Parsing glacier mass balance and flux divergence: challenges and implications of field measurements on remote sensing solutions

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Background

- Mountain glaciers are rapidly changing

- We can measure surface elevation change for all glaciers on Earth (e.g., Hugonnet et al. 2021, Jakob & Gourmelen 2023)

- ***We need to translate distributed elevation change observations into climatic mass balance observations that can constrain global glacier models***

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…

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

…so we need this…

Climatic Mass Balance

- Ablation stakes
- Snow pits

(in-situ)

Total Mass Balance

- DEM differencing

(remote sensing)

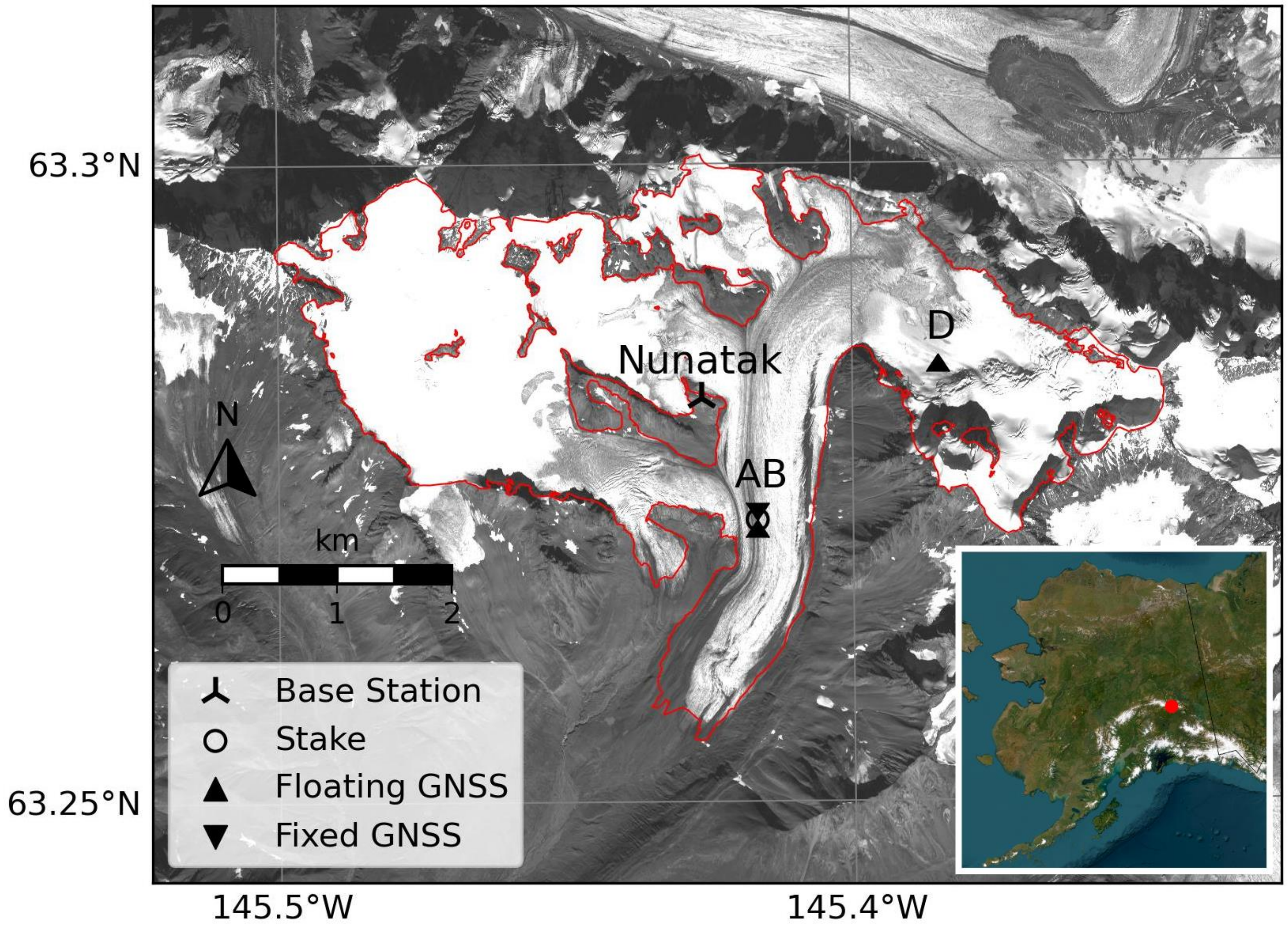
Flux Divergence

- Derived from ice thickness & velocity *(remote sensing)*
- Field methods? *(in-situ)*

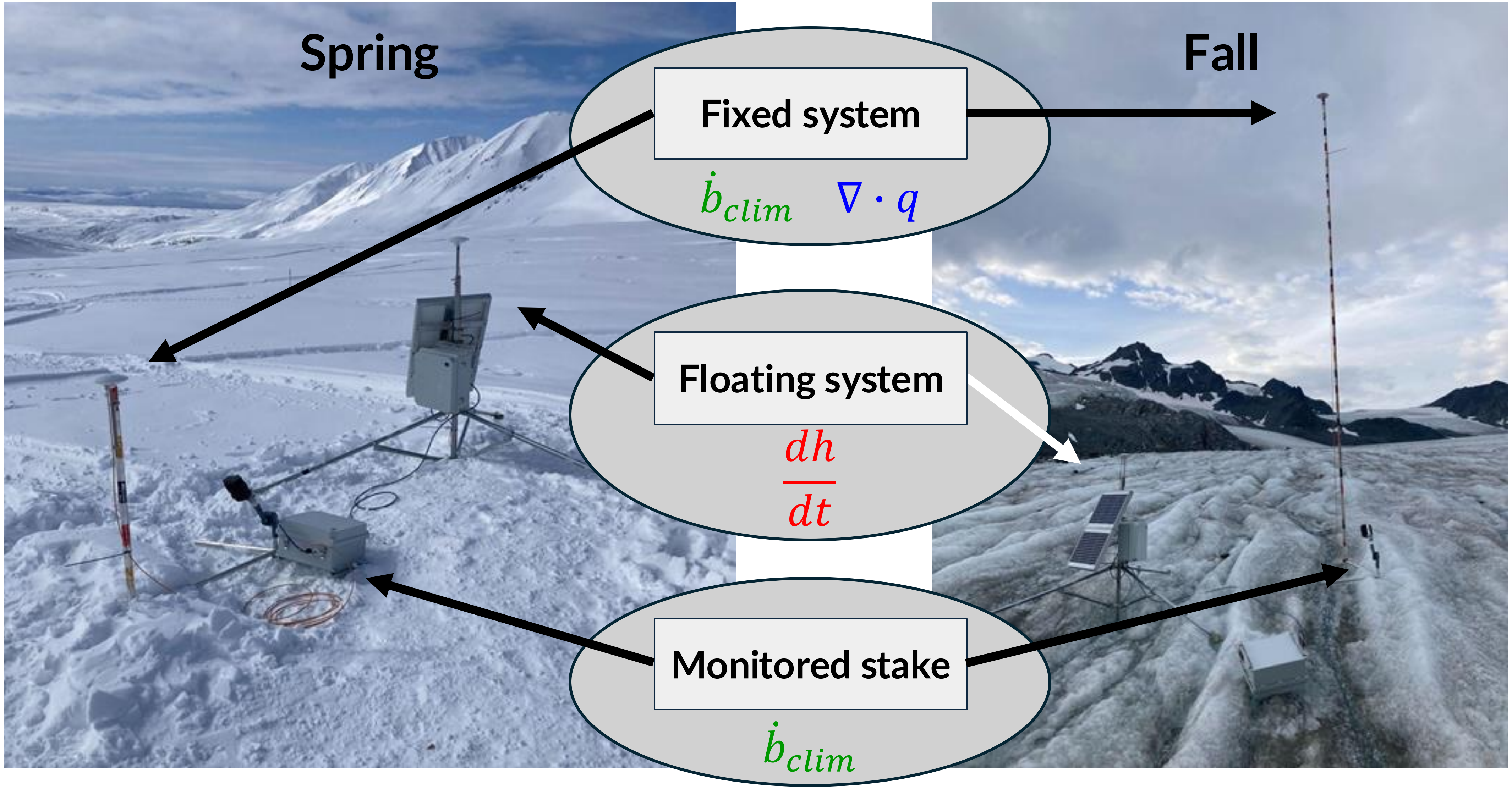
…for which ground-truth data is essential

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

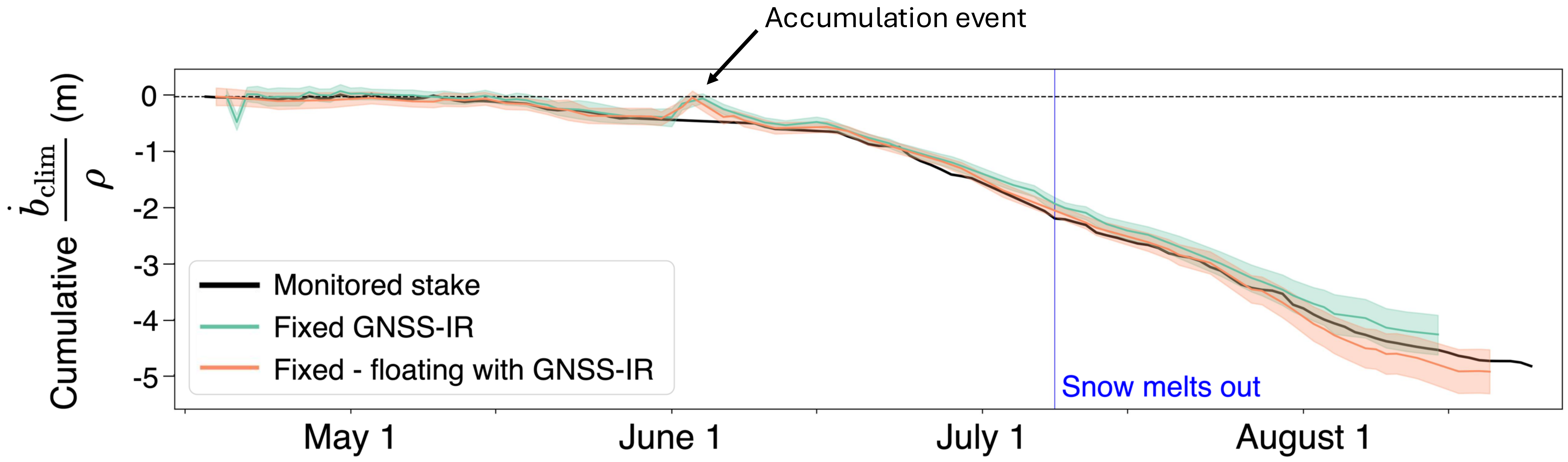
Equipment on Gulkana Glacier (Summer 2023)



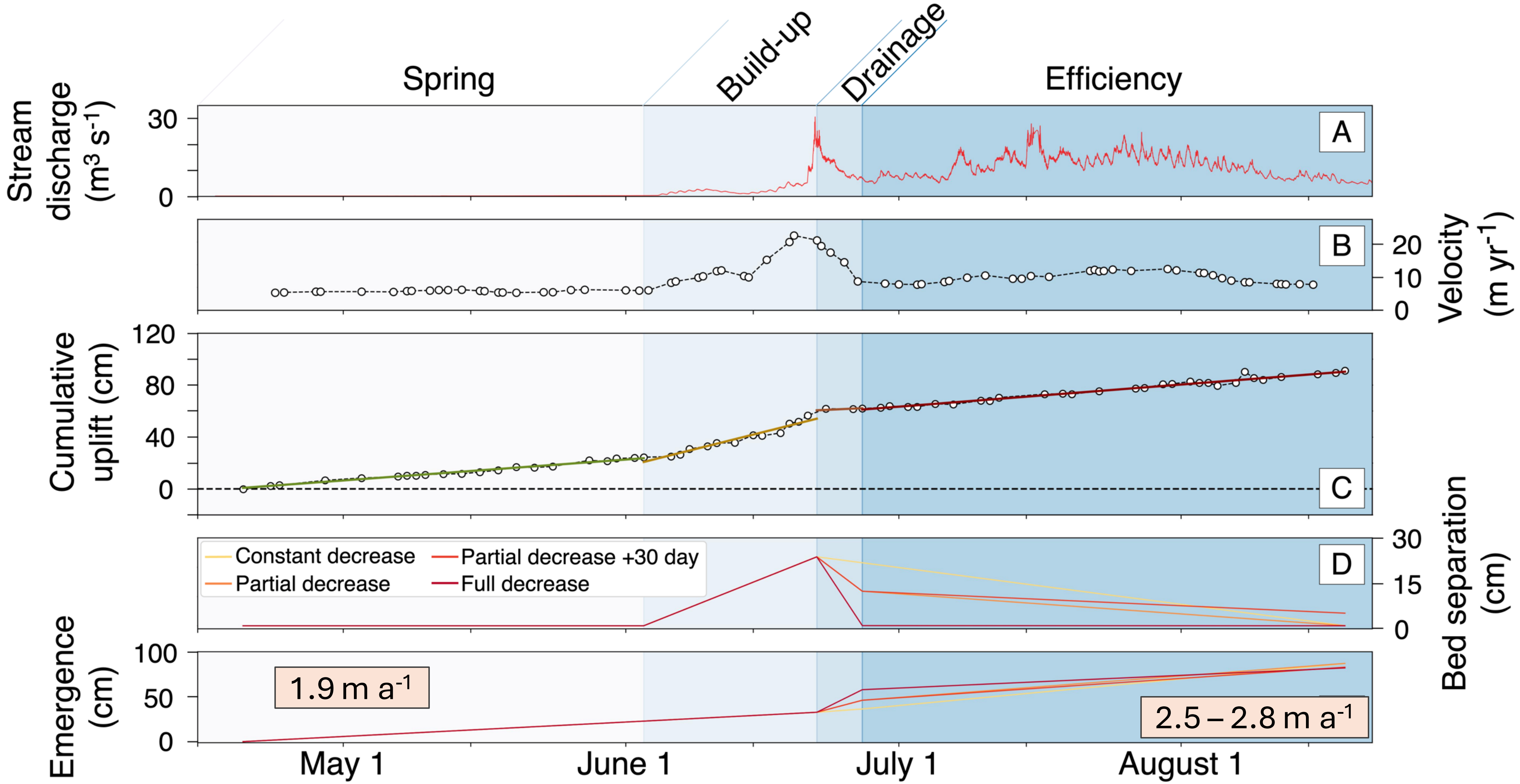
Field setup


Spring
Fall
Fixed system
$\dot{b}_{clim}$ $\nabla \cdot q$
Floating system
$\frac{dh}{dt}$
Monitored stake
$\dot{b}_{clim}$

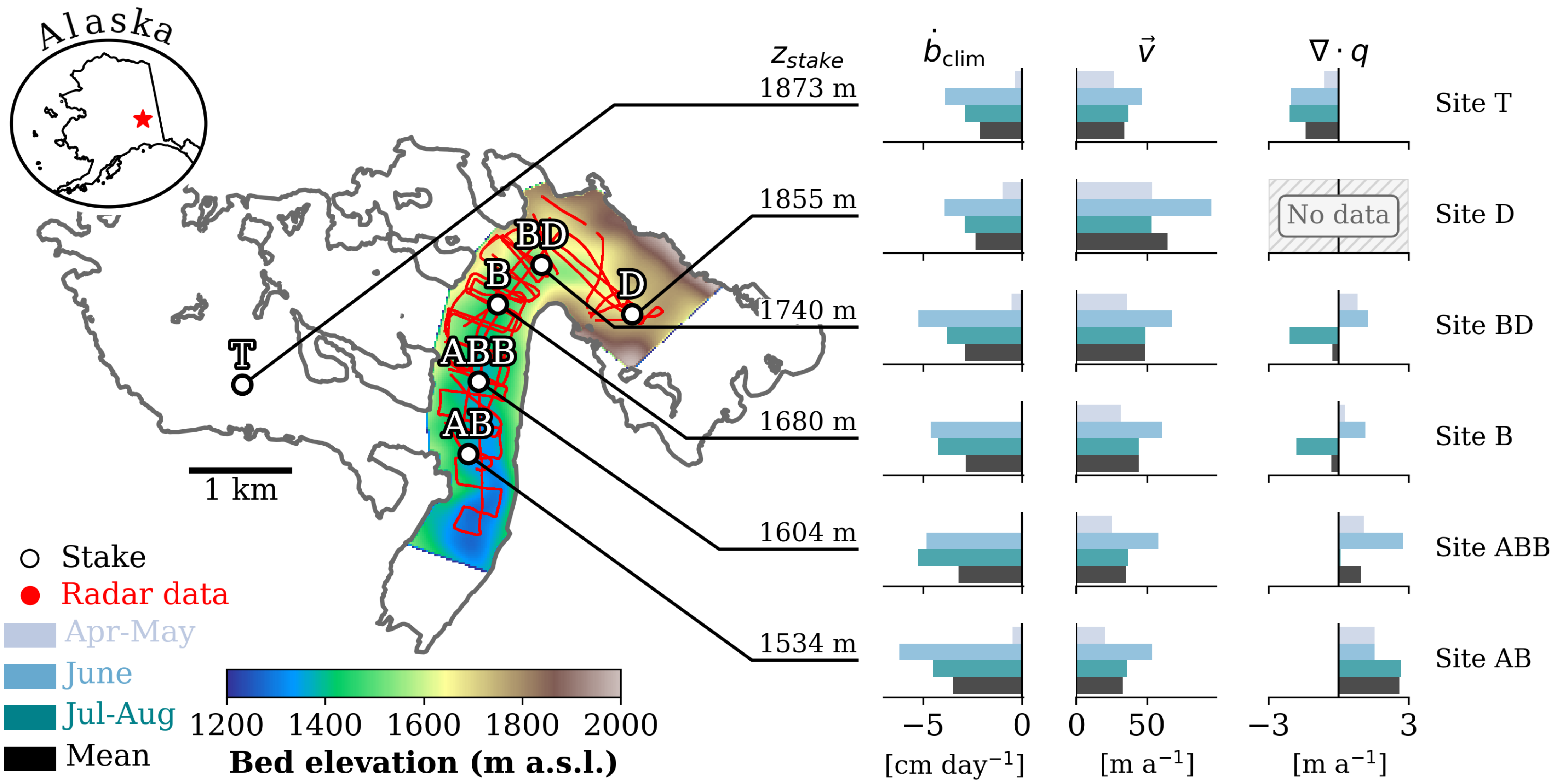
Mass balance: all methods



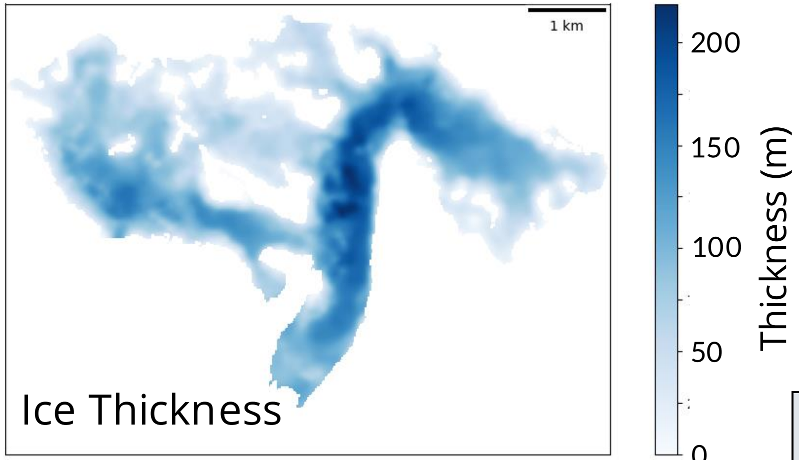
Flux divergence affected by ice-bed separation

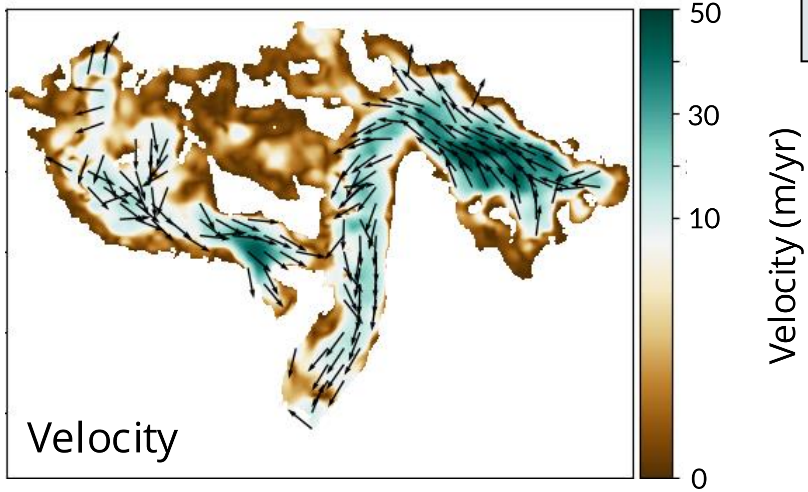


Expansive fixed GNSS network in 2024

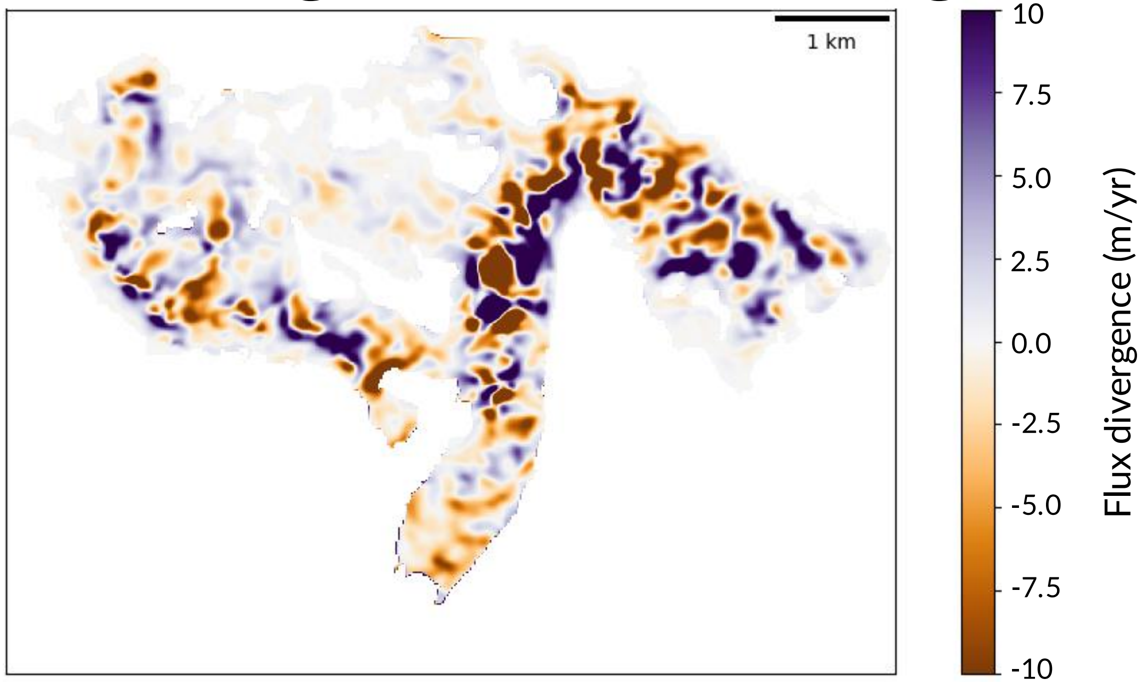


Remote sensing products are still far off





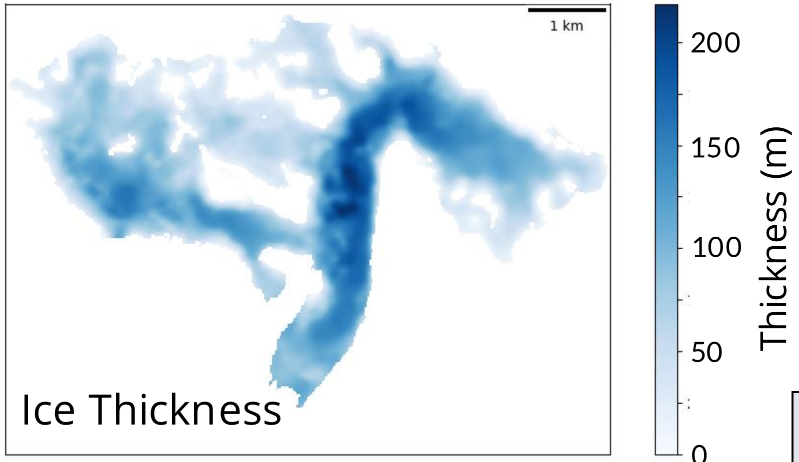
Flux divergence (no smoothing)

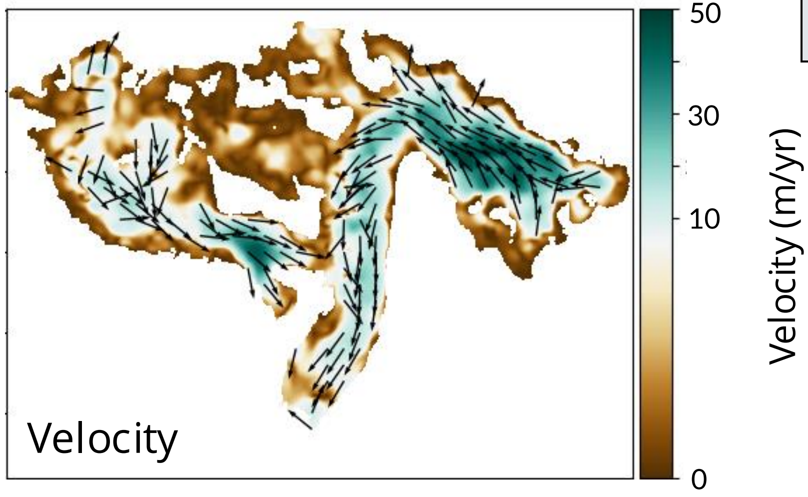


$$\nabla q = h \cdot \left(\frac{du_x}{dx} + \frac{du_y}{dy} \right) + u \cdot \left(\frac{dh}{dx} + \frac{dh}{dy} \right)$$

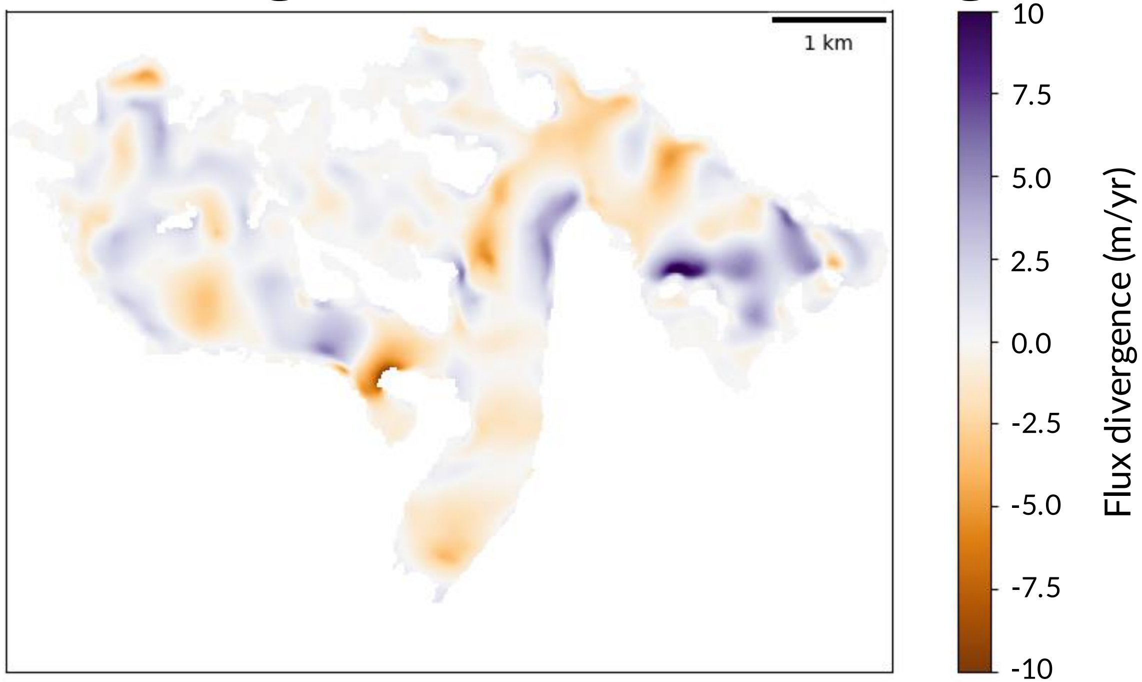
Millan et al. 2022, *Nat. Geosci.*

Remote sensing products are still far off





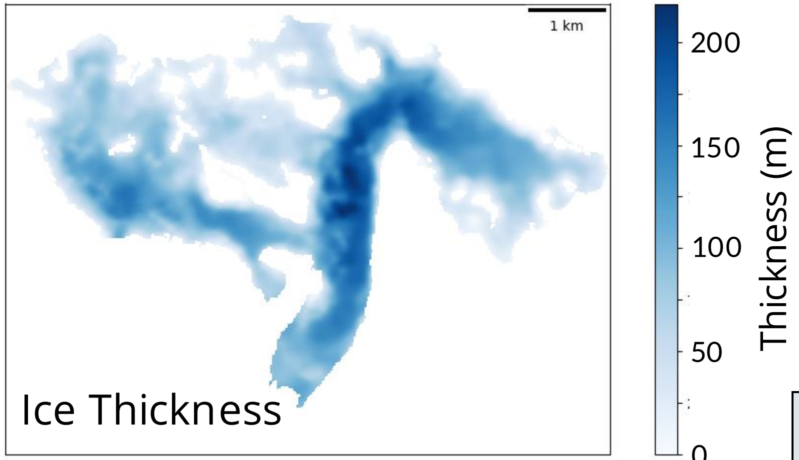
Flux divergence (with smoothing)

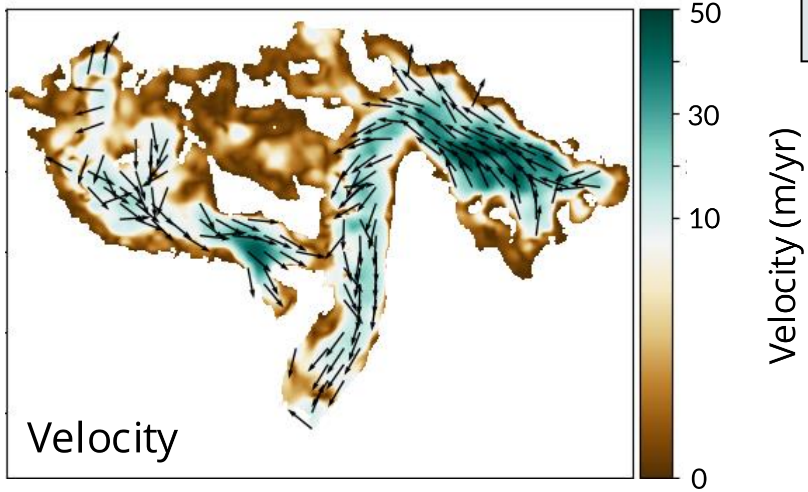


$$\nabla q = h \cdot \left(\frac{du_x}{dx} + \frac{du_y}{dy} \right) + u \cdot \left(\frac{dh}{dx} + \frac{dh}{dy} \right)$$

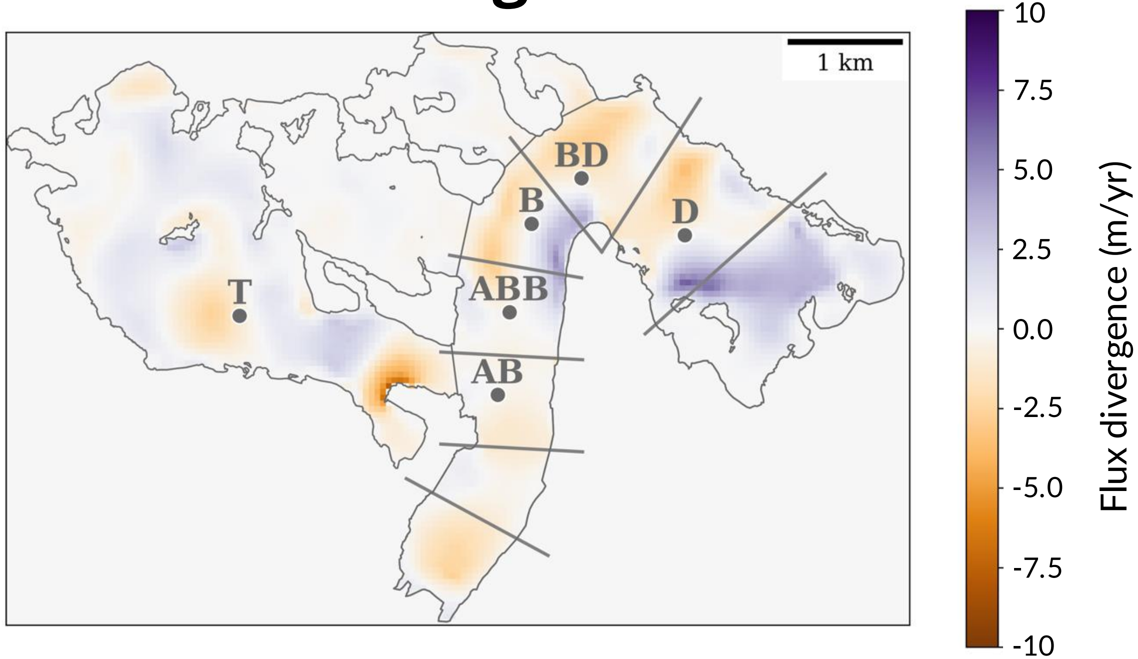
Millan et al. 2022, *Nat. Geosci.*

Remote sensing products are still far off

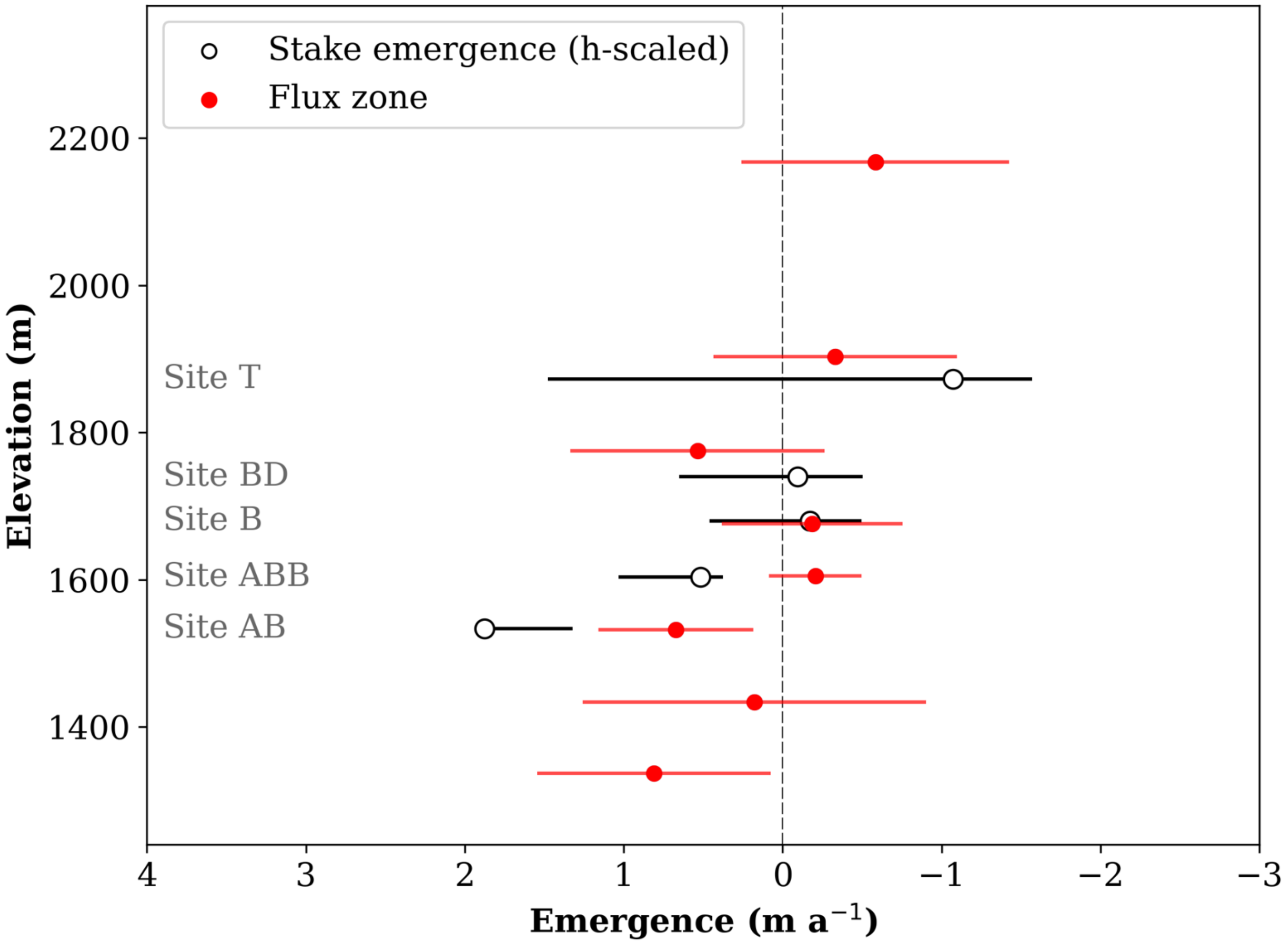




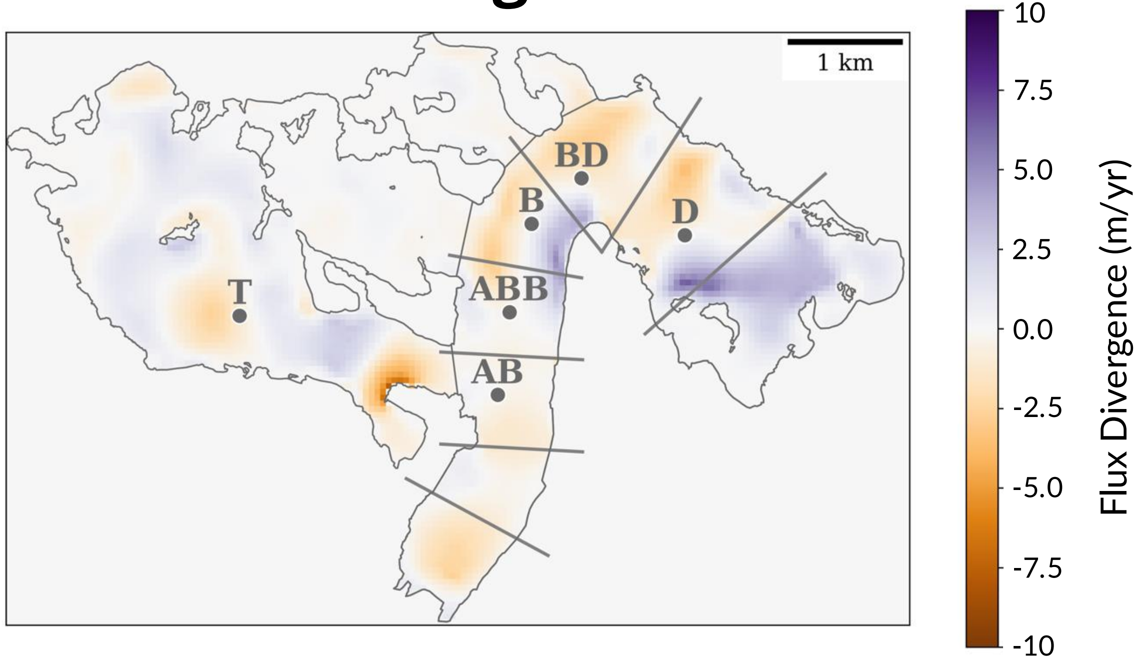
Flux gate



Remote sensing products are still far off



Flux gate



Takeaways

- A fixed GNSS system with a monitored ablation stake accurately derives all elements of the continuity equation
- Sub-seasonal changes in flux divergence complicate the problem: requires contemporaneous data
- Remote sensing data products are insufficient on Gulkana Glacier

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Next Steps

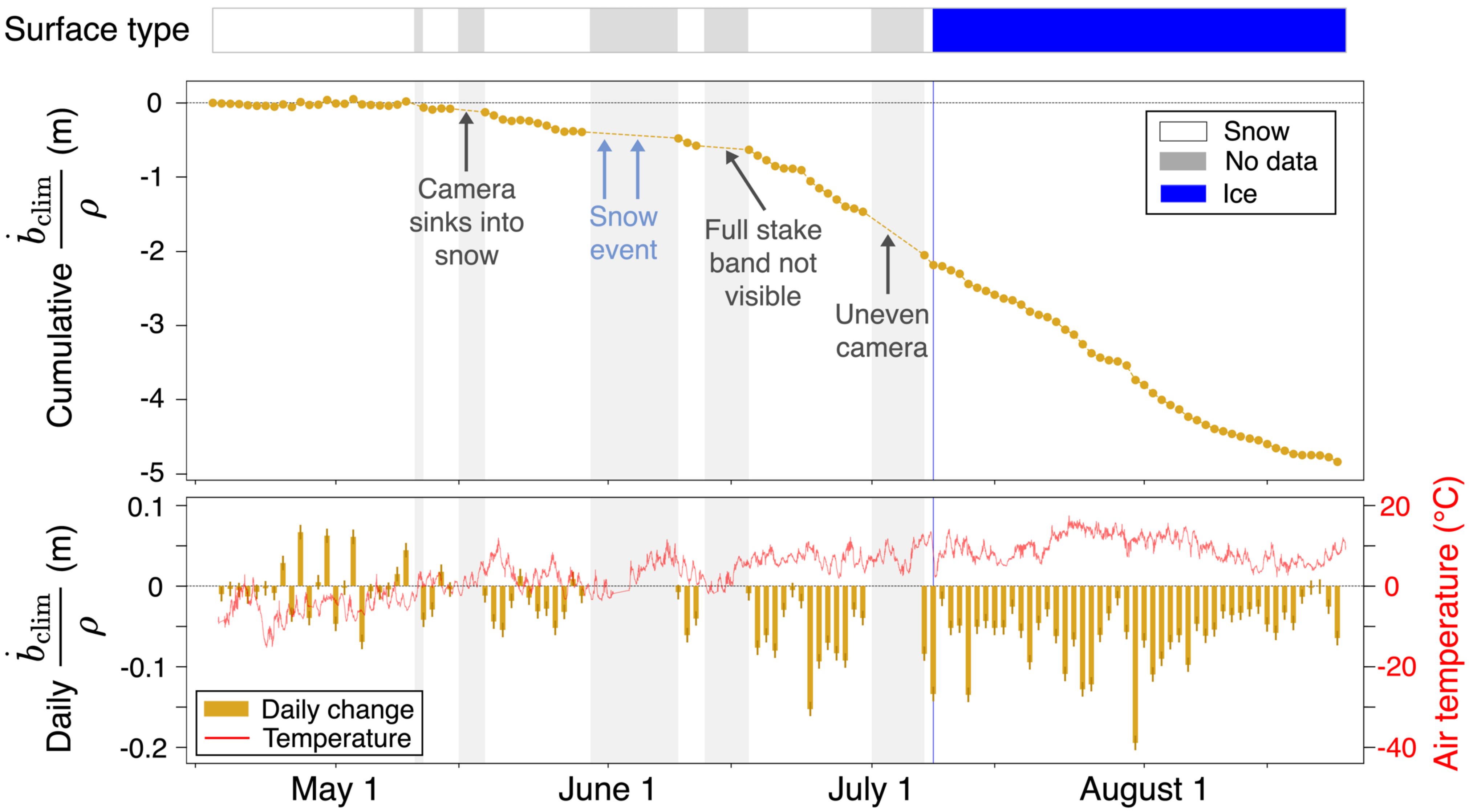
- Incorporate higher-order flow models?

Thank you! Questions?

Modeling albedo reduction by black carbon deposition
Poster by Claire Wilson
until 5:30!

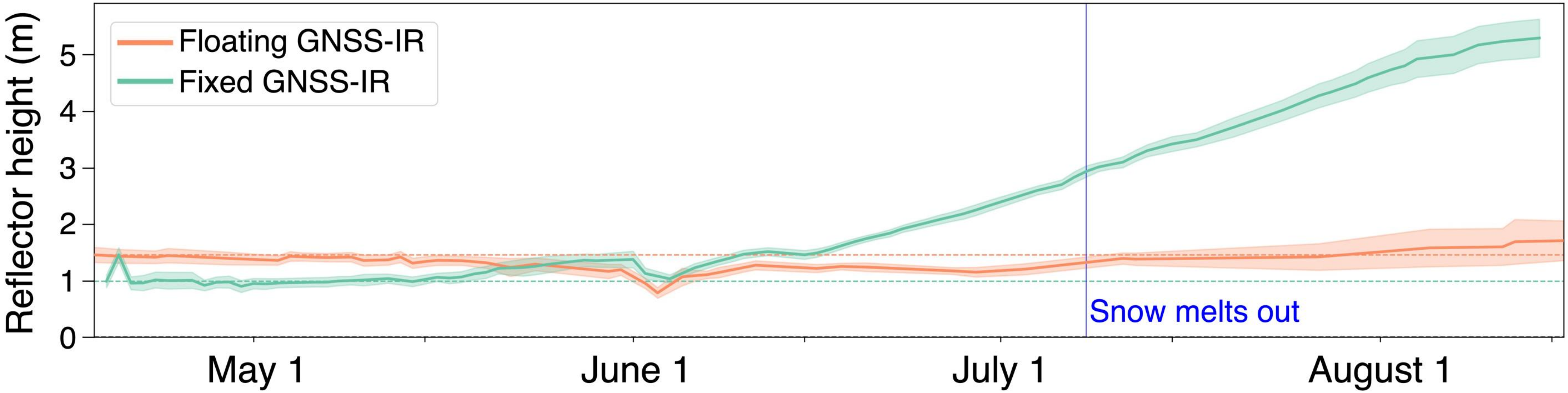
A. Wells, D. Rounce, L. Sass, C. Florentine, A. Garbo, E. Baker, and C. McNeil. "GNSS Reflectometry from Low-Cost Sensors for Continuous in Situ Contemporaneous Glacier Mass Balance and Flux Divergence." J. Glac., 2024, 1–12. https://doi.org/10.1017/jog.2024.54.

Mass balance: monitored ablation stake

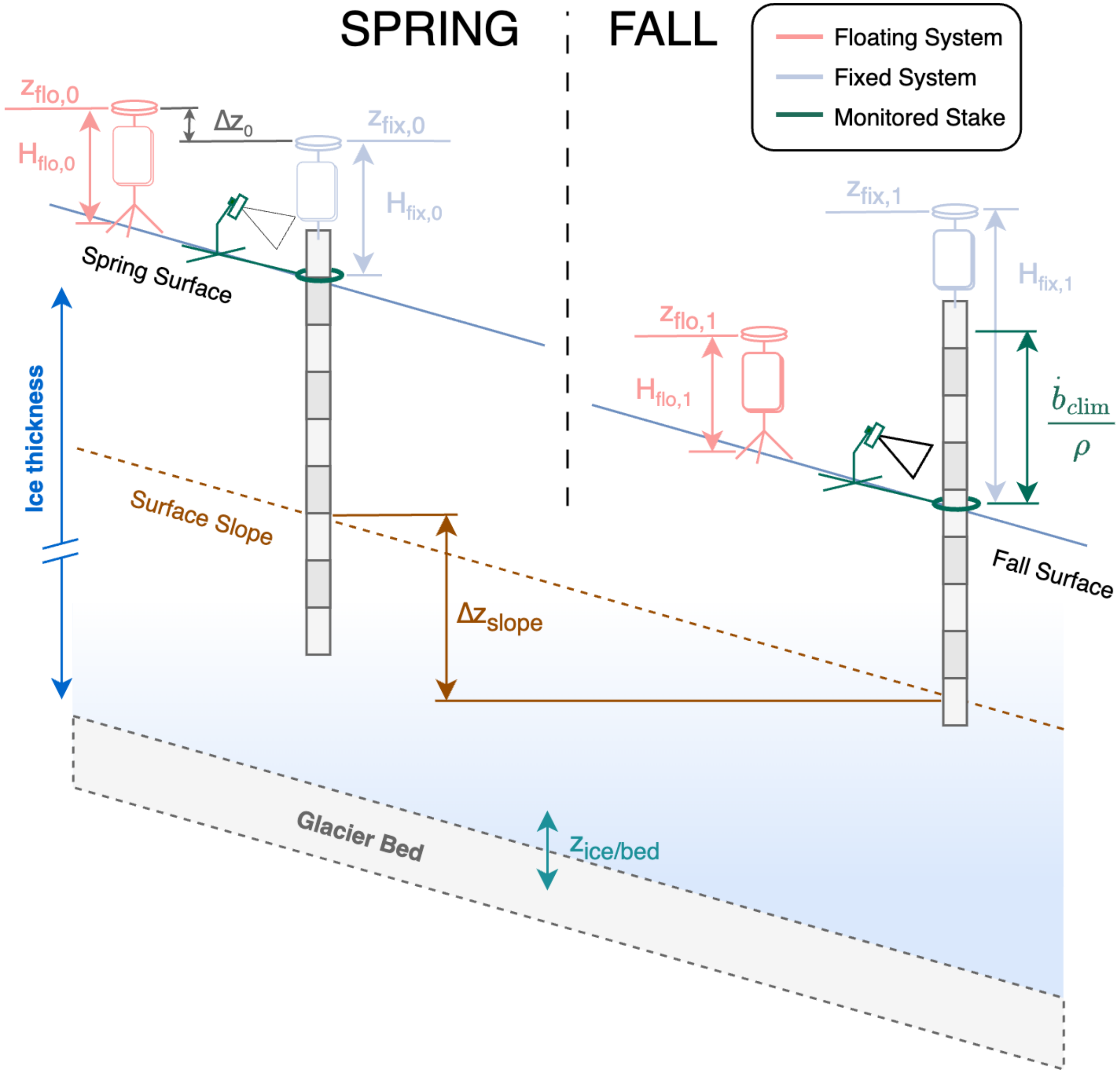


Stake height from GNSS-reflectometry

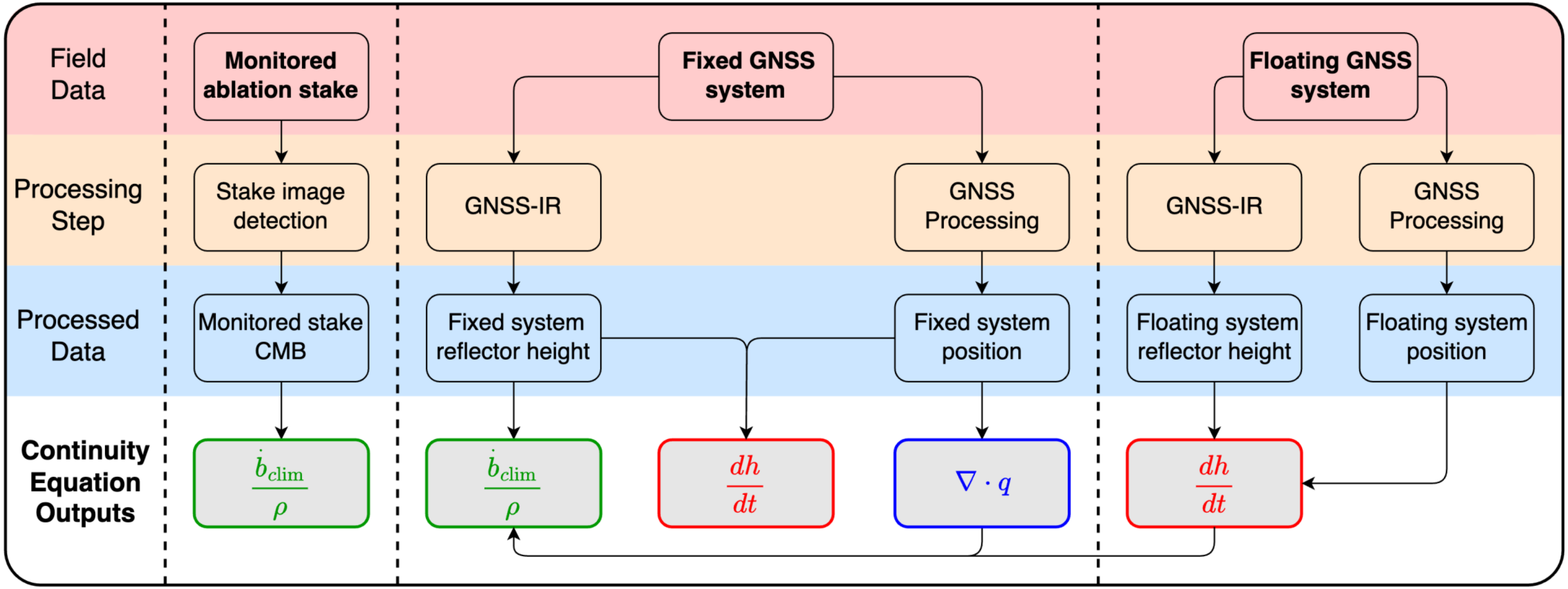
- GNSS-reflectometry estimates antenna height relative to a surface by using the signal-to-noise data from direct and reflected GPS signals



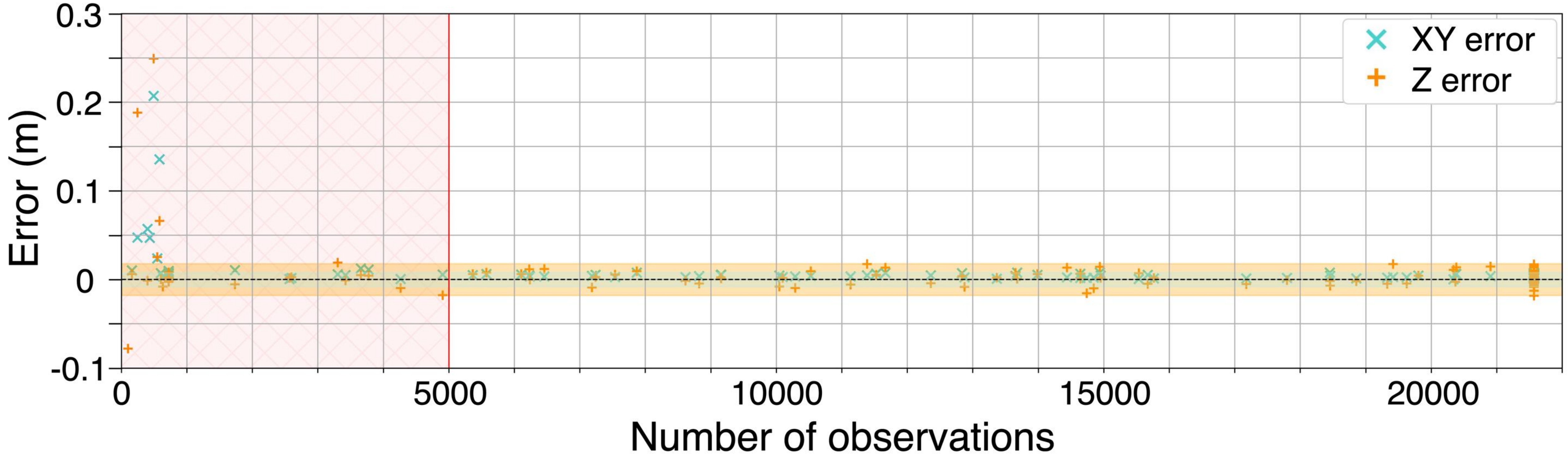
GNSS setup components



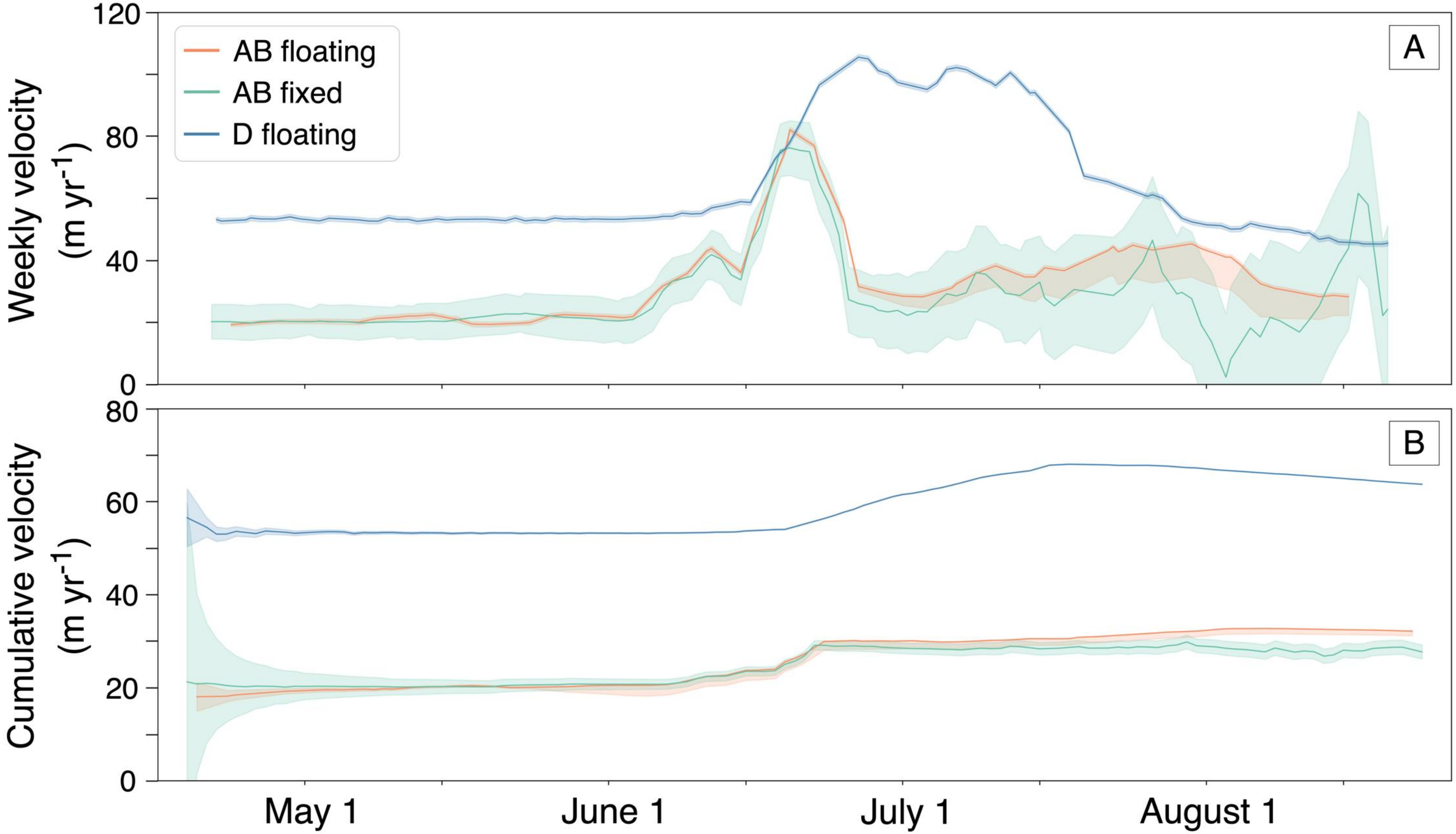
Three methods for climatic mass balance



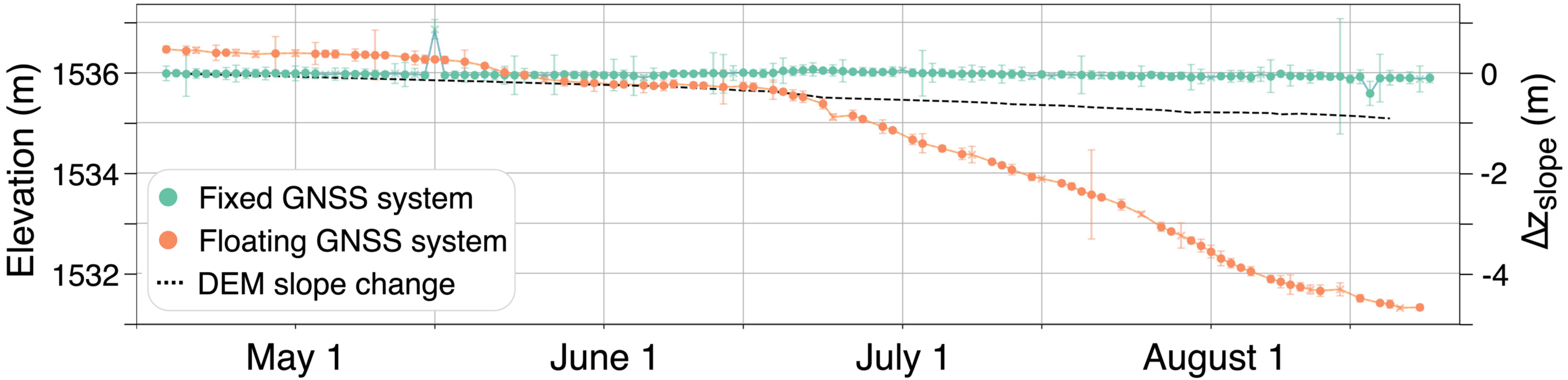
GPS position accuracy



Site velocity



GNSS system slope-corrected elevation change



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

"Glacier mass change due to the climate"
"Surface (+ internal) mass balance"

Total Mass Balance

"Glacier surface elevation change"
"Change in glacier thickness"

Flux Divergence

"Dynamic contribution to glacier surface change"
"Elevation change from a difference in mass flux"

NOTE: the climatic mass balance and the total mass balance are equal glacier-wide, but vary spatially across the glacier