A wide-angle aerial photograph of a massive glacier. The glacier's surface is a mix of white ice and brownish sediment. It flows from the background, where several snow-capped mountain peaks are visible, down towards the foreground. The surrounding terrain is a mix of dark, rocky slopes and patches of green vegetation. The sky is overcast with white and grey clouds.

Methods and Challenges to Understanding Glacier Response to the Climate

ALLDERDICE RESEARCH SYMPOSIUM
MARCH 23, 2022

Albin Wells

A quick intro...



Allderdice c/o 2017



CMU !!



Brown University c/o 2021

Pursuing a Ph.D. in Civil and Environmental Engineering, studying glaciers

Received an Sc.B. in Mechanical Engineering



Why are glaciers important?

GLACIERHUB BLOG

Bridge Collapse in Pakistan Due to Glacier Lake Outburst Flood

Glacial melt in Indus raises water concerns

BY HAMNA TARIQ

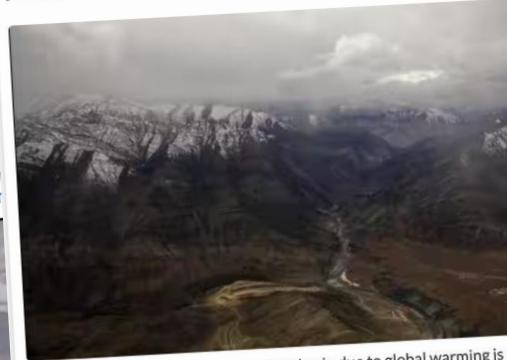
By Jayashree Nandi, New Delhi

Extraordinary record
Hassanabad Bridge
unprecedented heat
flooded, wiping out
power plants.

This event is the last
outburst floods, in
important to analyze
urge immediate action

PAMIR T
@pamirti

Hassanabad
glacial lake
#ClimateEmergency
#GlobalWarming



Increased glacial melt in the Indus river basin due to global warming is likely to raise strategic concerns over the sharing of water in the region. A recent study has indicated that research article in the Current Science journal has indicated.

11h
484

How melting glaciers fueled Pakistan

imate change is melting them into

Millions face threat of flooding from glacial lakes

7 February

NEWS

CITY NEWS

DEHRADUN NEWS

‘77 new glacial lakes in Kumaon Himalayas, can cause

flash flood’

GAURAV TALWAR / TNN / Updated: Mar 2, 2023, 08:31 IST

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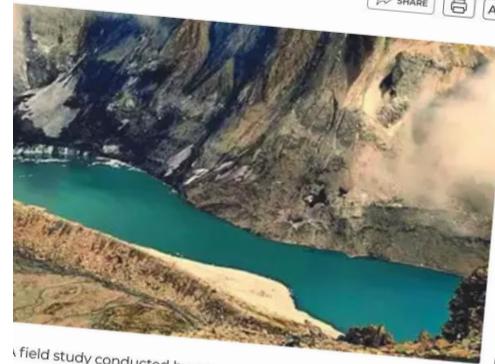
Alaska tourism threatened as iconic
glaciers melt away

By Michael Fanelli, Alaska Public Media - Anchorage - February 24, 2023



A view of Exit Glacier from the National Parks trail. (Courtesy National Parks Service)

▶ 0:00 / 4:27



A field study conducted by a professor of Kumaon University has found the presence of 77 new glacial lakes in the Gori Ganga region of the Kumaon Himalayas. The water bodies, situated at an elevation of over 3,500 meters, have formed over three decades — between 1990 and 2020 — due to shrinking of mountain areas.

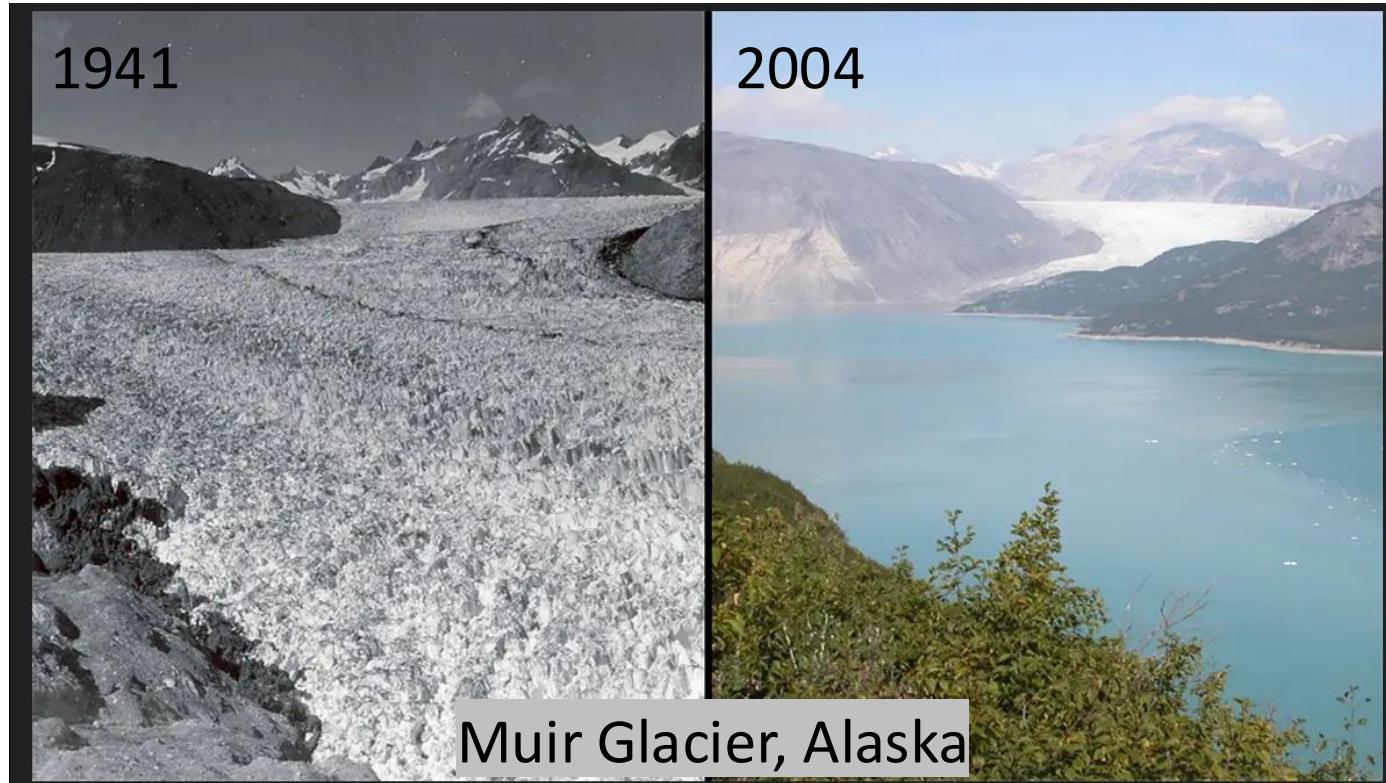
region mainly consists of Milam, Gonkha, Ralam, Lwan and Martoli glacial lakes, with a 2.7km diameter, was found in Gonkha. "Any activities can cause the lake to burst, triggering a flash flood," the professor said.

other glacial lakes, too, which are tributaries of the main glacial lakes. Dr. Parth Parikh, professor of geography at the Nainital campus of the University of Lucknow, said.

A recent study found that two-thirds of the world's glaciers could disappear by the end of this century. That may sound pretty far into the future, but in Alaska those frozen landmarks are a strong attraction for the state's tourism industry.

For at least one glacier-focused company, Seward-based Exit Glacier Guides, which takes visitors to its icy namesake, the end is already in sight.

Glacier mass loss is occurring worldwide



Waggonwaybreen, Svalbard

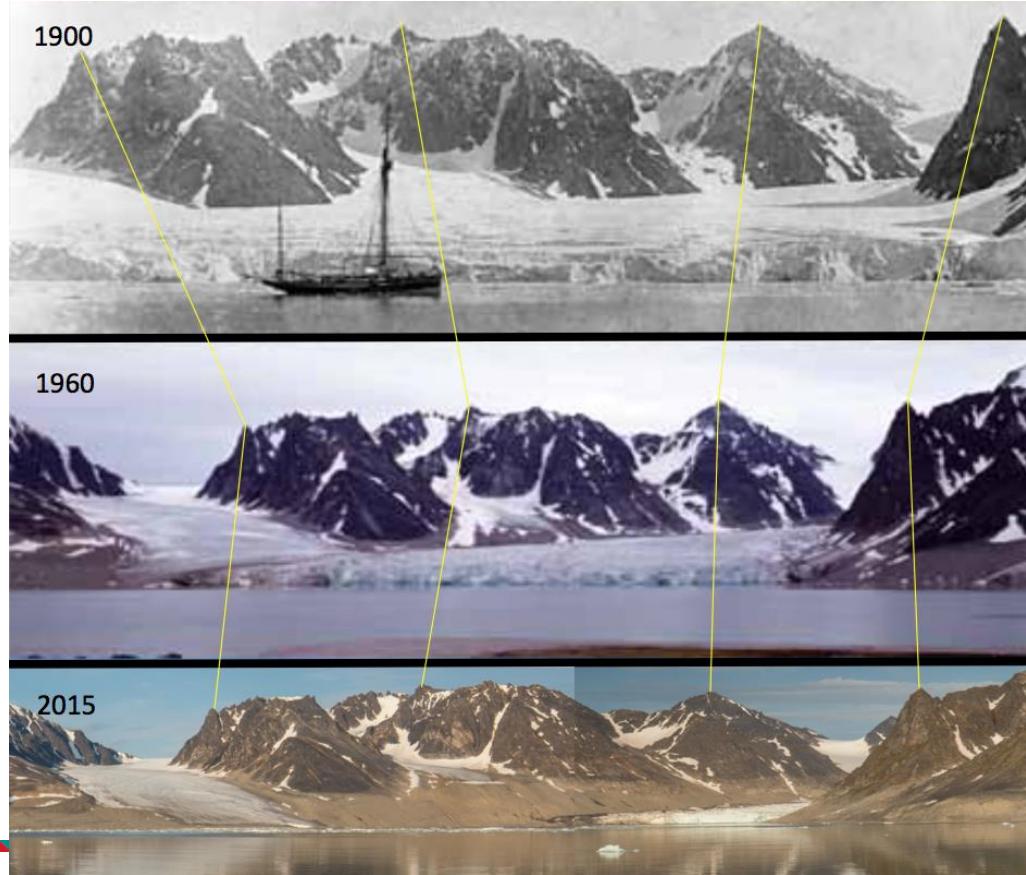


Image Credit: Andreas Weith

Kyetrak Glacier, Tibet



Extreme mass loss is also observed over the last few years

Bear Glacier, Alaska



Fox Glacier, New Zealand



Image Credit: Dr Ian Fuller

The most recent models project ~50-80% of global glaciers to melt by 2100

- Glaciers account for only **1% of global ice volume**
- Account for **1/4 to 1/3 of observed sea-level rise** in recent years
- Global average thinning rates of **0.85 m/yr** (2006-2015)

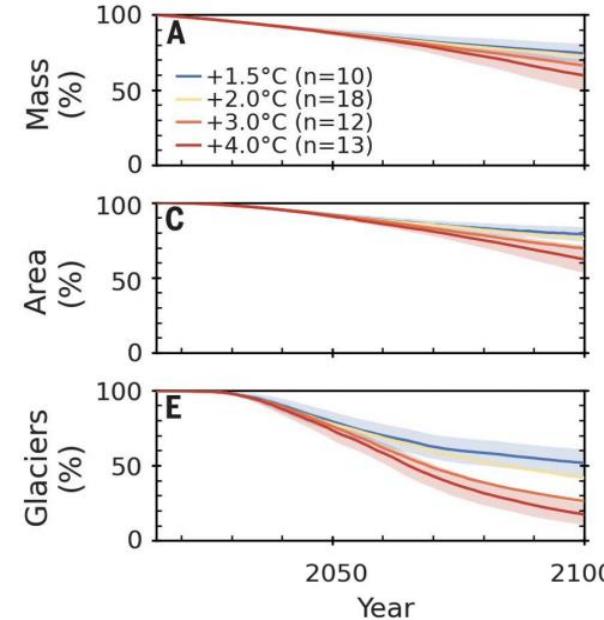


Figure from Rounce et al. 2023

What regions are losing the most mass?

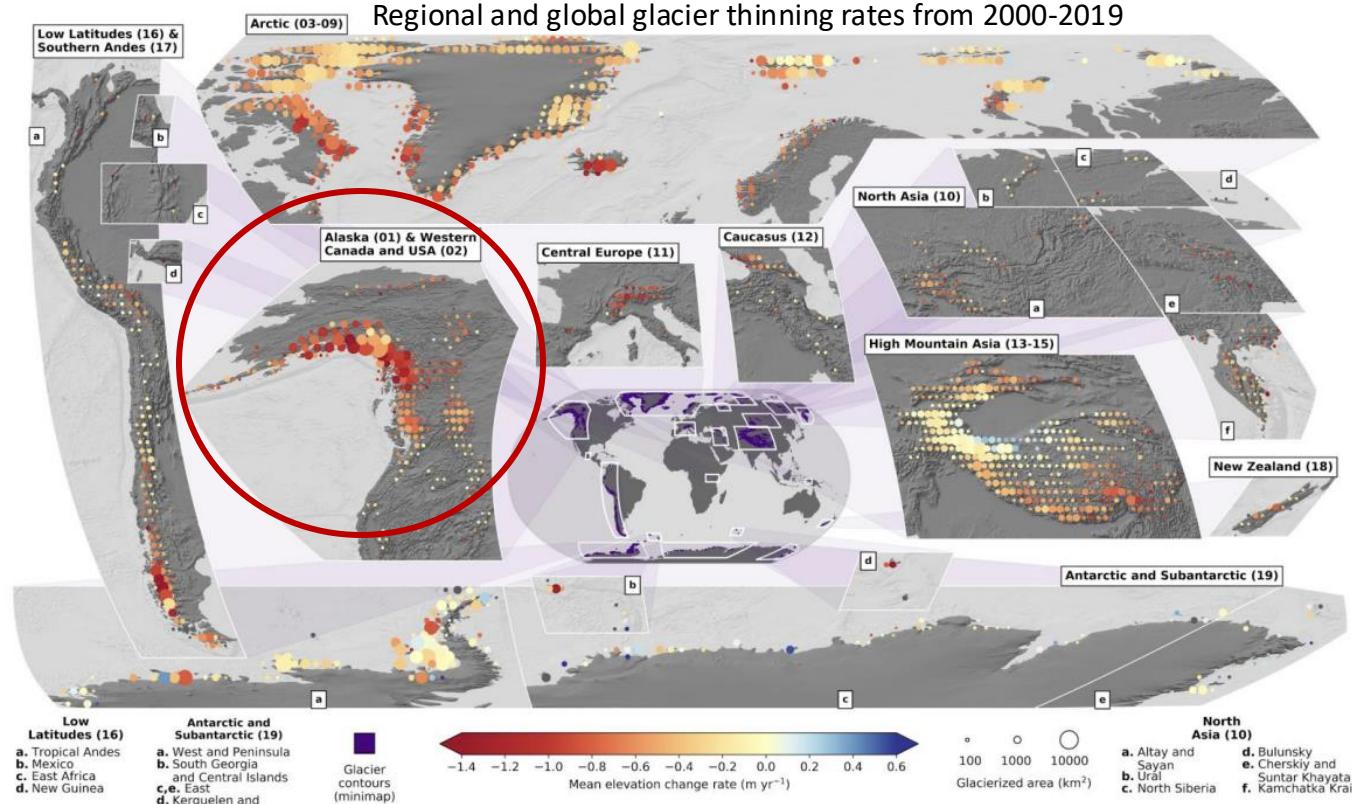


Figure from Hugonet et al. 2021

So, how can we predict a glacier's response to the climate?

First, we need to understand how glaciers work!

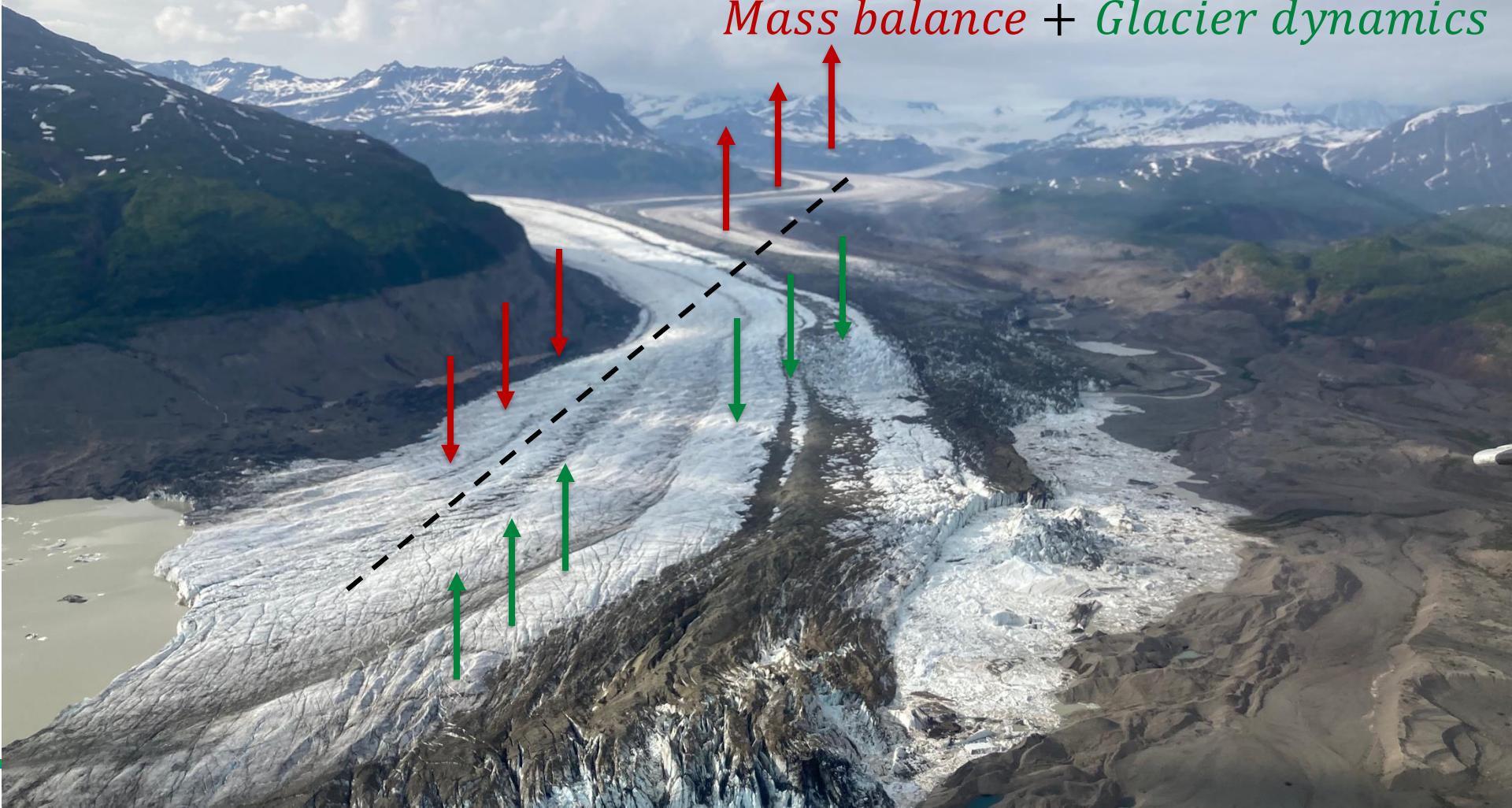
An aerial photograph of a massive glacier winding its way through a rugged mountain range. The glacier is a light blue-grey color, with deep crevasses and dark, rocky outcrops where it meets the land. In the background, a range of mountains is partially covered in snow, with some peaks reaching high into the sky. The foreground shows the raw, rocky terrain of the glacier's bedrock. The overall scene is one of natural geological power and beauty.

Climate + Gravity

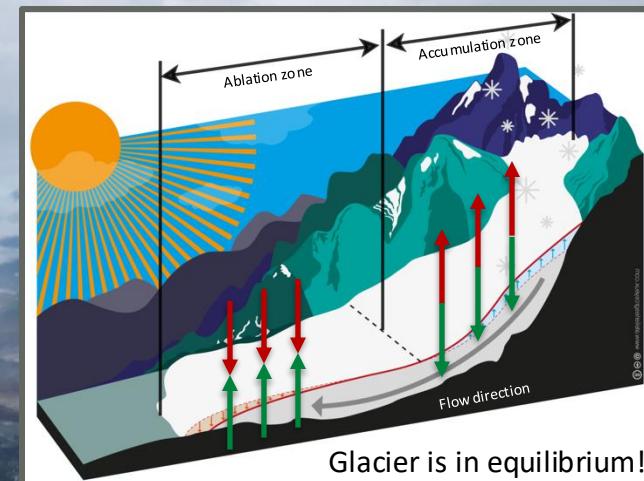
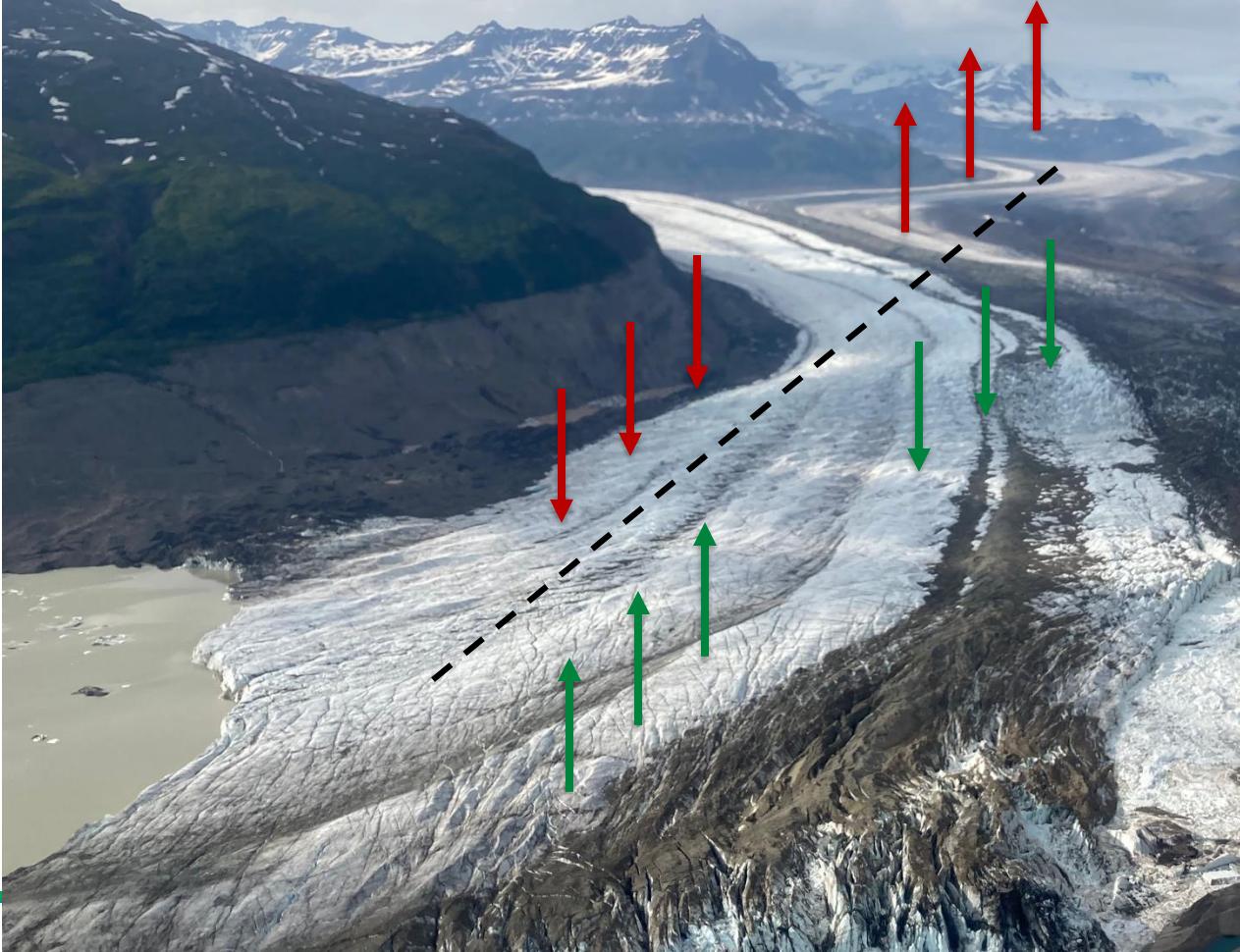
Mass balance + Glacier dynamics



Mass balance + Glacier dynamics

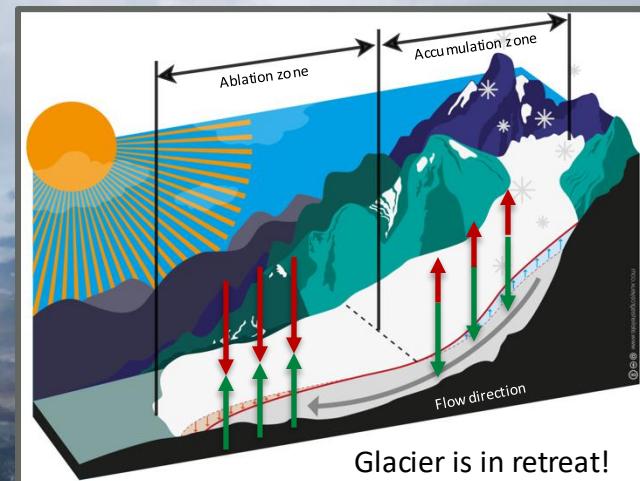
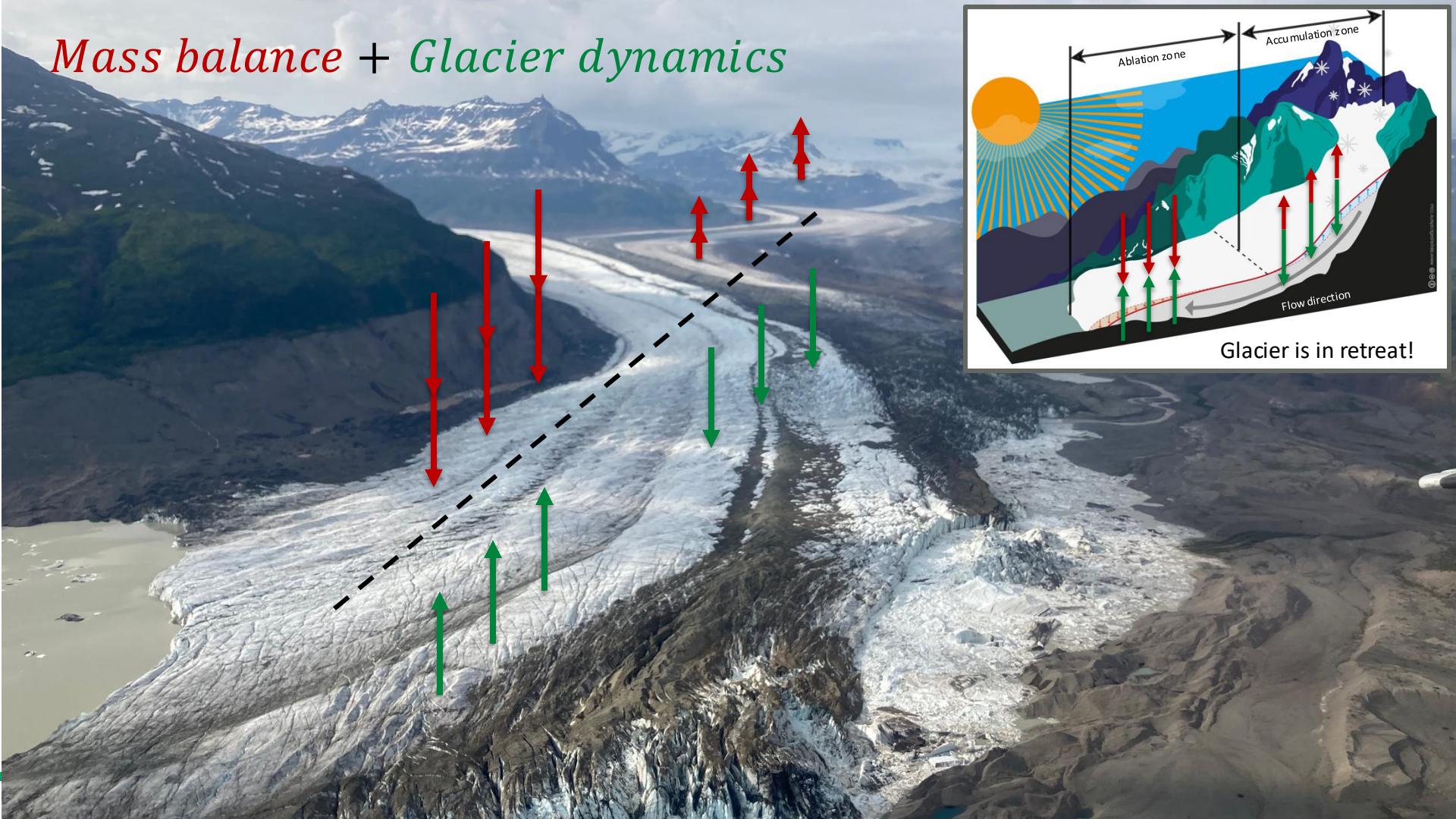


Mass balance + Glacier dynamics



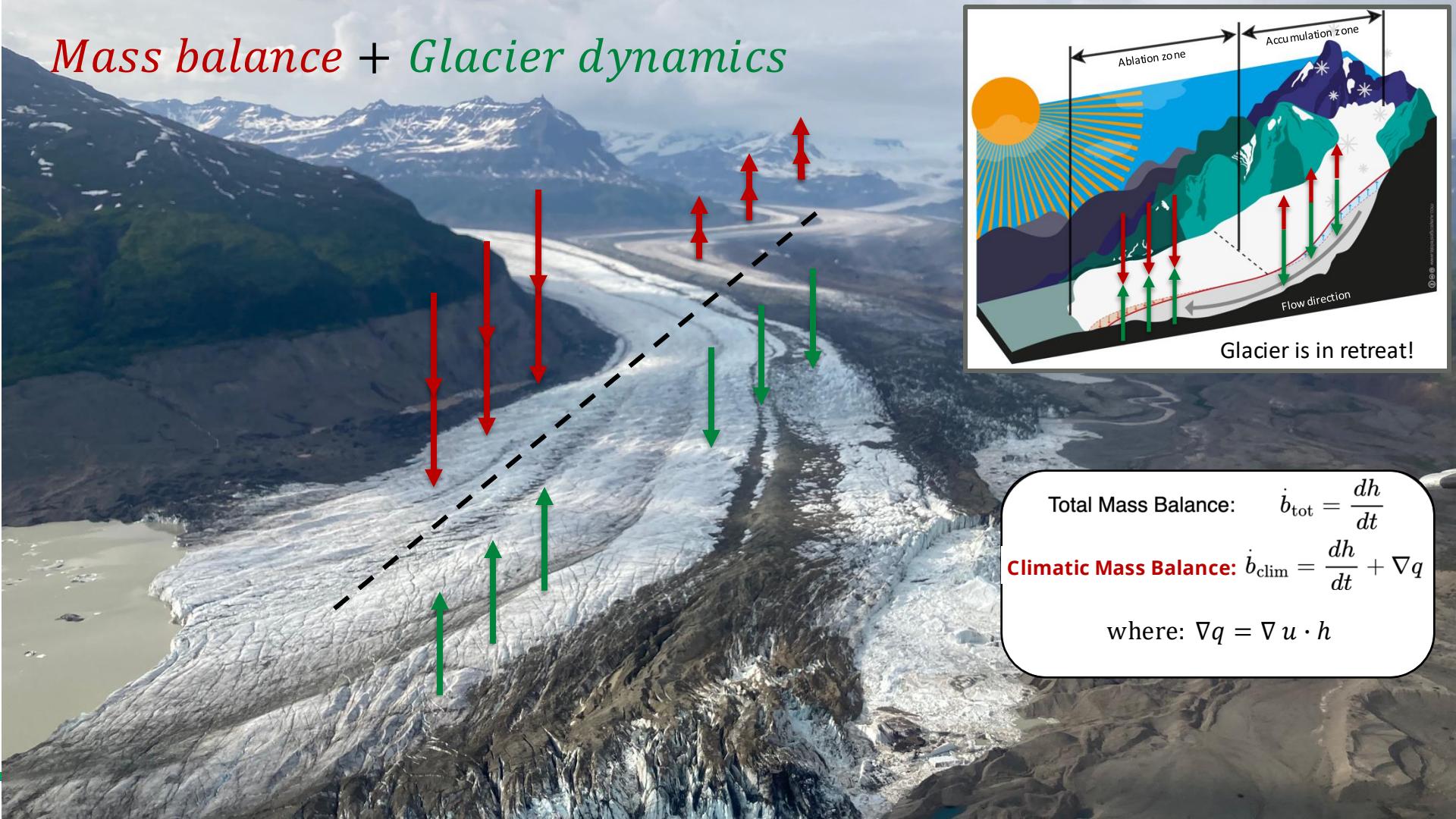
Glacier is in equilibrium!

Mass balance + Glacier dynamics



Glacier is in retreat!

Mass balance + Glacier dynamics



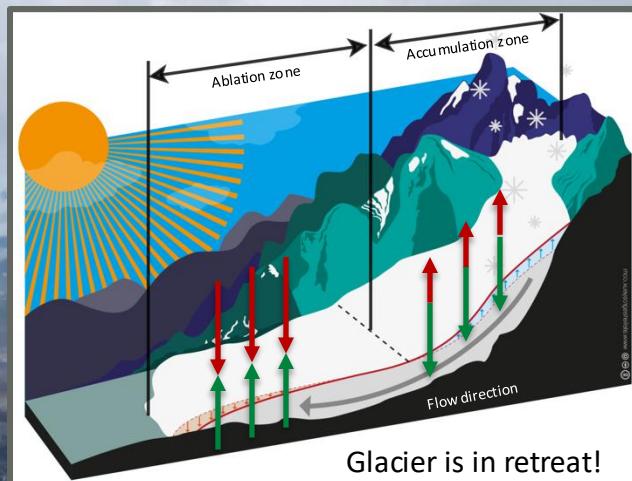
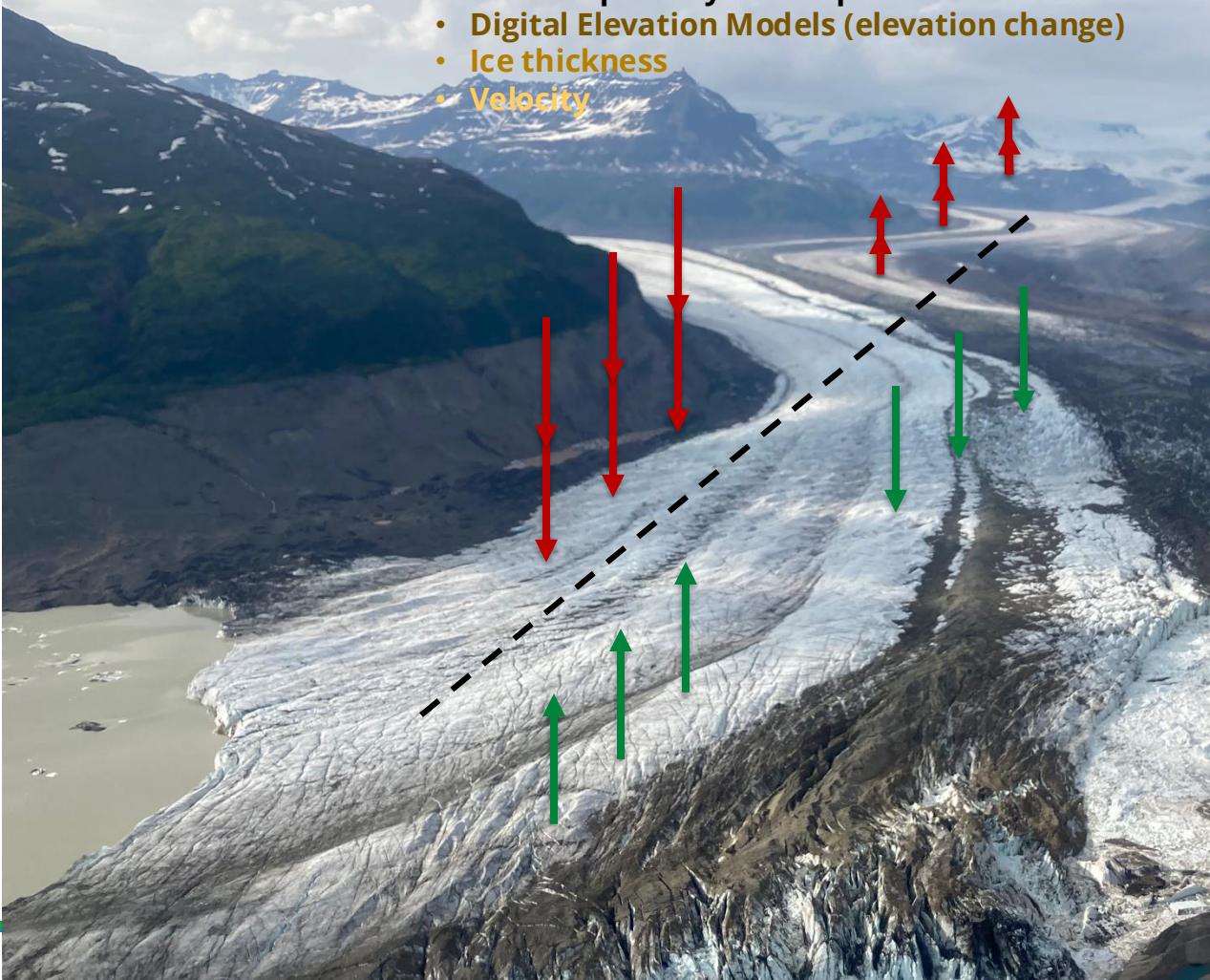
Total Mass Balance: $\dot{b}_{\text{tot}} = \frac{dh}{dt}$

Climatic Mass Balance: $\dot{b}_{\text{clim}} = \frac{dh}{dt} + \nabla q$

where: $\nabla q = \nabla u \cdot h$

We need 3 primary data inputs:

- Digital Elevation Models (elevation change)
- Ice thickness
- Velocity



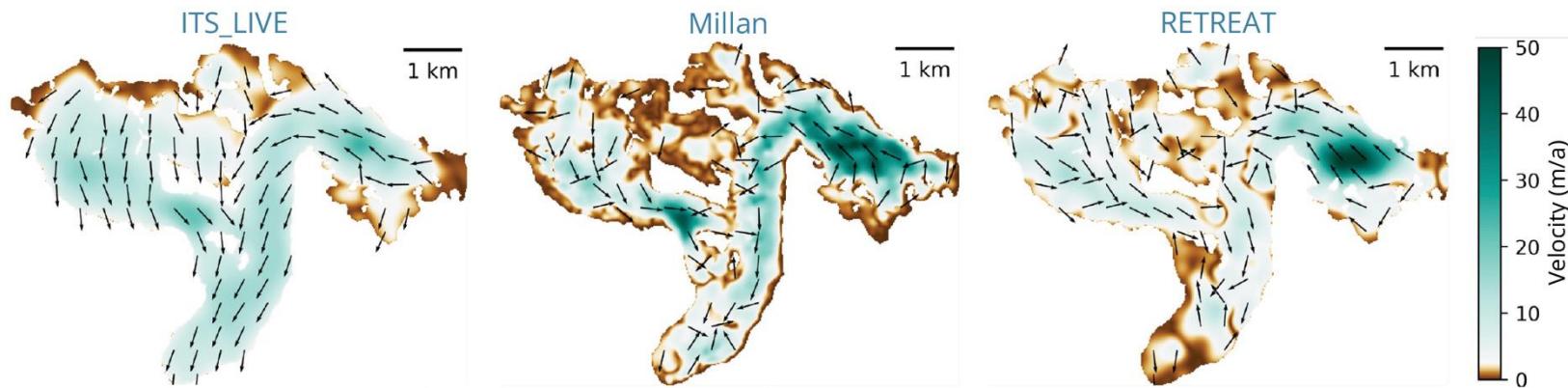
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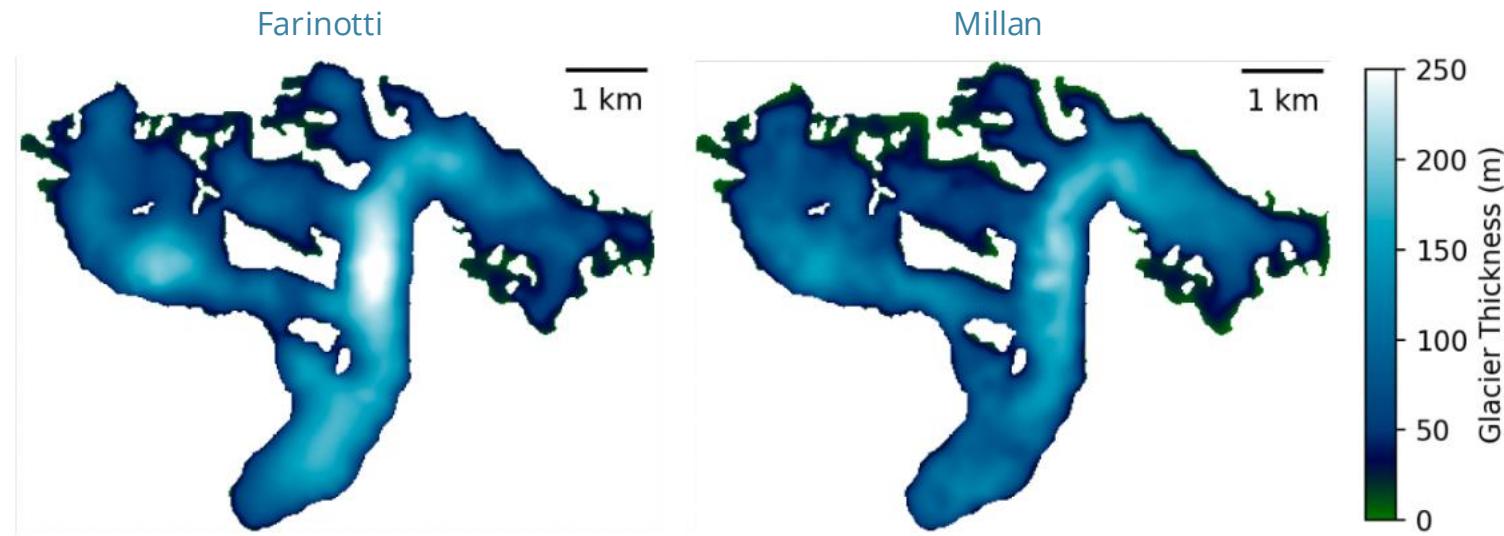
where: $\nabla q = \nabla u \cdot h$

Large-scale, systematic remote sensing products have discrepancies

- Gulkana Glacier in Alaska is $\sim 17.5 \text{ km}^2$
- Global velocity products show large deviations in magnitude and spatial distributions



Modeled ice thickness products also differ

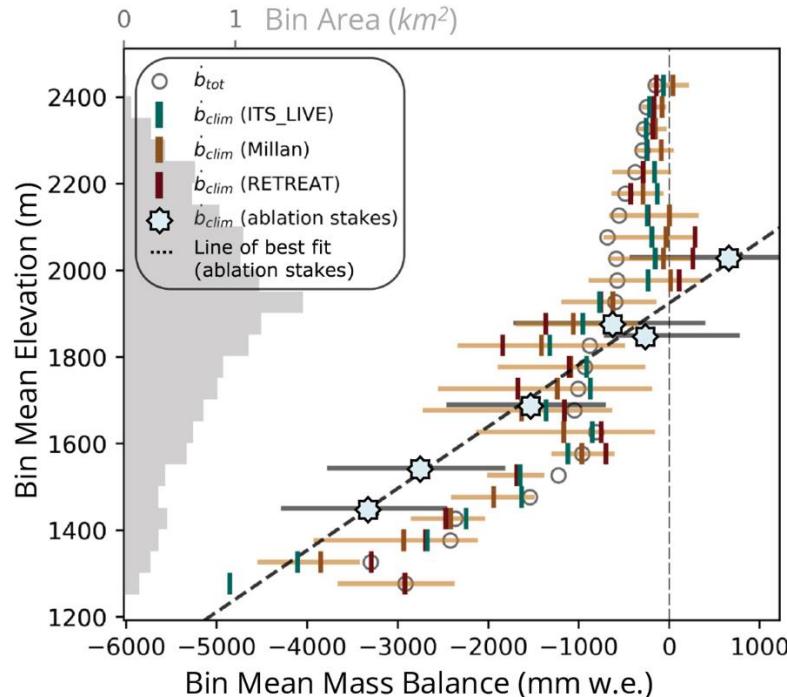


Our confidence in global datasets is limited by a paucity of validation data that address issues pertaining to noise, bias, and uncertainty!

Velocity and ice thickness impact our ability to calculate the climatic mass balance

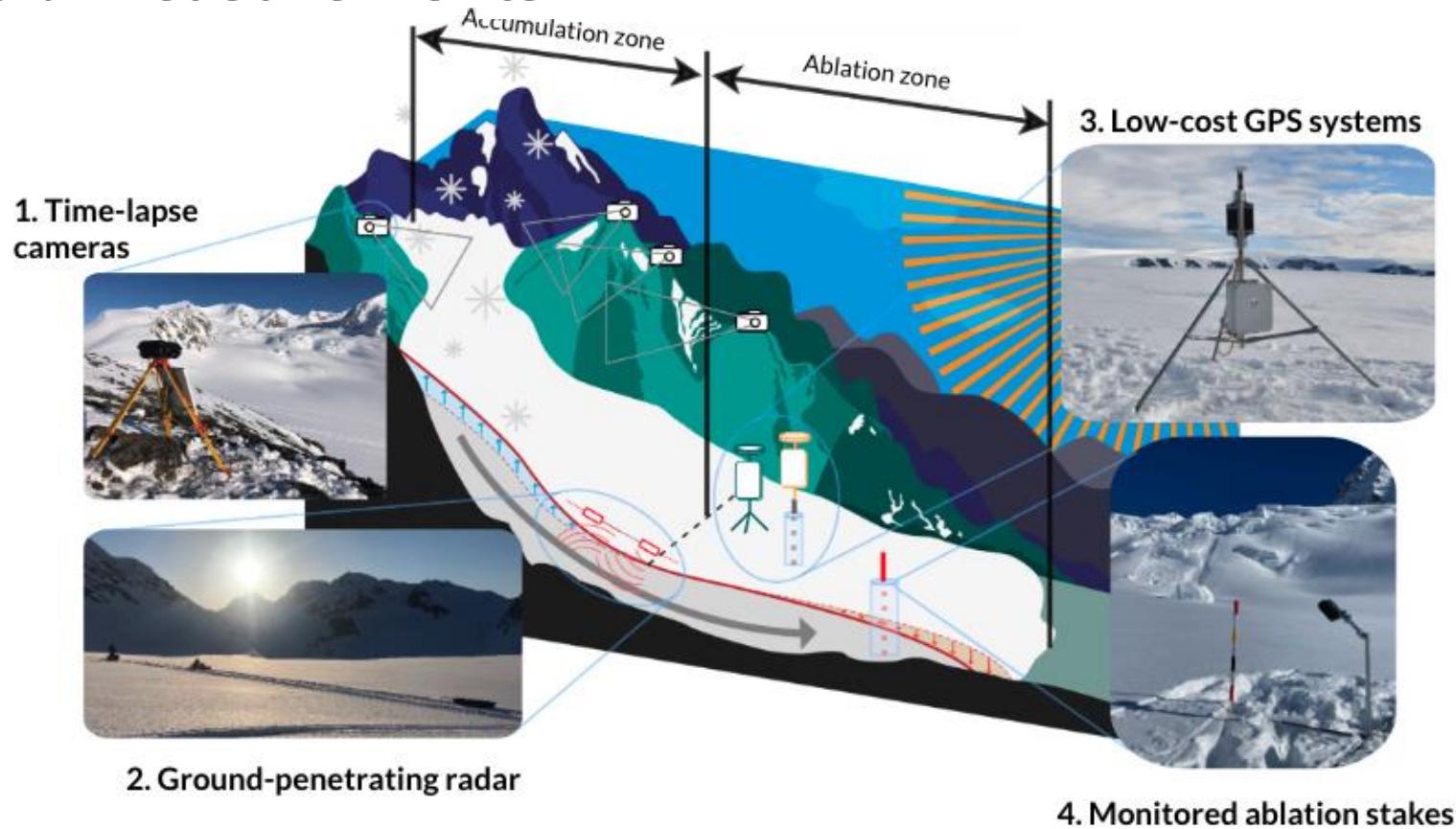
The climatic mass balance gradient is off by >50% compared to the observed stake data!

Gulkana Glacier climatic mass balance as a function of elevation



We can try to reconcile these discrepancies by leveraging field measurements and models

Field Measurements



Field Measurements

Total Mass Balance:

$$\dot{b}_{\text{tot}} = \frac{dh}{dt}$$

- Time-lapse cameras
- Low-cost GPS systems

Climatic Mass Balance:

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

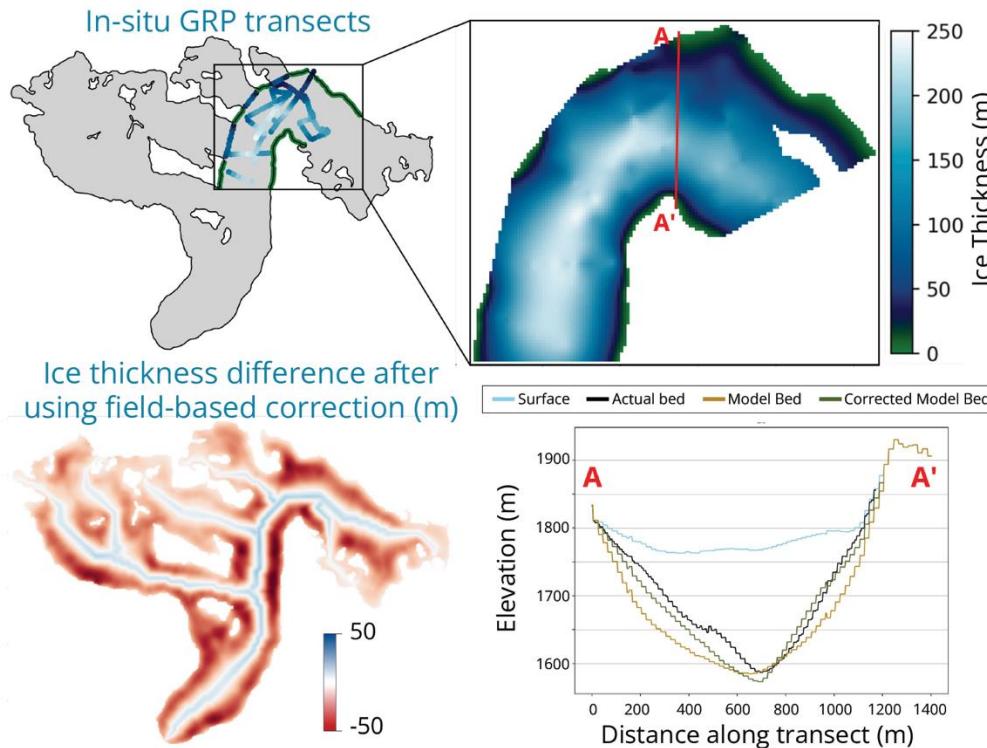
- Monitored ablation stakes
- Low-cost GPS systems

Flux Divergence:

$$\nabla q = \nabla (h \cdot u)$$

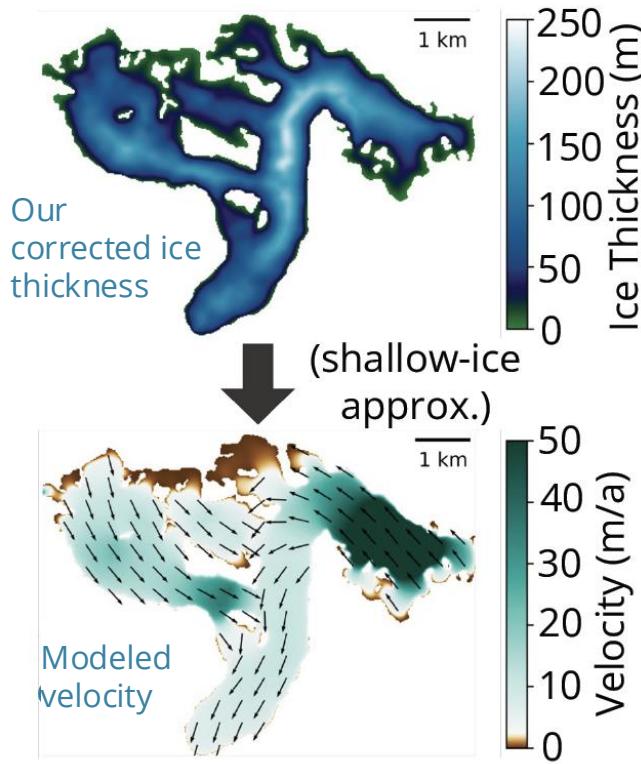
- Time-lapse cameras
- Ground-penetrating radar
- Low-cost GPS systems

Integrating field measurements with existing data products: Ice thickness

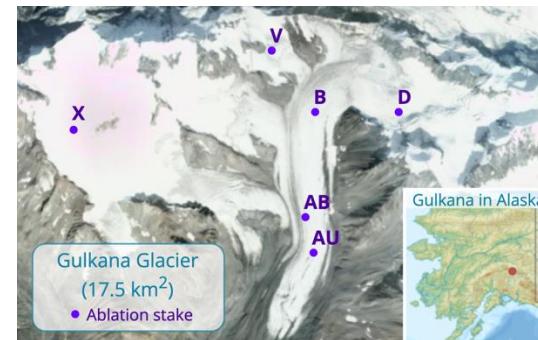


- On Gulkana, ice thickness products...
 - underestimate thickness along the centerline
 - overestimate ice thickness along the margins
- Essentially, our data is used to correct the ice thickness product for the proper bed shape

Integrating models: Velocity



- Also deriving our own velocity products from high-resolution remote sensing
- Future steps to integrate models with observations using Bayesian inference
 - combine prior belief (model) with observations (remote sensing)
- Use our point data as validation

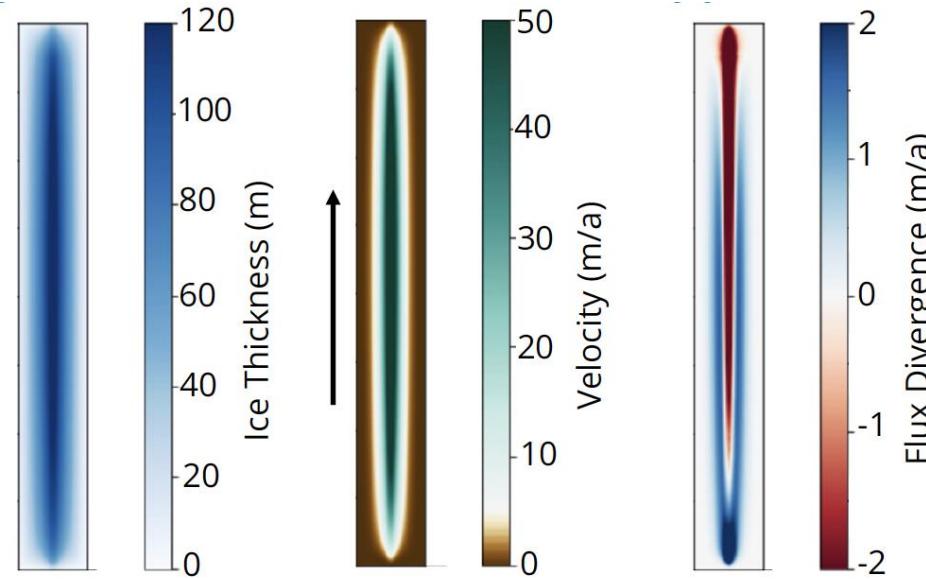


Velocity at Ablation Stake Locations (m/a)

Data Source	Stake	Location			
		AU	AB	B	D
Millan		15.9	5.3	26.3	46.7
ITS_LIVE		14.7	13.8	13.0	20.5
RETREAT		6.1	3.3	3.9	20.9
Model		10.8	10.6	13.1	61.7

A theoretical approach to the climatic mass balance

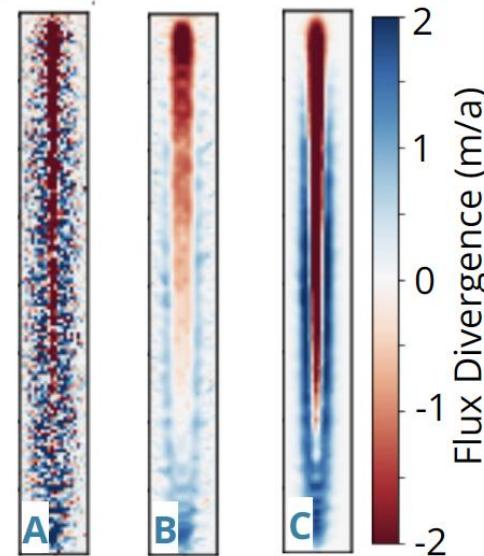
- *How accurate do ice thickness and velocity need to be?*
- Start with idealized glacier and derive physically consistent ice thickness and velocity



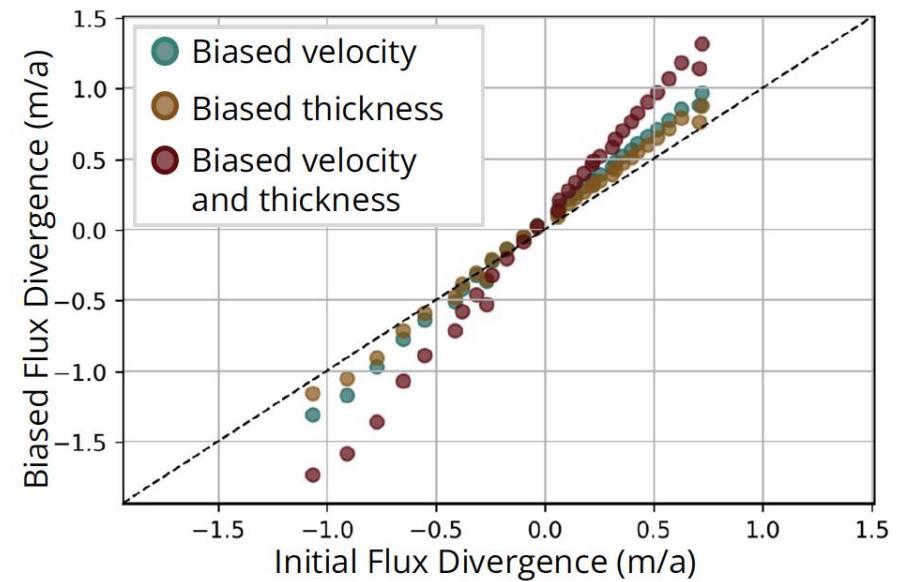
A theoretical approach to the climatic mass balance

- Then, introduce noise and/or bias into the data and see how it affects our results

Flux divergence from noisy (A), smoothed (B), and corrected (C) inputs



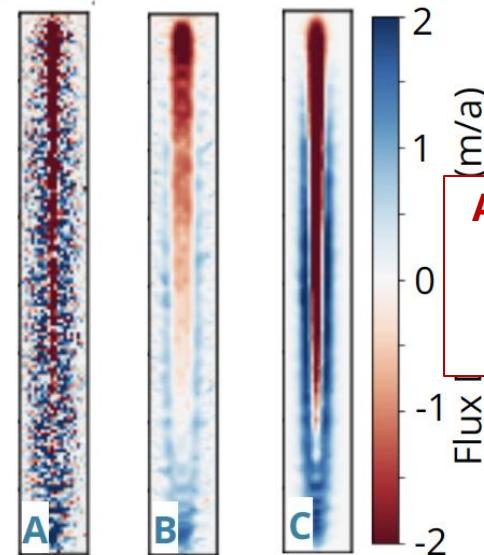
Overestimation bias effect on flux divergence



A theoretical approach to the climatic mass balance

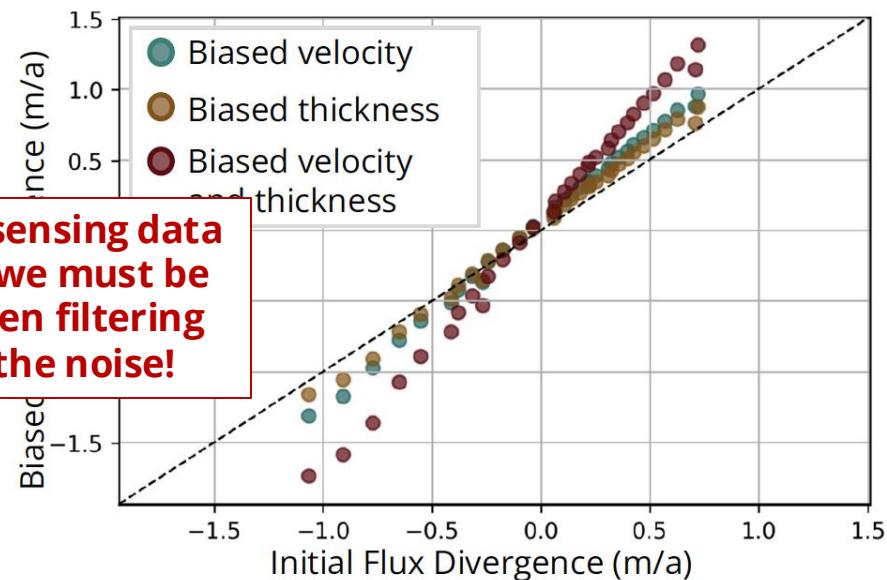
- Then, introduce noise and/or bias into the data and see how it affects our results

Flux divergence from noisy (A), smoothed (B), and corrected (C) inputs



All remote sensing data has noise; we must be careful when filtering through the noise!

Overestimation bias effect on flux divergence



Takeaways and Conclusions

- The impacts of glacier mass loss are ubiquitous: **understanding glacier response to the climate has implications for billions of people across the globe**
- Glaciers are losing mass at unprecedented rates as a result of climate change, and new, systematic **remote sensing offers a unique ability to monitor mass loss globally**
- However, our ability to resolve the ***climatic mass balance*** is hindered by noise and bias in data
- **Field measurements and models provide opportunities to validate and improve remote sensing data products**, but integrating these products is still a work in progress!

Next Steps

- Increase complexity of synthetic glacier study
- Increase model complexity for deriving velocities
- Assess potential effects of glacier processes (avalanching, wind distribution, firn compaction) on stake observations
- Obtain new/more field data!
- Apply methods to other glaciers in Alaska

Thank you! Questions?



Gulkana Glacier, August 2022