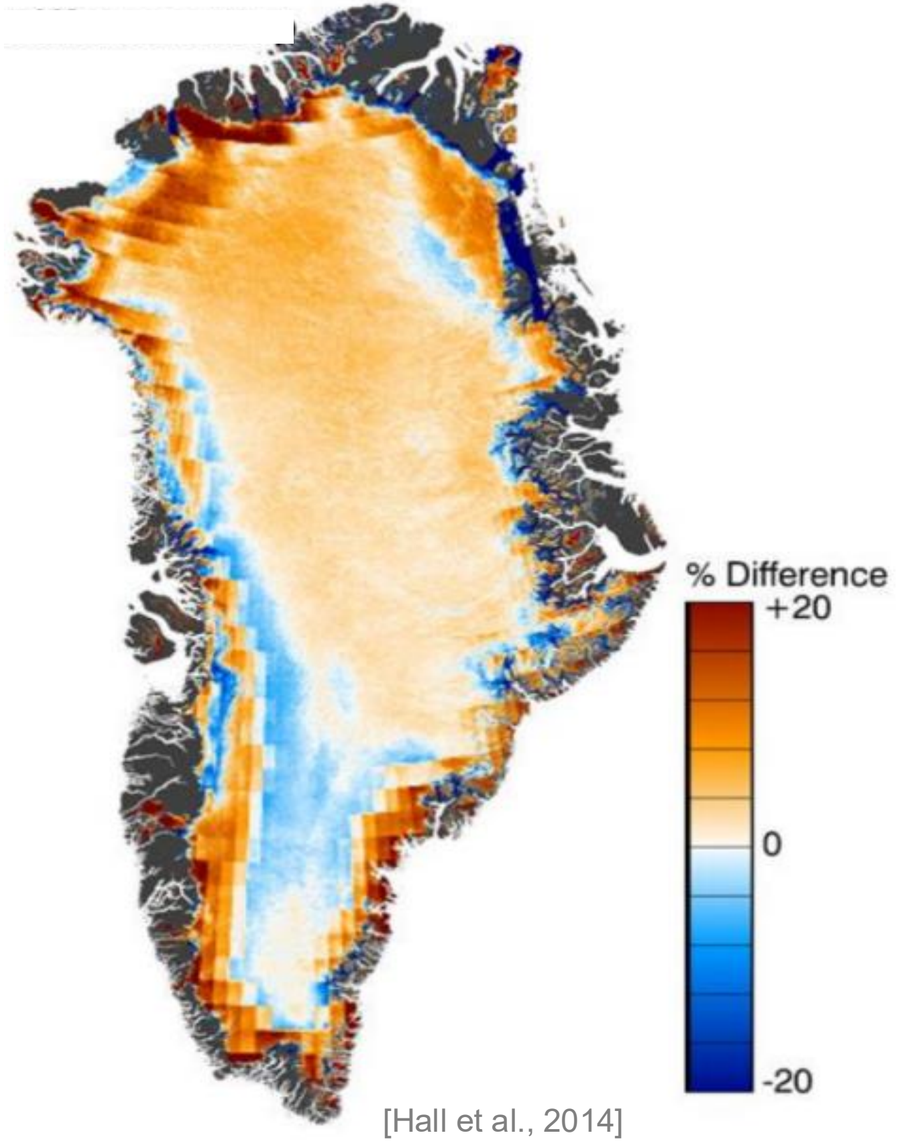
Improving surface mass balance



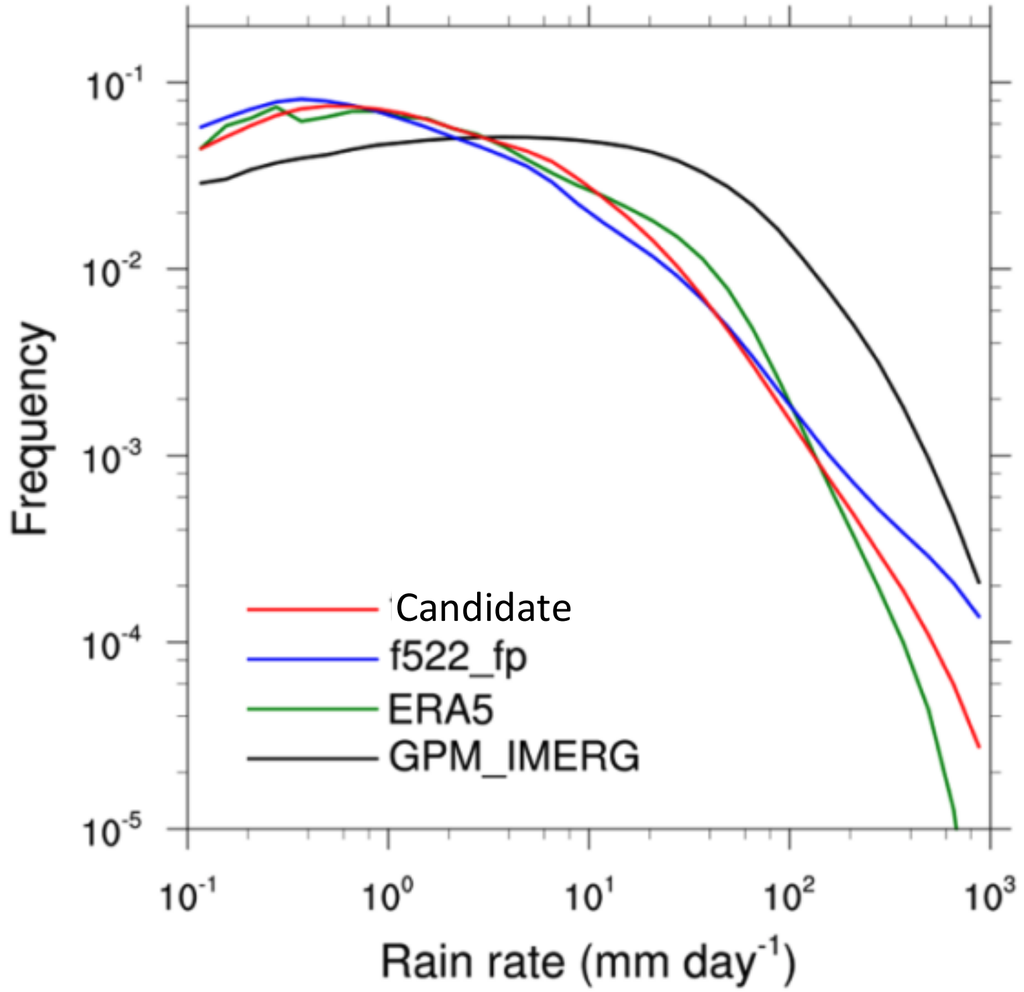
MODIS – MERRA-2 Albedo (July 2015)



[Hall et al., 2014]

Improving surface mass balance

- Updates to the cloud convection parameterization and cloud microphysics between MERRA-2 and GEOS-R21C & PolarMERRA reduce low and high intensity precipitation events.
- This persistently reduces total precipitation across both sea ice and Arctic land.



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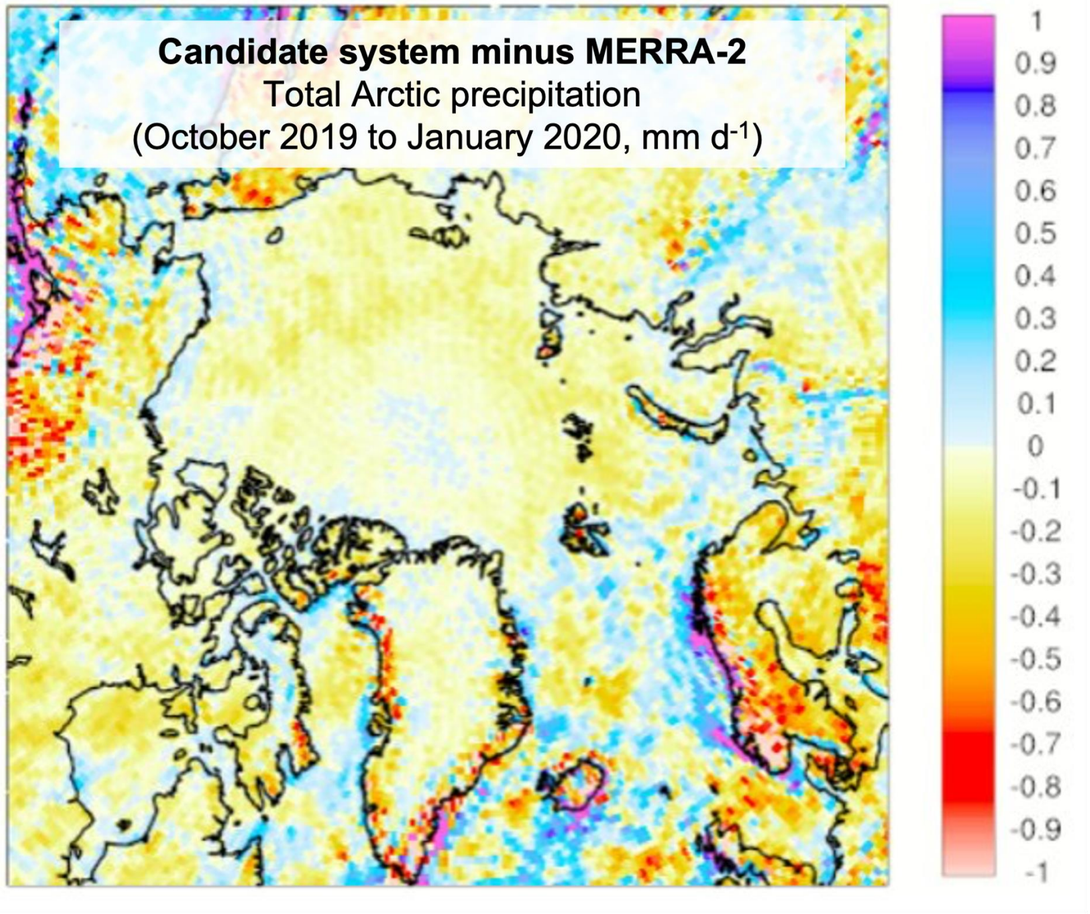
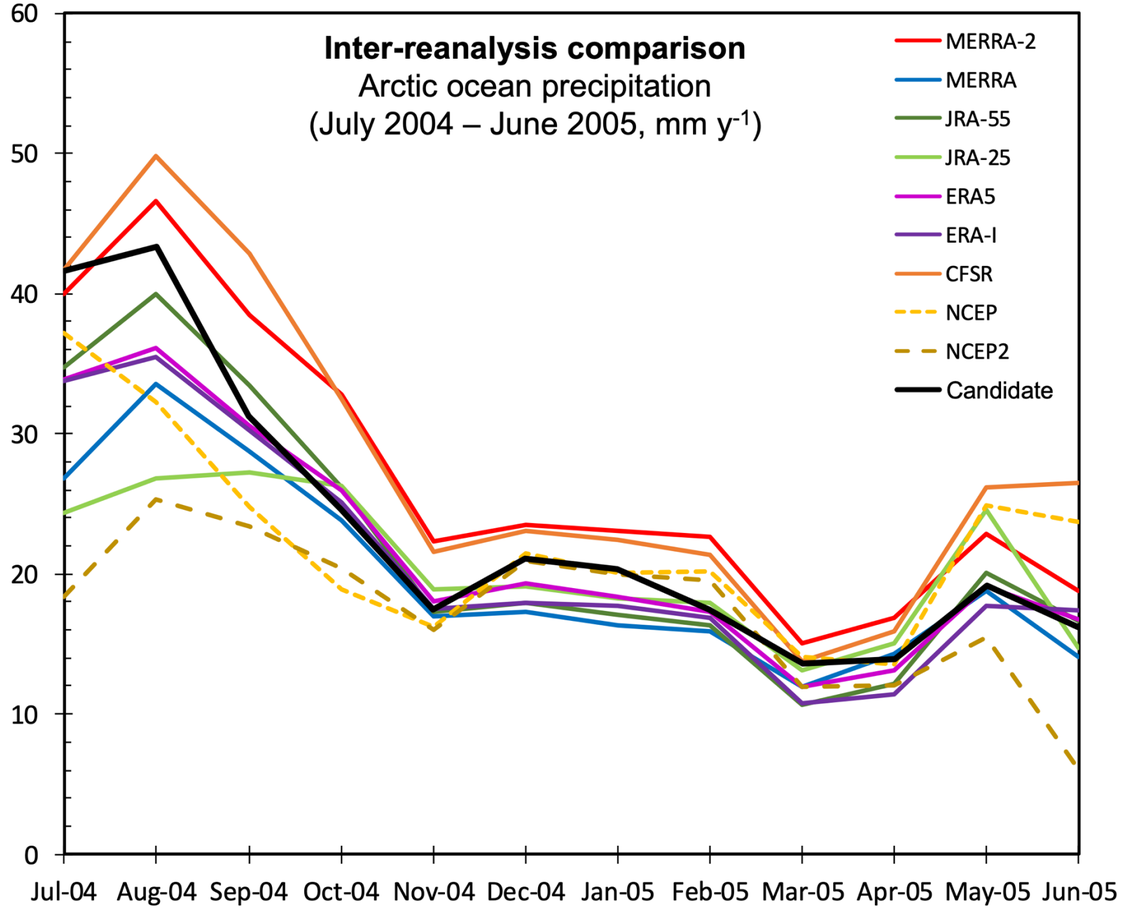
Improving surface mass balance





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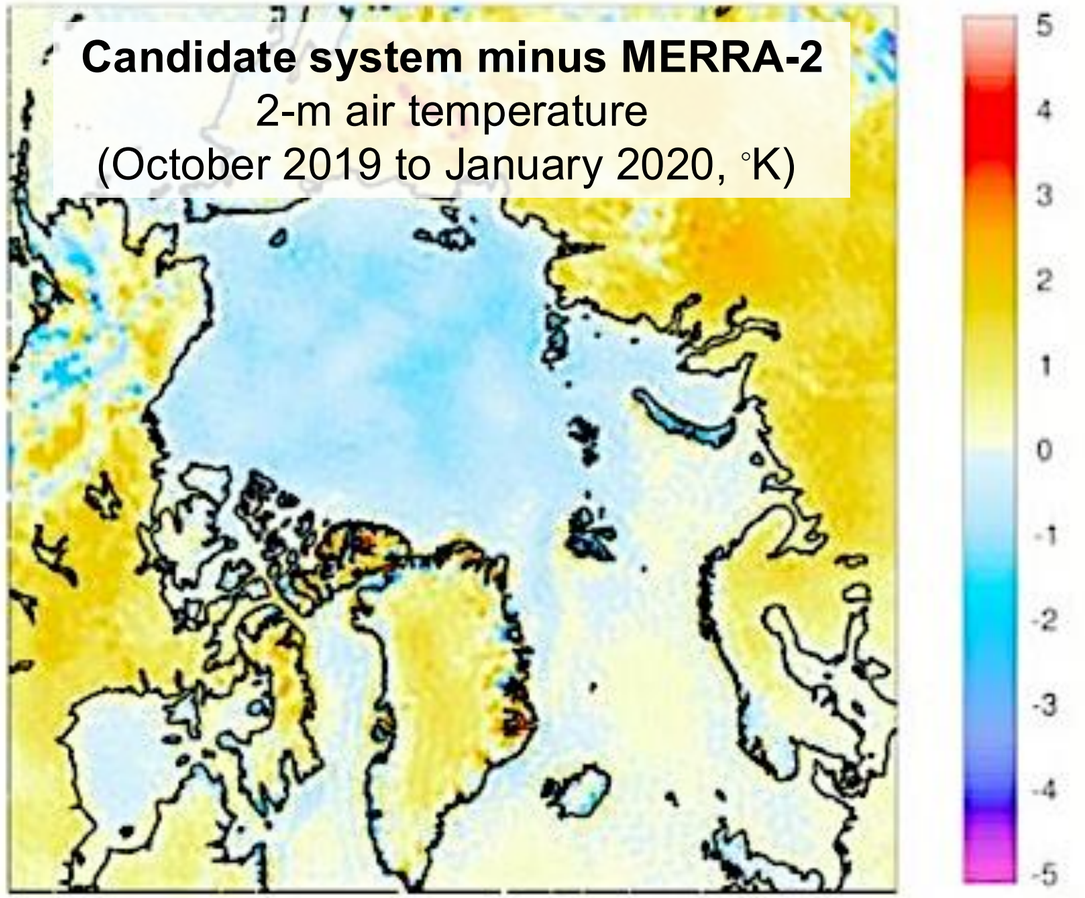
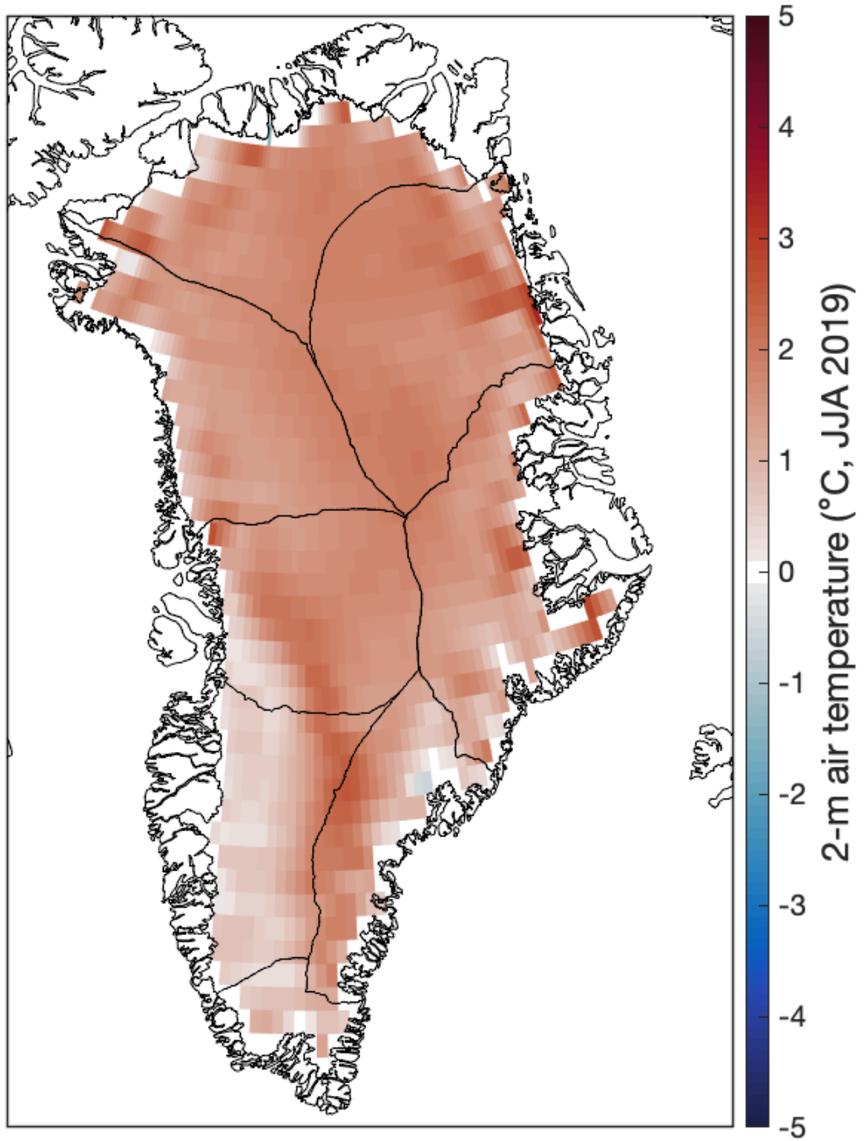
Improving surface mass balance



Candidate – MERRA-2



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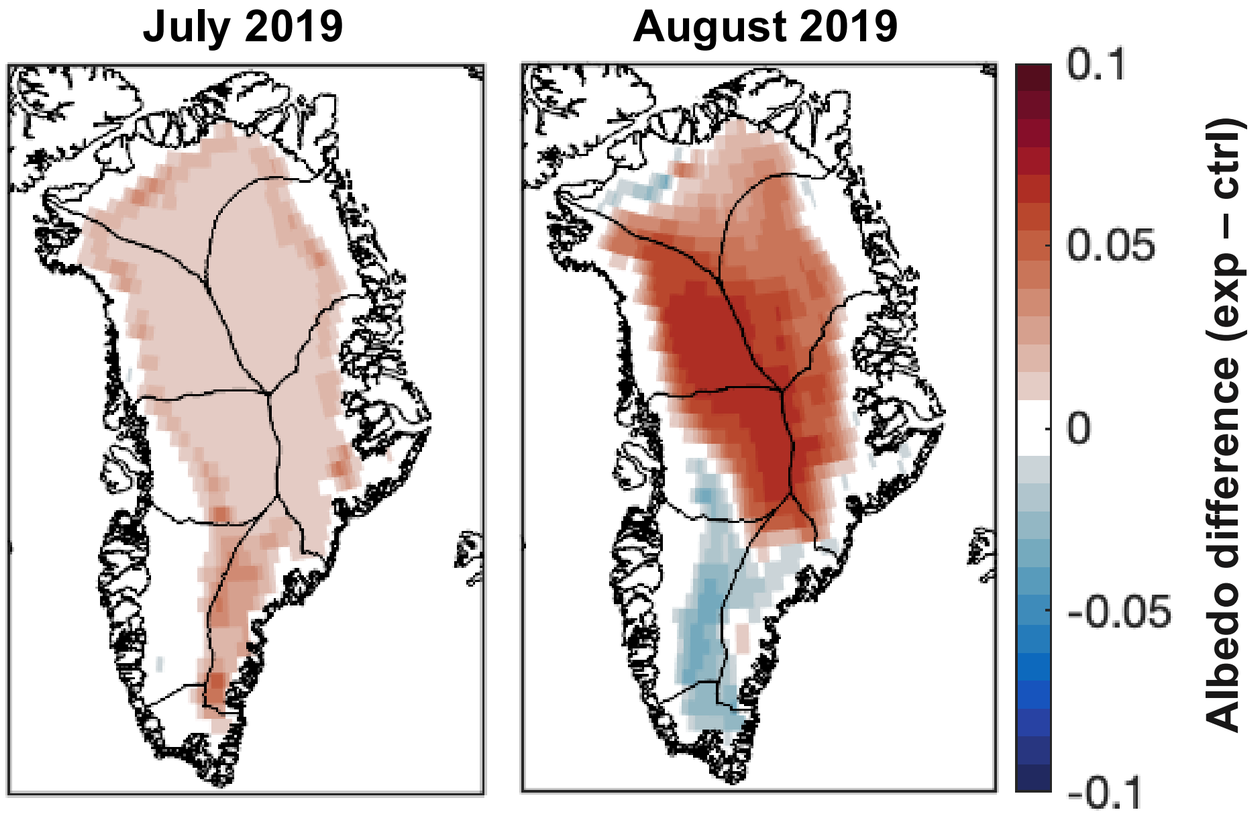
Improving surface mass balance

- Increased downwelling longwave in the new GEOS systems, such that reflected shortwave and sensible heat fluxes overcompensate and warm the surface.
  - Exacerbated by reduced precipitation and subsequent increases in surface albedo.
- Currently testing improvements to polar snow densification and ice sheet surface roughness to mitigate these problems.



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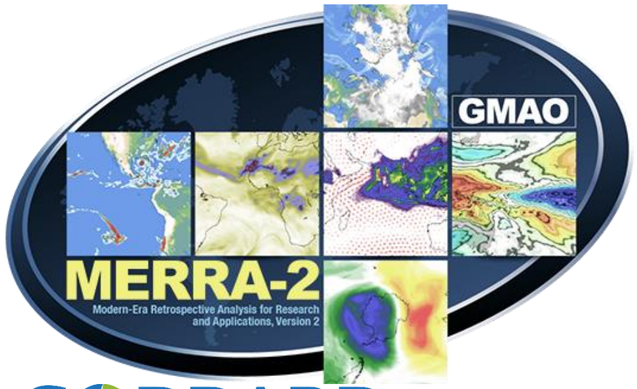
M21C-Polar

- Downscaled replay with updated model version and truncated GEOS-R21C analysis increments
  - Including improvements to land ice and sea ice representation
- Global, c1440 (~6km) horizontal resolution, 72 vertical levels
  - Balances complex physics and computational resource needs
- 1998 – 2025, same length as MERRA-21C
- Polar-specific and relevant collections



GEOS-IT, MERRA-21C → M21C-Polar → MERRA-3

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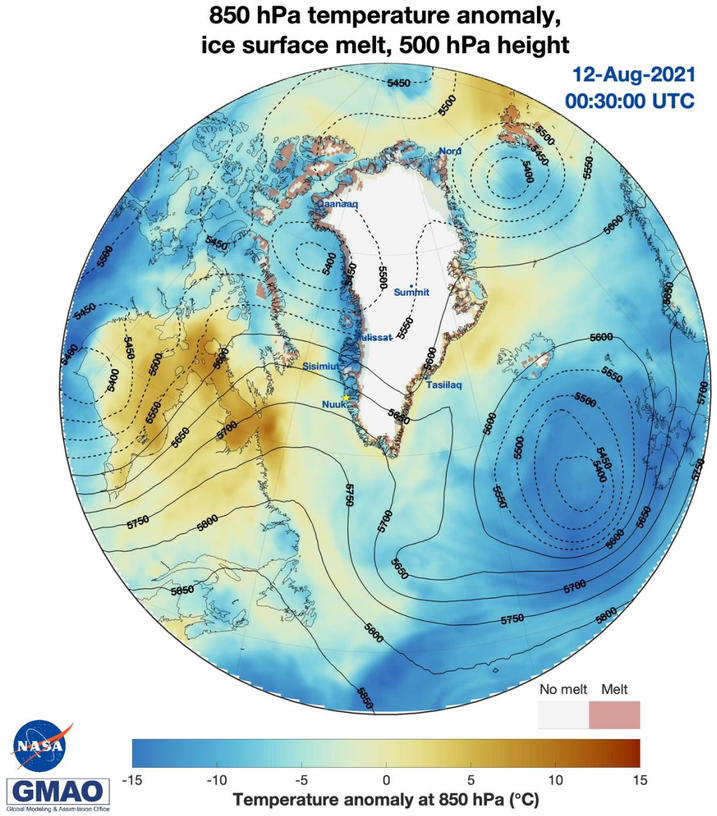
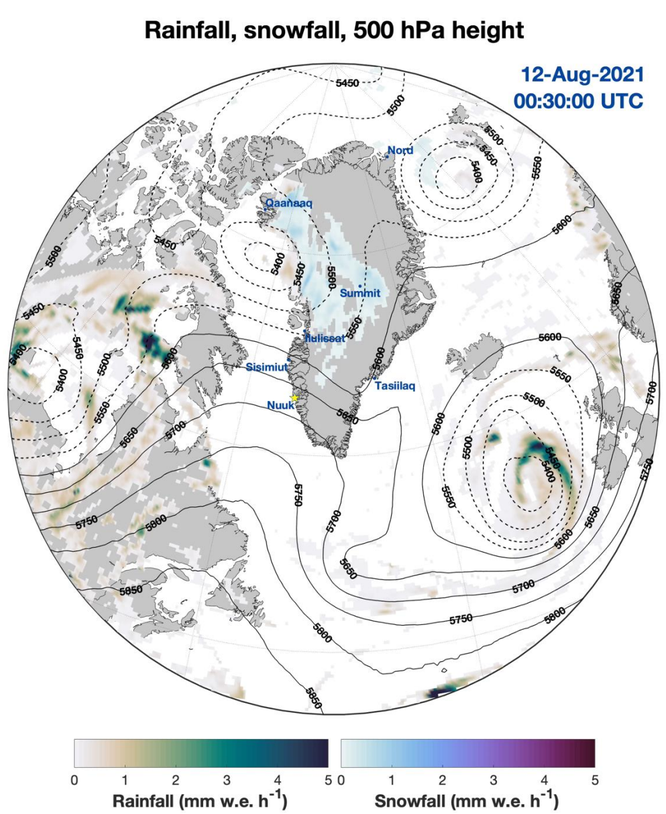
M21C-Polar

Goal 1. Development of assessment framework & improved polar parameterizations for the GEOS system

Goal 2. Downscaled replay of MERRA-R21C, **M21C-Polar** (timeline is M21C dependent).

Goal 3. Collaborations to facilitate polar improvements and knowledge transfer to the MERRA-3 reanalysis.





Final Thoughts

- Better quantifying surface mass balance and surface melt will improve our ability to understand and quantify dynamical processes.

- Modeling surface meltwater storage and routing is critical to understanding ice sheet behavior.

- Your thoughts, questions, comments: lauren.c.andrews@nasa.gov