



# Glaciology – what we (don't) know

J. F. (Jakob) Steiner

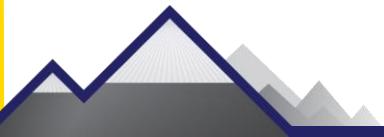
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Quaternary Climate and Global Change



# Topics

- Glaciers today
- Concepts and field measurements
- Understanding the past and forecasting into the Future





# Glaciers Globally

## Total Area:

RGI: 734 933 km<sup>2</sup>

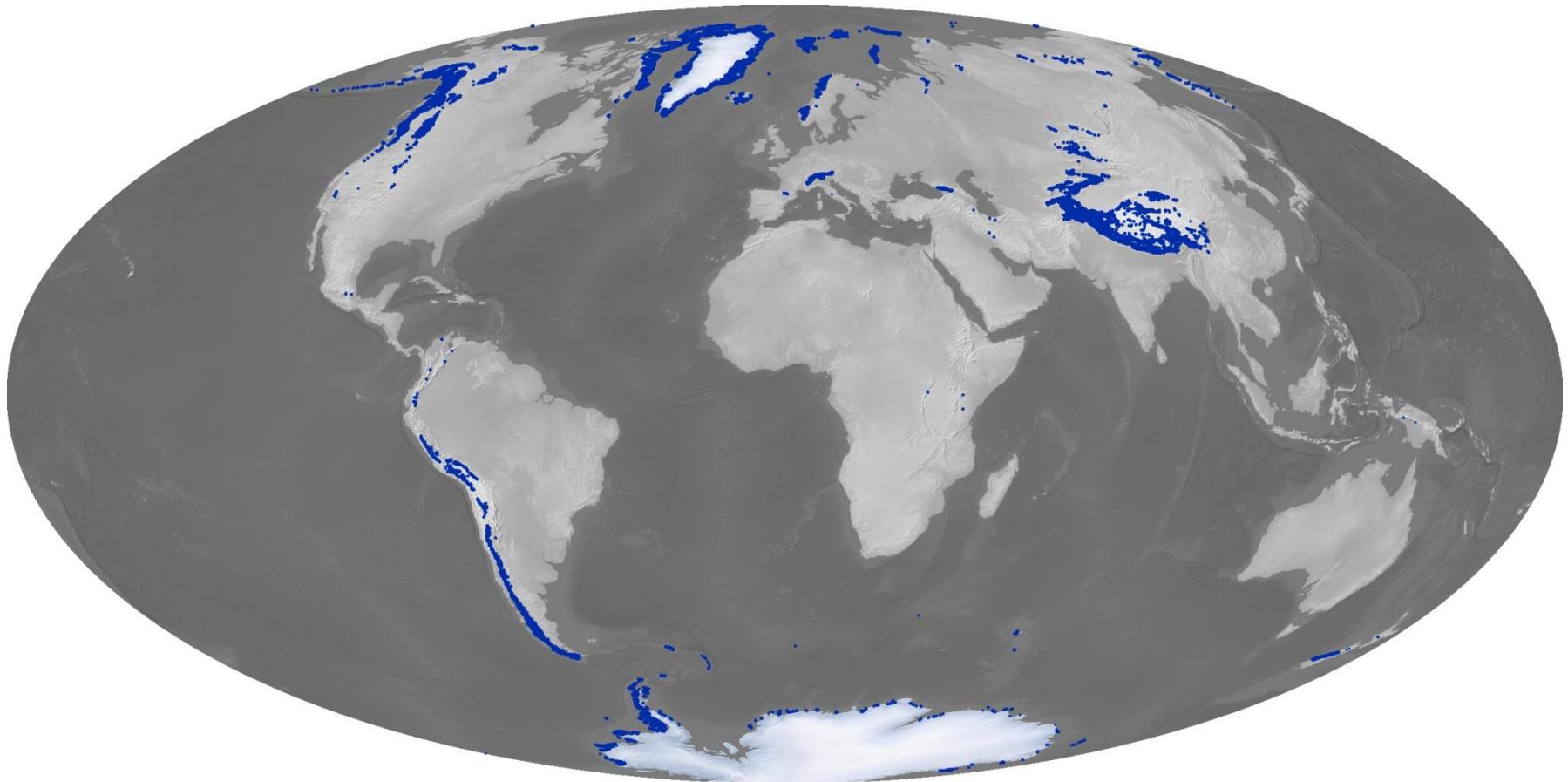
WGI: 747 688 km<sup>2</sup>

## Volume (SLE, m):

Radic & Hock, 2010: 0.60 +/- 0.07

Huss & Farinotti, 2012: 0.43 +/- 0.06

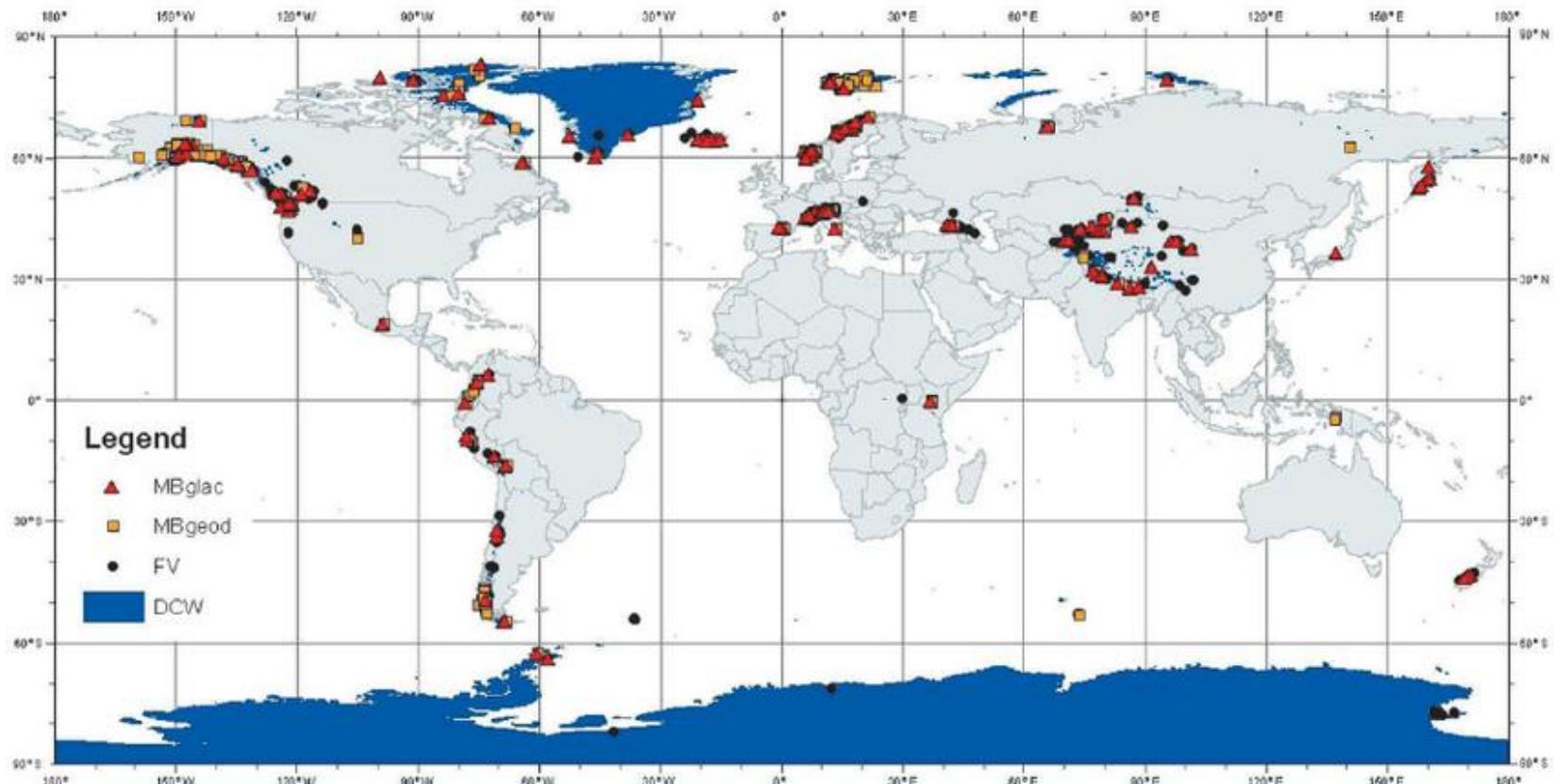
Grinsted, 2013: 0.35 +/- 0.07



R. Simmon, NASA; based on RGI4 (2013)



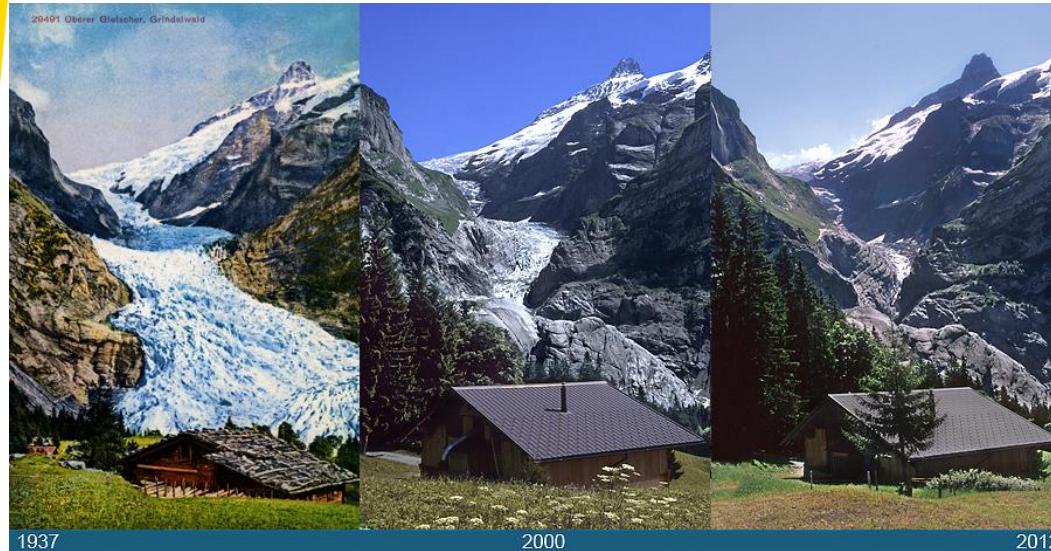
# Measurements



Zemp et al., (2013) in *Global Land Ice Measurements from Space*, Springer



# From Observations to Models



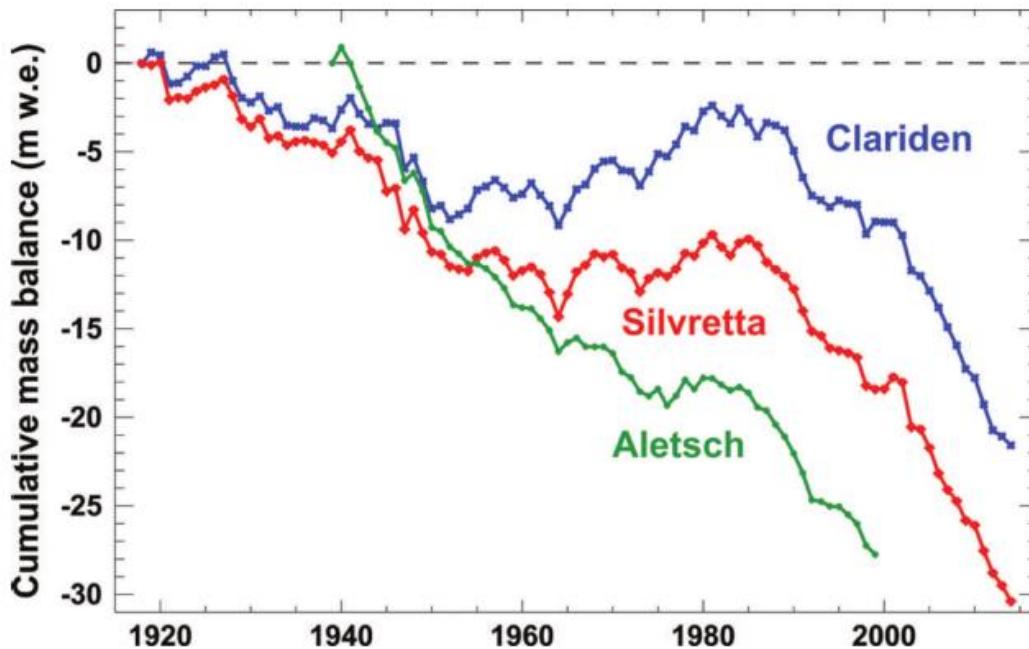
Year 2007 Rhone glacier



Grindelwaldgletscher (top) and Triftgletscher (bottom); Source: [www.gletscherarchiv.de](http://www.gletscherarchiv.de)



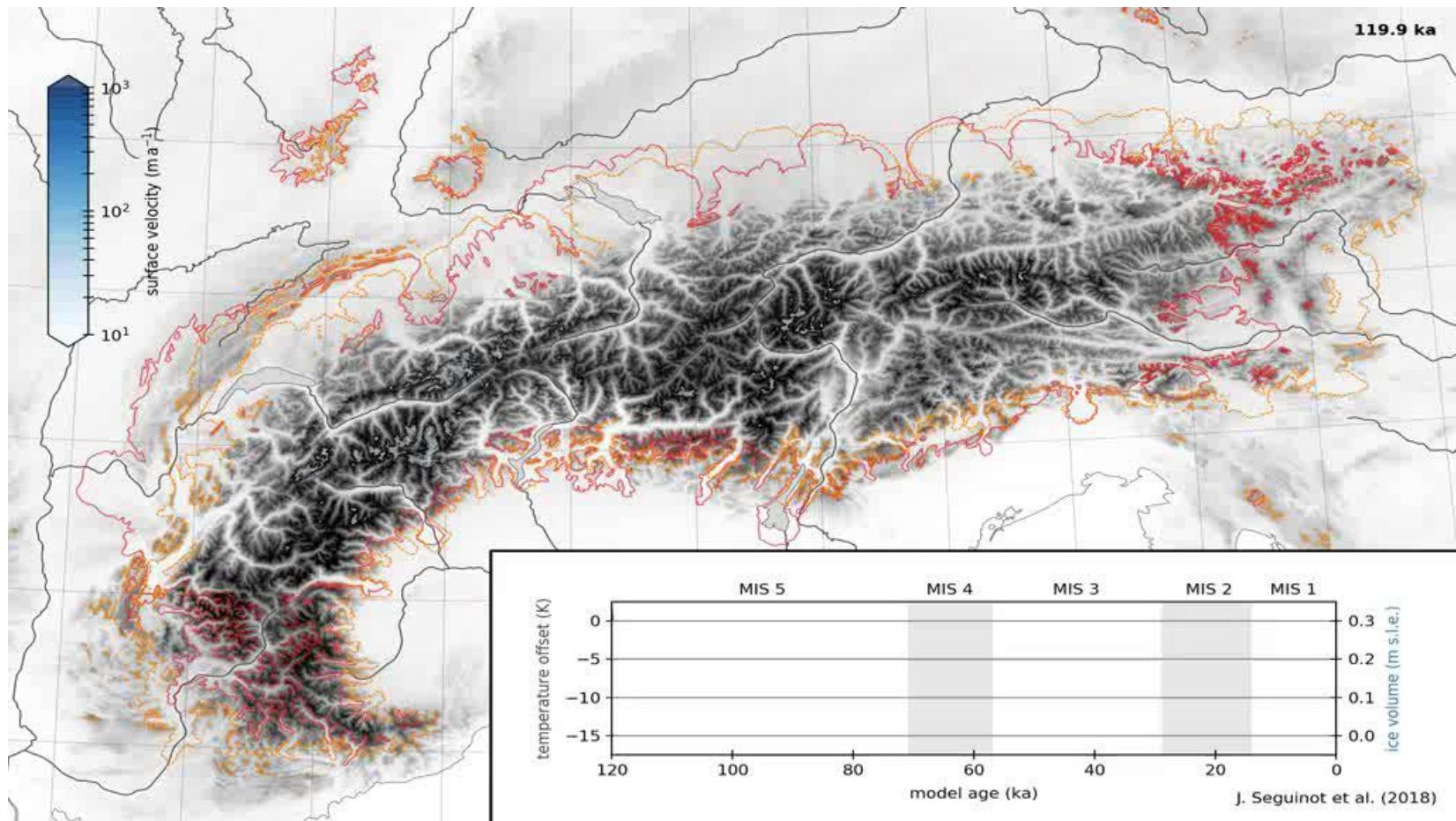
# Mass Balance Time Series



**Fig. 4.** Cumulative mass balance for Clariden and Silvretta (1918–2014) and Aletsch (1939–1999).

Huss et al., 2015 JoG

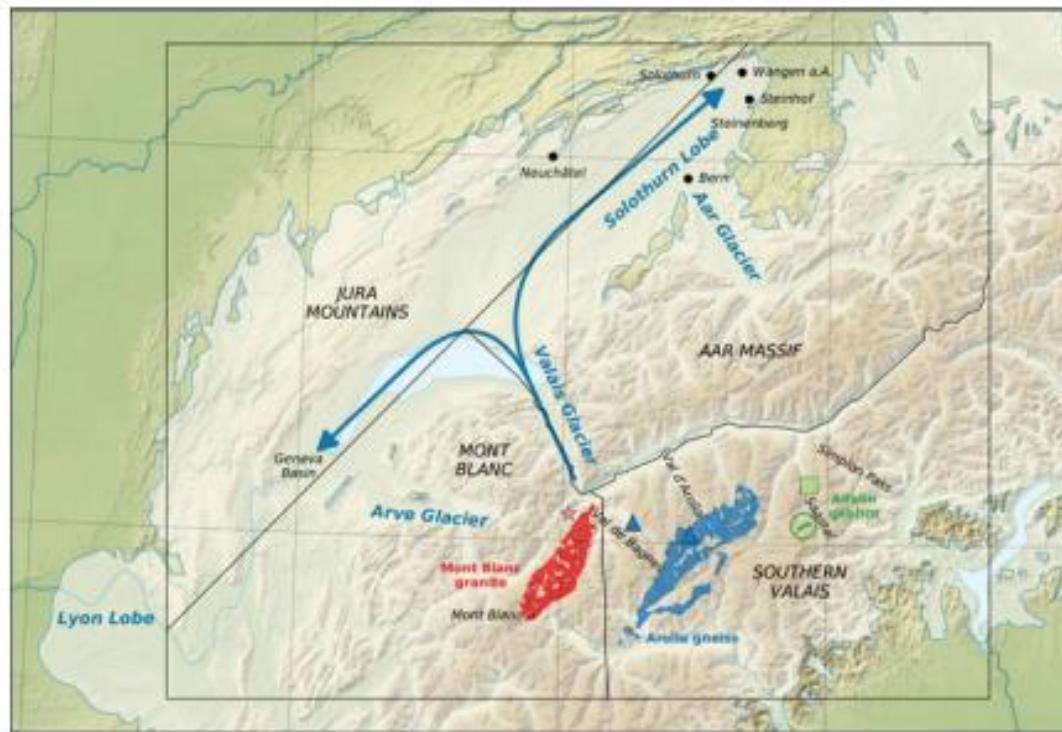
# Reconstructing ice extents



J. Seguinot et al. (2018)



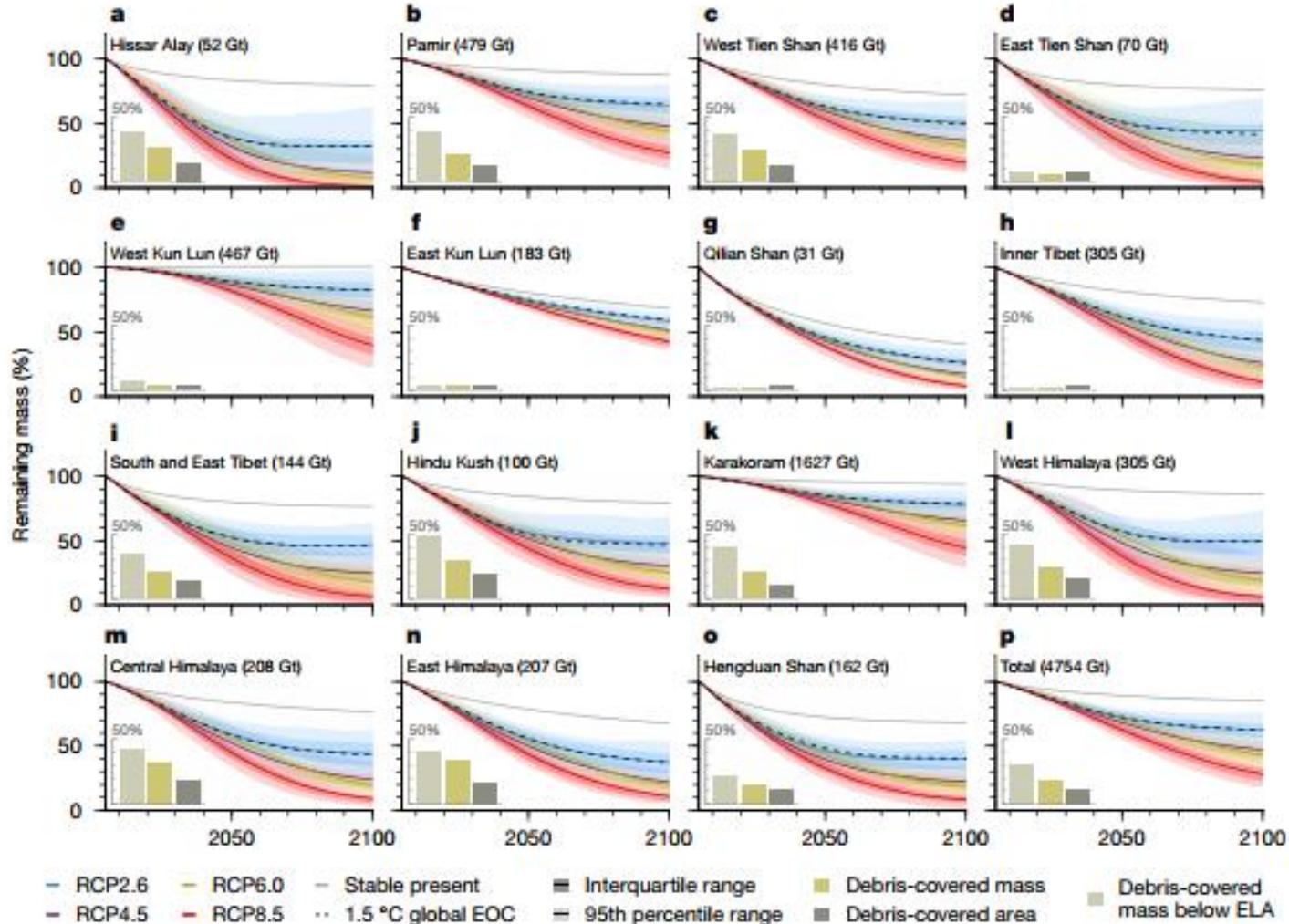
# Glacier change and erratic boulders



**Fig. 1.** Relief map of the north western alps showing the LGM extent of the alpine ice cap (blue line, after Ehlers and others, 2011). The arrows indicate the direction of the former ice flow from the Rhone Valley toward the Solothurn and Lyon lobes. The modelling domain (black rectangle) was divided into four precipitation zones: Mont Blanc, southern Valais, Jura Mountains and Aar Massif. Source regions of characteristic lithologies considered in this study (Mont Blanc granite, Arolla gneiss, and Allalin gabbro) are reproduced from (Swisstopo, 2005). Corresponding marker starting points used for modelling are shown by symbols  $\star$ ,  $\blacktriangle$  and  $\blacksquare$ . The background map consists of SRTM (Jarvis and others, 2008) and Natural Earth Data (Patterson and Kelso, 2015).

Jouvet et al., 2016, JoG

# Future glacier volumes





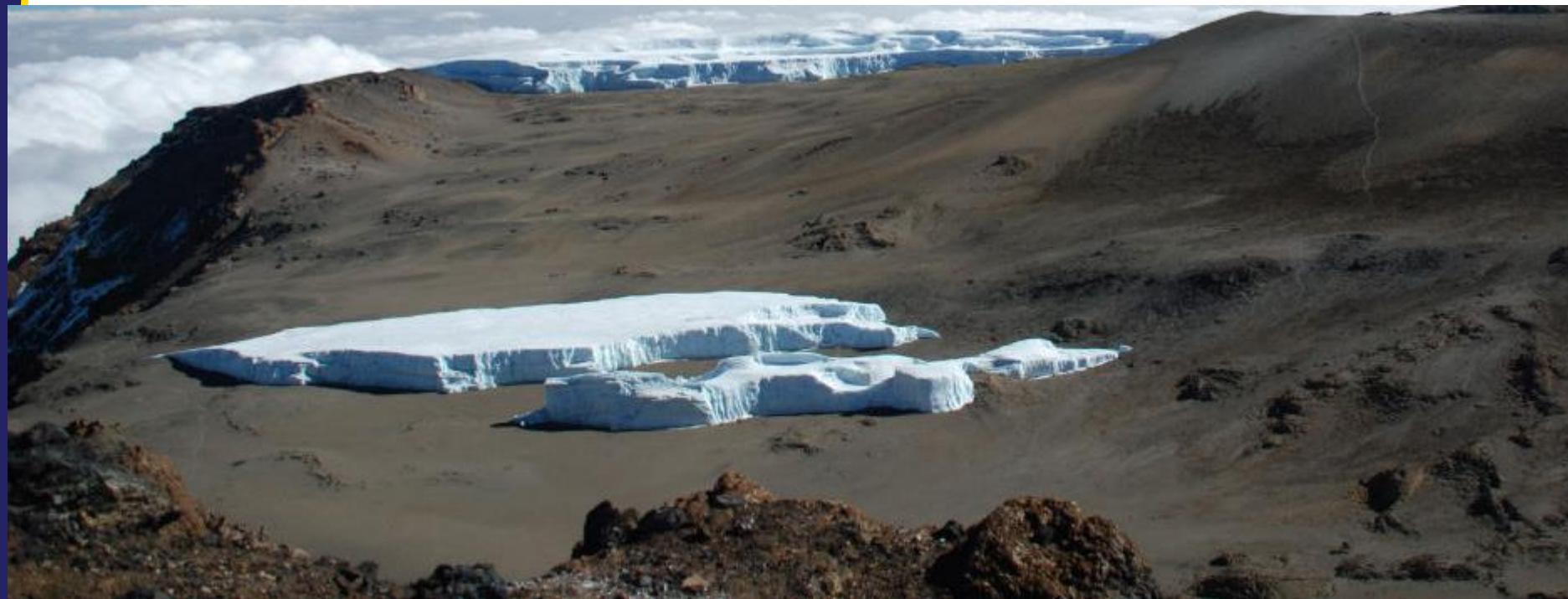
Elephant Foot Glacier,  
NE - Greenland



Baltoro Glacier,  
Karakoram/Pakistan



Belvedere Glacier,  
Val d'Aosta, Italian Alps



Furtwangler Glacier,  
Kibo/Kilimanjaro,  
Tanzania



# Fieldwork in Greenland

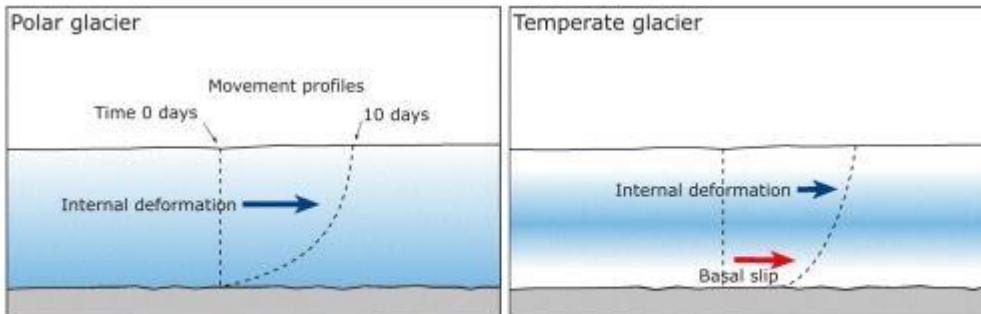








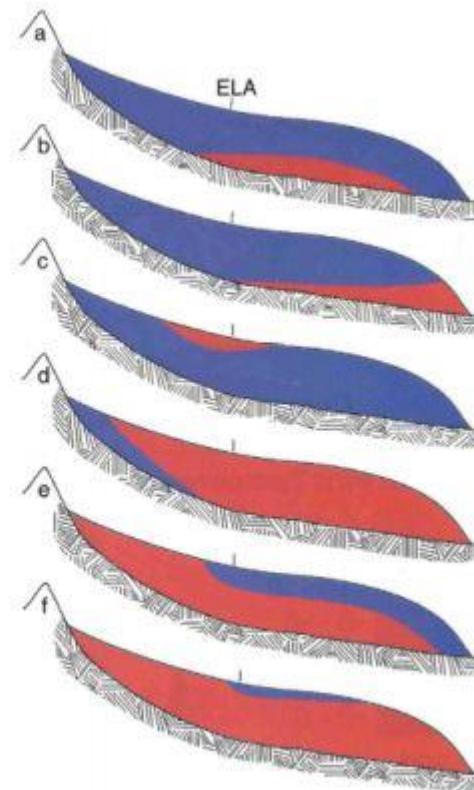
# Ice temperature -> Ice flow



Components of ice movement with a polar and temperate glaciers

- a typical for the high Arctic
- b many Arctic glacier, e.g. central flow line of Gornergletscher
- c high Arctic, very cold climate (high Himalayas)
- d high mountains
- e maritime Arctic, e.g. Storglaciären
- f ?

(from Benn and Evans, 1998)





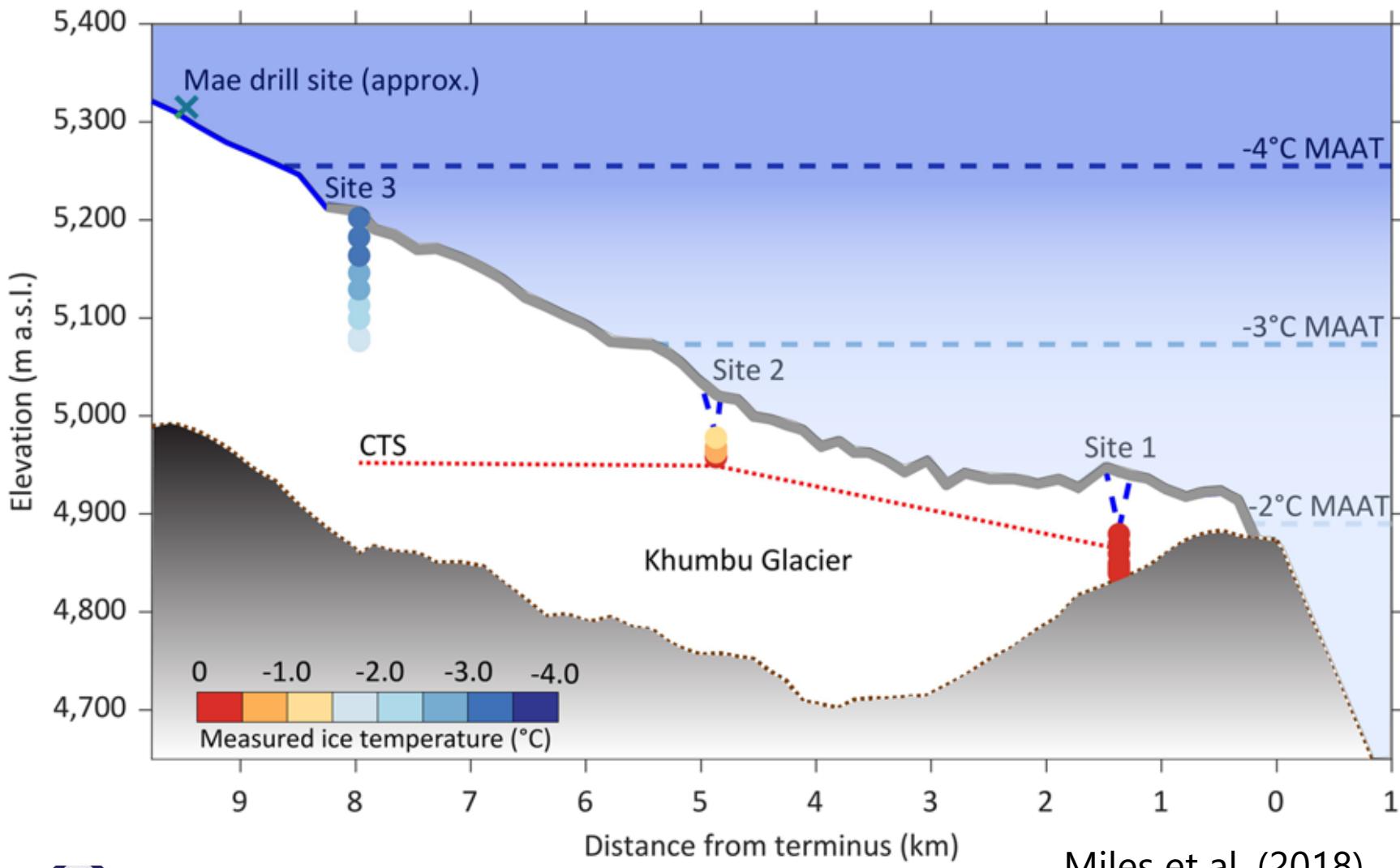
# Ice temperature -> Ice flow







# Ice temperatures in the Himalaya

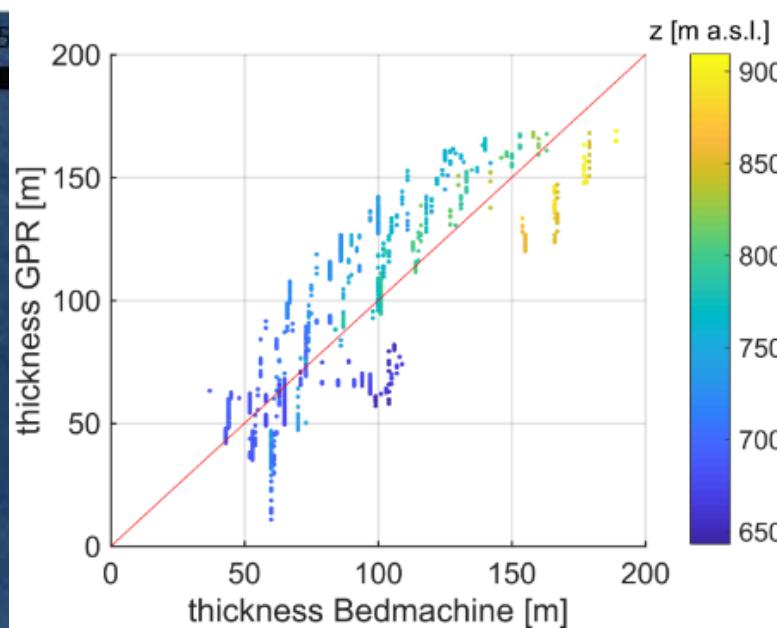
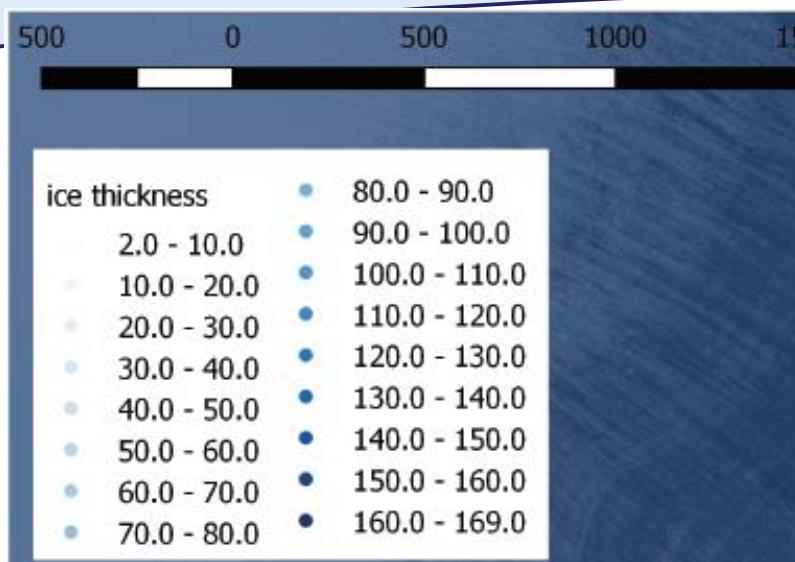


Miles et al. (2018)



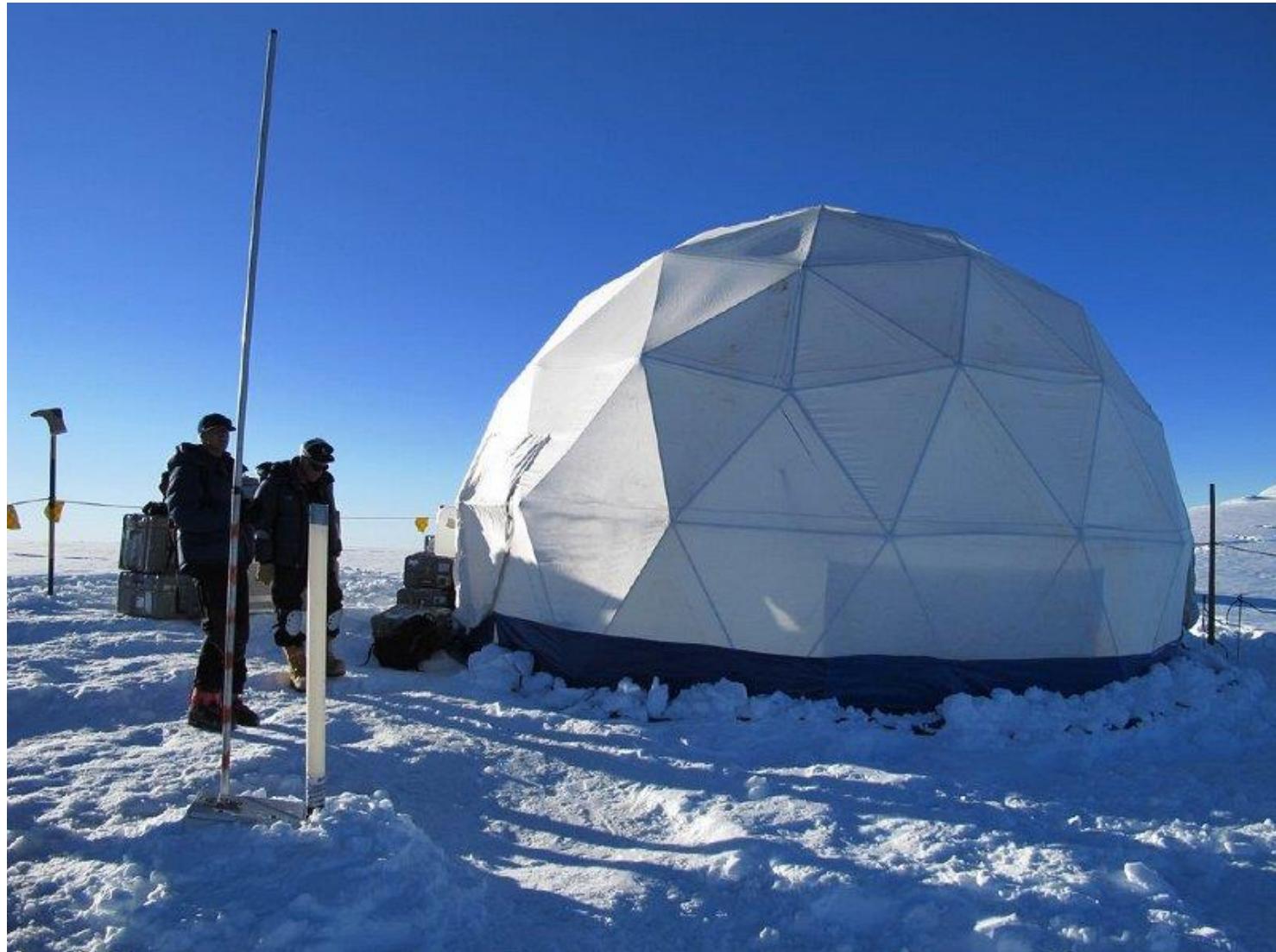
# Ice thickness



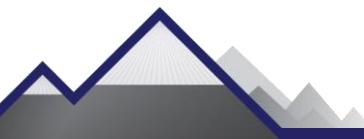


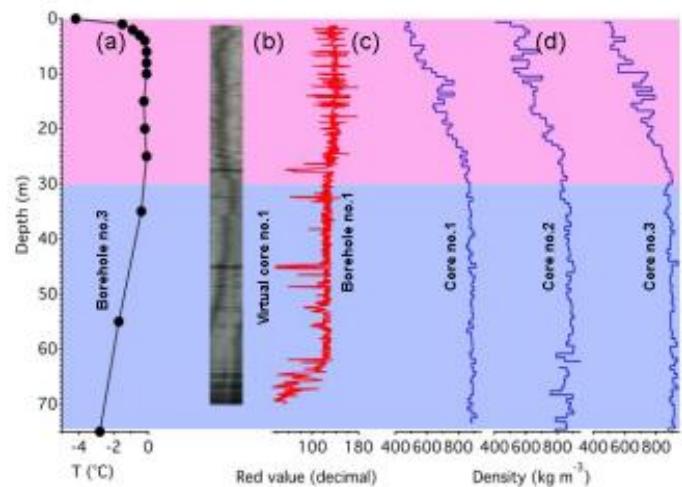


# Inside the Glacier ...



Ortles Project  
European Alps



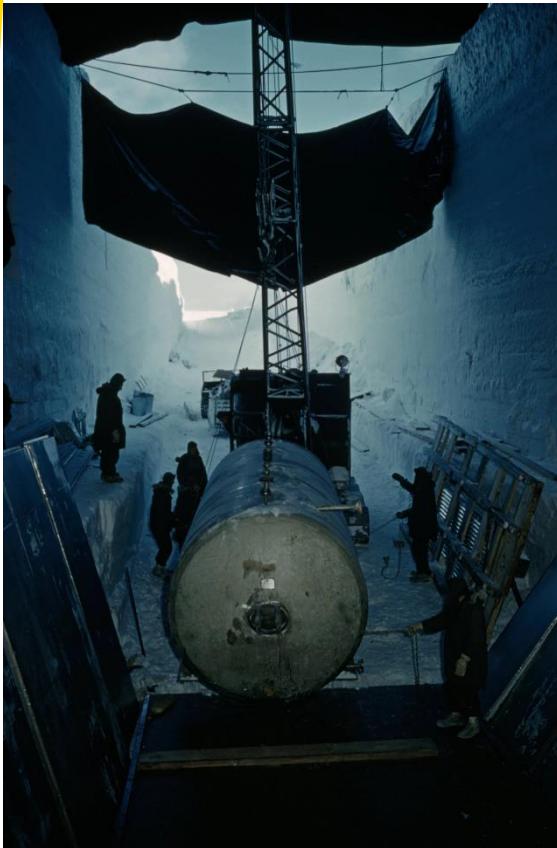


**Figure 7.** Physical characteristics of the Mt. Ortles cores. The temperate firn portion is enclosed in red shading, while the cold ice is in blue. (a) Borehole no. 3 temperatures recorded 43 days after the end of the drilling operations (from Gabrielli et al., 2012). (b) Virtual image of core no. 1 reconstructed from  $360^\circ$  Televiwer visual scanning of borehole no. 1. (c) Red component of the RGB digital signal obtained by means of visual scanning. High values indicate higher light reflection. (d) Densities of the Mt. Ortles ice cores no. 1, no. 2 and no. 3.

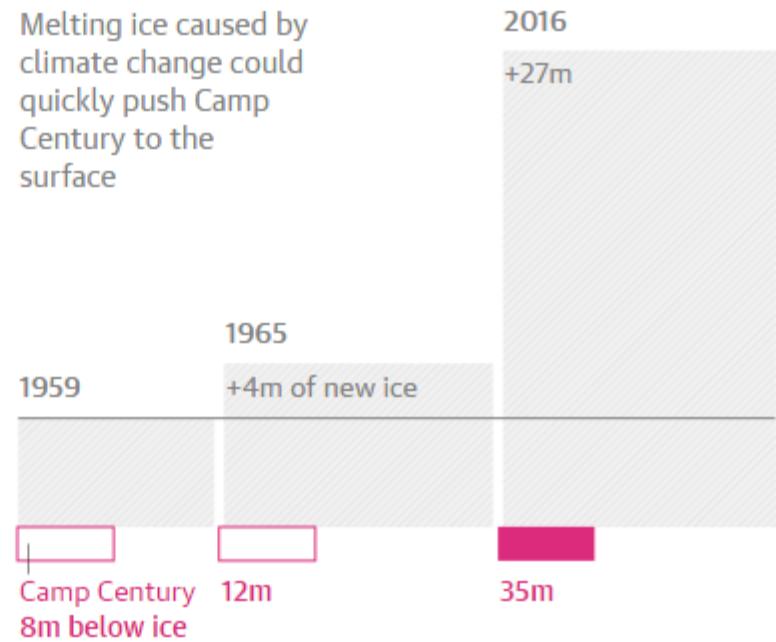




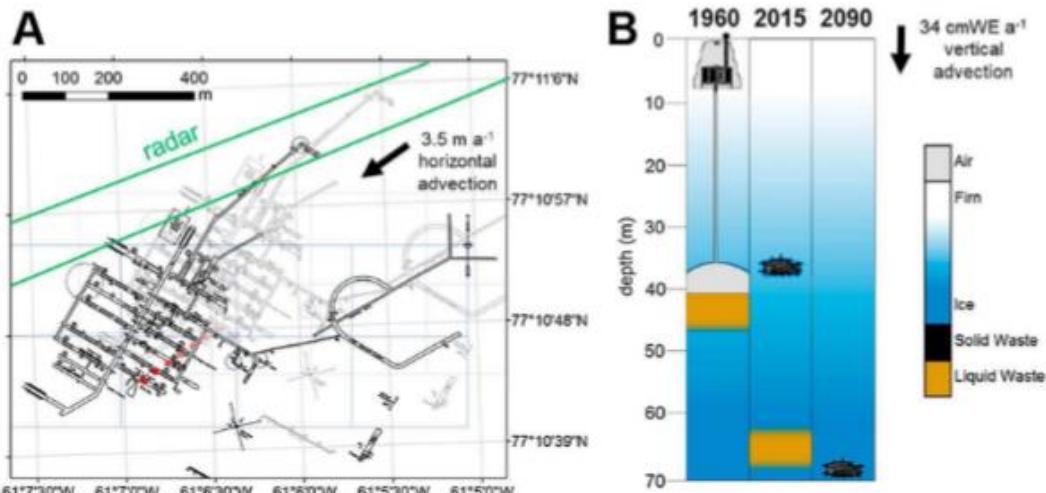
# Camp Century – Project IceWorm



Melting ice caused by climate change could quickly push Camp Century to the surface



Graphic: The Guardian, 27/09/2016

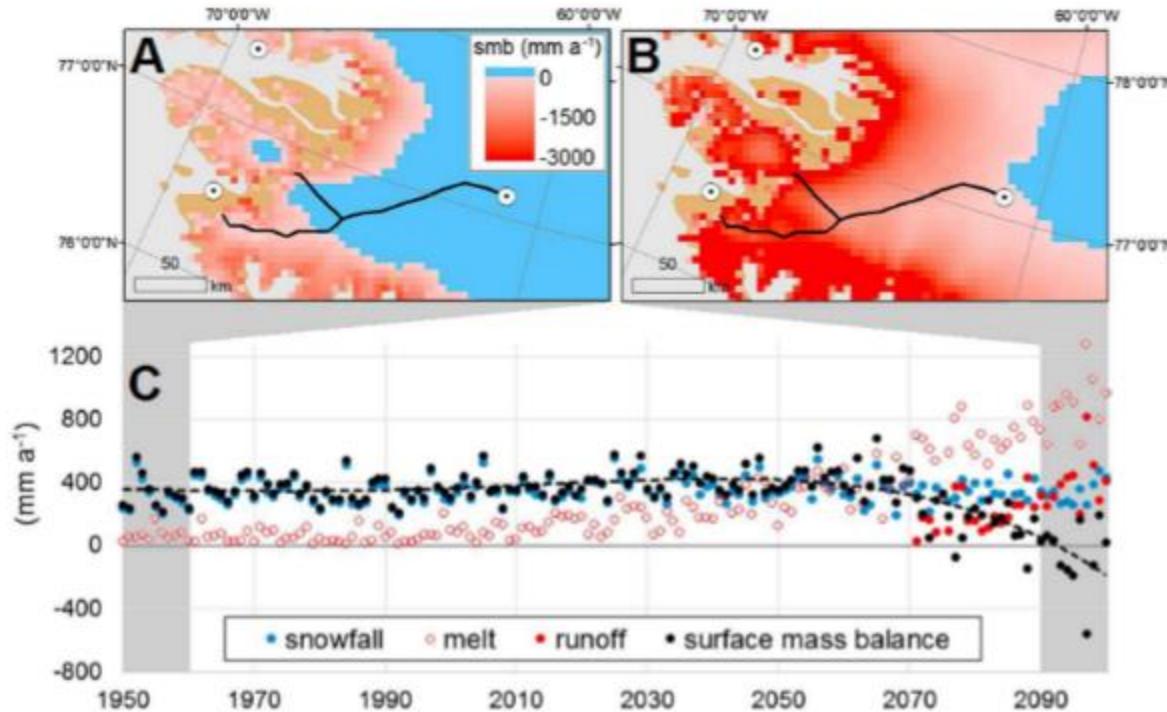


**Figure 2.** (a) Camp Century "as built" map georeferenced to 1960 (grey) and 2020 (black) locations [Kovacs, 1970], based on past surveys of the borehole location and horizontal advection associated with ice flow (Supplementary Methods). The red points denote decadal borehole location from 1960 to 2020. The green lines denote radar profiles shown in Figure 3. (b) Estimated Camp Century solid and refrozen liquid waste depths in 1960, 2015, and 2090, based on vertical advection rates (Figure S3). The horizontal extent of the liquid waste, while large relative to tunnel width, is small relative to camp width.



Colgan et al., 2016, GRL

# Future Ice melt in a changing climate ...



**Figure 4.** (a) Surface mass balance in Northwest Greenland during the 1950s (1950–1959) and (b) 2090s (2090–2099) as simulated by MAR v3.5 forced by CanESM2 under RCP8.5 [Fettweis et al., 2013]. The color bars saturate at minimum and maximum values. The blue shading denotes the accumulation area where surface mass balance is positive. (c) Surface mass balance, and its components, at Camp Century during 1950–2100 as simulated by MARv3.5 and forced by CanESM2. The dashed line denotes polynomial trend. The NorESM1 simulation is shown in Figure S2.

Colgan et al., 2016, GRL

... what about horizontal movement?

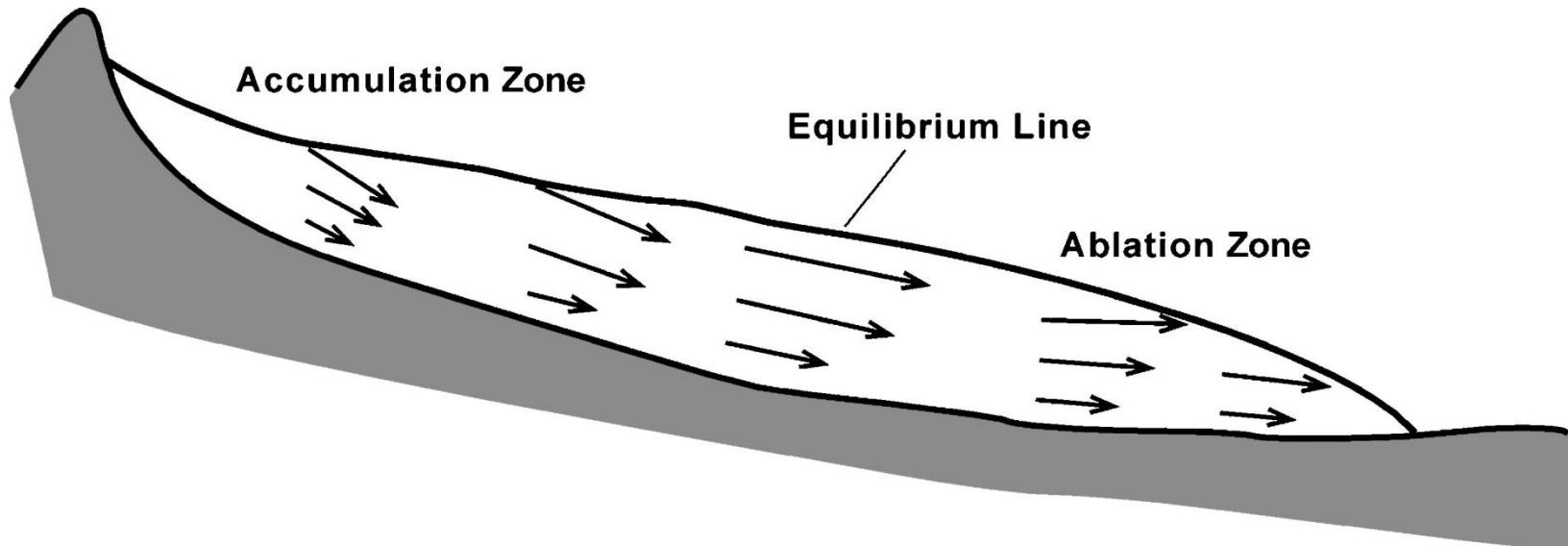


# Theory

- Mass Balance
  - Field Measurements
  - Remote Sensing
- Energy Balance
  - Basic Principles
- Flow Dynamics



# Mass Balance – Accumulation and Ablation



Cuffey and Patterson (2010)

- ELA – Equilibrium Line Altitude
- AAR – Accumulation Area Ratio ( $= A_{Acc} / A_{total}$ )



Claridenfirn, Switzerland  
G. Kappenberger

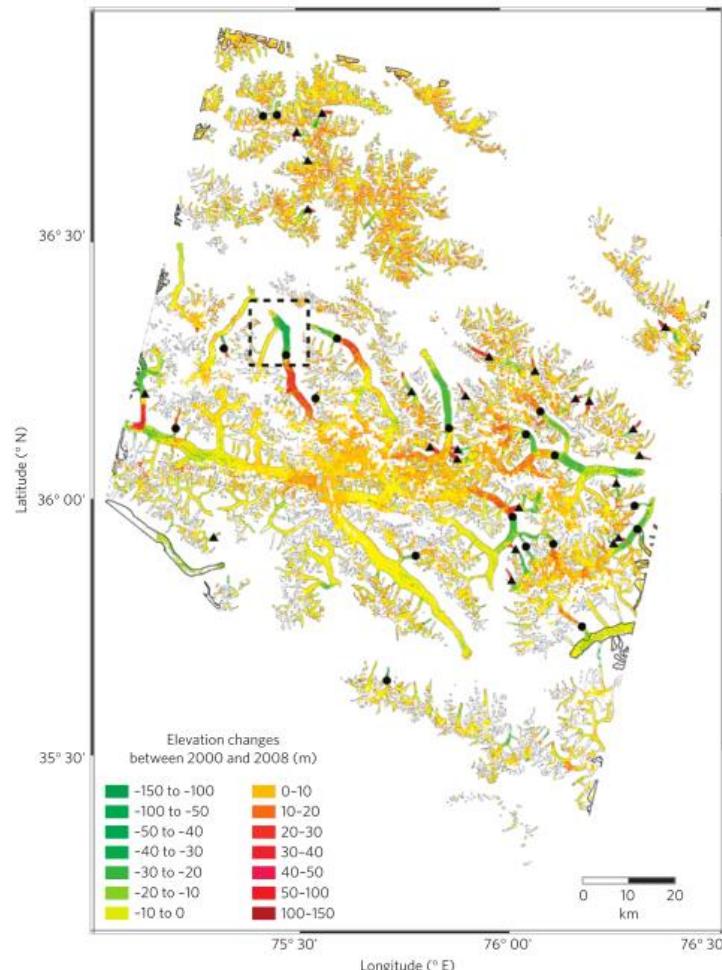


Claridenfirn, Switzerland  
G. Kappenberger





# Geodetic Mass Balance



**Figure 2 | Map of glacier elevation changes between February 2000 and December 2008.** Grey polygons correspond to the glacier outlines (thick black polygons correspond to edge glaciers that were excluded from the mass-balance computation). The total ice-covered area is 5,615 km<sup>2</sup>. The black triangles represent glaciers in a surge phase; black circles represent glaciers in a post-surge or quiescent phase. The dashed black box defines the area shown in Supplementary Fig. S1. 41% of elevation changes do not exceed ±5 m. Elevation differences off-glaciers are shown in Supplementary Fig. S4.

Gardelle et al., NatGeo (2012)



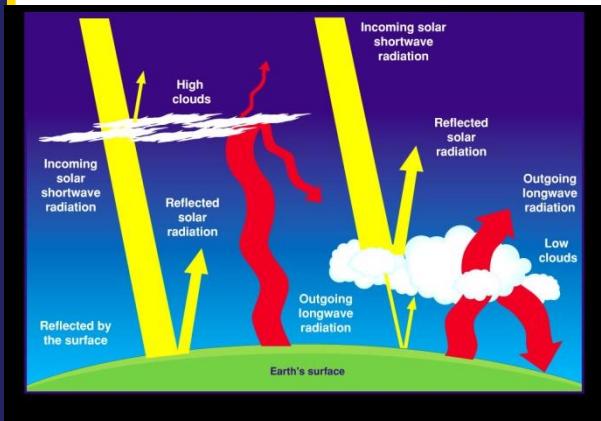
# Energy Balance

- ... to melt ice we need Energy

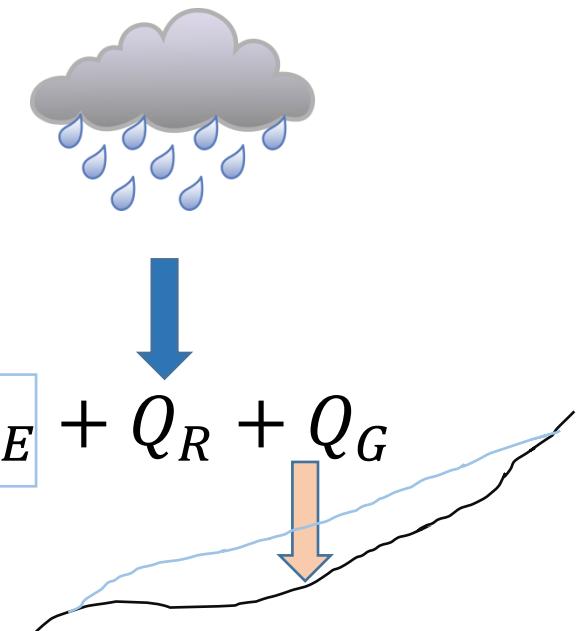
$$h_{we} \text{ [m w.e.]} = \frac{E \text{ [J]}}{\rho_w \text{ [kg m}^{-3}\text{]} L_f \text{ [J kg}^{-1}\text{]}}$$

$$Q_M \text{ [W m}^{-2}\text{]} = \frac{\delta E \text{ [J]}}{\delta t \text{ [s]}}$$

$$Q_M = \boxed{Q_{SW} + Q_{LW}} + \boxed{Q_H + Q_{LE}} + Q_R + Q_G$$



Radiative fluxes



Turbulent fluxes



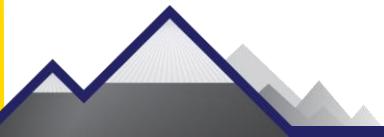


# Sensors on Glaciers



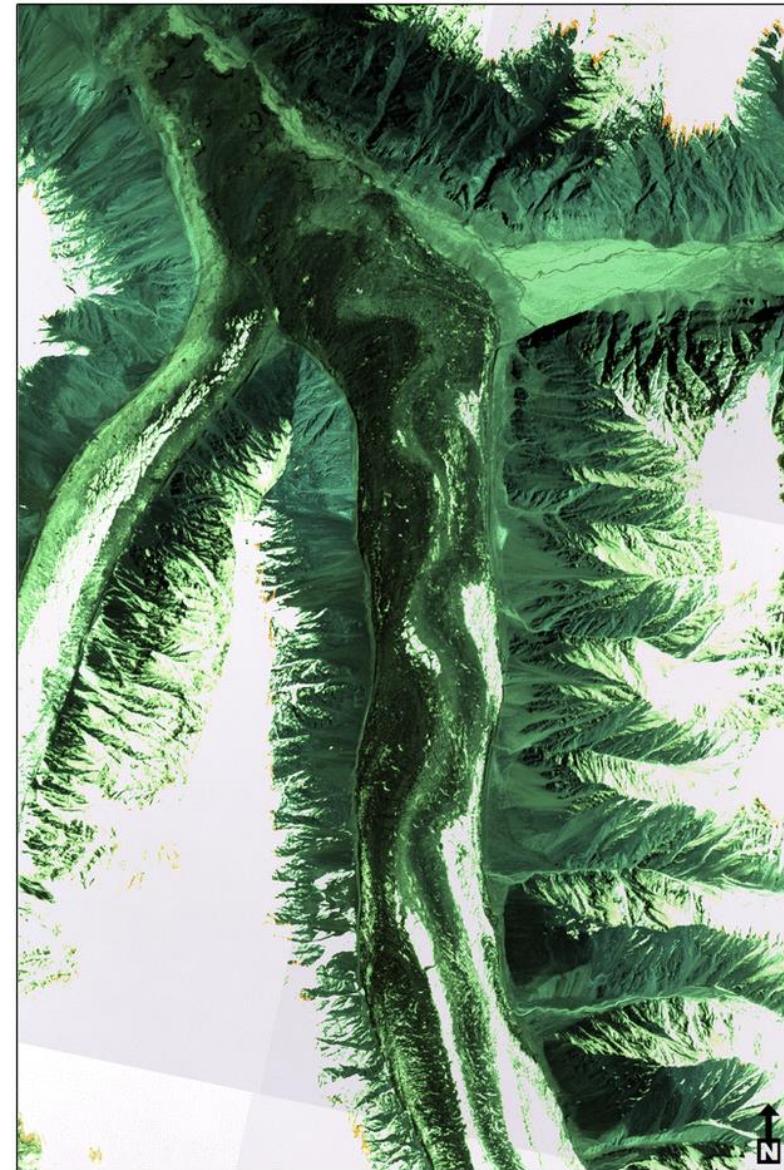
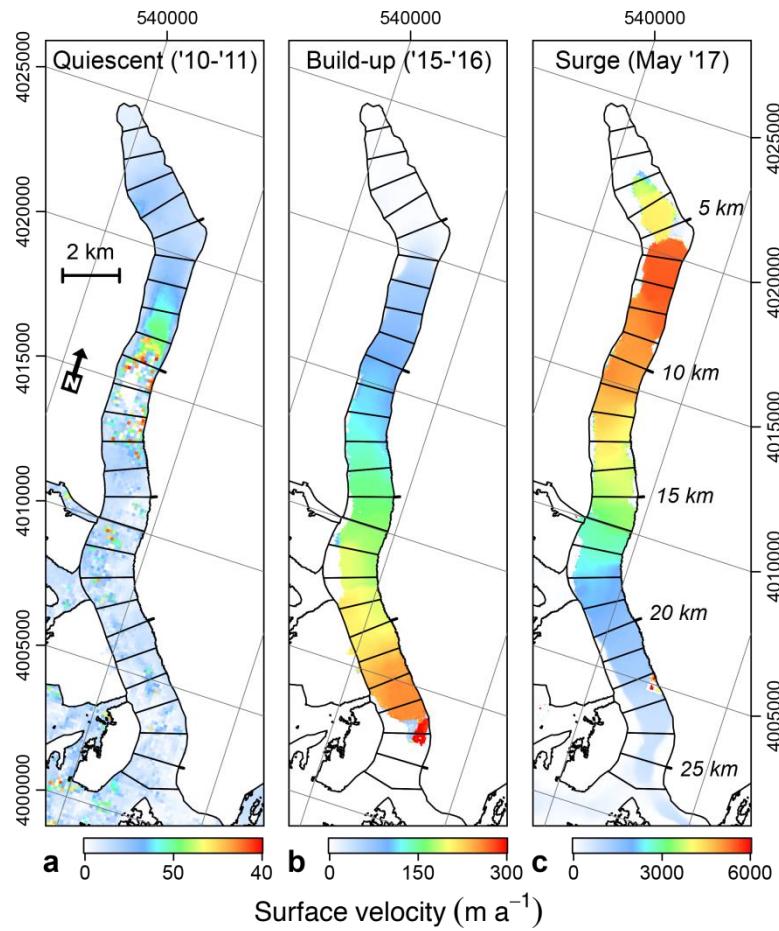


# Rapid recession and monitoring





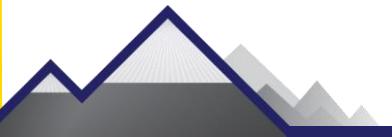
# Glacier Flow





# Physics of Glacier Movement

- Plastic deformation – water pressure
- Basal Slip – basal temperatures
  - Basal velocity
  - Shear Stress
  - Water Pressure and Volume at Bed
  - Bedrock Topography
  - Sediment Properties
- .... But we only see surface velocity and past evidence on bed rock





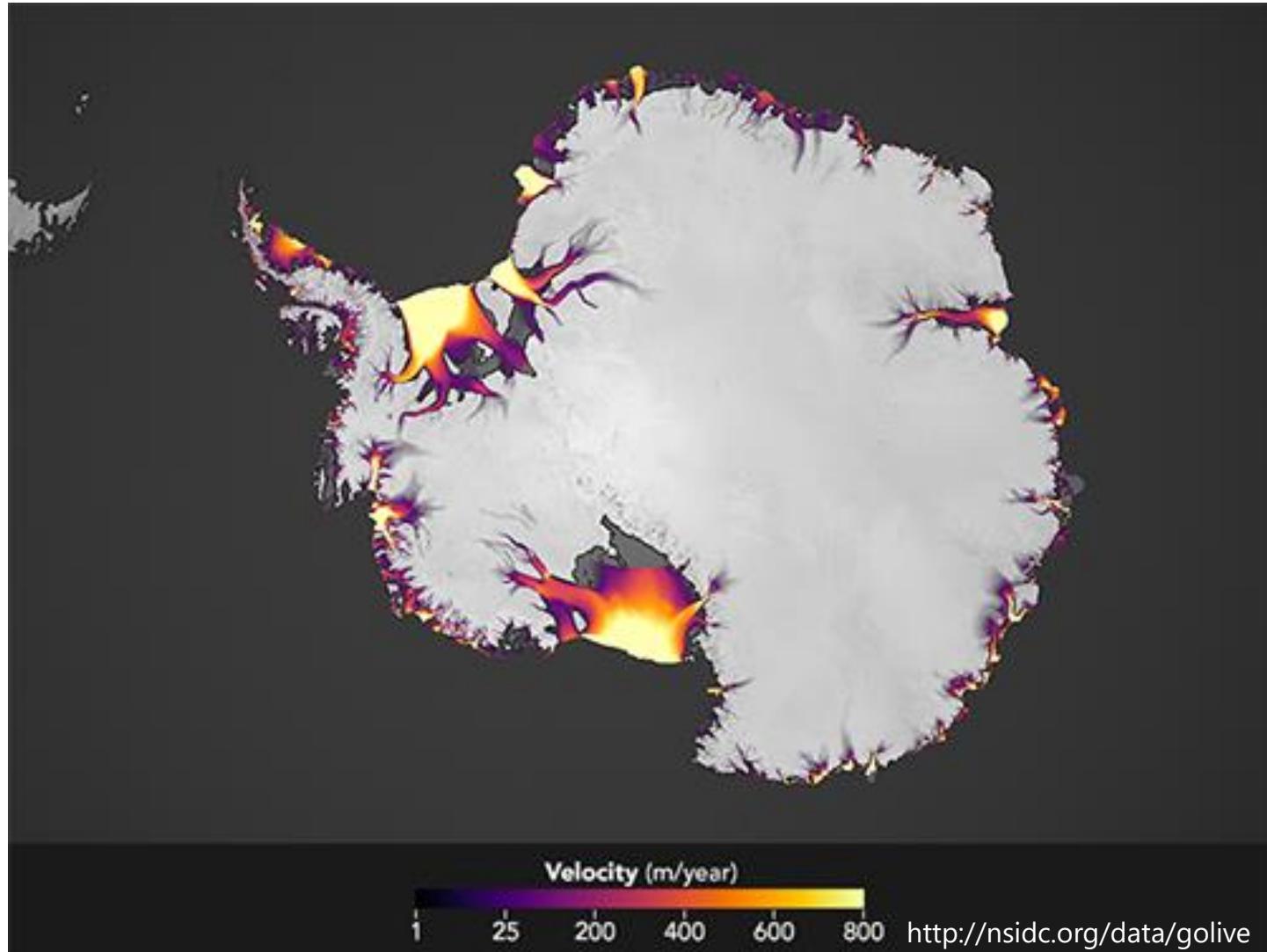
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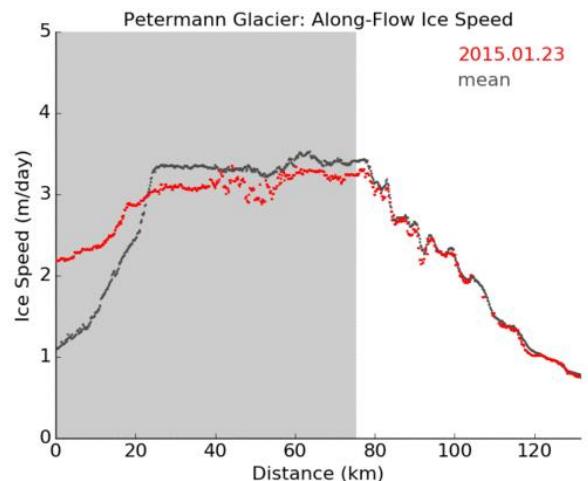
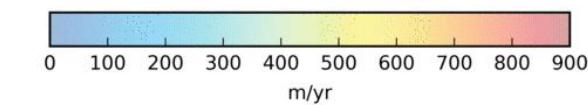
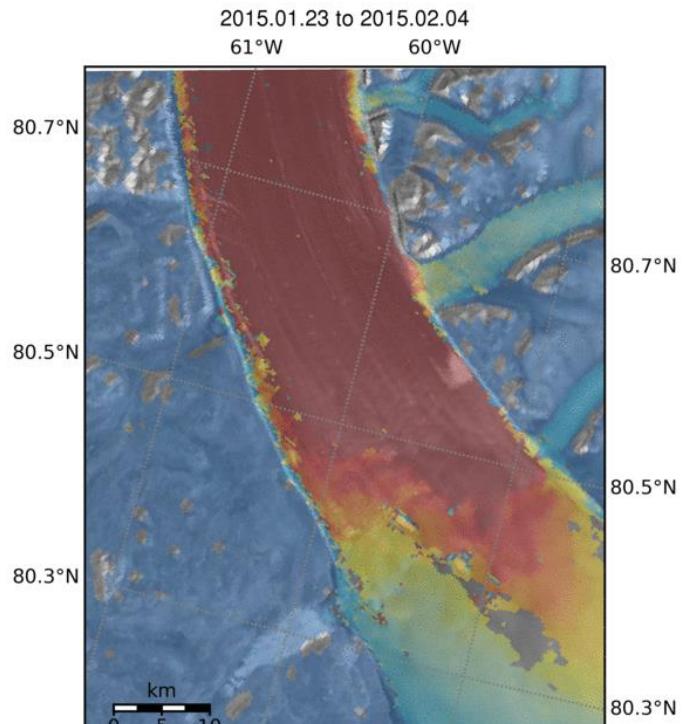


# Velocity Fields – Coarse Resolution





# Velocity Fields – High Resolution



Sentinel Satellites (ESA)