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The Anthropocene in the sediments of Lake Geneva:

Does climate change control river sediment flux, even in highly human impacted mountain catchments?

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SEDFATE Team (Fritz Schlunegger UniBE and colleagues at UniGE and ETHZ)

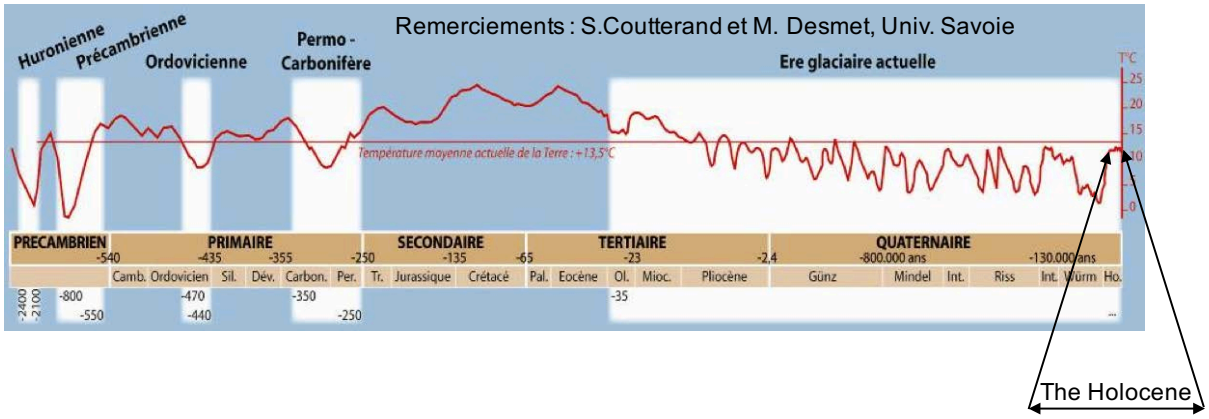
| le savoir vivant |

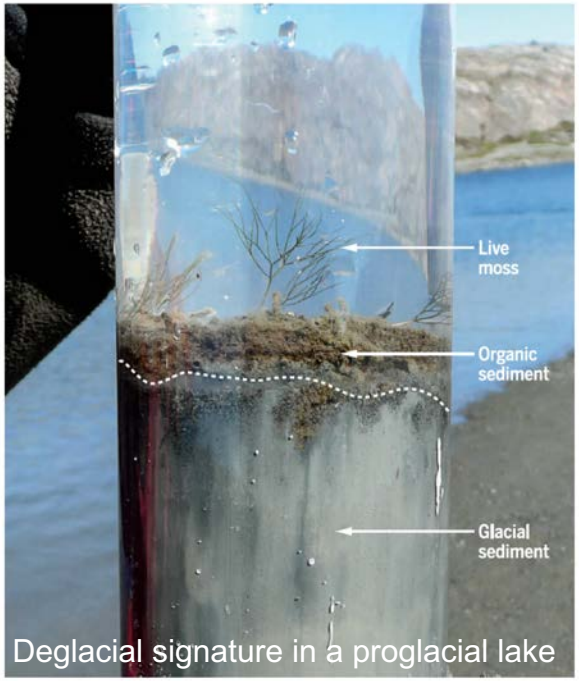
ALPWISE
Alpine Environments: Water, Ice, Sediments and Ecology

The Anthropocene

"Any formal recognition of an Anthropocene epoch in the geological time scale hinges on whether humans have changed the Earth system sufficiently to produce a stratigraphic signature in sediments and ice that is distinct from that of the Holocene epoch."

Waters et al., 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, **351**, 137





Taken from Waters et al., 2016

1. Evidence in terms of the deposition of plastics, fly ash, radionuclides, metals, pesticides, reactive nitrogen and consequences of greenhouse gases – but where is the **sediment** ?

2. Sediment deposition is a natural process (as is organic matter deposition), so what we have to consider is changes in sedimentation **rates**

3. The Anthropocene complicates things because the stratigraphic signature is not just about regional to global scale drivers but also **local to regional** scale **drivers**

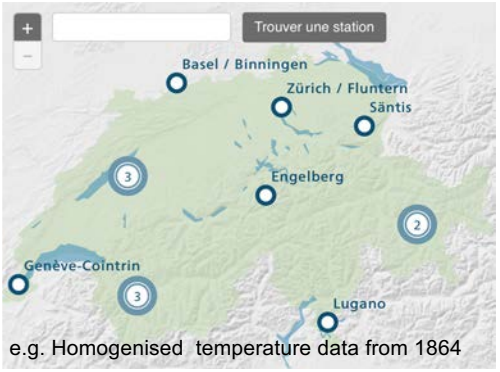
The challenge : doing sediment is not easy

The "easy" sciences ?

climatology (climate change)

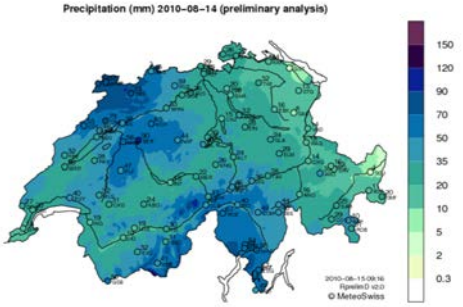
glaciology (glacier retreat)

hydrology (river flows)



e.g. Homogenised temperature data from 1864

Daily gridded rainfall data from 1961 météosuisse



Répartition spatiale des précipitations en mm (ou l/m2) en Suisse le 14.08.2010. Les stations indiquent des valeurs de mesure in situ.

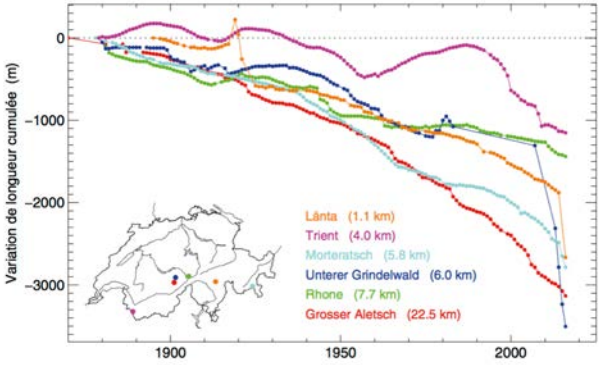
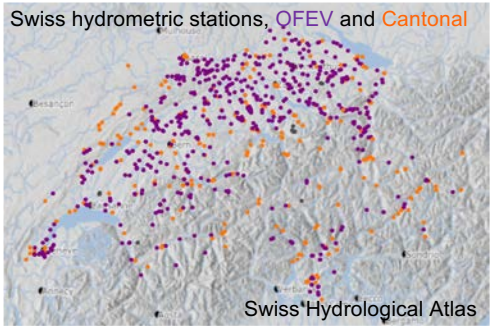


Figure 4
Variations annuelles cumulées (en mètres) de la longueur de certains glaciers du réseau de mesures présentant différents comportements d'adaptation au climat. Grafique: GLAMOS

Swiss hydrometric stations, OFEV and Cantonal



The challenge : doing sediment is not easy

The science of sediment is harder because

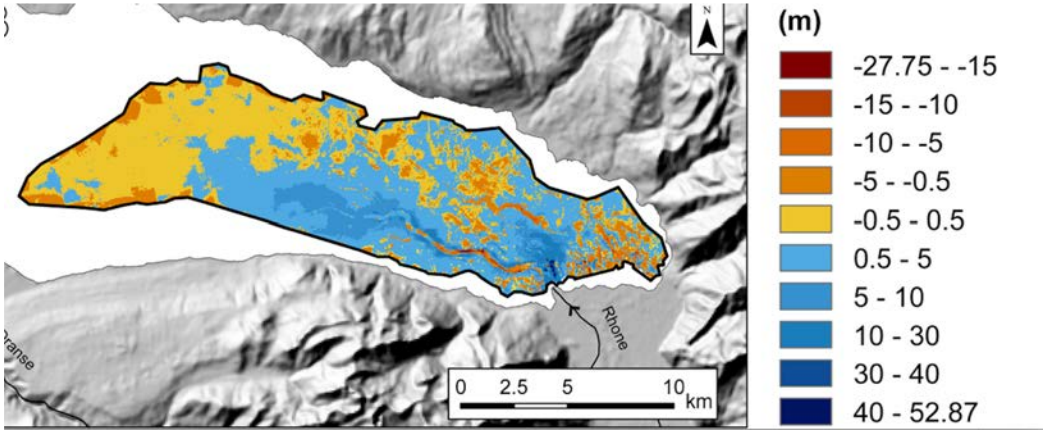
we have less tradition of measuring it *and*

because it is harder to measure

Lake cores

Sedimentation in Upper Lake Geneva, 1889-2014

Tiago Silva et al. in review. *Sedimentology (*SEDFATE project, UniGE*)*



Measurement stations

Classic example is the WSL Erlenbach station

Strongly reliant on indirect measurements supported by calibration

Because there are few of them, they don't necessarily tell you about the systems of interest

The SEDFATE project: UniBE, UniGE, UNIL, ETHZ

Can we quantify how we are making the sedimentary record in Lake Geneva ?

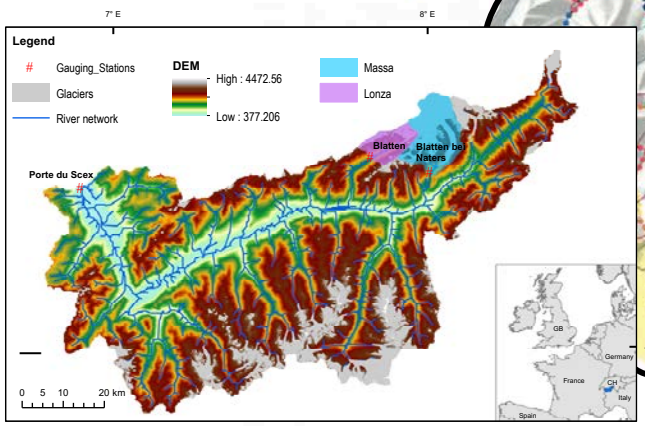
Bathymetric survey
Data assimilation
Lake cores for rate and provenance studies

Sediment provenance studies
Long-term erosion rates (Be)

Sediment flux analysis
Multivariate modelling

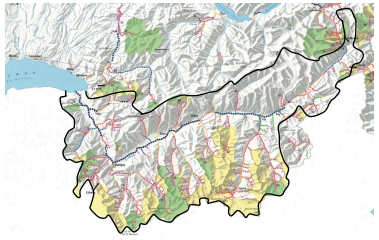
Sediment flux measurement
Morphological reconstruction
Repeat topographical measurement

FNSNF
FONDS NATIONAL SUISSE
DE LA RECHERCHE SCIENTIFIQUE

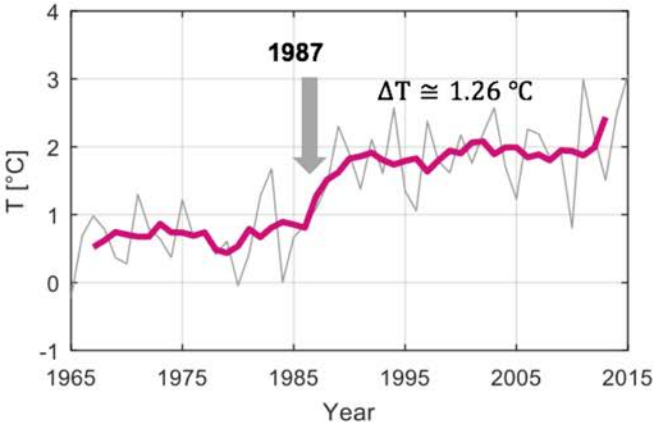


2014-2018

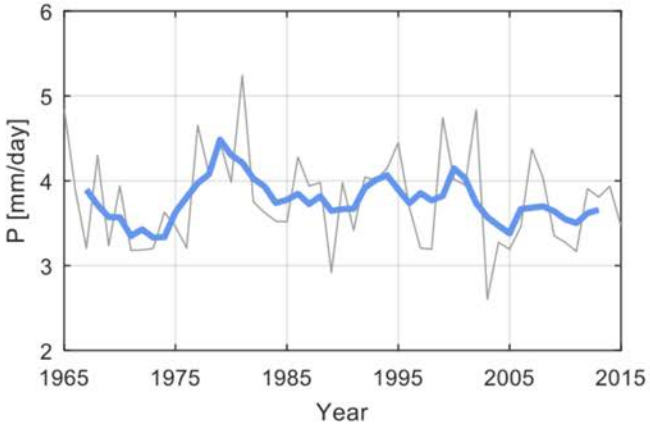
Sediment loading to (and sediment cores in) Lake Geneva



(a) Basin averaged mean annual temperature



(b) Basin averaged mean annual precipitation



Costa, Molnar, Stutenbecker, Bakker, Silva, Schlunegger, Lane, Loizeau and Girardclos, 2018. *Hydrology and Earth System Science,* 22, 509-528

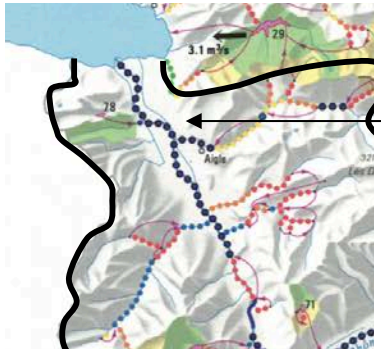
Sediment loading to Lake Geneva

Change in mean monthly suspended sediment concentration

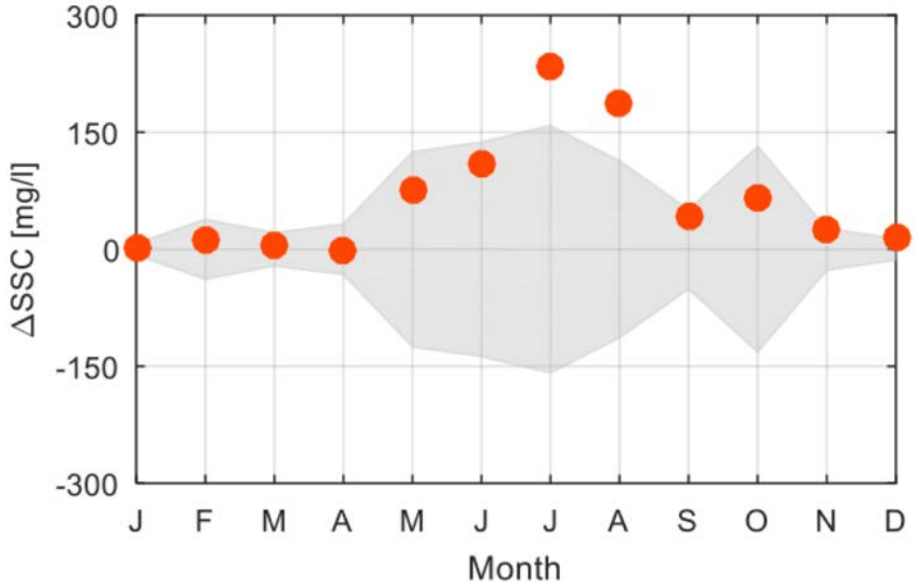
Porte du Scex

1965-1986 versus 1987-2015

Grey = 95% confidence limits



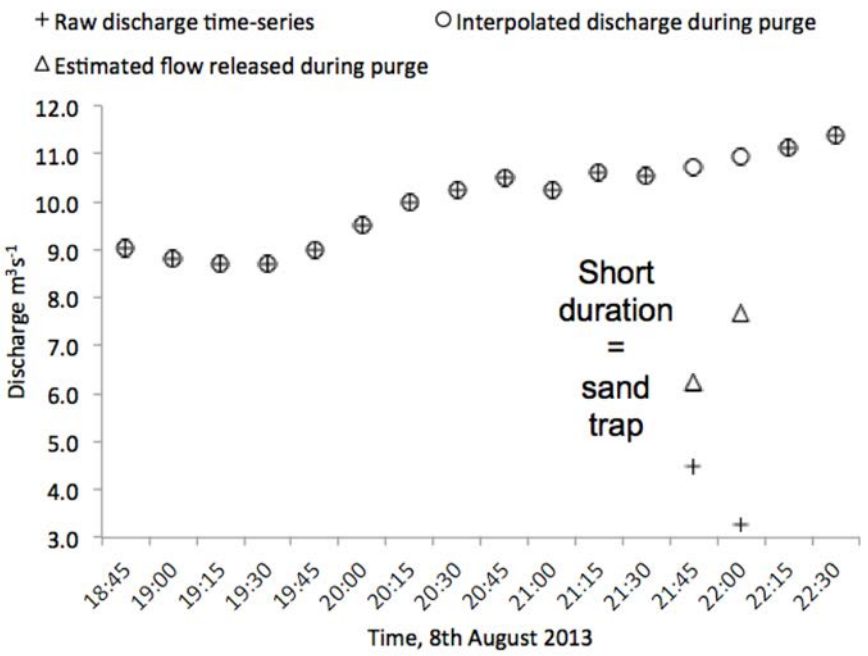
We need a process that is associated with greater *summer* sediment loading

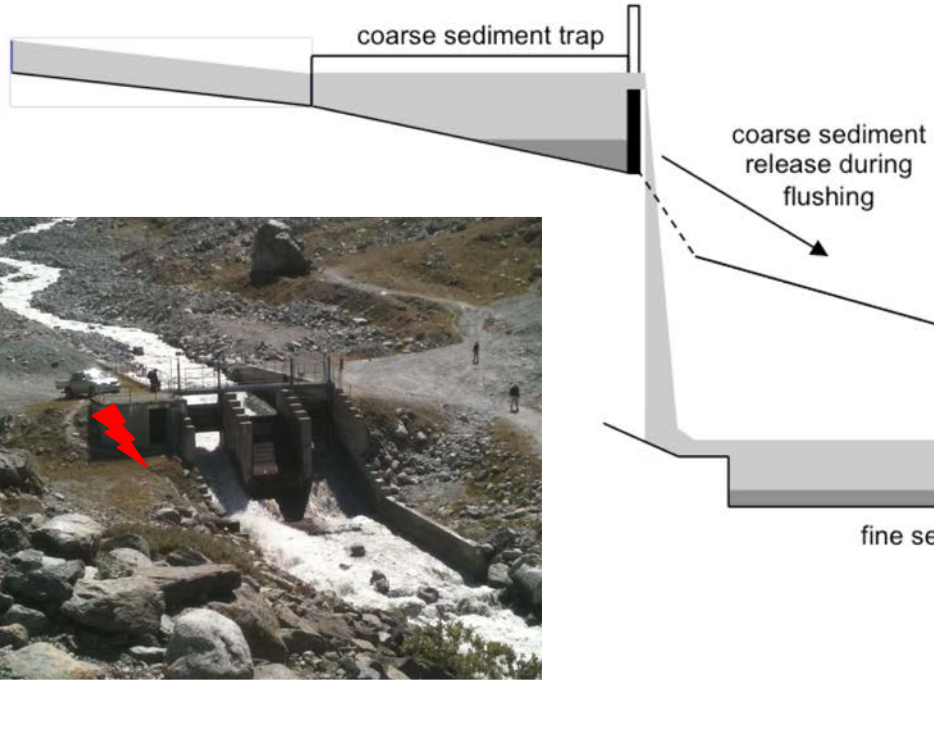


Costa, Molnar, Stutenbecker, Bakker, Silva, Schlunegger, Lane, Loizeau and Girardclos, 2018. *Hydrology and Earth System Science,* 22, 509-528

Sediment export from high mountain basins

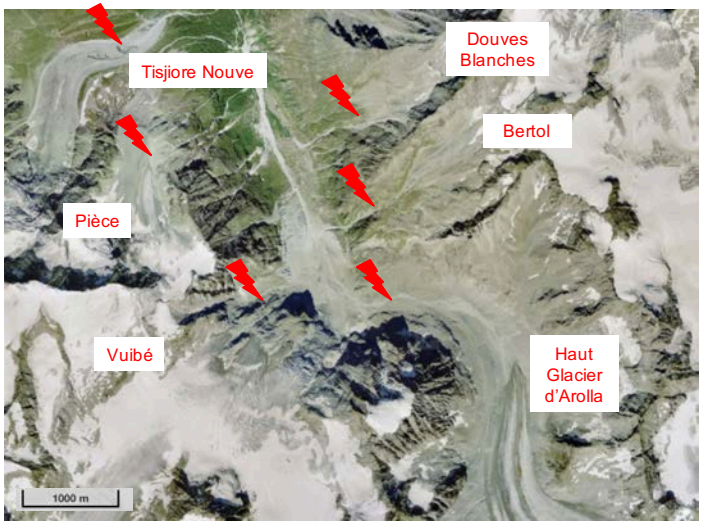
- High altitude gauging stations, with records starting in the 1960s (flow) and which can **also** be used to determine sediment yield from the 1970s

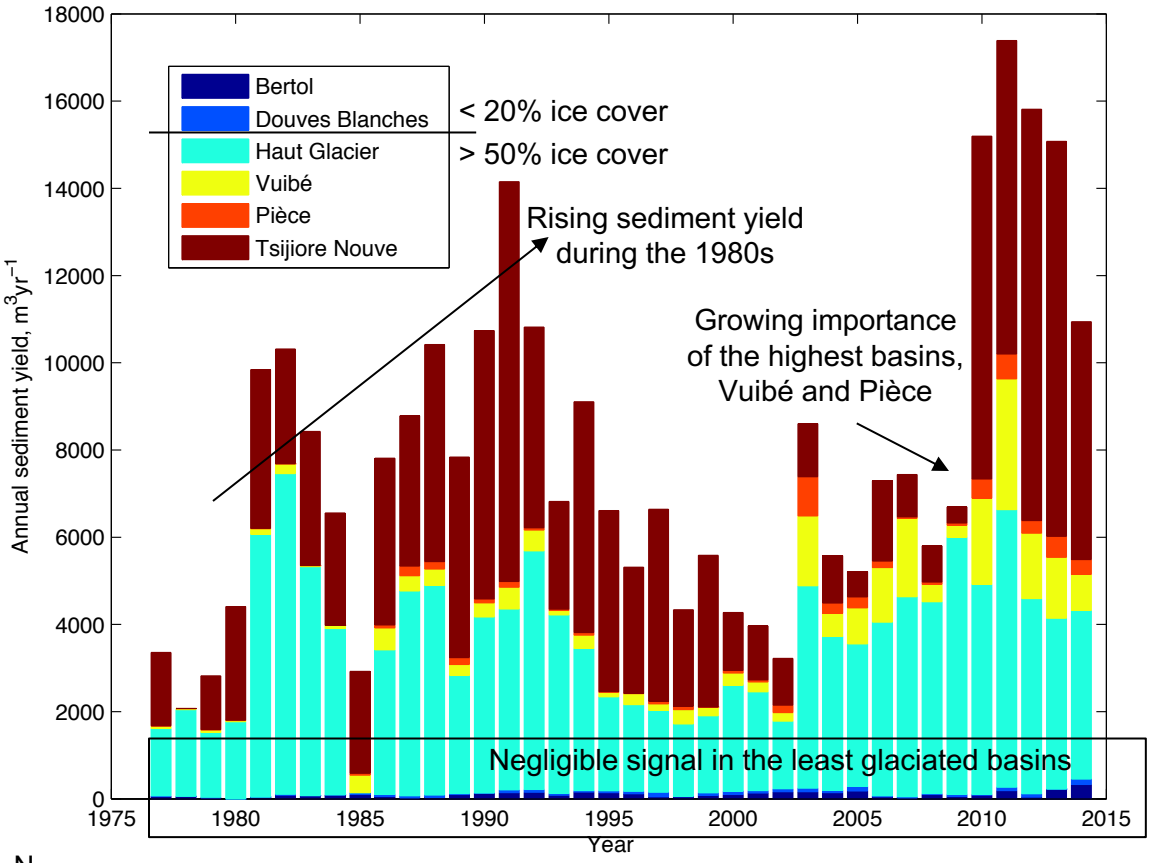




washload excluded

Sediment export from high mountain basins



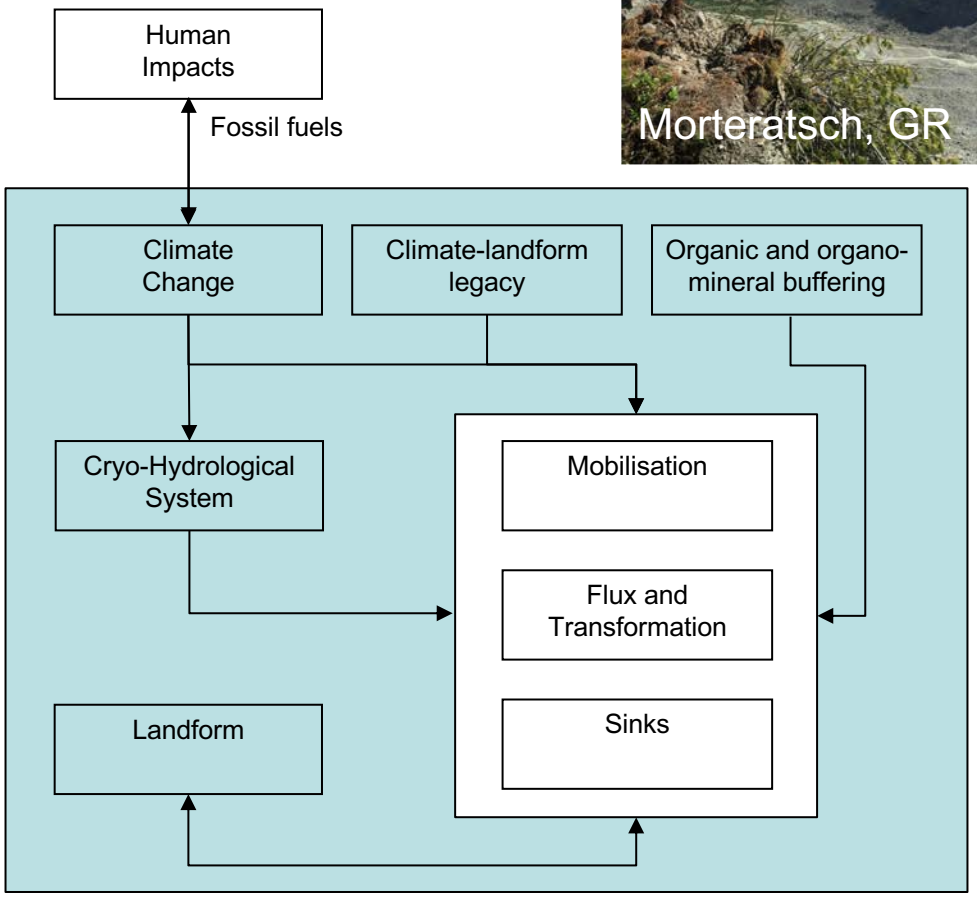


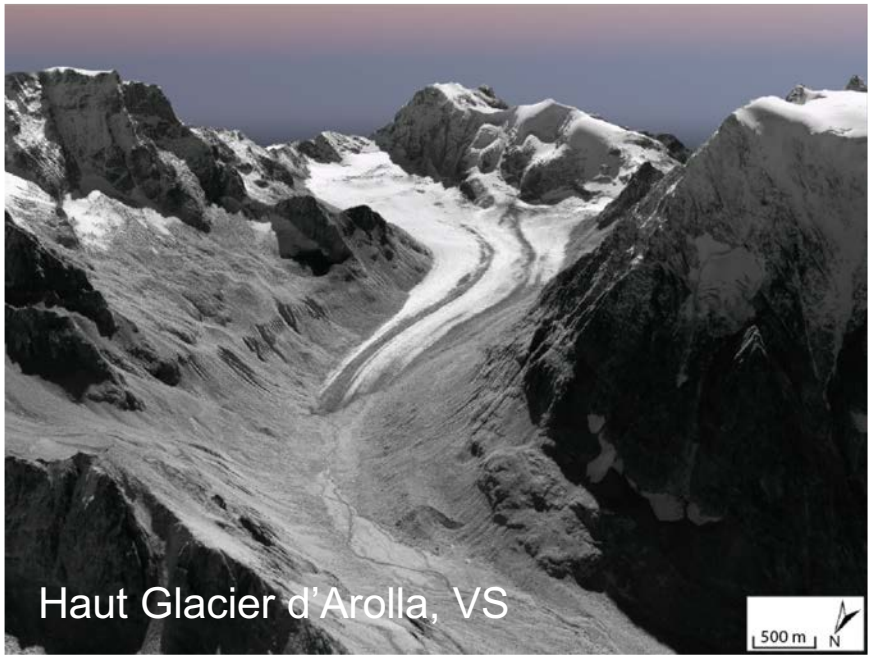
N

Gauging Station

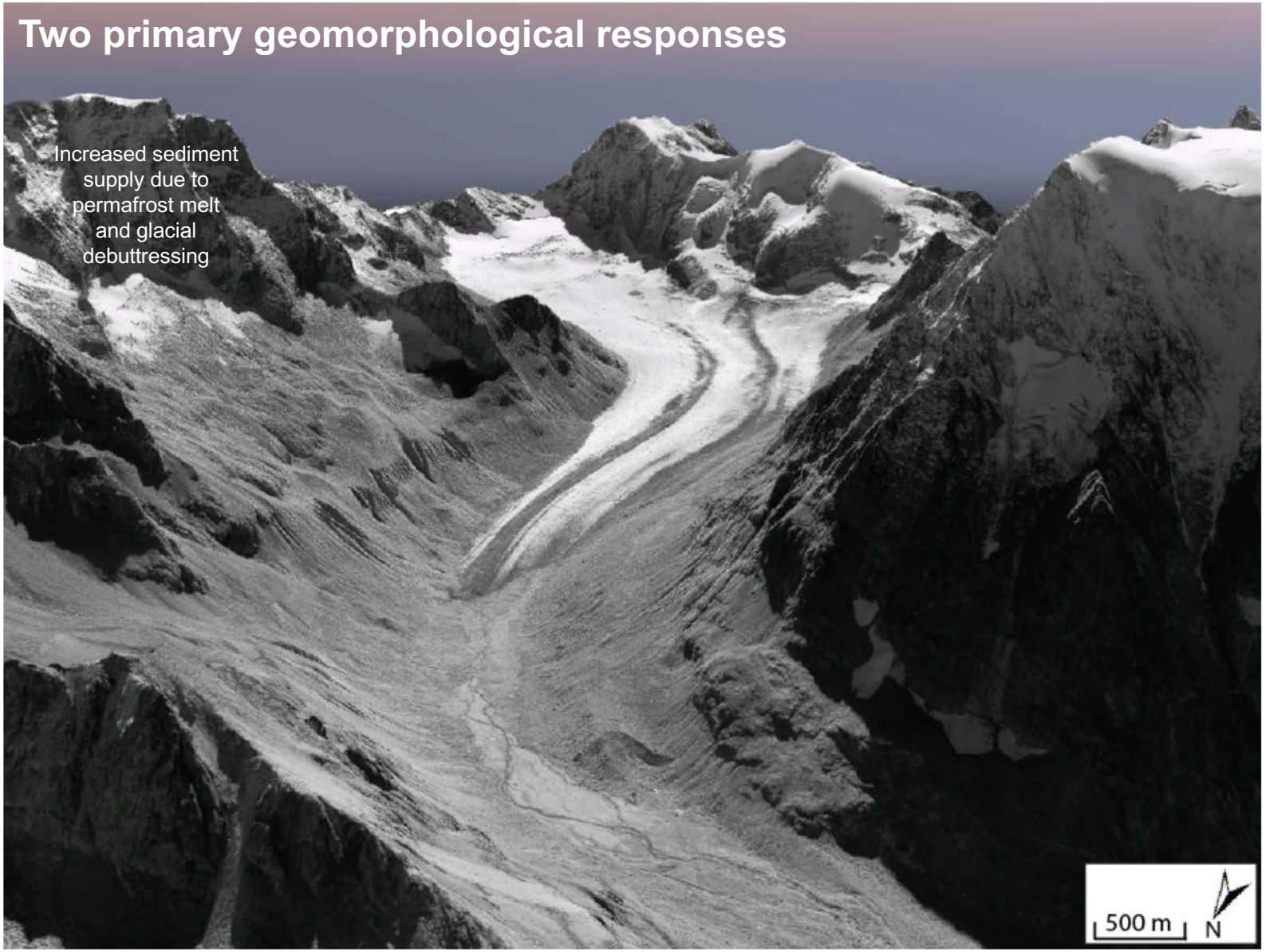
2'300 – 2'600 m asl, data from the 1960s to present, 15 minute resolution

Climate forcing of sediment export from Alpine basins



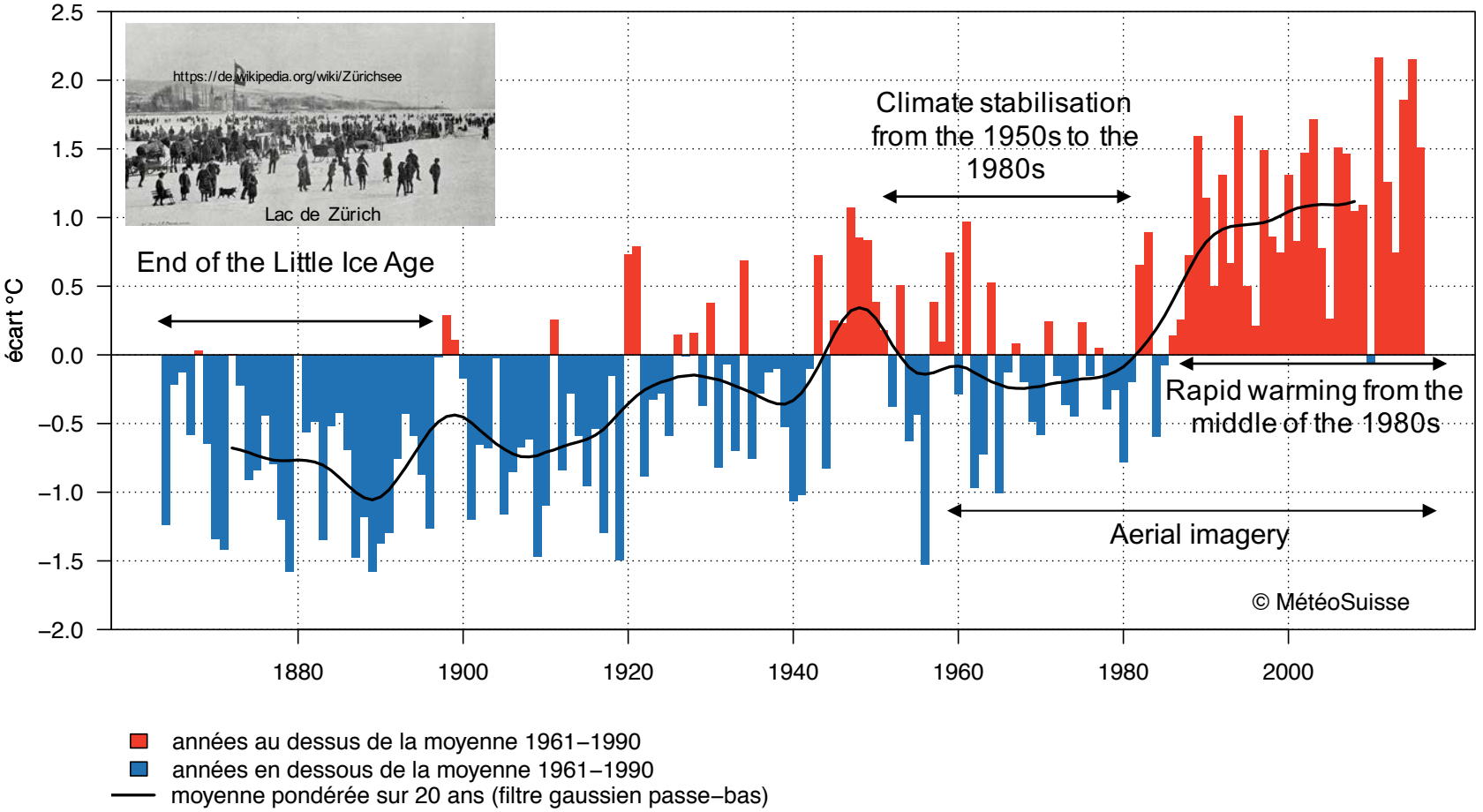


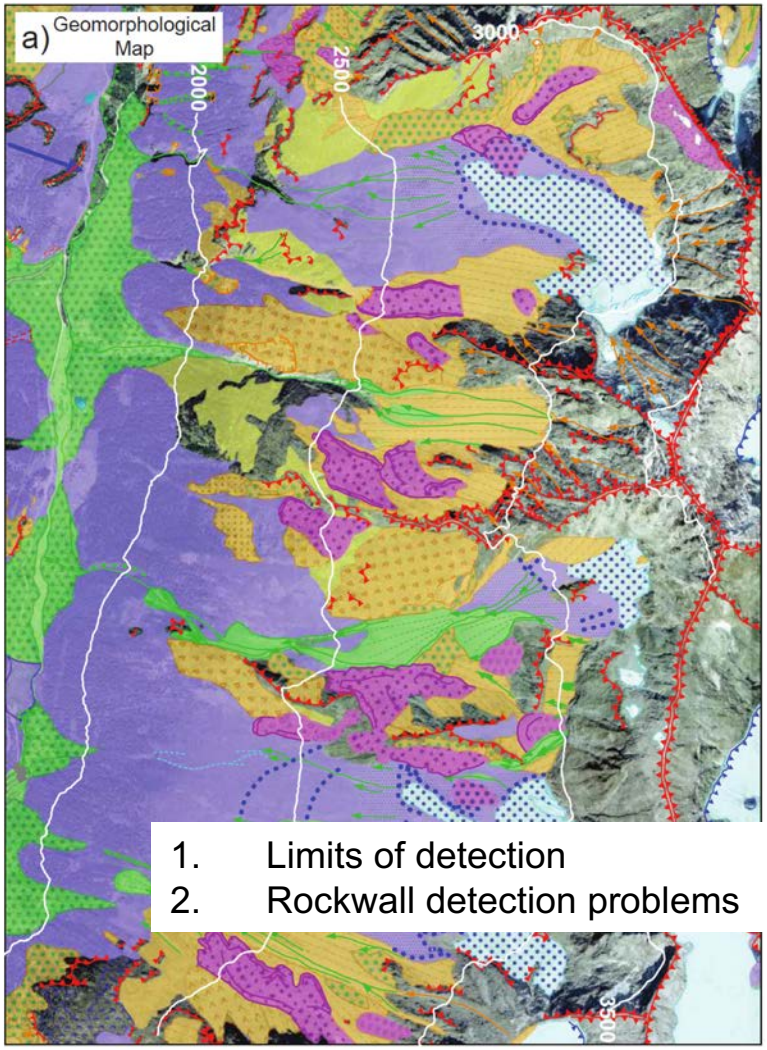
Two primary geomorphological responses

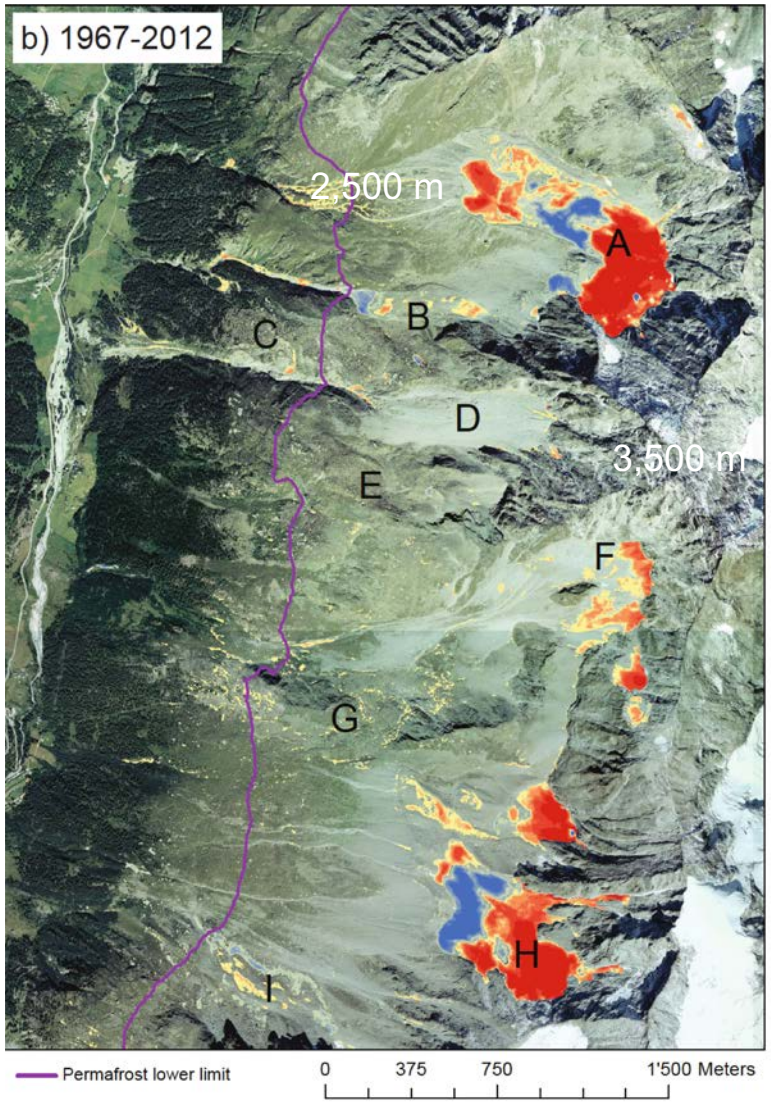


The Context

mean annual temperature deviation from the 1961-1990 mean

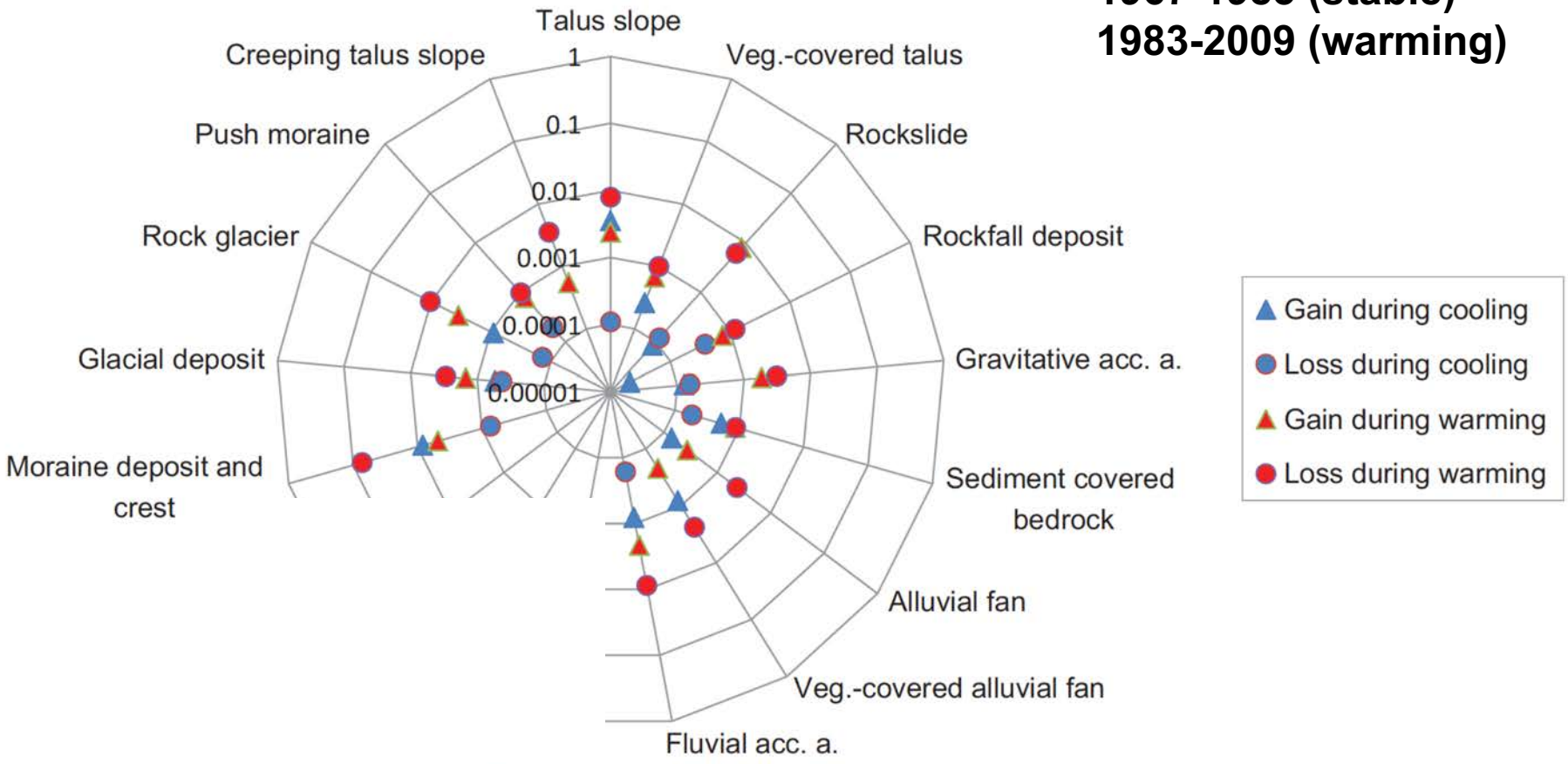






Micheletti, N., Lambiel, C. and Lane, S.N. 2015. *Journal of Geophysical Research - Earth Surface*, 120, 2155-75
Micheletti, N. and Lane, S.N. 2016. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. *Water Resources Research,* 52, 4924–4943

Change in m / year
1967-1983 (stable)
1983-2009 (warming)



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Rock
Glacier
Surface
Velocities

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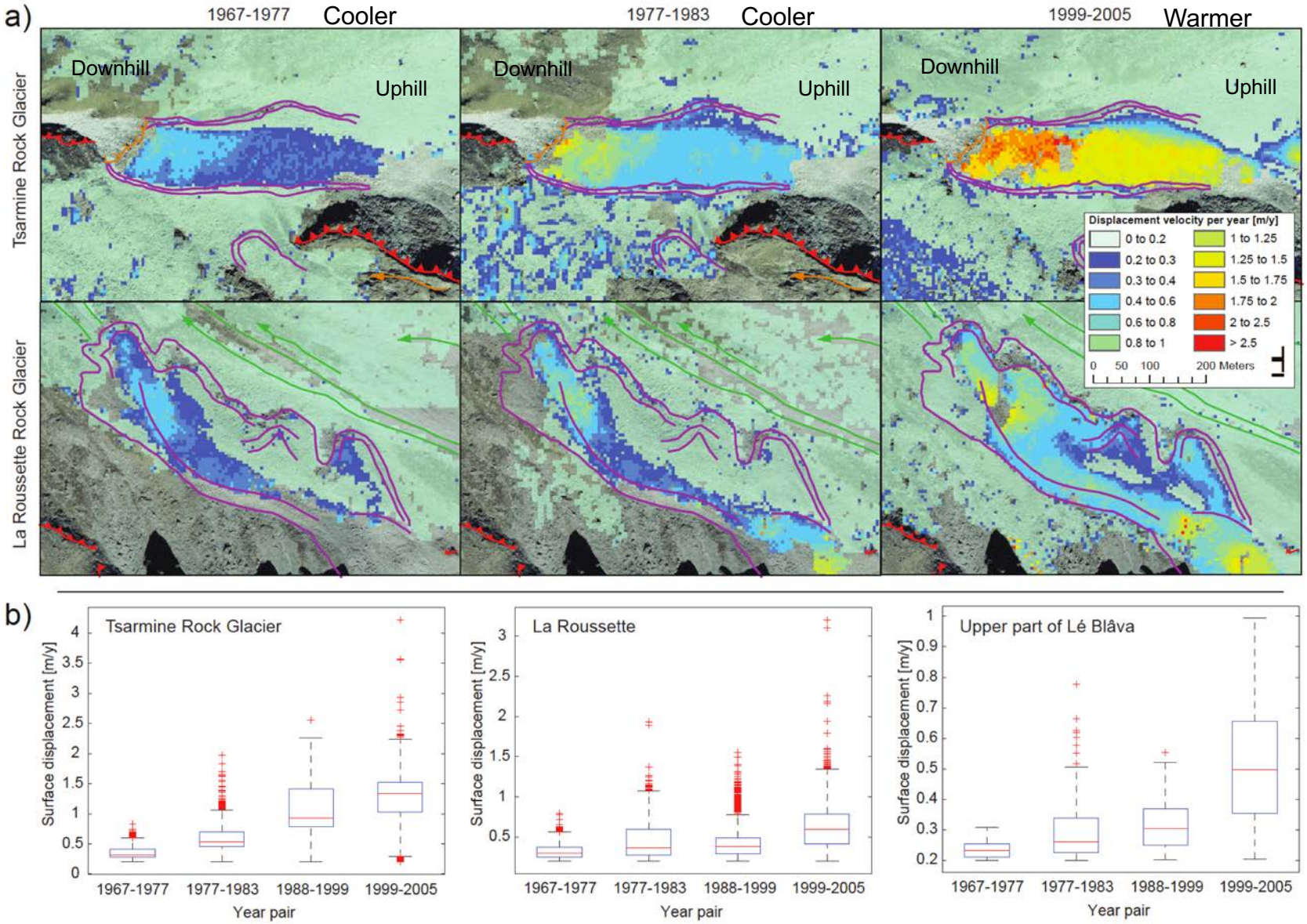
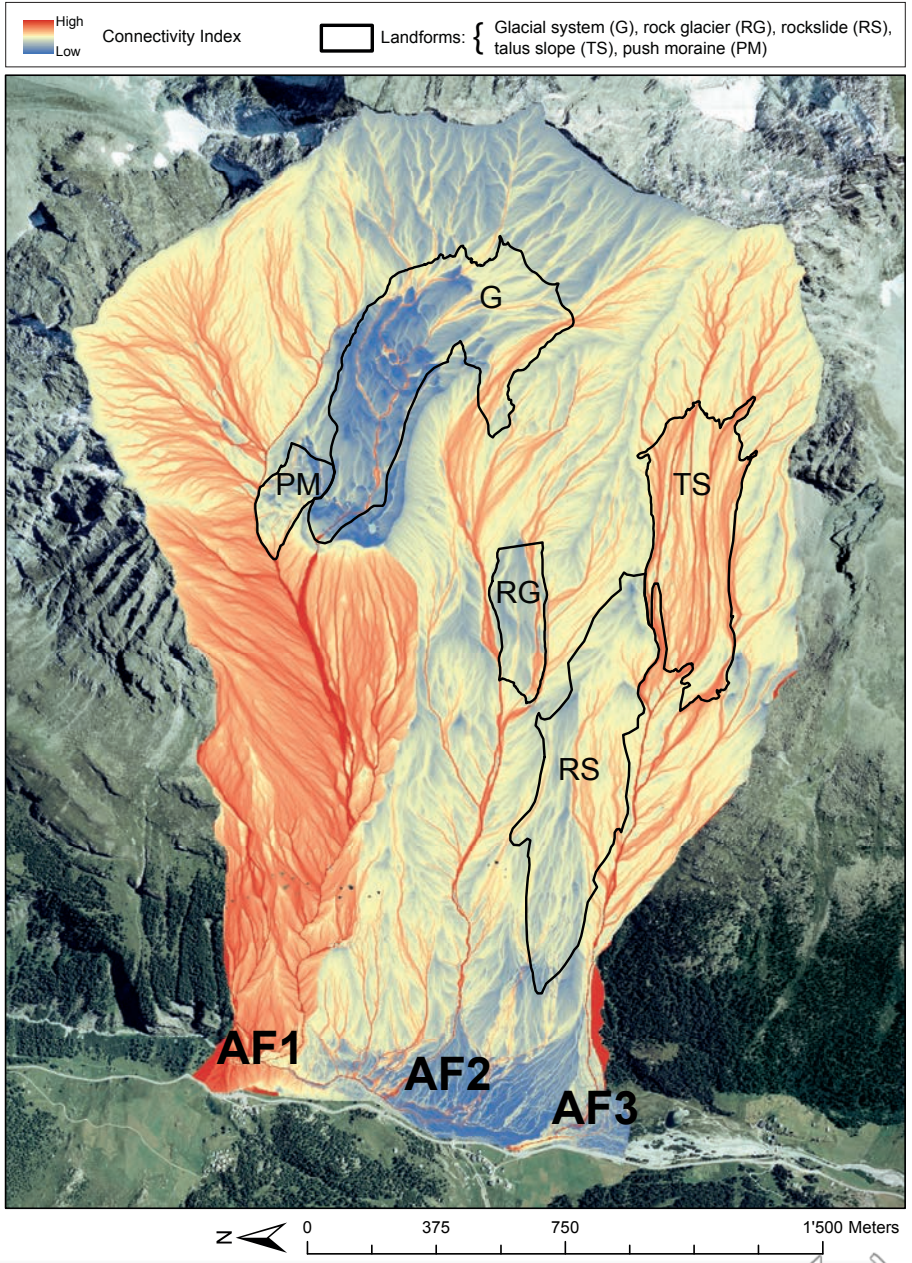
Rock Glacier Surface Velocities



Micheletti, N., Lambiel, C. and Lane, S.N. 2015. *Journal of Geophysical Research - Earth Surface*, 120, 2155-75

The importance of disconnection

The
“Cavalli Index”



A note on extreme events

Bondo, GR

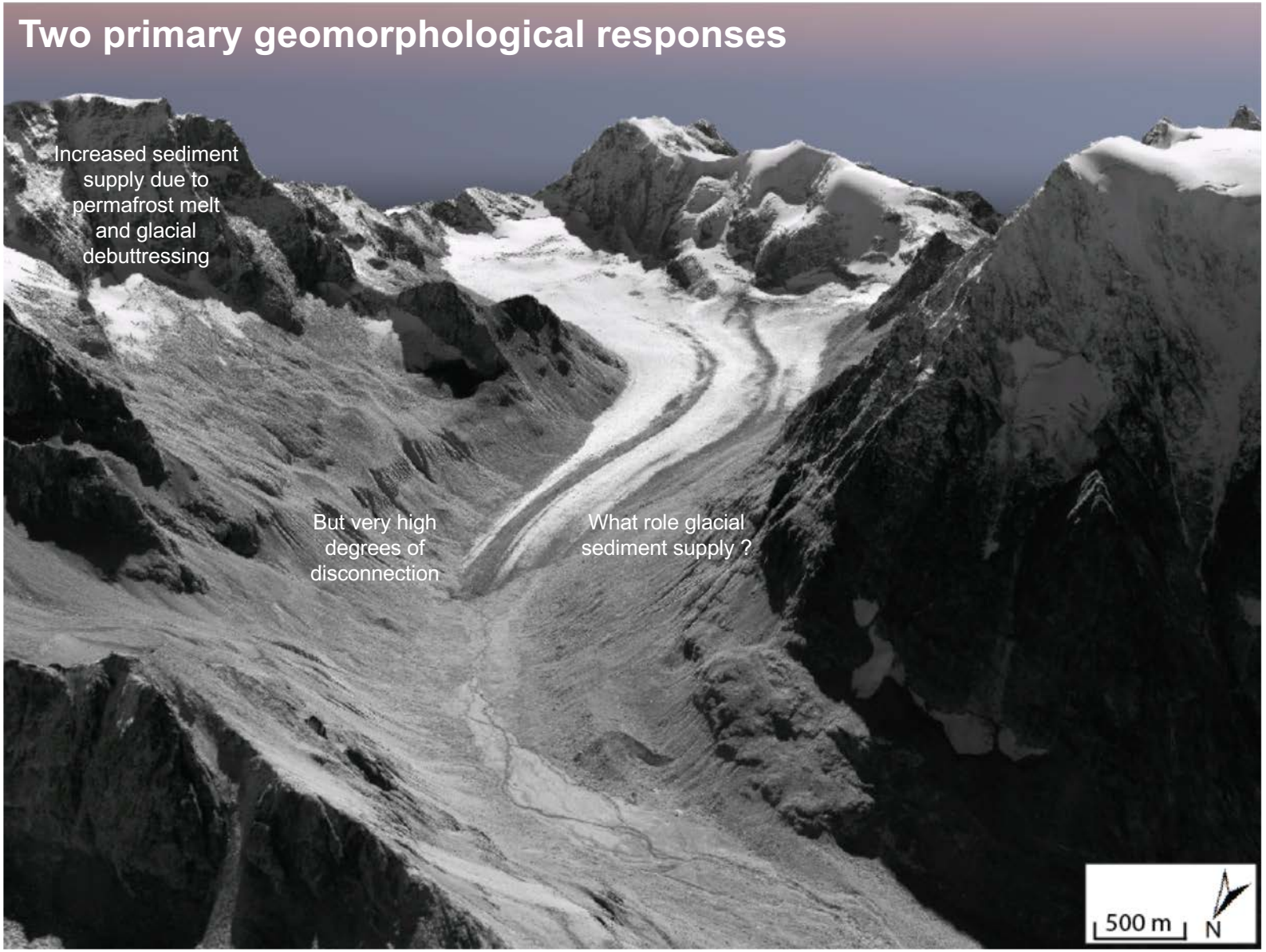
High magnitude
Low frequency (in time *and* space)

A "back of the envelope calculation

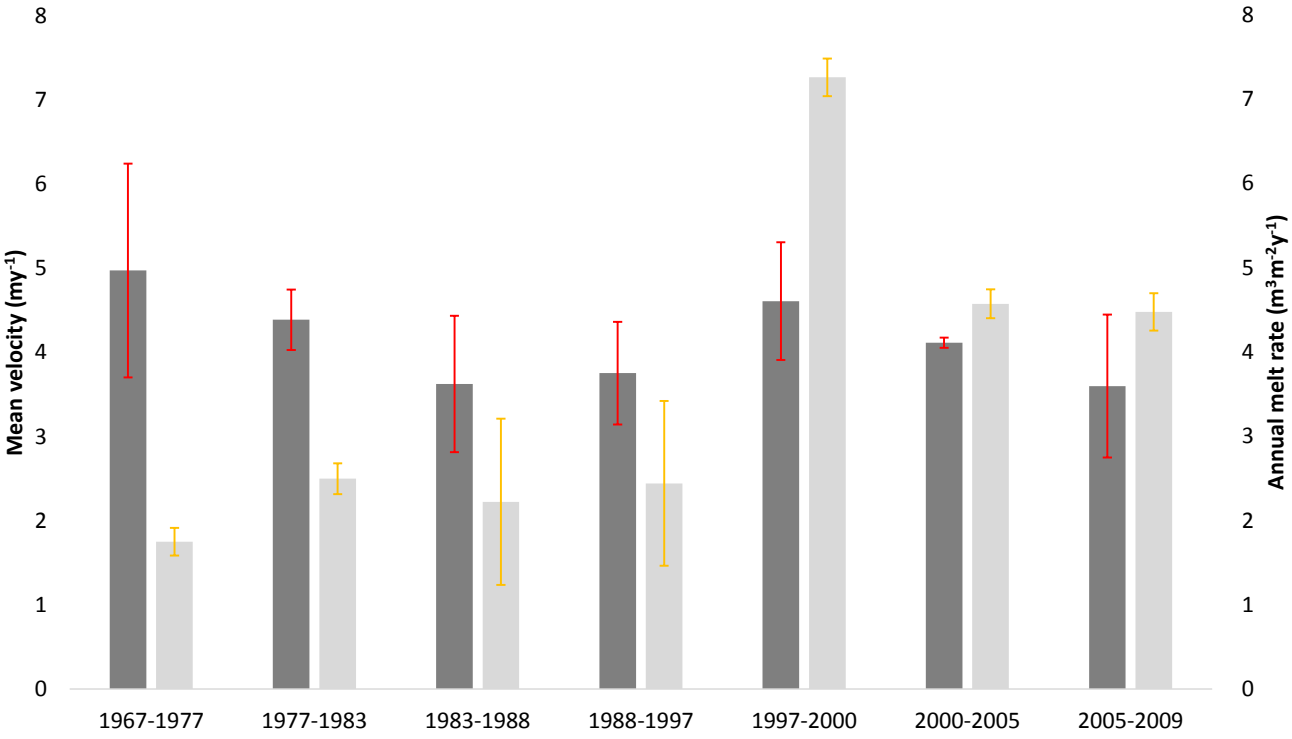
Imagine a Bondo sized event in the Rhône system:

- 3 x 10^6 m^3 of material
- 10% released over 24 hours
- To a Rhône discharge of 250 m^3s^{-1}
- Contribution to annual average sediment concentration of c. 80 mgl^{-1}
- Measured Porte du Scex average annual increase of 70 mgl^{-1}

Two primary geomorphological responses

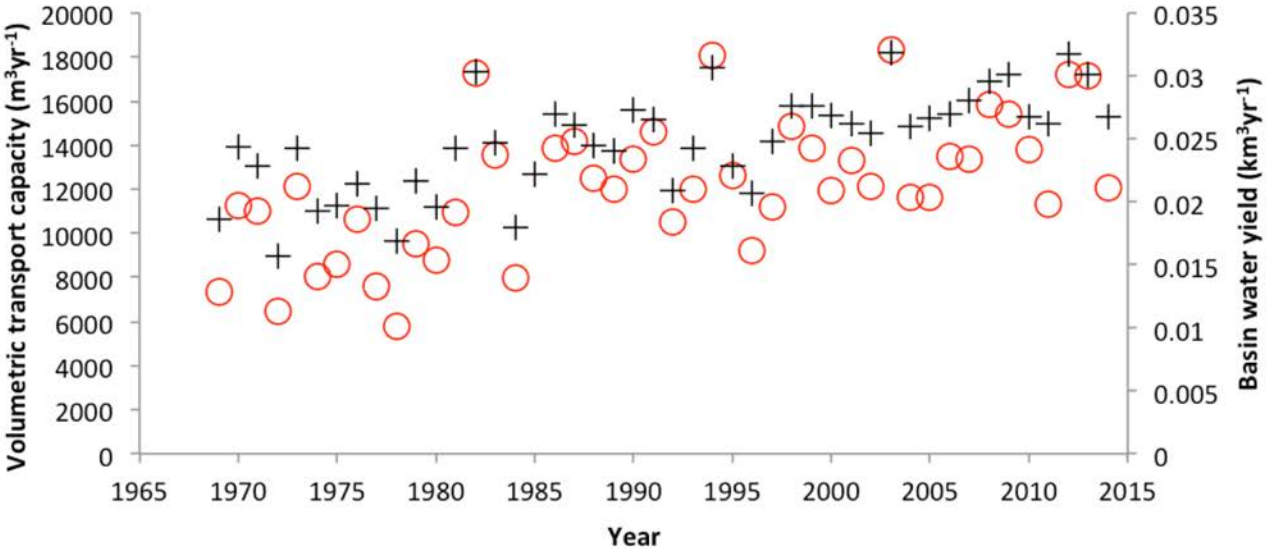


Glaciers don’t evacuate sediment efficiently, subglacial rivers do



Gabbud, C. Micheletti, N. and Lane, S.N., 2016. *Geografiska Annaler A: Physical Geography*, 98, 81-95

Glaciers don't evacuate sediment efficiently, subglacial rivers do



Water yield and evacuation potential

Volumetric Transport Capacity

Yield

Lane, Bakker, Gabbud, Micheletti, and Saugy, 2017. *Geomorphology*, 277, 210-27

Ferguson et al. (2007) and Nitsche et al. (2011)

$$v_{tot} = \frac{6.5(gRS)^{0.5} 2.5\left(R/D_{84}\right)}{\left[6.5^2 + 2.5^2\left(R/D_{84}\right)^{1.67}\right]^{0.5}}$$

$$v_0 = 6.5(gRS)^{0.5}\left(R/D_{84}\right)^{0.167} \qquad S_0 = S\left(\frac{v_{tot}}{v_0}\right)^{1.5}$$

Sediment transport treatment after Rickenmann (2001)

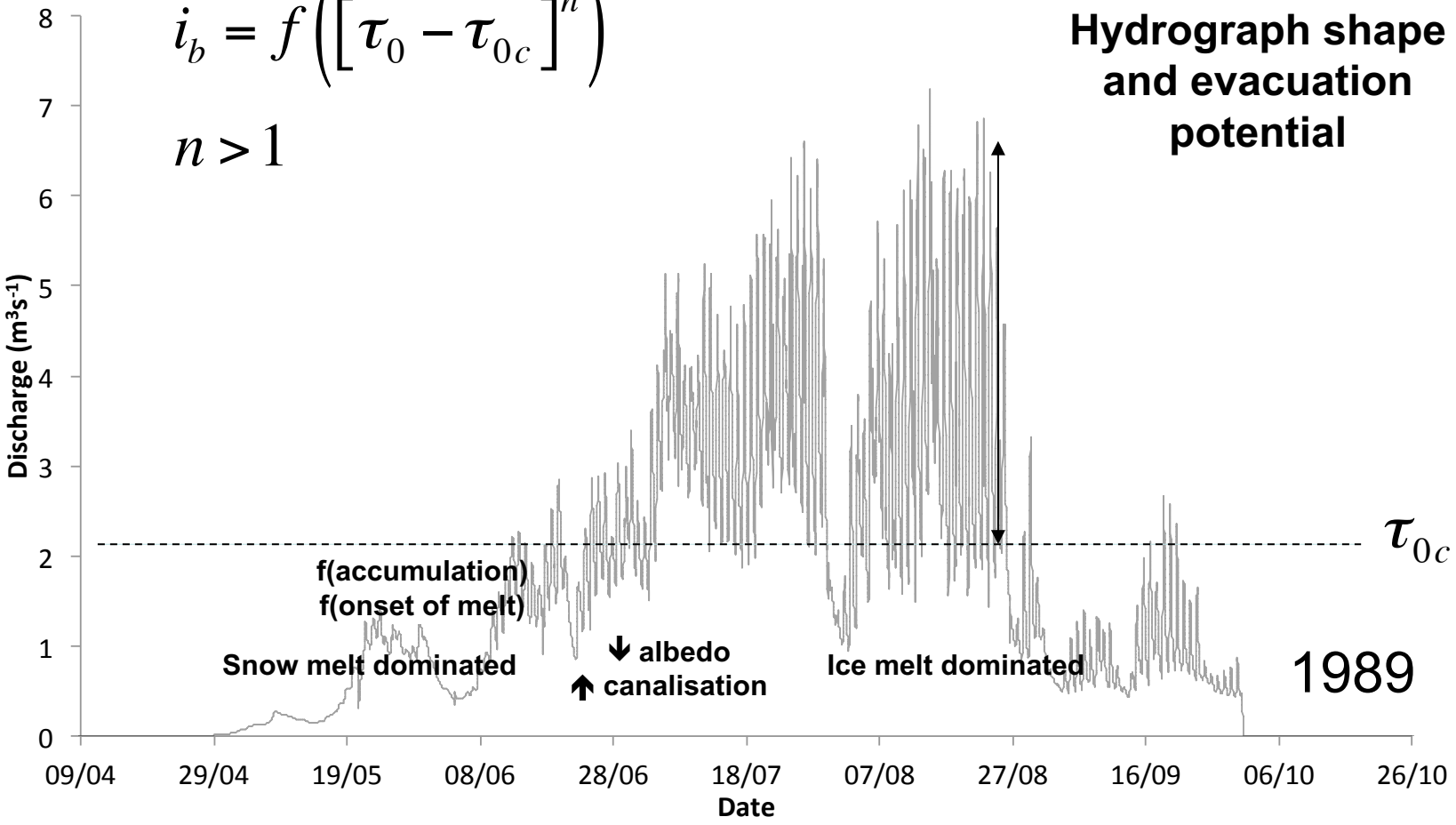
$$q_b = \left(\rho_s/\rho\, g D_{50}^3\right)^{0.5} 2.5\sqrt{\theta_r}\left(\theta_r - \theta_{rc}\right) Fr$$

$$\theta_r = \frac{RS_0}{\left(\left[\rho_s/\rho\right]-1\right)D_{50}} \qquad \theta_{rc} = \frac{R_c S_{0c}}{\left(\left[\rho_s/\rho\right]-1\right)D_{50}}$$

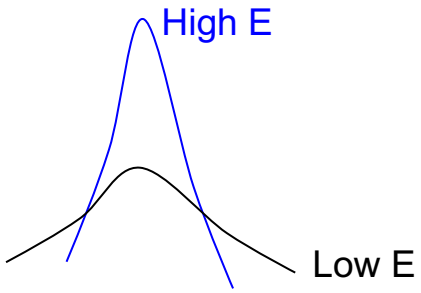
Glaciers don't evacuate sediment efficiently, subglacial rivers do

$$i_b = f\left(\left[\tau_0 - \tau_{0c}\right]^n\right)$$

$$n > 1$$

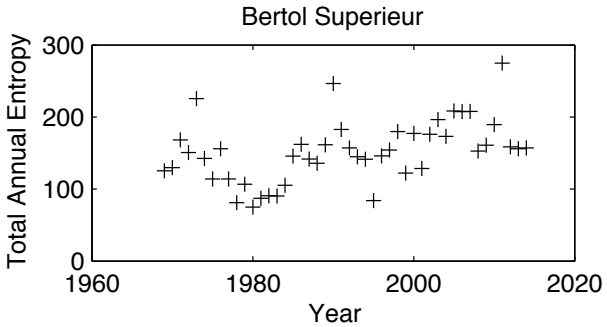


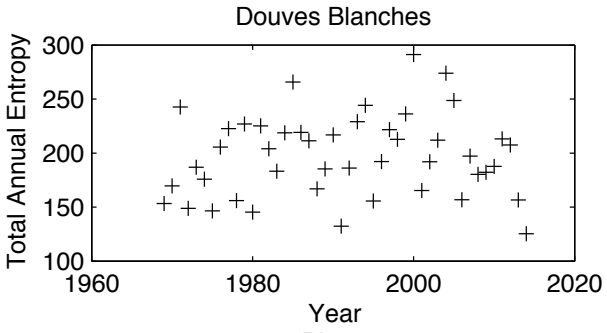
Glaciers don't evacuate sediment efficiently, subglacial rivers do

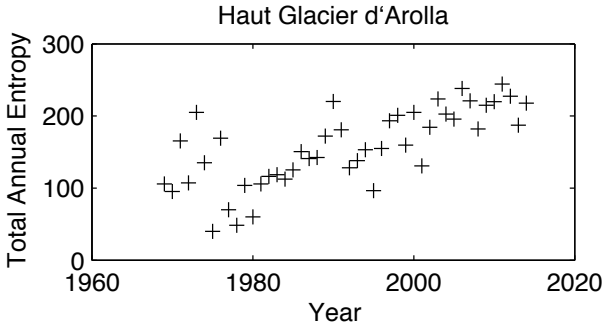


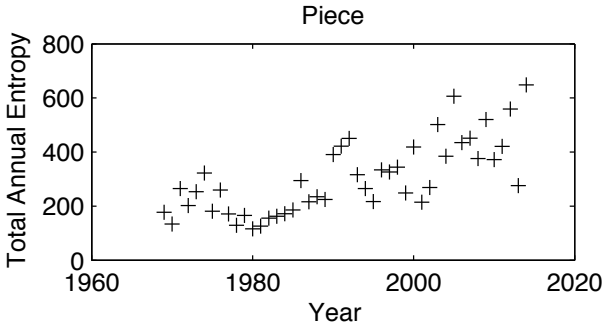
Generalised Entropy, E, calculated daily on discharge hydrograph

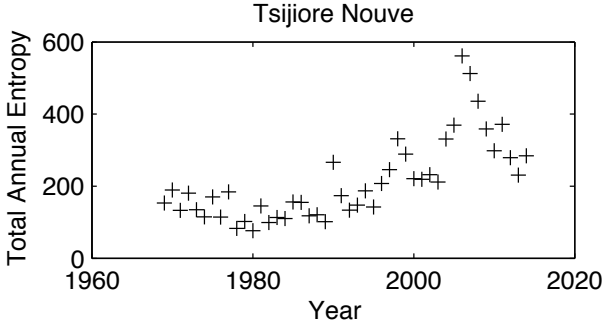
$$E = \frac{1}{N}\sum_{1=1}^{N}\frac{Q_i}{\overline{Q_i}}\ln\frac{Q_i}{\overline{Q_i}}$$









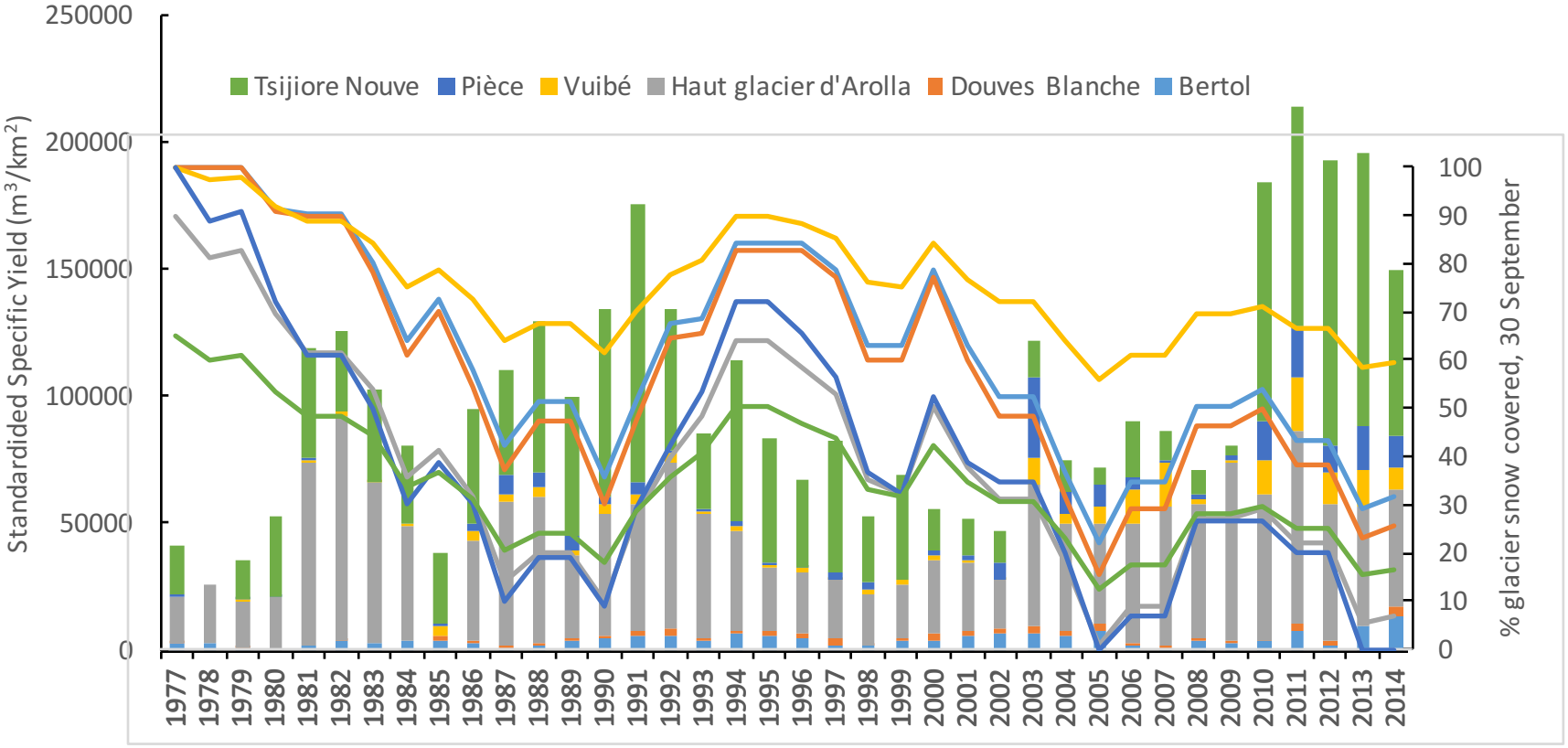


Intensity of diurnal discharge variation is increasing under a warming climate

earlier onset of snow-free ice melt

Glaciers don’t evacuate sediment efficiently, subglacial rivers do

% of each glacier that is snow-covered at the end of September each year
Data from Micheletti, Lambiel and Lane, 2015. *JGR-ES*, 120, 2155-75



Glaciers don’t evacuate sediment efficiently, subglacial rivers do

Correlations with annual sediment yield

Partial correlations due to variable inter-correlations

Glacier	Grand Saint Bernard Temperature anomaly	% glacier snow covered 30th September	Annual water yield (partial correlation accounting for entropy)	Annual entropy (partial correlation accounting for water yield)
Bertol	0.355*	‘-0.279*	-0.024	0.322*
Douves Blanches	0.469*	-0.544*	0.420*	0.135
Haut Glacier d’Arolla	0.276*	-0.295*	0.292*	0.031
Vuibé	0.408*	-0.460*	Missing	Missing
Pièce	0.355*	-0.337*	0.290*	0.352*
Tsijiore Nouve	0.156	-0.195	0.256*	0.121

* = significant at p = 0.05

Sediment loading to Lake Geneva

We need a process that is associated with greater *summer* sediment loading

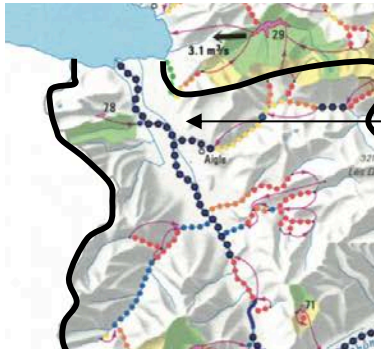
- Warming driven snowline recession
- Increased efficiency of glacier melt
- More intense diurnal discharge variability
- More efficient subglacial sediment evacuation

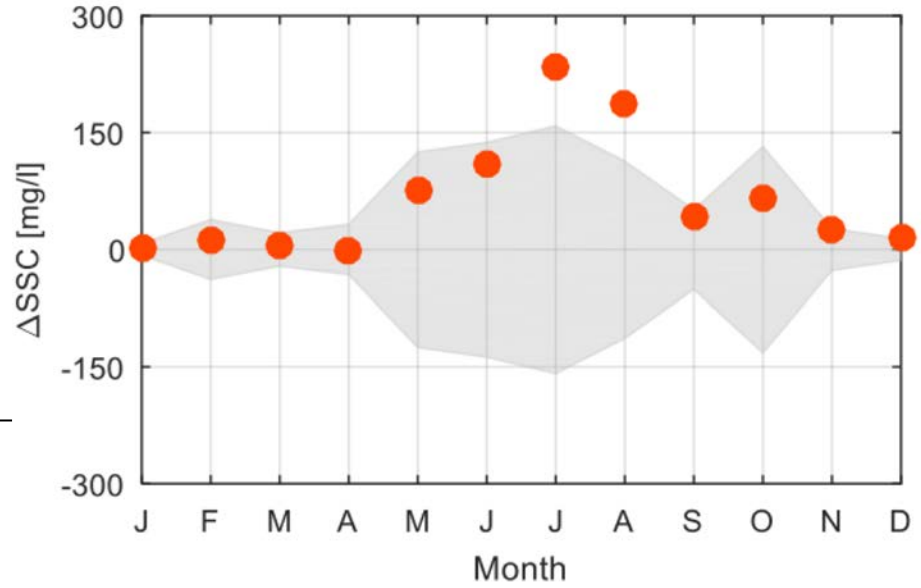
Change in mean monthly suspended sediment concentration

Porte du Scex

1965-1986 versus 1987-2015

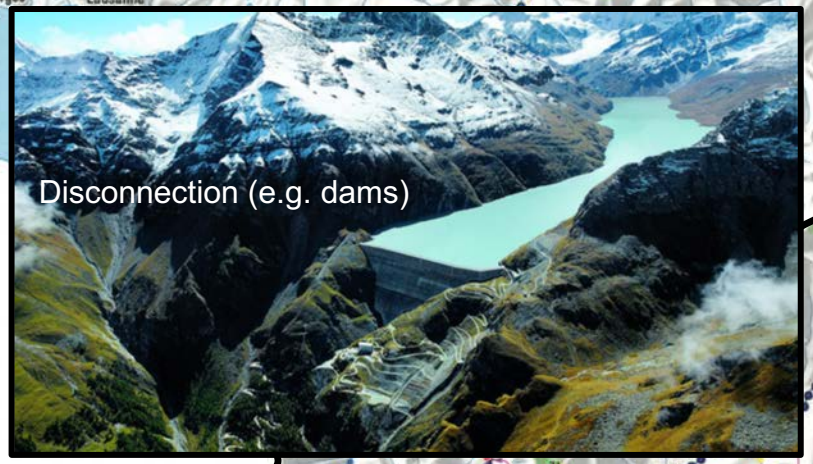
Grey = 95% confidence limits

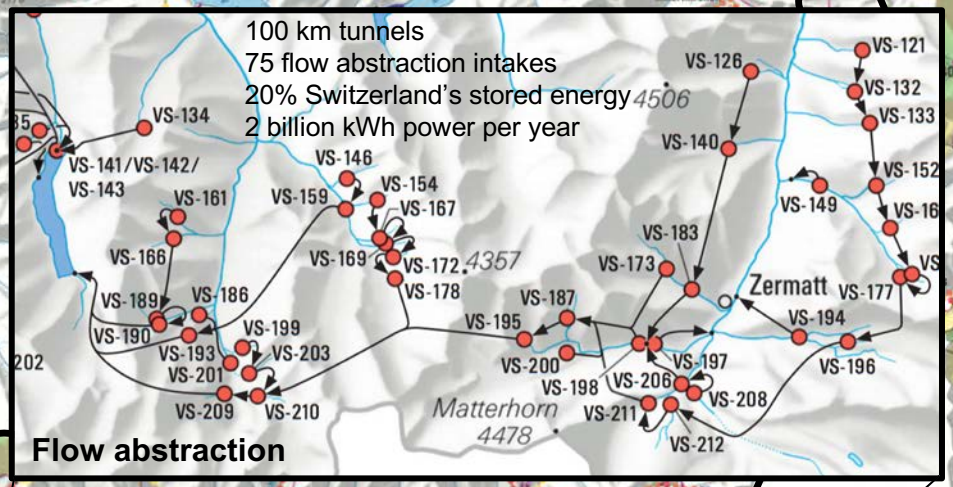




Costa, Molnar, Stutenbecker, Bakker, Silva, Schlunegger, Lane, Loizeau and Girardclos, 2018. *Hydrology and Earth System Science,* 22, 509-528

But … dams *and* intakes





Very strong coupling of hydropower management to climate change due to sediment management

Storage Dams

Inter-basin transfers

Within-basin transfers

© Swiss Hydrological Atlas

Conclusions

1. Specifically
   a. It is possible to see a **signature of human-induced climate change** in the sediments being deposited in Lake Geneva
   b. Growing sediment yield is a signal of **warming-induced glacier retreat**
   c. The signal is observed **despite** the Swiss Rhône being heavily impacted by human activity that in theory should disconnect sediment flux
2. More generally
   a. When we think about the stratigraphy we are making we need to think about the impacts of global change **plus** local human impacts (e.g. the very special nature of Swiss hydropower production)
   b. In the Anthropocene, it is possible that we both **increase** or **decrease** the rate of production of stratigraphy under the same global forcing
   c. There may be a strong **coupling** between global change and local human impacts

Thank you for listening and …

… many thanks to

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We are progressively making these datasets available via ebibalpin.unil.ch