Geodetic mass balance of glaciers

Marin Kneib, glaciologist at Institut des Géosciences de l’Environnement (Grenoble) & University of Innsbruck

Programme

- 1 hour lecture (17/09 14:00-15:00)
- 2 hours exercice in smaller groups:
  - 17/09 16:00-18:00
  - 18/09 08:30-10:30

- Contact: marin.kneib@univ-grenoble-alpes.fr

Programme

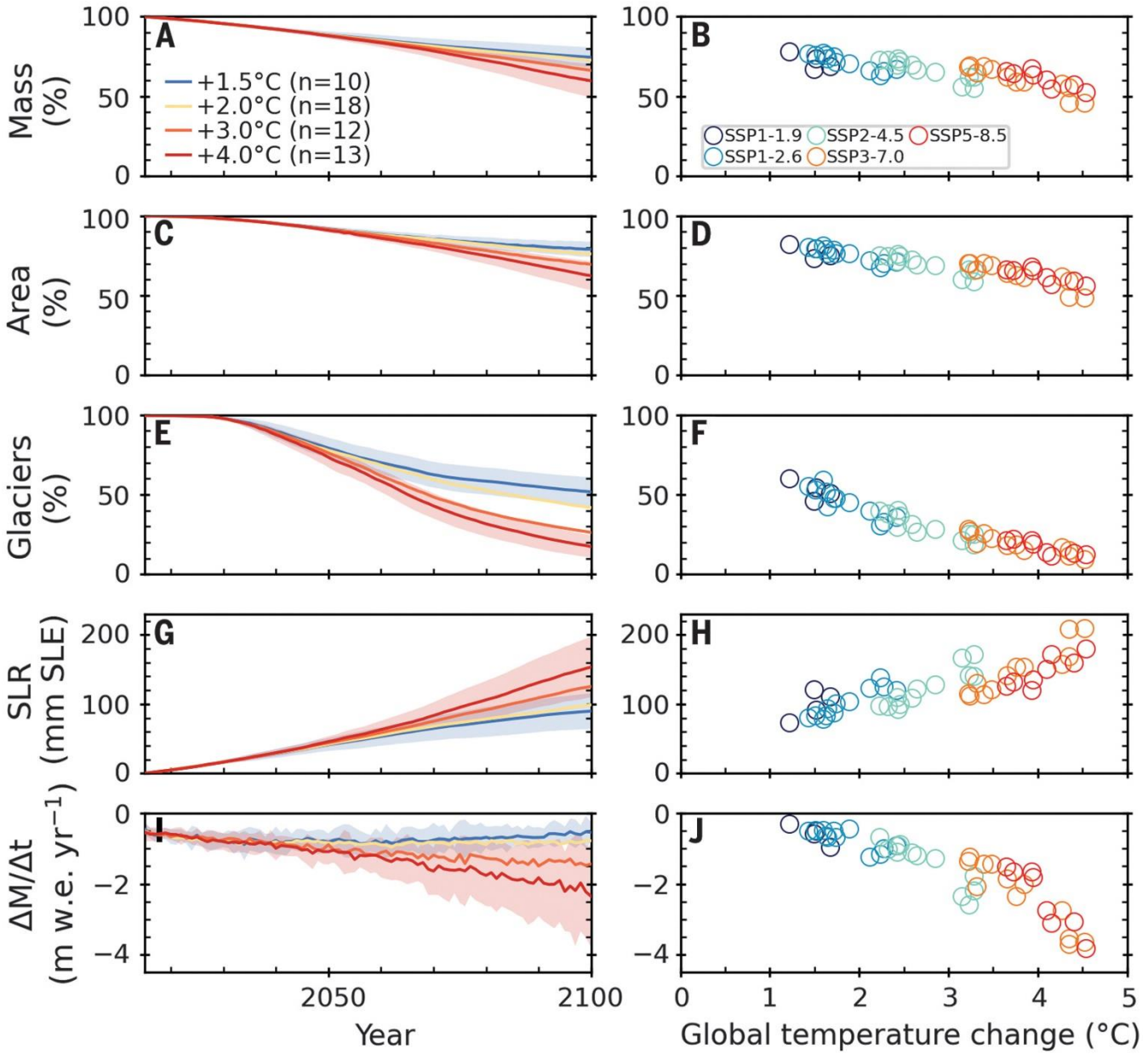
1. Introduction to geodetic mass balance (what for?)
2. Principles
3. Stereo-processing for the generation of DEMs
4. DEM co-registration & differencing
5. Volume & mass changes calculations
6. Uncertainty estimations
7. Perspective: linking geodetic & glaciological mass balance
8. ***Exercices with geoutils & xdem (python, Jupyter notebook)***

Objectives:

1. **Get familiar with the overall processing chain from satellite image acquisitions to mass change calculation along with the underlying assumptions & limitations**
2. **Calculate your own geodetic mass balance of a glacier based on two DEMs**

Geodetic mass balance? What for?

Geodetic mass balance? What for?



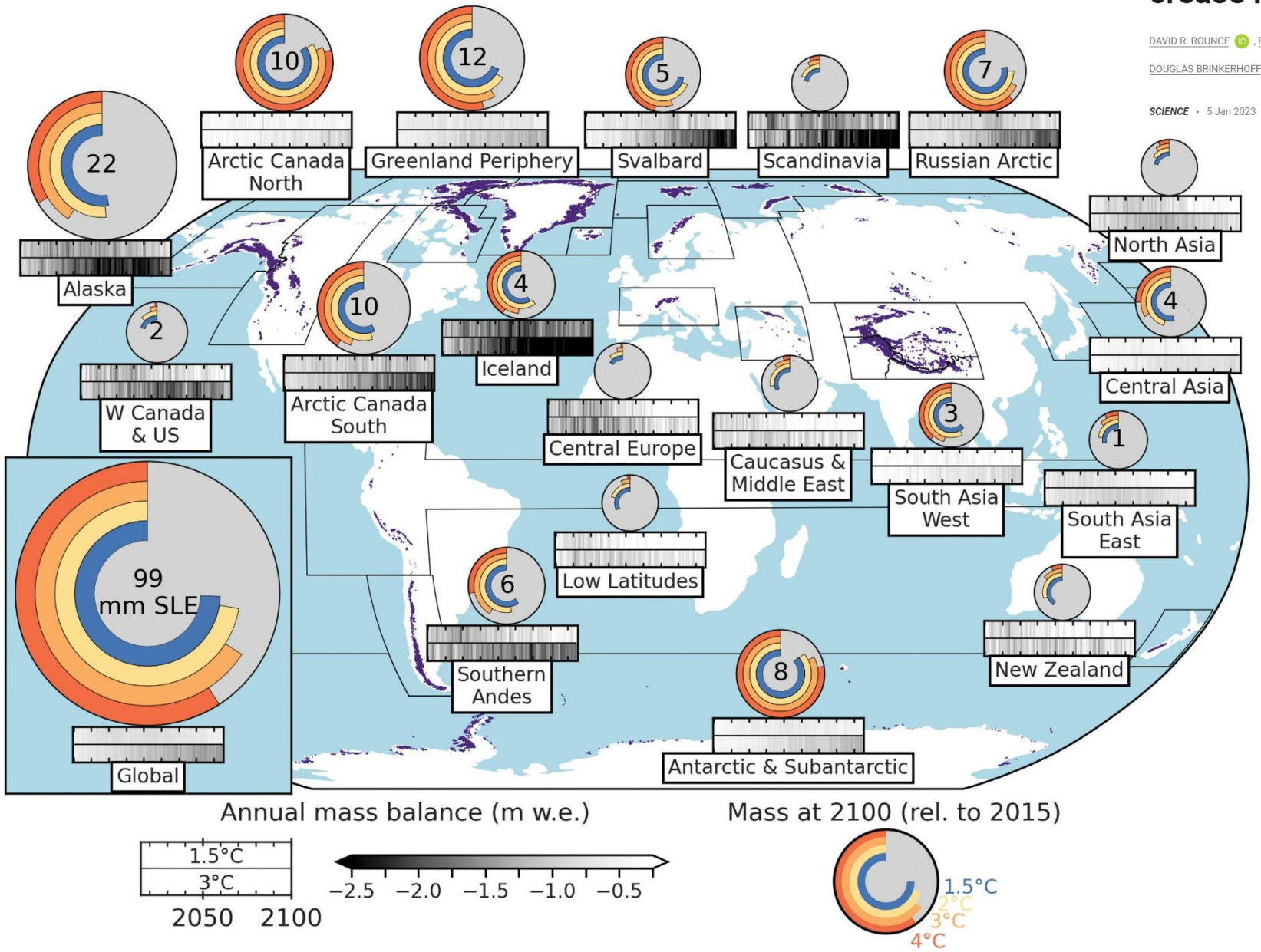
RESEARCH ARTICLE | GLACIERS

Global glacier change in the 21st century: Every increase in temperature matters

DAVID R. ROUNCE, REGINE HOCK, FABIEN MAUSSION, ROMAIN HUGONNET, WILLIAM KOCHTITZKY, MATTHIAS HUSS, ETIENNE BERTHIER, DOUGLAS BRINKERHOFF, LORIS COMPAGNO, [...], AND ROBERT W. MCNABB +3 authors Authors Info & Affiliations

SCIENCE • 5 Jan 2023 • Vol 379, Issue 6627 • pp. 78-83 • DOI: 10.1126/science.abo1324

Geodetic mass balance? What for?



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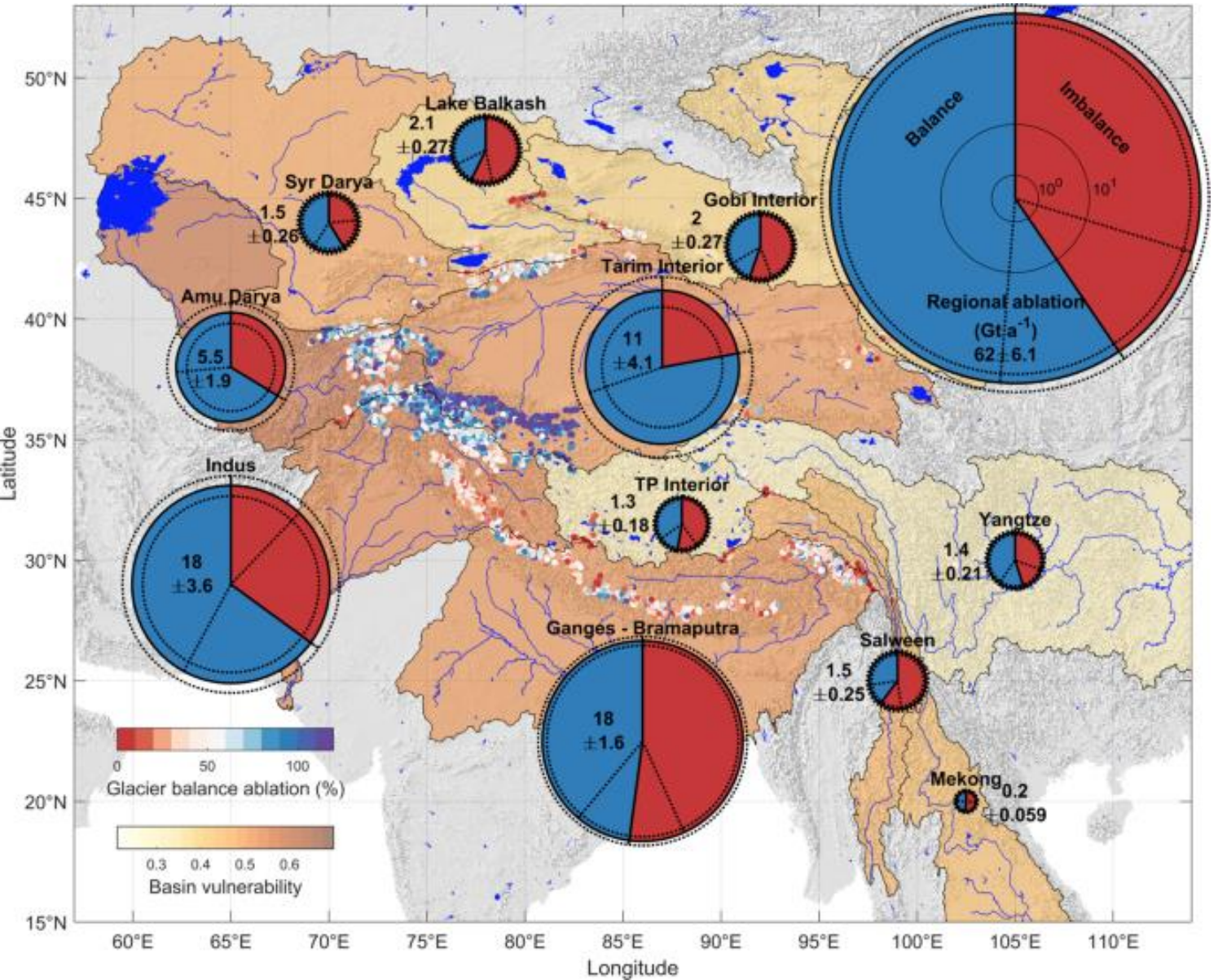


Article | Open access | Published: 17 May 2021

Health and sustainability of glaciers in High Mountain Asia

Evan Miles, Michael McCarthy, Amaury Dehecq, Marin Kneib, Stefan Fugger & Francesca Pellicciotti

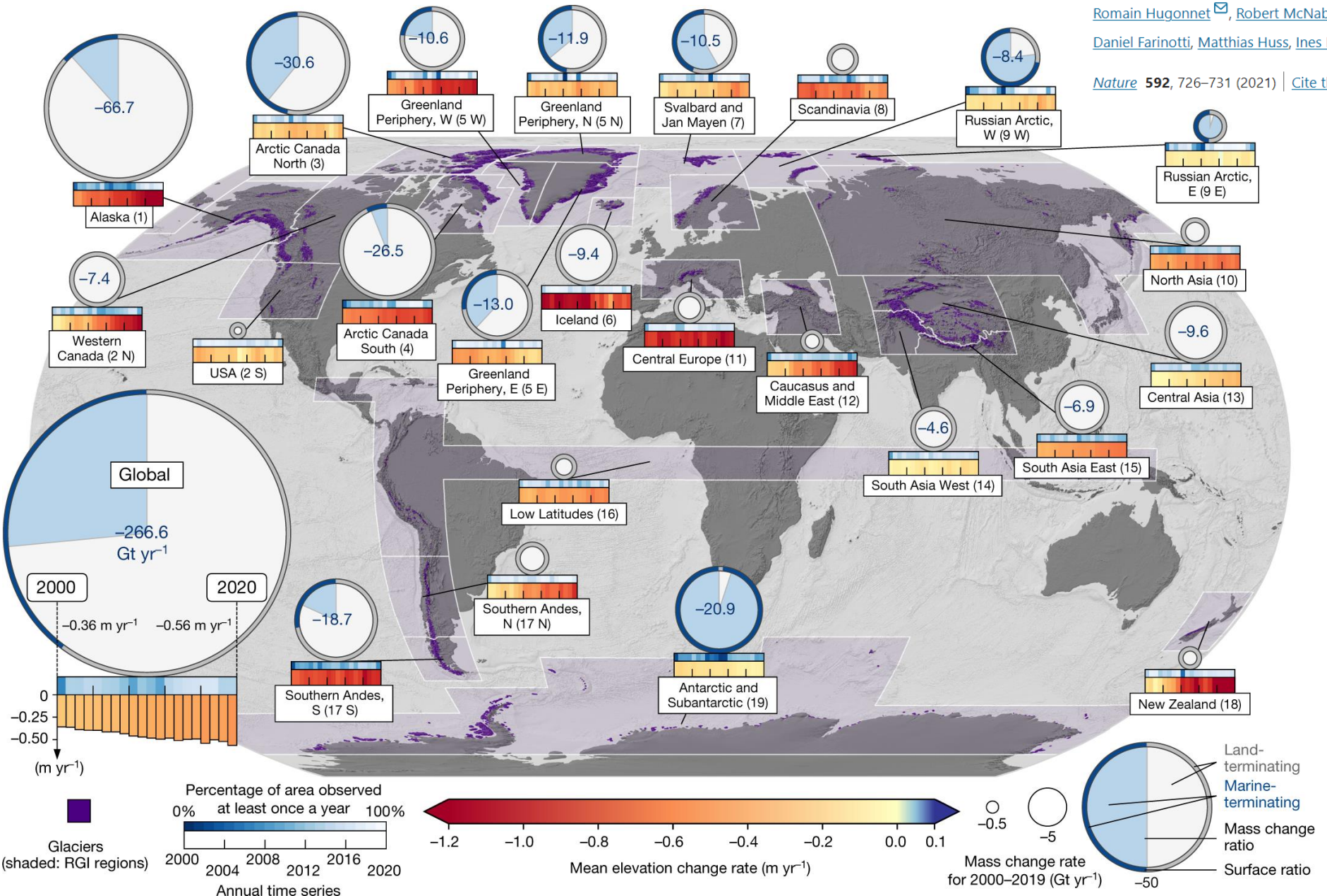
Nature Communications **12**, Article number: 2868 (2021) | Cite this article

Geodetic mass balance? What for?

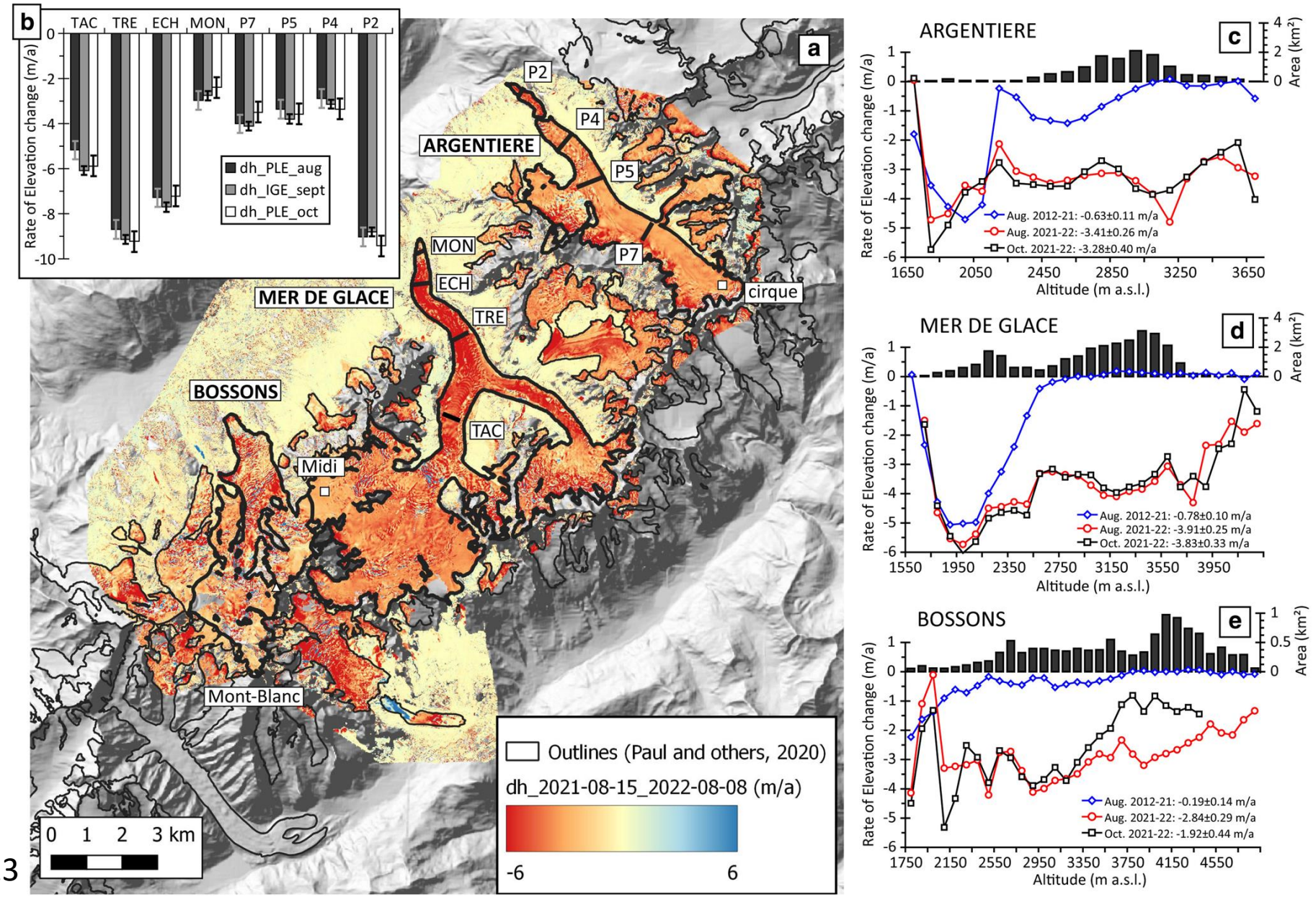
Accelerated global glacier mass loss in the early twenty-first century

Romain Hugonnet, Robert McNabb, Etienne Berthier, Brian Menounos, Christopher Nuth, Luc Girod, Daniel Farinotti, Matthias Huss, Ines Dussaillant, Fanny Brun & Andreas Kääb

Nature **592**, 726–731 (2021) | Cite this article



Geodetic mass balance? What for?



Berthier et al., 2023

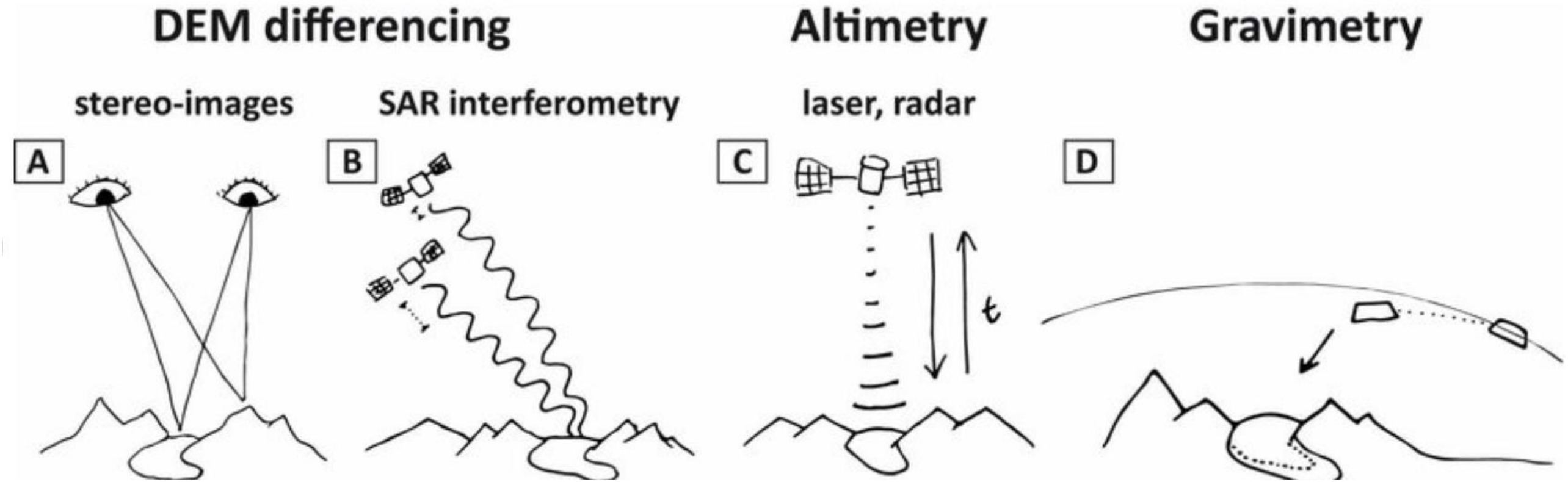
Geodetic mass balance? What for?

Geodetic mass balance: Mass change of glaciers calculated from a difference of digital elevation models acquired multi years apart

Digital elevation model (DEM): gridded representation of topography

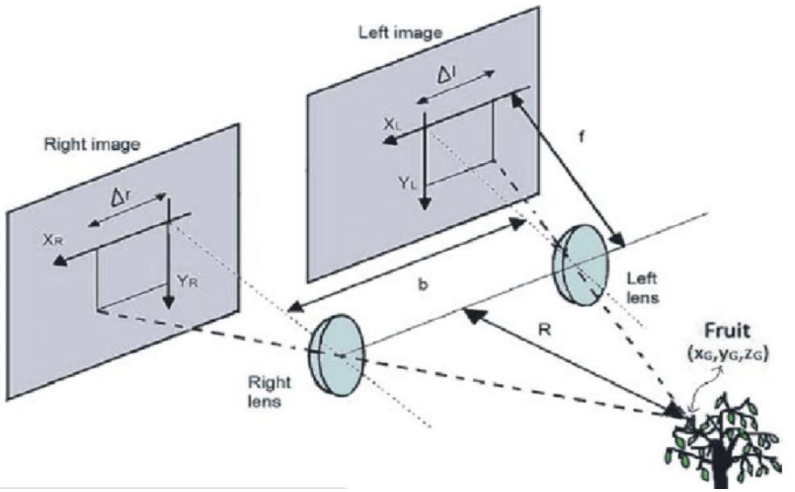
Principles of geodetic mass balance

Measurements of mass/volume changes from space



Berthier et al., 2023b

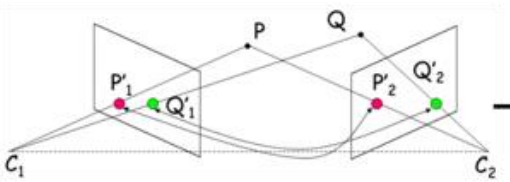
Optical stereo data



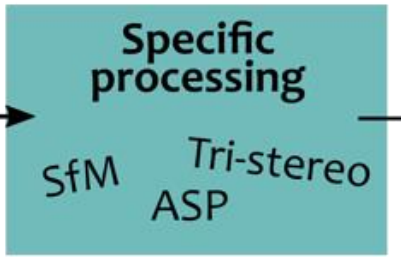
- Advantages:
  - High spatial resolution (up to 50 cm of ground sampling distance)
  - Based on images in visible and near infra-red -> easy to interpret by humans

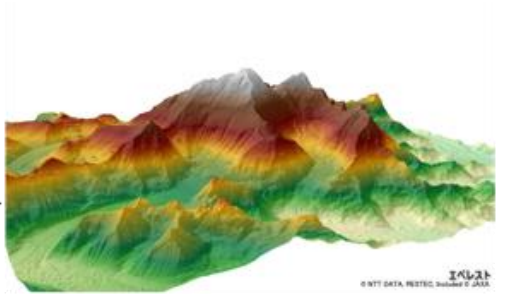
- Drawbacks:
  - Obscured by clouds and polar night. Some problems in the steep faces in the shade.
  - Sensor specific problems (e.g. jitter, undulations, tilt…)

- Some examples:
  - ASTER
  - Pléiades
  - KH9
  - Worldview (HMA DEM)



Principle of photogrammetry

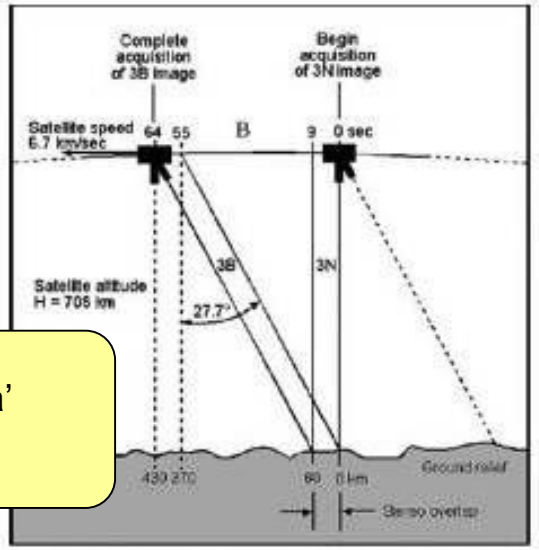




Digital elevation model (DEM)

- Processing:
  - 2-3 images
  - Stereo-processing
  - Software: AMES Stereo Pipeline (ASP), Erdas Imagine, Agisoft Metashape…

2 sources of stereo-images/DEMs



'public data' sensor

ASTER 3N & 3B, 15 m
Along track stereo using two telescopes

↓

30 m DEM
generated using the Ames Stereo Pipeline (ASP)

Commercial satellites

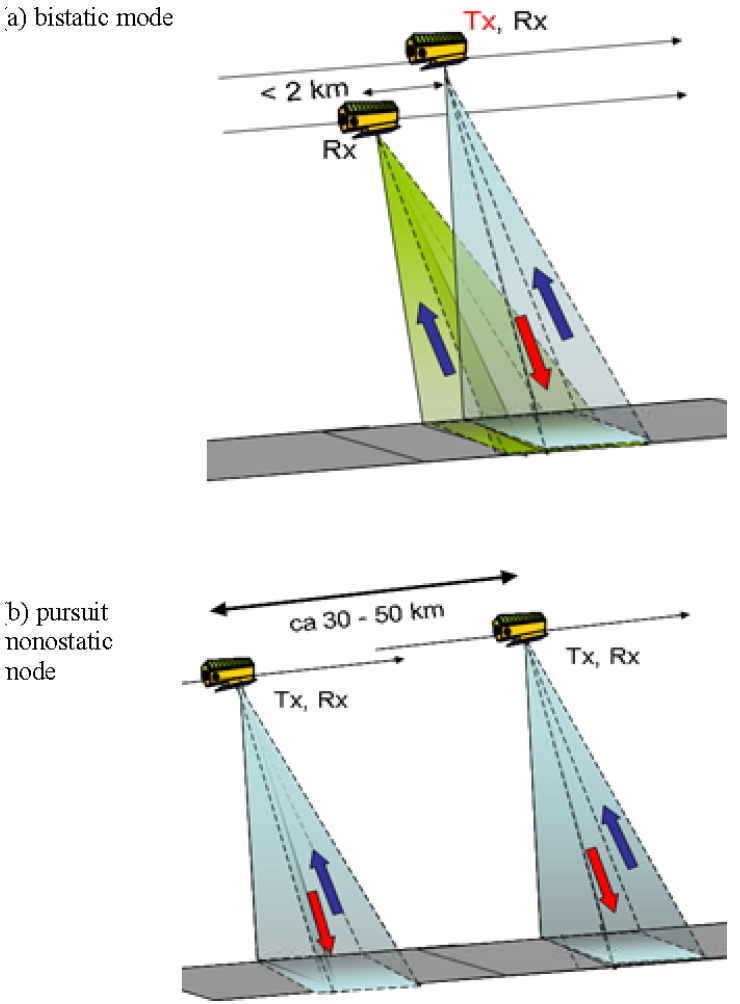
Pléiades 1A & 1B, 0.5 m Along-track stereo satellite agility

↓

DEM generation using the Ames Stereo Pipeline

InSAR data

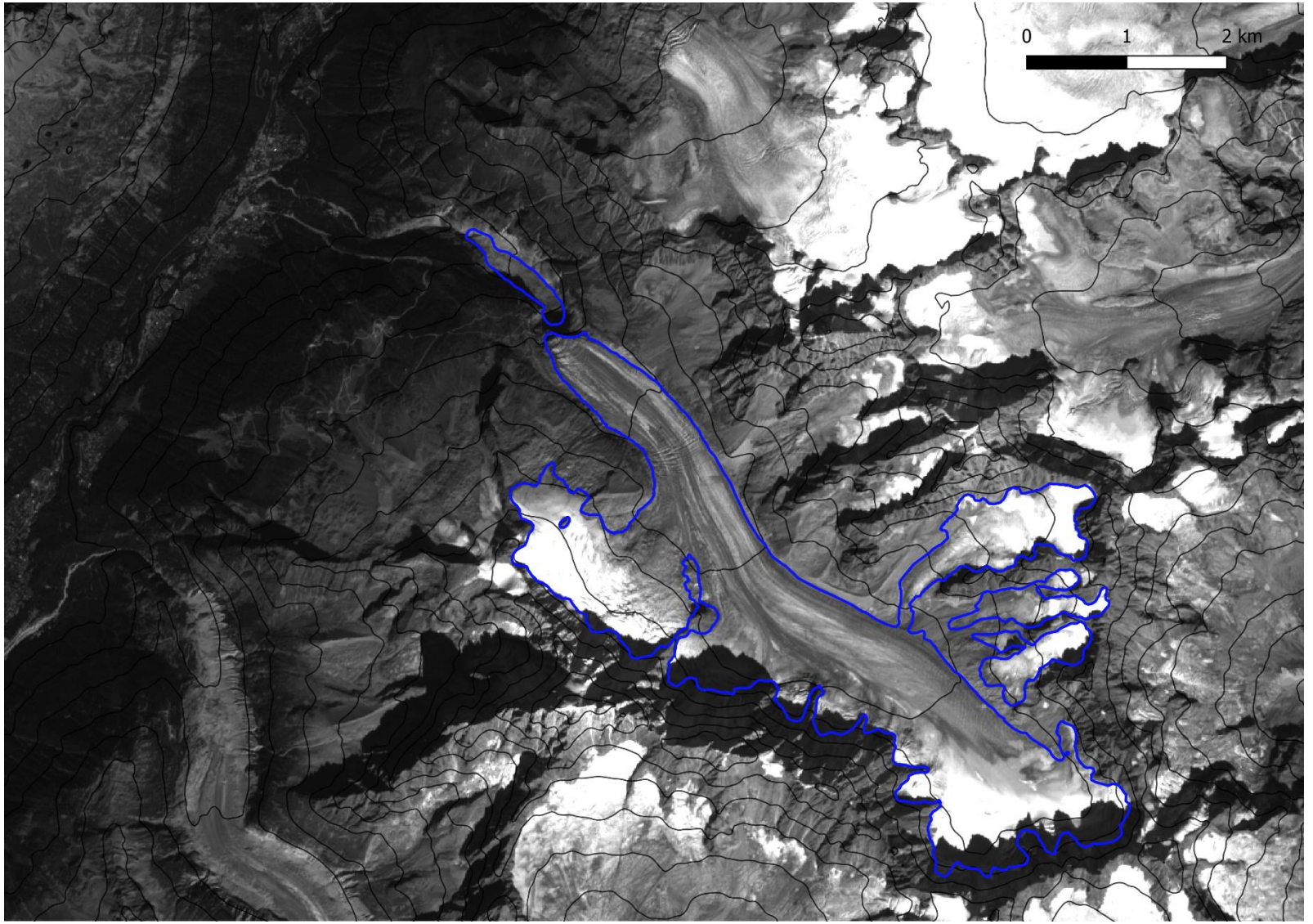
- Advantages:
  - Insensitive to clouds and night
- Drawbacks:
  - Penetration of the radar signal into snow and ice
  - Potential large errors in steep topography
- Some examples:
  - SRTM
  - TanDEM-X



UAV data

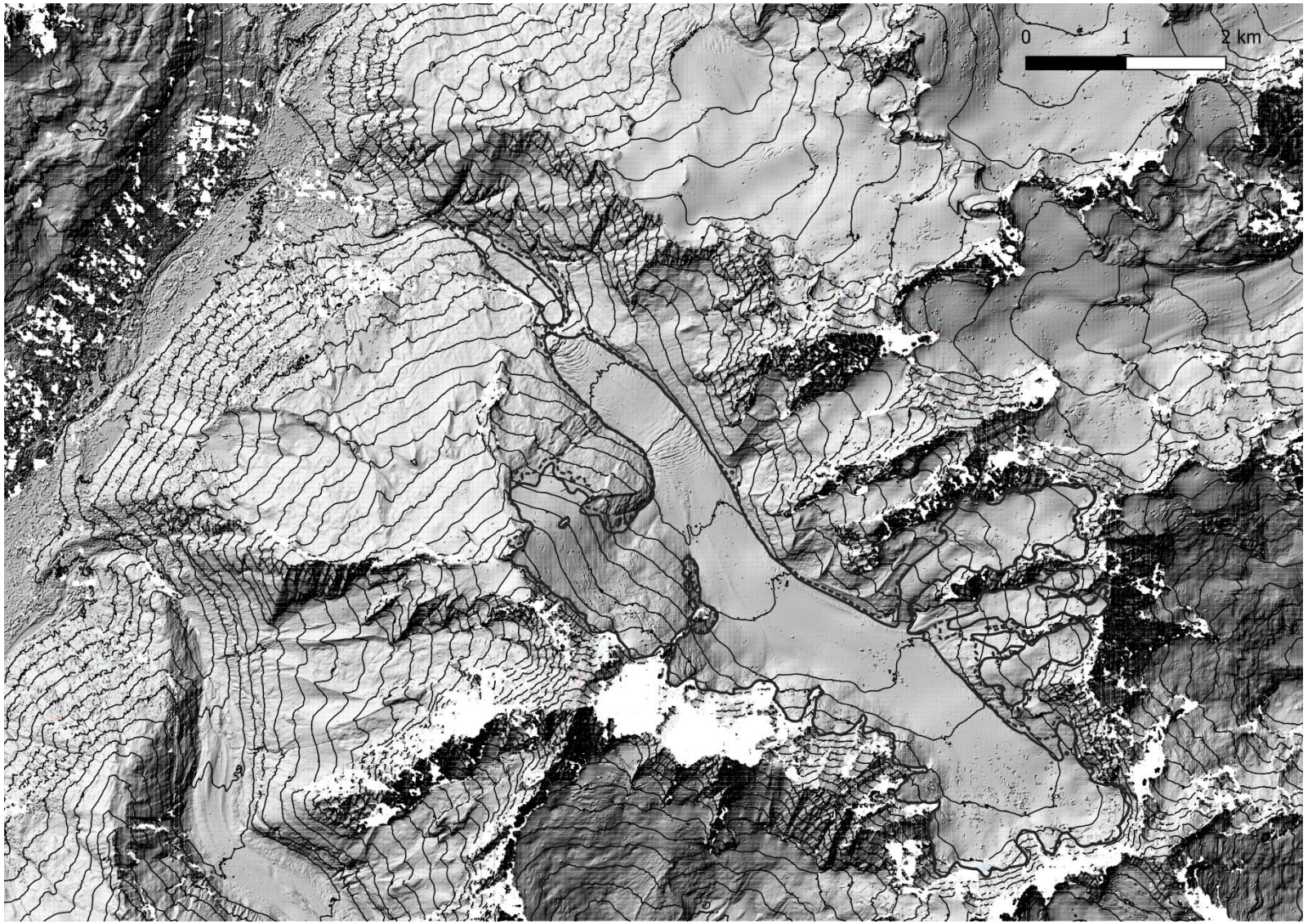
- Advantages:
  - Very high resolution (<10 cm)
  - Constrained only by conditions in the field
  - Possibility of repeat flights
- Drawbacks:
  - Limited spatial coverage
  - Needs some ground control to constrain geometry
- Some examples:
  - Quadcopters
  - Fixed wings/VTOL drones
- Processing:
  - > 100 images
  - Structure-from-motion photogrammetry
  - Software: Agisoft Metashape, Pix4d…

Example: Argentière Glacier



Kneib et al., 2024

Example: Argentière Glacier

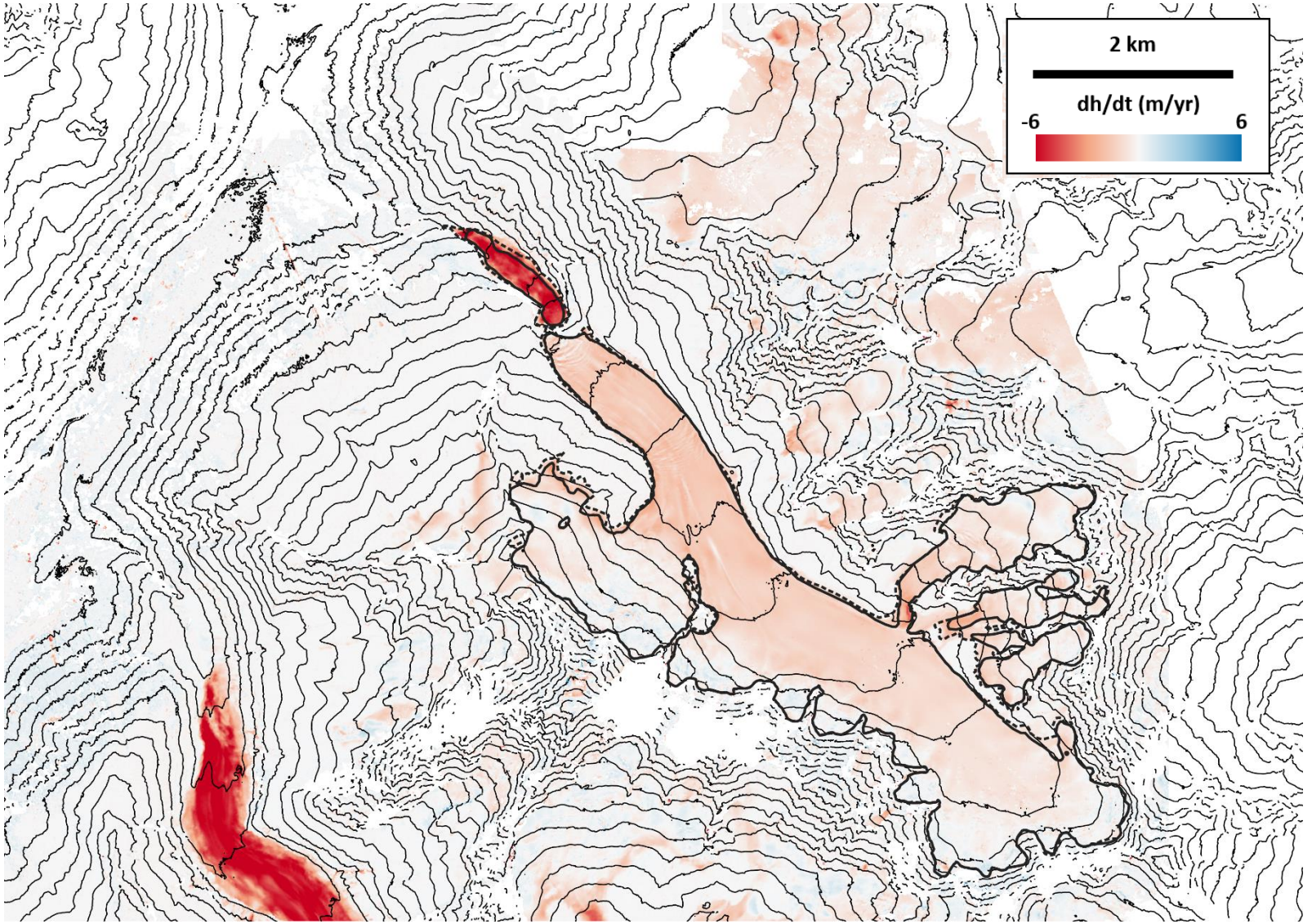


Kneib et al., 2024

Example: Argentière Glacier

Geodetic mass balance (2012-2021):

dh = -0.85 +/- 0.07 m/yr
dh_we = -0.72 +/- 0.08 m w.e./yr



Kneib et al., 2024

Stereo-processing: a brief overview

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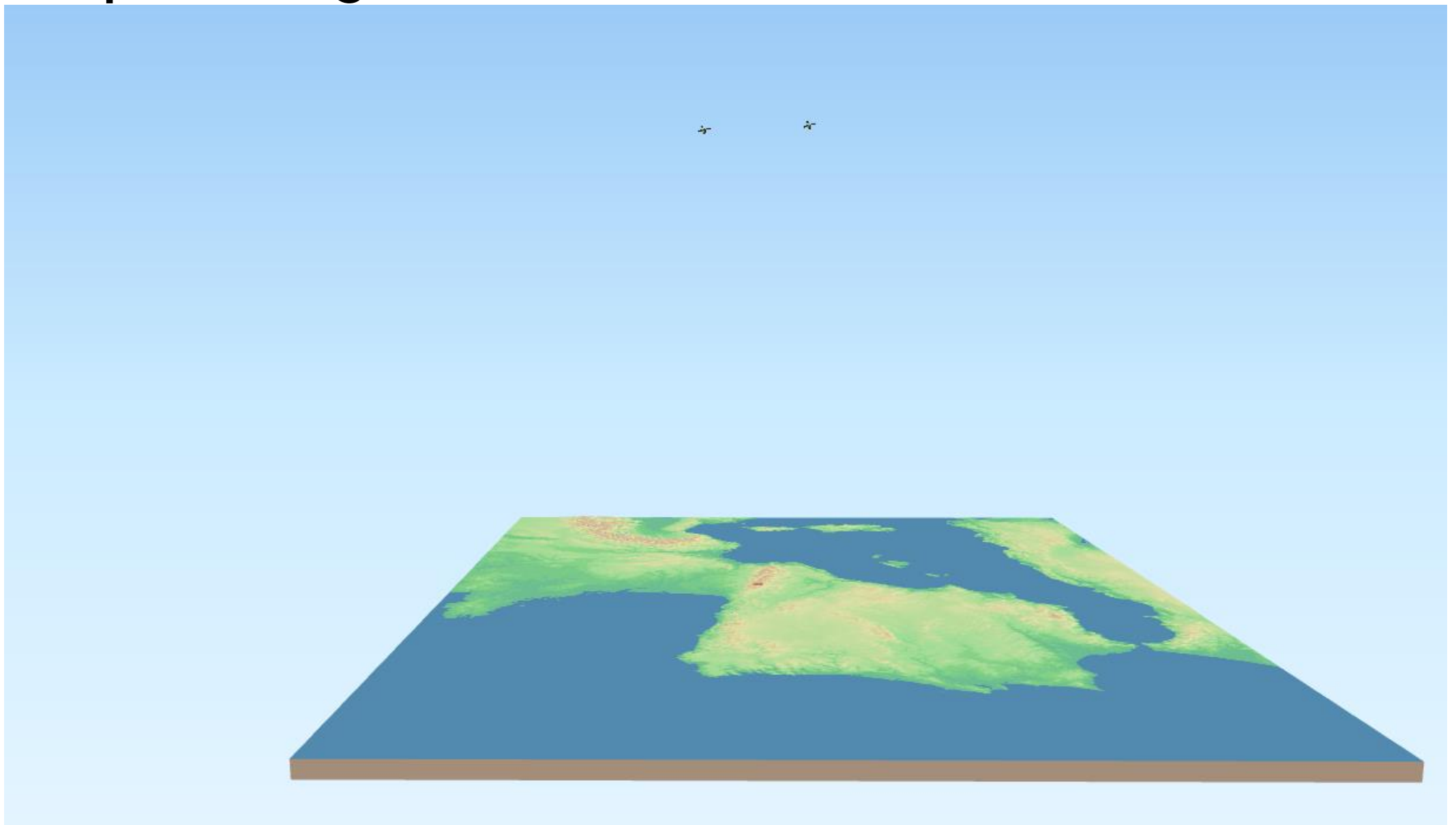

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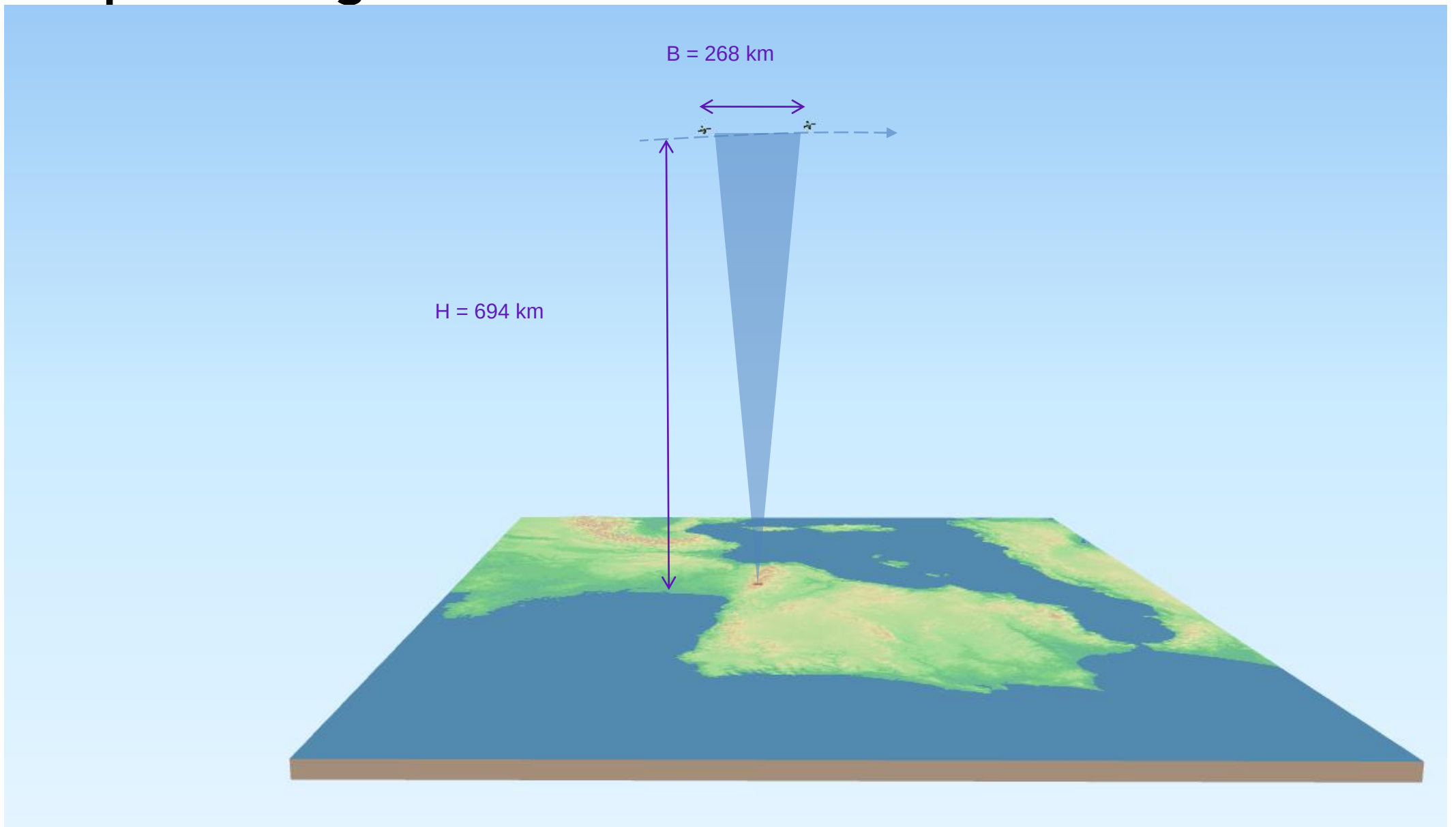

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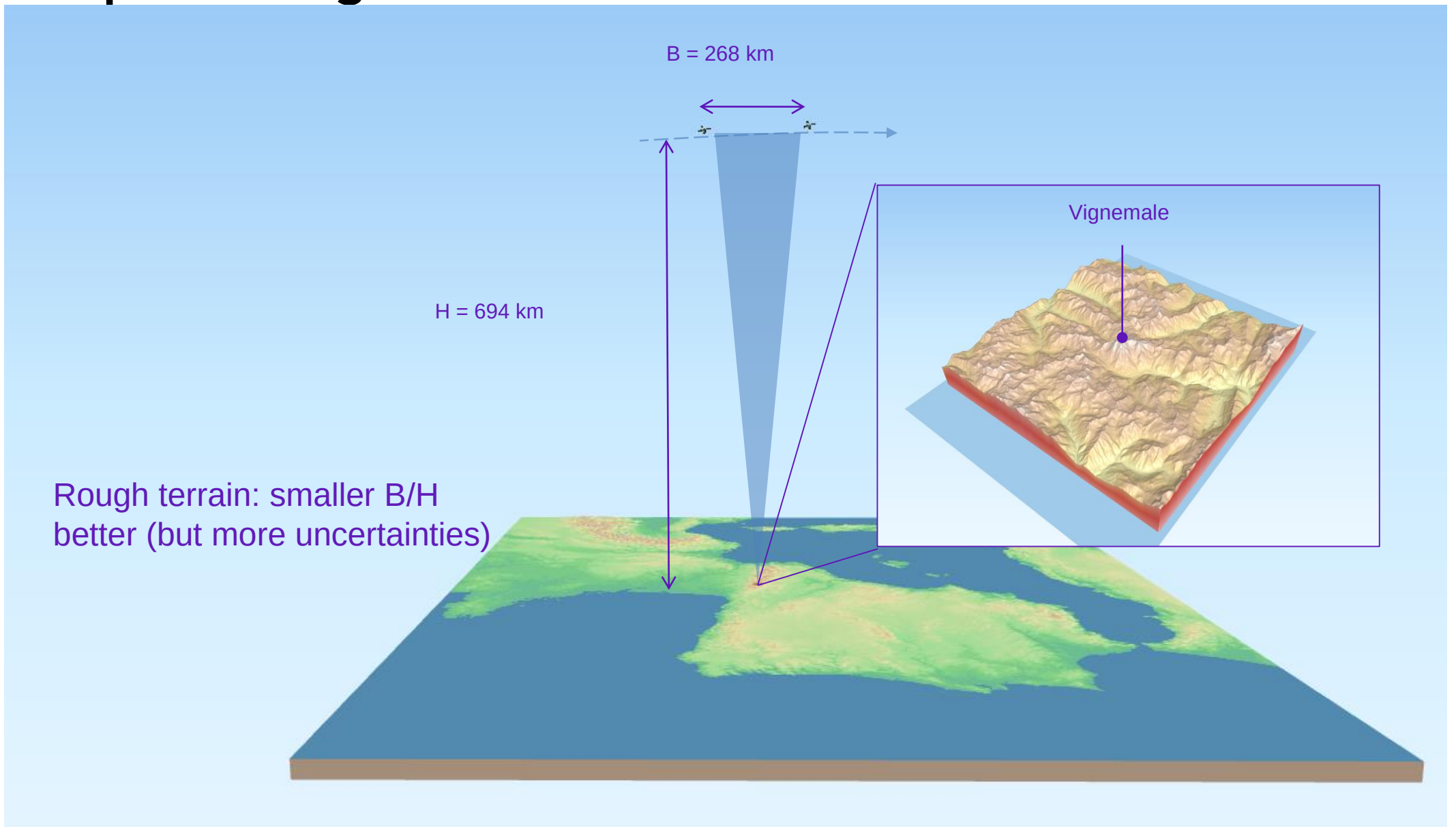
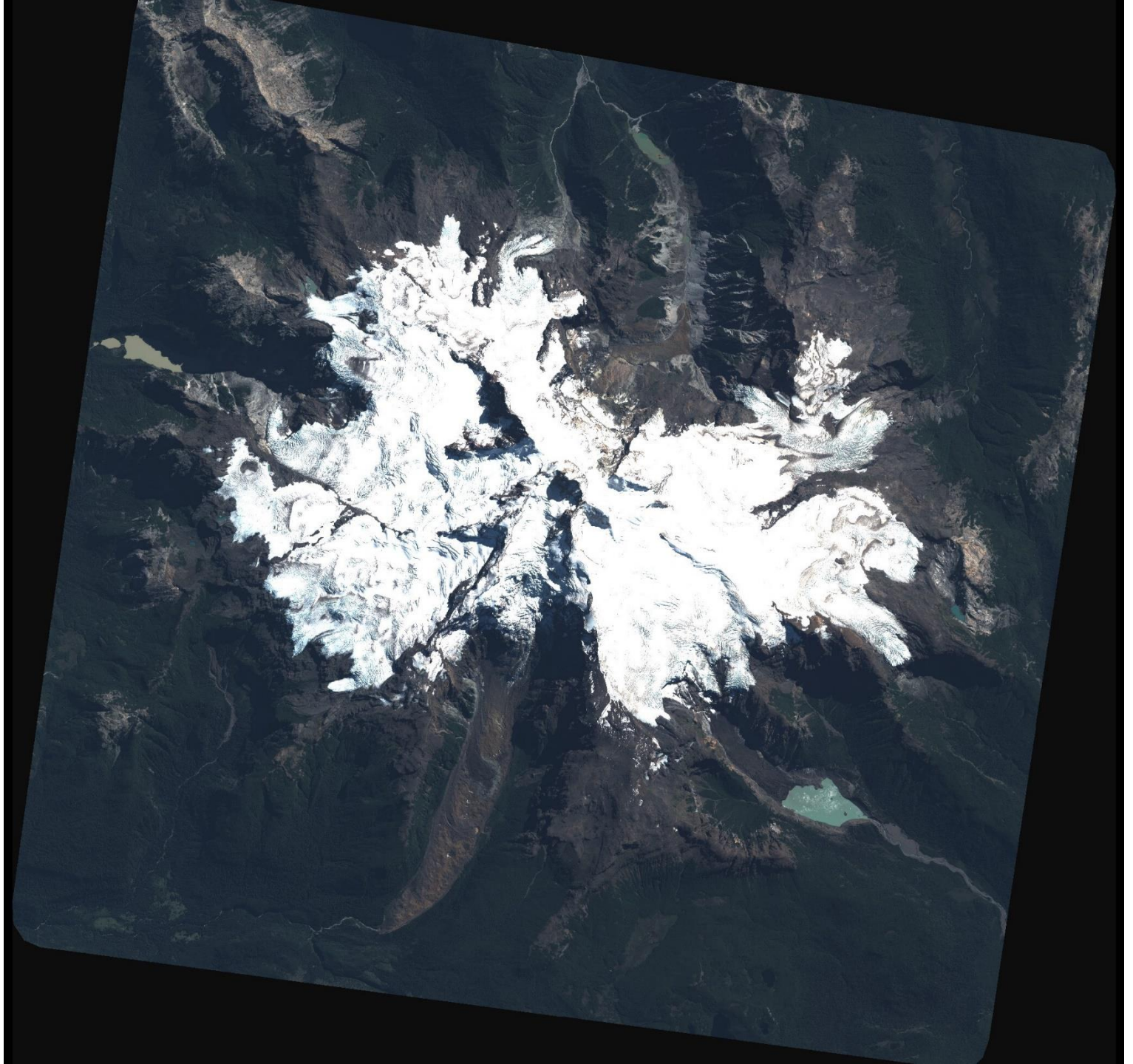


Rough terrain: smaller B/H better (but more uncertainties)

Stereo images



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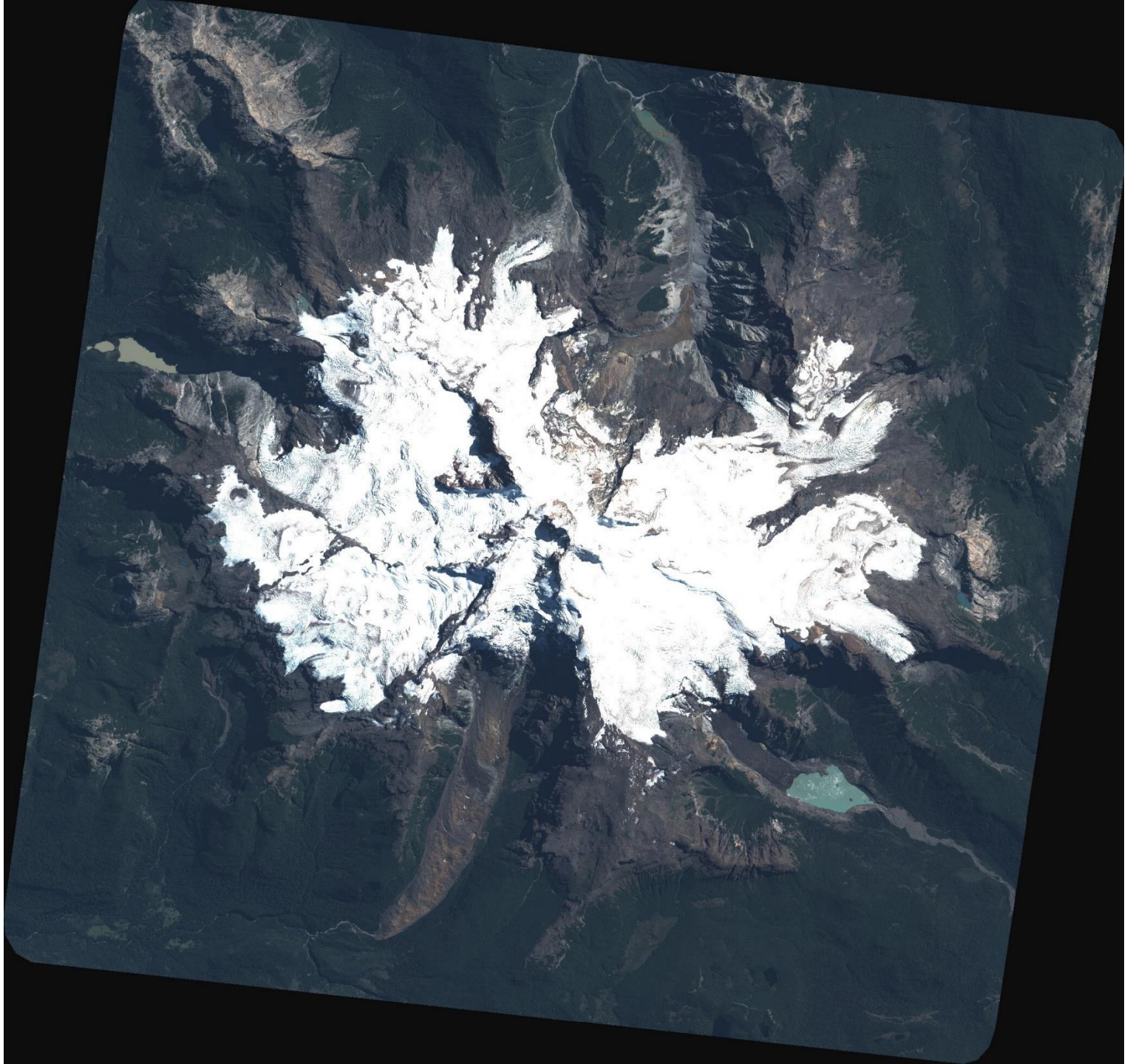

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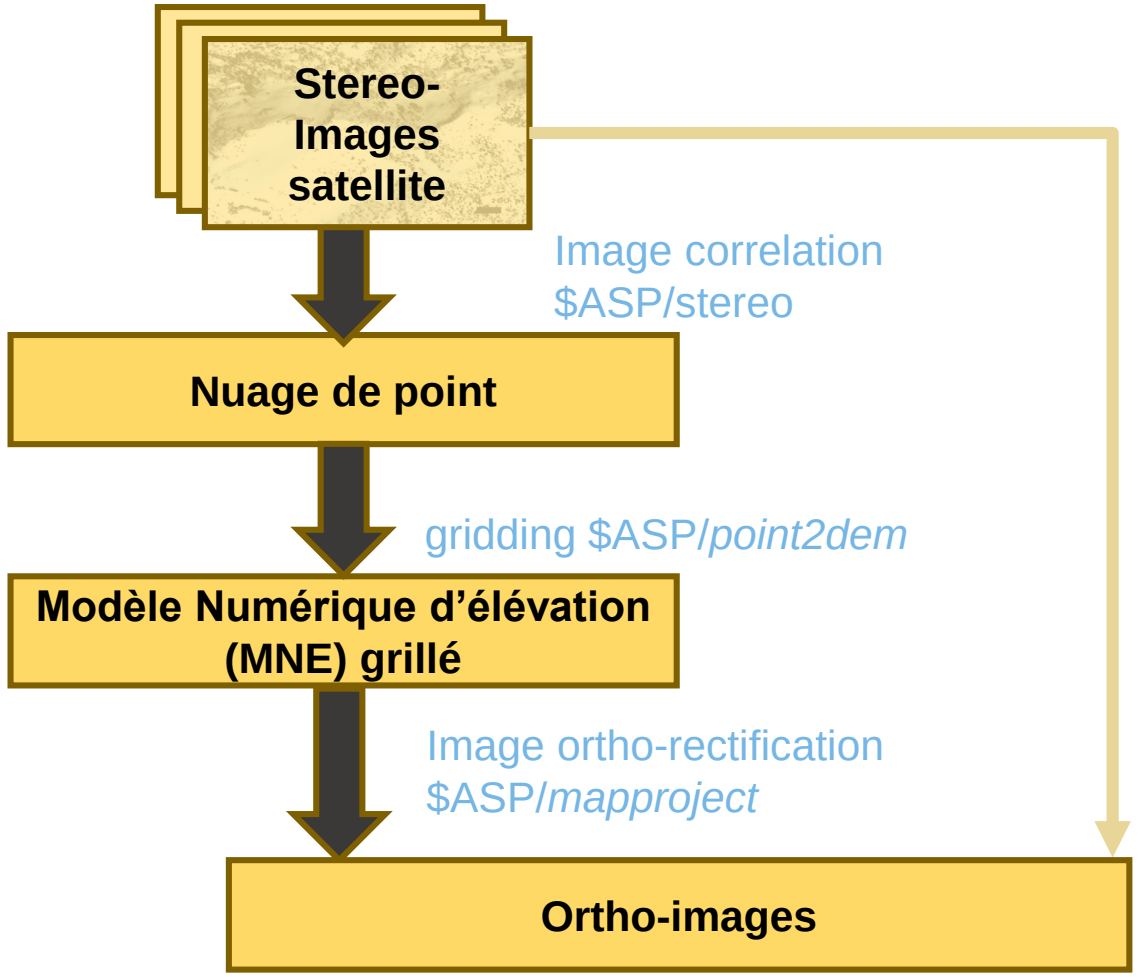
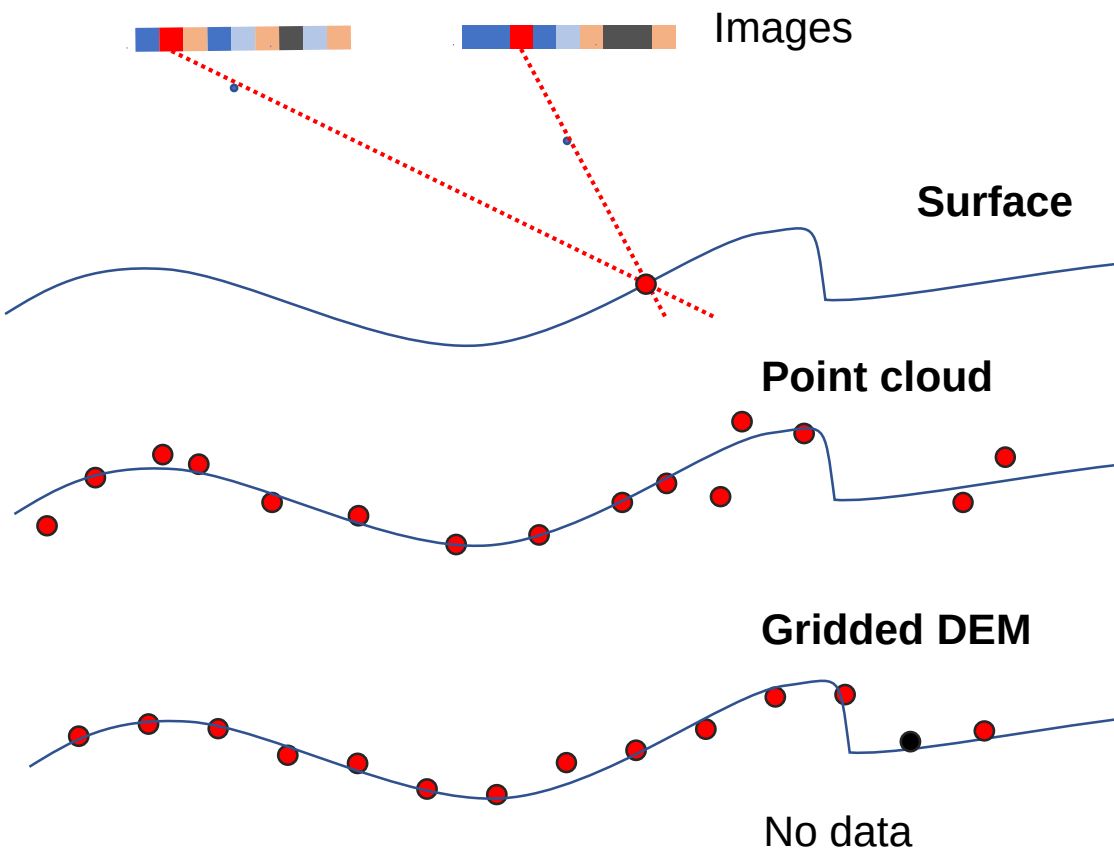


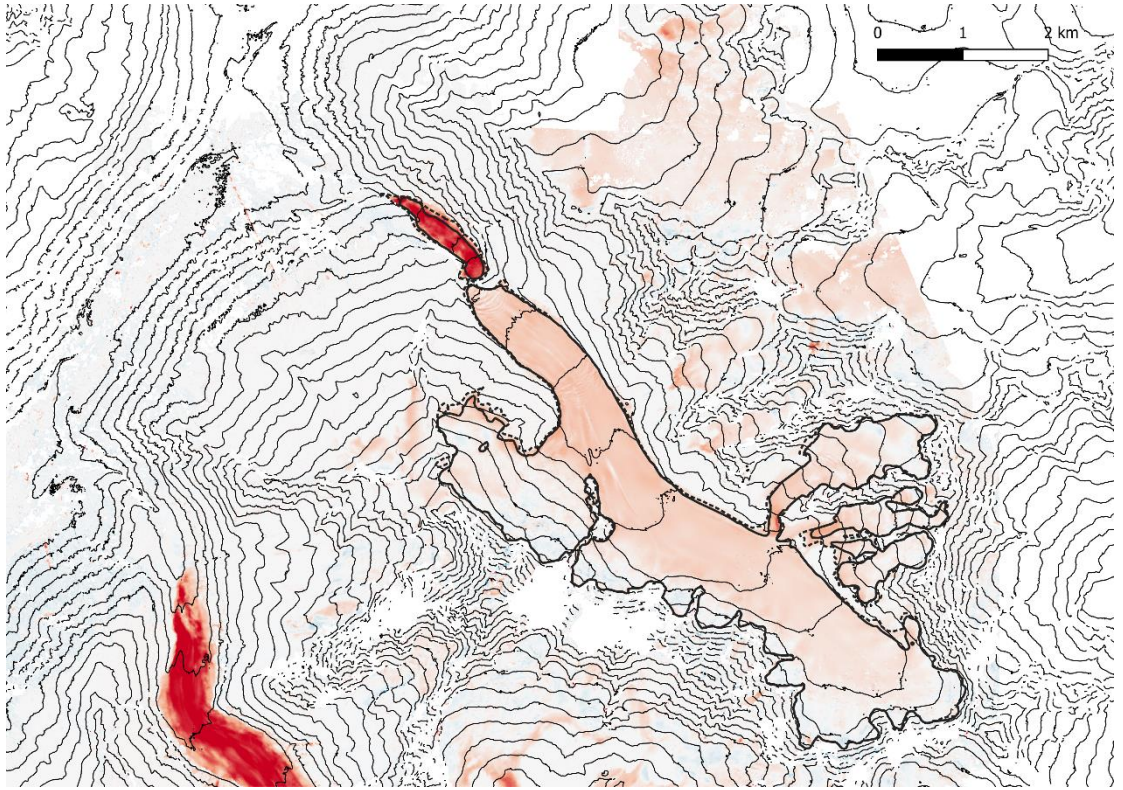


Recommended software: AMES stereo-pipeline

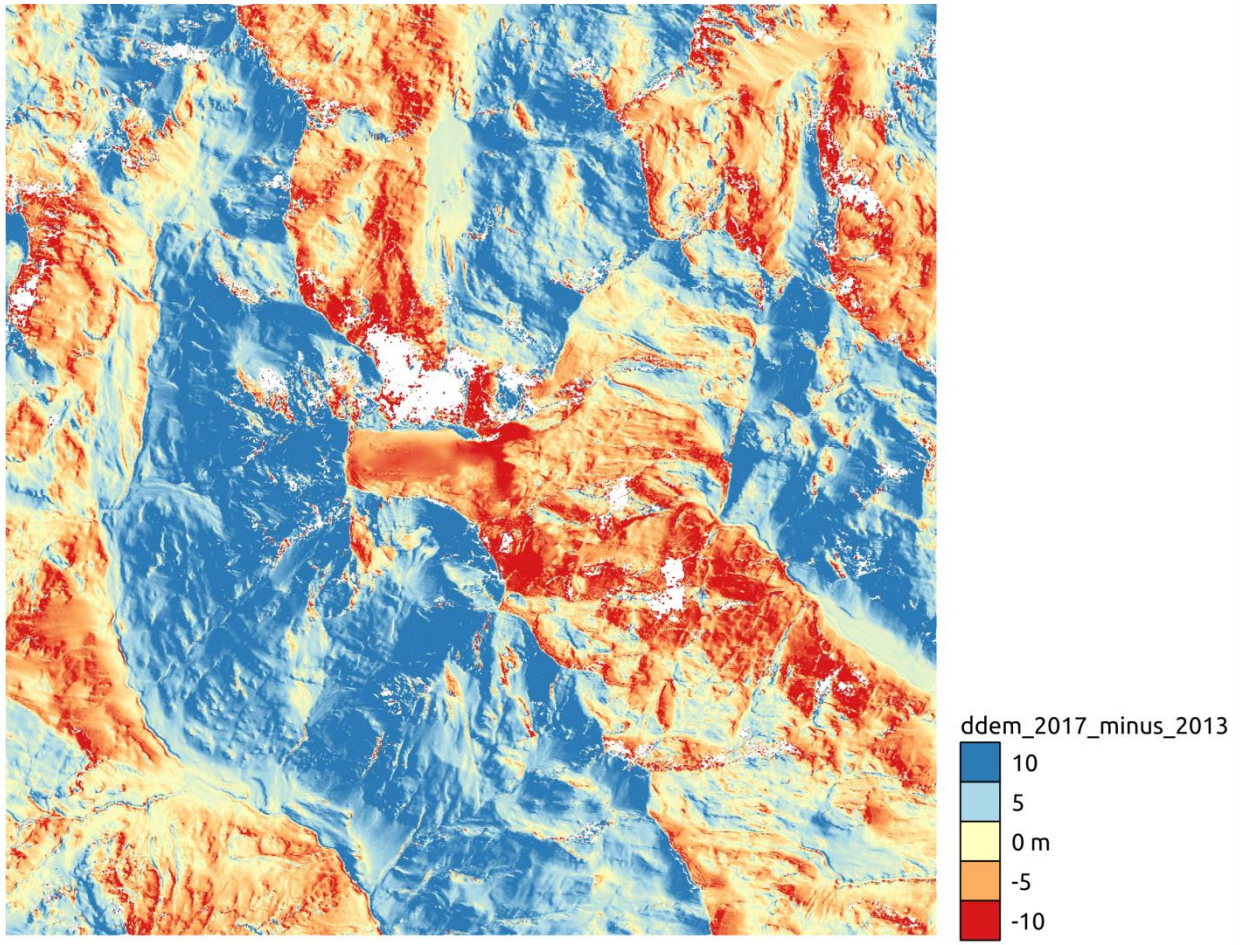
DEM differencing & co-registration

DEM differencing & co-registration

What we want:

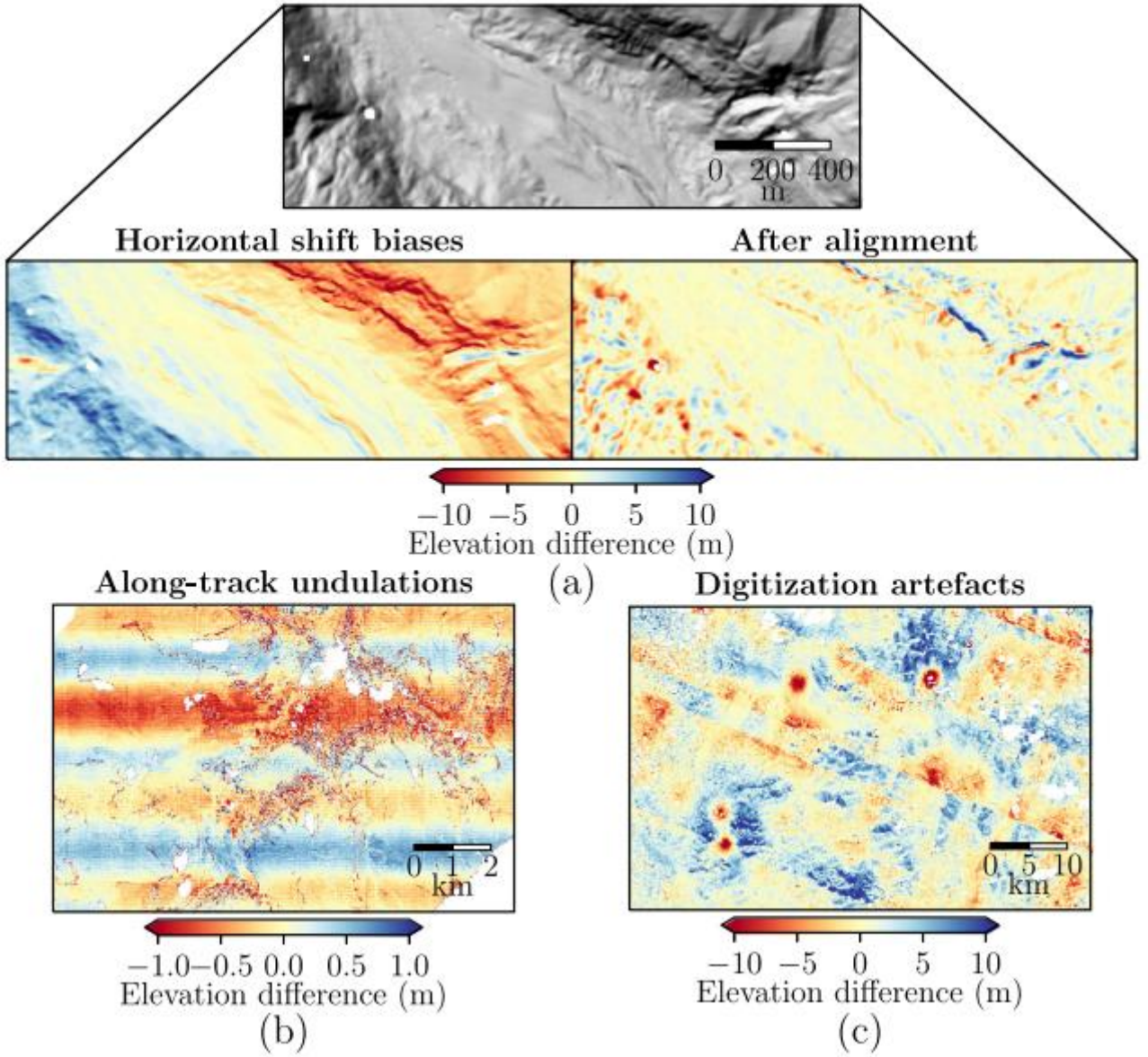


What we get:



DEM difference on Ossoue Glacier (Gascoin et René 2018)

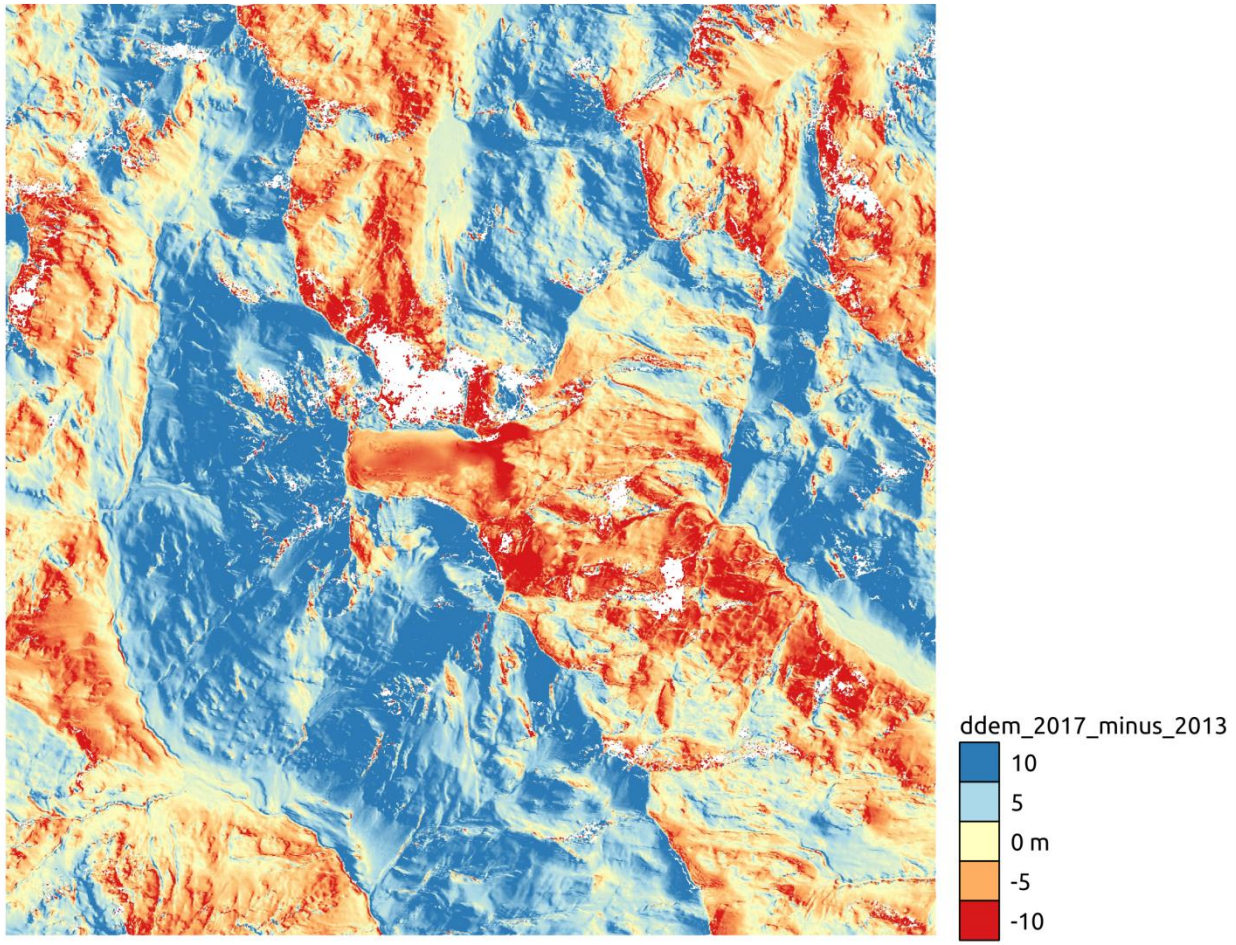
DEM differencing & co-registration

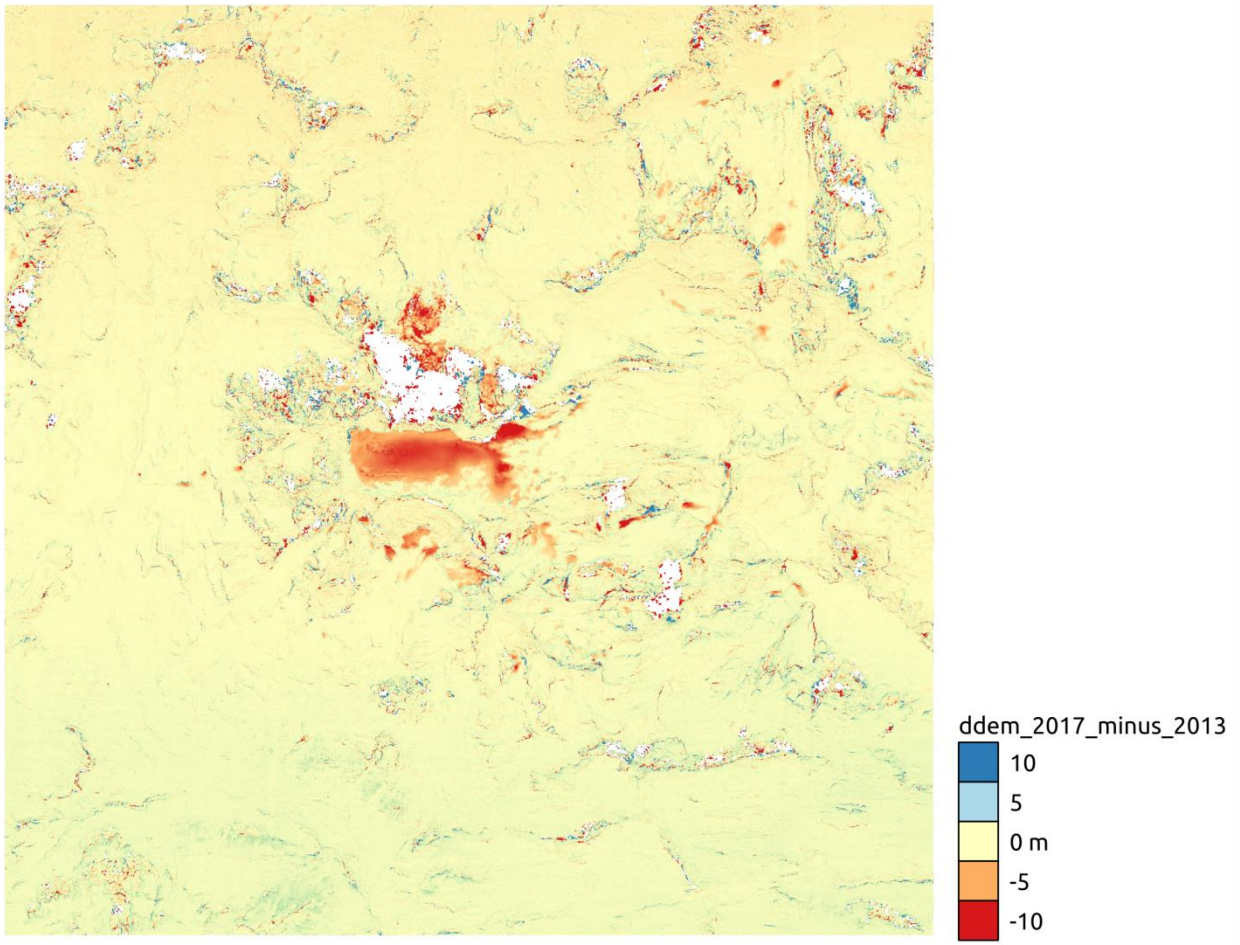


Hugonnet et al., 2022

DEM differencing & co-registration

Idea: use stable terrain to co-register DEMs

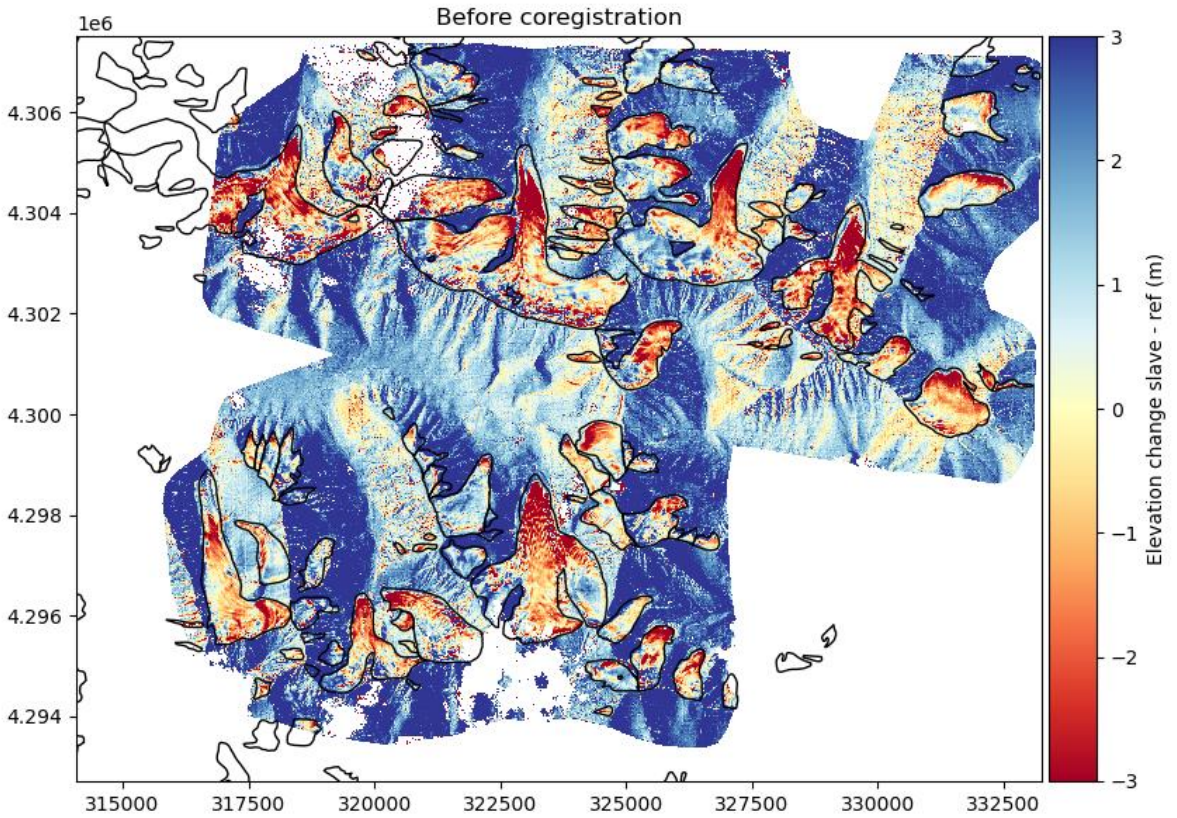


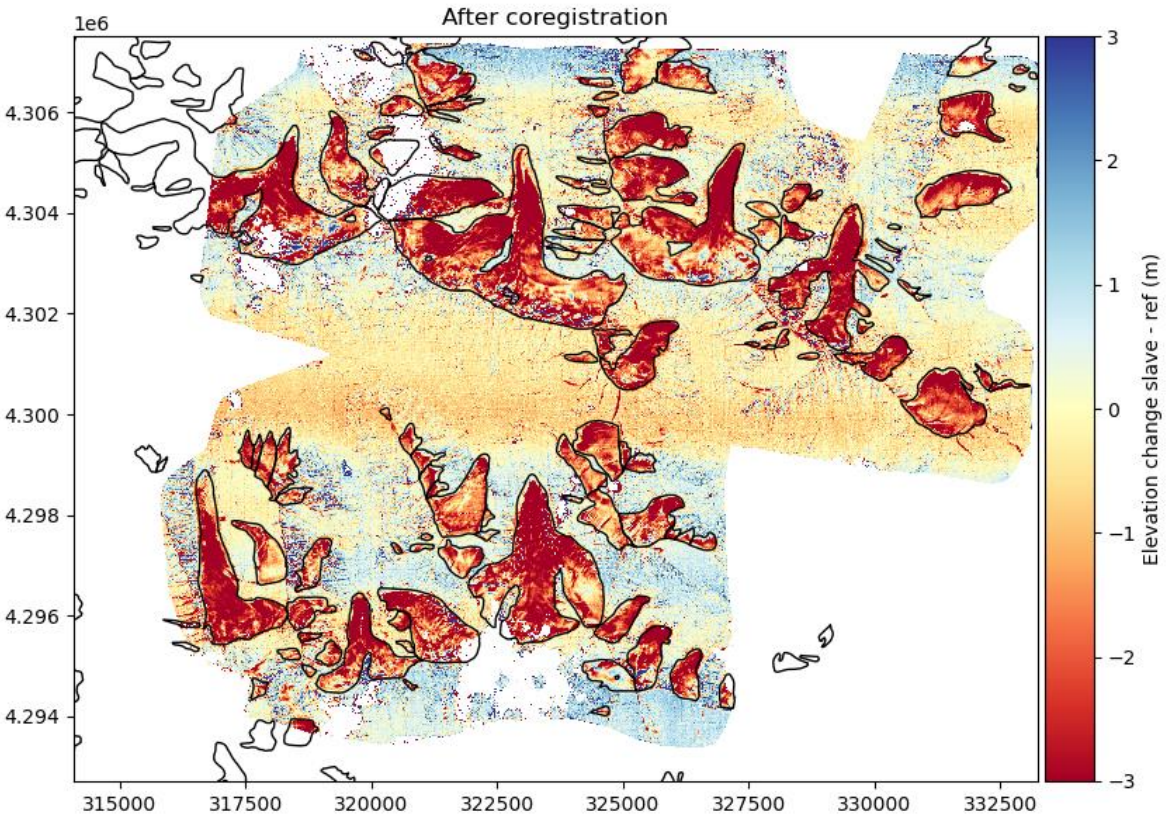


DEM difference on Ossoue Glacier (Gascoin et René 2018)

DEM differencing & co-registration

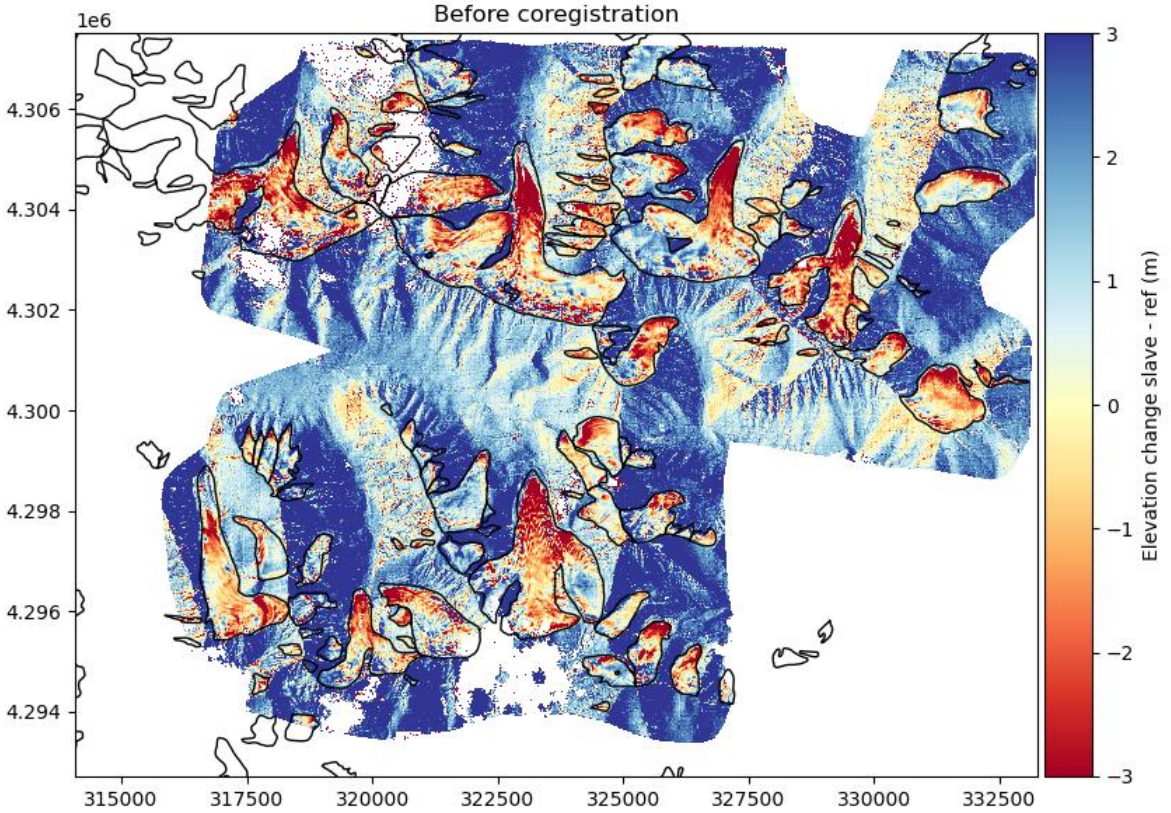
08/2019-08/2024, Tajikistan

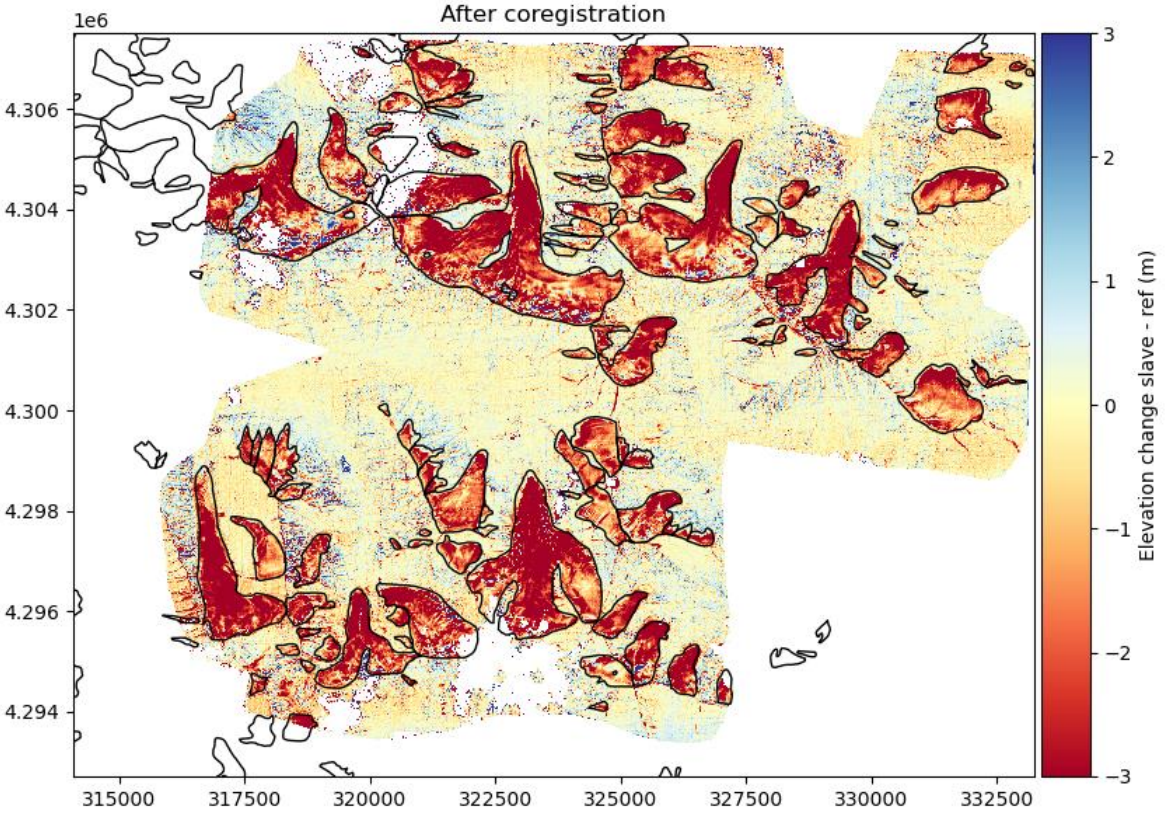




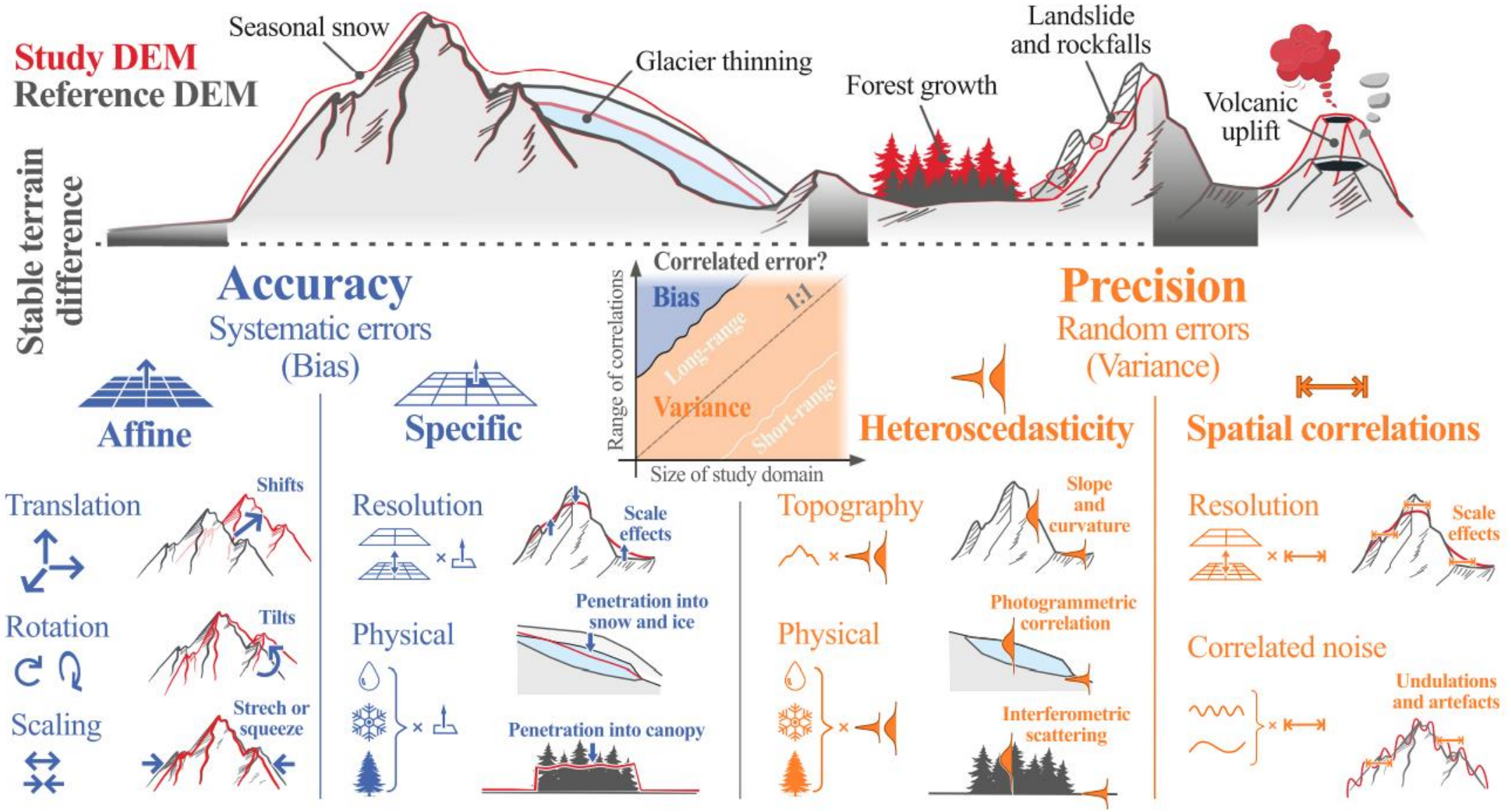
DEM differencing & co-registration

08/2019-08/2024, Tajikistan



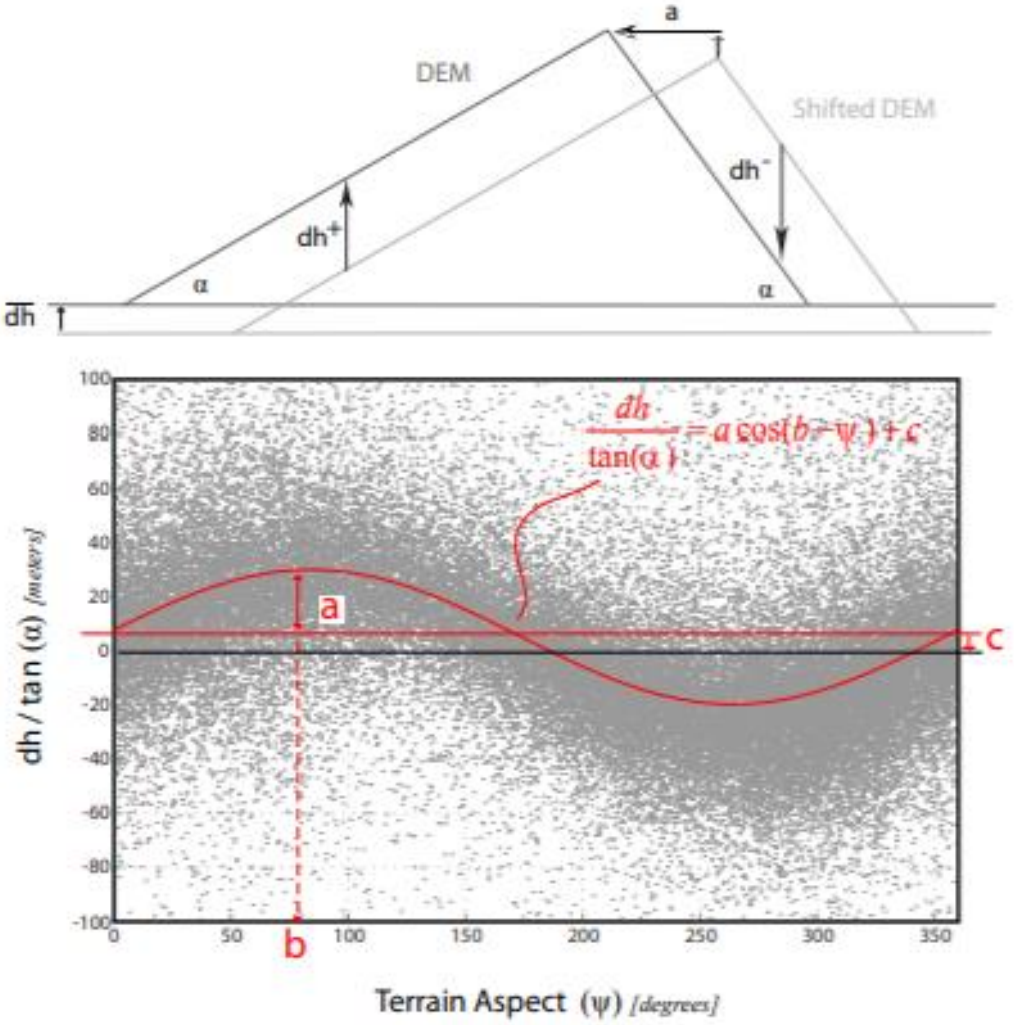


DEM differencing & co-registration



Hugonnet et al., 2022

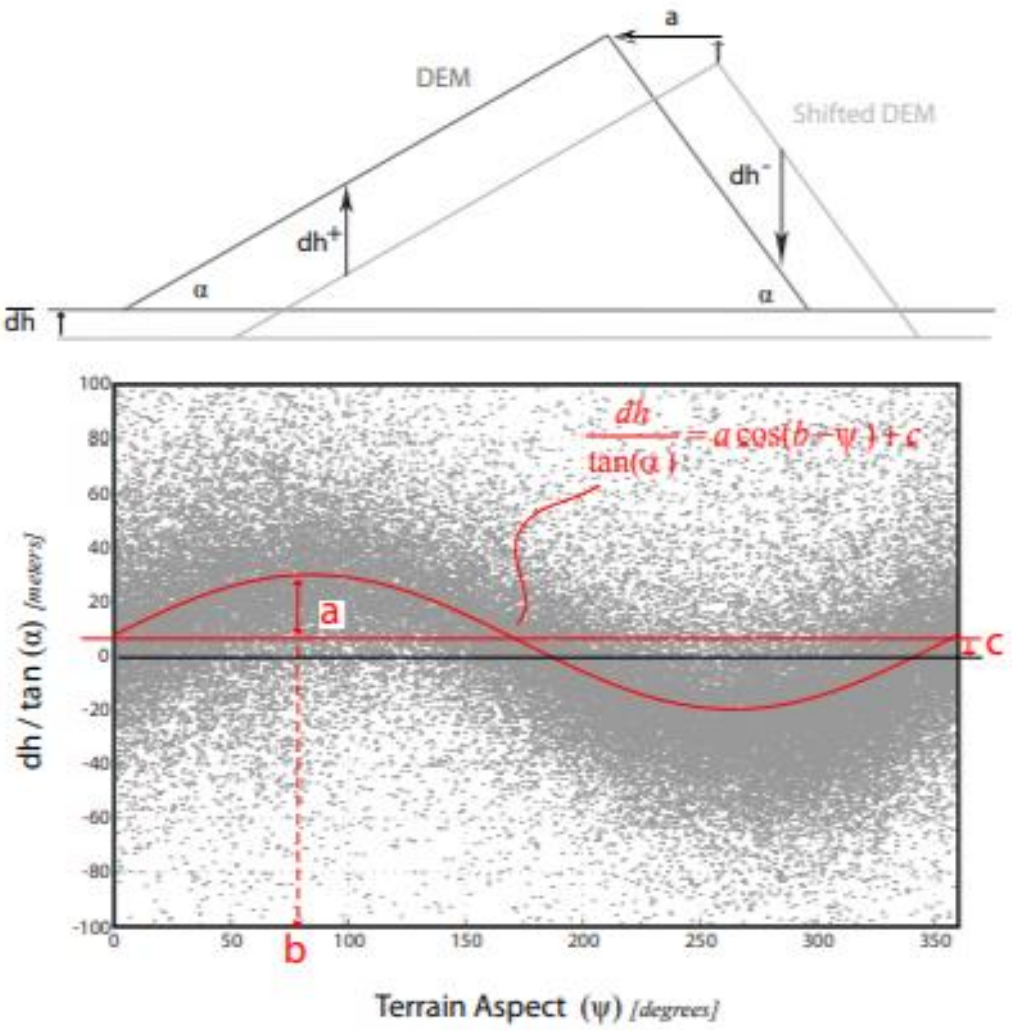
DEM differencing & co-registration



Nuth & Kääb, 2011

DEM differencing & co-registration

Nuth & Kääb, 2011



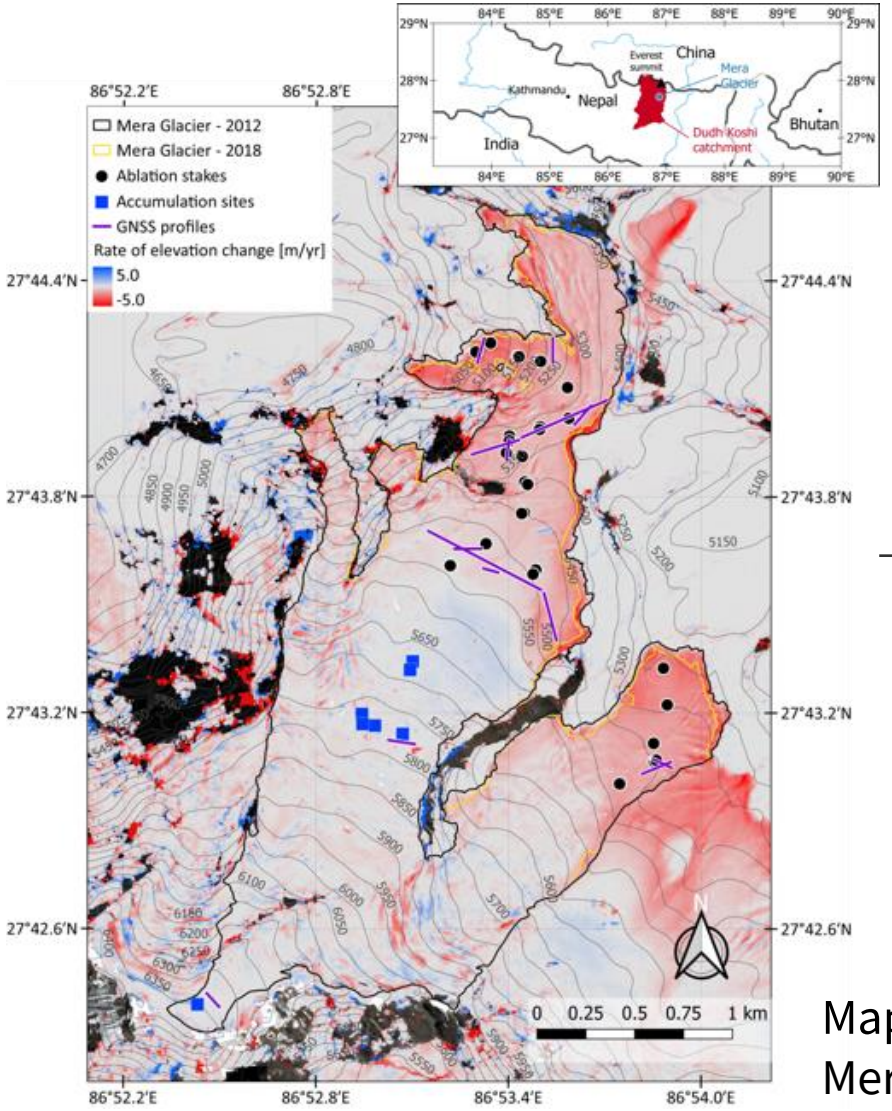
Possible methods:

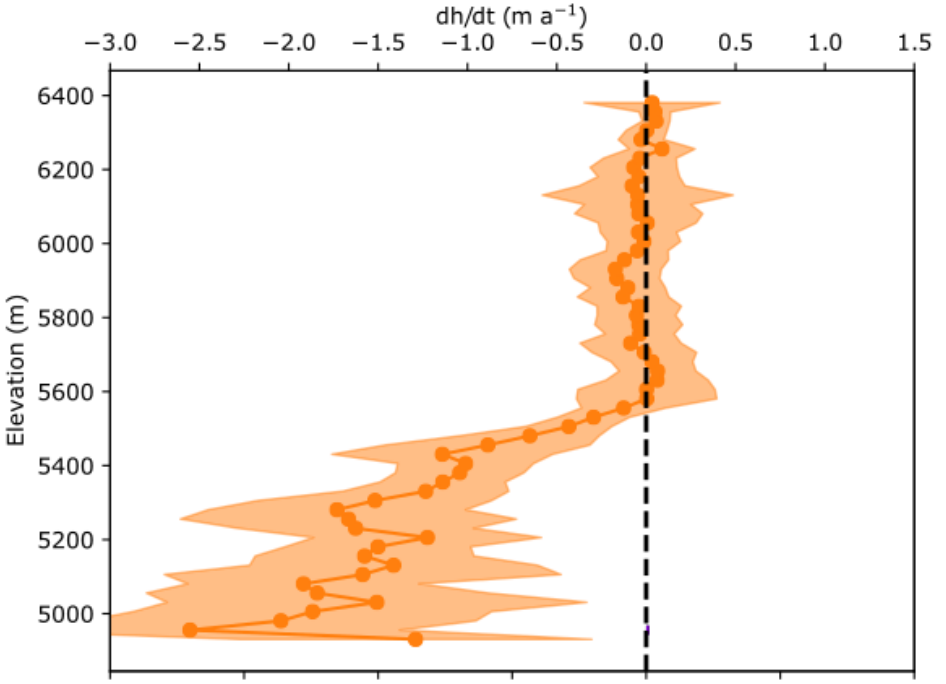
- Nuth & Kääb, 2011: translations & vertical shifts
- Iterative Closest Points (ICP): useful for rotations, scaling
- De-ramping: for 2D-plane tilt correction
- Vertical shifts

Often one needs to apply a combination of several methods

Volume & mass change calculation

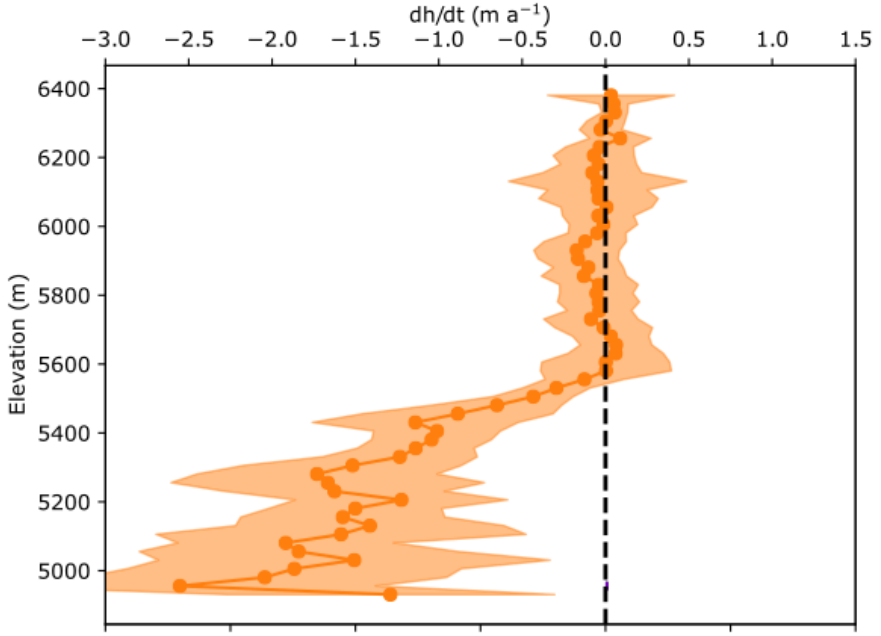
Volume change calculation





Map of elevation change of Mera Glacier from 2012 to 2018

Volume change calculation



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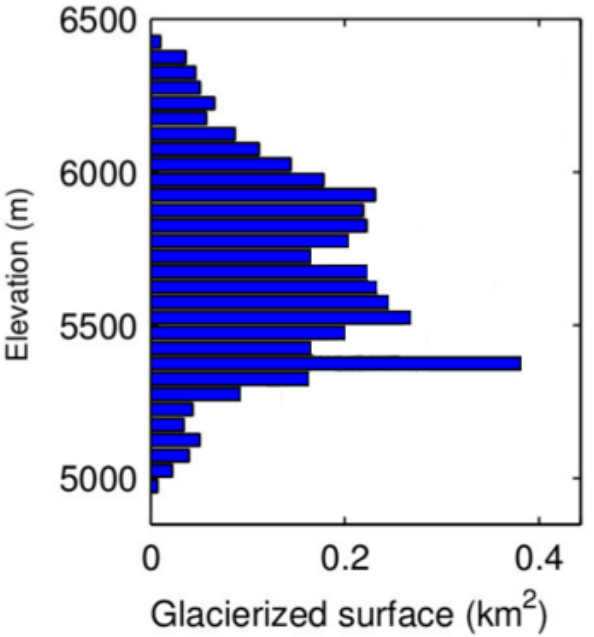

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Glacier-wide mass balance

Density conversion

Current reference (but far from perfect): Huss, 2013

$$\frac{\partial M}{\partial t} = \frac{\partial(\rho V)}{\partial t}. \longrightarrow \Delta M = \Delta\rho V + \Delta V \rho,$$

$$\Delta M = \left(\frac{\Delta\rho V}{\Delta V} + \rho\right) \cdot \Delta V = f_{\Delta V} \cdot \Delta V$$

$f_{\Delta V}$ = 850 +/- 60 kg/m^3

Density conversion: where does this come from?

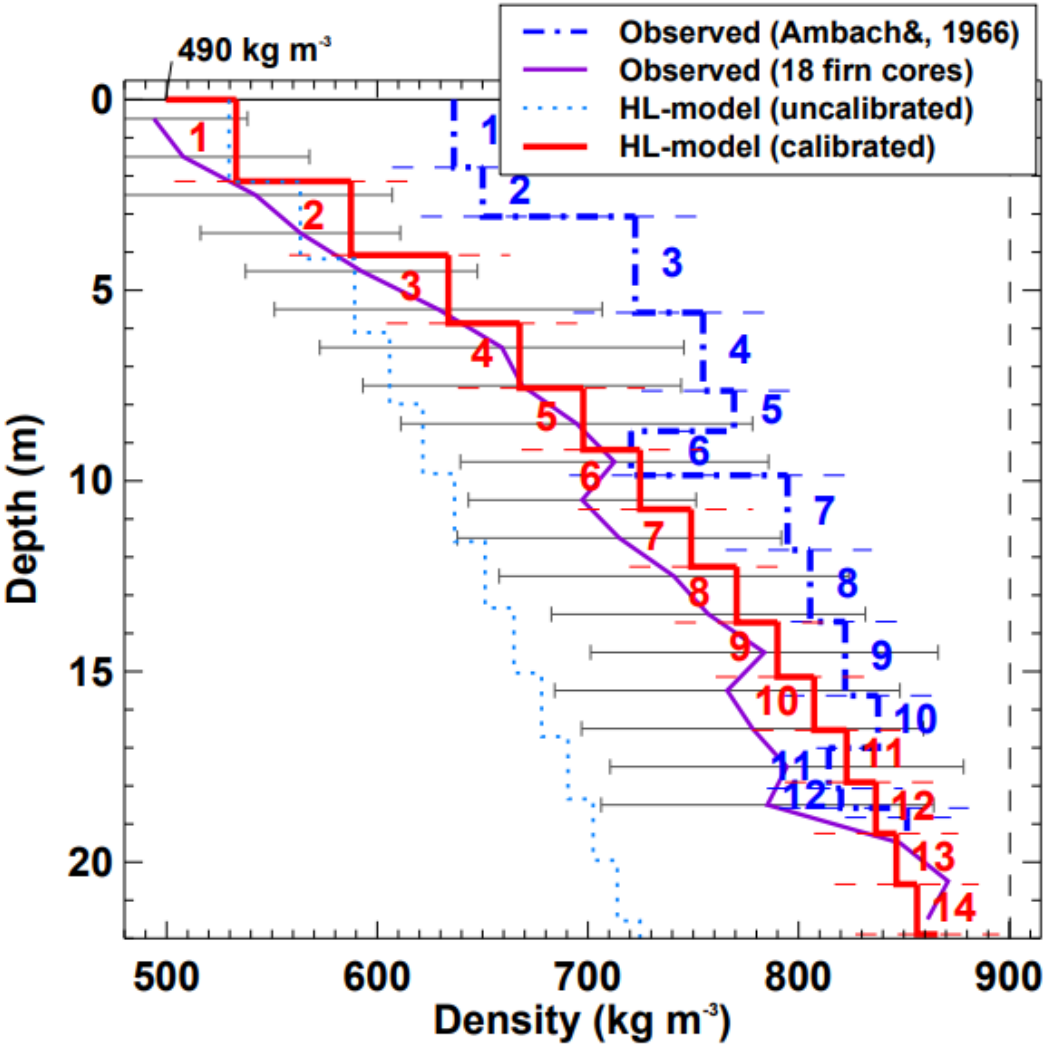
Mera Glacier, November 2023

Argentière Glacier, May 2024

Density conversion: where does this come from?

Orders of magnitude:

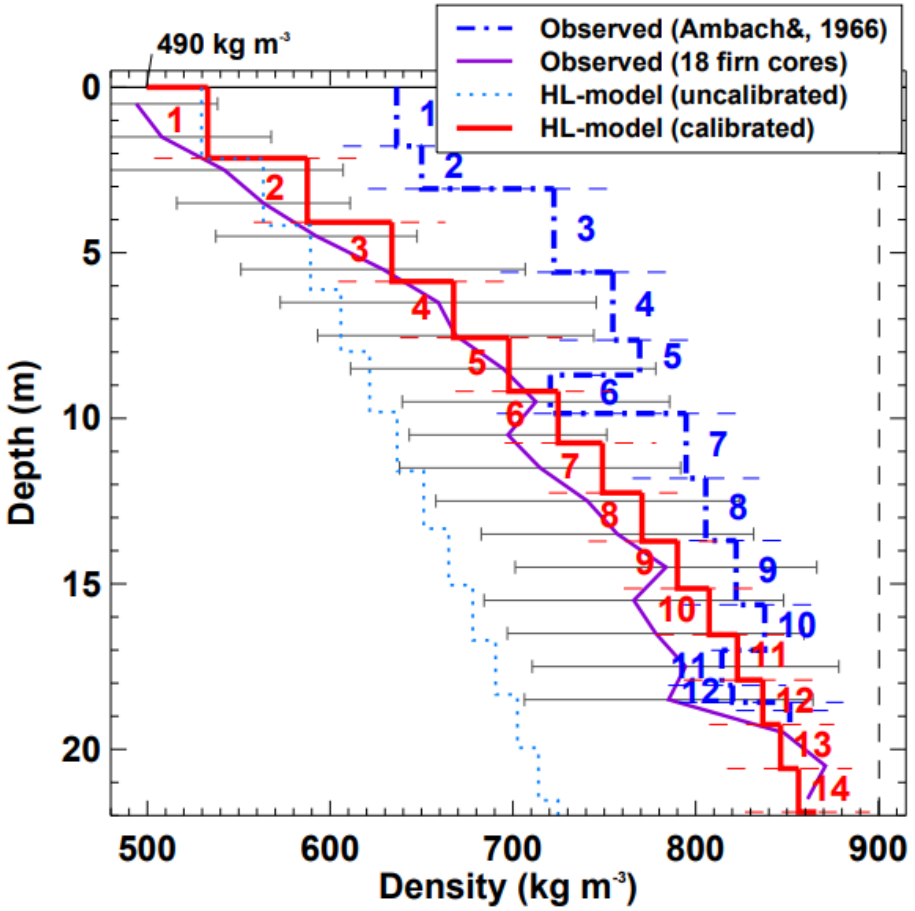
	Density (kg/m3)
Ice (no air bubles)	917
Ice (mountain glaciers)	~900
Firn (upper snow layer after one year)	500-600
Fresh snow	50-200

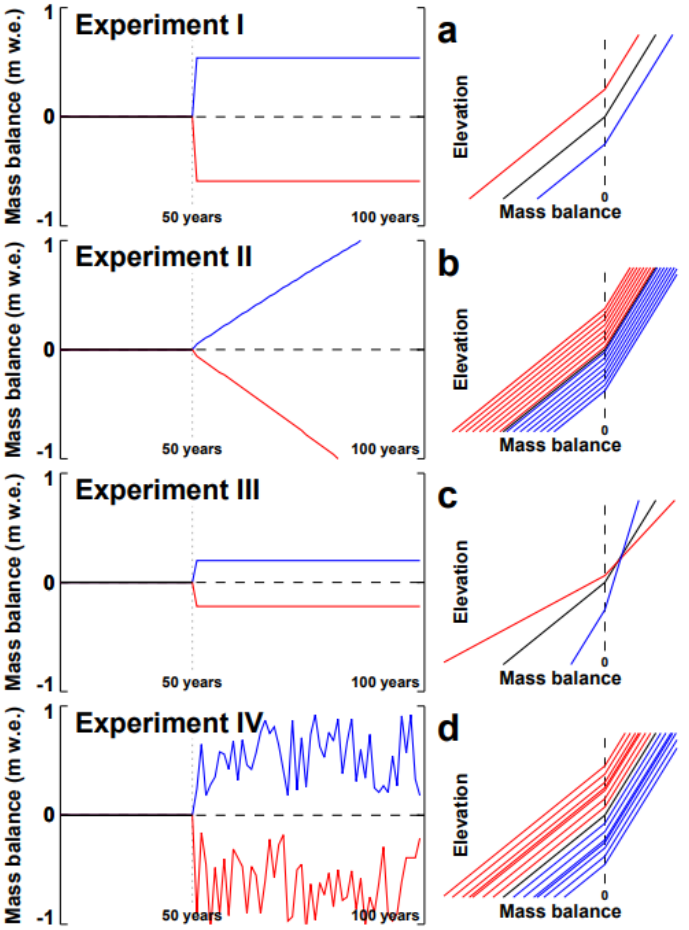


Huss, 2013

Density conversion: where does this come from?

Experiments on synthetic glaciers to compute $f_{\Delta V}$:





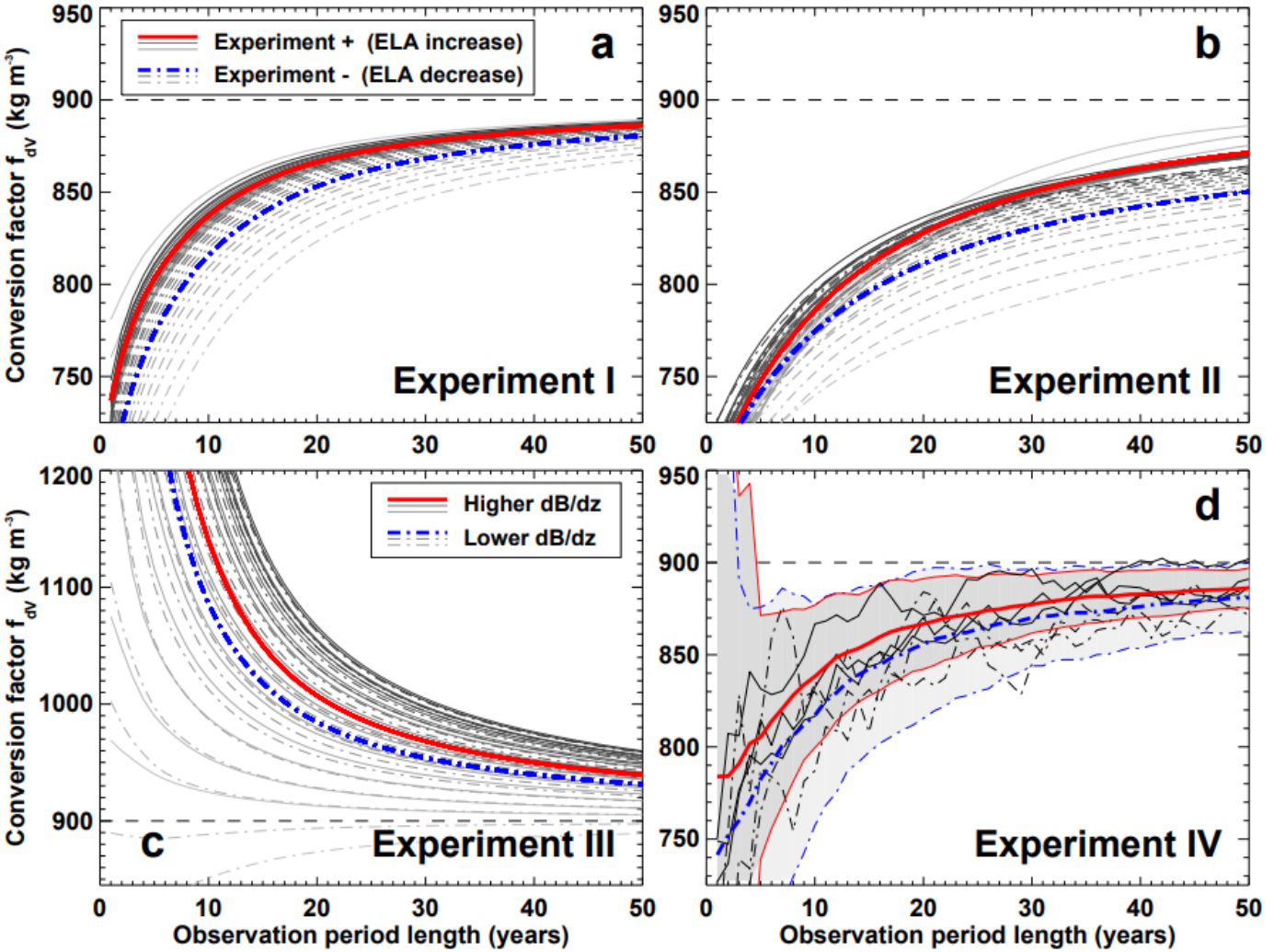
Glacier-wide volume & mass changes

Huss, 2013

Density conversion: where does this come from?

Experiments on synthetic glaciers to compute $f_{\Delta V}$:

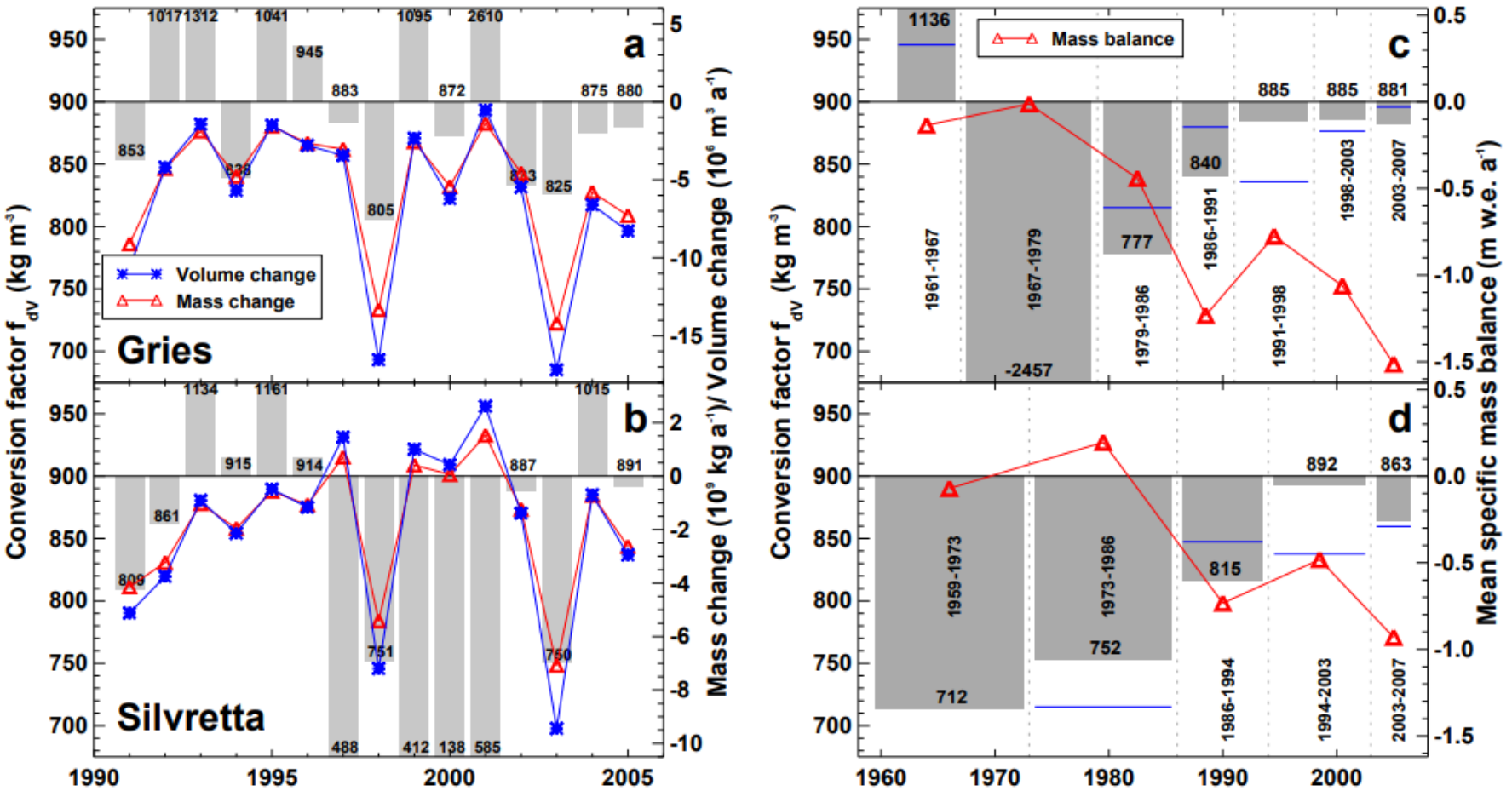
$f_{\Delta V}$ can be higher than 900 kg/m3: think about a glacier with constant mass but volume change due to compaction…



Huss, 2013

Density conversion: where does this come from?

Testing on real glaciers:



Huss, 2013

Density conversion: where does this come from?

Outcome:

- **The conversion factor $f_{\Delta V}$ is, in most cases, below the ice density** which is used in numerous studies for calculating mass balance from geodetic volume change. The effect is relatively small, yielding a **typical overestimate of mass change of roughly 2–15 %, but it is systematic**, and thus needs to be accounted for.
- **$f_{\Delta V}$ = 850 ± 60 kg.m^{-3} is recommended in the case of periods longer than 5 yr**, with stable mass balance gradients, the presence of a firn area, and volume changes significantly different from zero. The conversion factor can however strongly diverge from this mean value for particular conditions, and the density assumption might represent a **significant component of uncertainty** in geodetically determined mass balances that is larger than previously assumed.

Huss, 2013

What about uncertainties?

Uncertainty estimation

Combination of uncertainties:

- ***Volume -> elevation change***
- ***Area***
- ***Density***
- ***+ some gaps needing to be filled & accounted for***

Uncertainty on the mass change:

$$\sigma_{\Delta M} = \sqrt{(\sigma_{\Delta V} \times \rho)^2 + (\sigma\rho \times \Delta V)^2} \times \frac{1}{A_{mean}}.$$

Uncertainty on the volume change (accounting for gaps in the data):

$$\sigma_{\Delta V} = \sqrt{(\sigma h_{\Delta DEM} \times A_{mean}(p + 5 \times (1 - p)))^2 + (\sigma A \times h_{\Delta DEM})^2}.$$

p is the share of non-voided glacier area and then interpolated and assigning an uncertainty factor of 5 to this area (Berthier et al., 2014)

Beraud et al., 2023

Uncertainty estimation

Uncertainty on the elevation change:

Hypothesis: all systematic errors removed using stable terrain

The standard error $\sigma_{\overline{dh}}$ of the mean $\overline{dh}$ of the elevation changes samples dh can be written as:

$$\sigma_{\overline{dh}} = \frac{\sigma_{dh}}{\sqrt{N}},$$

where σ_{dh} is the dispersion of the samples, and N is the number of **independent** observations.

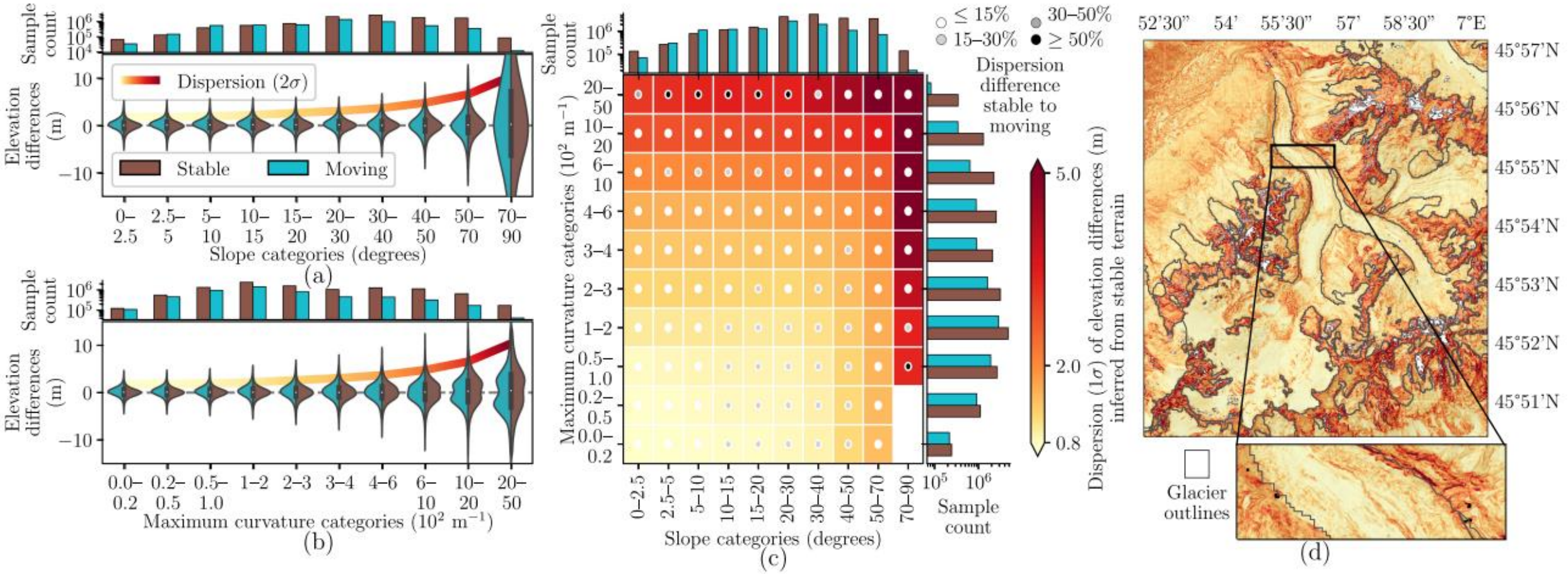
-> If all the observations are considered independent, N = number of pixels over which we are averaging => uncertainties drop quickly. However, this is in general NOT the case:

$$\frac{\sigma_{dh}}{\sqrt{N_{Pix}}} < \sigma_{\overline{dh}} = \frac{\sigma_{dh}}{\sqrt{n_f}} < \sigma_{dh}$$

Where n_f is given by the parameters of the variogram.

XDEM: https://xdem.readthedocs.io/en/stable/coregistration.html

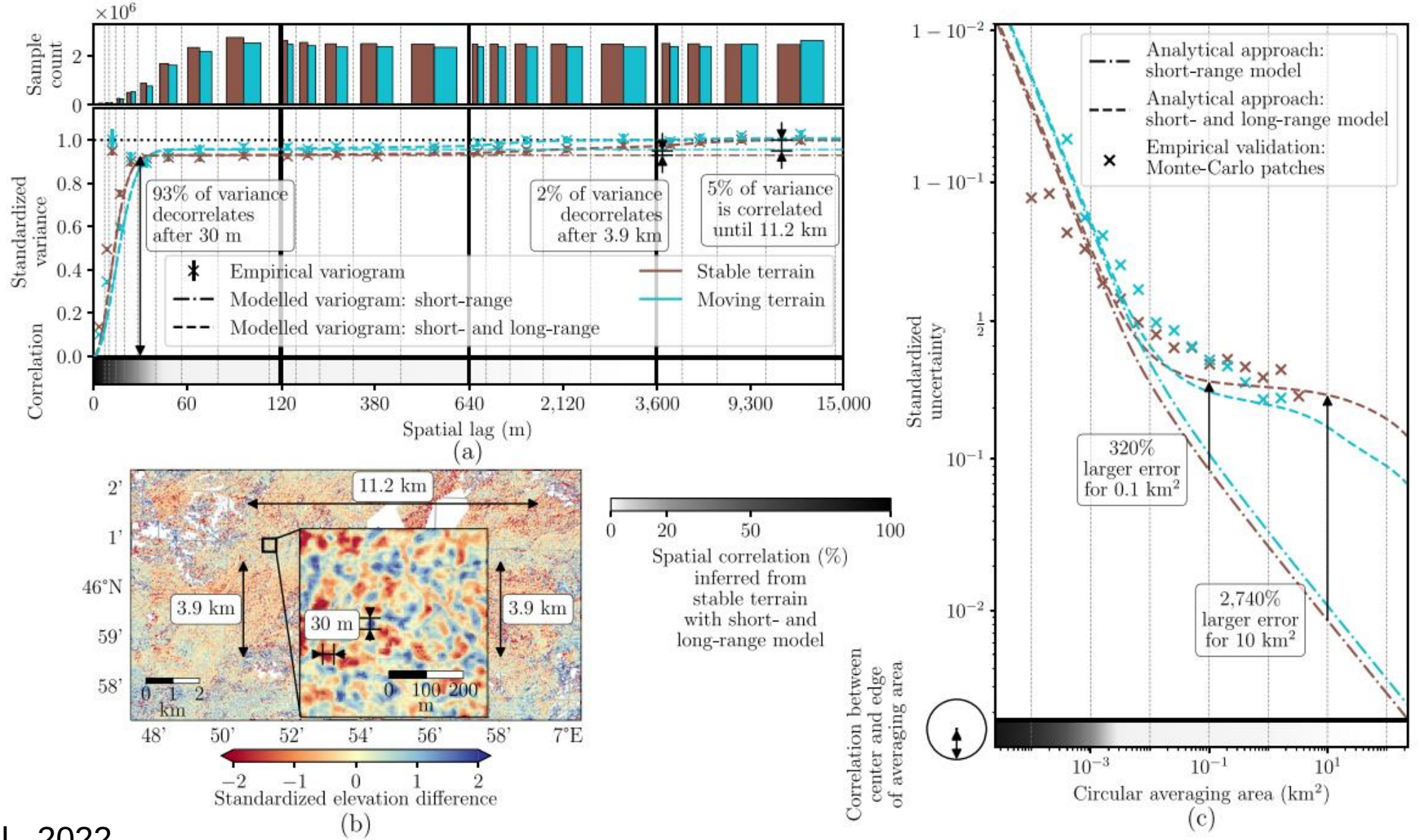
Uncertainty estimation: heteroscedasticity



-> Dependence on slope/curvature that needs to be accounted for to satisfy the 1st order stationarity hypothesis to compute the variograms (~ distance is the only controlling variable for the variance)

Hugonnet et al., 2022

Uncertainty estimation: spatial correlation



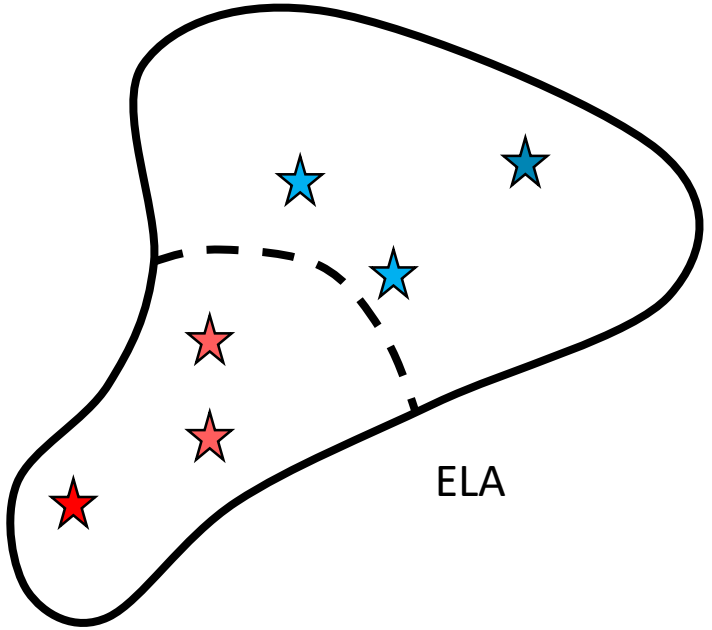
Hugonnet et al., 2022

Geodetic VS glaciological mass balance

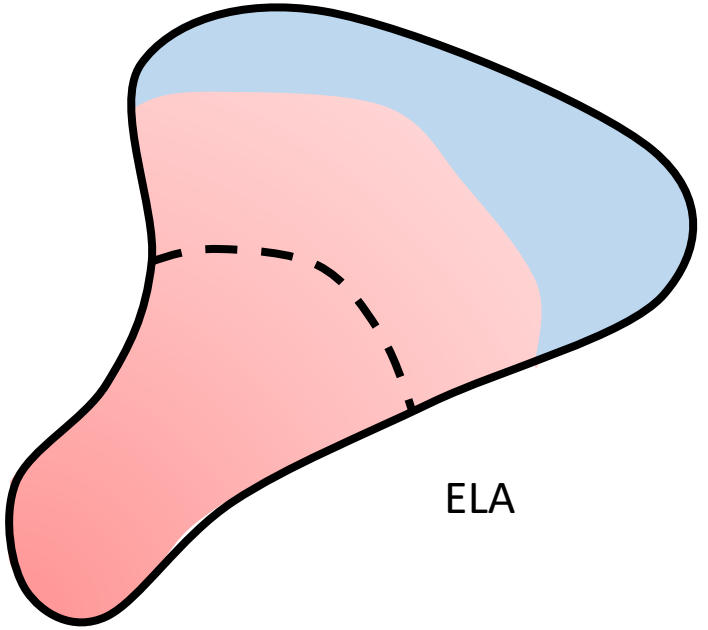
Geodetic VS glaciological mass balance

- Stakes: **point-scale** measurements of **melt** over a given time
- GMB: **mass gain/loss** of the **whole glacier** over a given time

Stakes

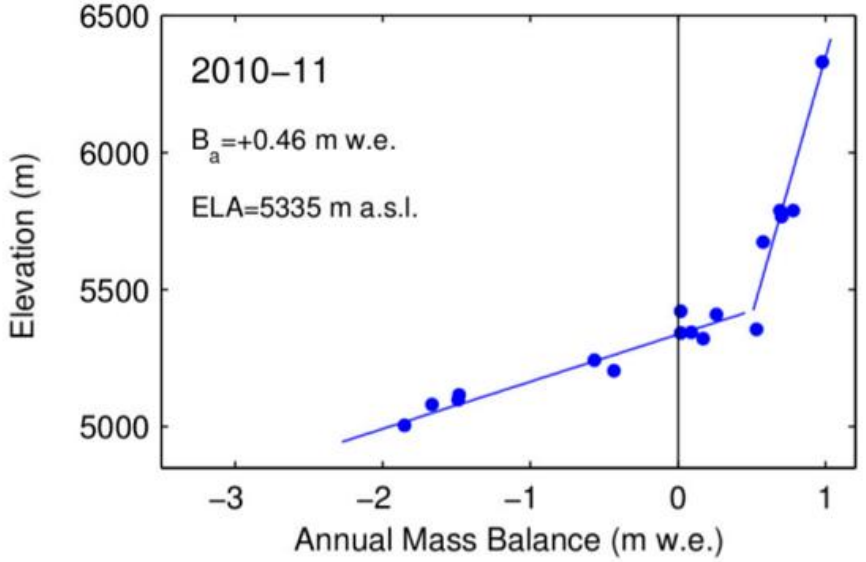


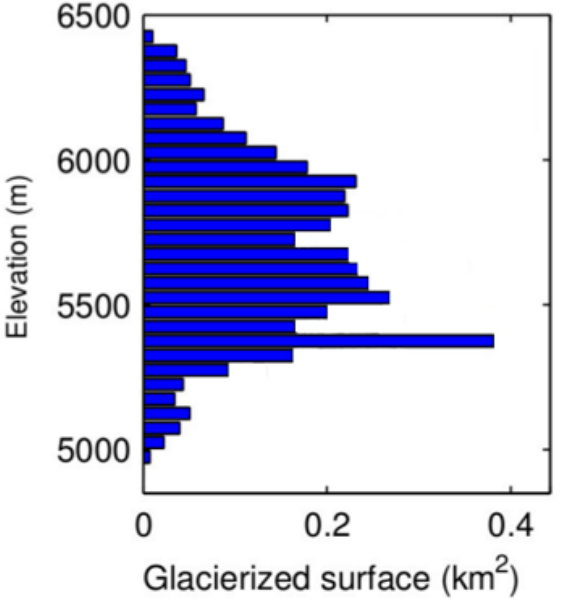
Full-glacier DH
(DH = DEM2 – DEM1)



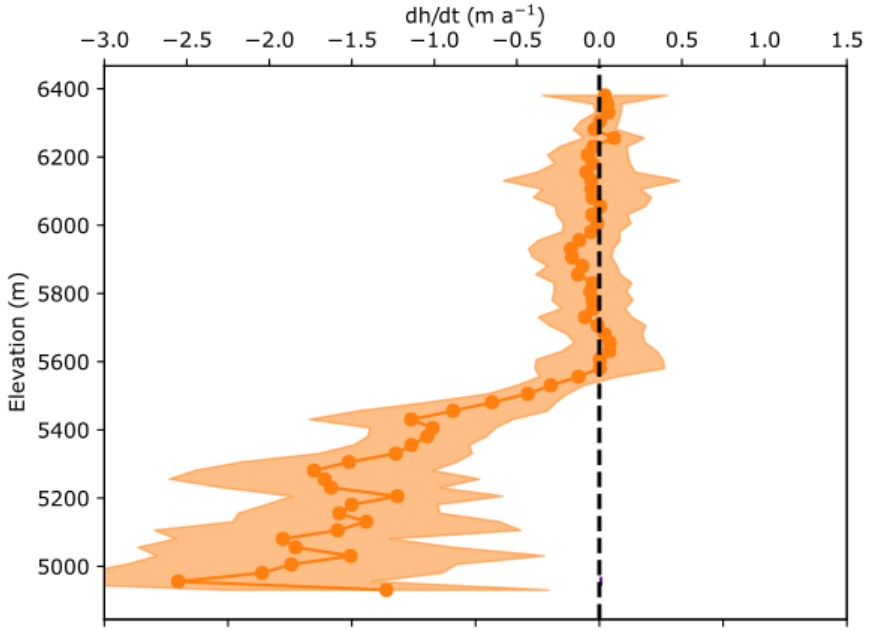
GMB = Mass gain in accumulation zone – Mass loss in ablation zone = Sum of all dH

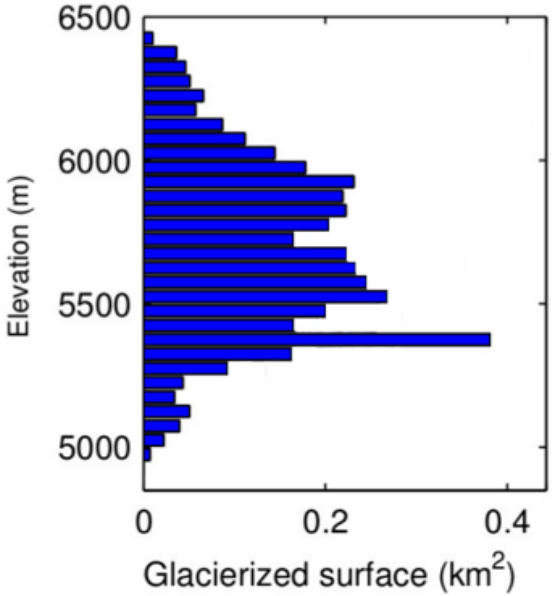
Geodetic VS glaciological mass balance





Glacier-wide mass balance





Glacier-wide mass balance

Geodetic VS glaciological mass balance

Rate of mass change [kg]

Englacial mass balance [kg m^{-2}]

$$\dot{M} = \int_A [\dot{b}_s + \dot{b}_e + \dot{b}_b] dA$$

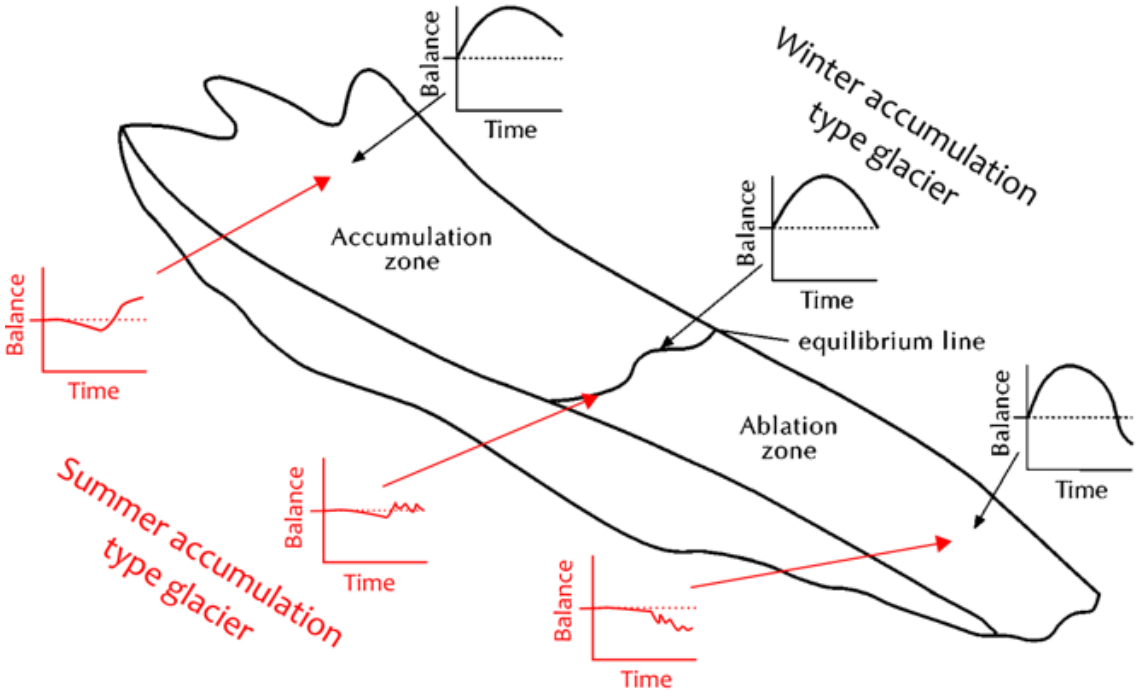
Glacier area [m^2]

Surface mass balance [kg m^{-2}]

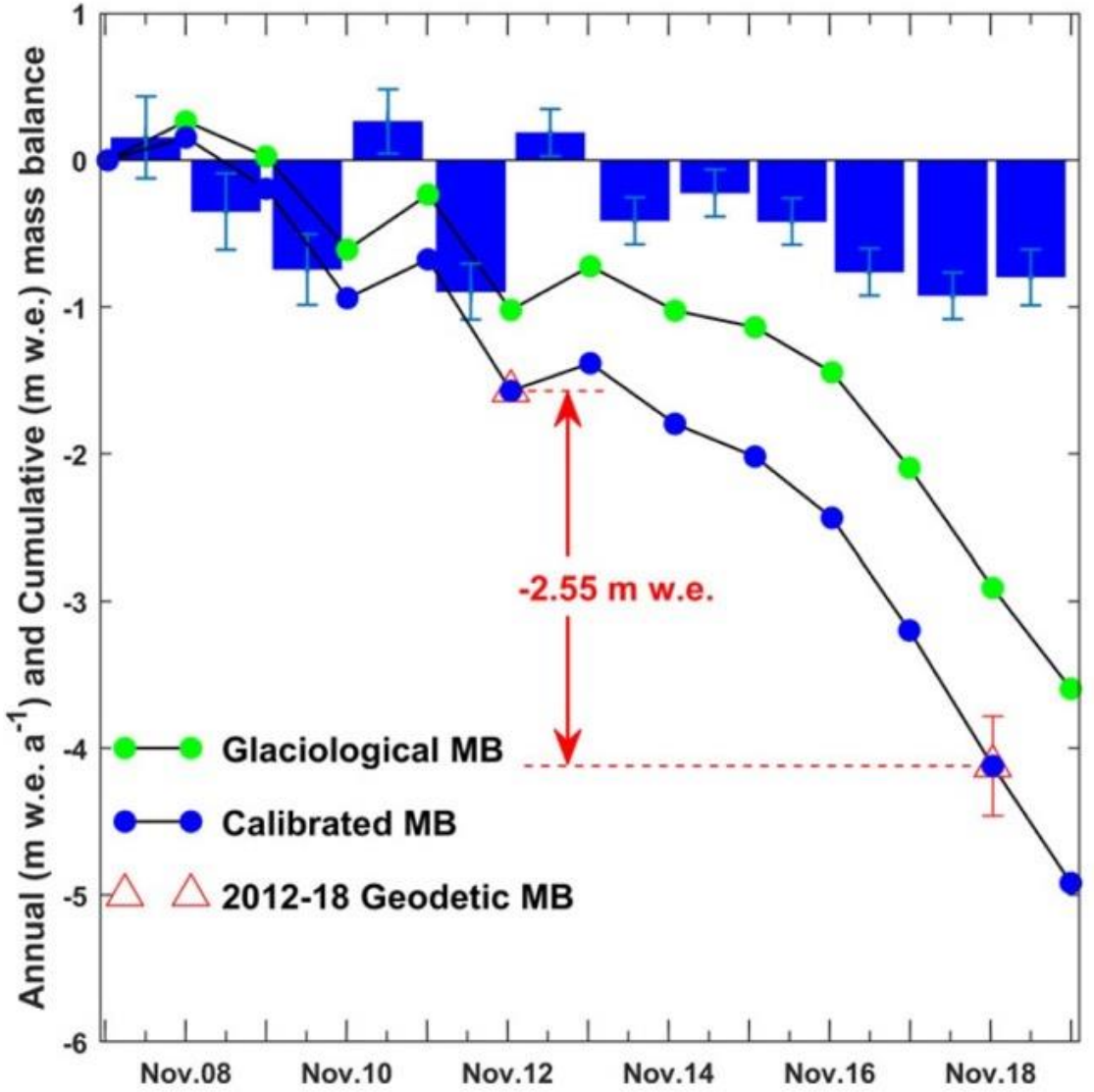
Basal mass balance [kg m^{-2}]

For temperate glaciers:

$$\dot{M} \simeq \int_A \dot{b}_s dA$$



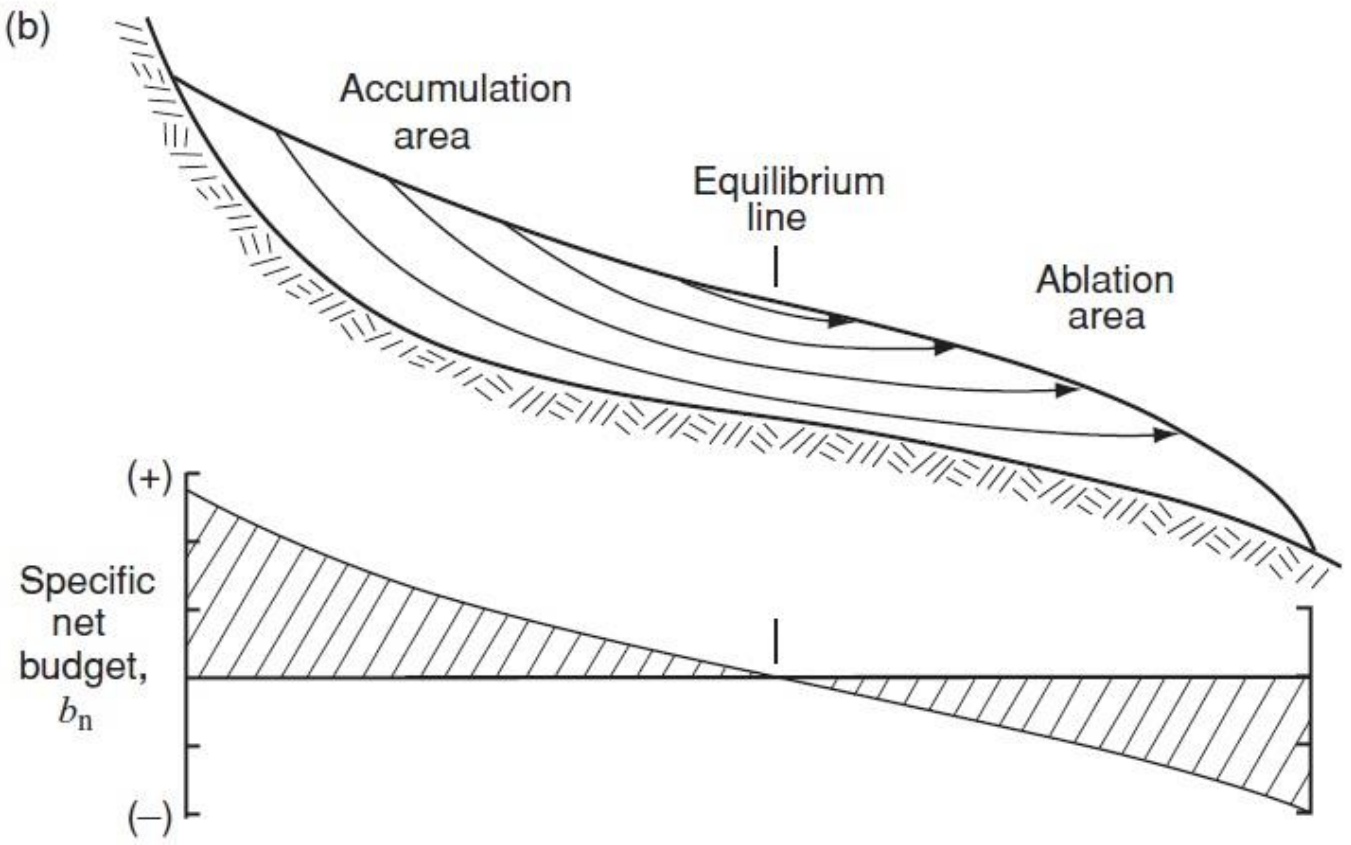
Geodetic VS glaciological mass balance



Glaciological mass balance series calibrated on geodetic series

Wagnon et al., 2021

Geodetic VS glaciological mass balance



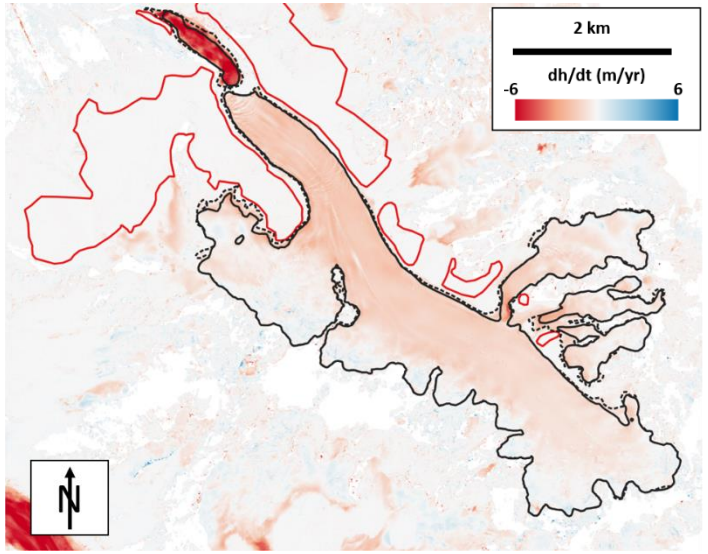
Longitudinal profile of a glacier [Hook, 2005]

In the accumulation area, flowlines are pointing **downward (submergence)**. In the ablation area, flowlines are pointing **upward (emergence)**.

In every point of the glacier, we then have:

$$\frac{\rho_{dH}}{\rho_{H_2O}}\frac{dH}{dt} = \dot{b} - \frac{\rho_{\nabla \boldsymbol{q}}}{\rho_{H_2O}}\nabla * \boldsymbol{q}$$

Distributed ‘geodetic’ mass balance?



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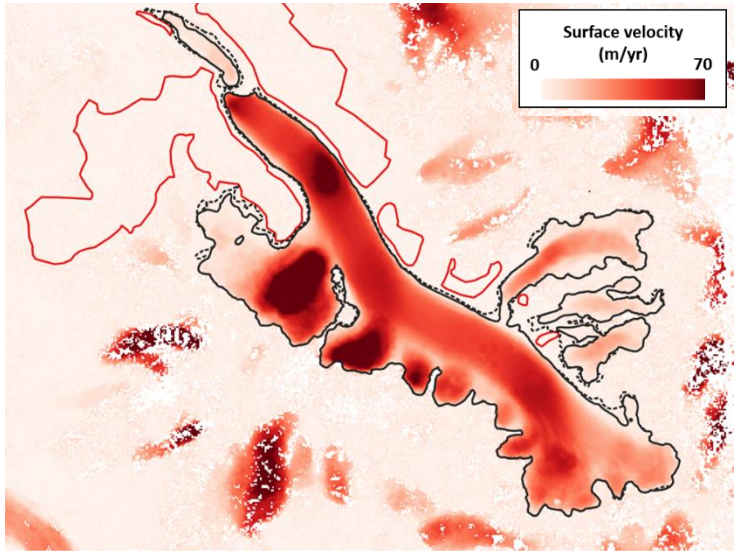

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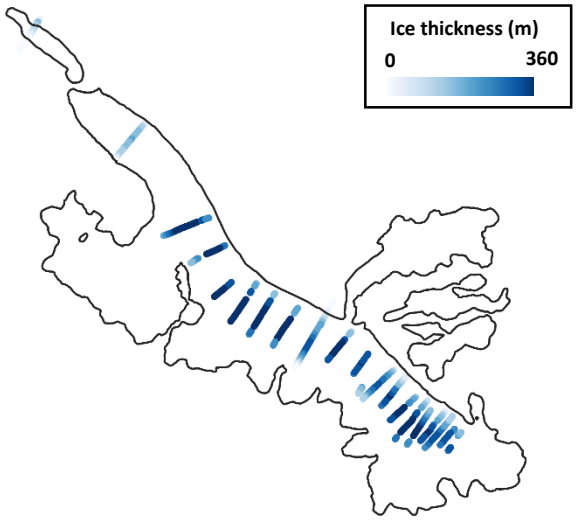

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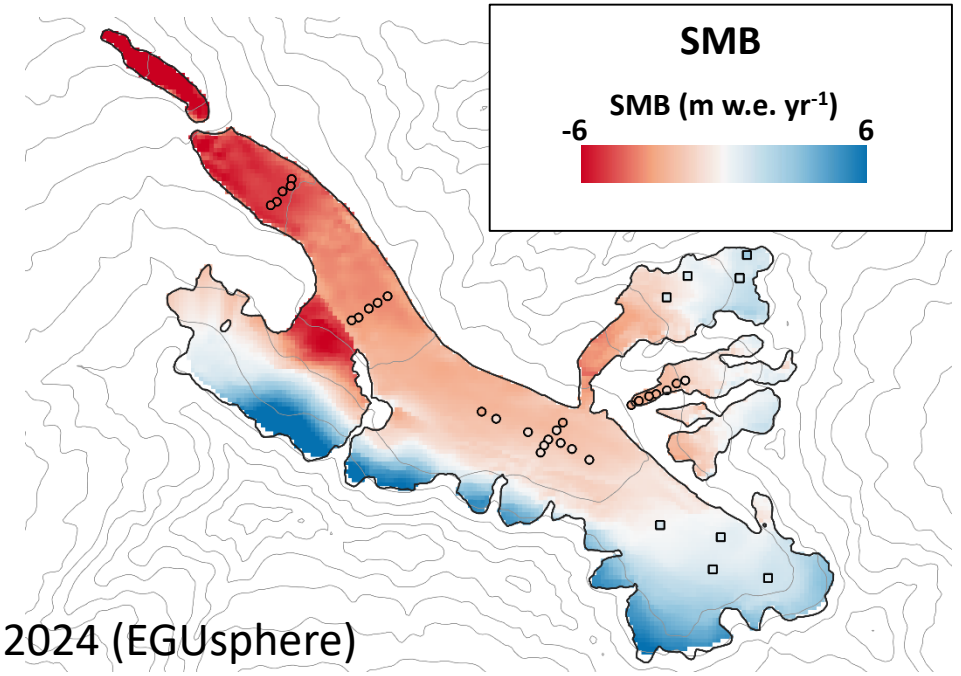


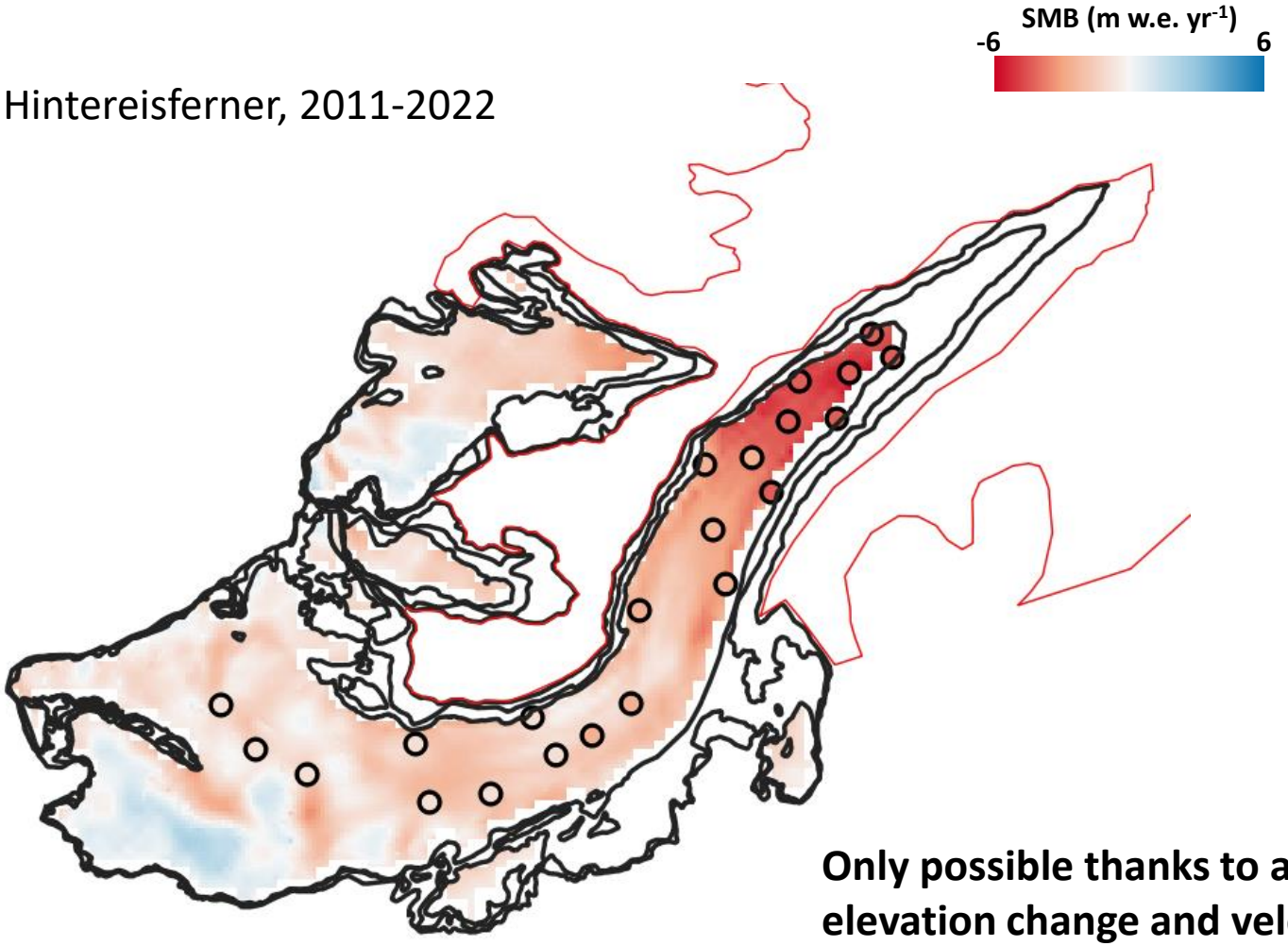
$$\frac{\rho_{dH}}{\rho_{H_2O}}\frac{dH}{dt} = \dot{b} - \frac{\rho_{\nabla q}}{\rho_{H_2O}}\nabla * \boldsymbol{q}$$

$$\boldsymbol{q} = h\gamma\boldsymbol{u}_s$$

Kneib et al., 2024 (EGUsphere)

Distributed ‘geodetic’ mass balance?

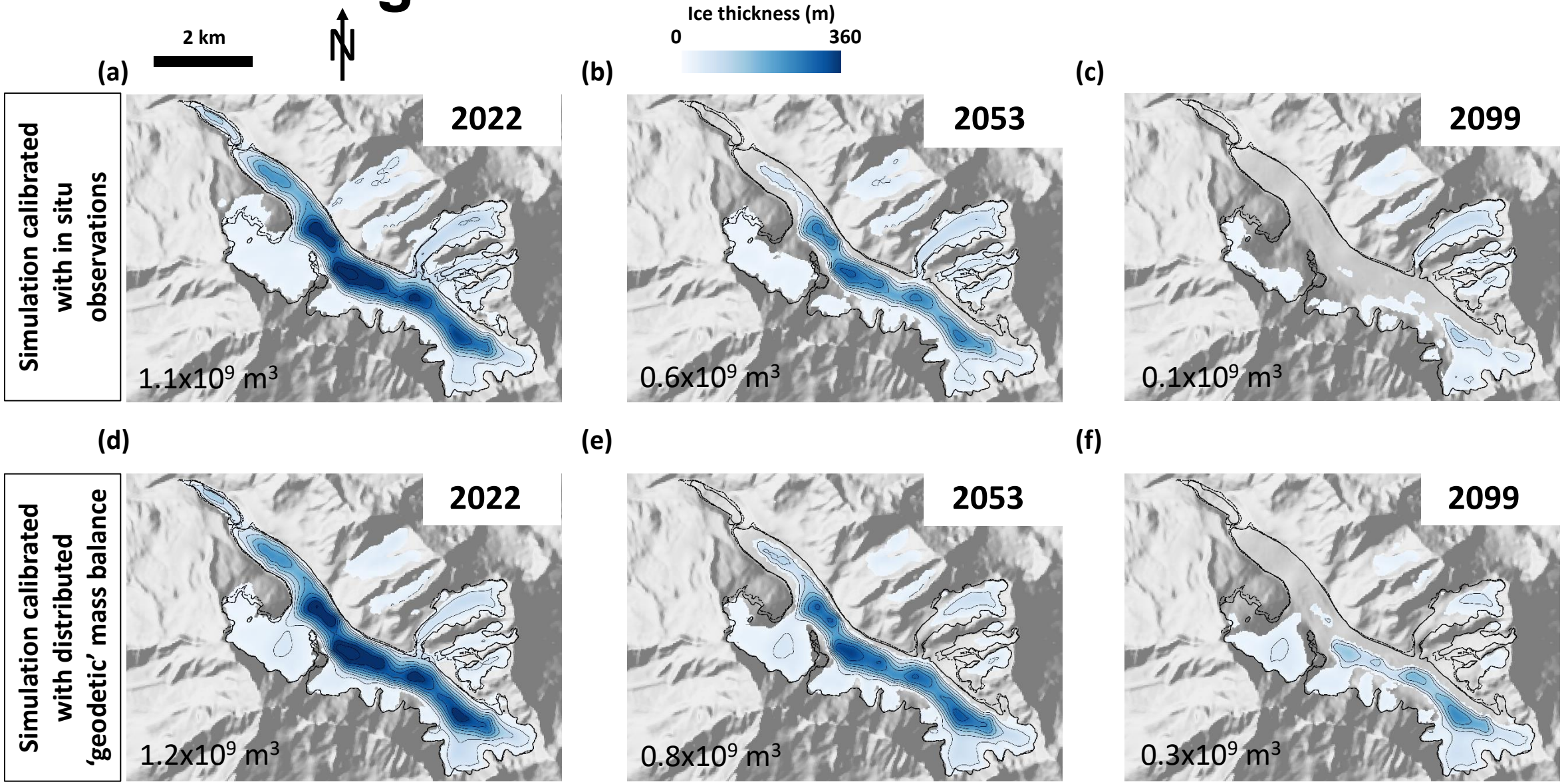
Hintereisferner, 2011-2022



Only possible thanks to a huge improvement in elevation change and velocity products!

Kneib et al., 2024 (EGUsphere)

Distributed ‘geodetic’ mass balance?



Kneib et al., 2024 (EGUsphere)

Thanks for your attention!