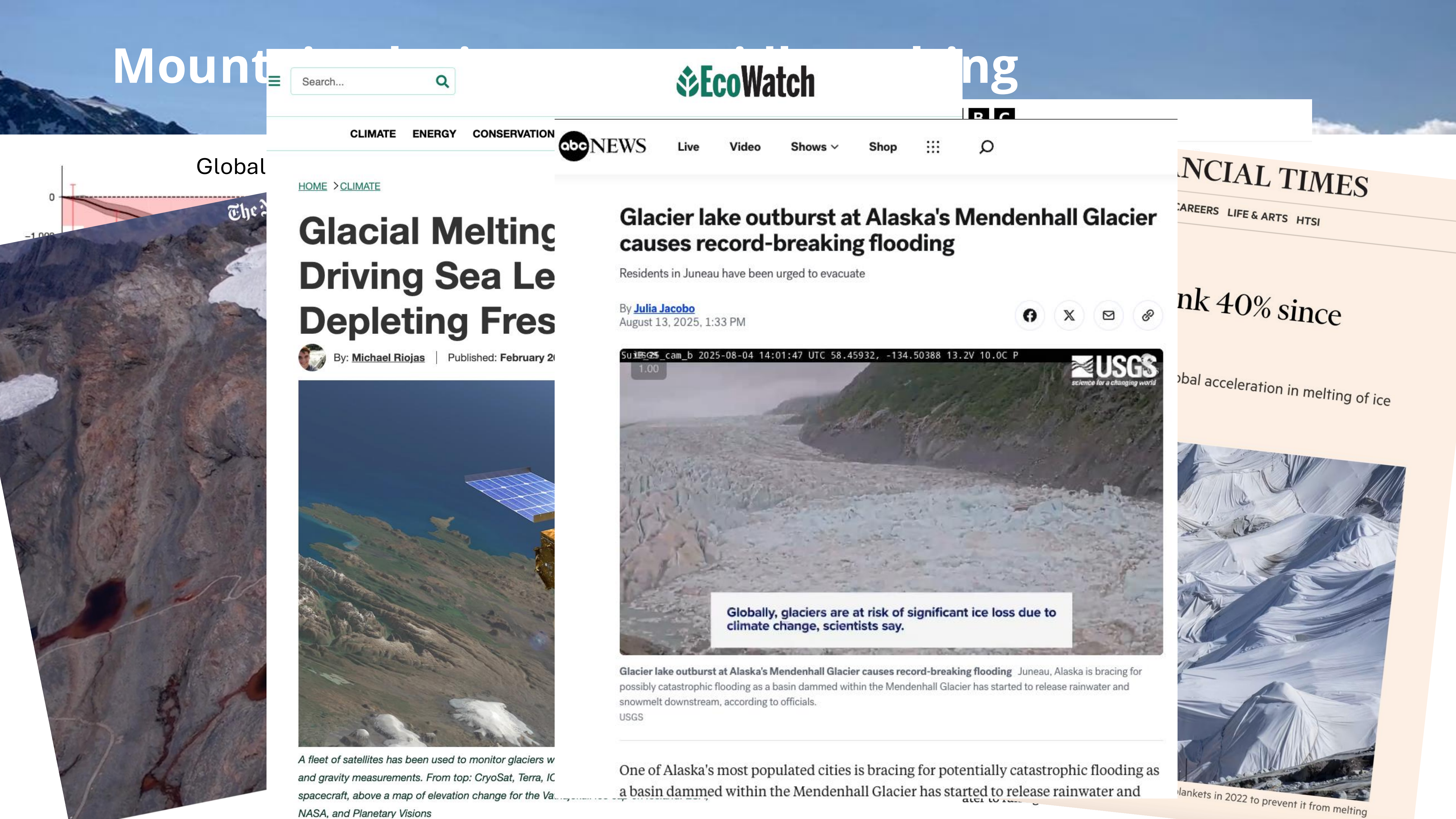
From the Ground Up: Integrating Field Measurements with Remote Sensing for Improved Glacier Evolution Modeling

Albin Wells

Carnegie Mellon University

PhD dissertation defense, 11 February 2026



Mount… ng

Global

EcoWatch

CLIMATE ENERGY CONSERVATION

HOME > CLIMATE

Glacial Melting … Driving Sea Le… Depleting Fres…

By: Michael Riojas | Published: February 2…

A fleet of satellites has been used to monitor glaciers w… and gravity measurements. From top: CryoSat, Terra, IC… spacecraft, above a map of elevation change for the Va… NASA, and Planetary Visions

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Glacier lake outburst at Alaska's Mendenhall Glacier causes record-breaking flooding

Residents in Juneau have been urged to evacuate

By Julia Jacobo
August 13, 2025, 1:33 PM

Glacier lake outburst at Alaska's Mendenhall Glacier causes record-breaking flooding Juneau, Alaska is bracing for possibly catastrophic flooding as a basin dammed within the Mendenhall Glacier has started to release rainwater and snowmelt downstream, according to officials.
USGS

One of Alaska's most populated cities is bracing for potentially catastrophic flooding as a basin dammed within the Mendenhall Glacier has started to release rainwater and

…NCIAL TIMES

CAREERS LIFE & ARTS HTSI

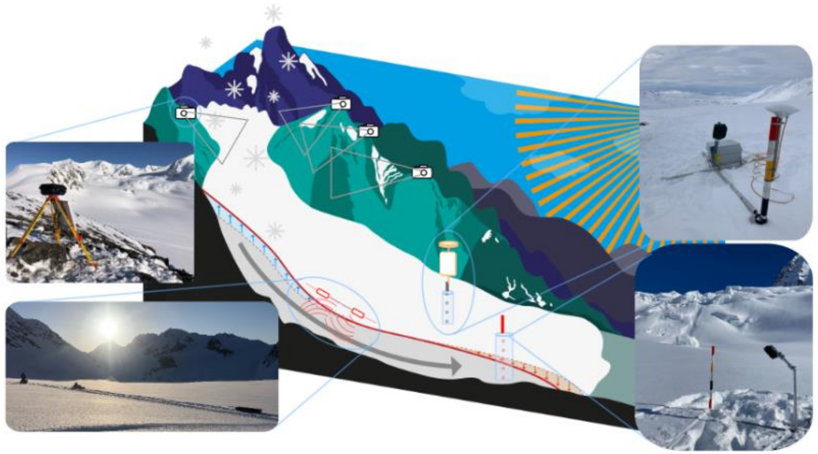
…nk 40% since

…bal acceleration in melting of ice

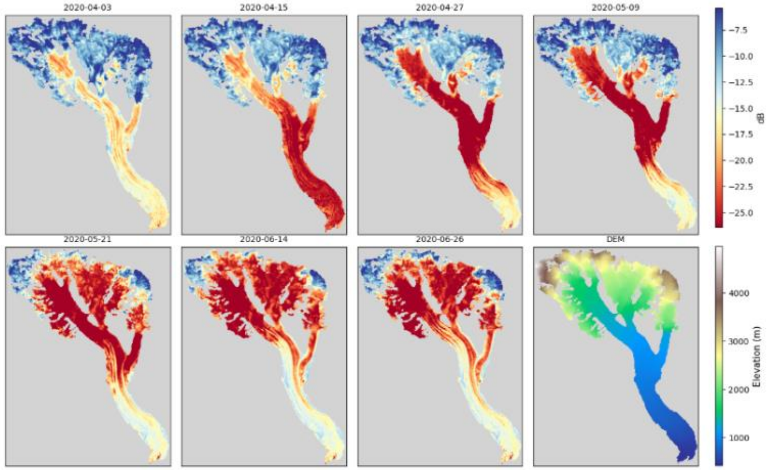
…lankets in 2022 to prevent it from melting

Methods to measure and predict glacier change

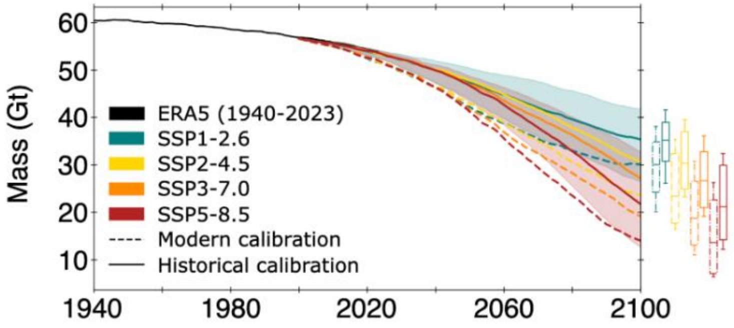
Field methods



Remote sensing



Modeling



Understanding glacier change on spatial and temporal scales

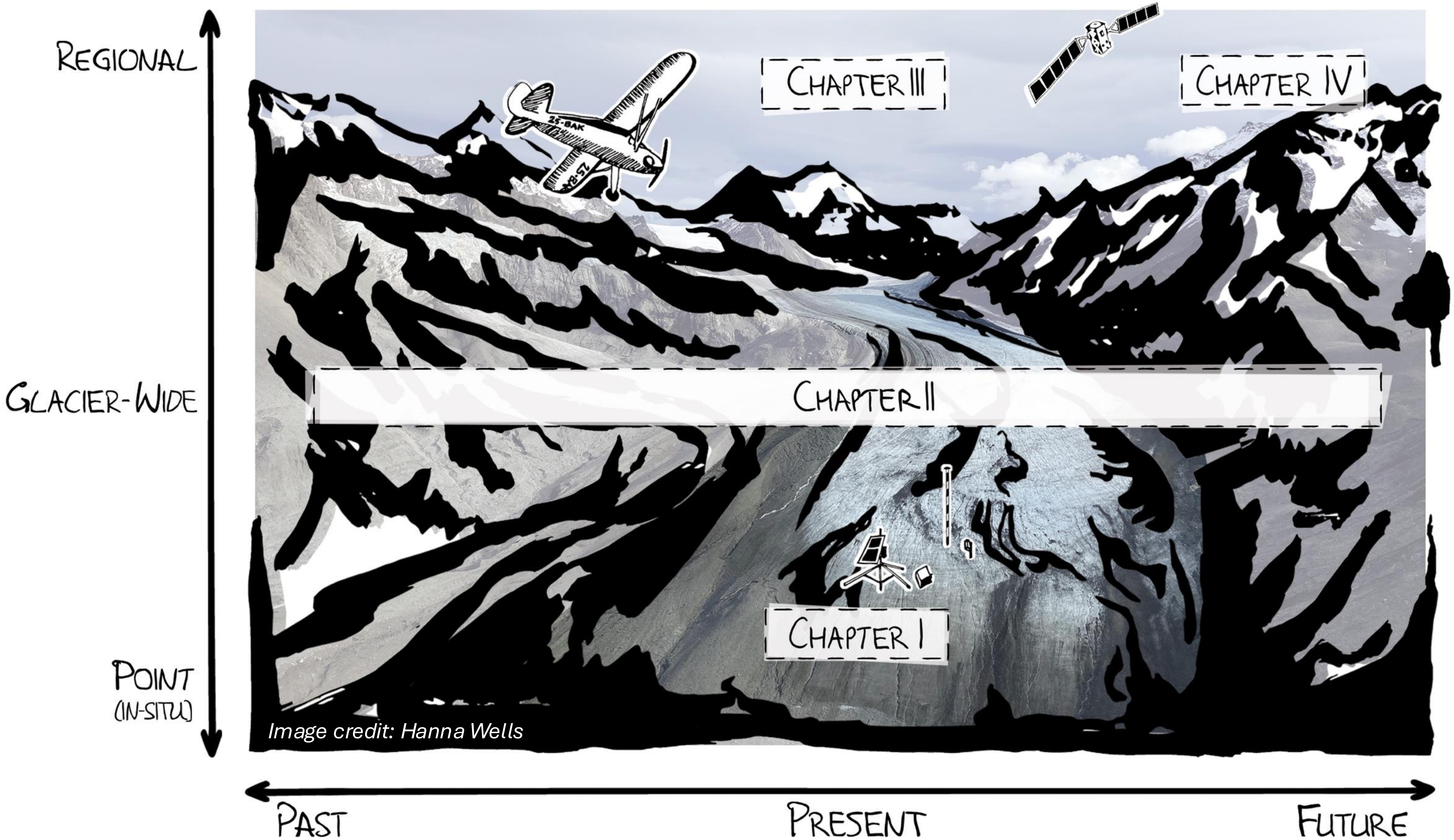
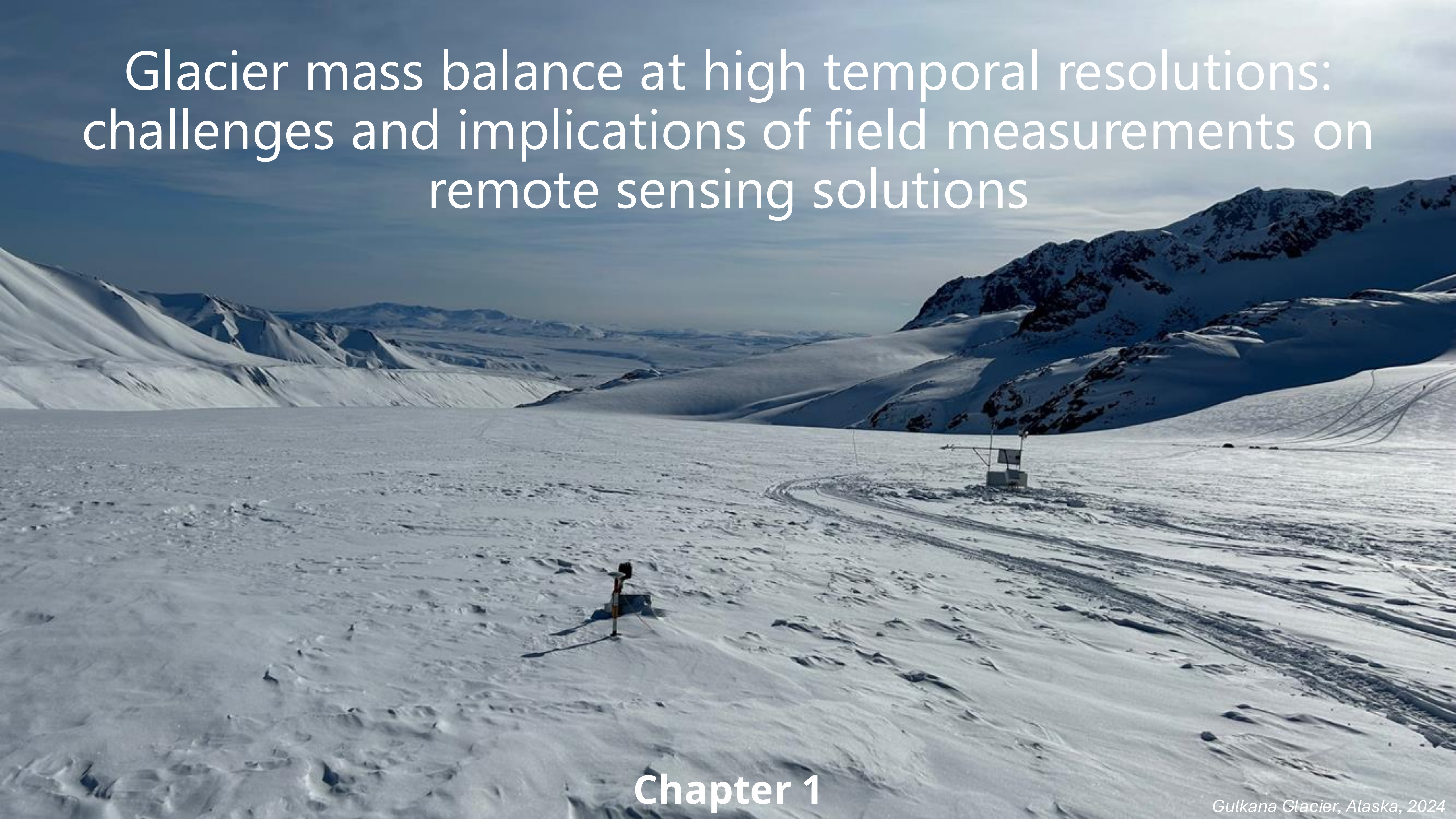


Image credit: Hanna Wells

Glacier mass balance at high temporal resolutions: challenges and implications of field measurements on remote sensing solutions



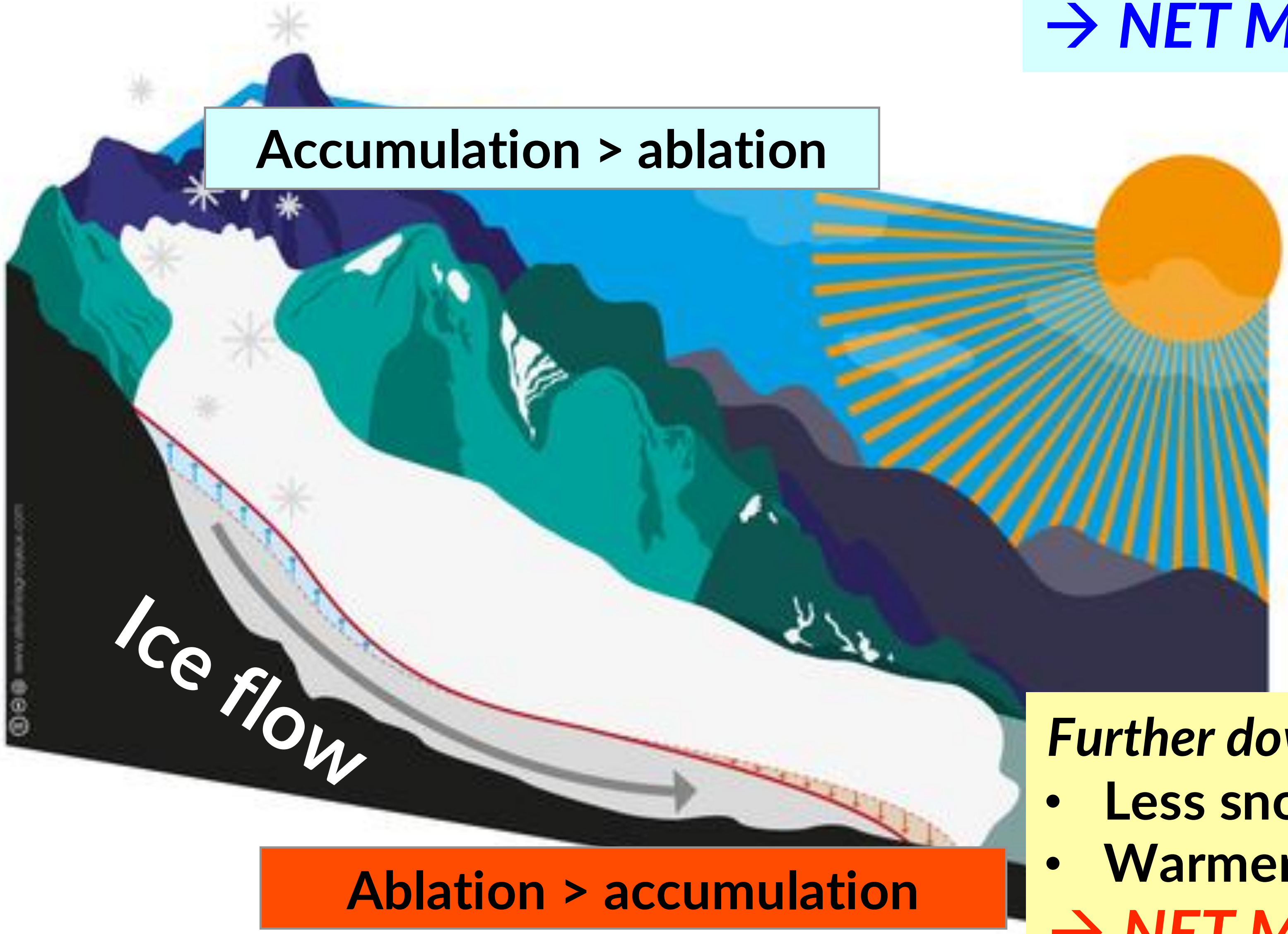
Gulkana Glacier, Alaska, 2024

Chapter 1

Anatomy of a glacier

Higher up:
- More snowfall
- Colder air temperatures → less melt

→ *NET MASS GAIN over the year*



Further down:
- Less snowfall
- Warmer air temperatures → more melt

→ *NET MASS LOSS over the year*

The *flux divergence* is a critical component needed to obtain the climatic mass balance

Climatic Mass Balance

$$\dot{b}_{\text{clim}} = \frac{dh}{dt} + \nabla \cdot q$$

Flux Divergence

Total Mass Balance

The *flux divergence* is a critical component needed to obtain the climatic mass balance

$$\dot{b}_{\text{clim}} = \frac{dh}{dt} + \nabla \cdot q$$

Climatic Mass Balance

- Ablation stakes
- Snow pits

(in-situ)

Total Mass Balance

- DEM differencing

(remote sensing)

Flux Divergence

- Derived from ice thickness & velocity

(remote sensing)

- Field methods?

(in-situ)

We have no scaled constraints on modeled climatic mass balance which is crucial for process-based understanding of present and future glacier changes

The *flux divergence* is a critical component needed to obtain the climatic mass balance

This is what we want, globally…

$$\dot{b}_{\text{clim}} = \frac{dh}{dt} + \nabla \cdot q$$

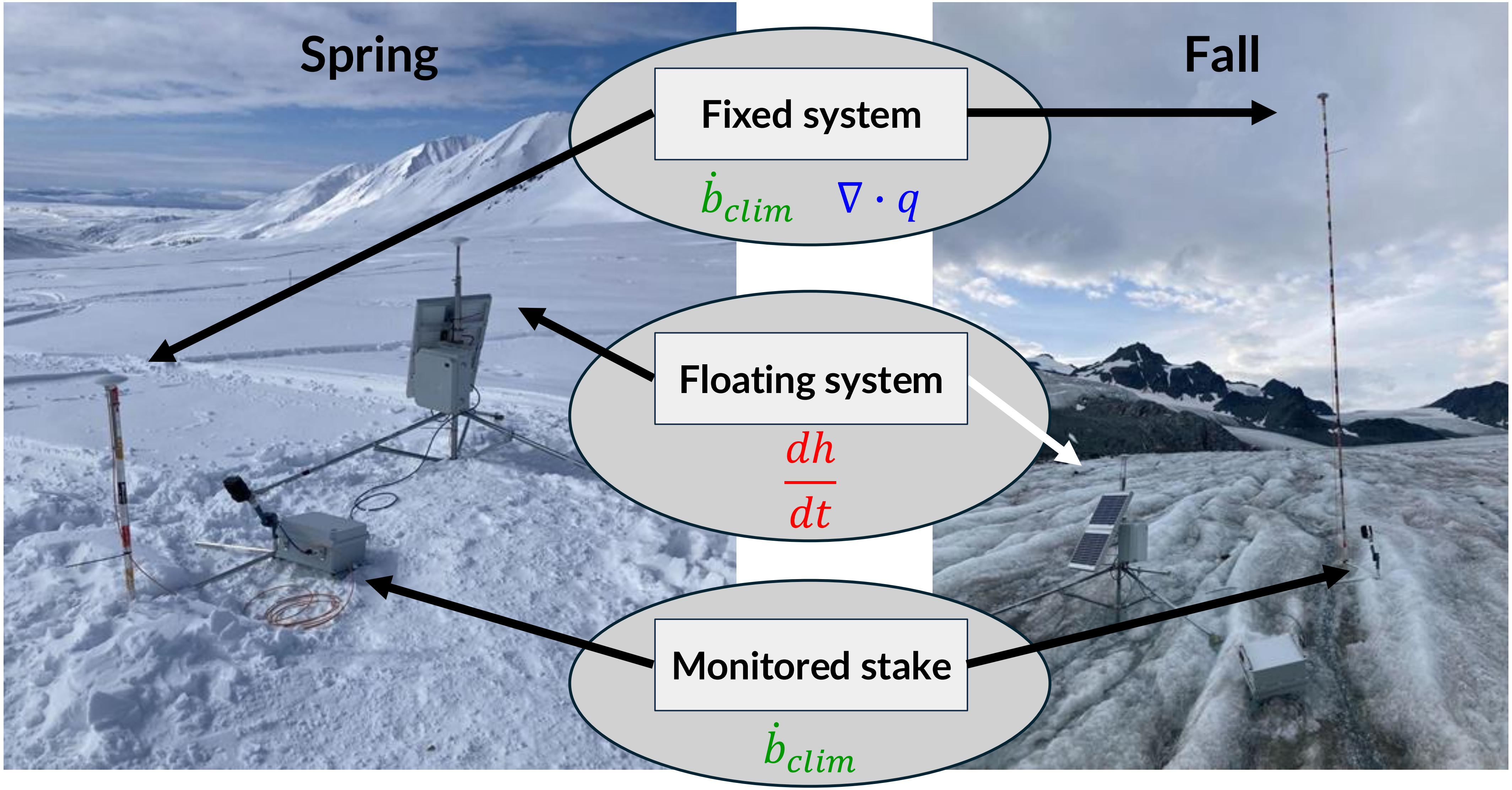
…so we need this…

Climatic Mass Balance	Total Mass Balance	Flux Divergence
• Ablation stakes • Snow pits *(in-situ)*	• DEM differencing *(remote sensing)*	• Derived from ice thickness & velocity *(remote sensing)* • Field methods? *(in-situ)*

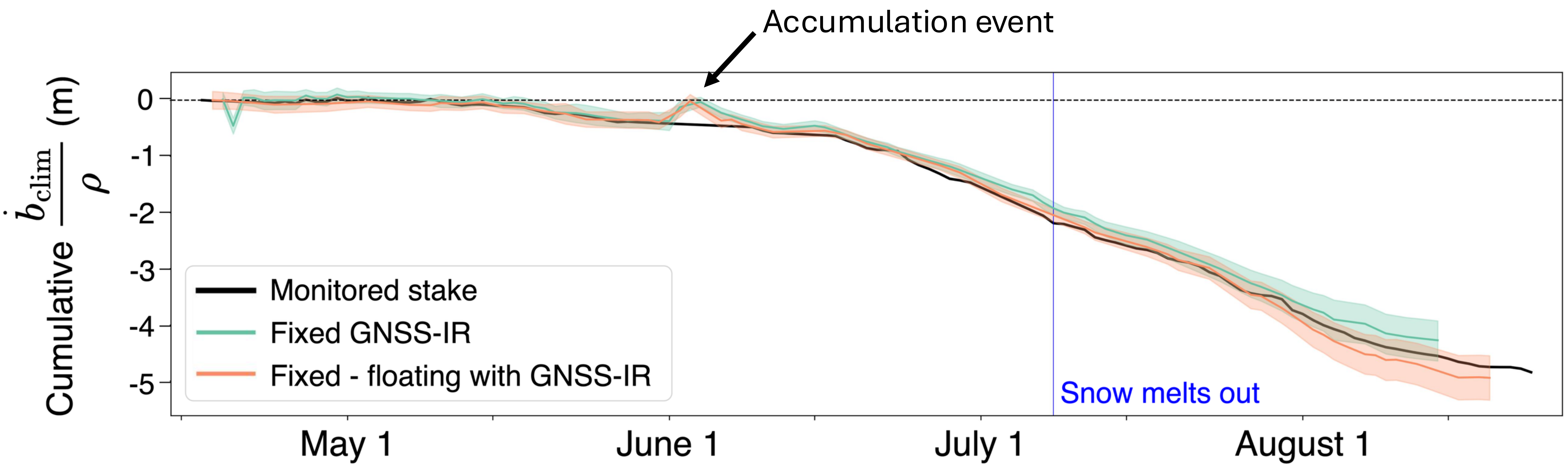
…for which ground-truth data is essential

We have no scaled constraints on modeled climatic mass balance which is … process-based understanding of present and future glacier change

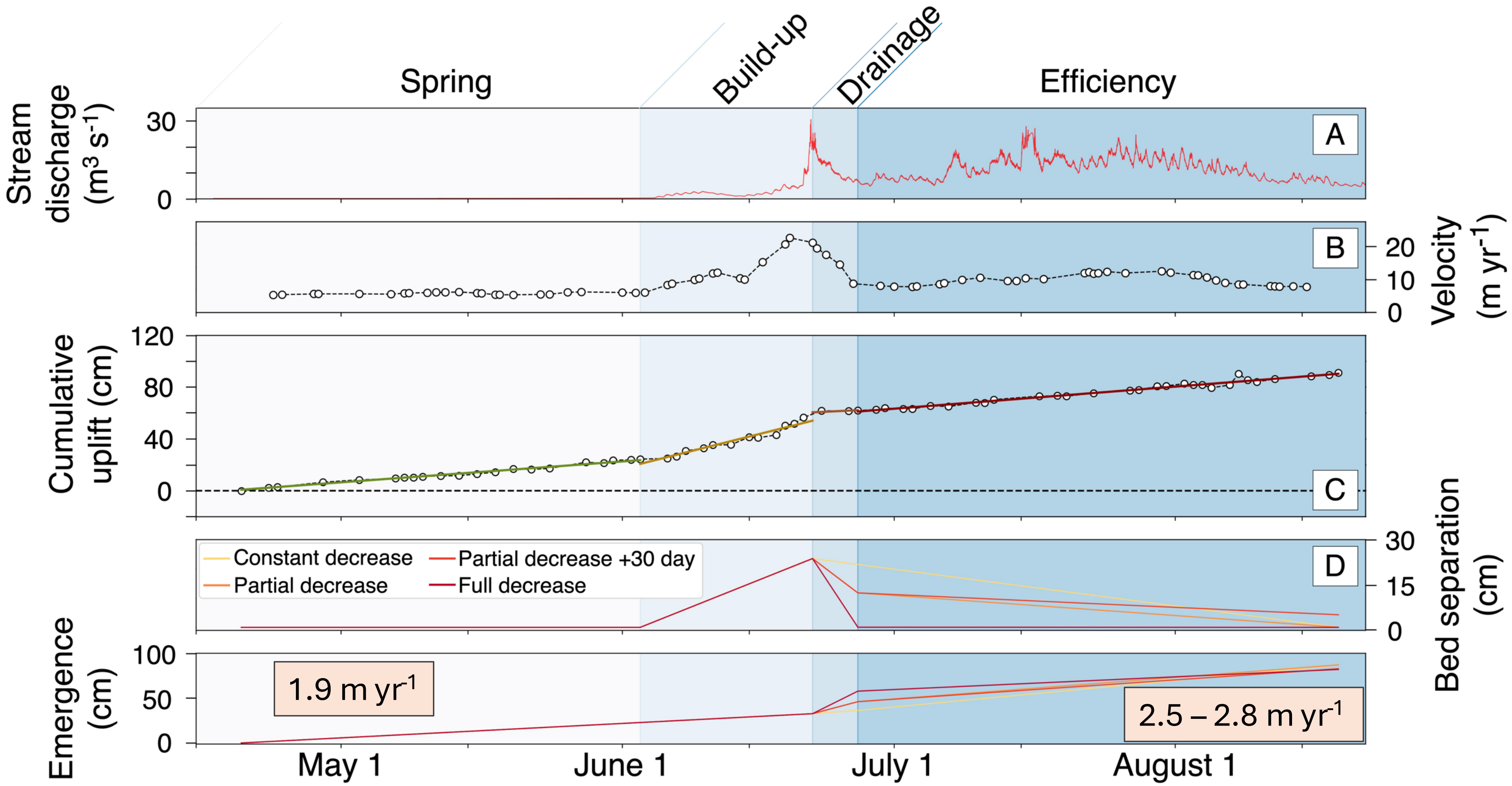
Redundant setup using low-cost sensors for mass balance components



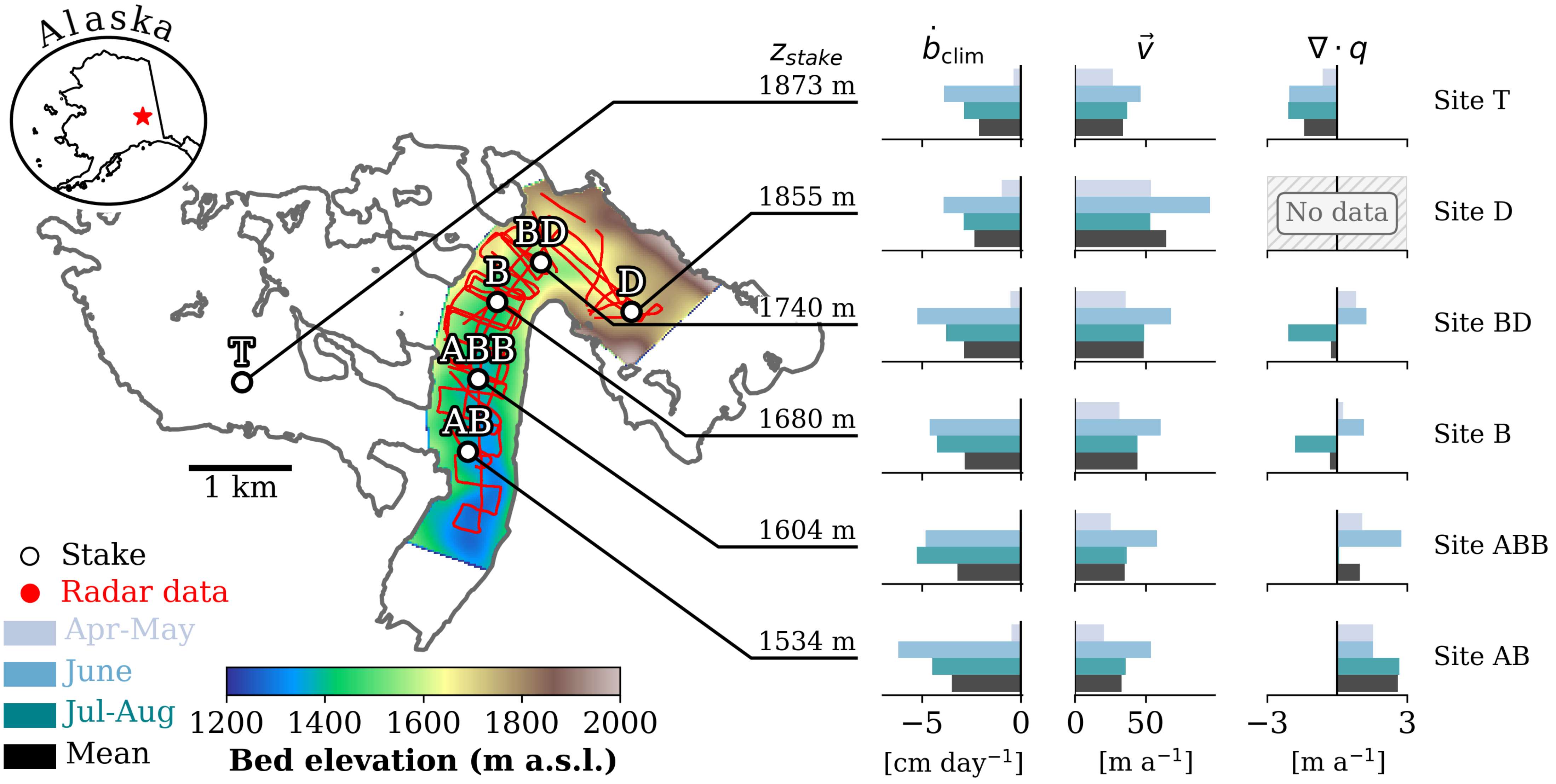
GNSS reflectometry captures daily mass balance & summer snow



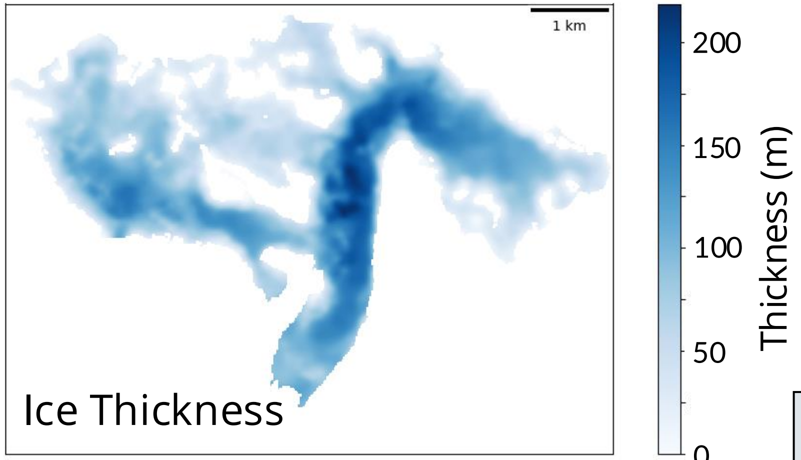
Large subseasonal changes in glacier dynamics

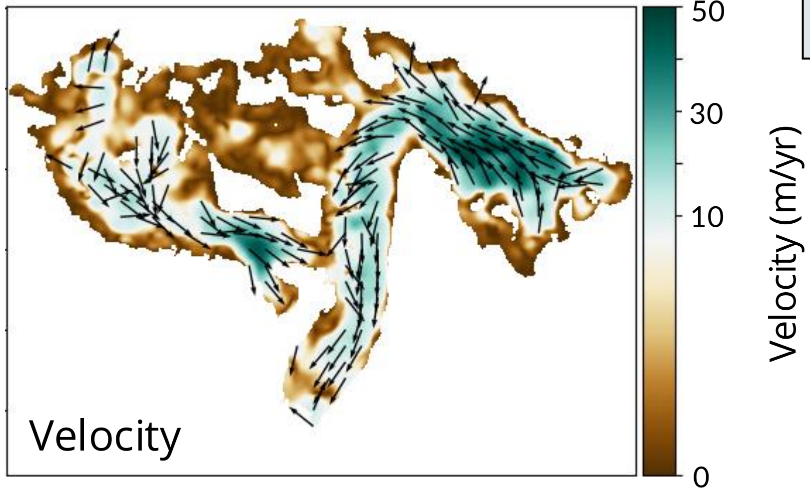


Expanded network of GNSS systems in 2024

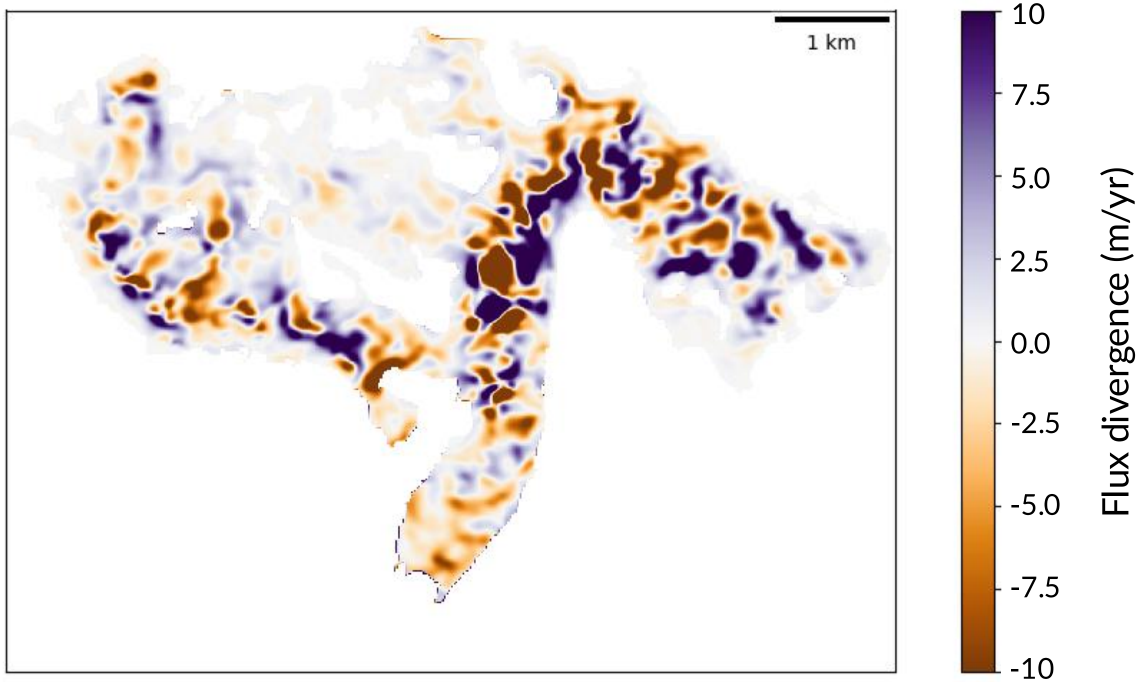


Can remote sensing reproduce field data?





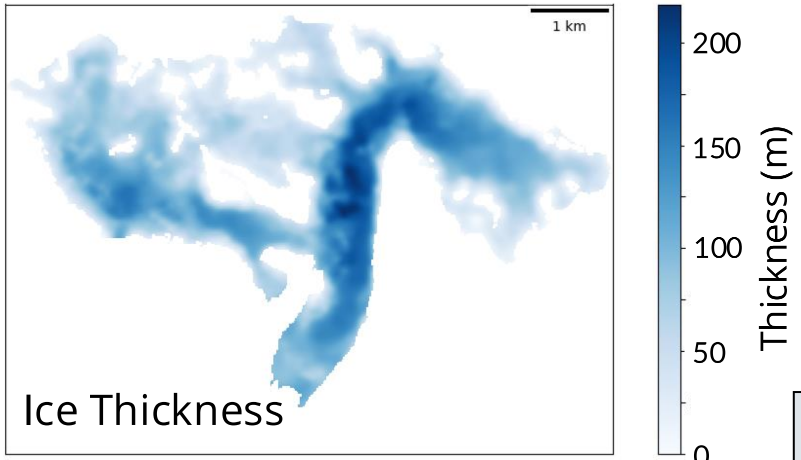
Flux divergence (no smoothing)

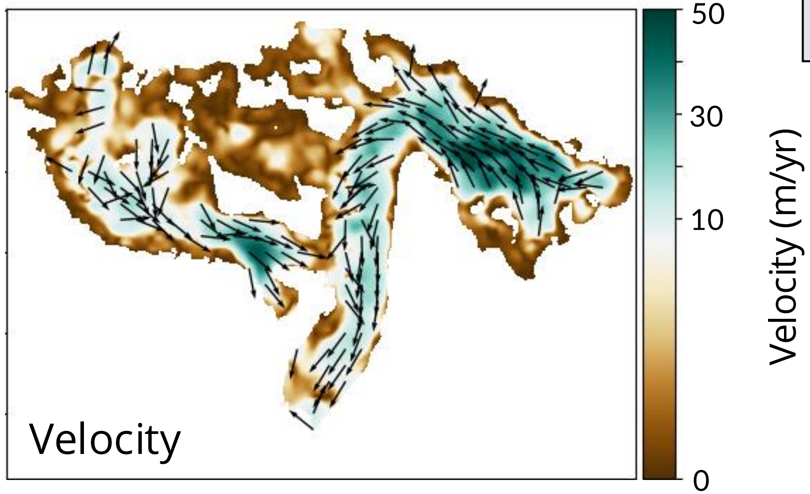


$$\nabla q = h \cdot \left(\frac{du_x}{dx} + \frac{du_y}{dy}\right) + u \cdot \left(\frac{dh}{dx} + \frac{dh}{dy}\right)$$

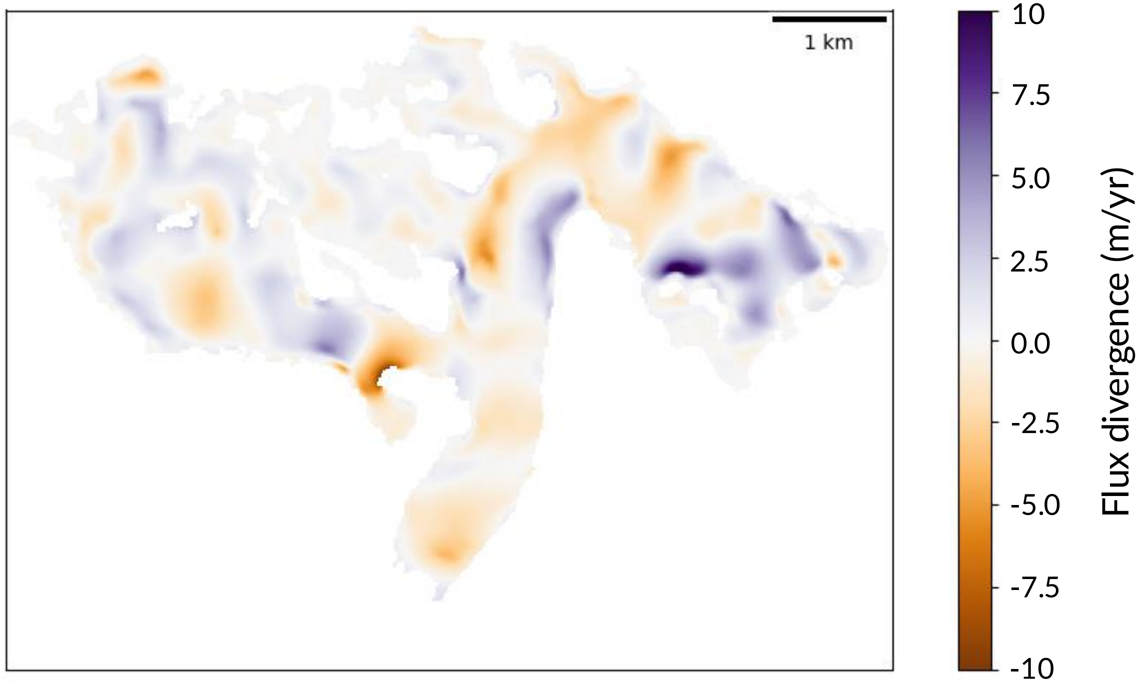
Millan et al. 2022, *Nat. Geosci.*

Can remote sensing reproduce field data?





Flux divergence (with smoothing)



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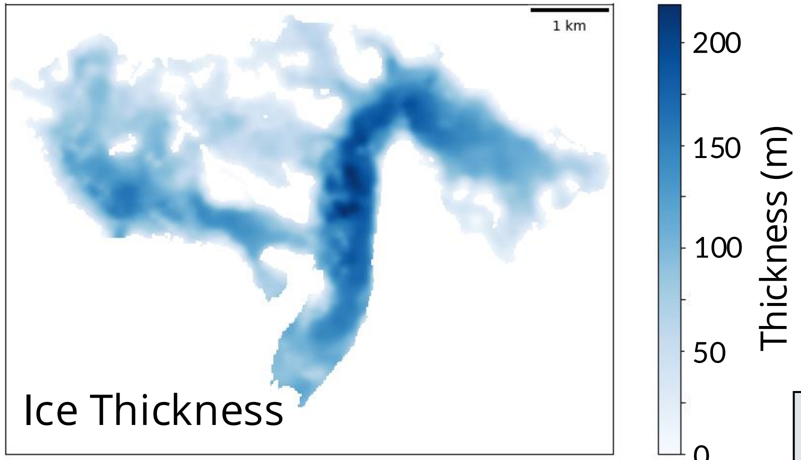
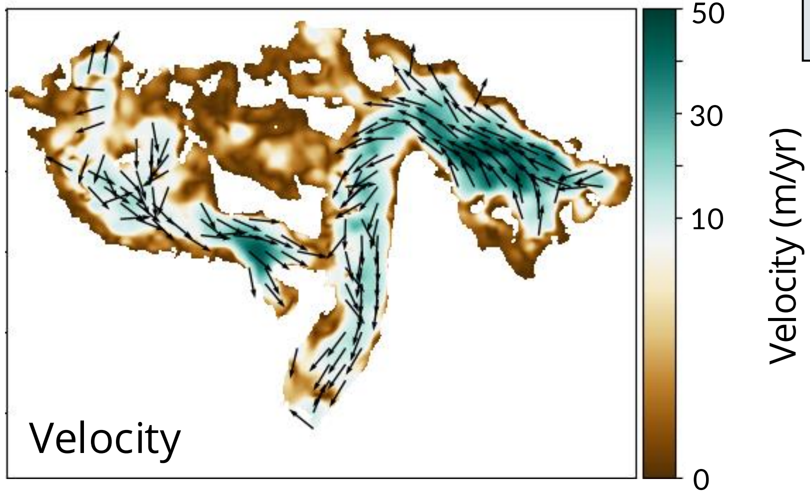
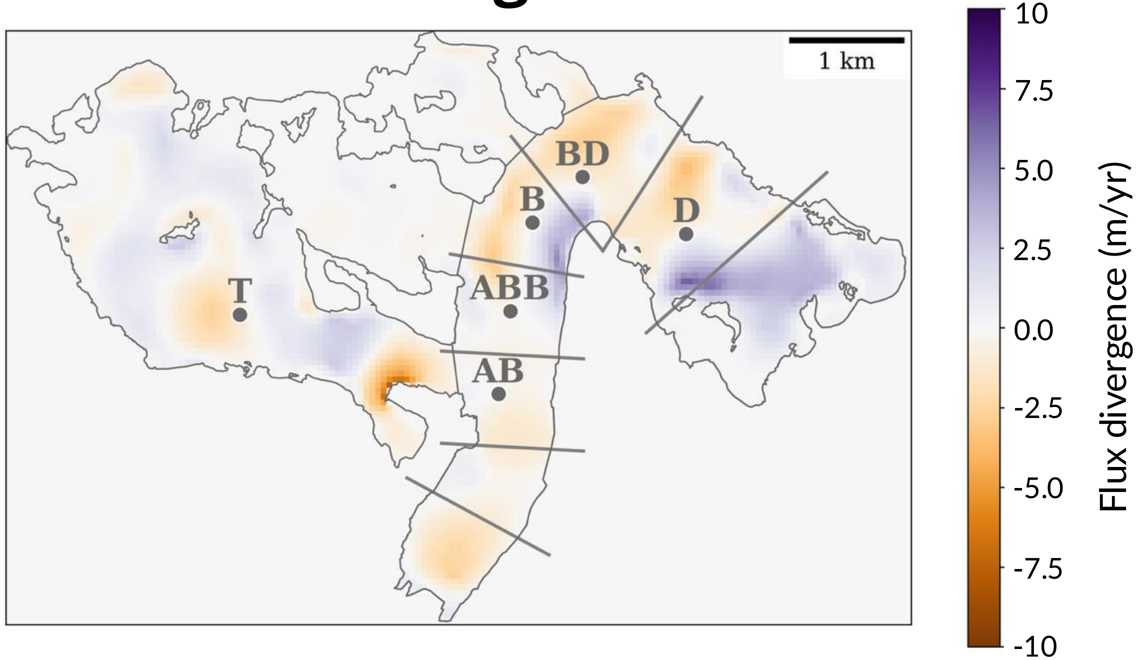
Millan et al. 2022, *Nat. Geosci.*

Can remote sensing reproduce field data?

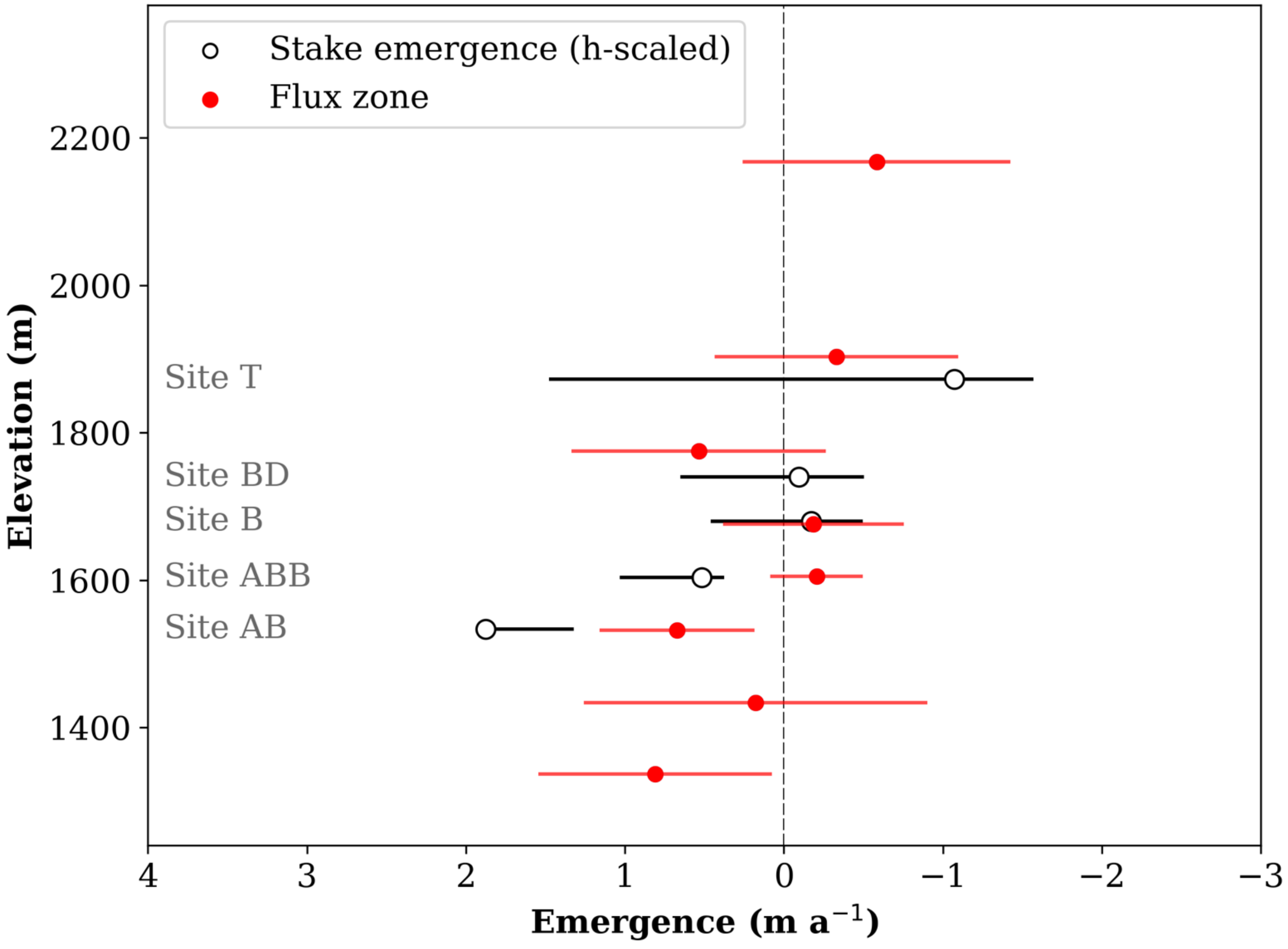




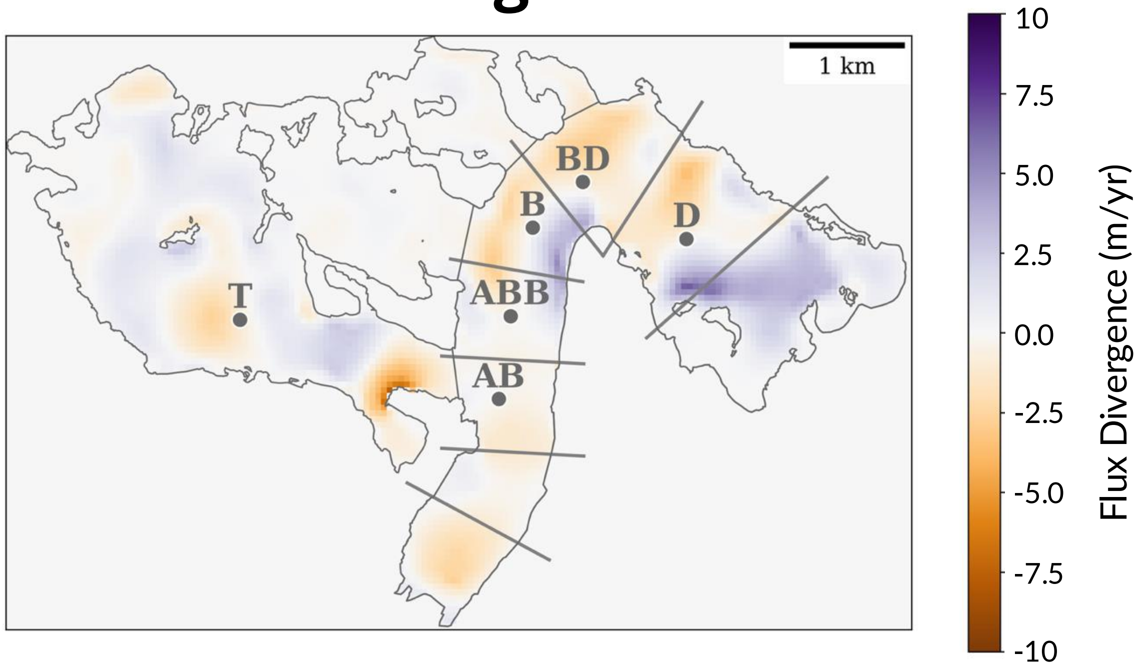
Flux gate



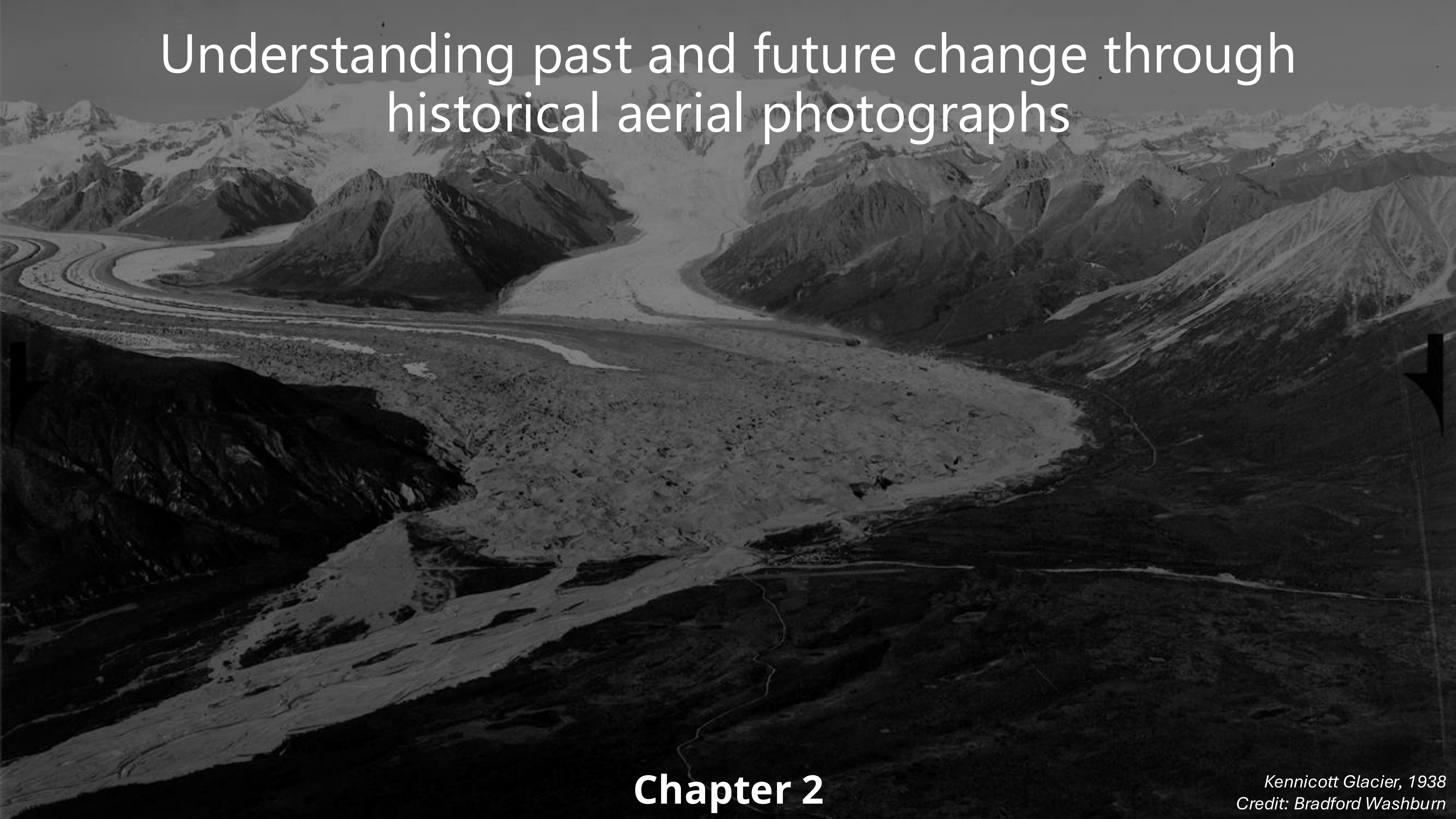
Remote sensing products are still far off



Flux gate



Understanding past and future change through historical aerial photographs



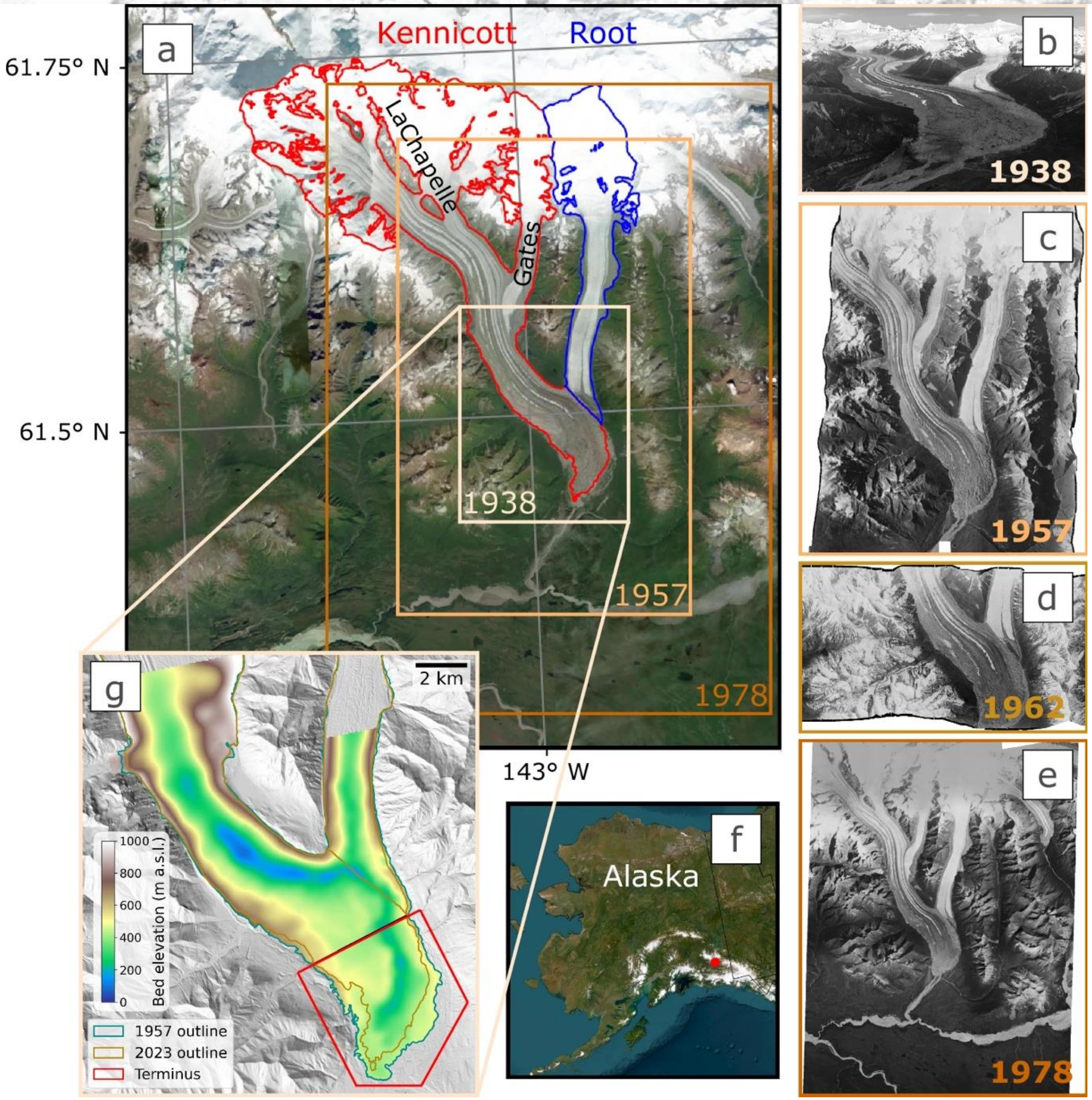
Chapter 2

Kennicott Glacier, 1938
Credit: Bradford Washburn

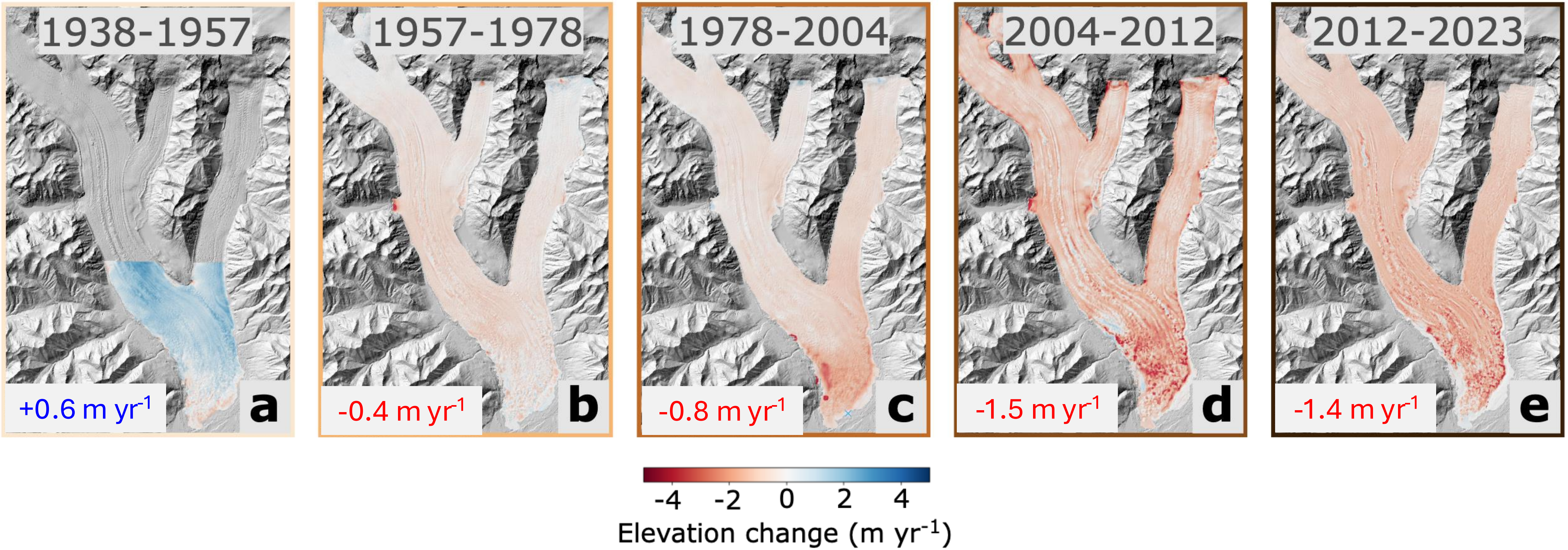
Kennicott and Root glacier are uniquely data-rich

- Historical DEMs (1938, 1957, 1962, 1978)
- Modern DEMs (2004, 2012, 2023)
- Bed data
- Velocity (Historical 1957-1962, ITS LIVE)
- Glacier outlines
- Climate data (1940-2100; ERA5, CMIP6)

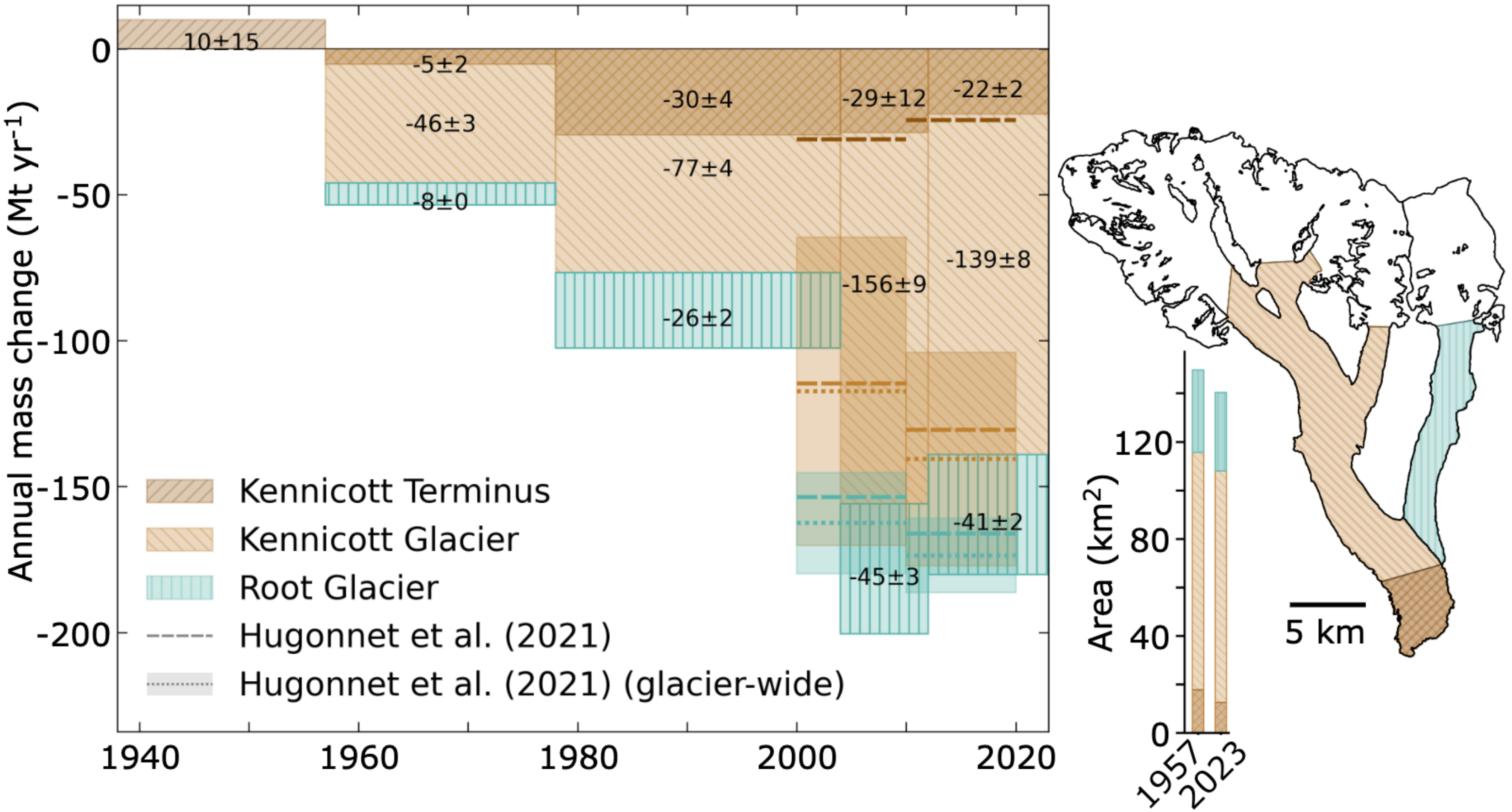
- ***Historical aerial photographs exist for much more of Alaska!***



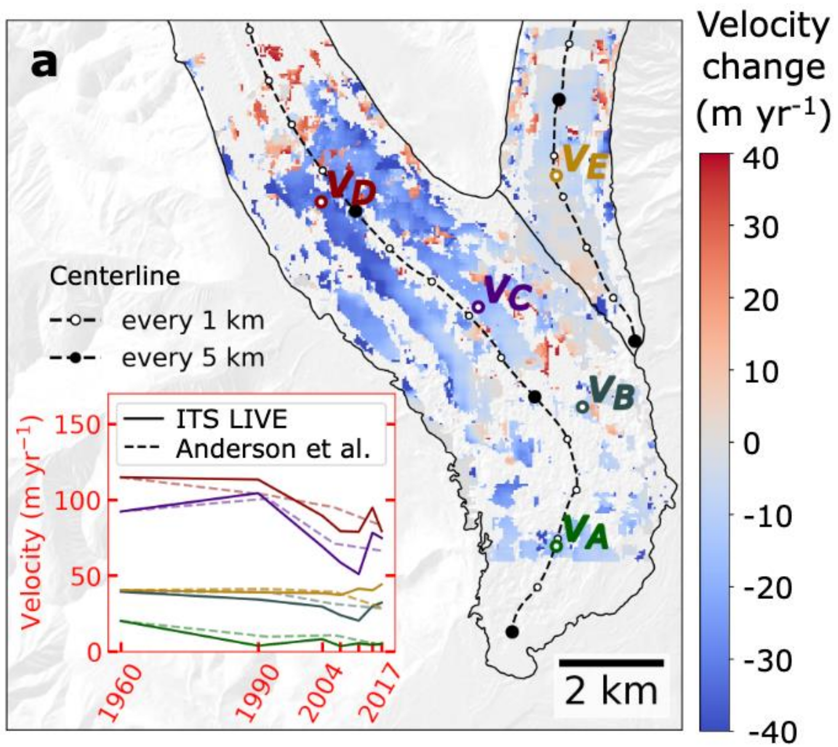
Historical record reveals accelerating thinning

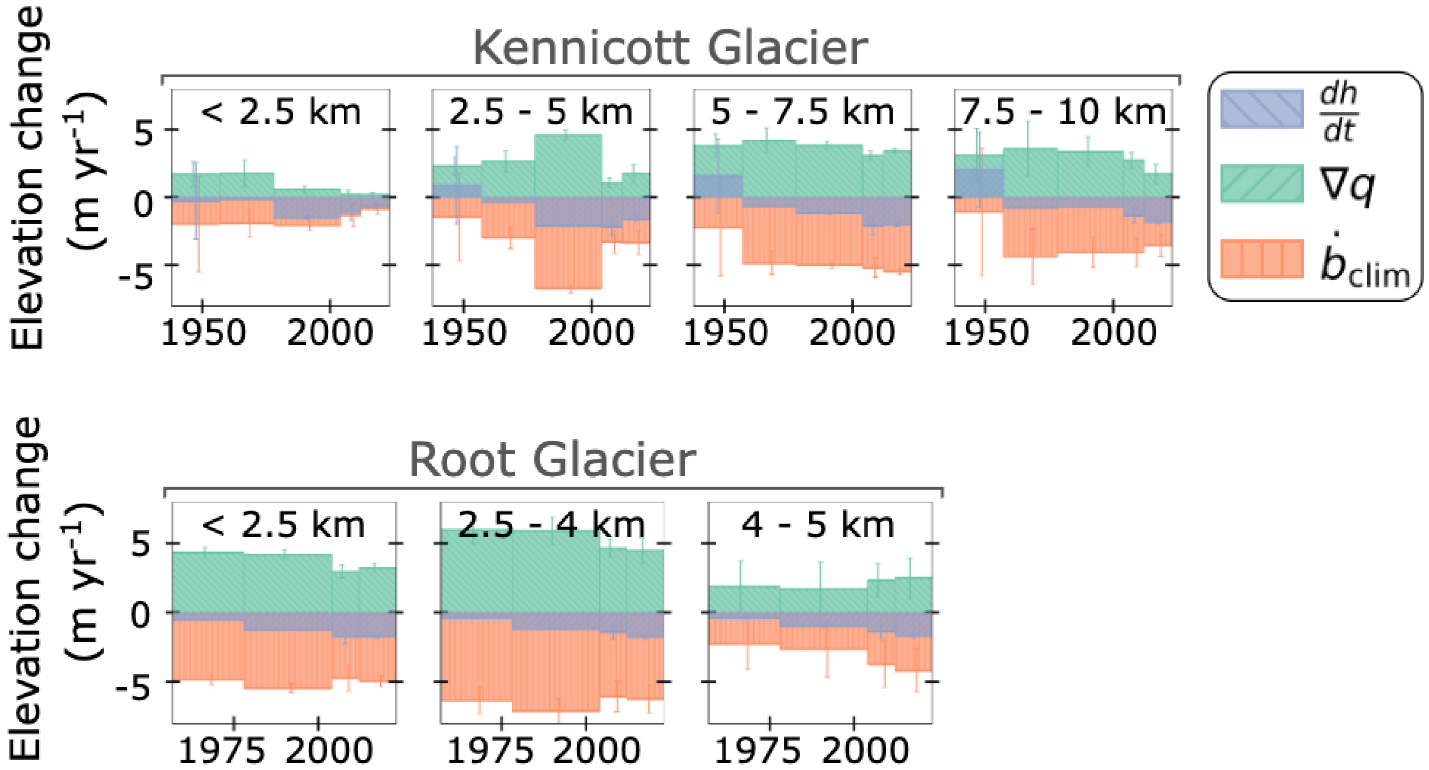


Historical record reveals accelerating mass loss

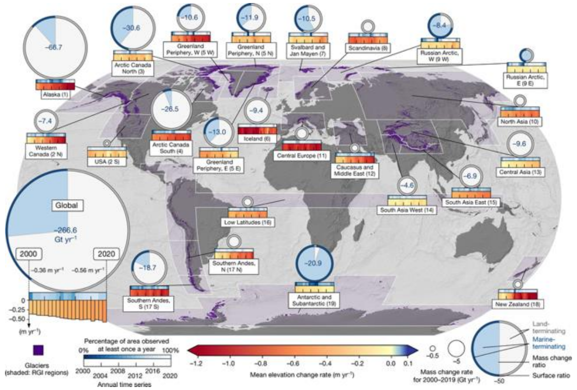


Glacier dynamics dictate thinning patterns

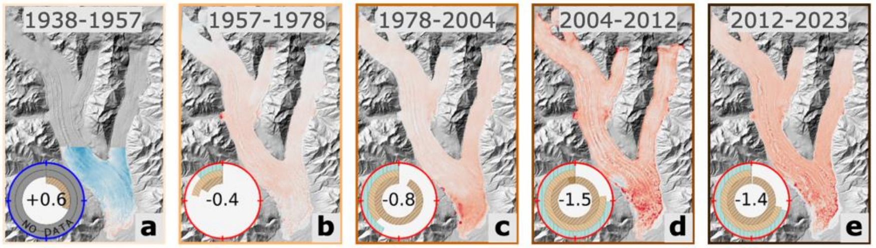




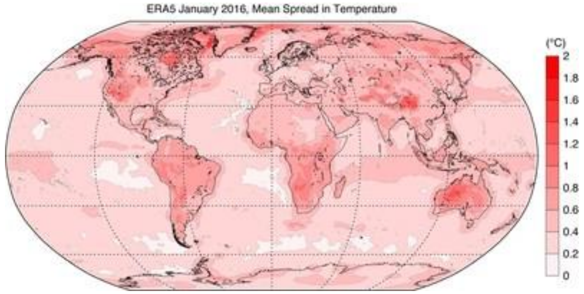
How do past observations affect projections?



2000 - 2020
(Hugonnet et al., 2021)

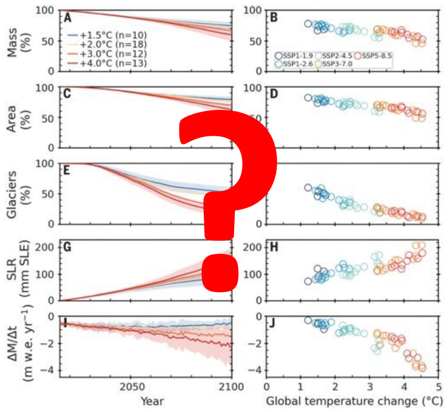


1938 – 2023



Climate data
(ERA5)

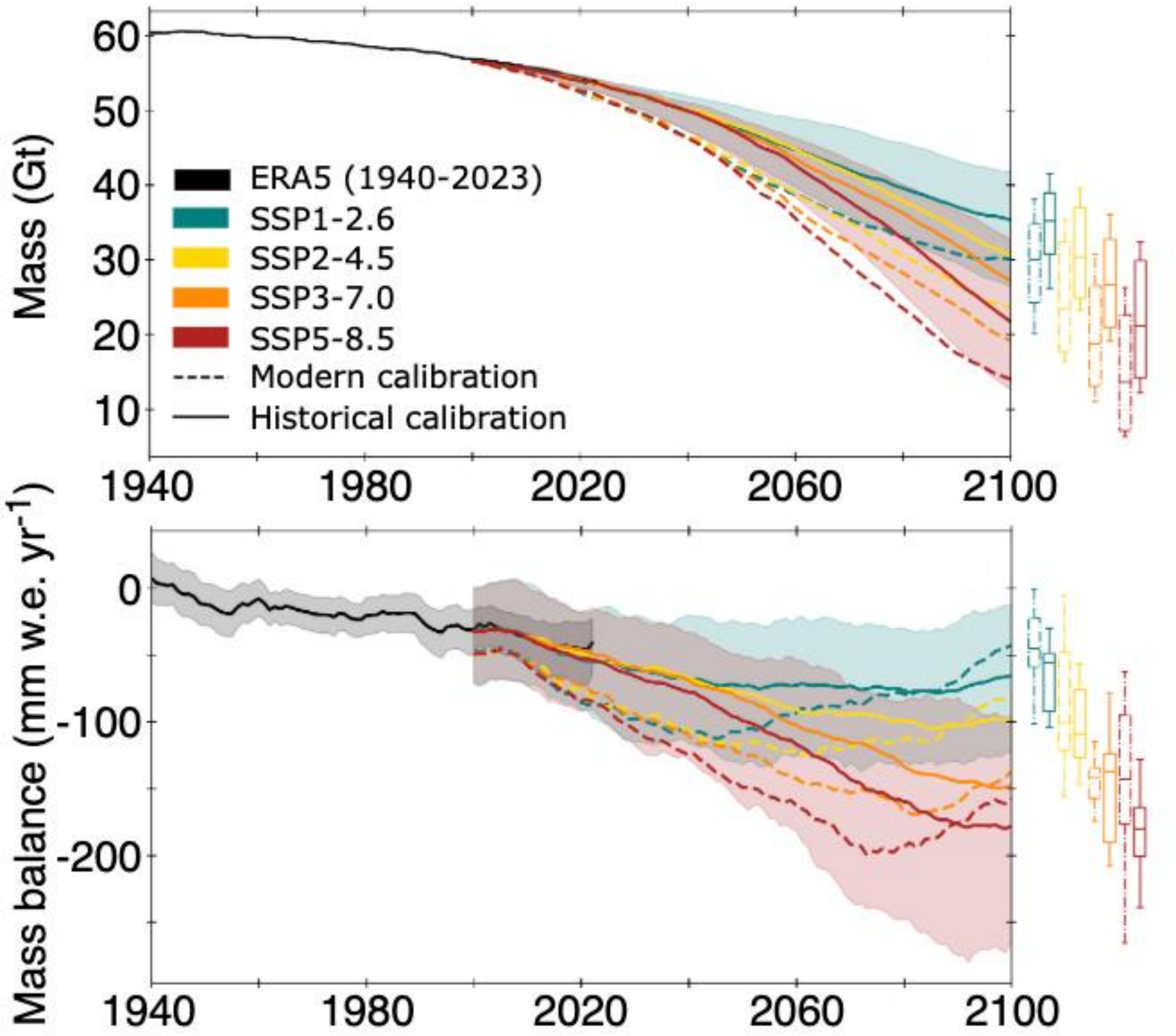
Glacier model (PyGEM)



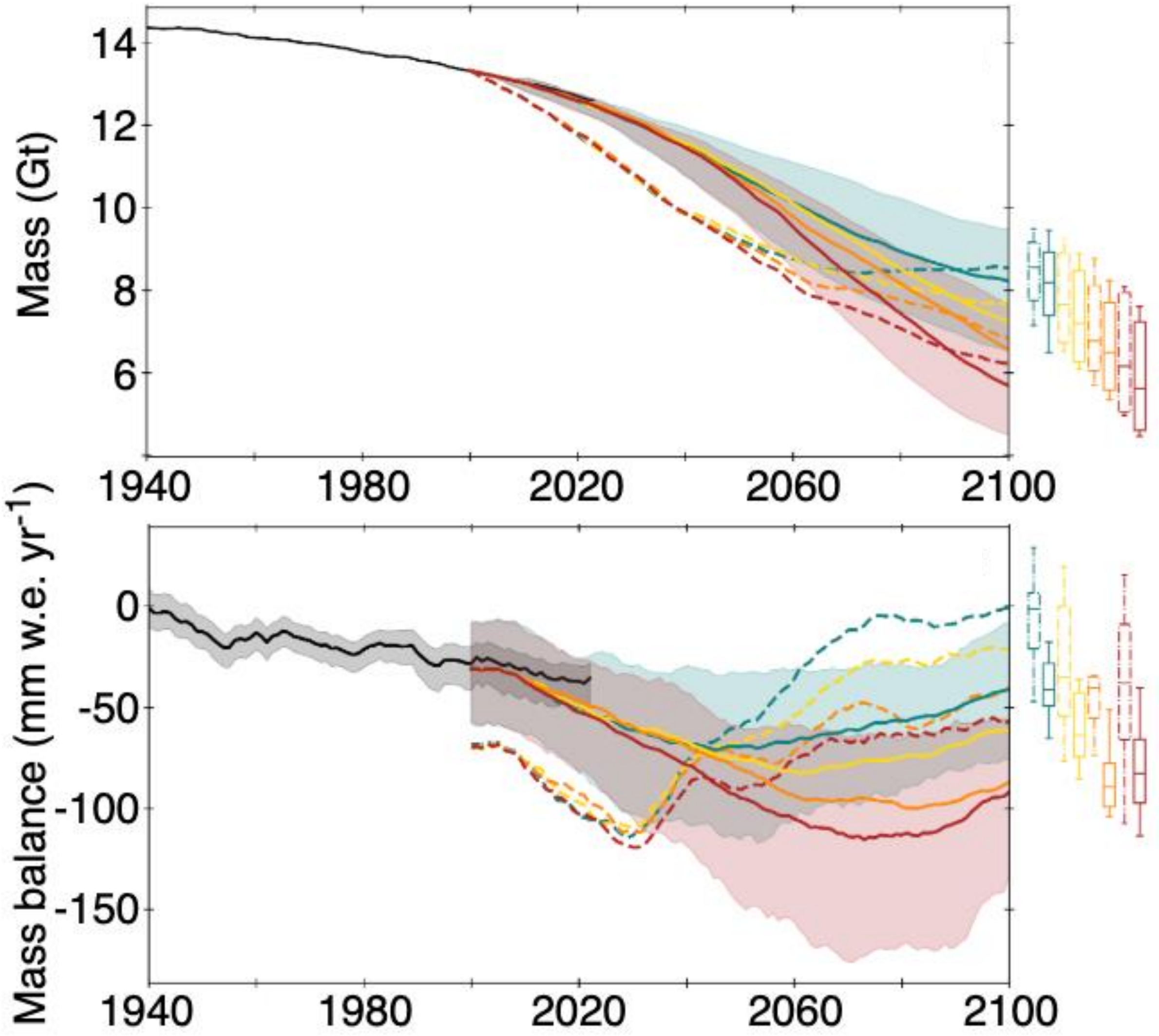
2000 - 2100
(Rounce et al., 2023)

Projections show significant mass loss to 2100

Kennicott Glacier



Root Glacier



Seasonal progression of melt and snowlines in Alaska reveals impacts of warming

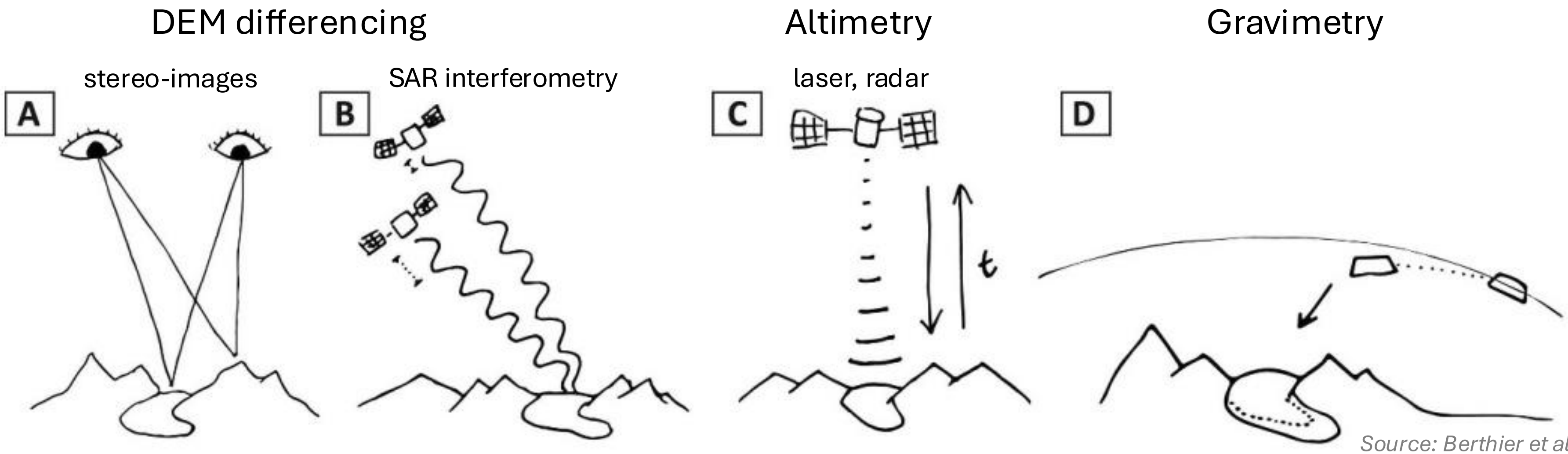
Chapter 3

Nizina Glacier, Alaska, 2022

Advances in glaciology benefit from scalable (sub)seasonal observations

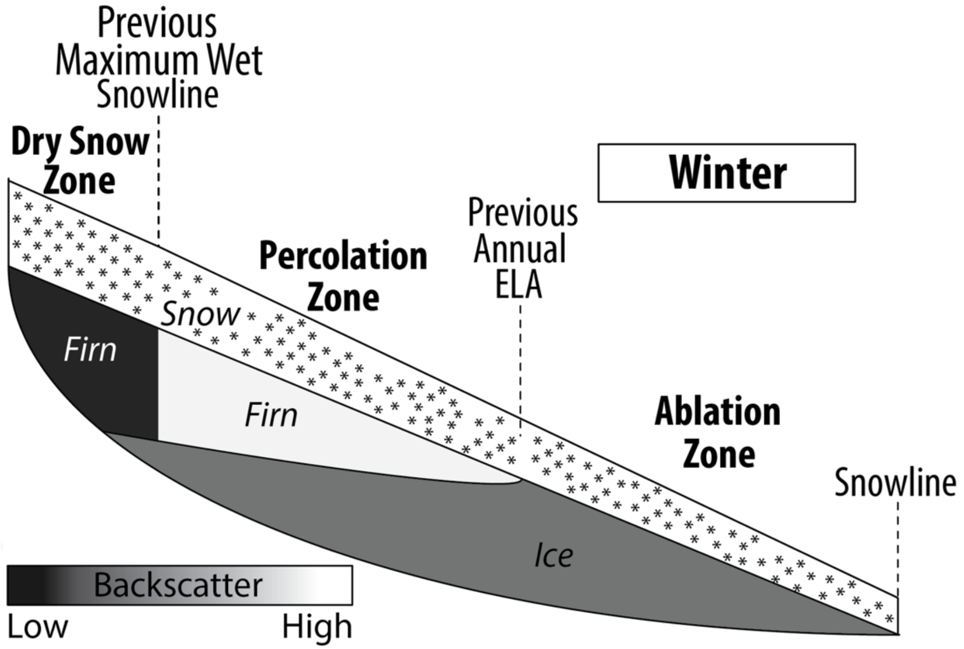
Synthetic aperture radar (SAR) has potential to reliably observe glaciers at weekly resolution, which is key towards understanding sub-seasonal glacier processes and as calibration for large-scale models

- Sentinel-1 SAR has a 12-day repeat (and two satellites)
- SAR penetrates clouds and doesn't require daylight
- SAR "backscatter" depends solely on physical properties of the surface



Source: Berthier et al., 2023

Backscatter indicates glacier surface properties

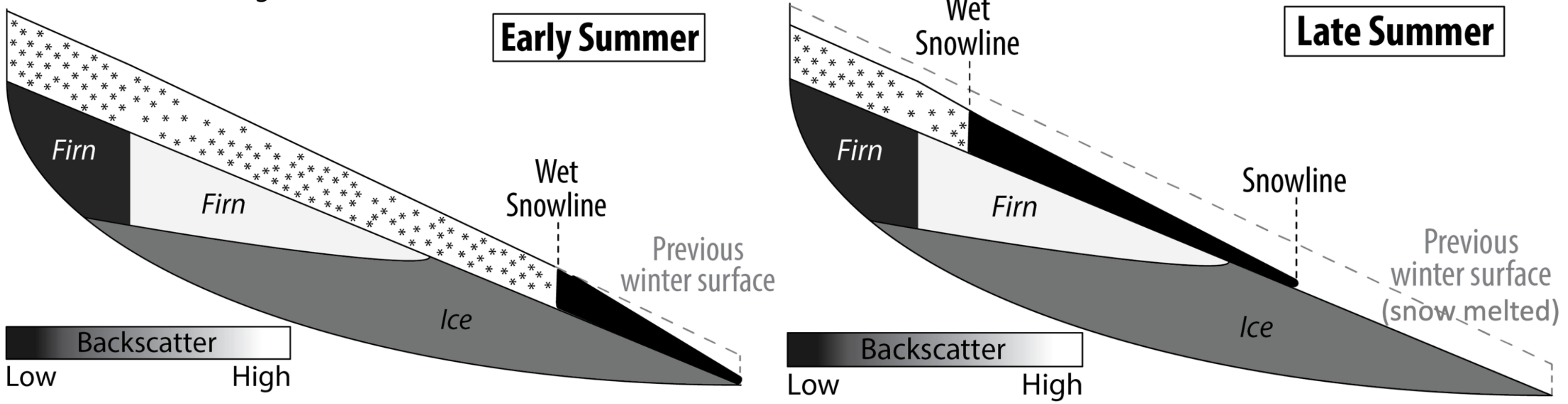


Dry snow allows microwave signal to penetrate surface several meters

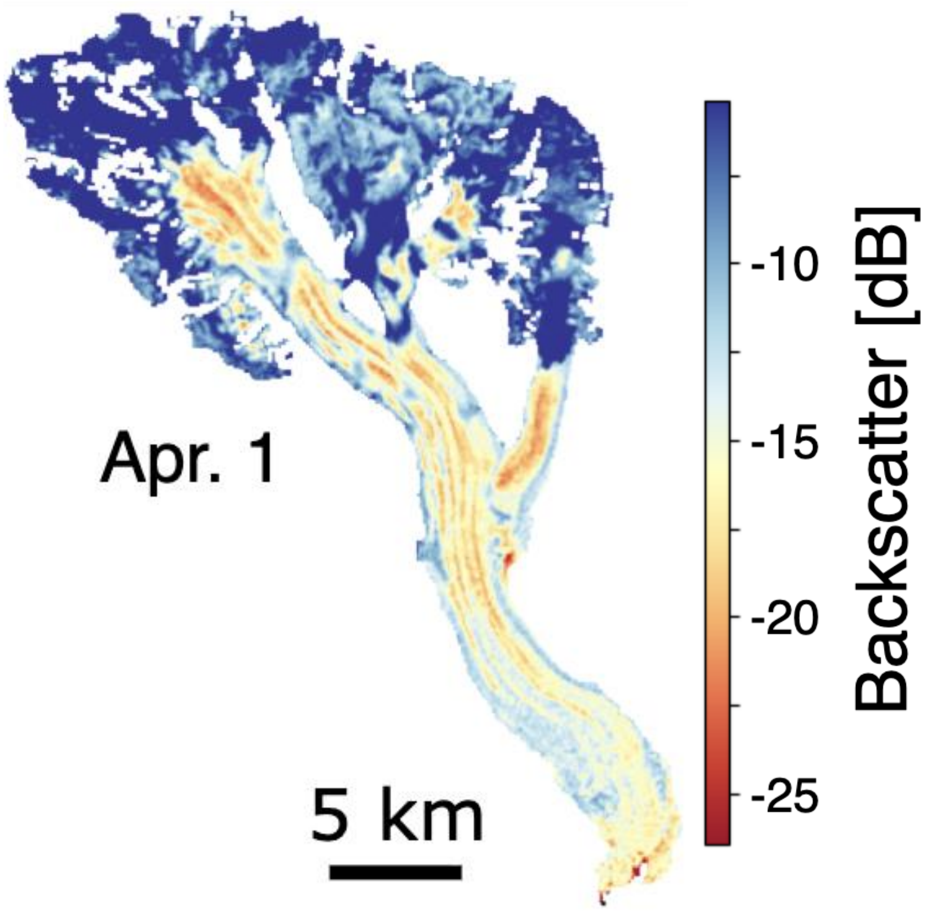
Liquid water on surface absorbs signal causing low backscatter

Winter backscatter reveal glacier zones due to characteristic differences

Melt extents apparent from drop in backscatter as liquid is on surface



Spatially-distributed backscatter varies seasonally



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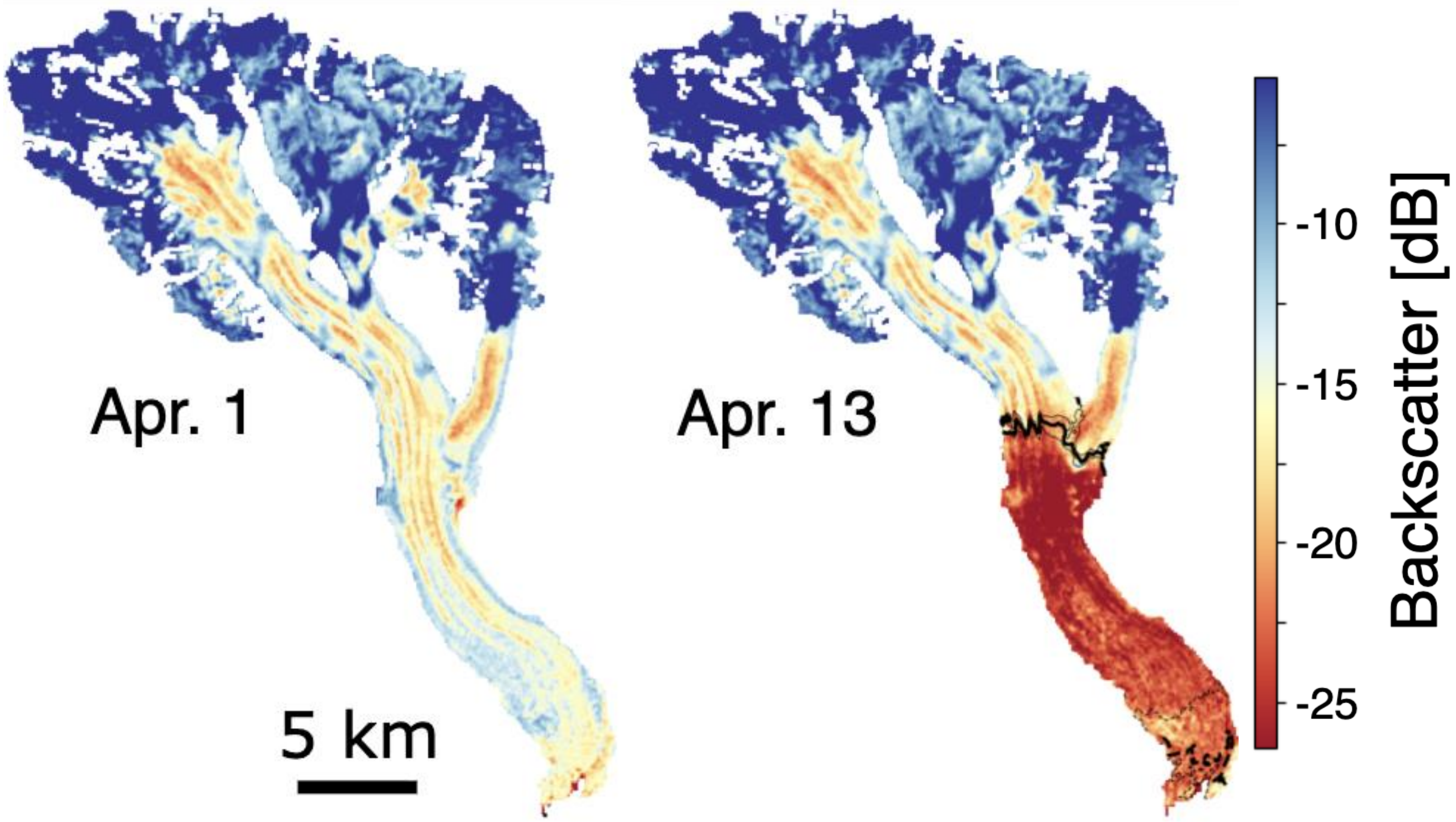

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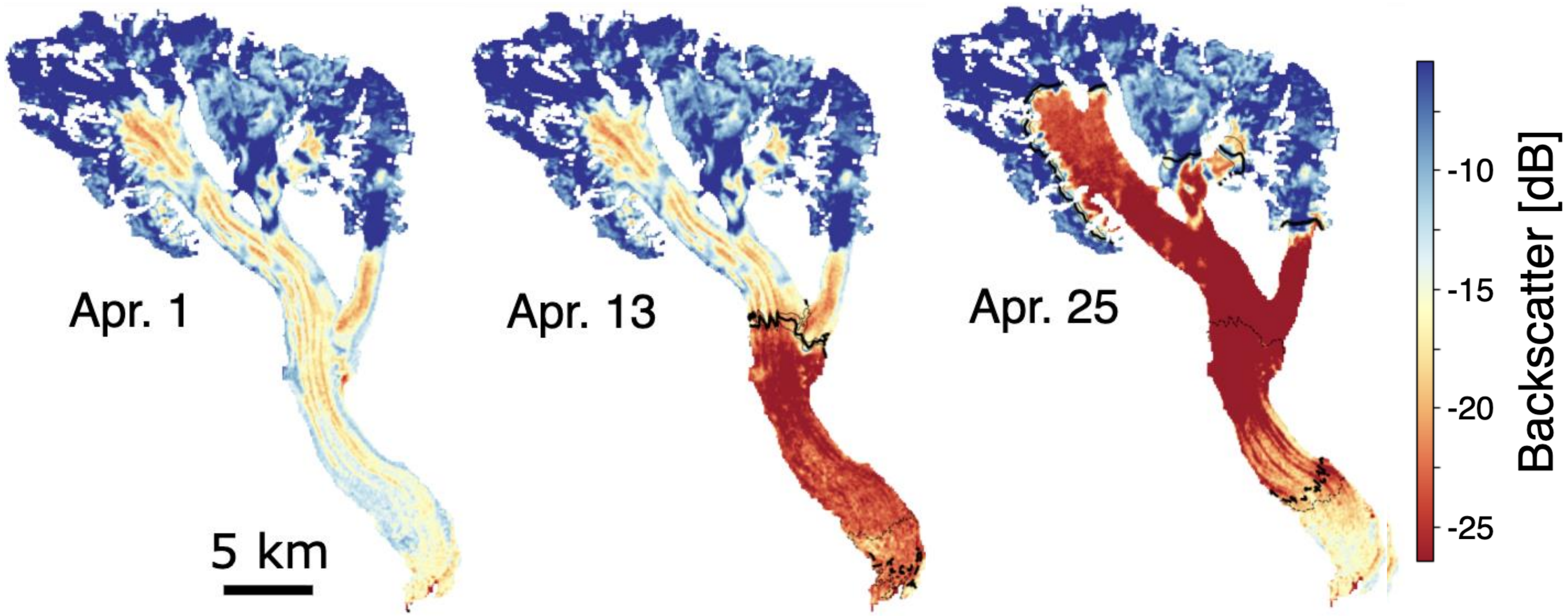
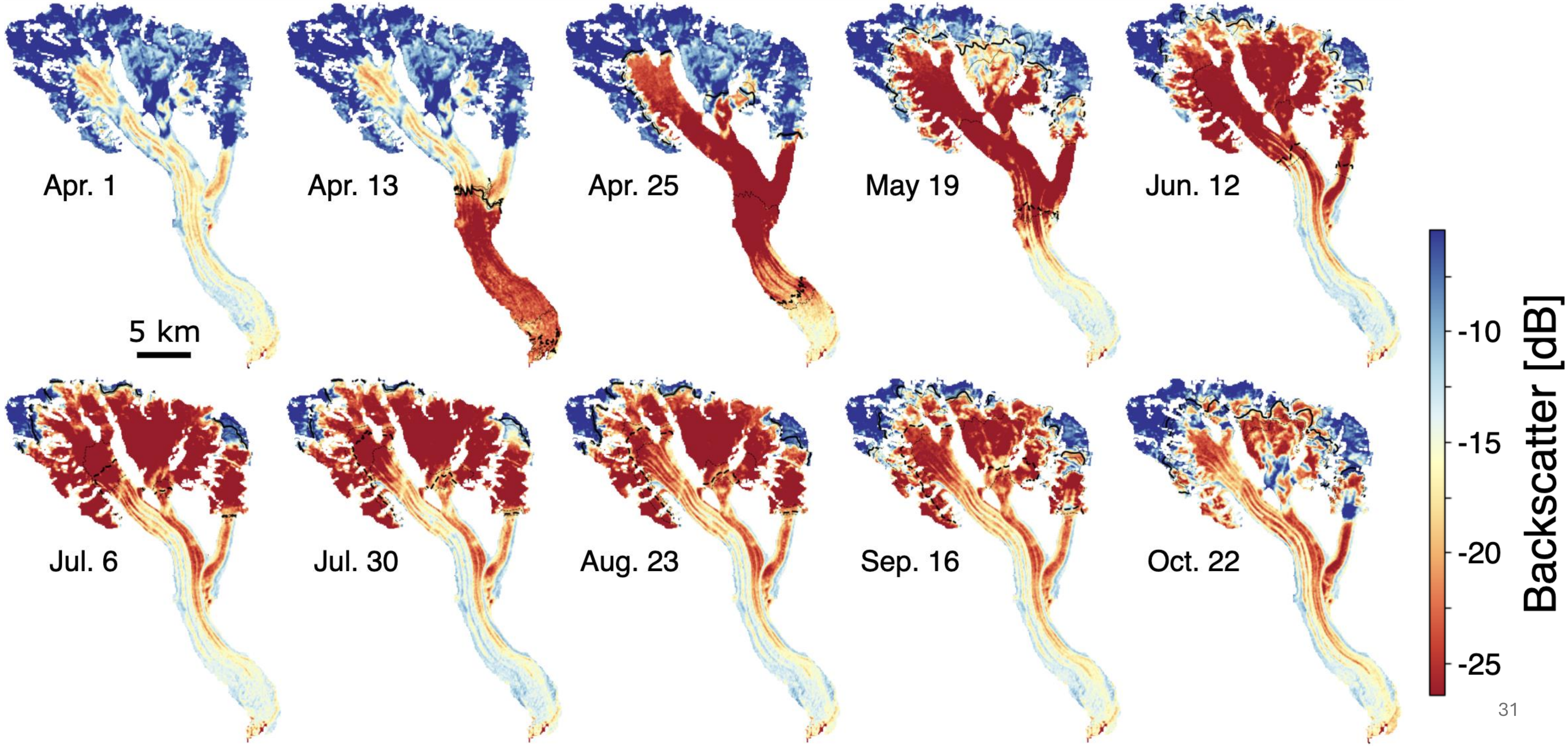
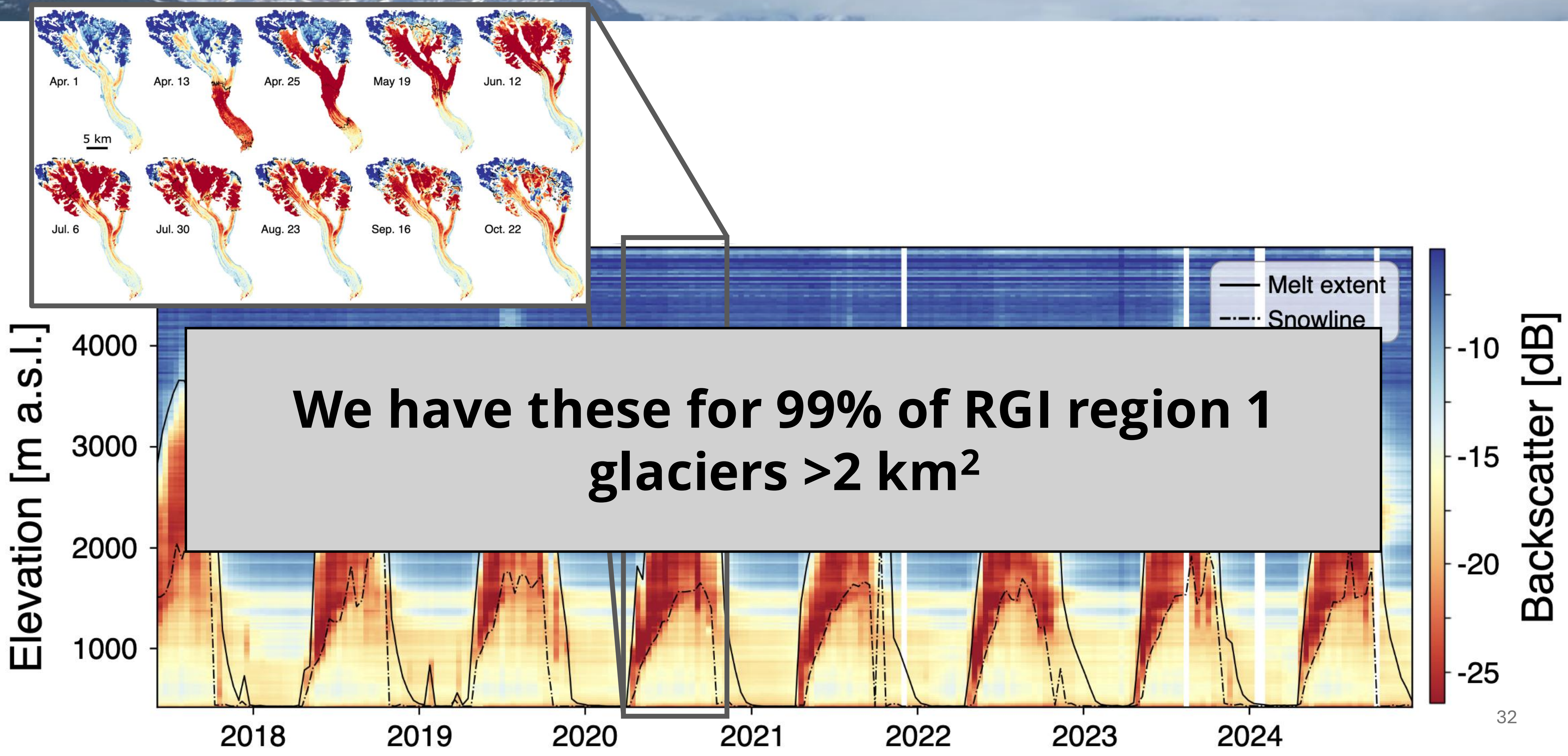


Spatially-distributed backscatter varies seasonally

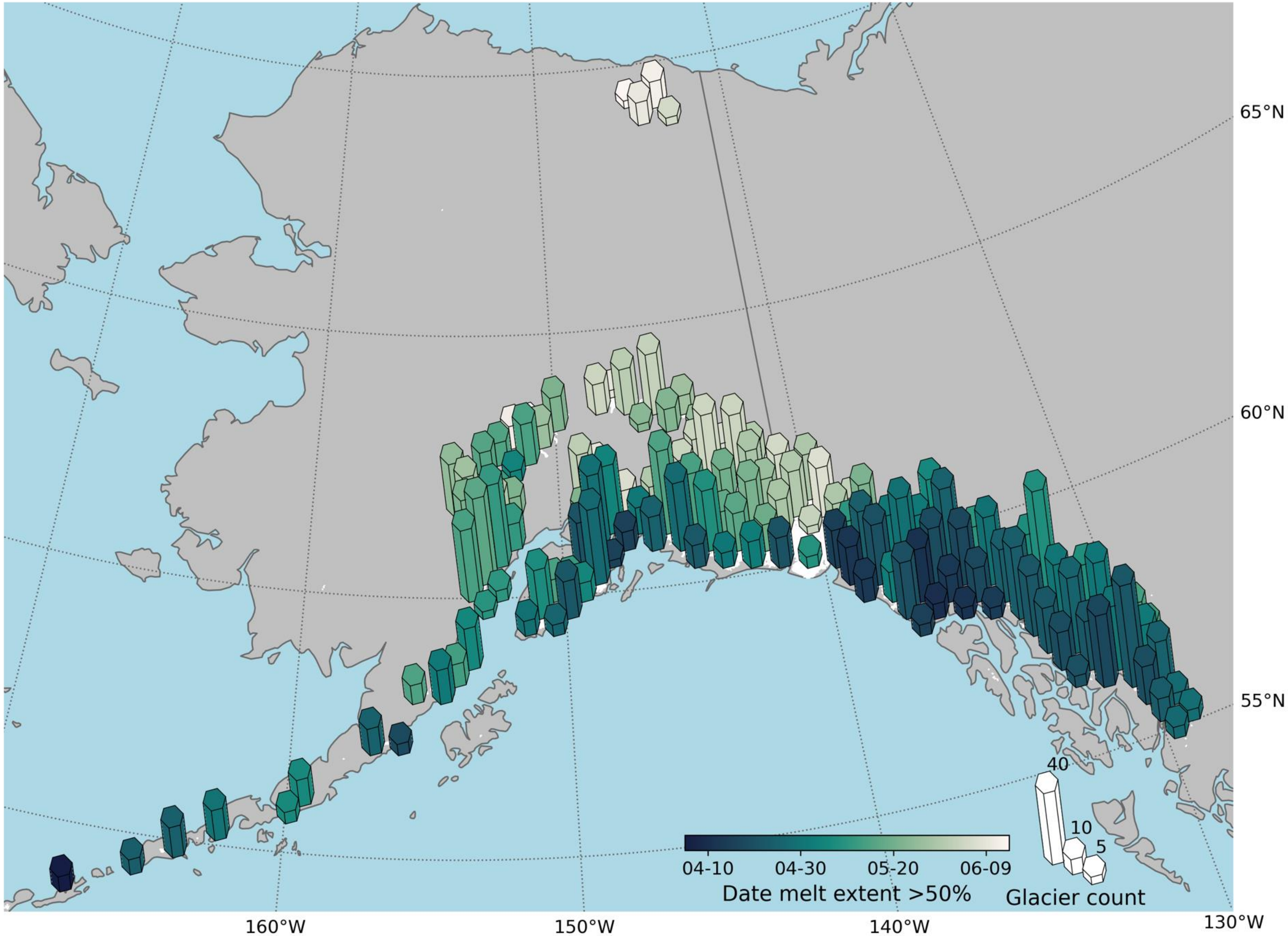


SAR automatically delineated melt and snowlines

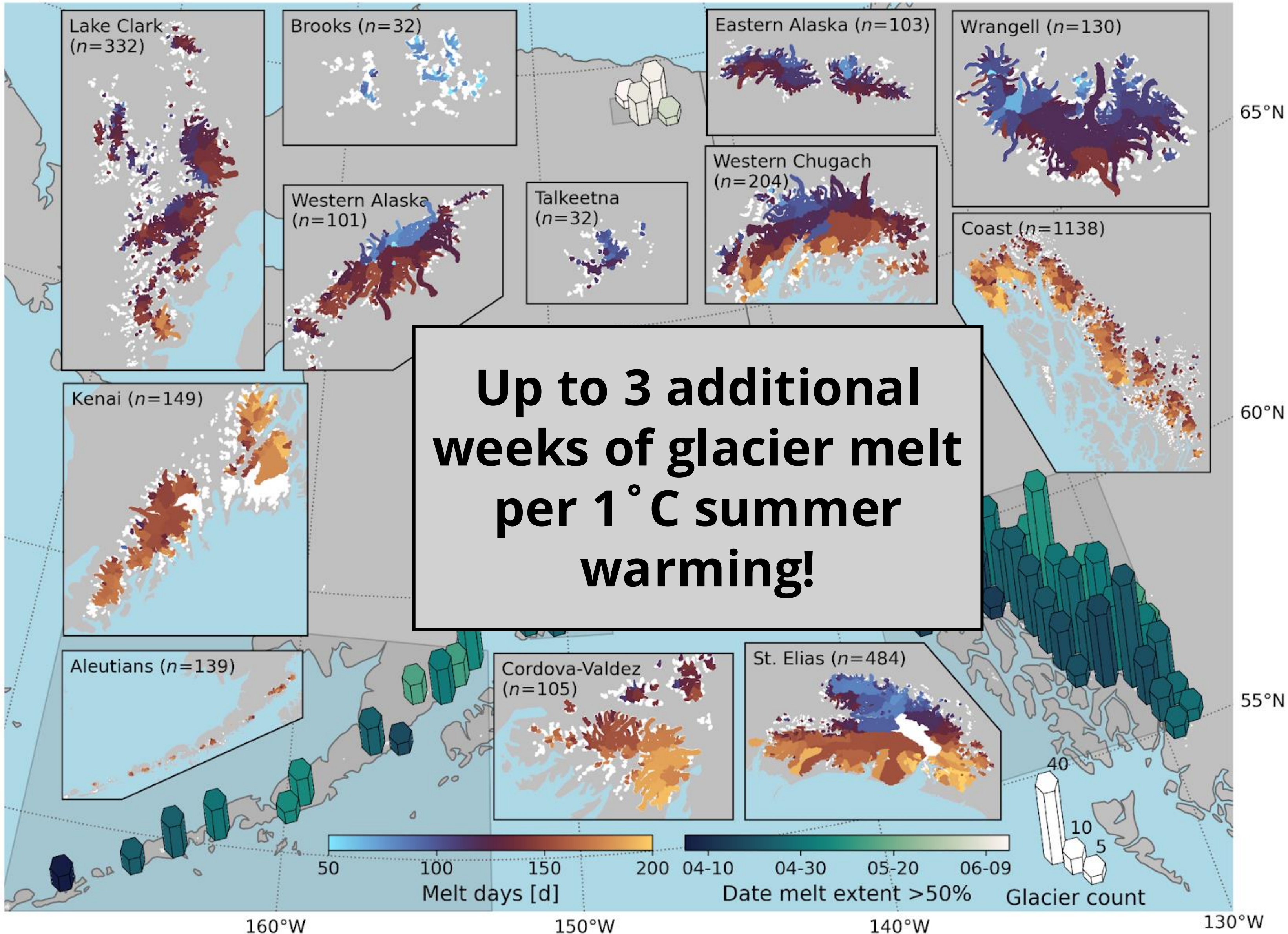


We have these for 99% of RGI region 1 glaciers >2 km^2

Melt varies greatly across mountain ranges

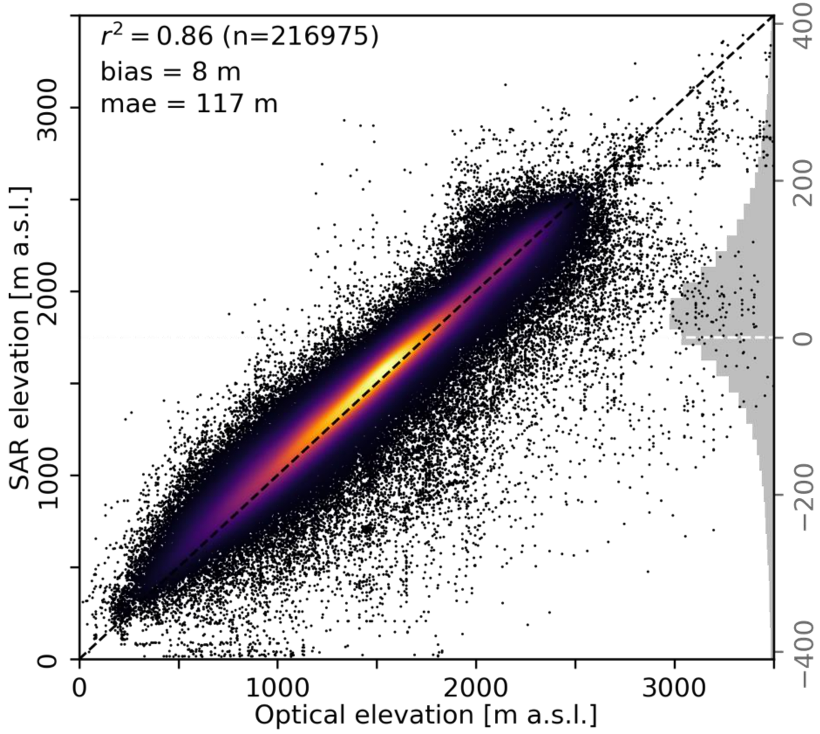


Melt varies greatly across mountain ranges

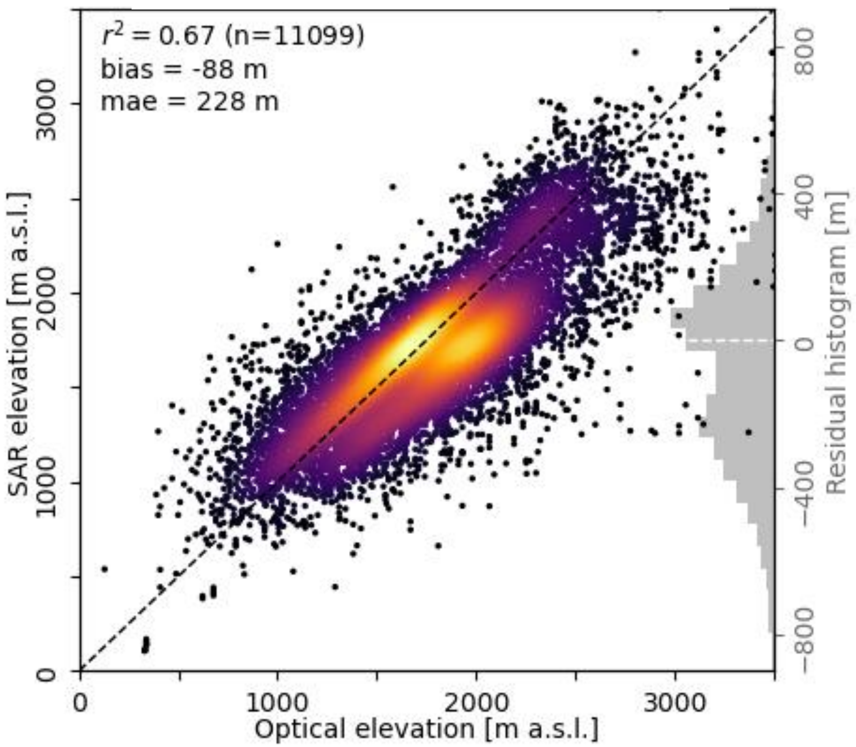


SAR snowlines are as accurate as optical

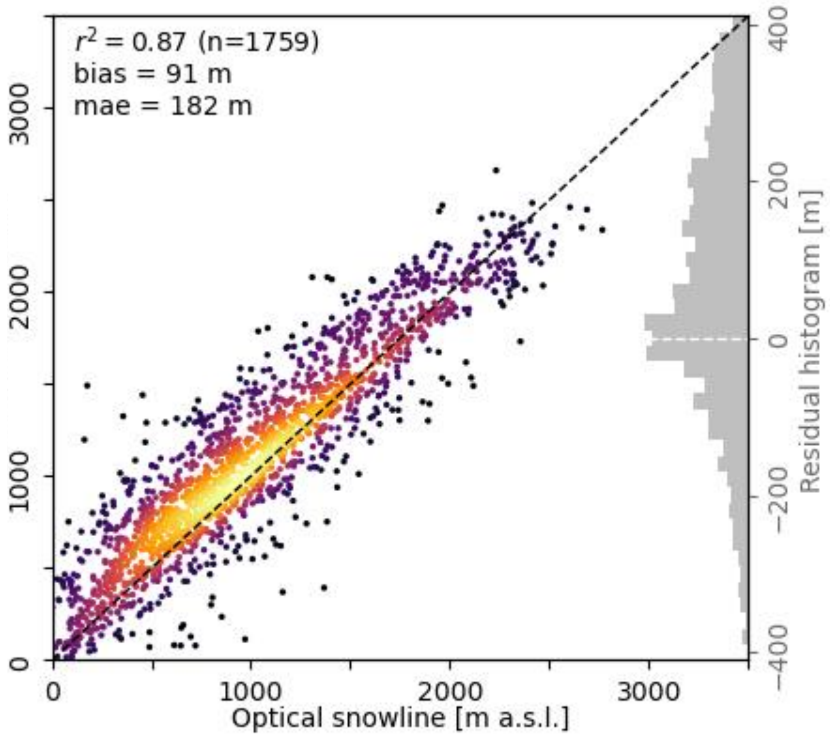
Bevington & Menounos, 2025
2017-2024



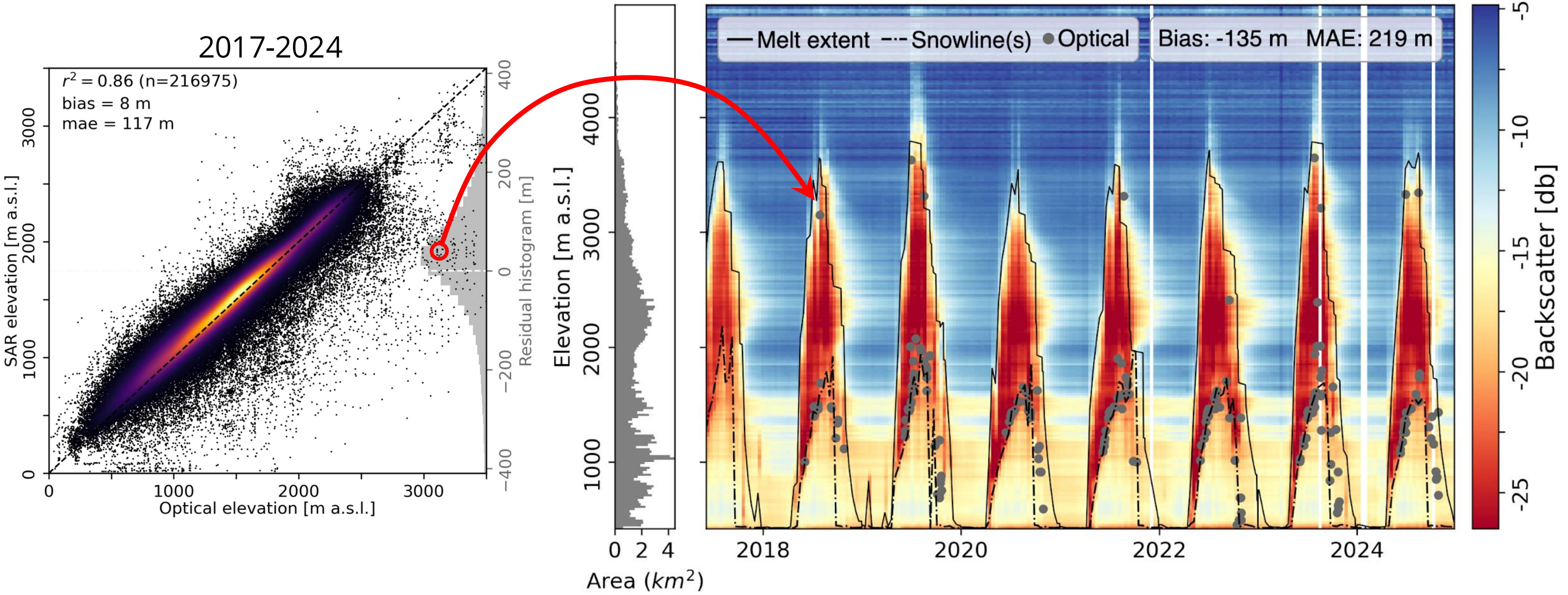
Zeller et al., 2025
2018-2022



Aberle et al., 2025
2017-2023

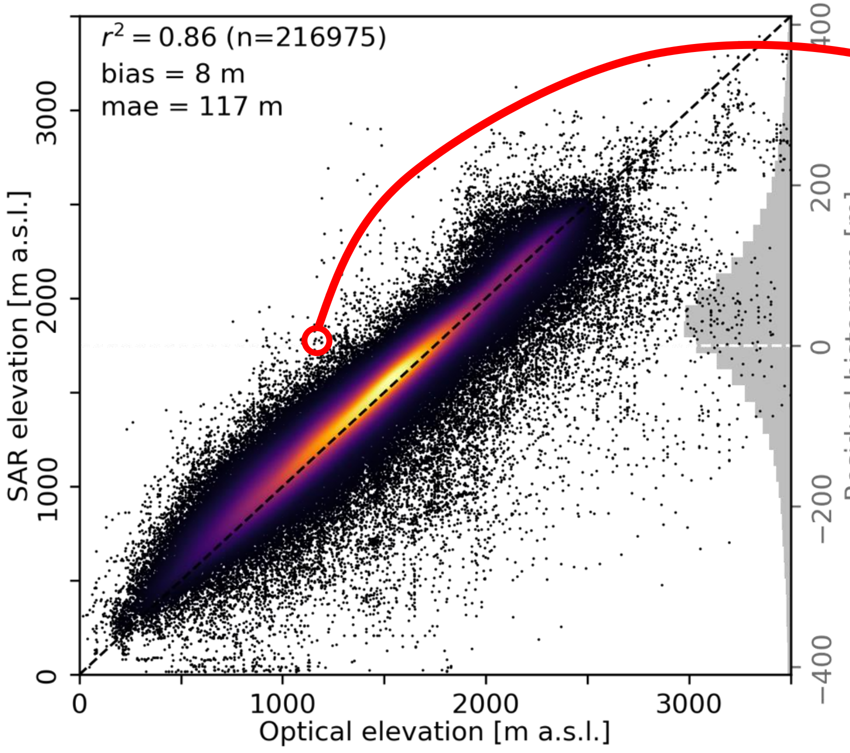


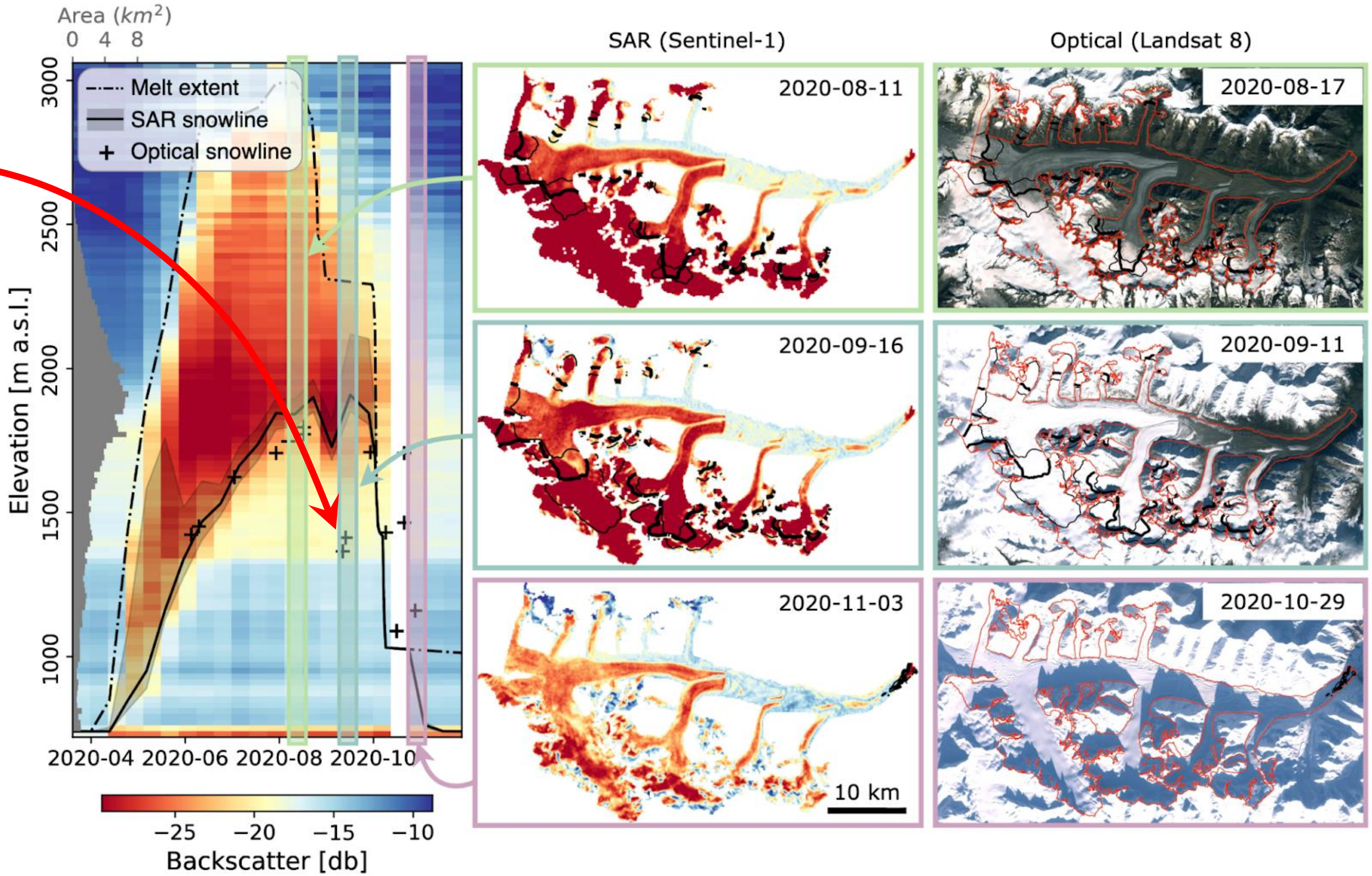
SAR snowlines are as accurate as optical datasets



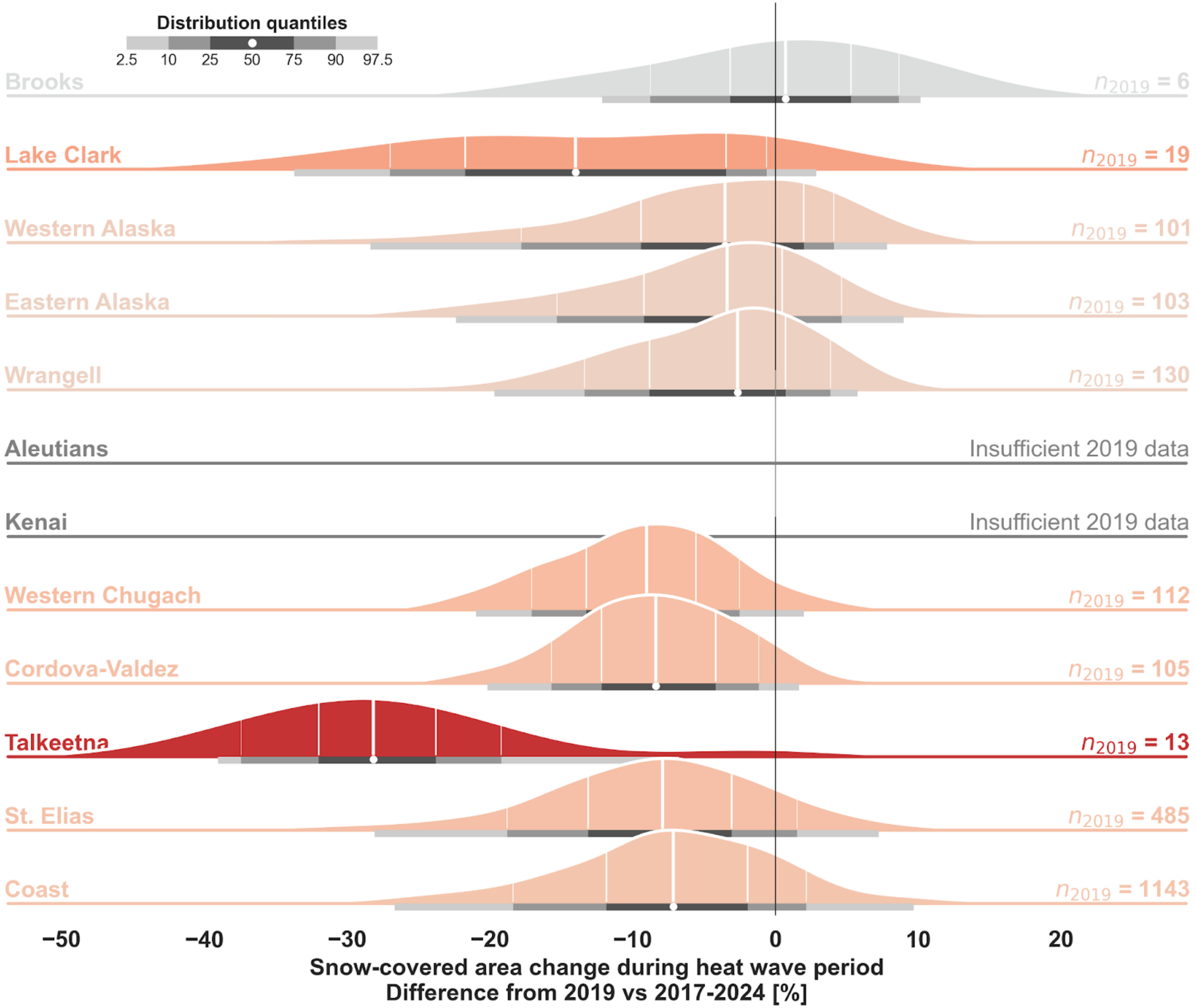
SAR snowlines are as accurate as optical datasets

2017-2024

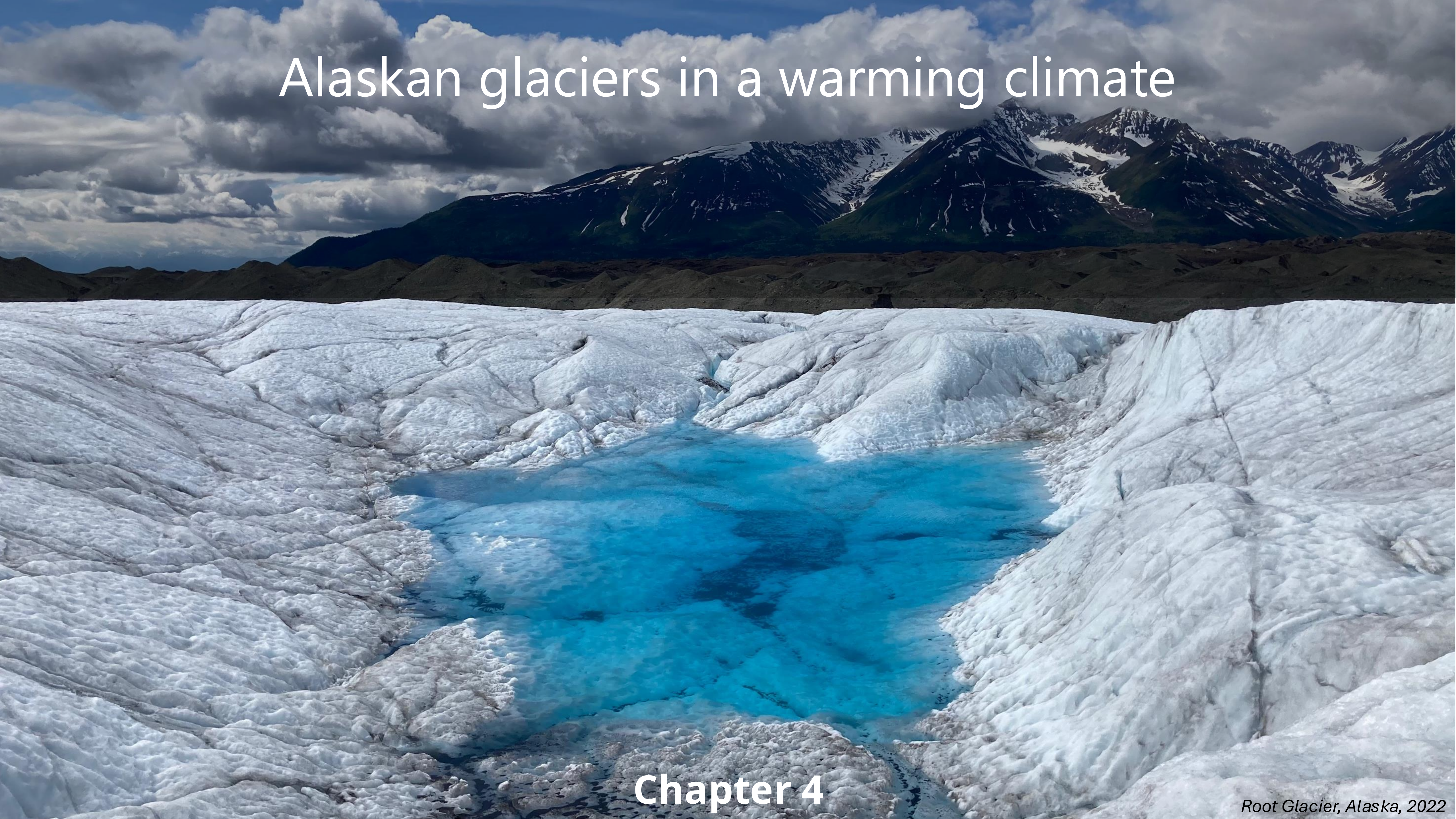




Impact of 2019 heat wave on snowline retreat



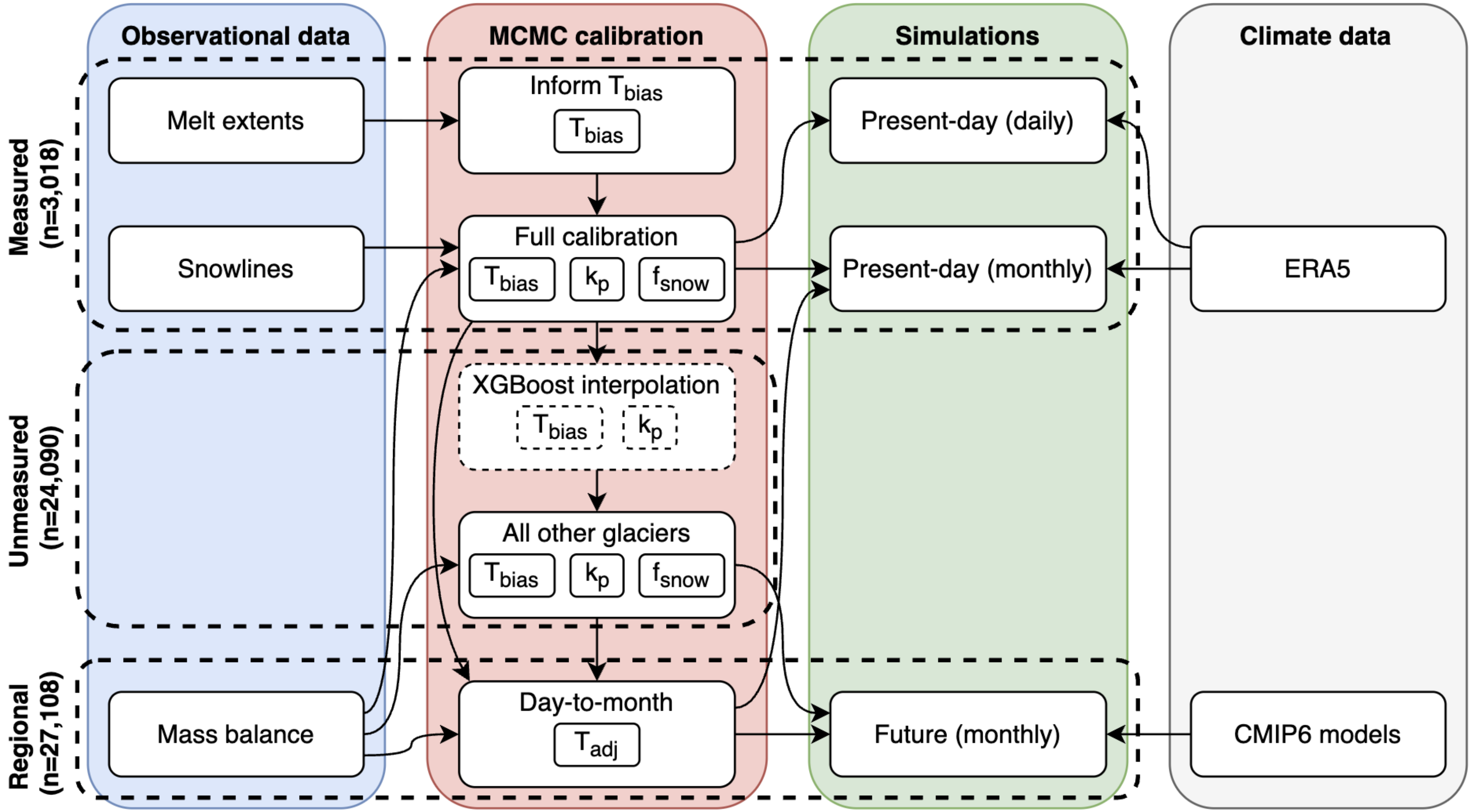
Alaskan glaciers in a warming climate



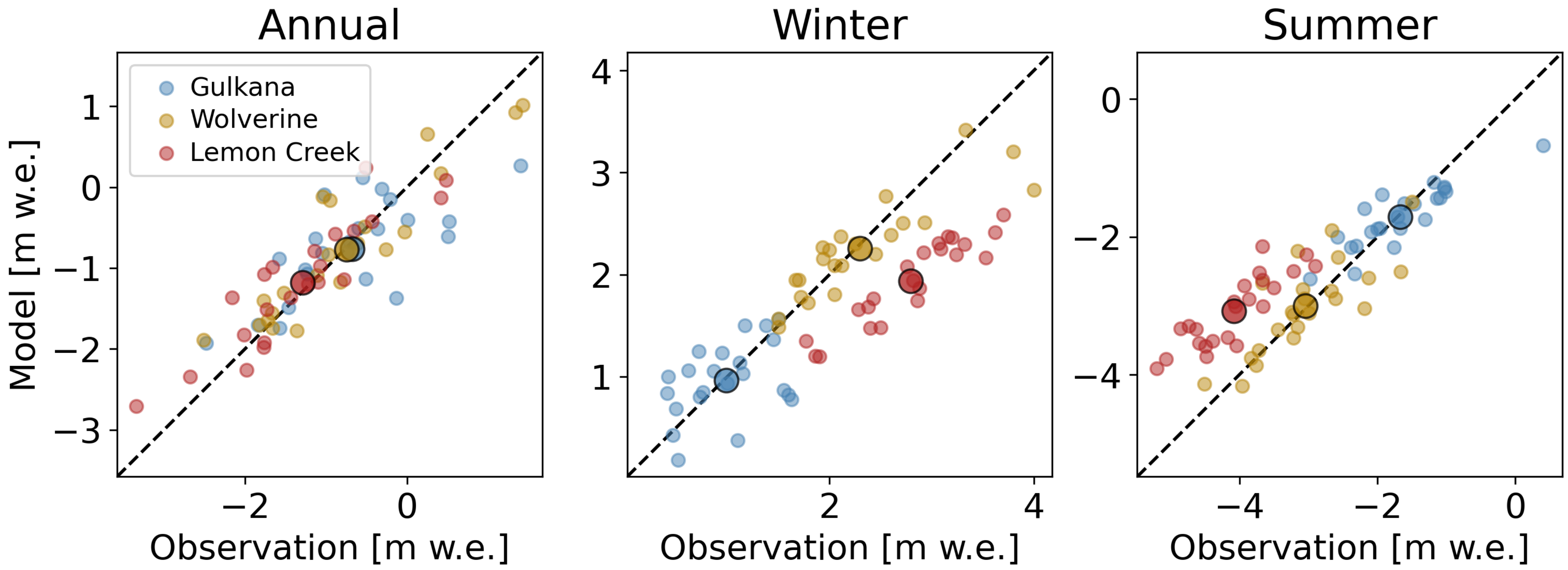
Chapter 4

Root Glacier, Alaska, 2022

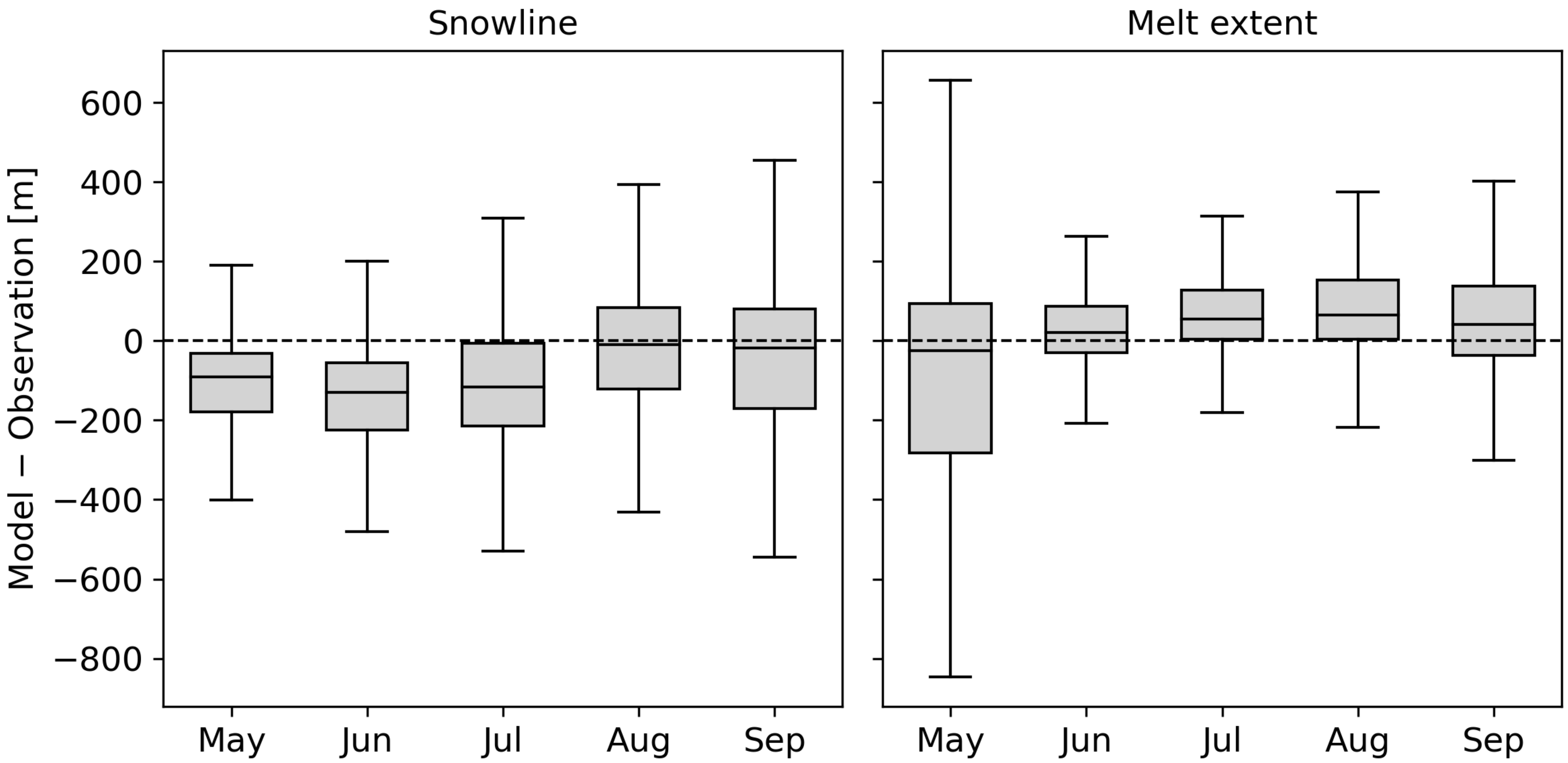
Models benefit from the integration of systematic observations



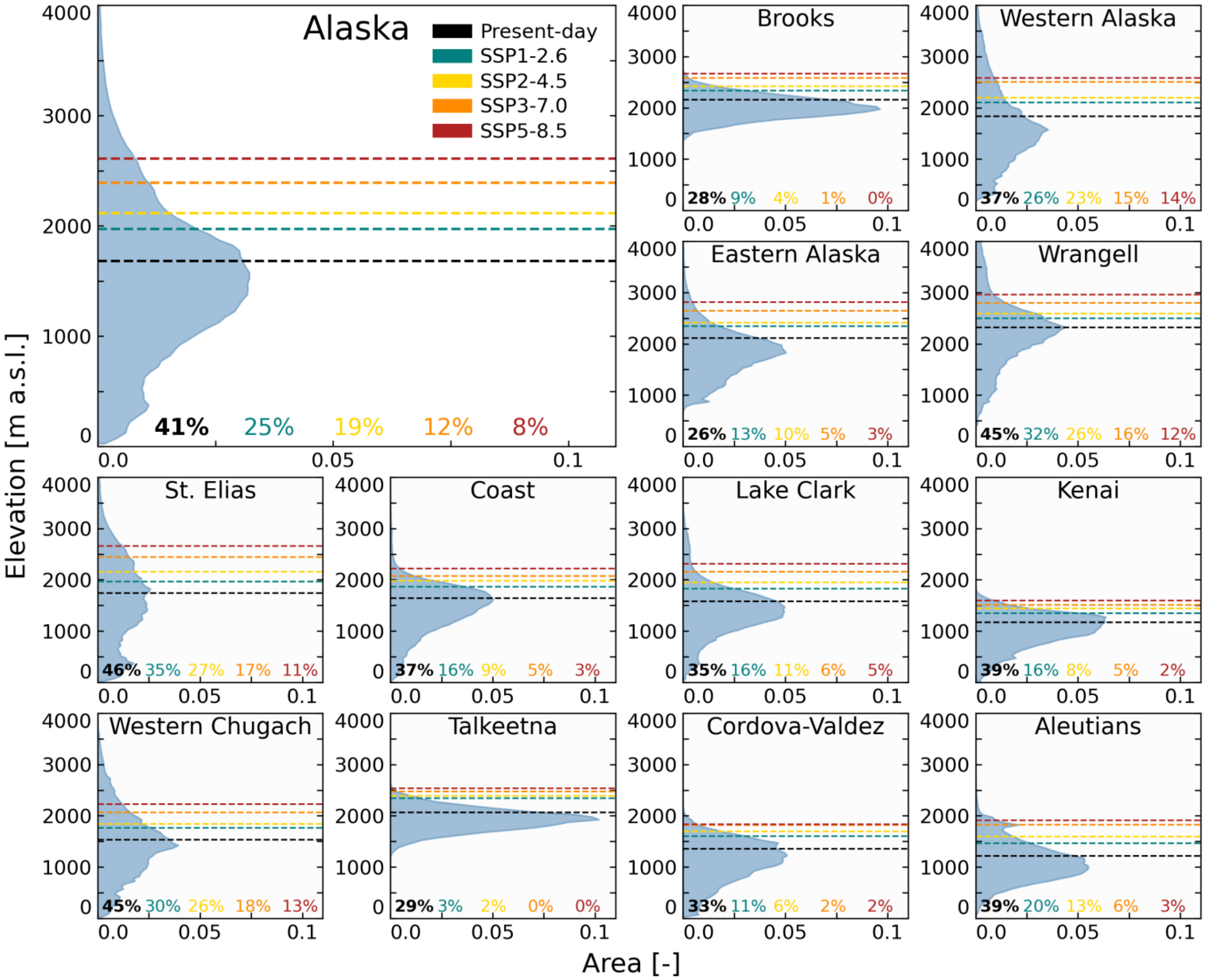
Model captures seasonal mass balances



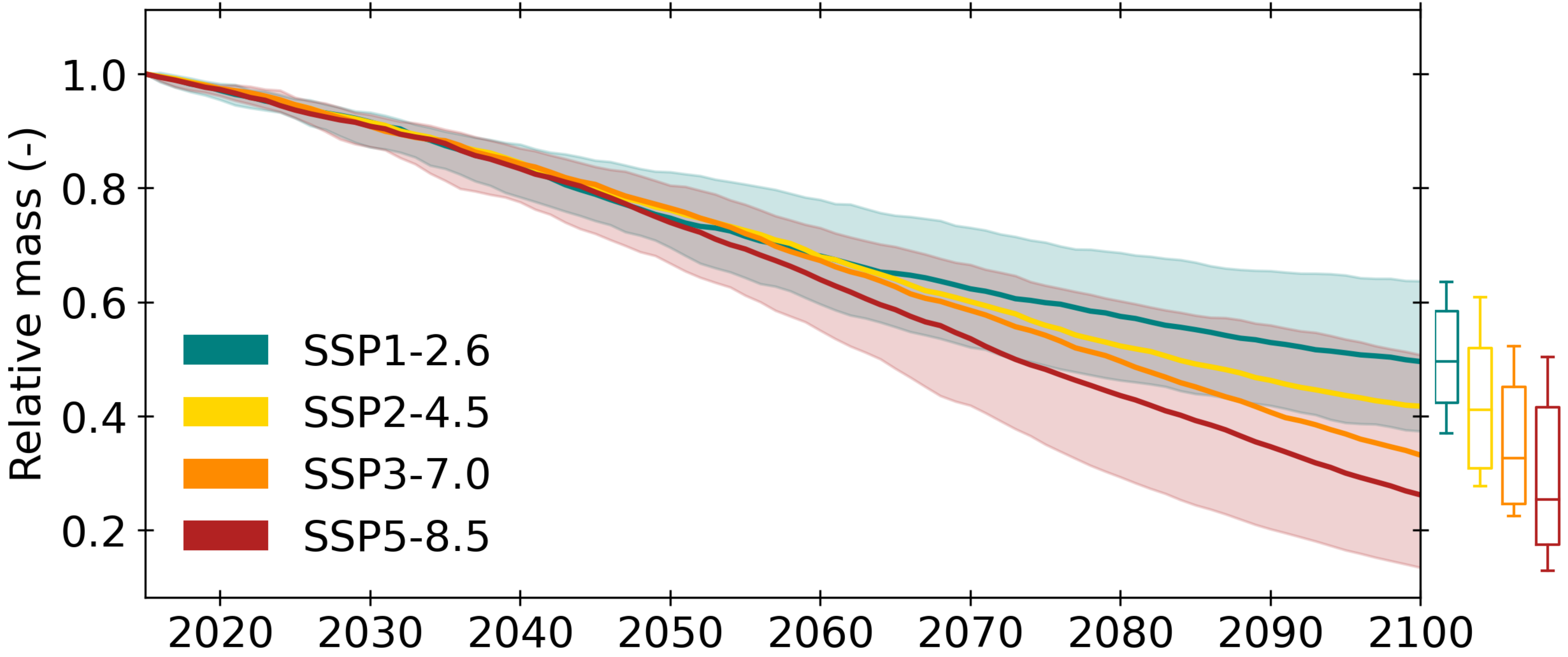
Models constrained by snowlines and melt extents show minimal bias



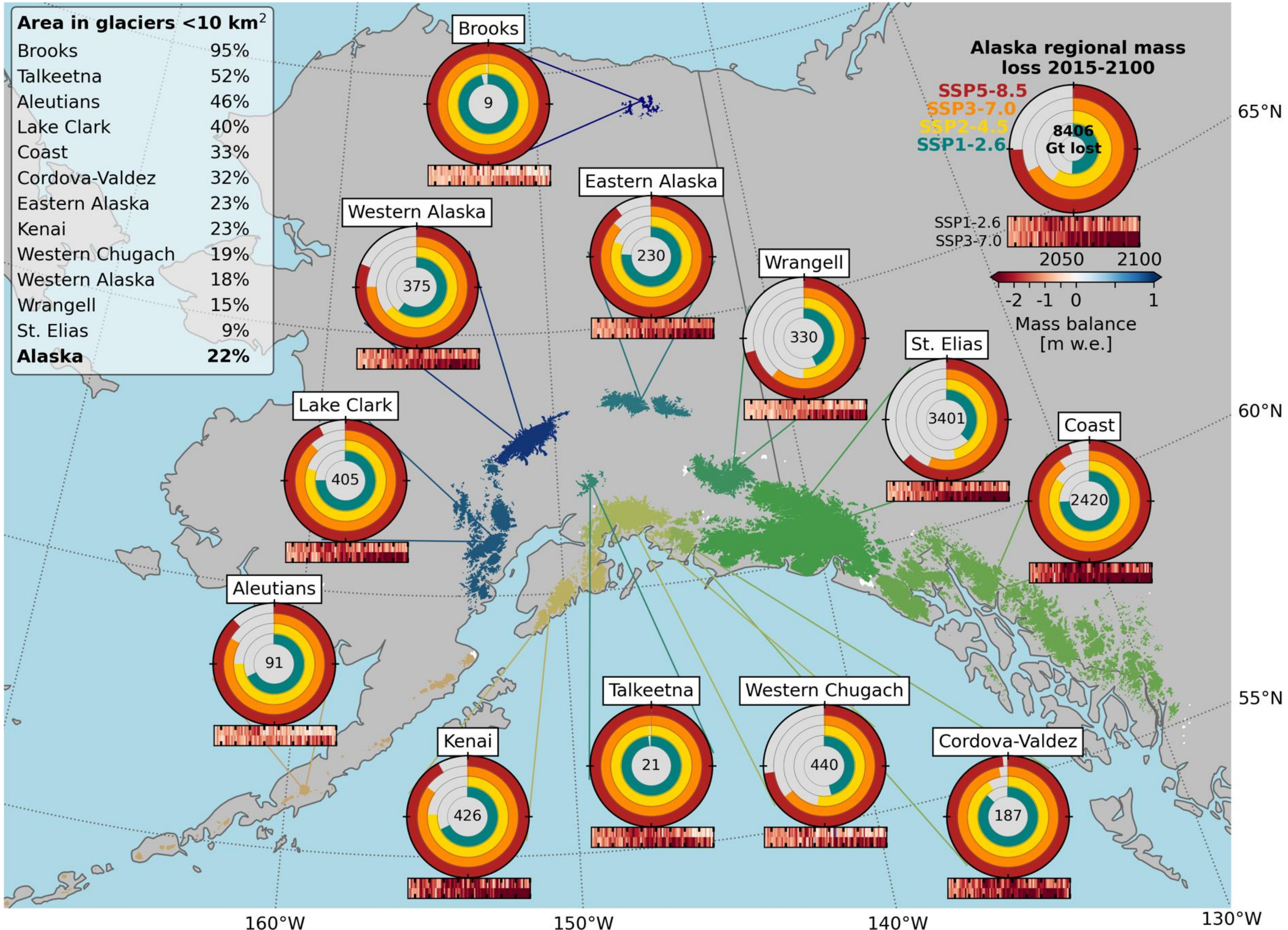
Subregions are vulnerable to rising equilibrium-line altitudes



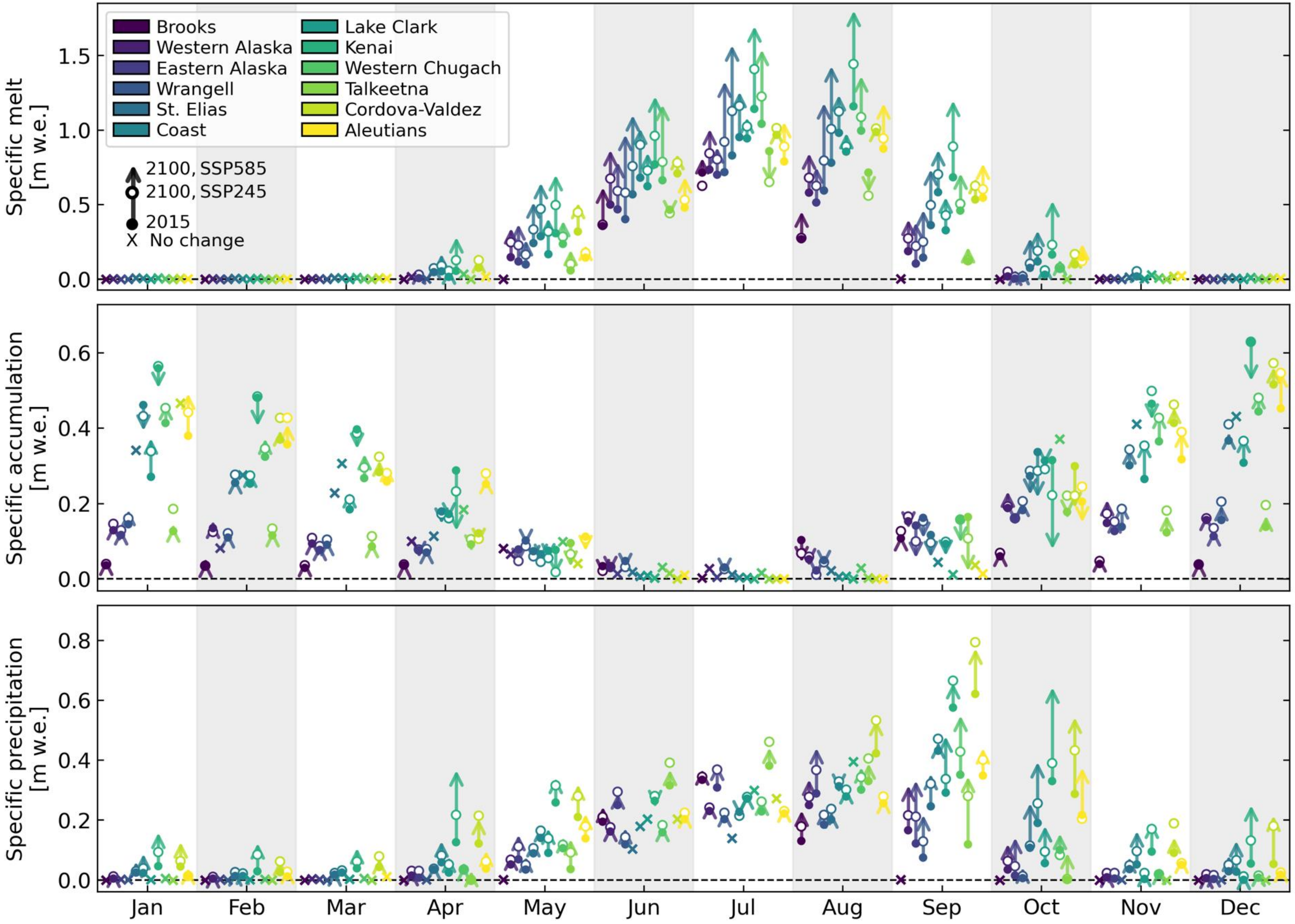
Alaska glaciers lose 50–75% of their mass by 2100



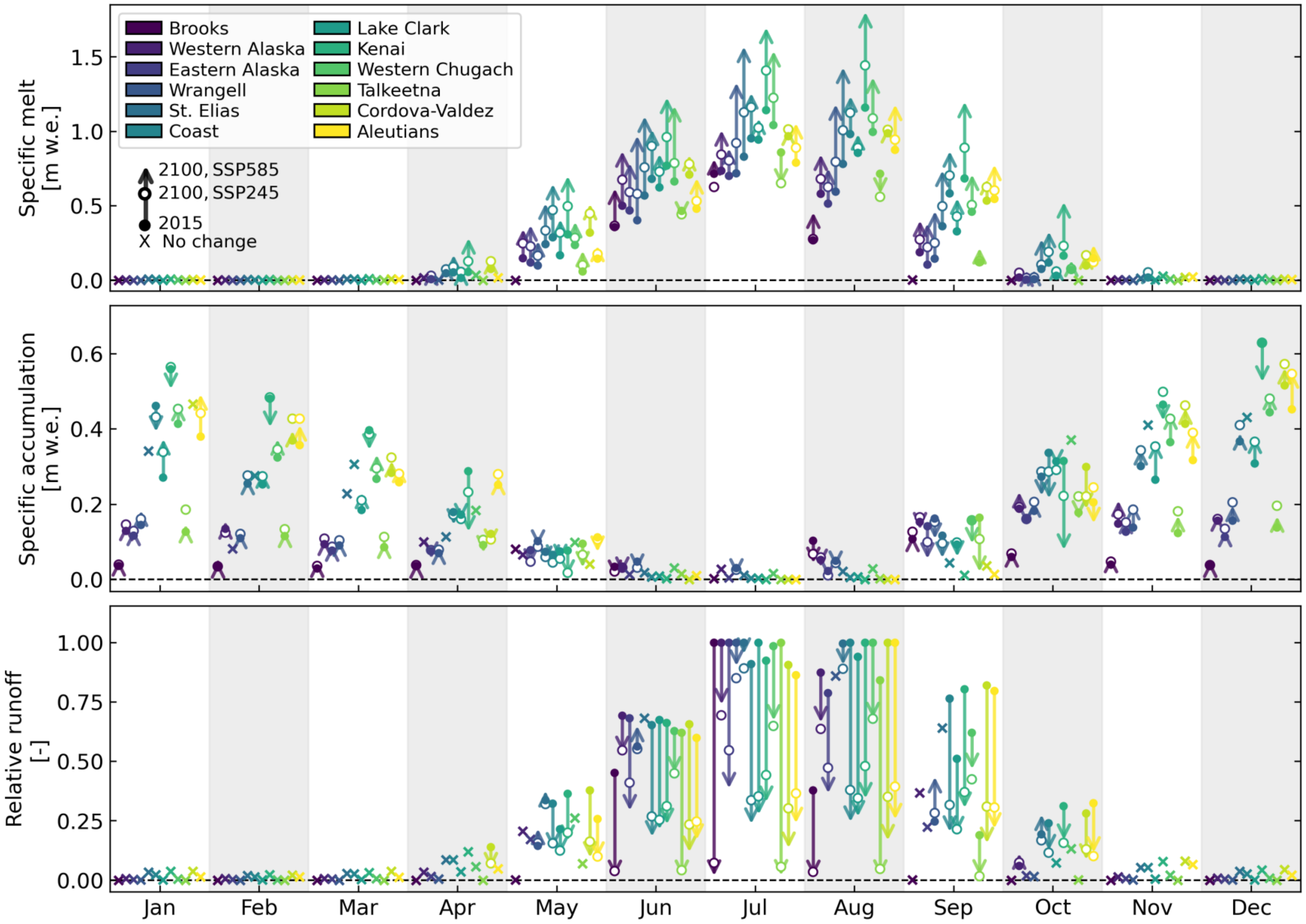
Some subregions projected to be completely deglaciated under high future emissions



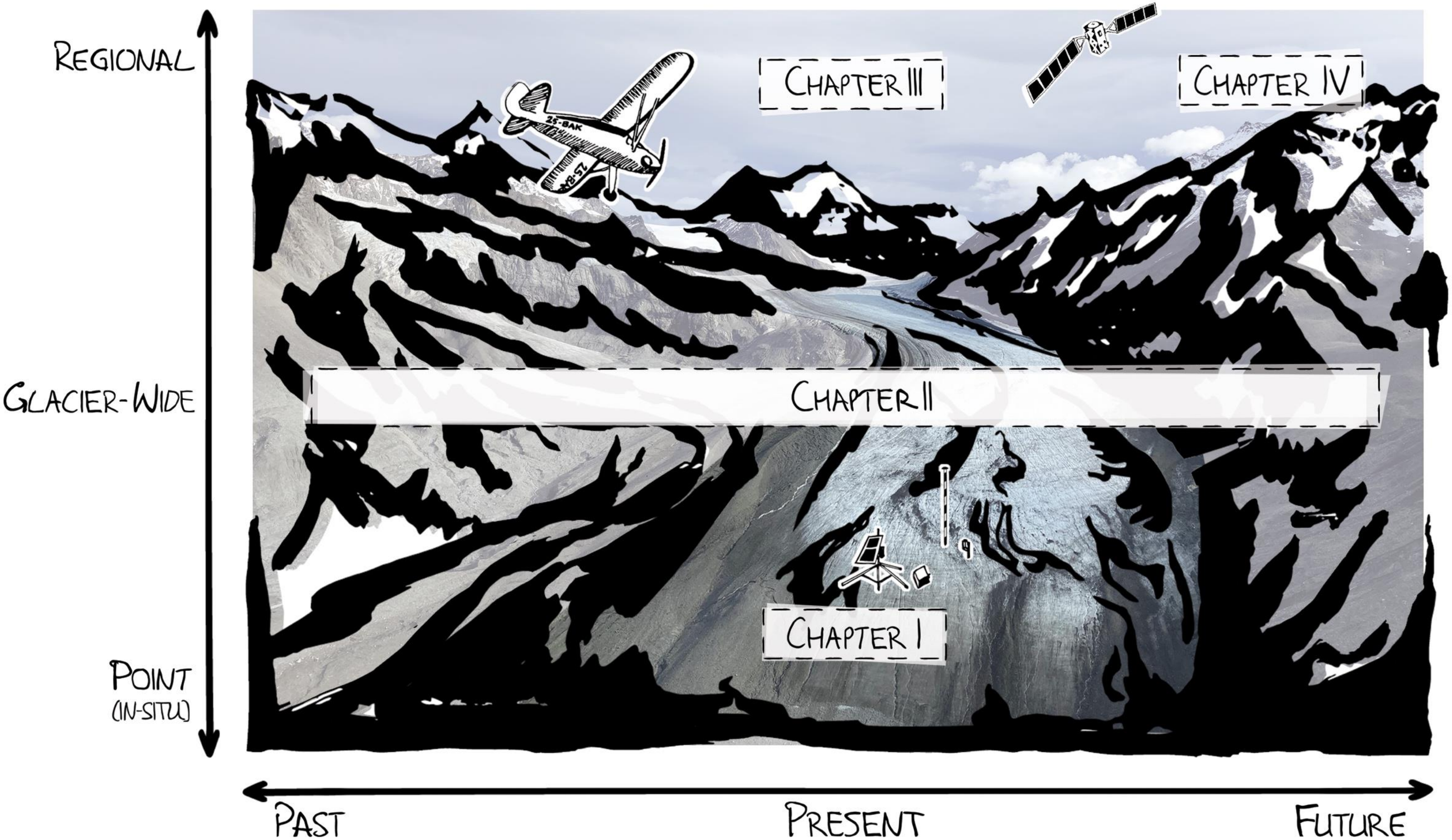
Mass loss driven by increased melt and shift from snow to rain in a warming climate



Mass loss driven by increased melt and shift from snow to rain in a warming climate



Understanding glacier change on spatial and temporal scales



Key conclusions

- Existing remote sensing products are insufficient for parsing glacier climatic mass balance
    - Subseasonal glacier dynamics necessitate contemporaneous measurements
    - Low-cost GNSS systems with GNSS-IR processing offer valuable constraints towards assess and addressing this challenge
- Historical data offers profound insights into ongoing and future glacier mass changes
    - Kennicott and Root glaciers were in near-equilibrium in 1957, but are rapidly losing mass today
    - We project these glaciers to lose 38–63% of their mass from 2000–2100
- Synthetic aperture radar (SAR) can measure transient melt extents and snowlines at regional scales
    - Alaskan glacier melt is correlated with temperature (1°C summer warming causes 3 additional weeks of melt)
    - Heatwaves have an outstanding impact on Alaskan glacier snowlines
- Global glacier evolution models are improved when calibrated with high-resolution data
    - Alaska is projected to lose 50–75% of its 2015 mass by 2100
    - Most susceptible subregions have large ice masses near present-day ELAs

Publications

- **Wells, A.,** Rounce, D., Sass, L., Florentine, C., Garbo, A., Baker, E., and McNeil, C. (2024) *GNSS reflectometry from low-cost sensors for continuous in situ contemporaneous glacier mass balance and flux divergence.* ***Journal of Glaciology*** 70, e5. doi:10.1017/jog.2024.54
- **Wells, A.**, Tober, B., Child, S., Rounce, D., Loso, M., Hults, C., Truffer, M., Holt, J., and Christoffersen, M. (2025) *An 85-year record of glacier change and impacts on future projections for Kennicott and Root Glaciers, Alaska.* ***Nature Communications*** 16, 7835. doi: 10.1038/s41467-025-62962-w
- **Wells, A.**, Rounce, D., and Fahnestock, M. (2026) *Seasonal progression of melt and snowlines in Alaska from SAR reveals impacts of warming.* ***npj Climate and Atmospheric Science***. doi: 10.1038/s41612-026-01321-y

Acknowledgments


Thank you!