An aerial photograph of a massive glacier flowing through a mountain valley. The glacier is a mix of white ice and dark grey sediment, creating a textured appearance. It winds from the upper left towards the bottom right, where it meets a body of water. The surrounding mountains are rugged, with patches of snow and green vegetation on the lower slopes. The sky is overcast with soft, 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

BY HAMNA TARIQ | 11

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

This event is the latest outburst floods, important to analyze immediate loss



PAMIR T @pamirt

Hassanabad glacial lake
#ClimateEmergency
#GlobalWarming

Glacial melt in Indus raises water concerns

By Jayashree Nandi, New Delhi

Mar 06, 2023 02:59 PM IST

"Climate change projections for the region suggest that tributary glacier melt water would peak in the middle of this century and that. Additionally, water demand for the basin is projected to increase in the future," said the study published in the latest issue of the peer-reviewed journal.



Increased glacial melt in the Indus river basin due to global warming is a strategic concern over the sharing of water. (Bloomberg/Representative)

Increased glacial melt in the Indus river basin due to global warming is a strategic concern over the sharing of water in the region, research article in the Current Science journal has indicated.

How melting glaciers fueled Pakistan

Climate change is melting them into

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 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.

Millions face threat of flooding from glacial lakes

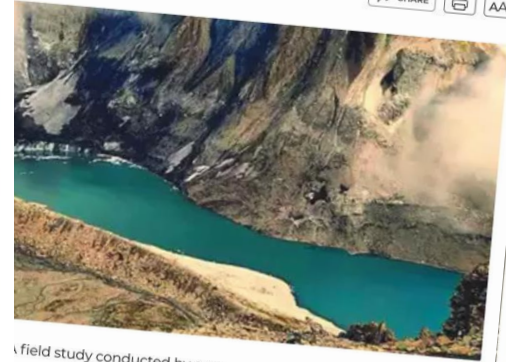
7 February

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

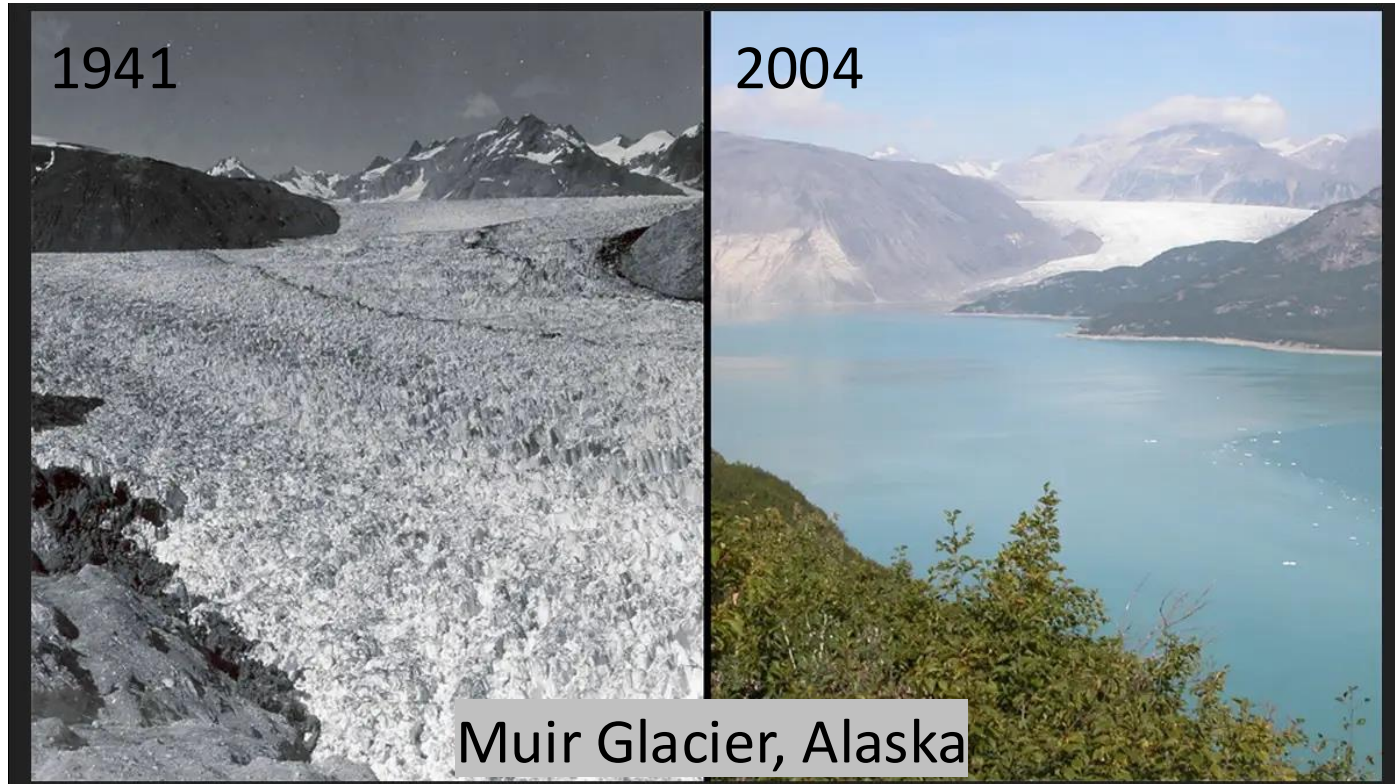


A field study conducted by a professor of Kumaon University has revealed the presence of 77 new glacial lakes in the Gori Ganga region of the Himalayas. The water bodies, situated at an elevation of over 3,500 meters, have formed over three decades — between 1990 and 2020 — due to shrinking glacier areas.

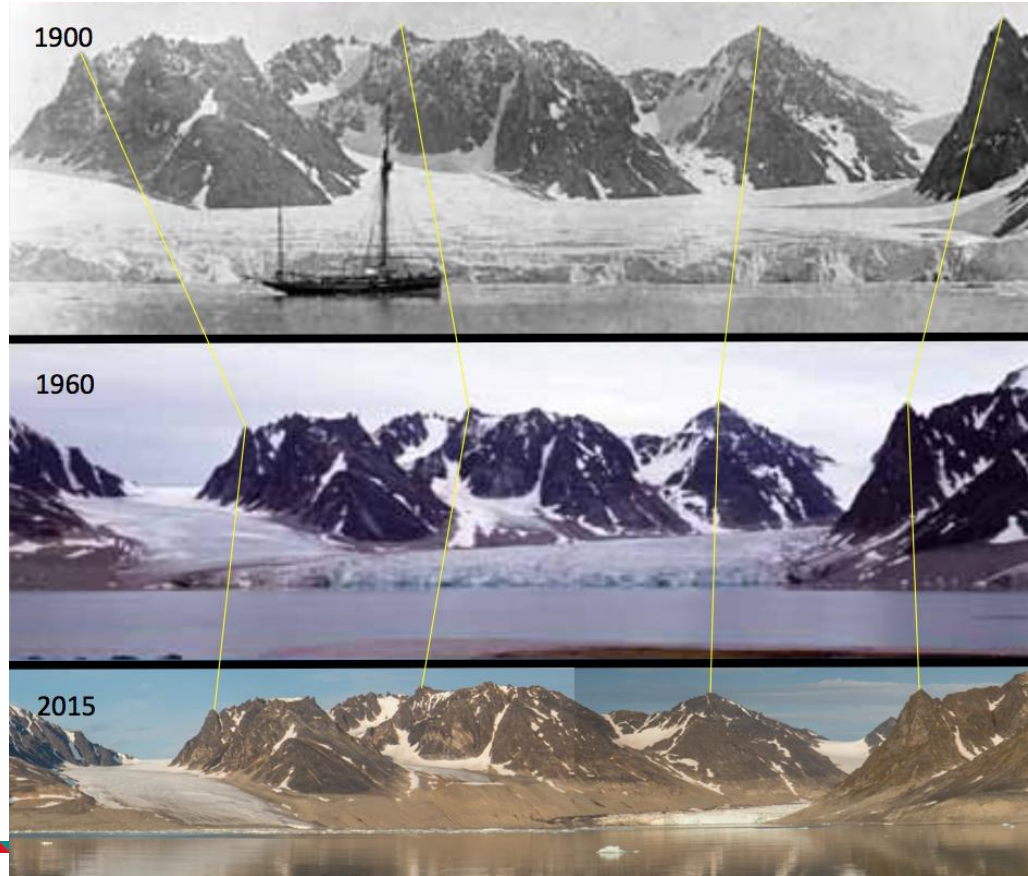
The region mainly consists of Milam, Gonkha, Ralam, Lwan and Martoli. The largest glacial lake, with a 2.7km diameter, was found in Gonkha. "Any activities can cause the lake to burst, triggering a flash flood," the study says.

Other glaciers, too, which are tributaries of the main glacial system, are also at risk. Dr. Parihar, professor of geography at the Nainital campus of the Uttarakhand University, said.

Glacier mass loss is occurring worldwide



Waggonwaybreen, Svalbard



Kyetrak Glacier, Tibet



Image Credit: David Breashears/Royal Geographic Society

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)

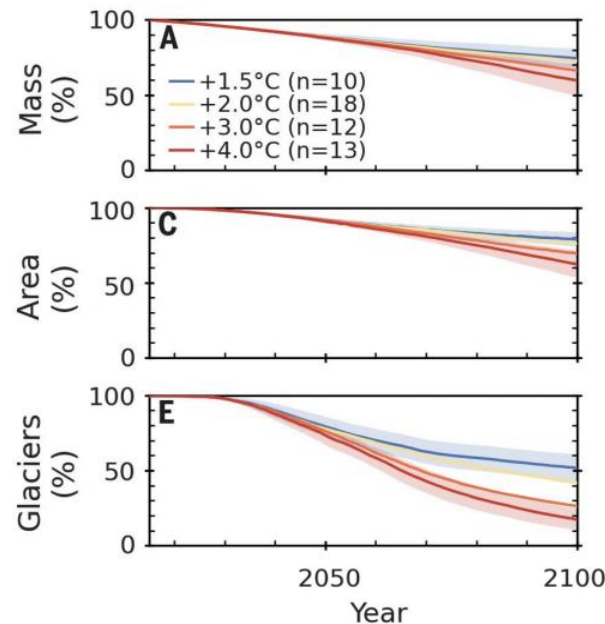


Figure from Rounce et al. 2023

What regions are losing the most mass?

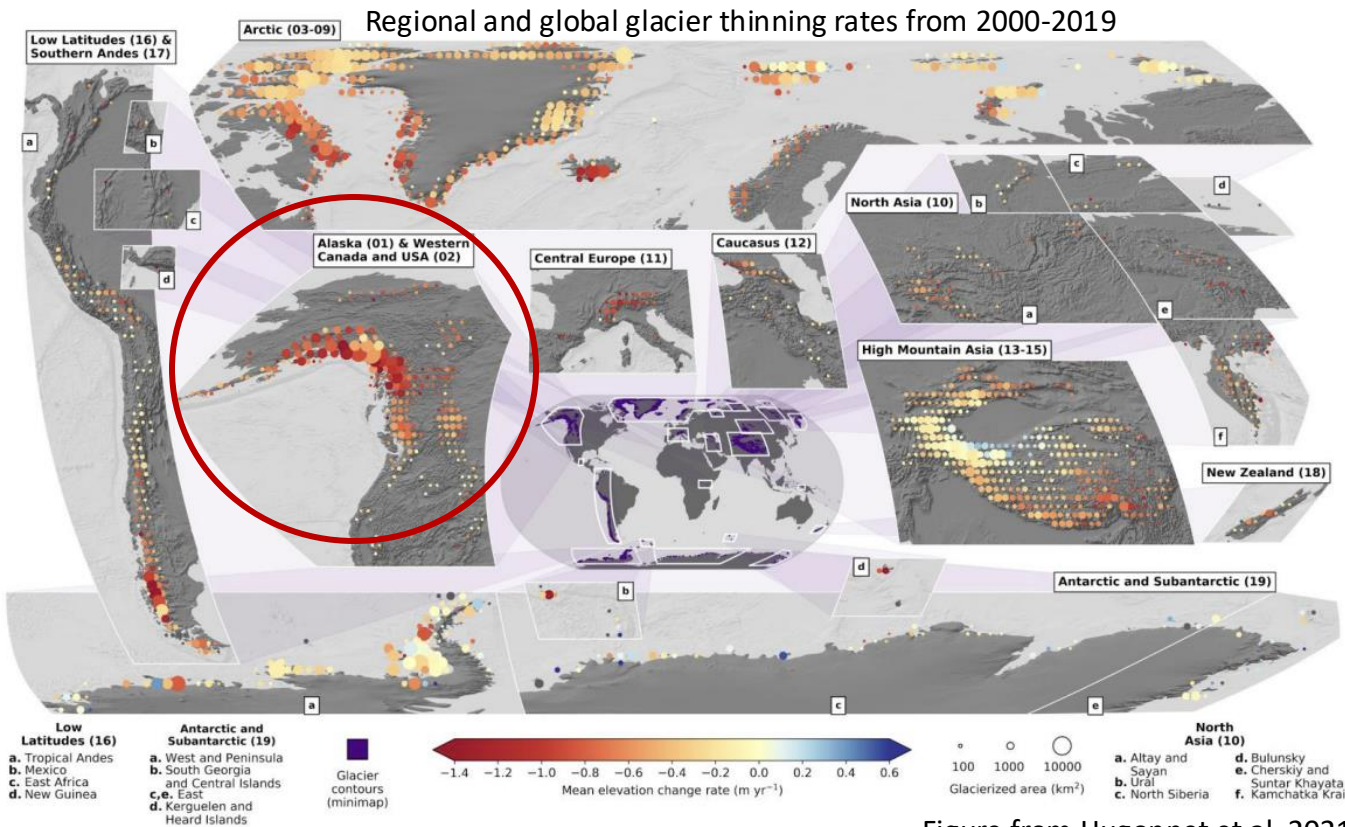


Figure from Hugonnet et al. 2021

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

First, we need to understand how glaciers work!



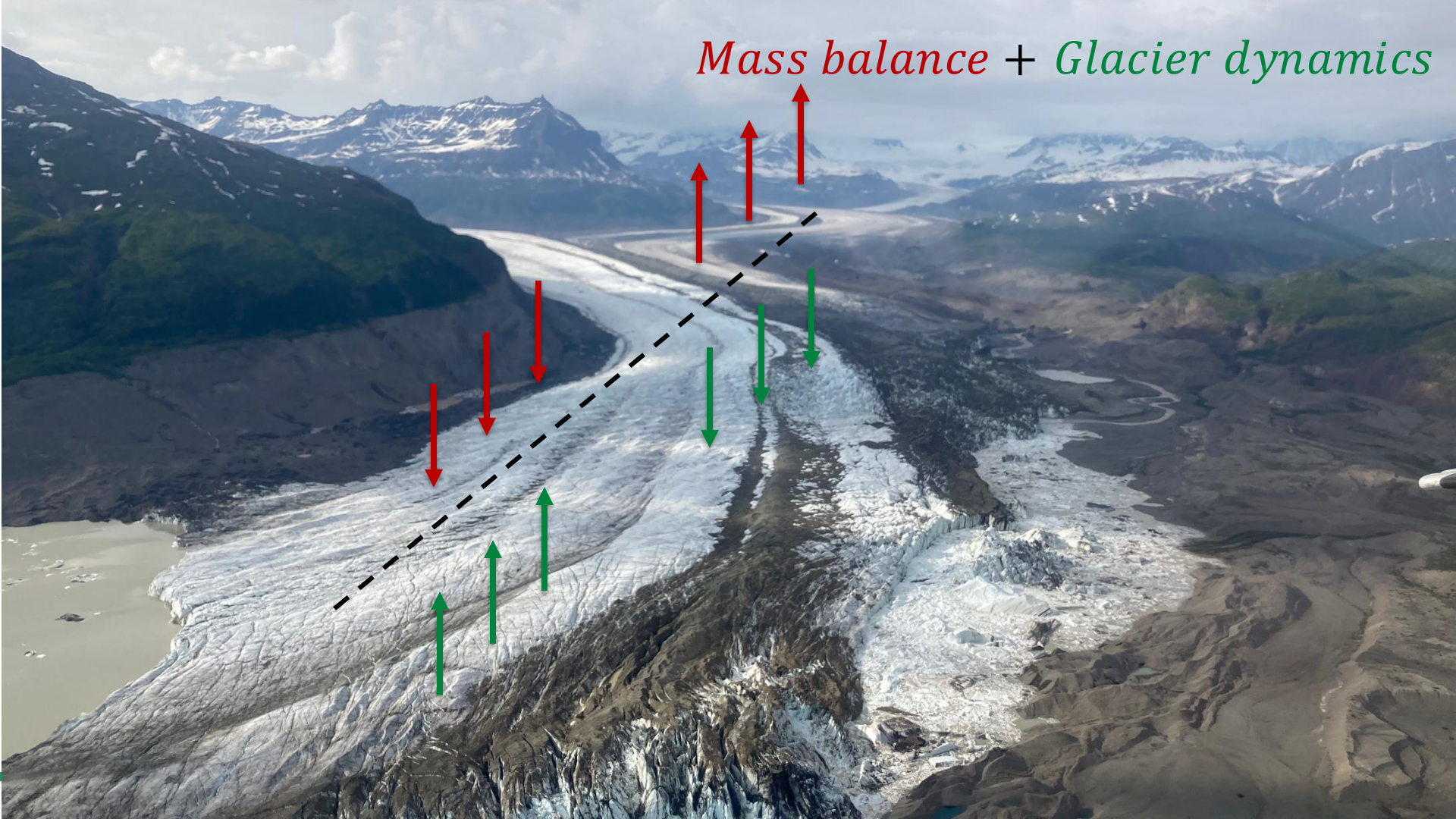
Climate + *Gravity*



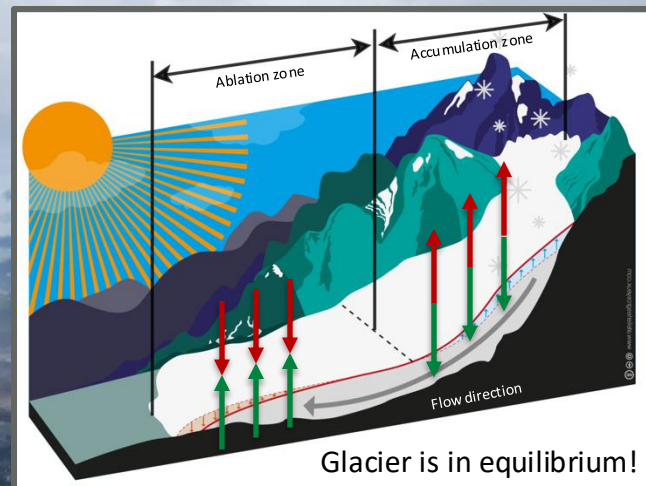
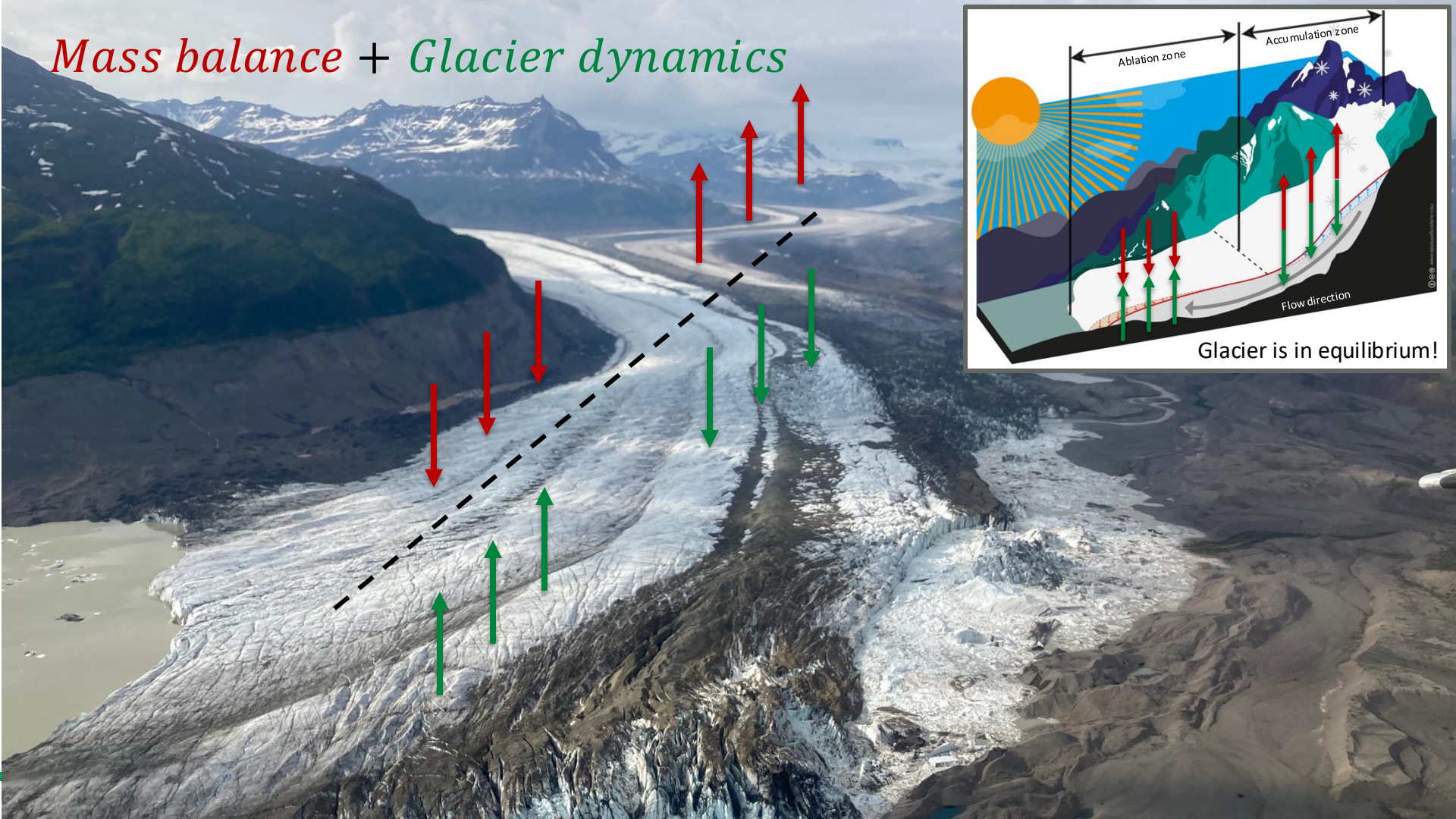
Mass balance + *Glacier dynamics*



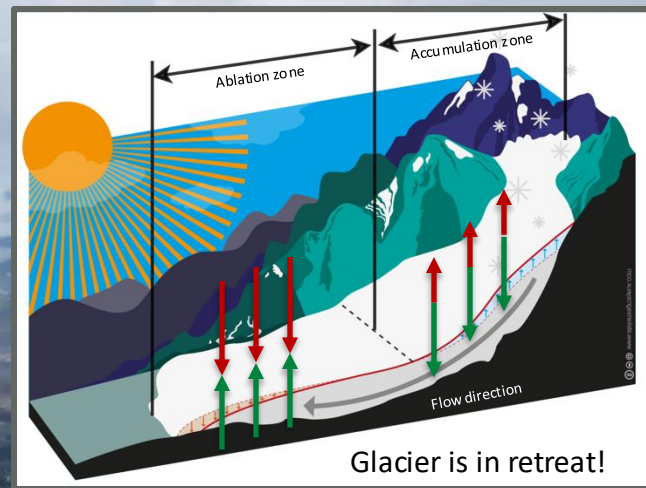
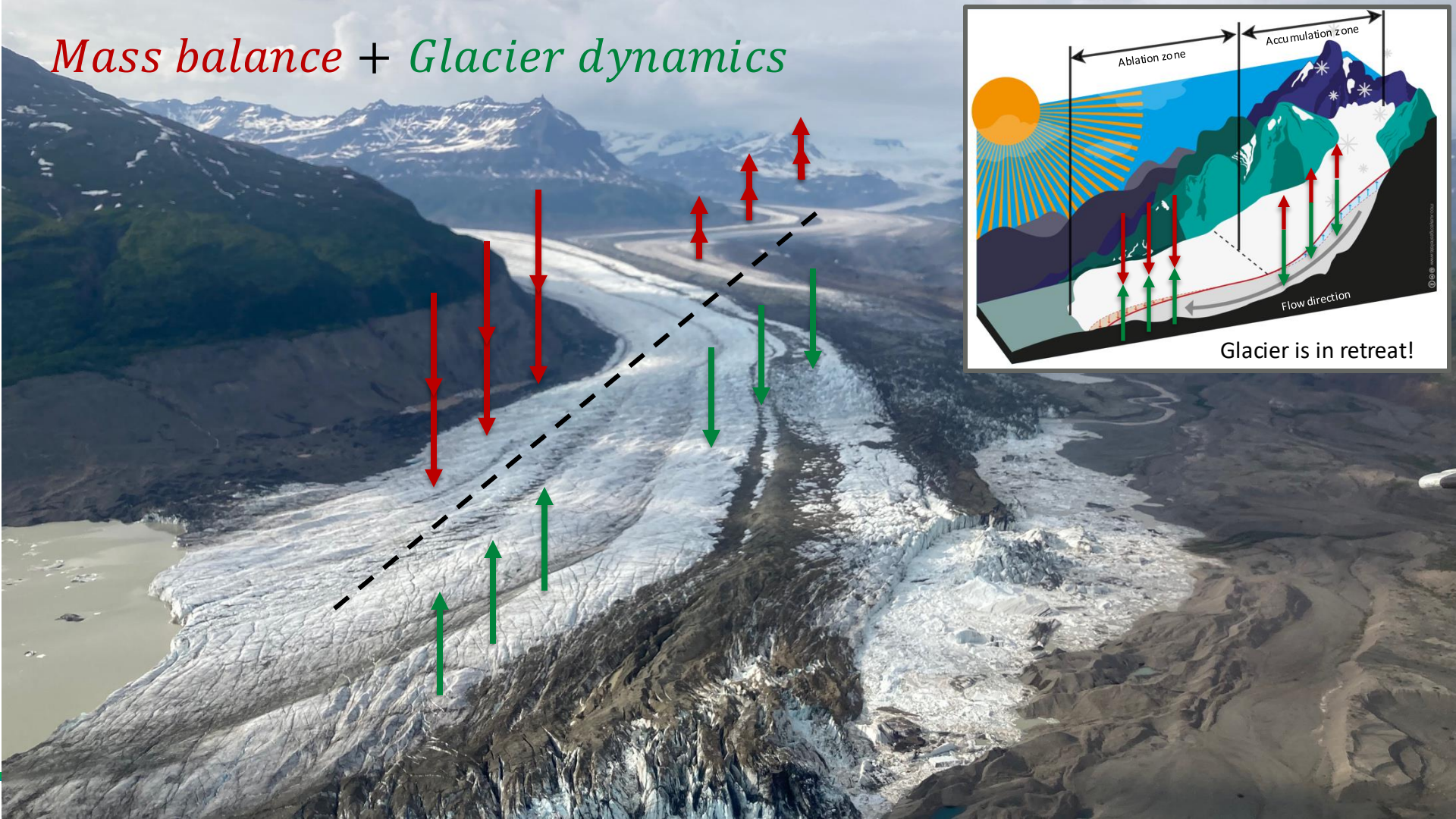
Mass balance + *Glacier dynamics*



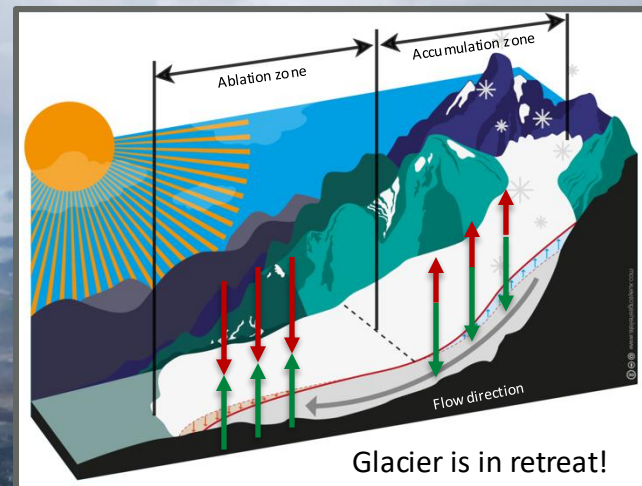
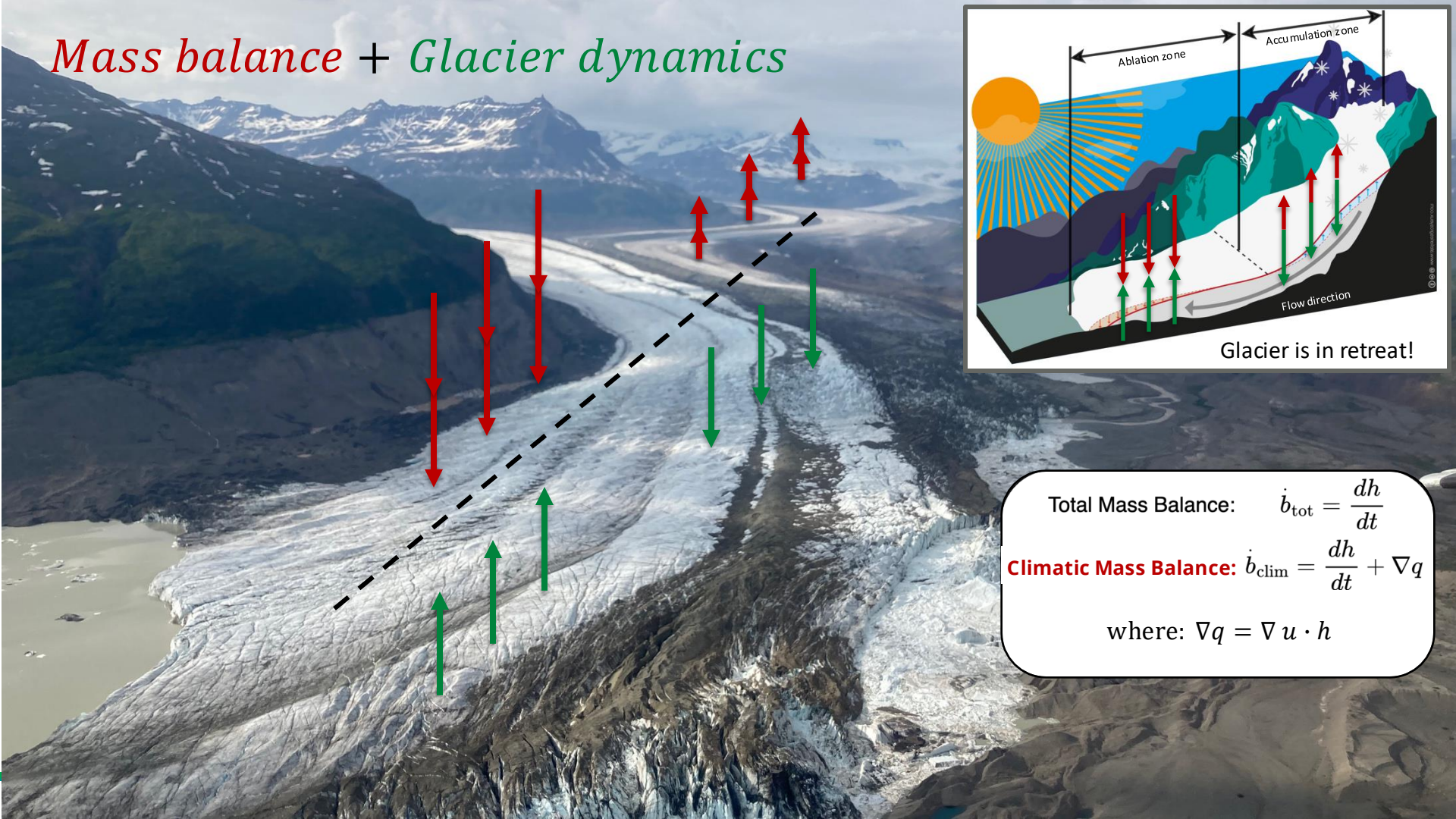
Mass balance + *Glacier dynamics*



Mass balance + *Glacier dynamics*



Mass balance + Glacier dynamics



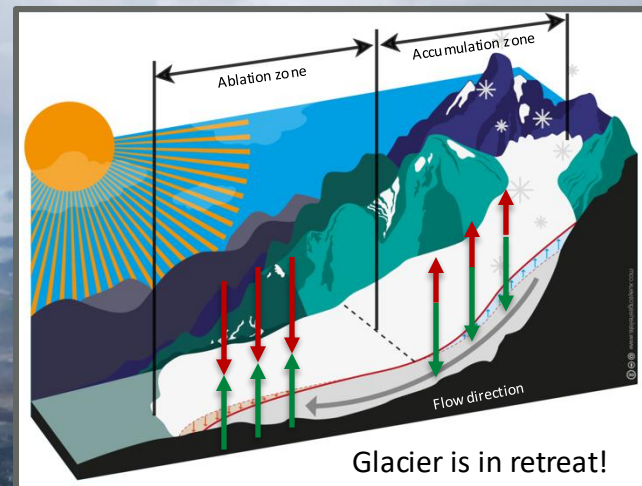
Total Mass Balance: $\dot{b}_{\text{tot}} = \frac{dh}{dt}$

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



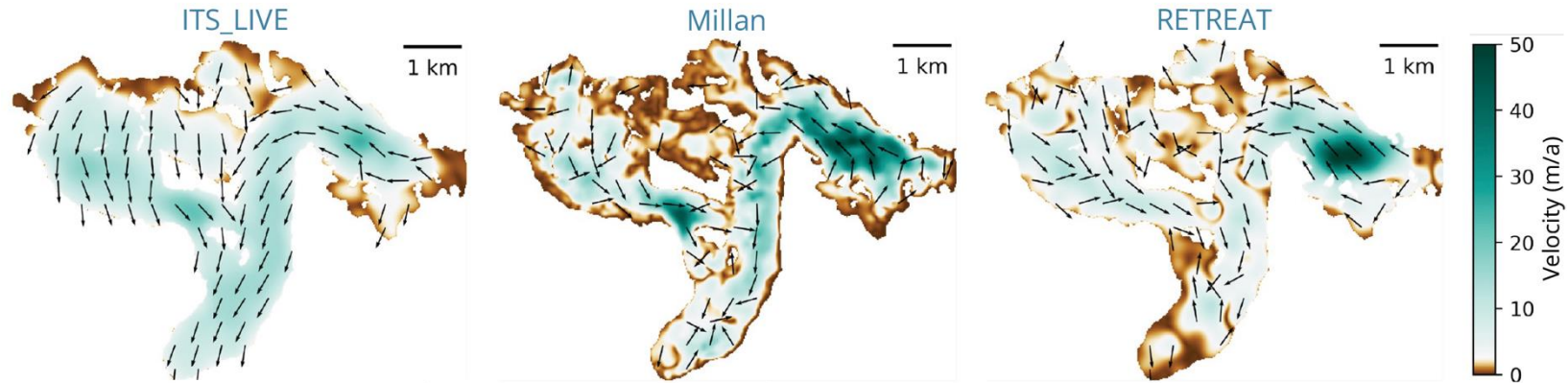
Total Mass Balance: $\dot{b}_{\text{tot}} = \frac{dh}{dt}$

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

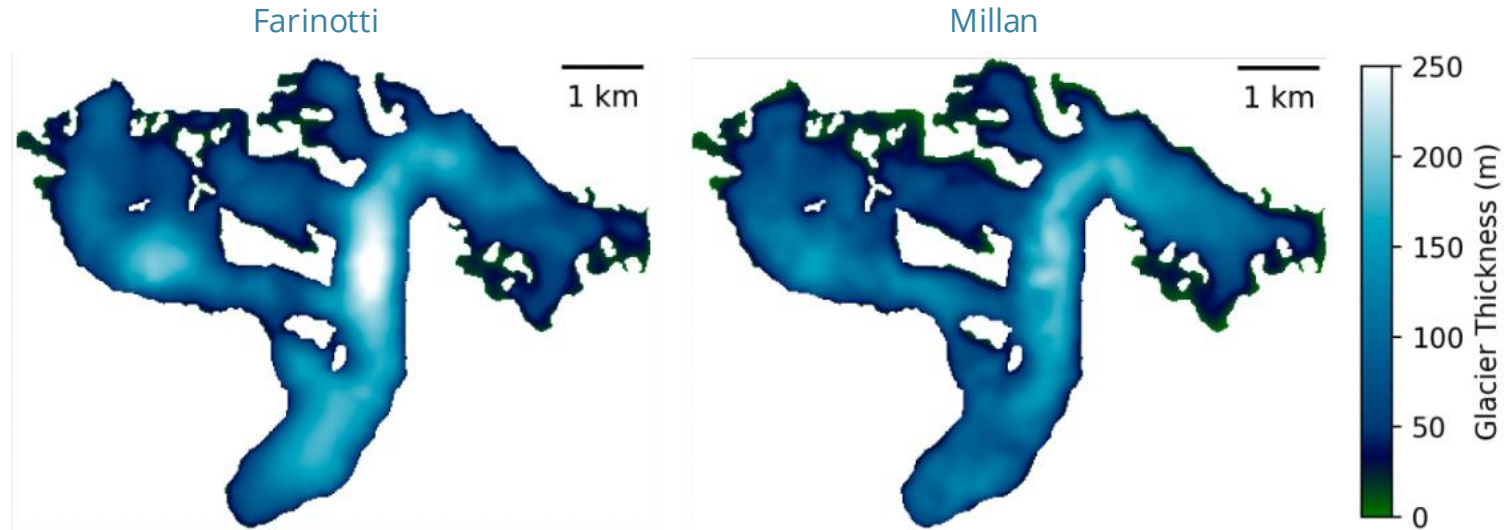
where: $\nabla q = \nabla u \cdot h$

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



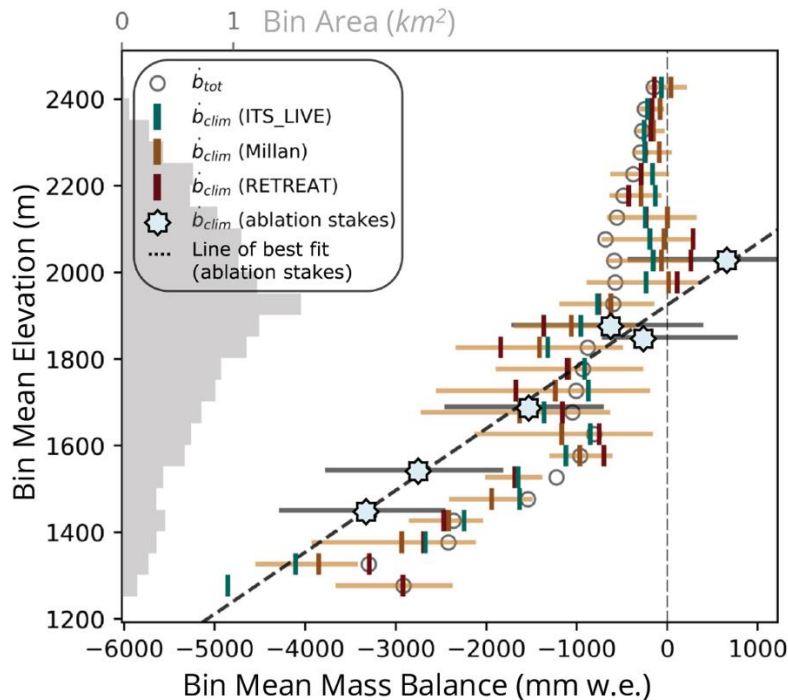
Modeled ice thickness products also differ



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

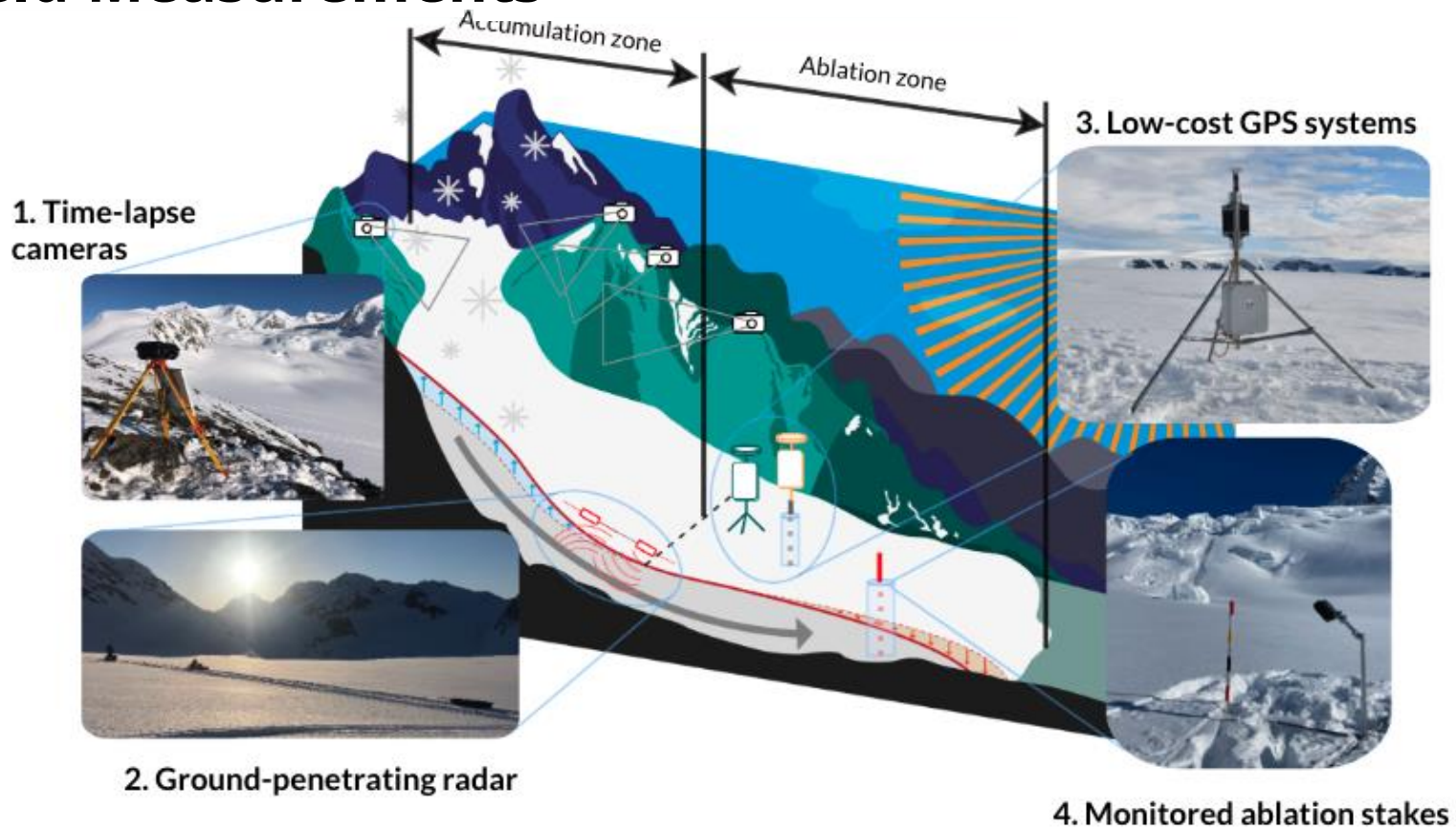
Gulkana Glacier climatic mass balance as a function of elevation



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

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:

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

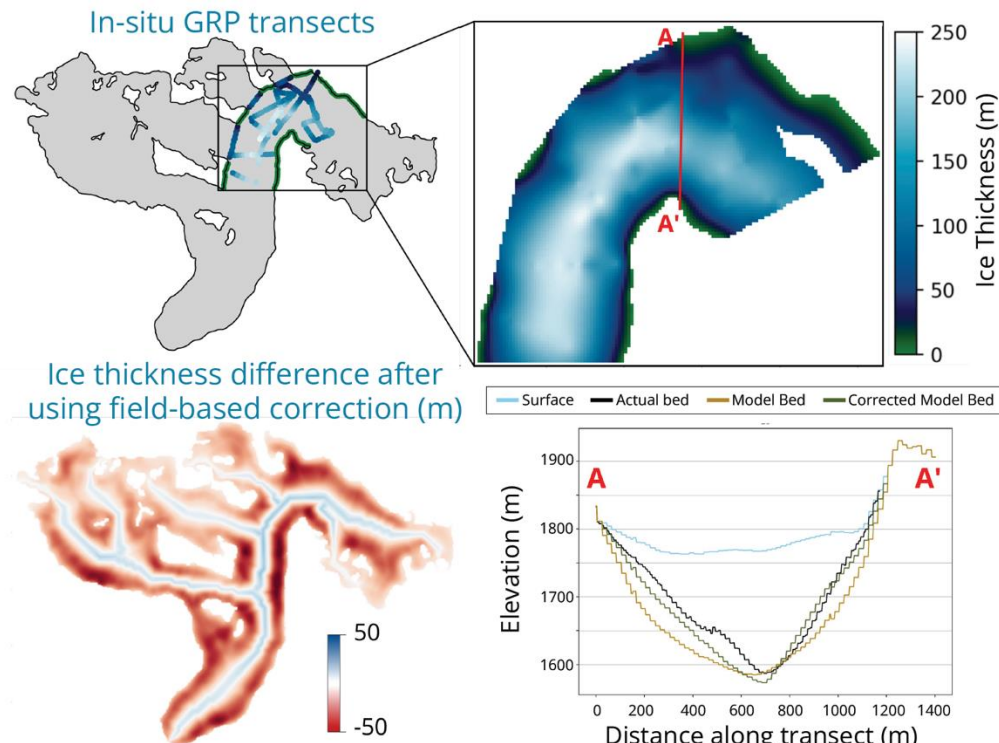
- Monitored ablation stakes
- Low-cost GPS systems

Flux Divergence:

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

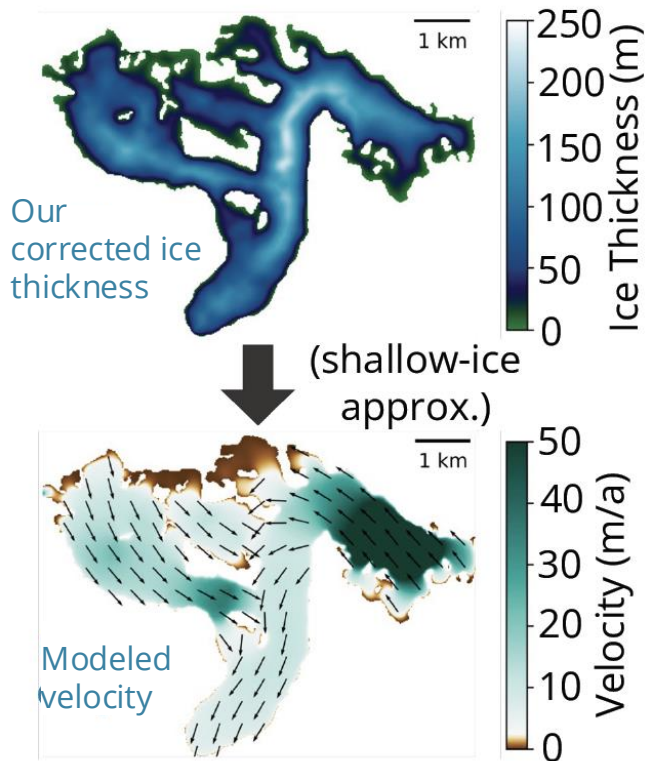
- Time-lapse cameras
- Ground-penetrating radar
- Low-cost GPS systems

Integrating field measurements with existing data products: Ice thickness

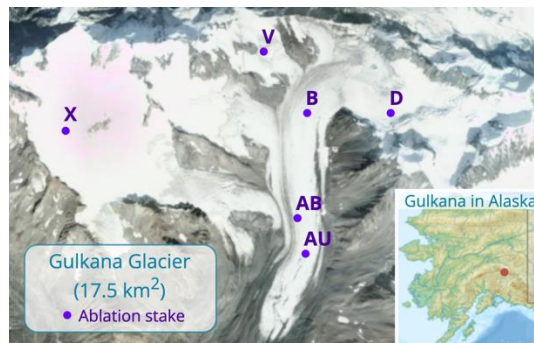


- On Gulkana, ice thickness products...
 - underestimate thickness along the centerline
 - overestimate ice thickness along the margins
- Essentially, our data is used to correct the ice thickness product for the proper bed shape

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

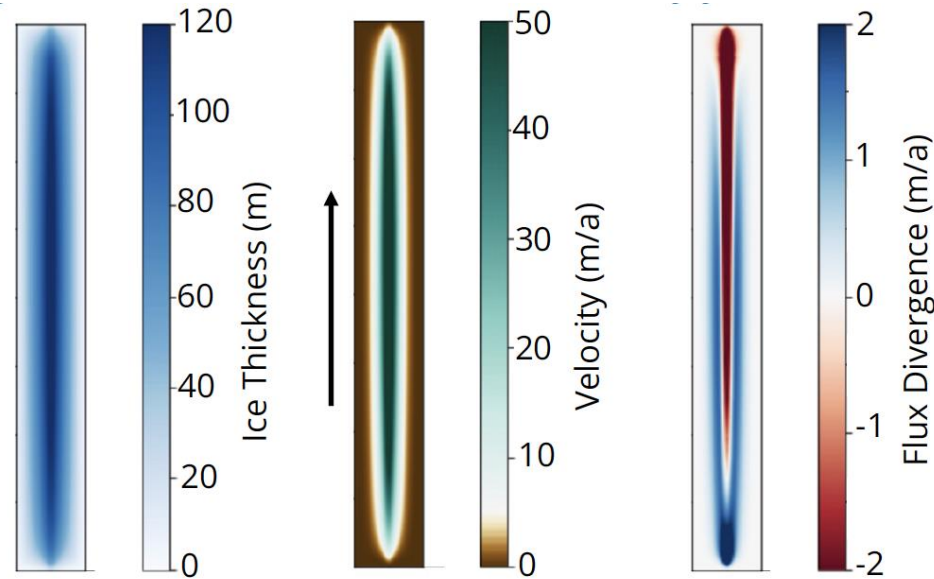


Velocity at Ablation Stake Locations (m/a)

		Location			
		AU	AB	B	D
Data Source	Stake	18.5	23.9	39.7	53.9
	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

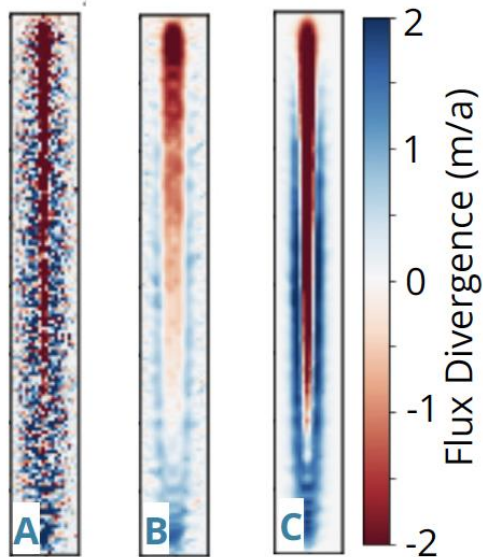
- *How accurate do ice thickness and velocity need to be?*
- Start with idealized glacier and derive physically consistent ice thickness and velocity



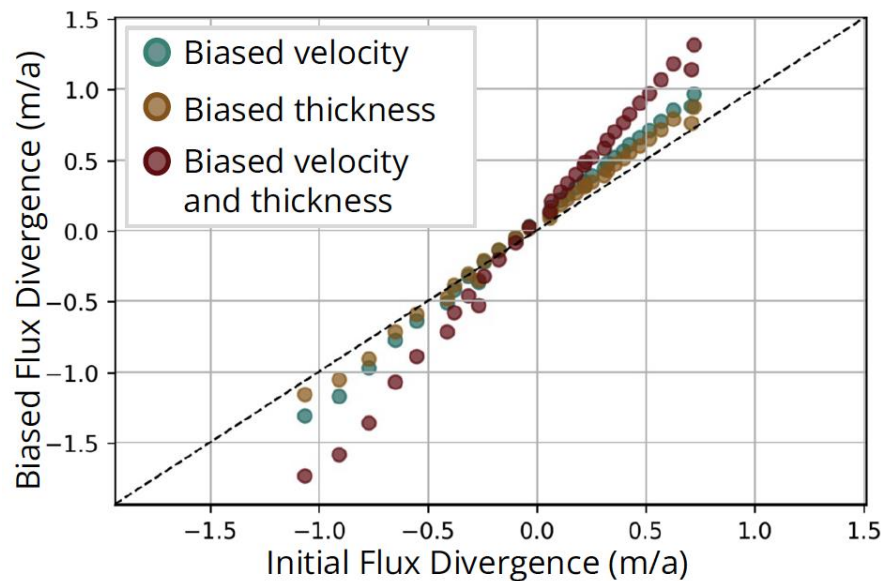
A theoretical approach to the climatic mass balance

- 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



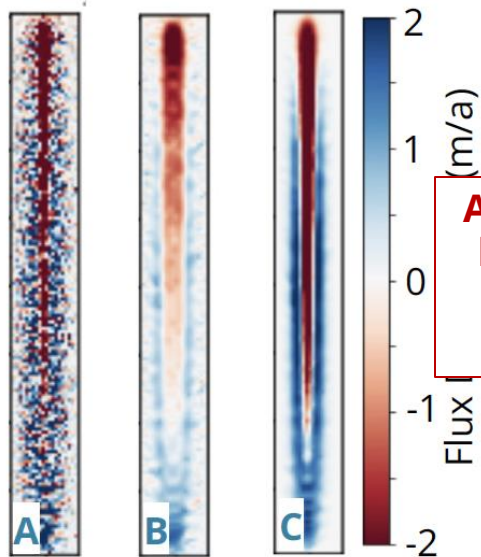
Overestimation bias effect on flux divergence



A theoretical approach to the climatic mass balance

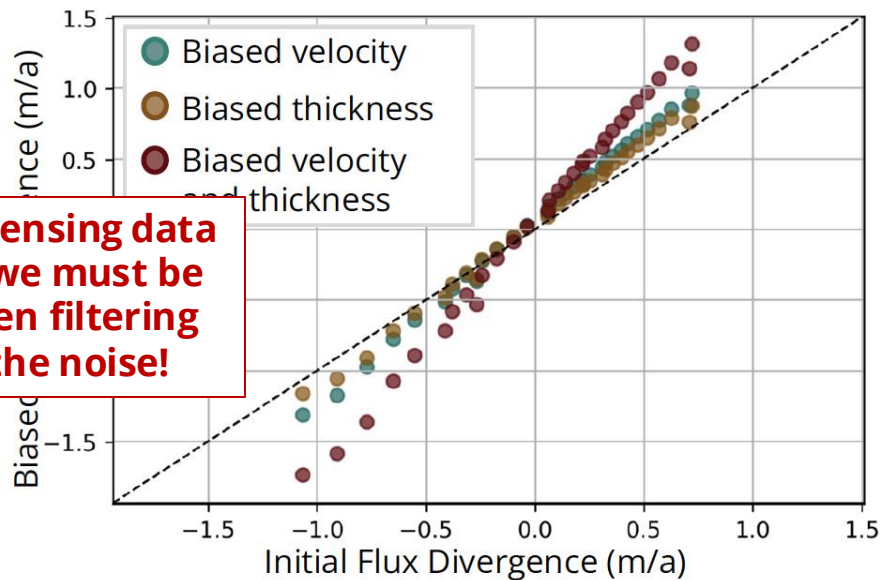
- Then, introduce noise and/or bias into the data and see how it affects our results

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