Glaciology – what we (don't) know

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Quaternary Climate and Global Change

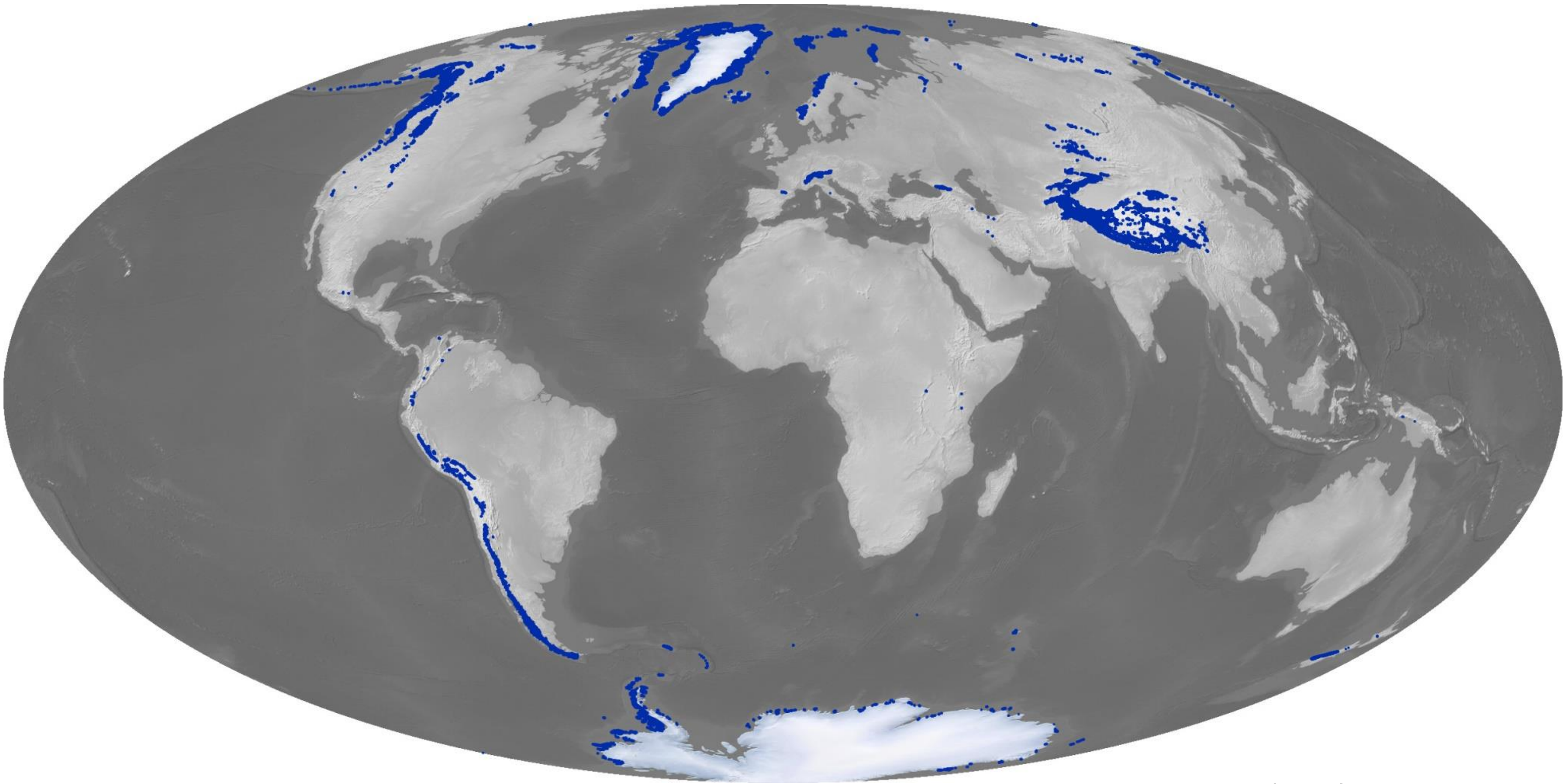
Topics

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

Glaciers globally

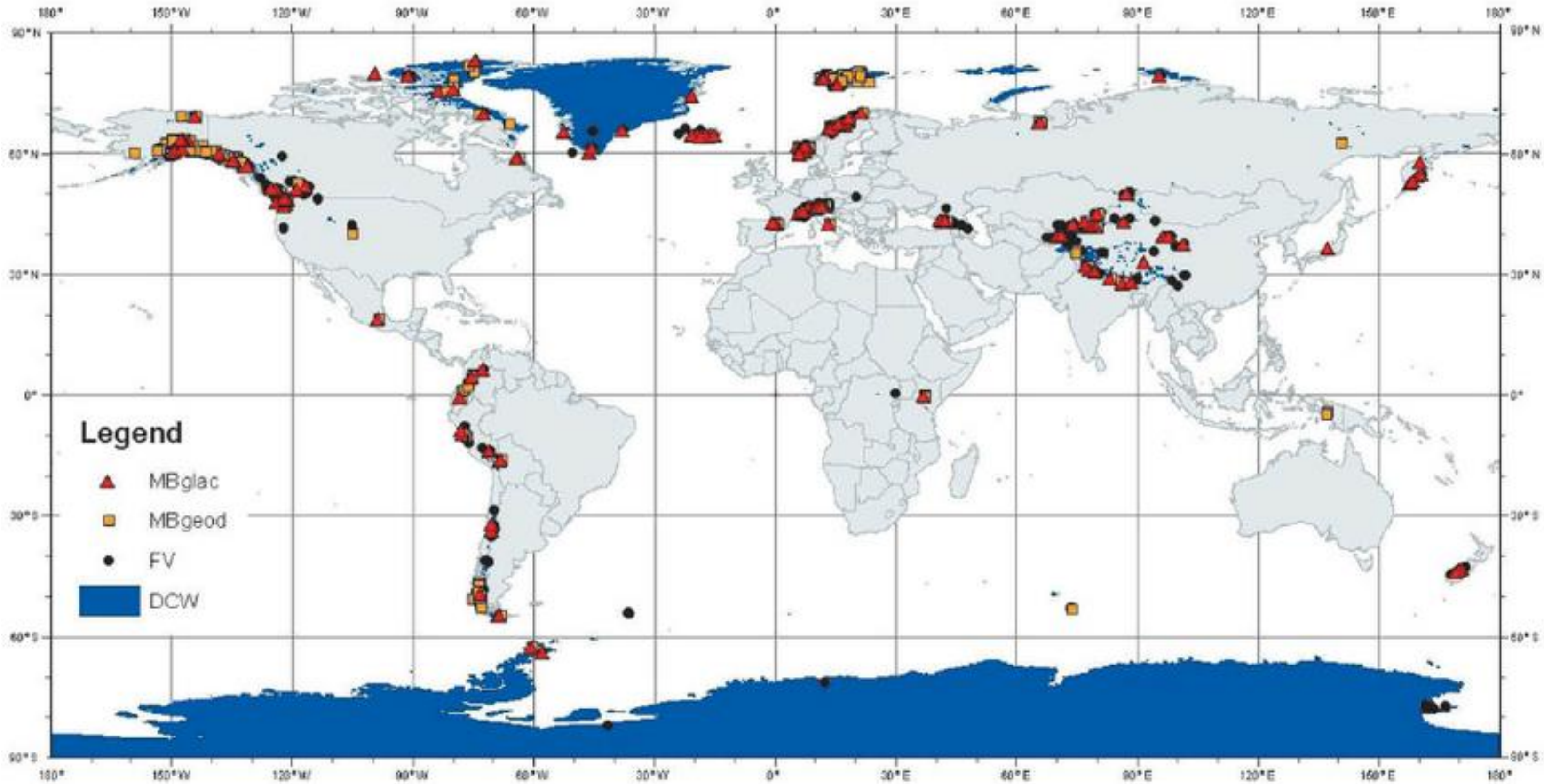
Total Area:
RGI: 734 933 km^2
WGI: 747 688 km^2

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

Grindelwaldgletscher (top) and Triftgletscher (bottom); Source: www.gletscherarchiv.de

Mass balance time series from the past

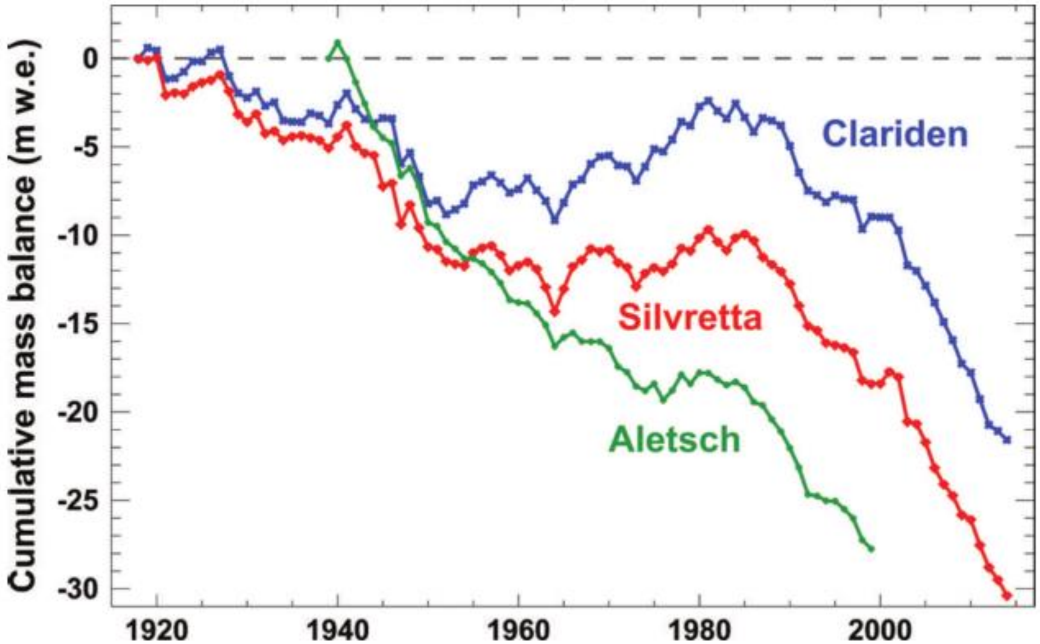
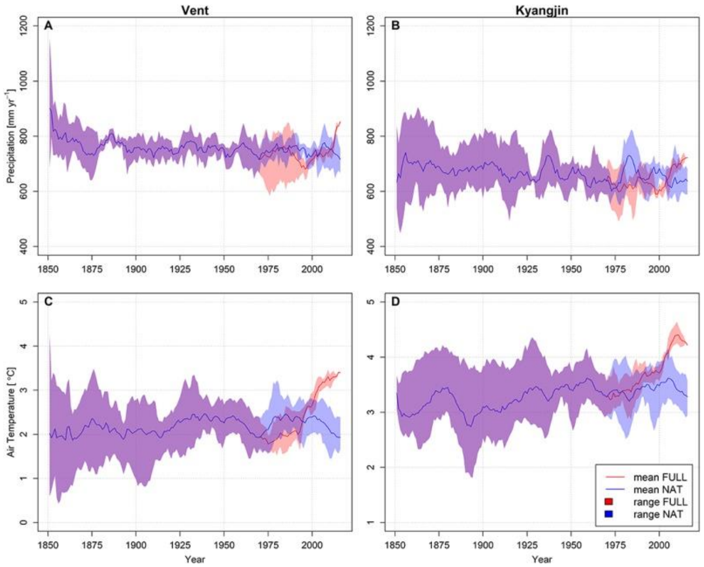


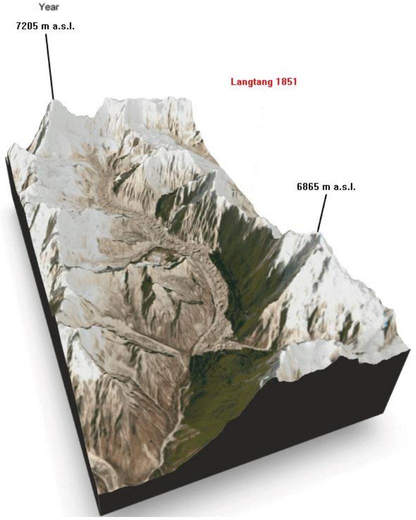
Fig. 4. Cumulative mass balance for Clariden and Silvretta (1918–2014) and Aletsch (1939–1999).

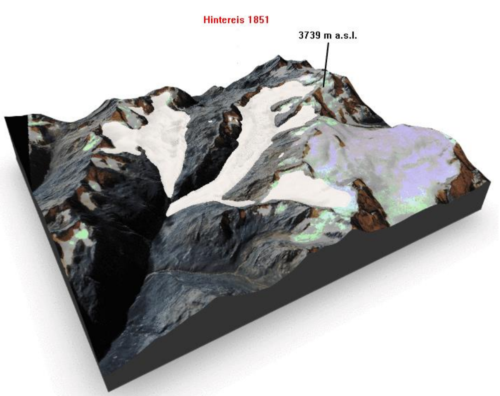
Huss et al., 2015 JoG

Forcing glacier models with climate data



Wijngaard et al. 2019, FoES





Glacier change and erratic boulders

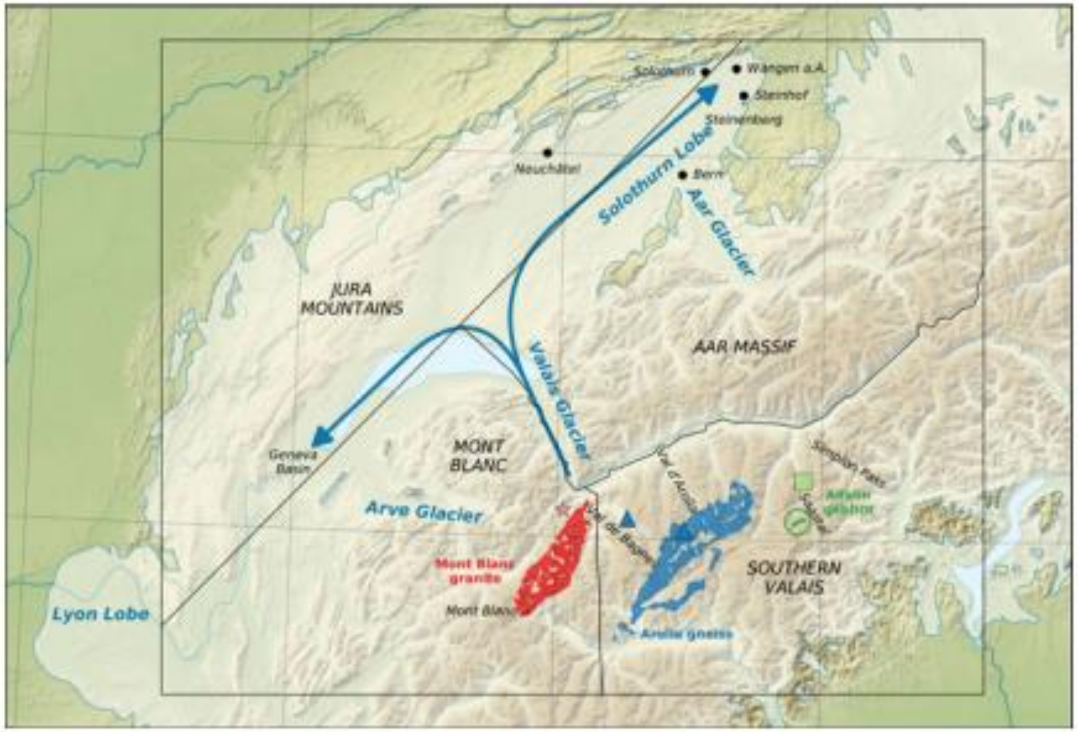
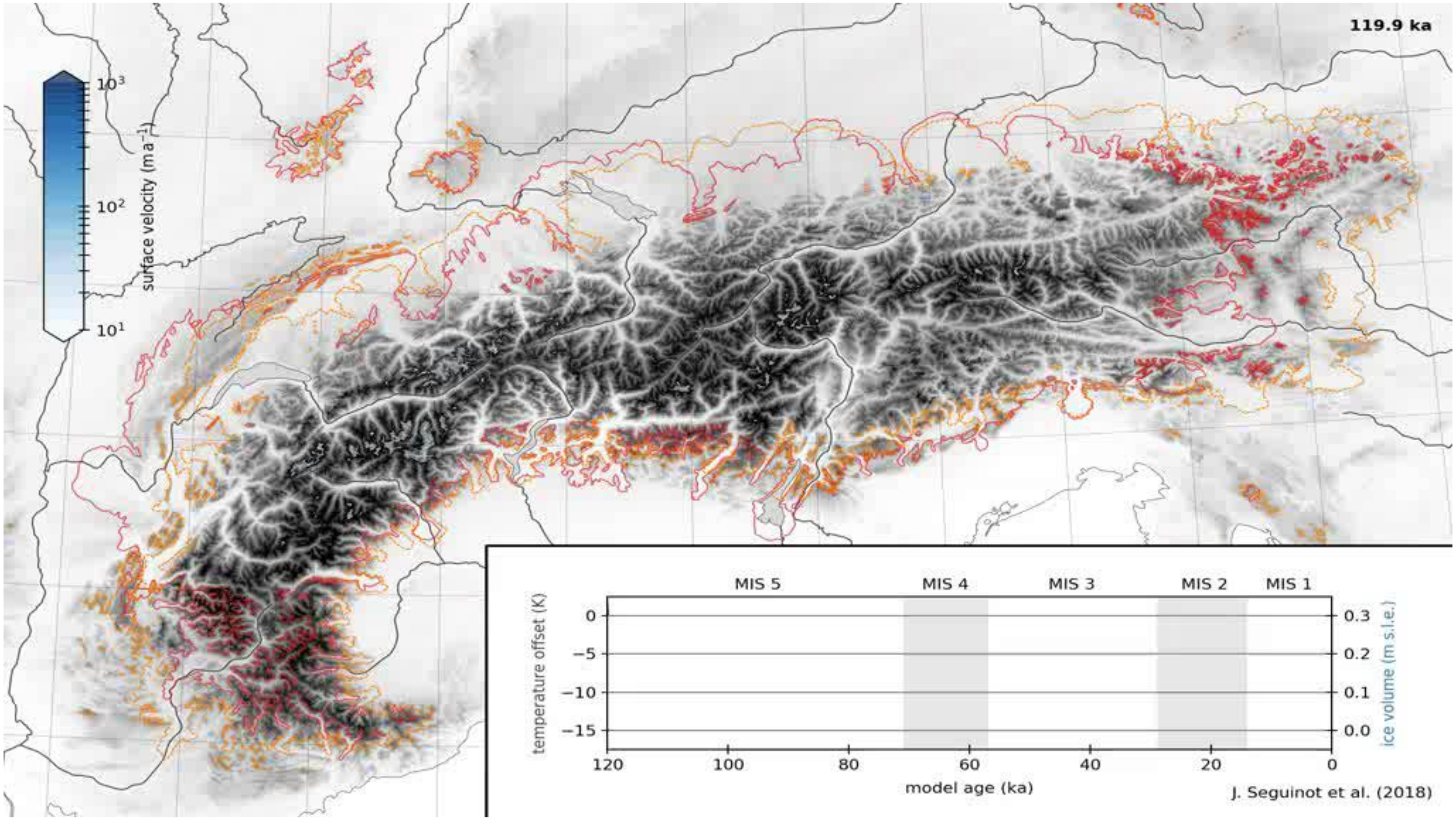


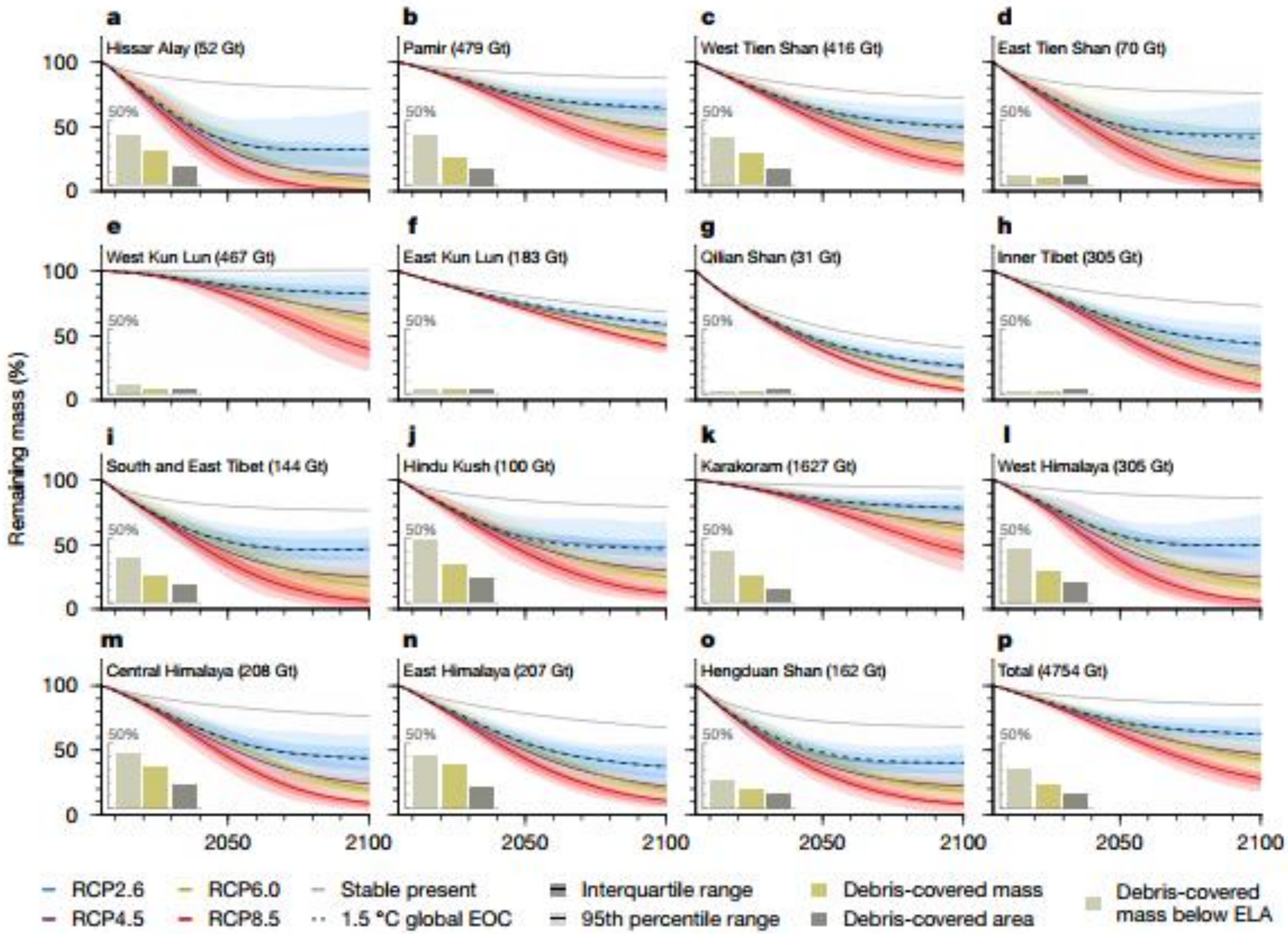
Fig. 1. Relief map of the north western alps showing the LGM extent of the alpine ice cap (blue line, after Ehlers and others, 2011). The arrows indicate the direction of the former ice flow from the Rhone Valley toward the Solothurn and Lyon lobes. The modelling domain (black rectangle) was divided 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 ⋆, ▲ and ■. The background map consists of SRTM (Jarvis and others, 2008) and Natural Earth Data (Patterson and Kelso, 2015).

Jouvet et al., 2016, JoG

Reconstructing ice extents



Future glacier volumes based on future climate projections



Kraaijenbrink et al., 2017, Nature

Many reasons projecting glacier change remains uncertain

- Large variety of glaciers in different climates
- Not all glacial processes well understood
- Large uncertainties in climate projections (and reconstructions)

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Elephant Foot Glacier,
NE - Greenland

Baltoro Glacier,
Karakoram/Pakistan

Belvedere Glacier,
Val d'Aosta, Italian Alps

Furtwaengler Glacier,
Kibo/Kilimanjaro,
Tanzania

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Theory

- Mass Balance
  - Field Measurements
  - Remote Sensing
- Melt modelling (energy balance, temperature index)
  - Basic Principles
- Flow Dynamics

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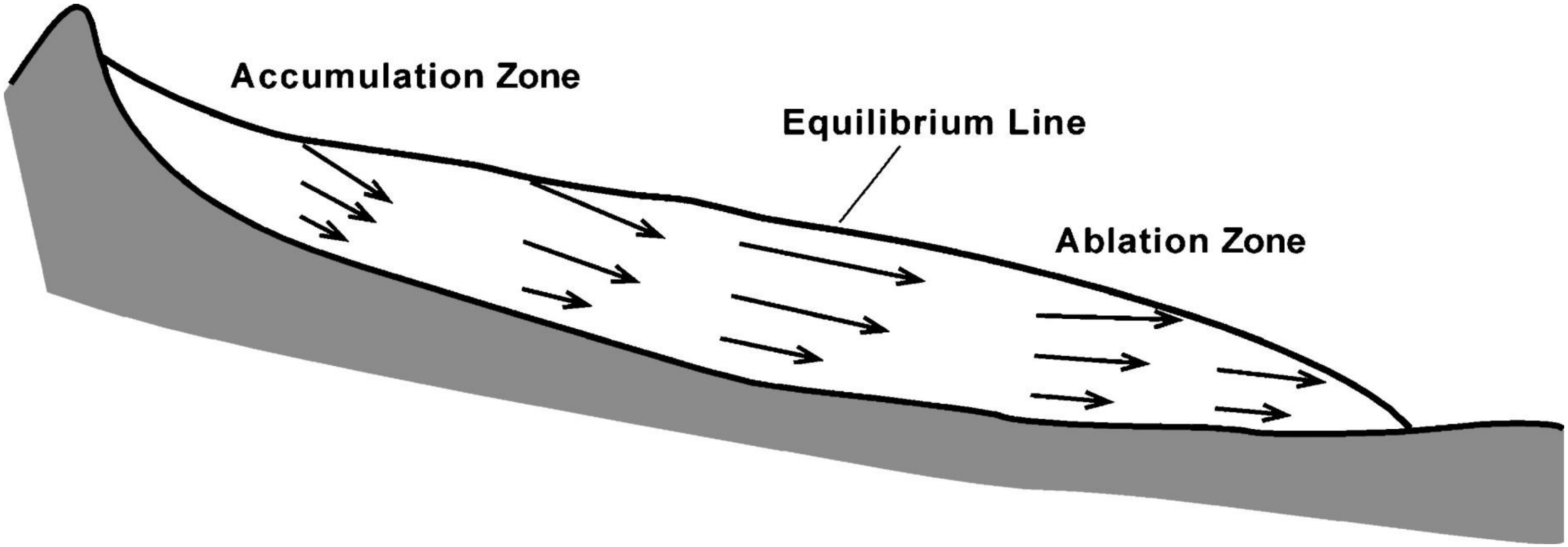
Mass Balance – Accumulation and Ablation



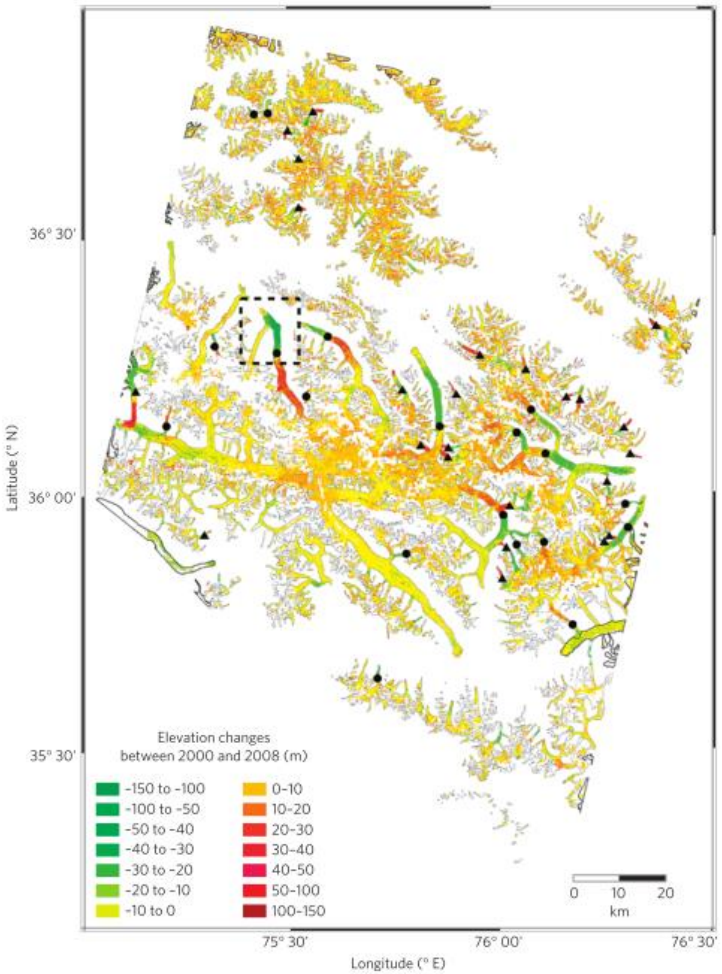
Cuffey and Patterson (2010)

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


Claridenfirn, Switzerland
G. Kappenberger


Claridenfirn, Switzerland
G. Kappenberger

Geodetic Mass Balance



Gardelle et al., NatGeo (2012)

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^2. 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.

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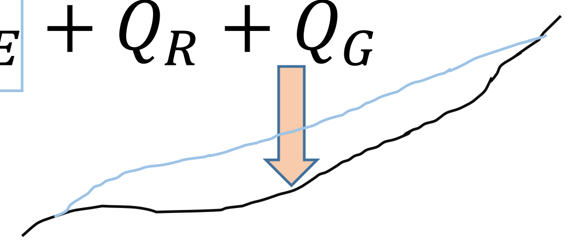
Energy Balance

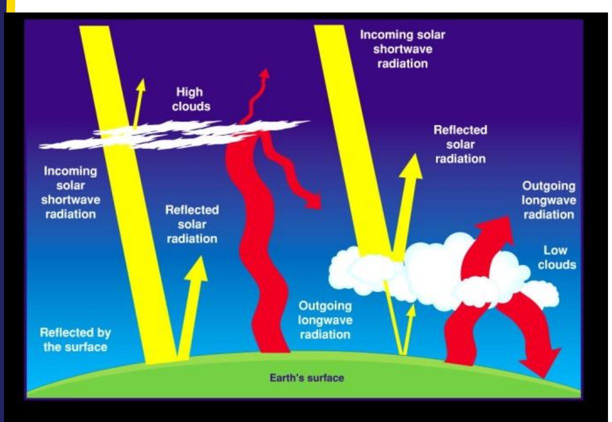
- … to melt ice we need Energy

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

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

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





Radiative fluxes

Turbulent fluxes

Simpler Melt Models

Gabbi et al., JoG (2014)
Hock, JoG (1999)
Pellicciotti et al., JoG (2005)

- Classical Temperature Index

  DDF [*mm d⁻¹ C⁻¹*]

$$M = \begin{cases} \frac{1}{n}\,\mathrm{DDF}_{\mathrm{ice/snow}}\,T_\mathrm{a} & : \quad T_\mathrm{a} > T_\mathrm{T} \\ 0 & : \quad T_\mathrm{a} \leq T_\mathrm{T} \end{cases}$$

- HTI

  RTI [mm m^2 h^{-1} W^{-1} C^{-1}]

$$M = \begin{cases} (\mathrm{MF} + R_{\mathrm{ice/snow}}\,I_{\mathrm{pot}})\,T_\mathrm{a} & : \quad T_\mathrm{a} > T_\mathrm{T} \\ 0 & : \quad T_\mathrm{a} \leq T_\mathrm{T} \end{cases}$$

- ETI

  TF [mm h^{-1} C^{-1}]

  SRF [mm m^2 h^{-1} W^{-1}]

$$M = \begin{cases} \mathrm{TF}\,T_\mathrm{a} + \mathrm{SRF}(1-\alpha)\,I & : \quad T_\mathrm{a} > T_\mathrm{T} \\ 0 & : \quad T_\mathrm{a} \leq T_\mathrm{T} \end{cases}$$

Sensors on Glaciers

Rapid recession and monitoring

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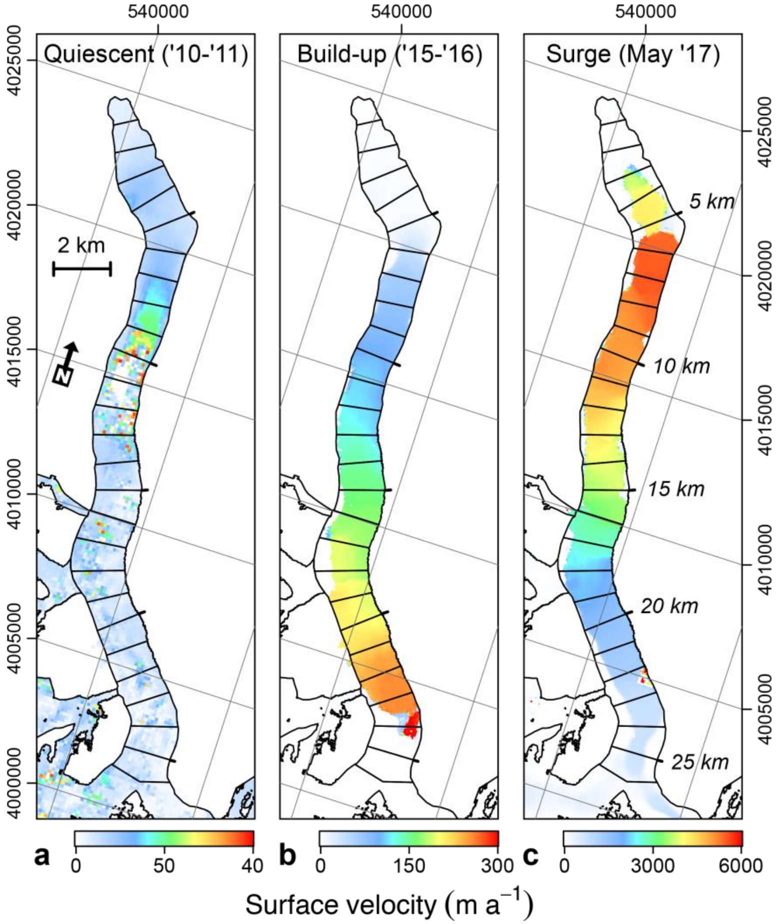
Glacier flow



Steiner et al., 2018, Cryosphere

Glacier flow

$$\boxed{U_{\mathrm{s}}} = U_{\mathrm{surf}} - \boxed{\frac{2A}{n+2}(\rho g \sin\alpha)^n\, h^{n+1}}$$

Sliding

Deformation

Observed surface velocity

Physics of Glacier Movement

- Plastic deformation
  - Ice temperature
  - Ice density
- Basal Slip
  - 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

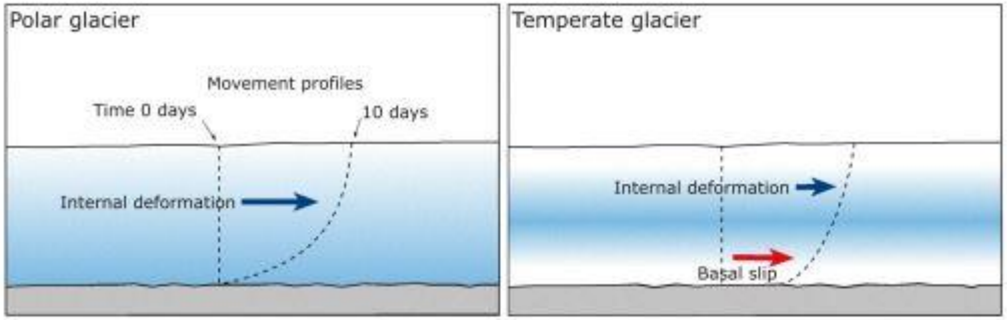
Ice deformation

Temperature Slope Ice thickness

$$U_{\mathrm{s}} = U_{\mathrm{surf}} - \frac{2A}{n+2}(\rho g \sin\alpha)^n h^{n+1}$$

Deformation

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

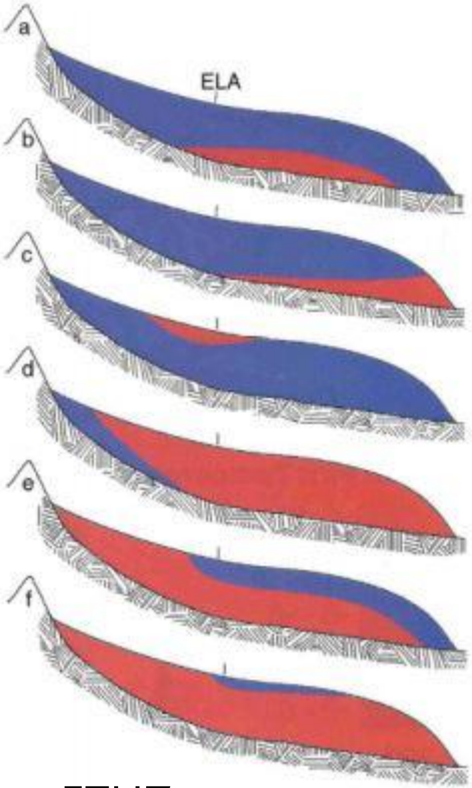
c high Arctic, very cold climate (high Himalayas)

d high mountains

e maritime Arctic, e.g. Storglaciären

f ?

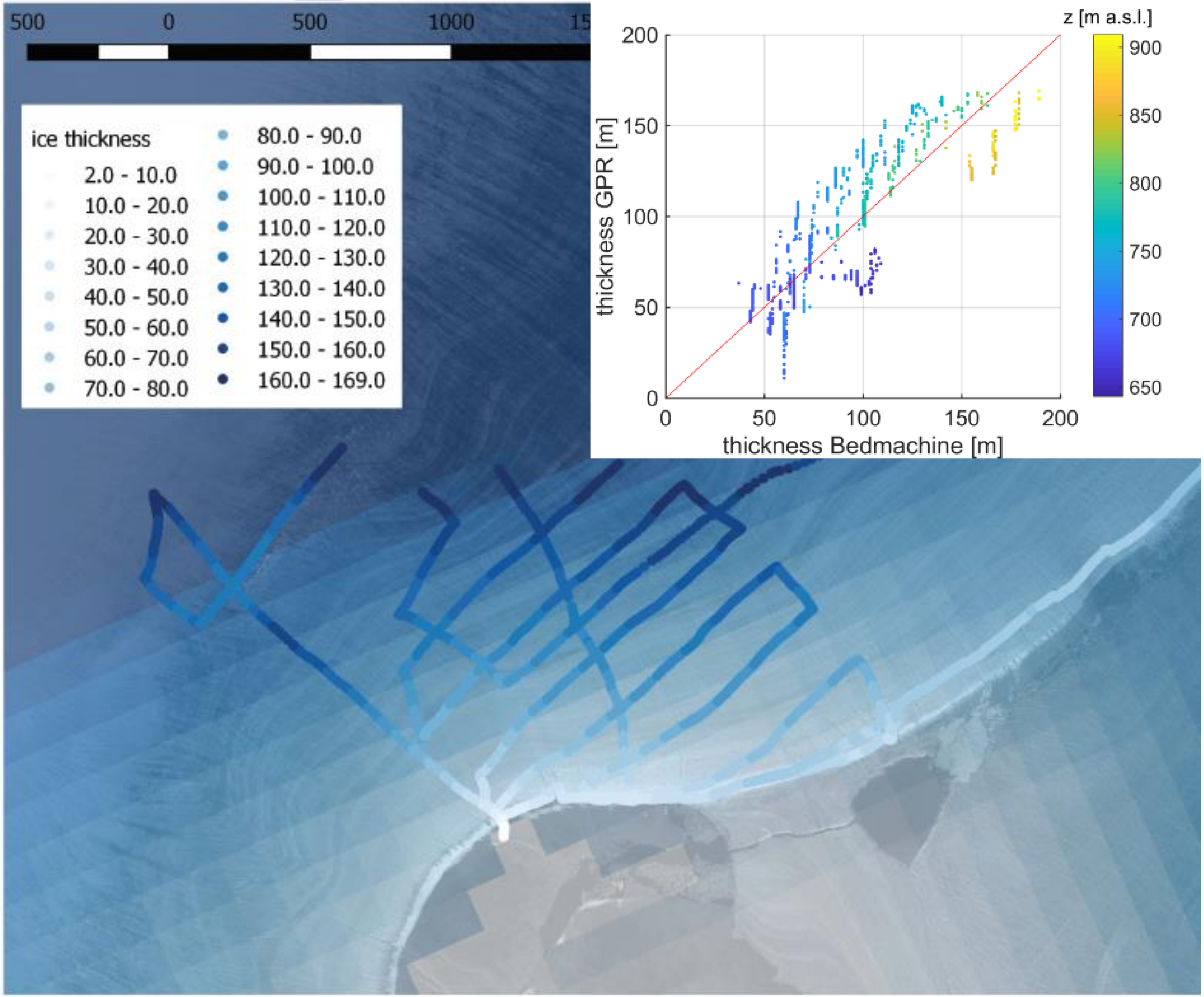
(from Benn and Evans, 1998)



Luethi, M.; Physics of Glaciers, ETHZ

Measuring ice temperature

Ice thickness



500
0
500
1000
ice thickness
2.0 - 10.0
10.0 - 20.0
20.0 - 30.0
30.0 - 40.0
40.0 - 50.0
50.0 - 60.0
60.0 - 70.0
70.0 - 80.0
80.0 - 90.0
90.0 - 100.0
100.0 - 110.0
110.0 - 120.0
120.0 - 130.0
130.0 - 140.0
140.0 - 150.0
150.0 - 160.0
160.0 - 169.0
thickness GPR [m]
thickness Bedmachine [m]
0
50
100
150
200
z [m a.s.l.]
900
850
800
750
700
650

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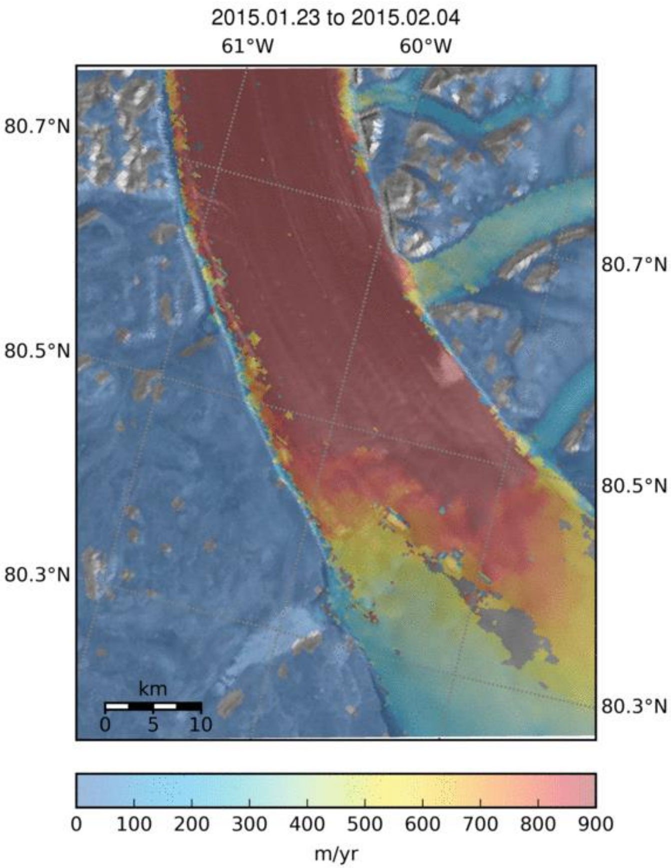
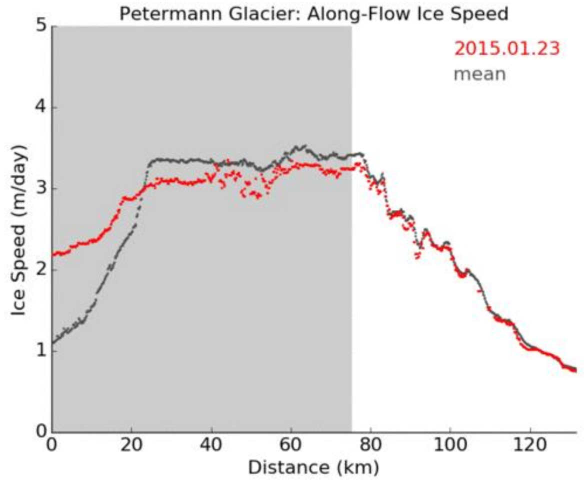
Velocity Fields – High Resolution





Sentinel Satellites (ESA)

Examples of glaciological investigation based on a field trip