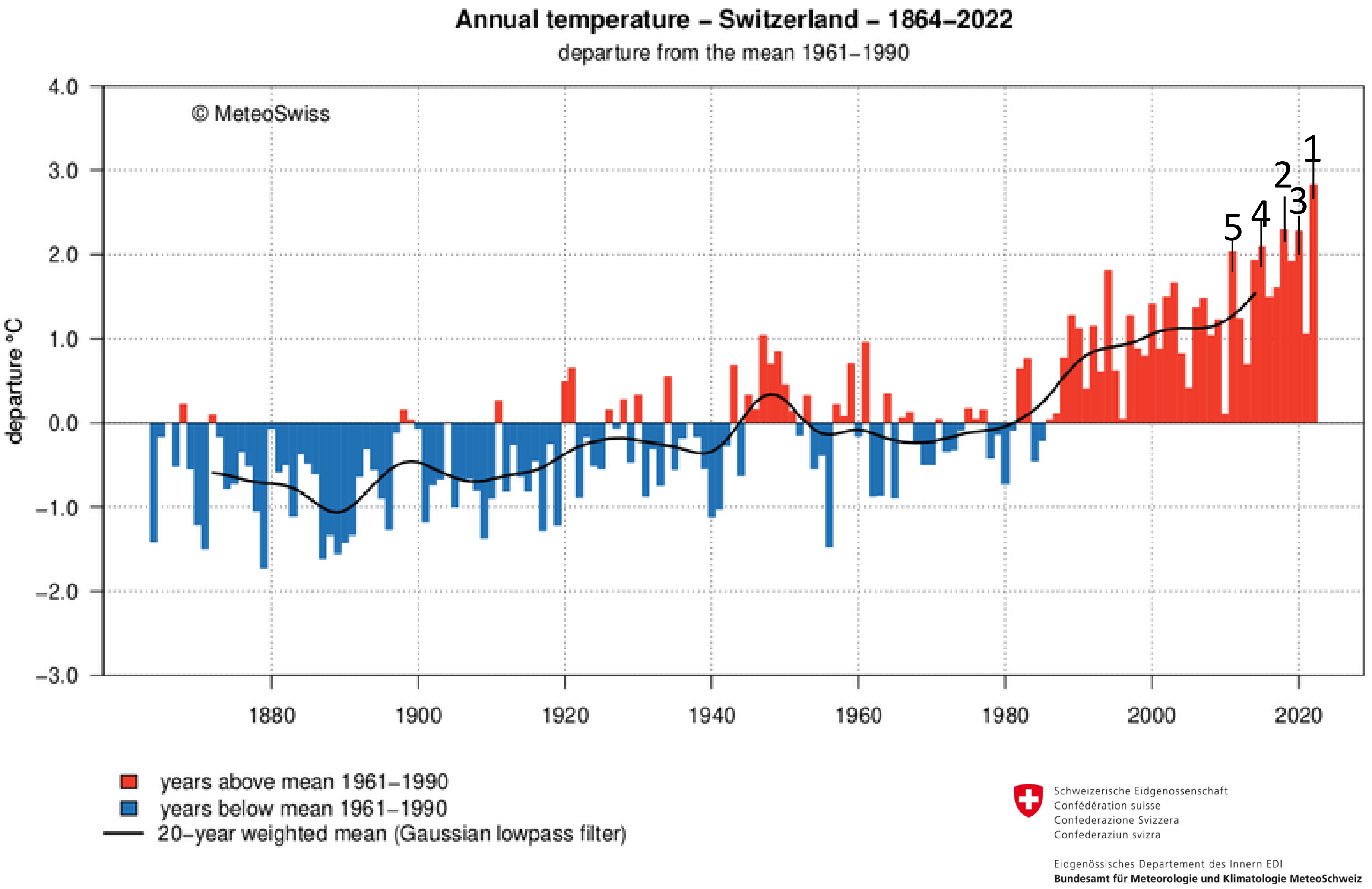
Theo M Jenk :: Scientist :: Laboratory for Environmental Chemistry (LUC) :: Paul Scherrer Institut

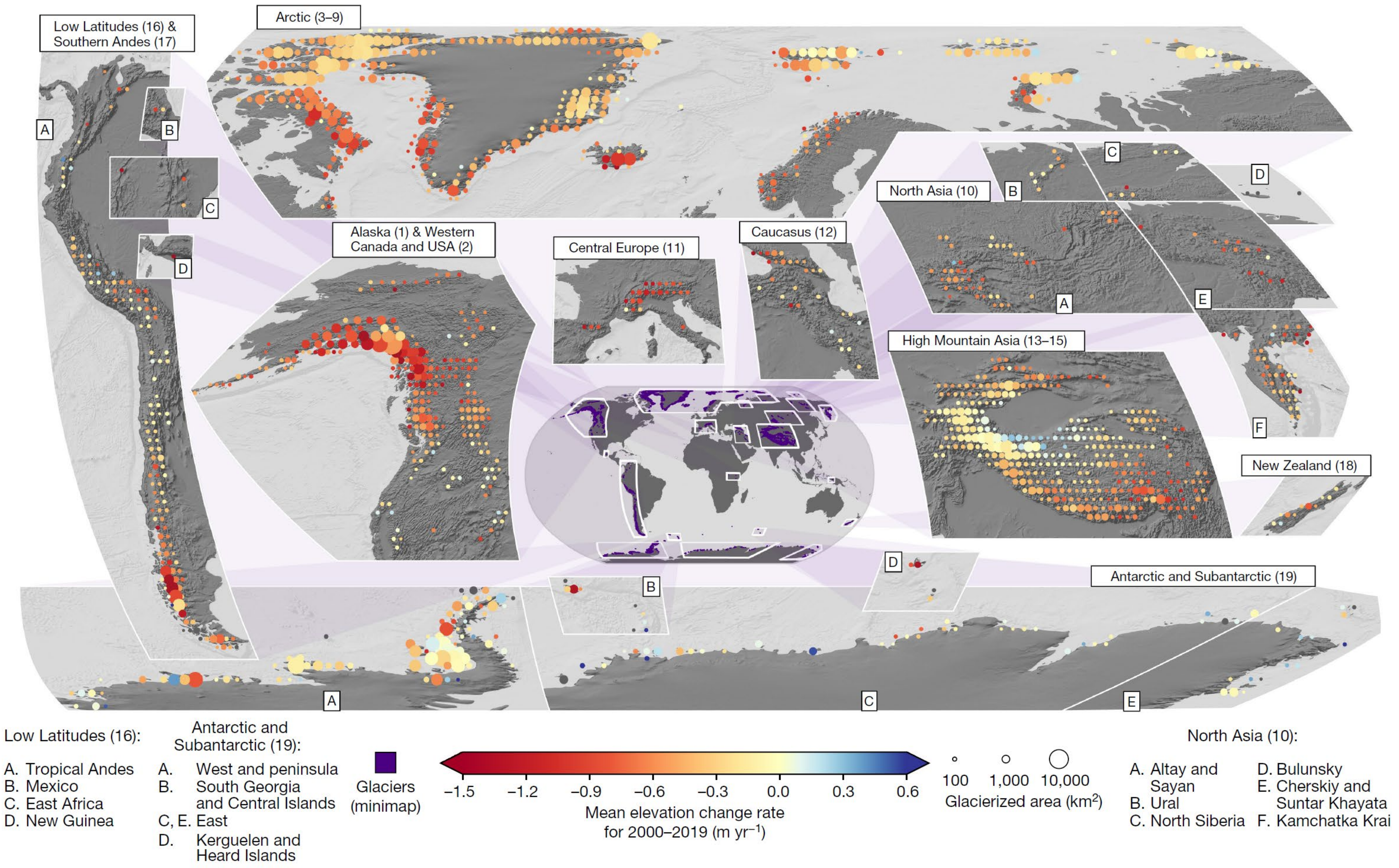
Frozen chemistry: Glaciers as archives of past environmental conditions

LTP-PSI Colloquium :: PSI, CH :: 09 Nov. 2023

Mean annual temperature in Switzerland 1871-2022

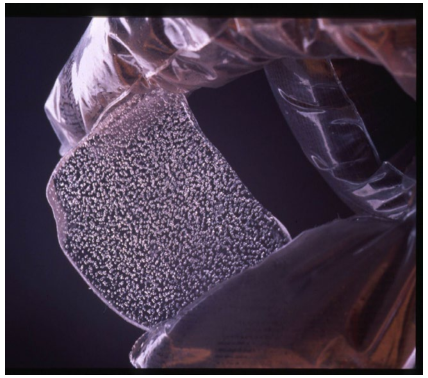


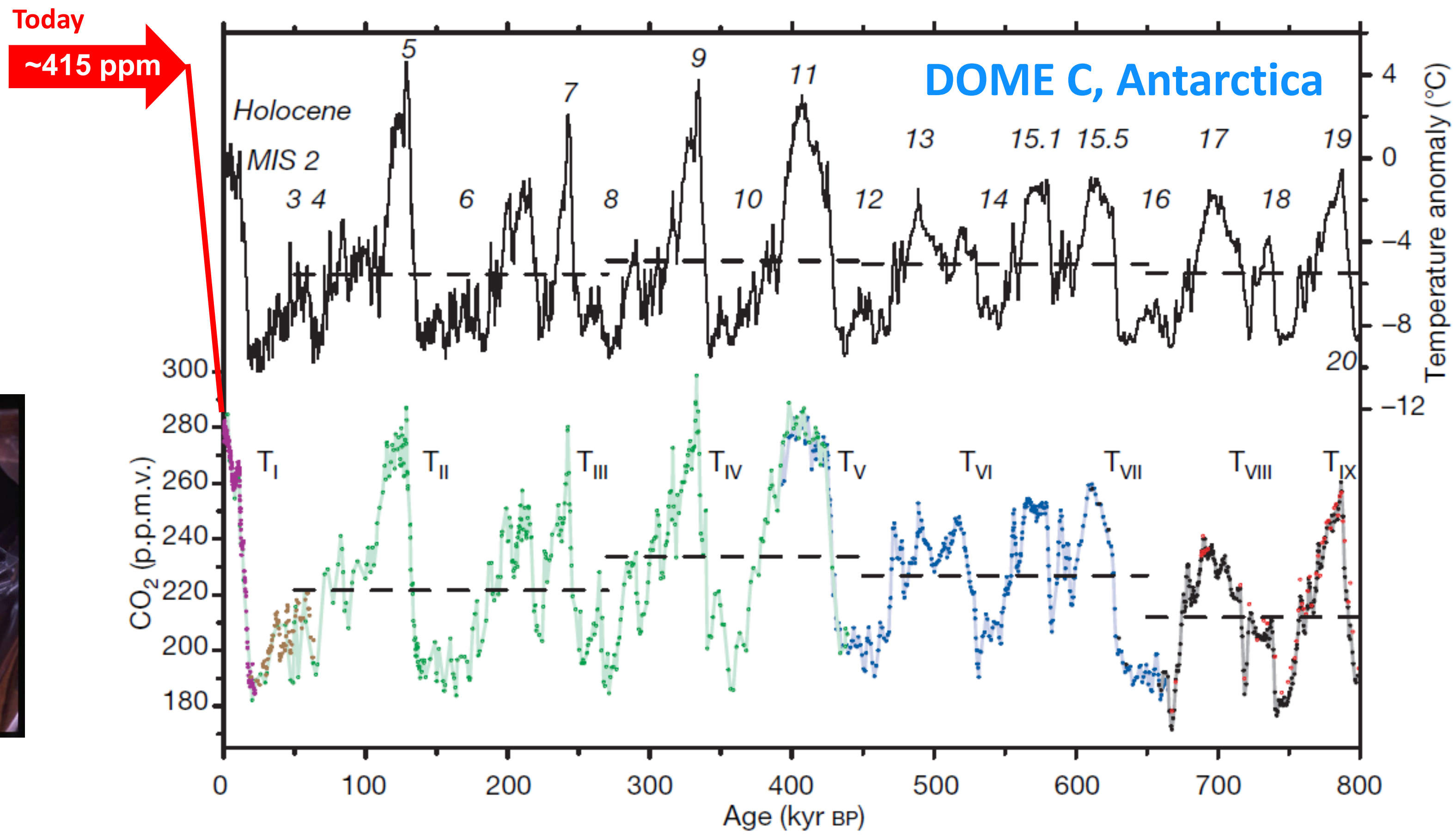
Glacier elevation change between 2000 and 2019 (Satellite data)



Hugonnet et al., 2021

800'000 years of temperature and CO_2





Lüthi et al., Nature, 2008

OUTLINE

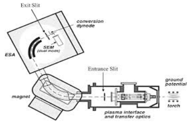
1. Introduction

2. Ice core drilling

3. Analytical techniques (method development) **& Ice core dating**

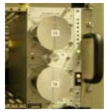
4. A few selected examples of paleo-reconstructions

5. Outlook

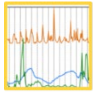


Trace elements:
ICP-SF-MS

^{14}C:
AMS

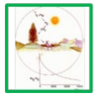


^{210}Pb:
α-spectroscopy

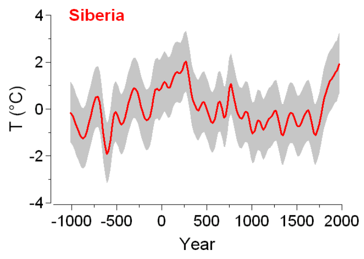


Annual layer counting

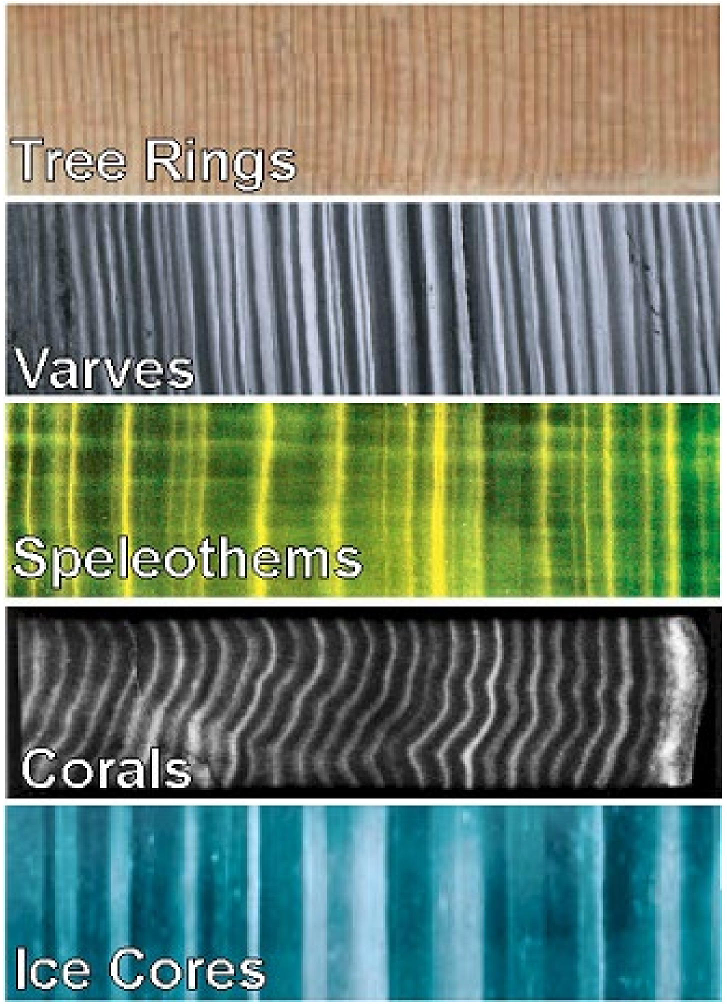
Time markers/horizons



^{210}Pb
^{14}C
Radiometric dating



Natural climate archives



Pages Newsletter, 2003

- **Instrumental records only cover a few decades**, up to around 150 years for temperature.

➢ **Too short to cover natural, pre-industrial conditions.** They do not allow to separate anthropogenic induced climate change from natural climate variability.

- **Paleo-records are crucial to understand the climatic processes under natural background conditions.**

- **Past climate is the benchmark for models projecting future climate.**

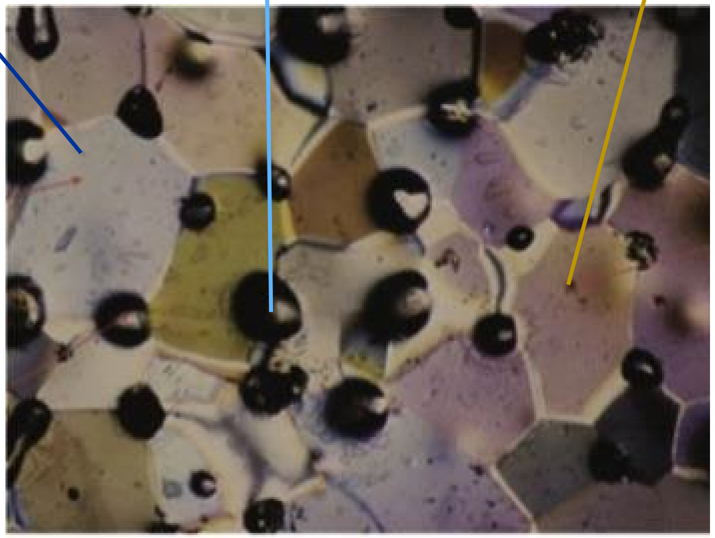
What makes ice cores special?

Ice cores – a multi-proxy archive

Water - H_2O
($H_2{}^{16}O$, $H_2{}^{18}O$, HDO)

Air
gases in air bubbles
(CO_2, $^{13}CO_2$, CH_4, ….)

Impurities
dust, sea salt, emissions from the biosphere, trace element pollution, volcanism,…



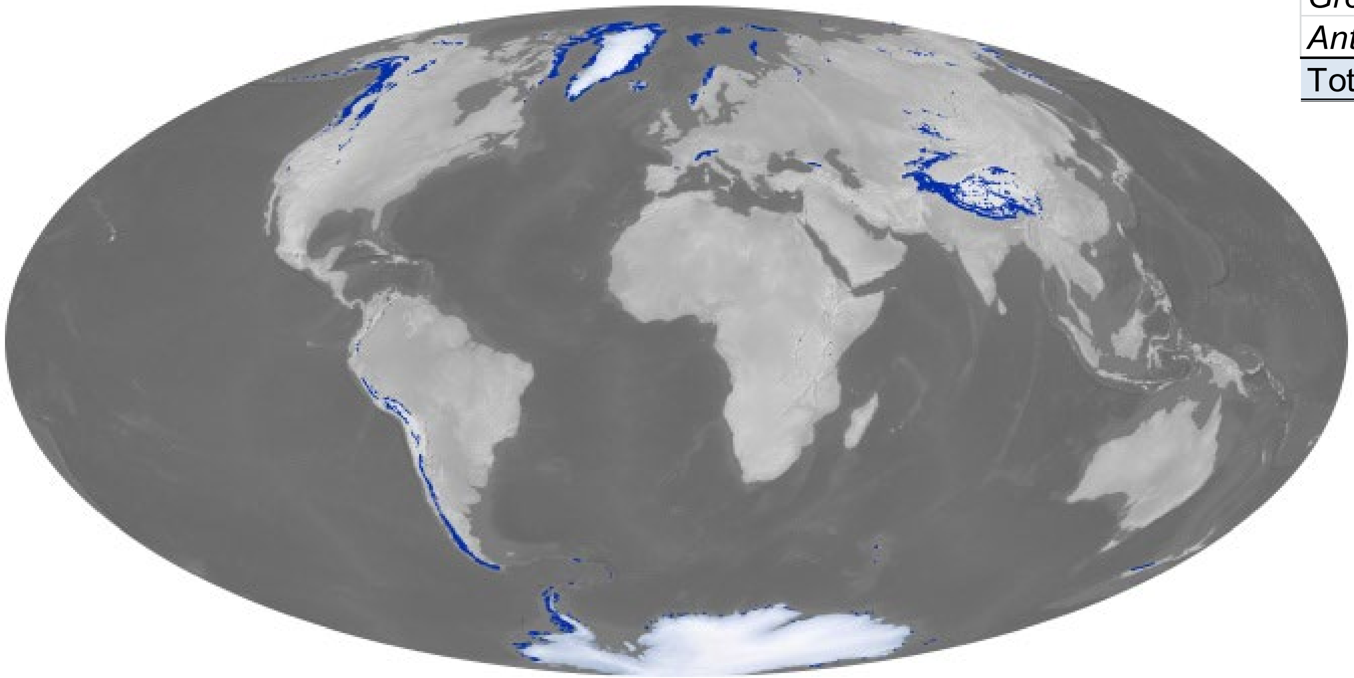
Raynaud et al., Paleoclimatology and Climate Change, 2020

Ice cores allow to reconstruct

- Greenhouse gases
- Air pollution
- Temperature
- Precipitation
- Volcanic activity
- Atmospheric circulation
- Solar variability
- and more…

Ice on earth

Region	Ice volume (km^3)	Instantaneous sea level rise (m)
Glaciers	180'000	0.45
Greenland	2'620'000	6.55
Antarctica	30'109'800	73.44
Total	32'909'800	80.44



Polar ice shields ⟷ **High-alpine glaciers**

Global/Hemispheric signal

Closer to populated regions

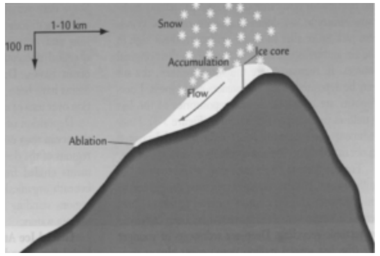
Closer to emission sources

Local/regional signal

Picture - https://earthobservatory.nasa.gov/images/83918/the-randolph-glacier-inventory/

Ice archives - alpine versus polar

	Alpine glaciers	Polar ice sheets
Thickness	50 to 300 m	> 3,000 m
Ice temperature	-18°C to 0°C	-56°C to -15°C
Elevation	3,900 to 7,200 m	2,480 to 3,233 m
Time scales	100-10,000 years *>500,000 years (Guliya)	130,000-800,000 years
Drilling	Dry hole, weeks Alpine expedition style Small teams	Drilling fluid, multiple seasons Semi- to permanent structures Large international operations

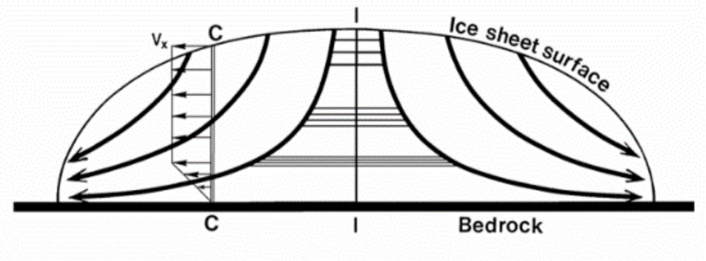


High-alpine glaciers

Δ thickness

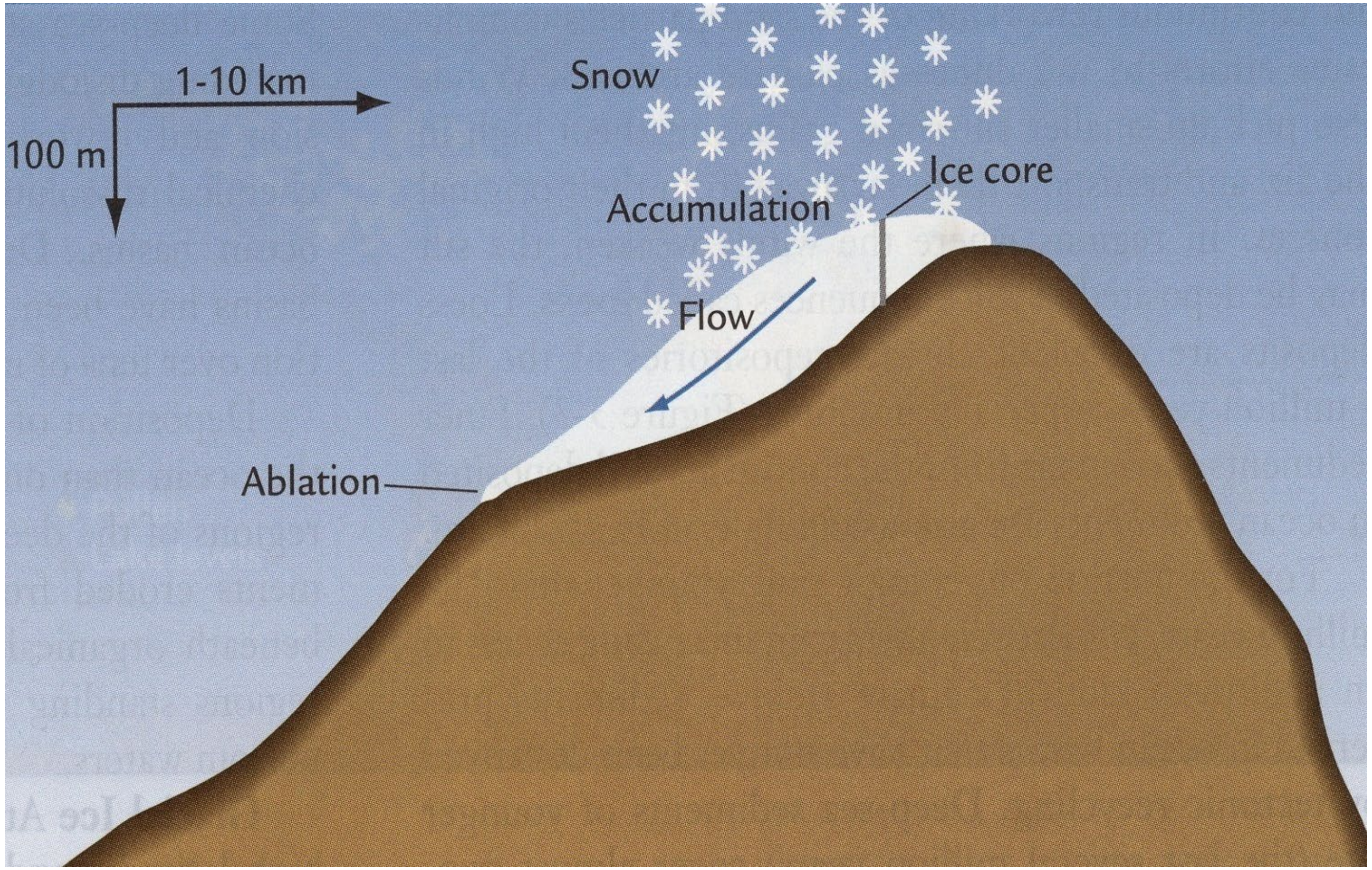
↔

Δ accessible timescale



Polar ice shields

Alpine glaciers as natural archives

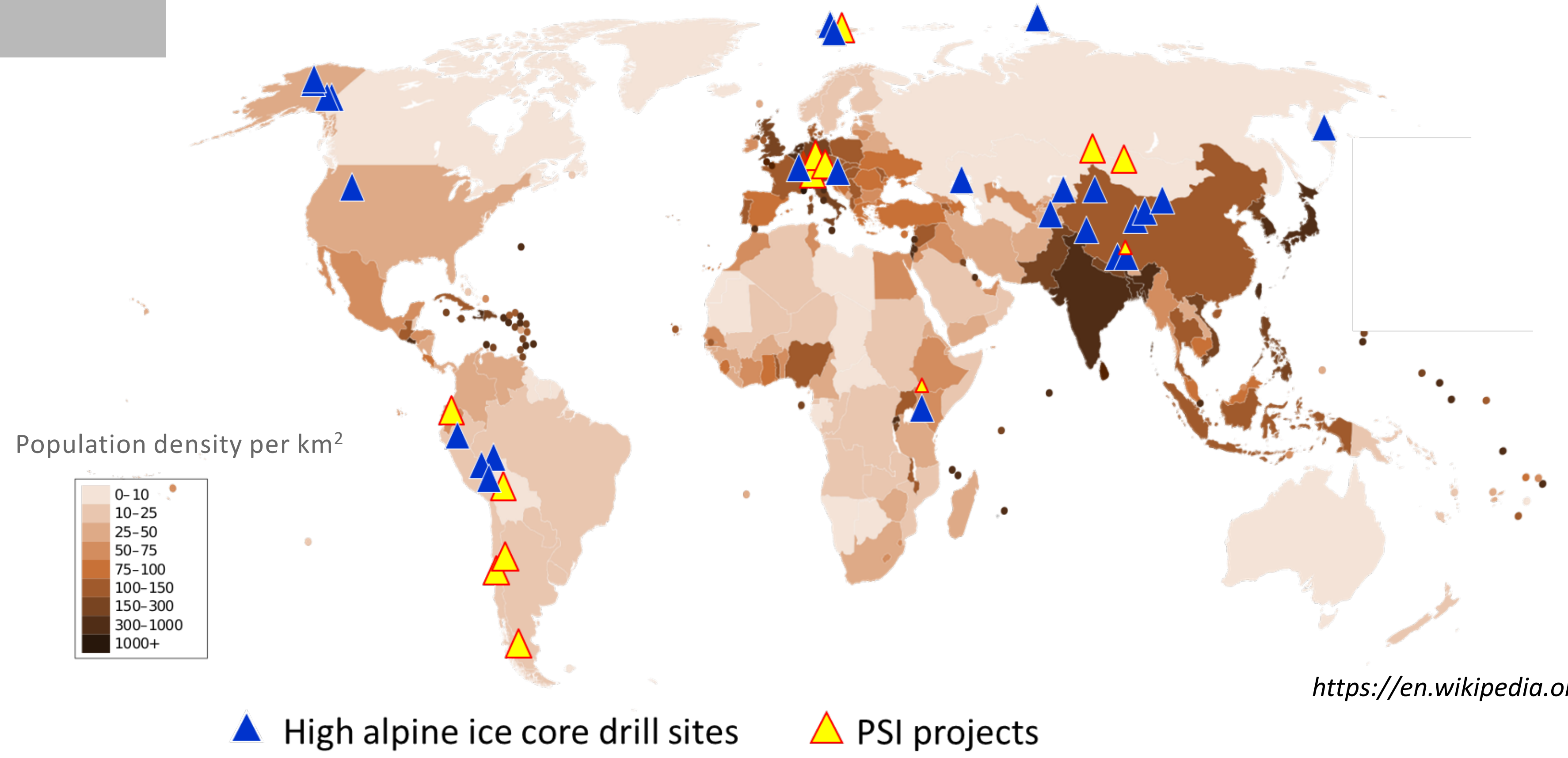


W.F. Ruddiman, Earth‘s Climate

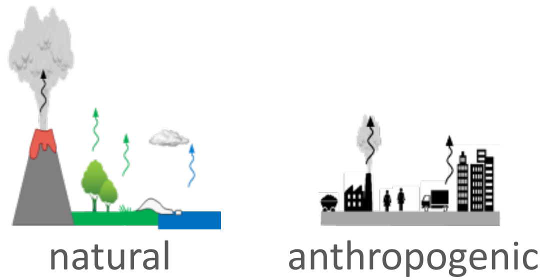
Alpine glaciers as natural archives

Population density

High alpine ice core locations



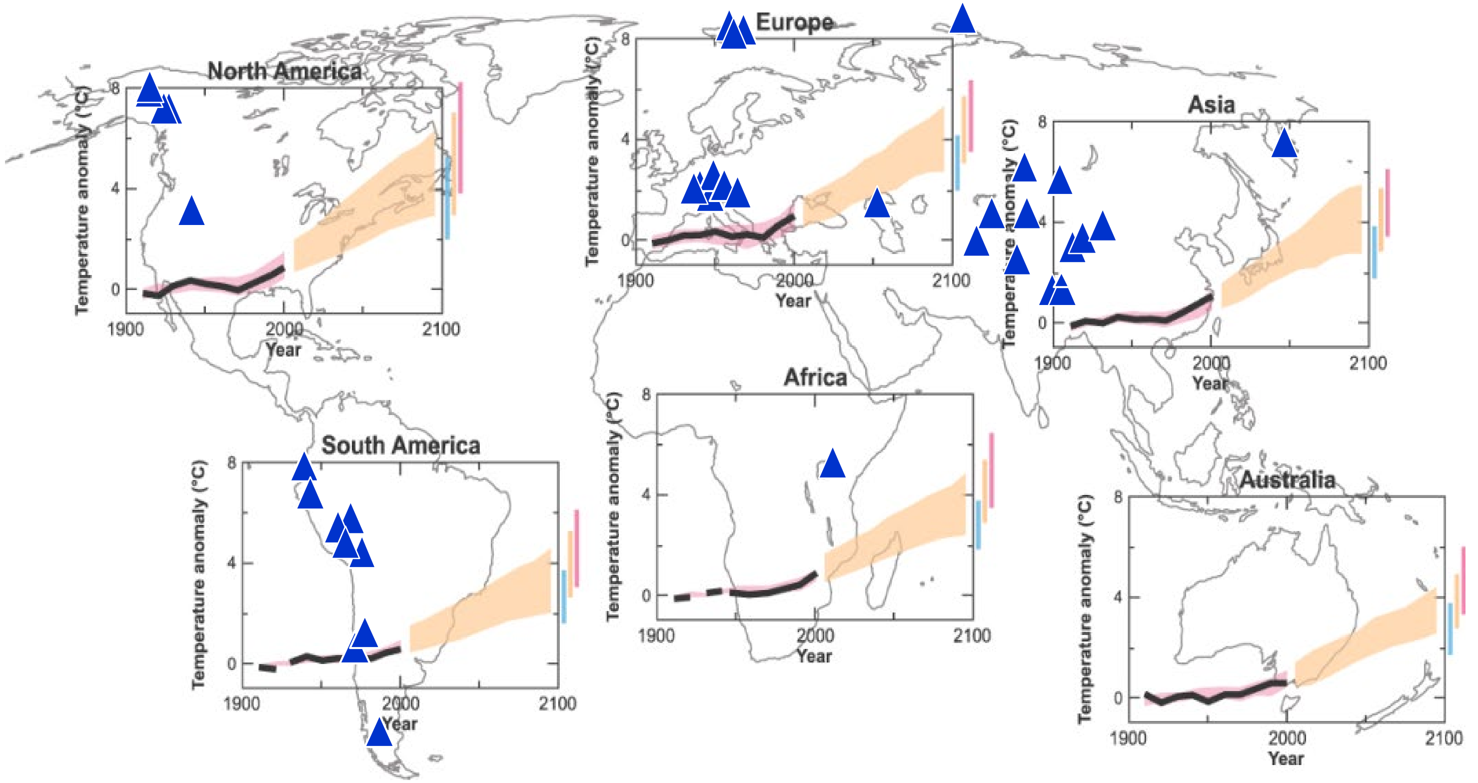
https://en.wikipedia.org/wiki/Population_density



Proximity to emission sources

- allows investigation of short-lived atmospheric species.

Regional expression of climate change



▲ High alpine ice core drill sites

IPCC, 2007

High alpine ice cores allow sampling in higher spatial resolution
(compared to polar ice cores)

Ice core drilling on high-alpine glaciers

Colle Gniffeti, Switzerland
(4450 m asl.)

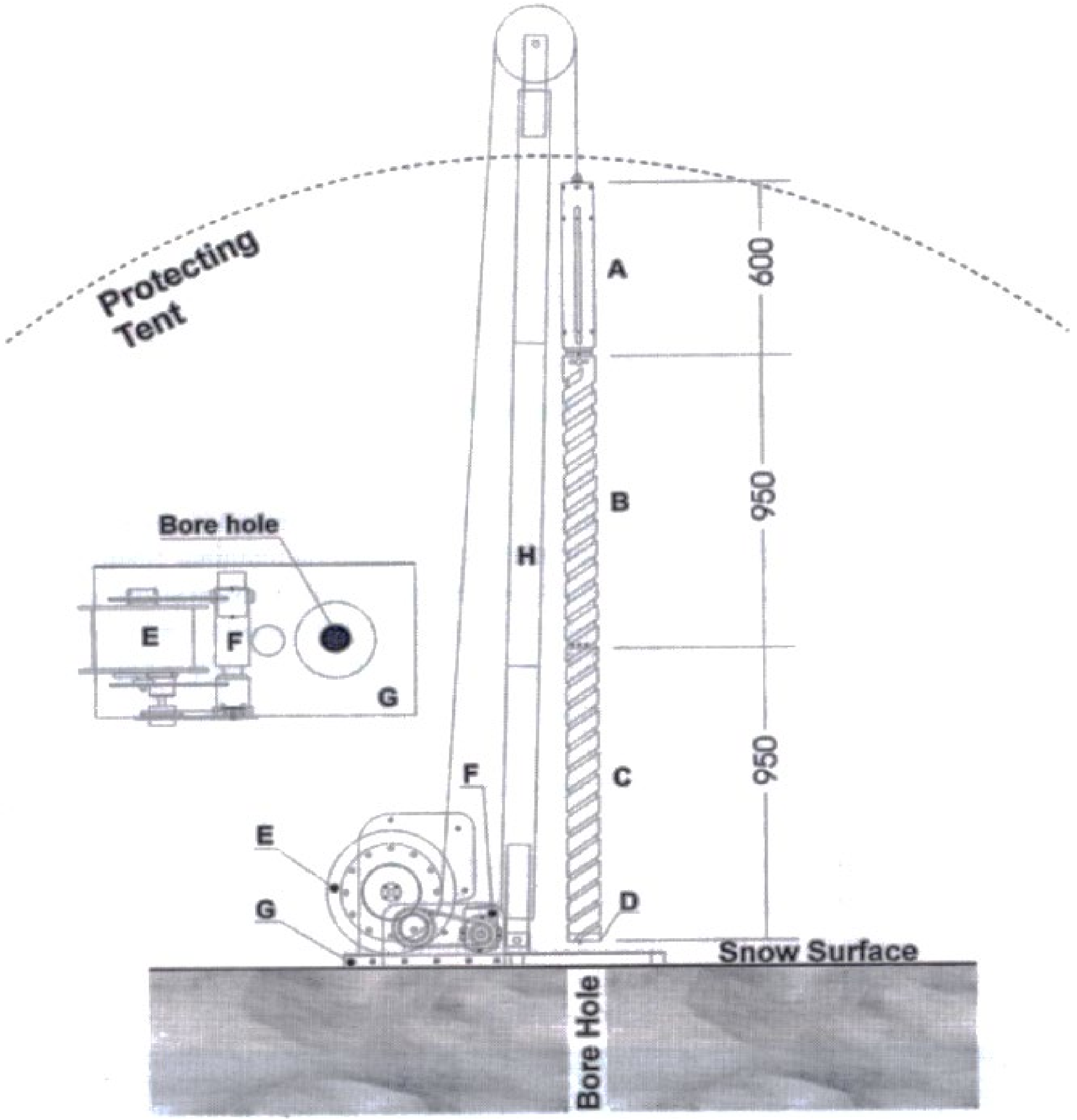
Tsambagarav, Mongolia (4100 m asl.)

Mercedario, Argentina
(6100 m asl.)

- Modular designed drill (electromechanical/ thermal) allowing transport by porters or pack animals.
- Work under extreme high-altitude conditions (above 5500 m): Easy to use and fast system for harsh conditions.

Illimani, Bolivia (6300 m asl.)

Drilling equipment – lightweight, modular design



FELICS

Fast Electromechanical Lightweight Ice Coring System – deep drilling

Ginot et al., 2002

Drilling equipment – lightweight, modular design

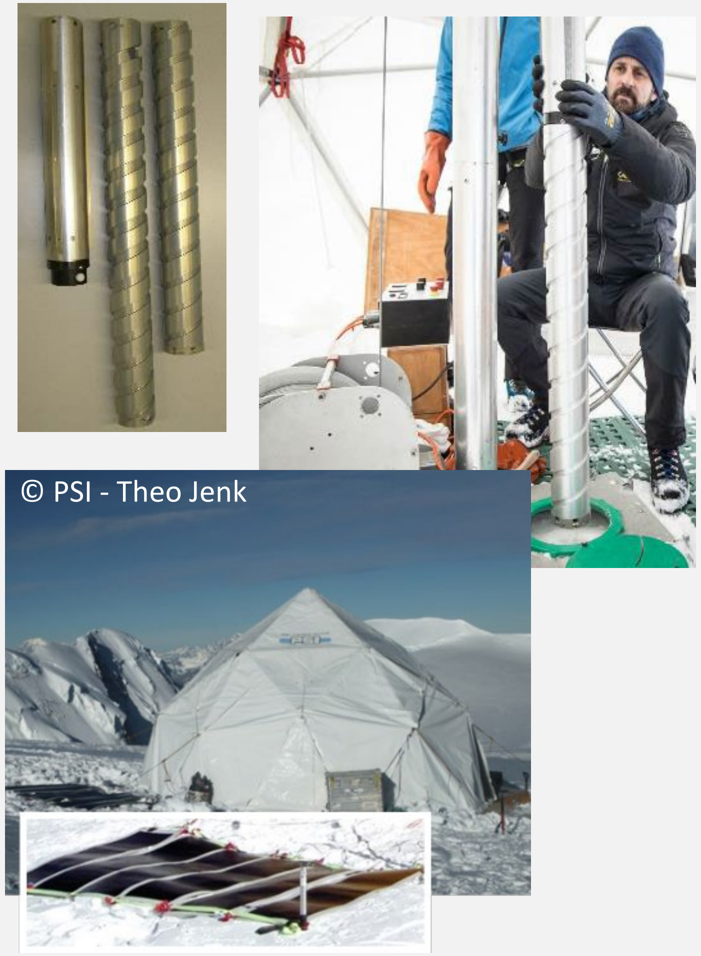
modular

FELICS small

“Backpack Drill” (electromechanical) – shallow/firn drilling for initial site recognition.

FELICS

Fast Electromechanical Lightweight Ice Coring System – deep drilling



Ginot et al., 2002

FELICS Thermal

for temperate ice conditions (warm & wet)

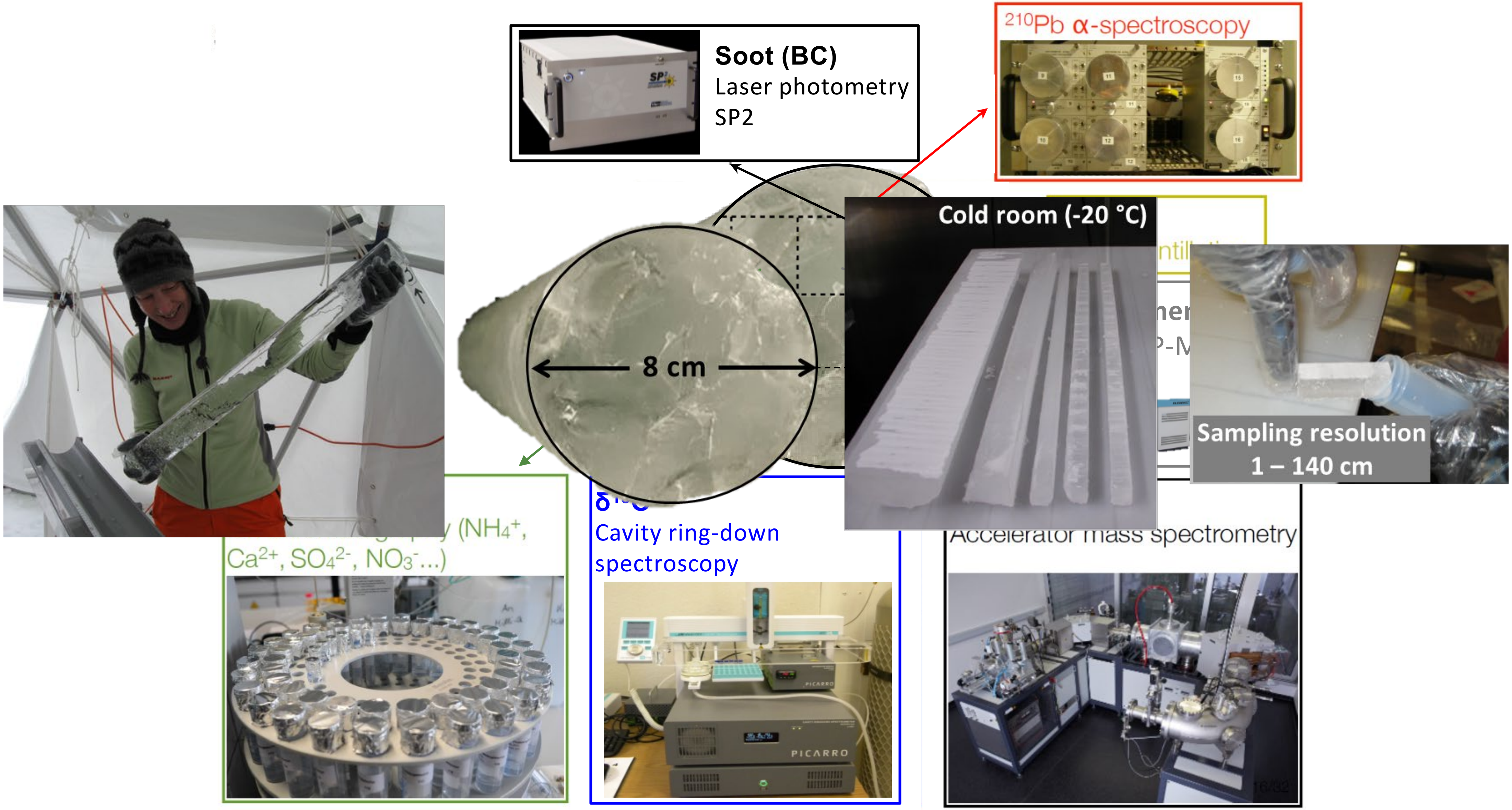
Melthead heated by hotspring coil heater

Schwikowski et al., AoG, 2014

Ice core drilling at high altitudes


Belukha drilling camp

Analytical methods - from the ice core to the sample



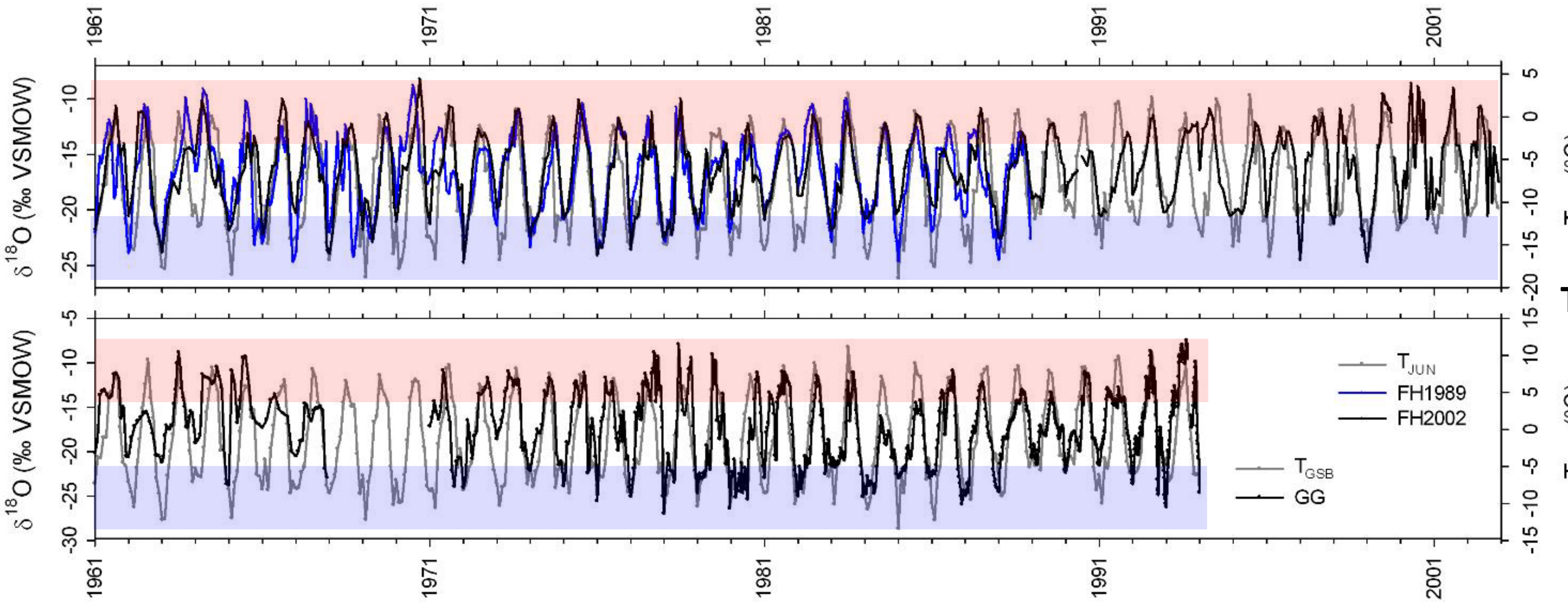
Dating of ice cores from high-alpine glaciers

Annual layer counting (seasonality of signal)

Fiescherhorn (CH)

$\delta^{18}O$

Grenzgletscher (CH)



warm

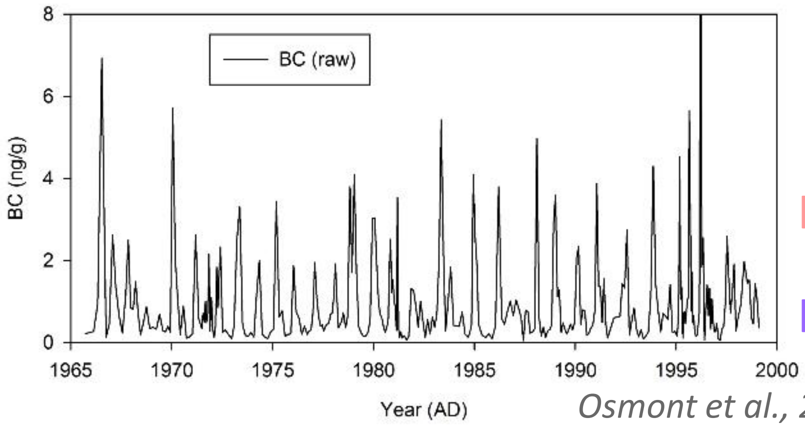
cold

Temperature

Mariani et al., 2014

Black carbon

Illimani, Bolivia



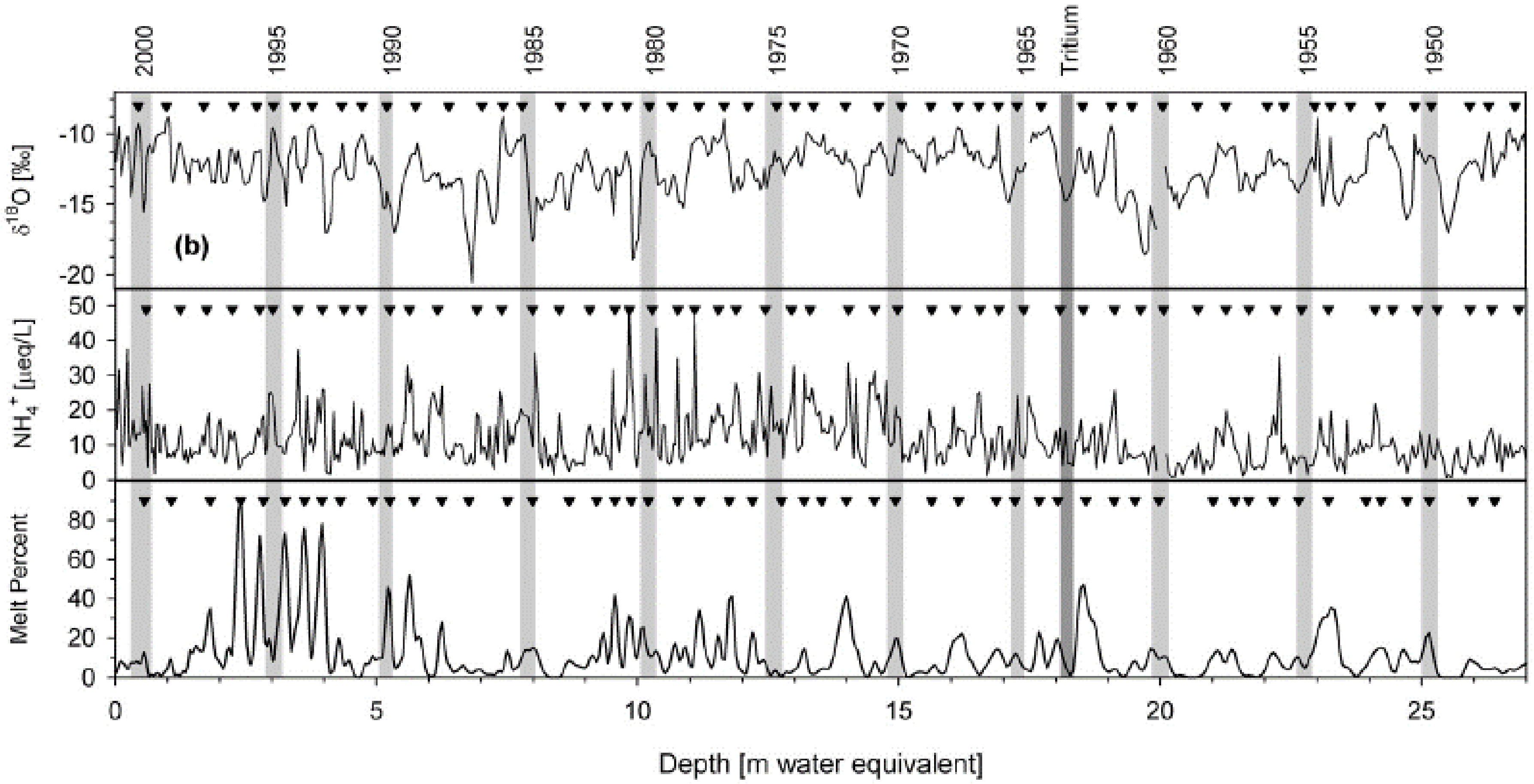
Osmont et al., 2018

high concentration → summer

low concentration → wimter

Dating of ice cores from high-alpine glaciers

Annual layer counting (seasonality of signal)



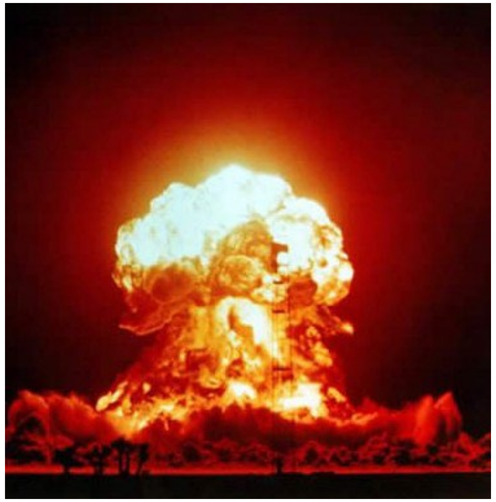
Belukha, Russia

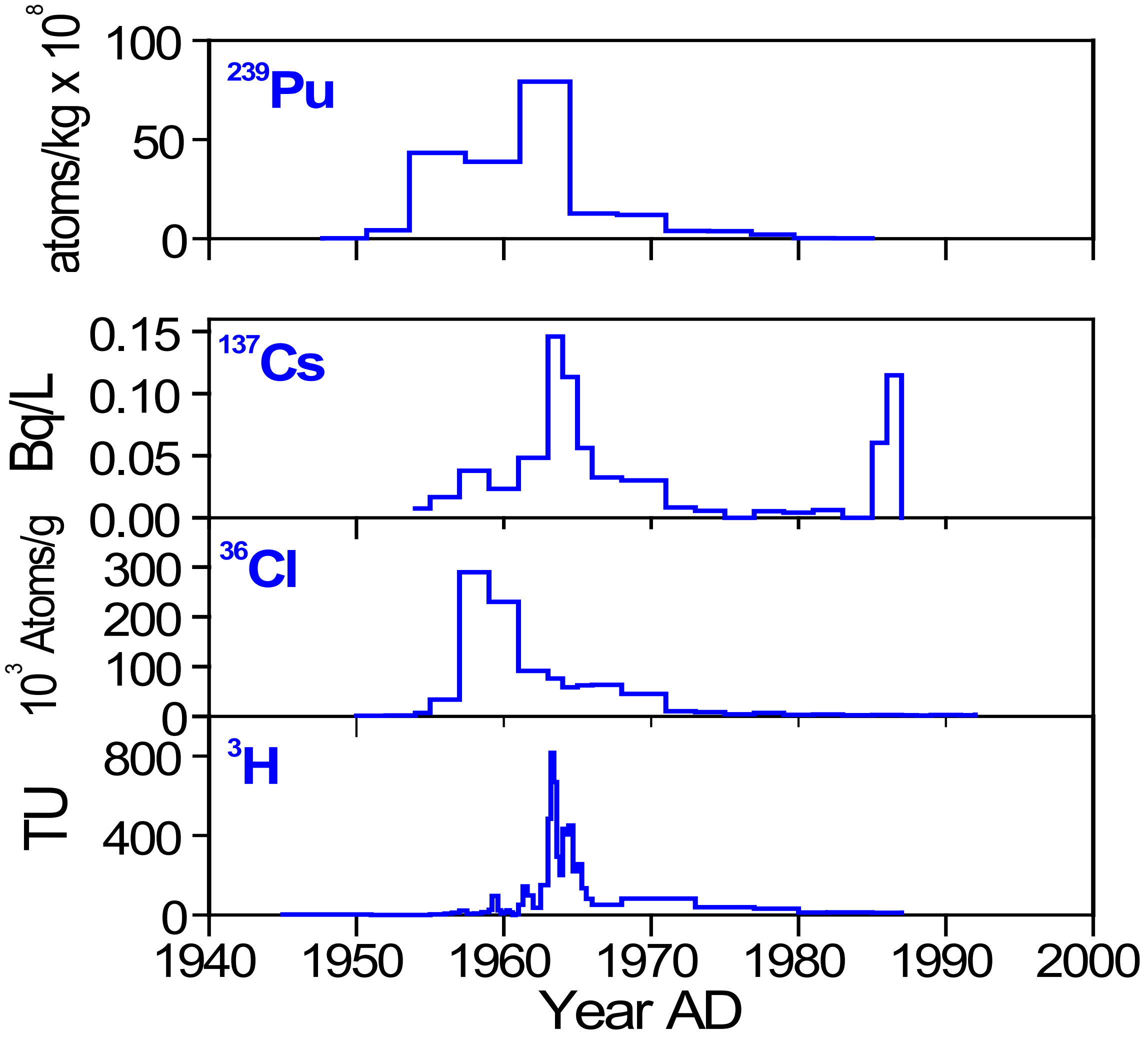
Olivier et al., 2006

Dating of ice cores from high-alpine glaciers

Time markers

Nuclear fallout horizons





Belukha, Russia

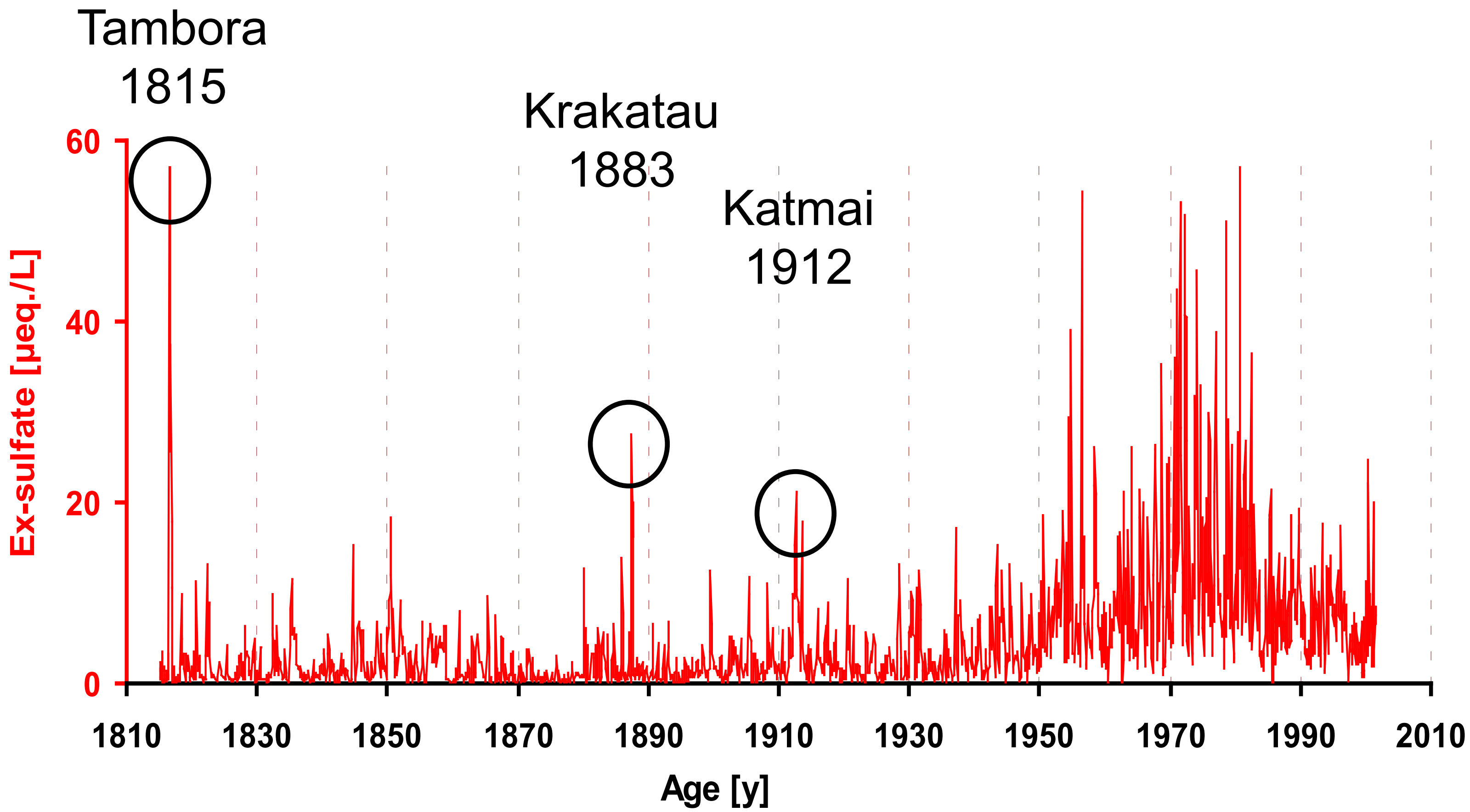
Olivier et al., 2004

Grenzgletscher, CH

Eichler et al., 2000

Time markers

Volcanic eruptions

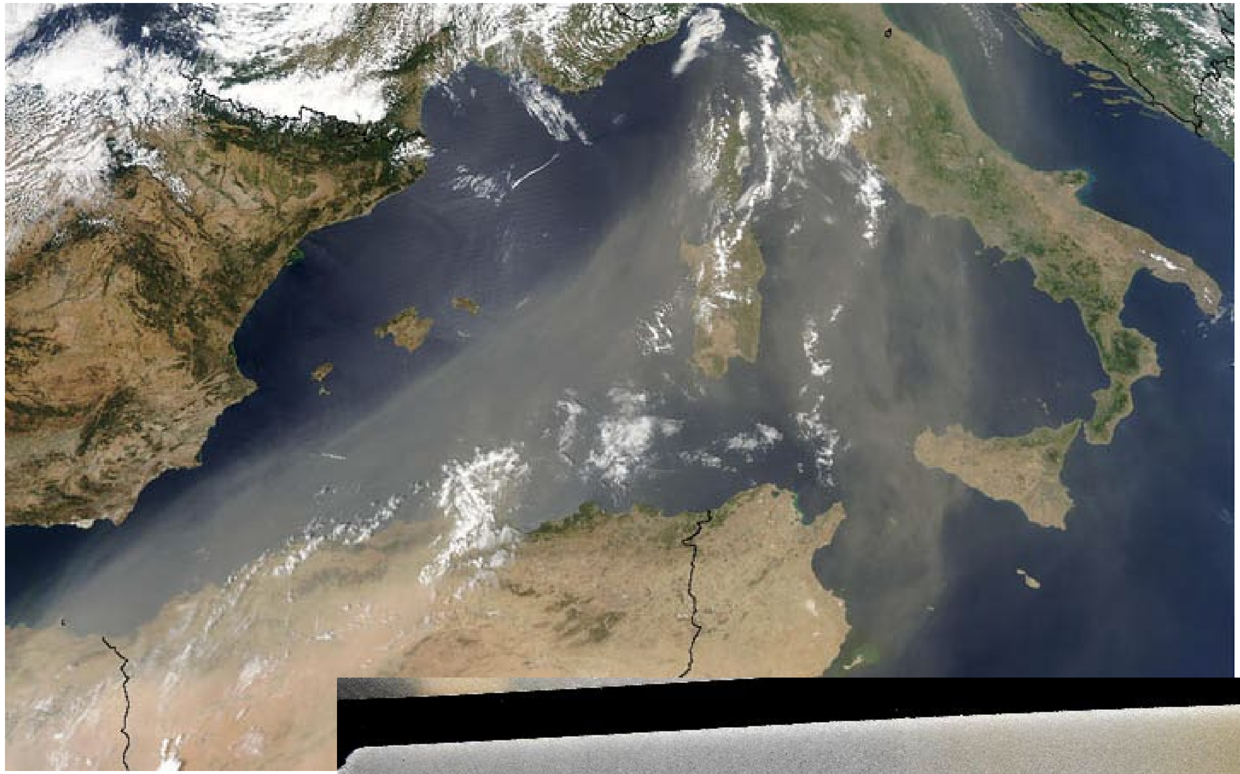


Belukha, Russia

Eichler et al., 2009

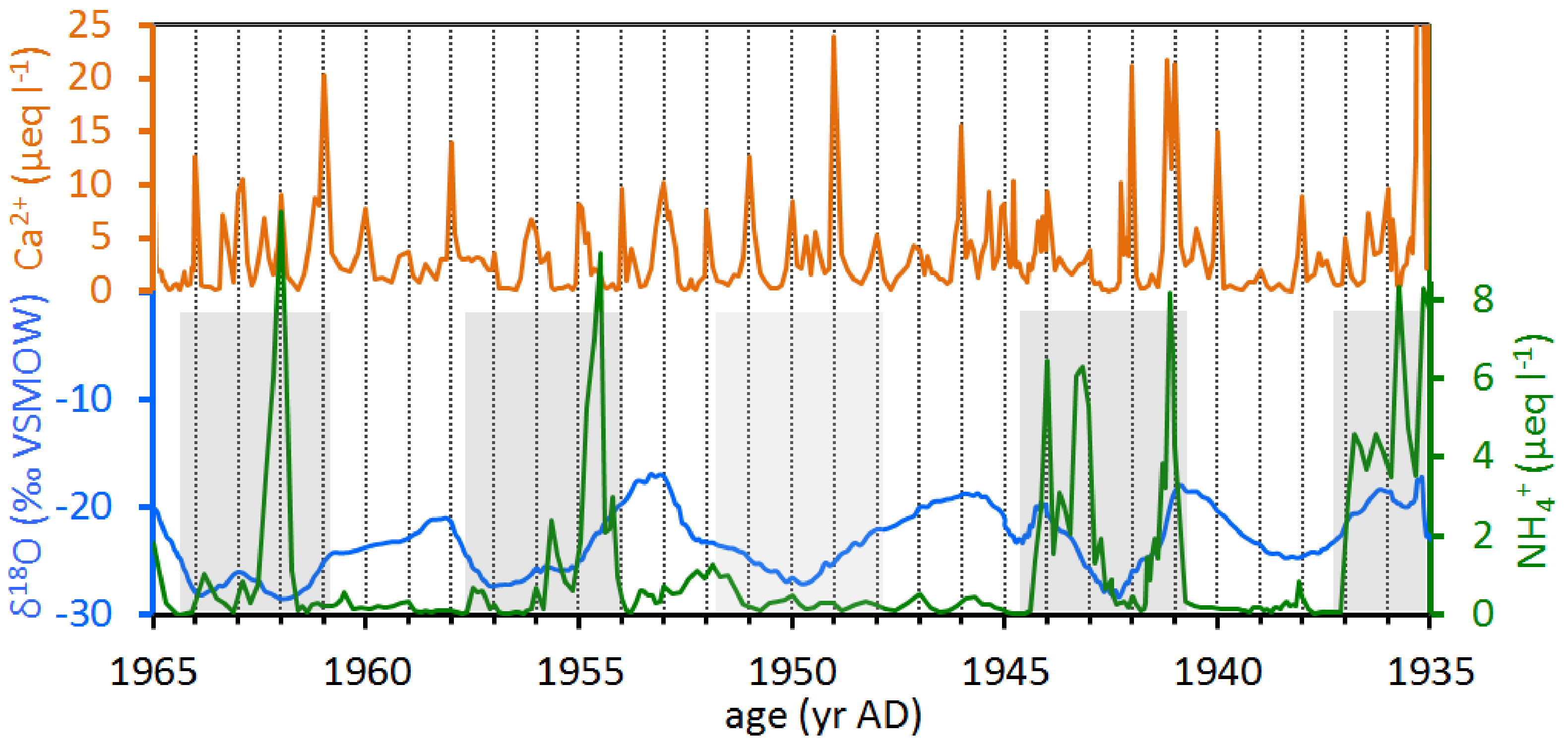
Time markers

e.g. documented Saharan dust events in the Alps (visible/significant peak in Calcium)



Challenges of annual layer counting

Seasonality may not be the predominant signal



Dominant signal (except for dust tracers):

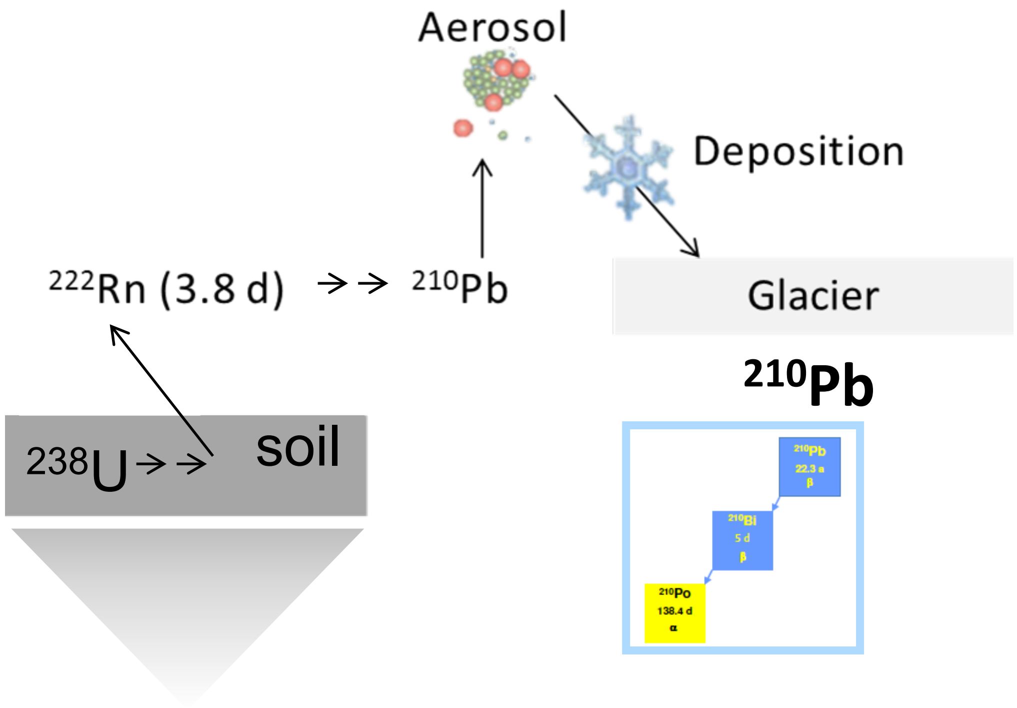
- **El Nino Southern Oscillation** (ENSO)
- **Frequency 2-7 years**

Mercedario, Andes, Argentina

Jenk et al., IUGG, 2015

Absolute dating based on radionuclides

^{210}Pb



^{210}Pb: half-life (T½)* = 22.3 years

- environmental radionuclide
- member of the natural U / Th decay series (^{238}U)
- dating of lake sediments, peat bogs & ice cores
- dating range: present to around 150 years

NOTE:

^{238}U (1.7 ppm) $\overset{10^3}{>>}$ **^{238}U** (3 ppb)

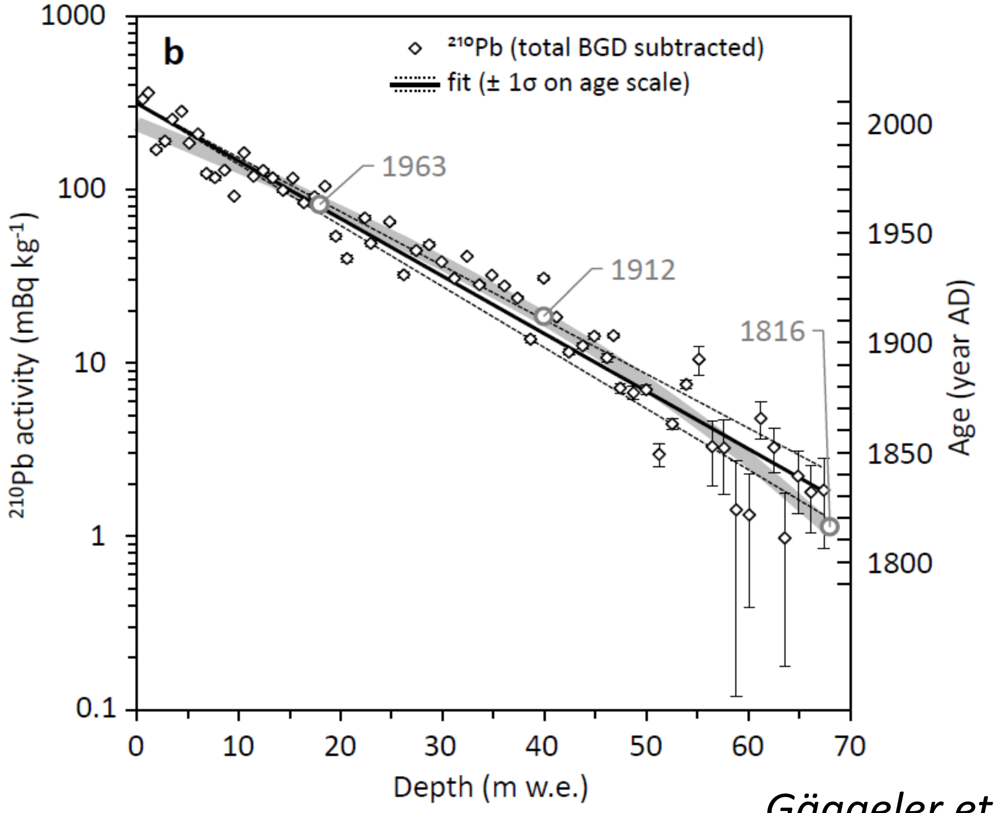
soil **ocean water**

*half-life (T½): time after which 50% of A_0 has decayed

^{210}Pb dating

$$t = \frac{-s}{ln\,(2)} \cdot T_{1/2} \cdot x$$

t: age since date of drilling, *s*: slope of the fit, *T½*: half-life of ^{210}Pb, *x*: depth in m w.e.



Gäggeler et al., JoG, 2020

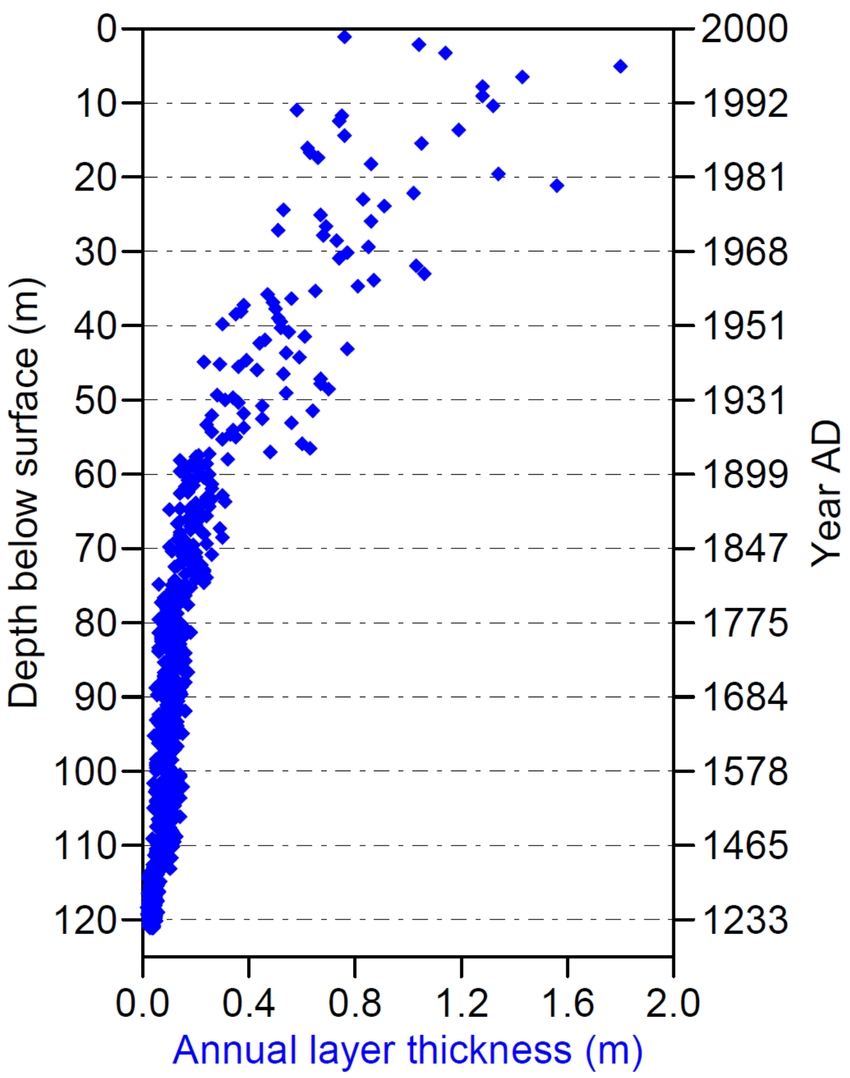
^{210}Pb activity concentration and derived age as a function of depth in an ice core from Belukha (4150 m asl).

Yields **age** and **mean annual net accumulation rate**…

- ➢ **…independent from other dating methods** (e.g. annual layer counting in ice cores)

Limitations of annual layer counting

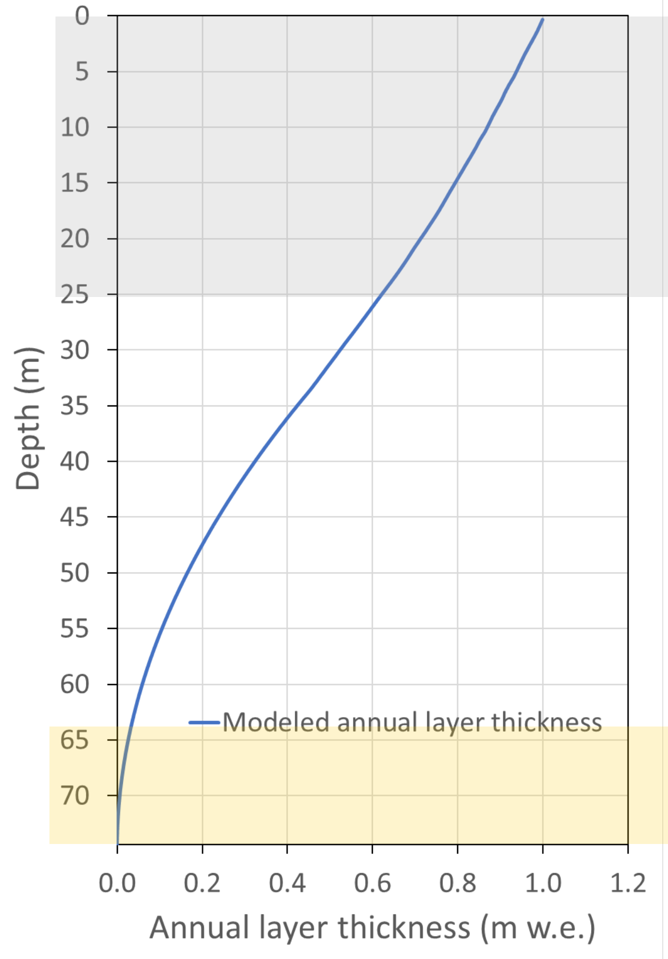
Annual layer thinning with depth

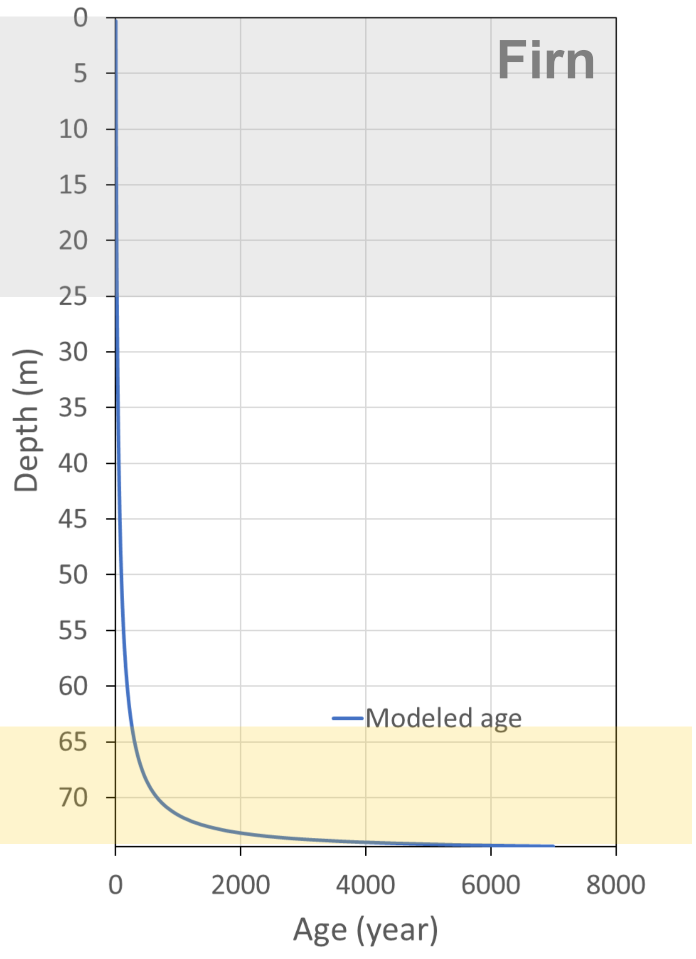


M. Schwikowski, A. Eichler, T.M. Jenk, I. Mariani, Past Global Changes Magazine 2014

Limitations of annual layer counting

Thinning of annual layers

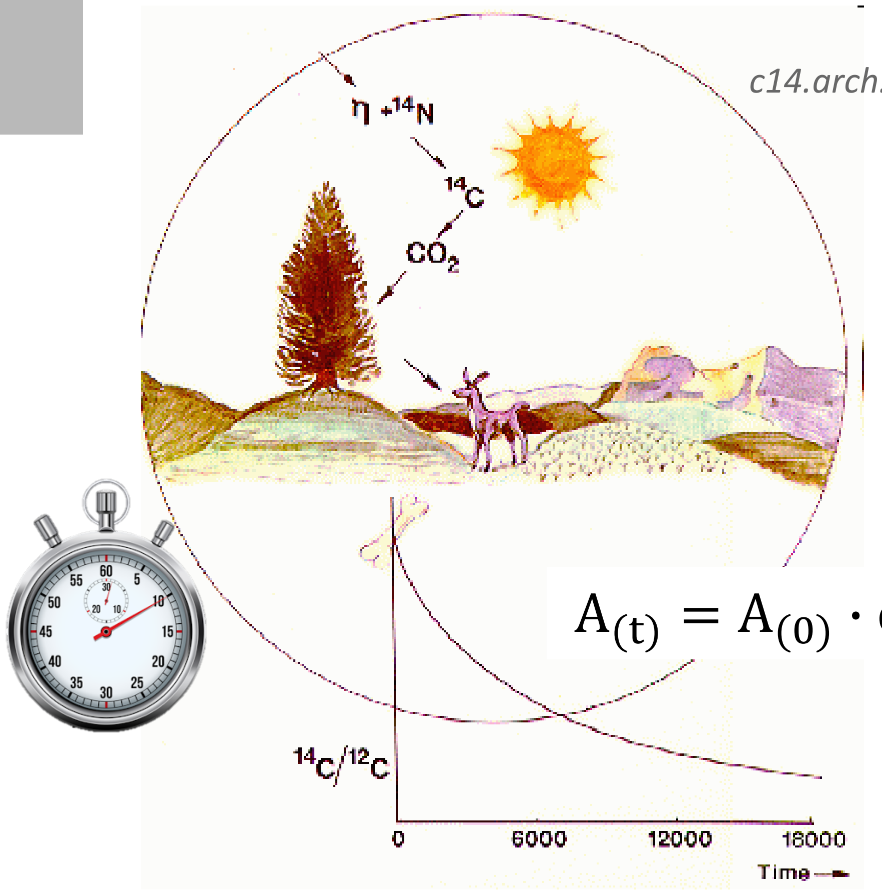




- Often around 95 % of the record in the lowermost ~10 % (for a cold site with ice frozen to bed)
- Loss of sub-annual resolution – annual layer counting based on seasonal variations thus impossible
- ^{210}Pb back to around 150 years.

→ **How can we date this?**

Radiocarbon (^{14}C) - dating



c14.arch.ox.ac.uk

$$A_{(t)} = A_{(0)} \cdot e^{-\lambda t}$$

- Half-life of 5730 years
- Permanently produced by (n-p) reaction of thermal neutrons with ^{14}N in the atmosphere (due to cosmic radiation)
- ^{14}C eventually oxidized to $^{14}CO_2$ and entering the carbon cycle → incorporated in living organisms
- Once the organism dies, the clock starts to tick (radioactive decay)

^{14}C dating (radiocarbon dating)

Unfortunately, ice contains carbon only in trace amounts

CO_2 in air bubbles

In-situ ^{14}C formation

Insect fragments, plant debris

Extremely rare

Basic idea

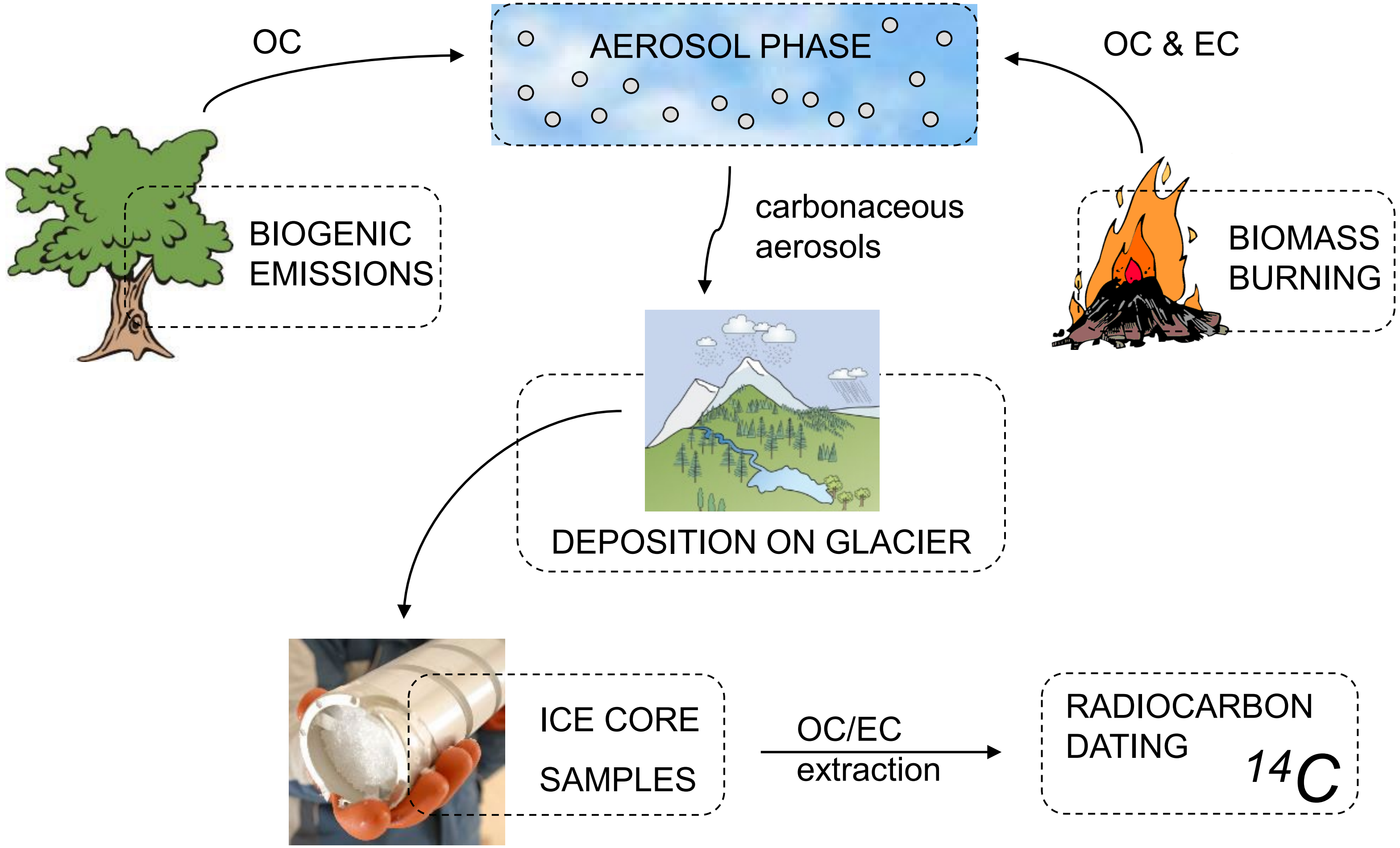


Figure from Zapf et al., 2013

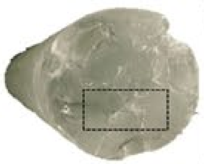
OC (organic carbon), hydrocarbons of low to medium molecular weight

EC (elemental carbon), highly polymerized hydrocarbons

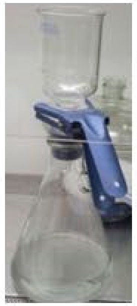
^{14}C dating of ice using carbonaceous particles

Analytical Method

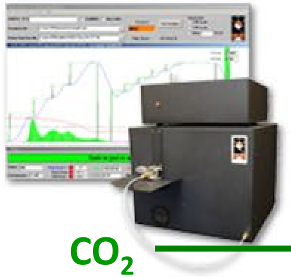
WIOC (water insoluble organic carbon)



Cutting & decontamination



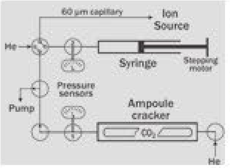
Filtration, acid treatment



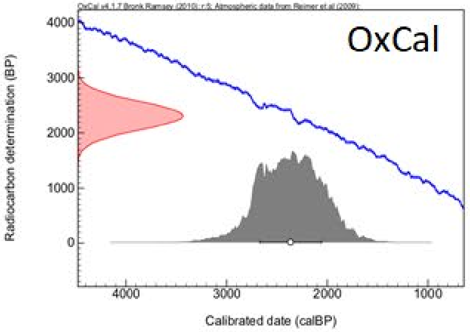
Controlled combustion - OC/EC separation

CO_2

Accelerator mass spectrometer (AMS)



Gas interface and ^{14}C-AMS

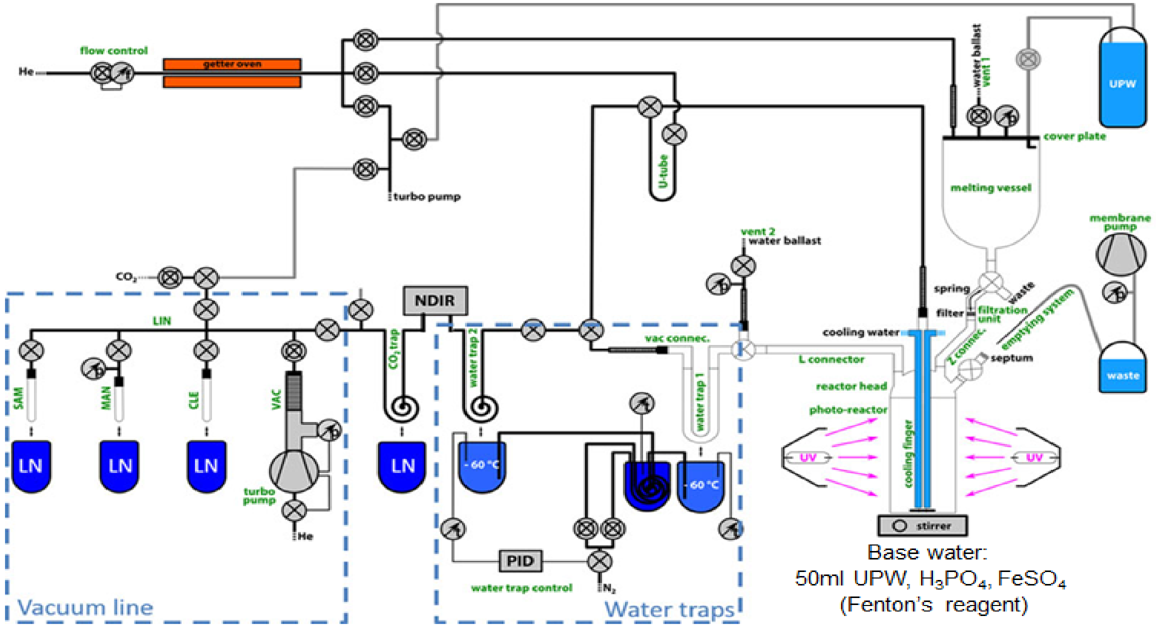


Evaluation & ^{14}C-calibration

Jenk et al., 2007
Uglietti et al., 2016

DOC (dissolved organic carbon)

CO_2

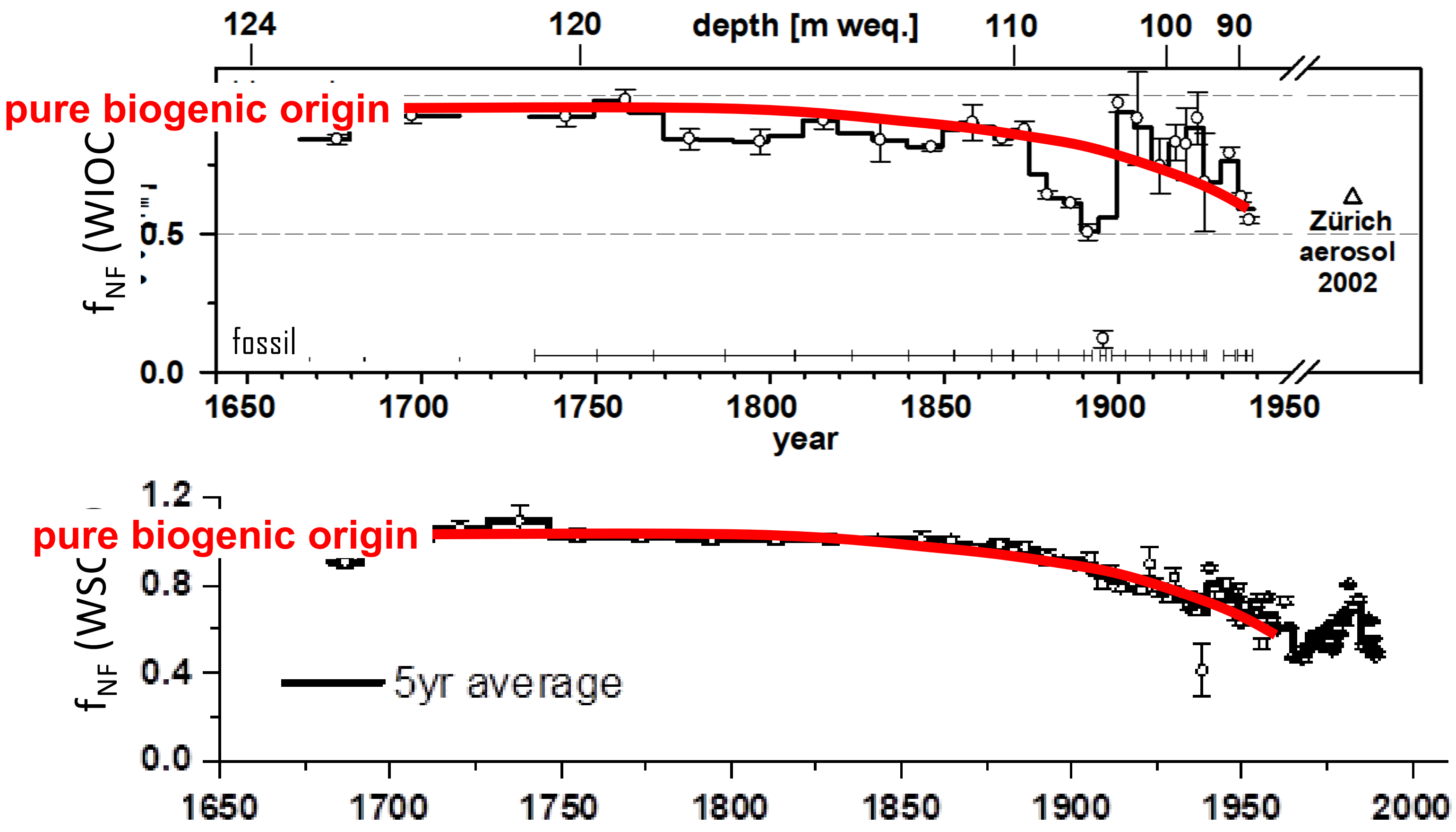


DOC extraction unit/ UV Oxidation

Fang et al., 2021

^{14}C dating of ice using organic carbon

In pre-industrial times of….

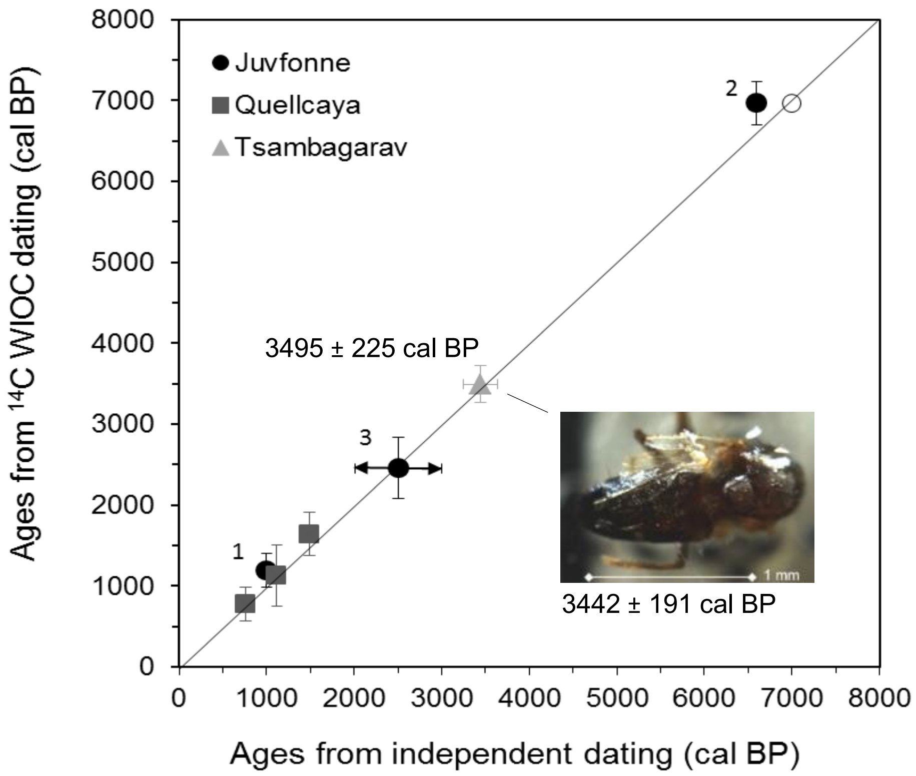


Jenk et al., ACP, 2006

Fang and Cao et al., ready for submission

Micro-Radiocarbon dating of Ice using OC (µg C amounts)

Direct comparison with independently dated ice.



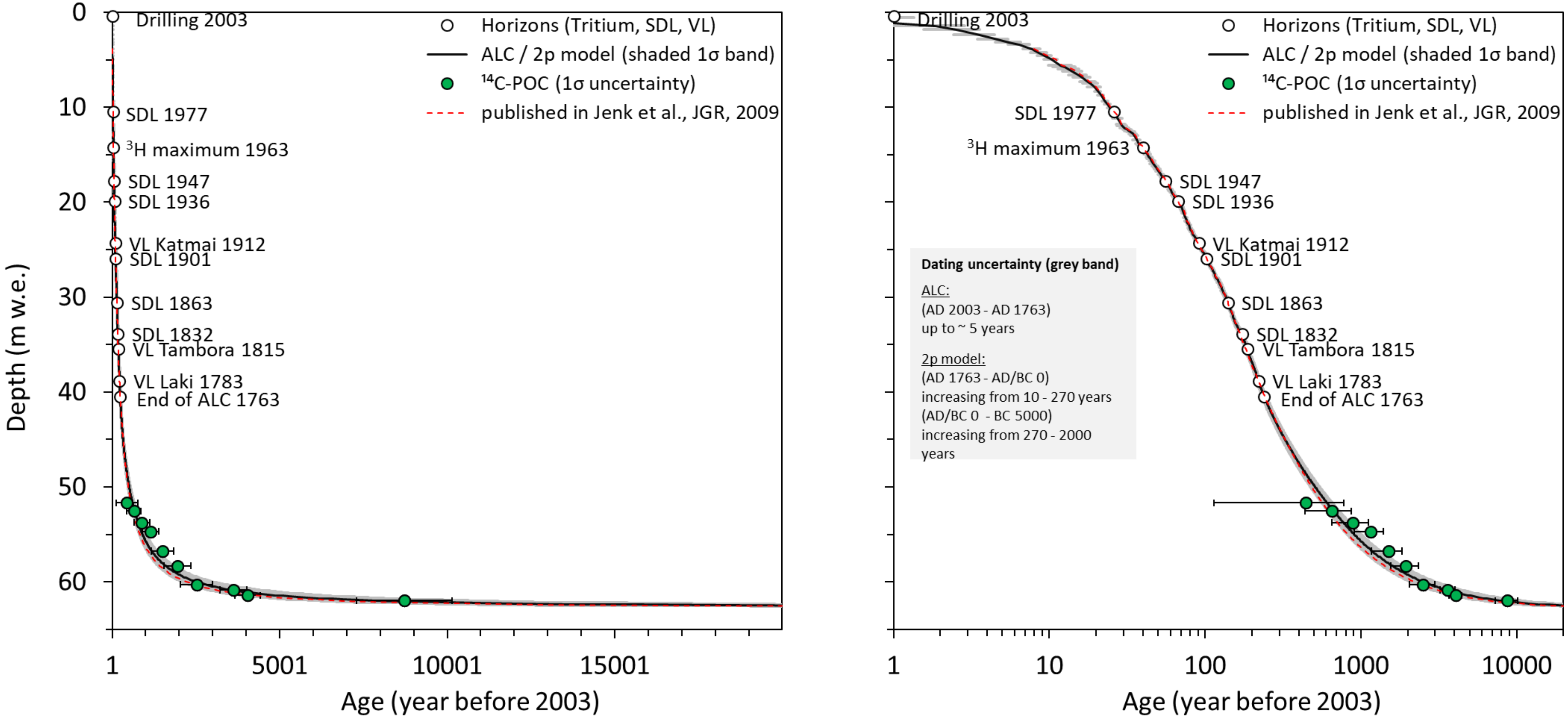
Continuous development of method and instrumentation over the past 20 years.

Uglietti et al., The Cryosphere, 2016

Dating of ice cores from alpine glaciers

Example final age-depth relationship: Dating of the Colle Gnifetti (CG03, Swiss Alps) ice core

➤ The oldest ice ever recovered in the Alps



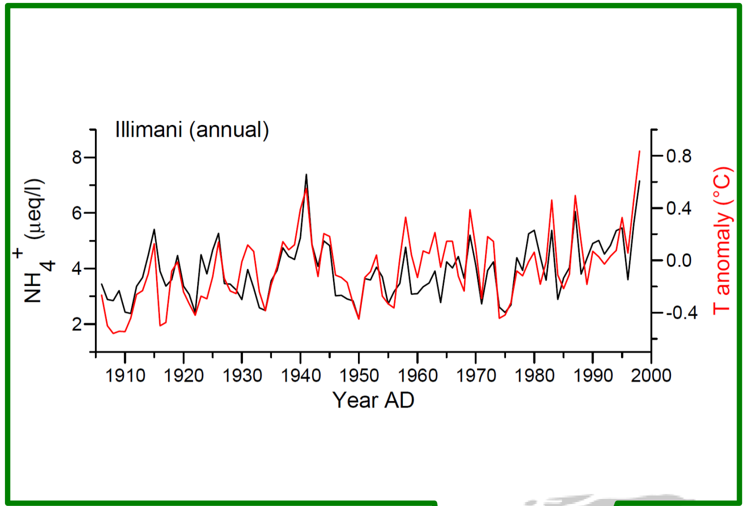
Adapted from Sigl et al., 2018

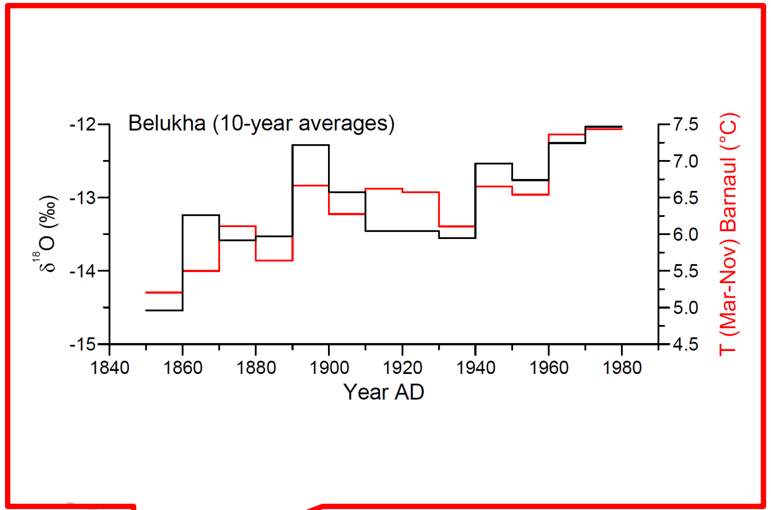
What we learned from high-alpine ice cores

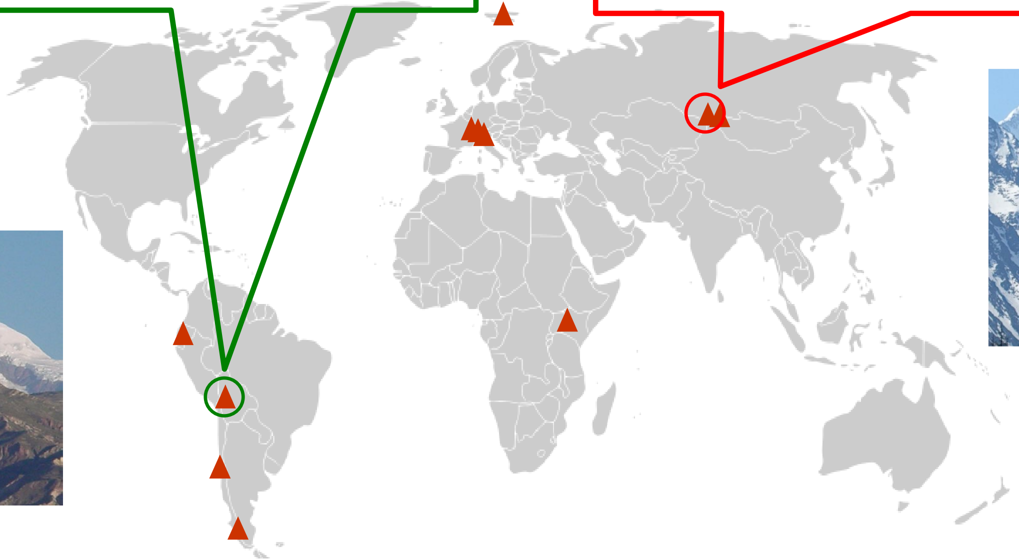
A small selection ...

Regional climate reconstructions

Calibration of ice core data for temperature reconstructions.





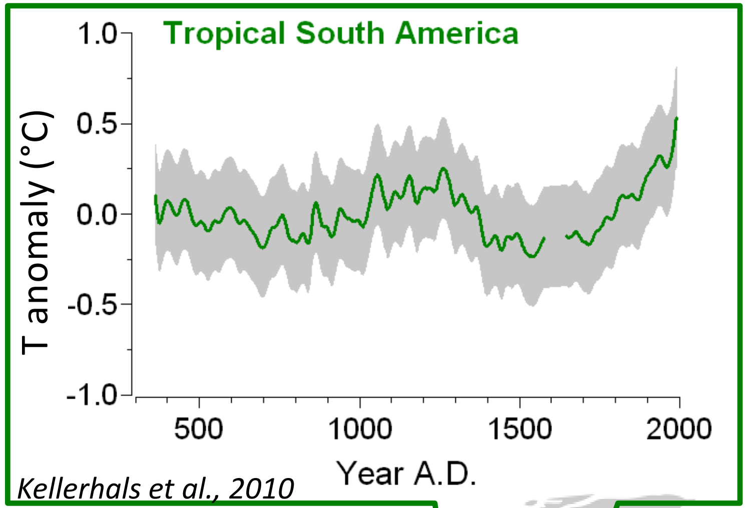


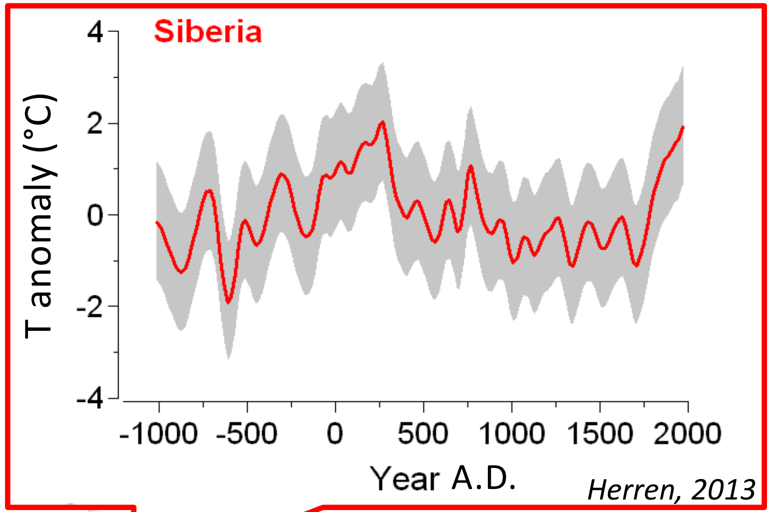
Illimani

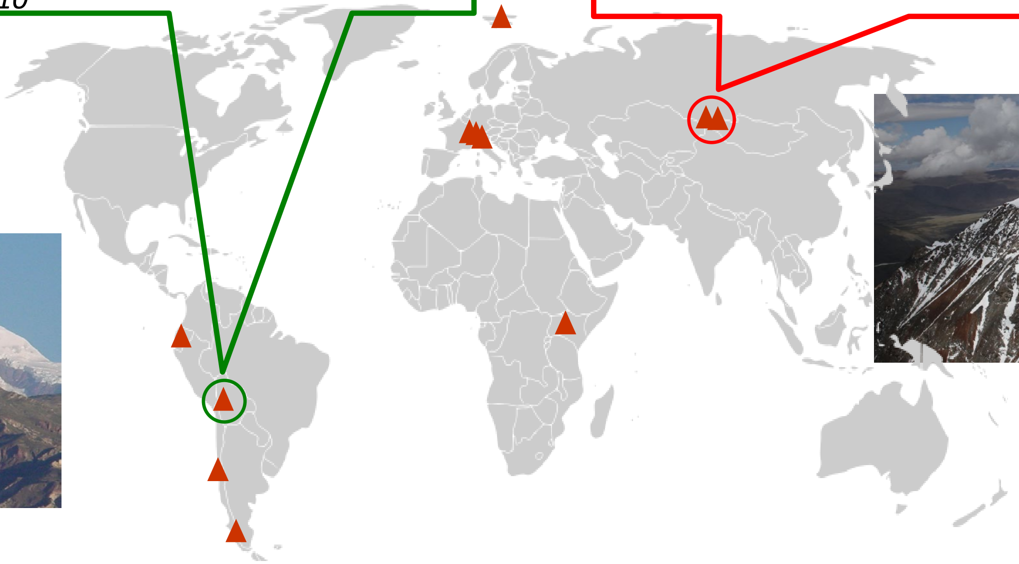
Belukha

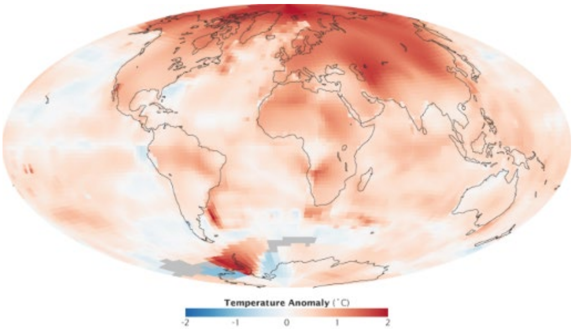
Schwikowski et al., Pages Newsletter, 2013

Regional developments of temperature.



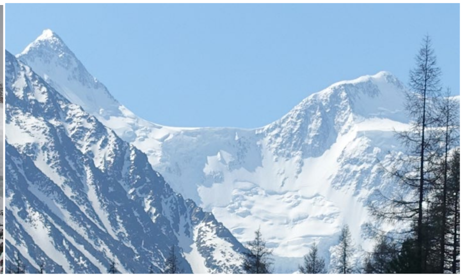






NASA GISS temperature trend 2000–2009

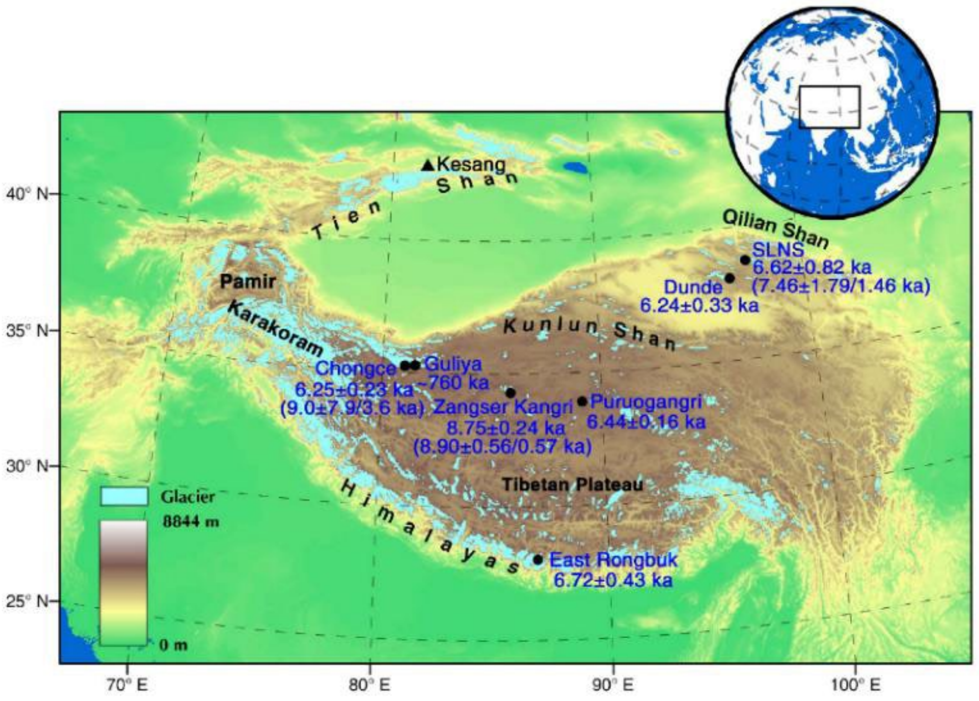
Illimani



Tsambagarav & Belukha

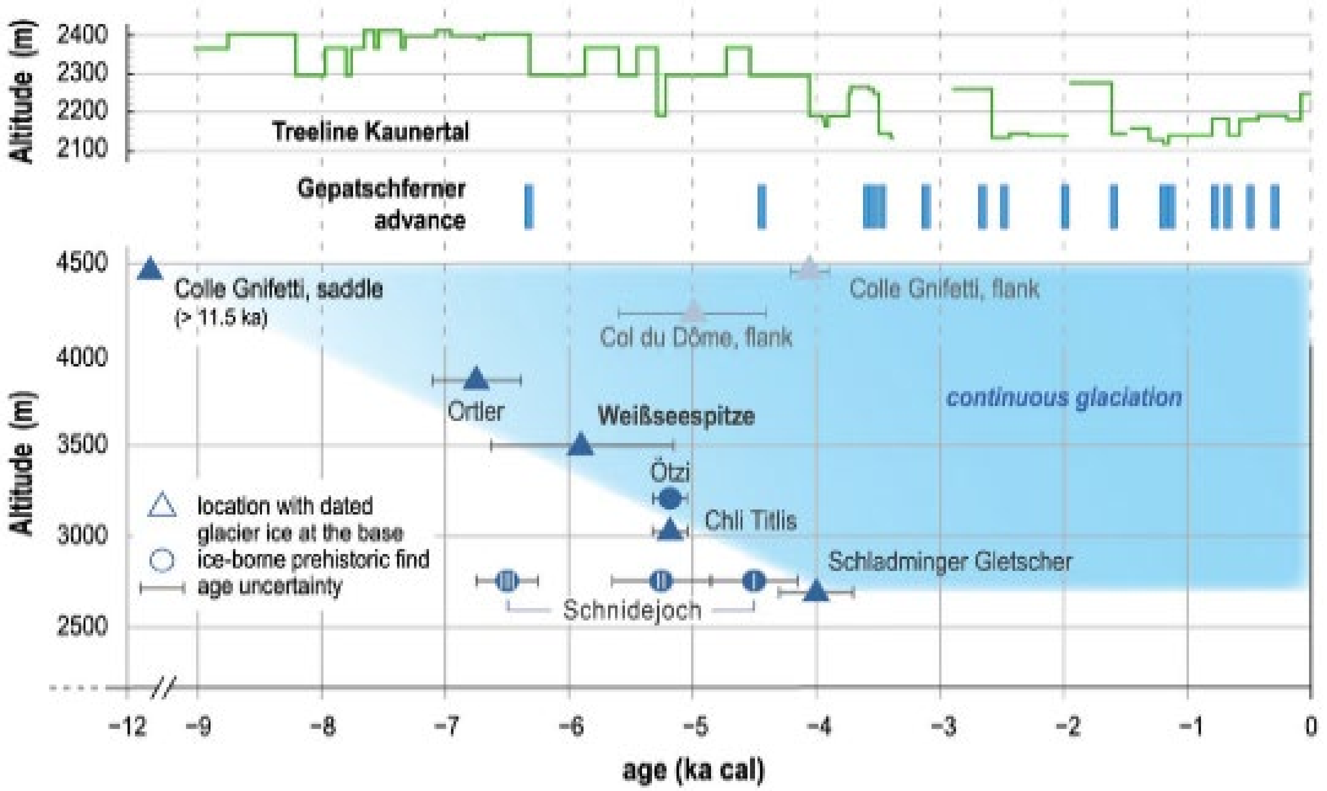
Holocene neoglaciation in Tibet and the Alps

Tibetan Plateau



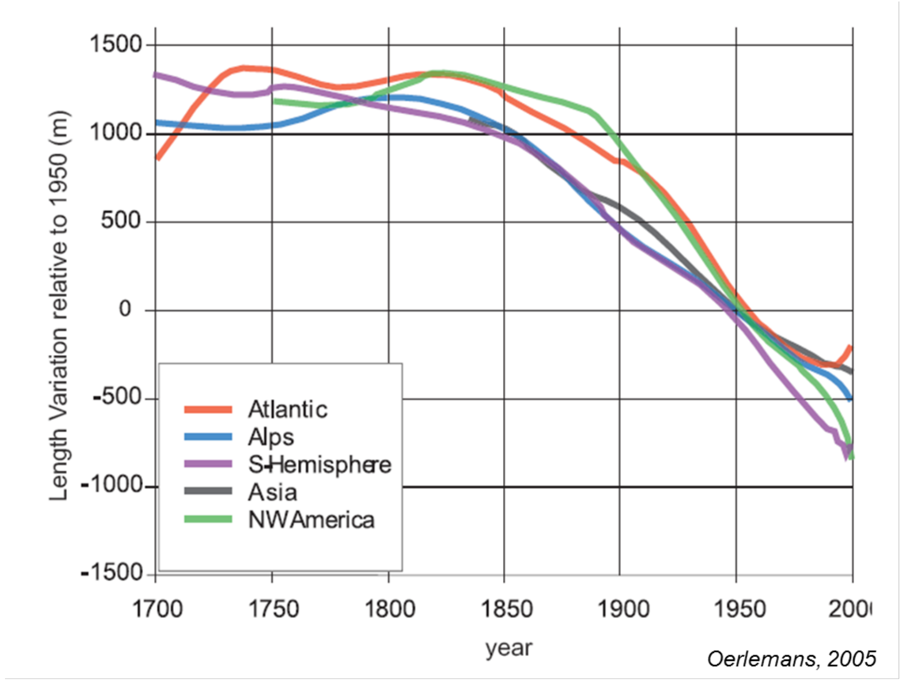
Hou et al., 2020

Alps



Bohleber et al., 2020

Recent fast retreat of high-altitude glaciers



Morteratsch glacier (Swiss Alps)

1985

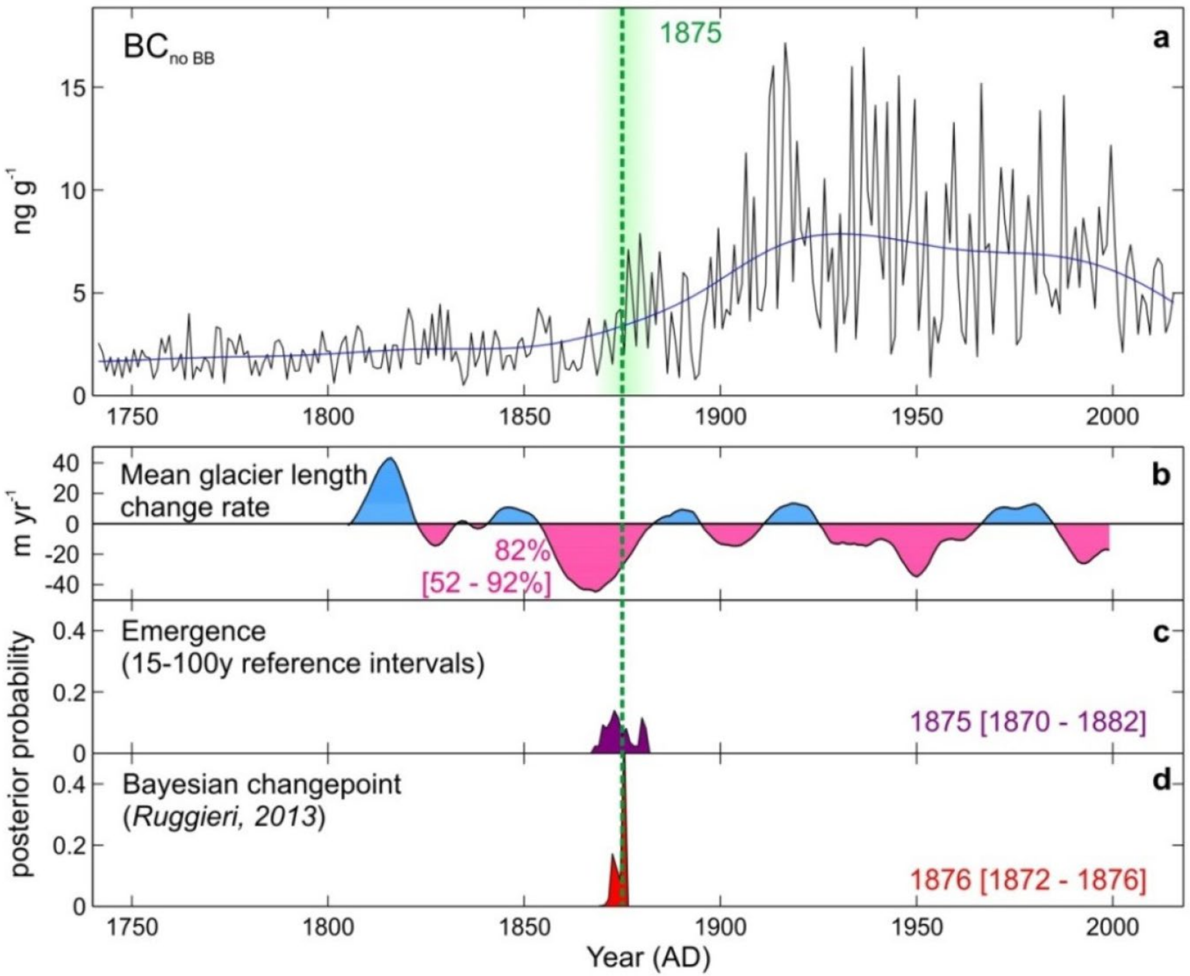
2007

2012

Fotos: J. Alean
www.swisseduc.ch

A record of black carbon (BC) from Colle Gnifetti, Swiss Alps

No role for industrial black carbon in forcing 19th century glacier retreat in the Alps.

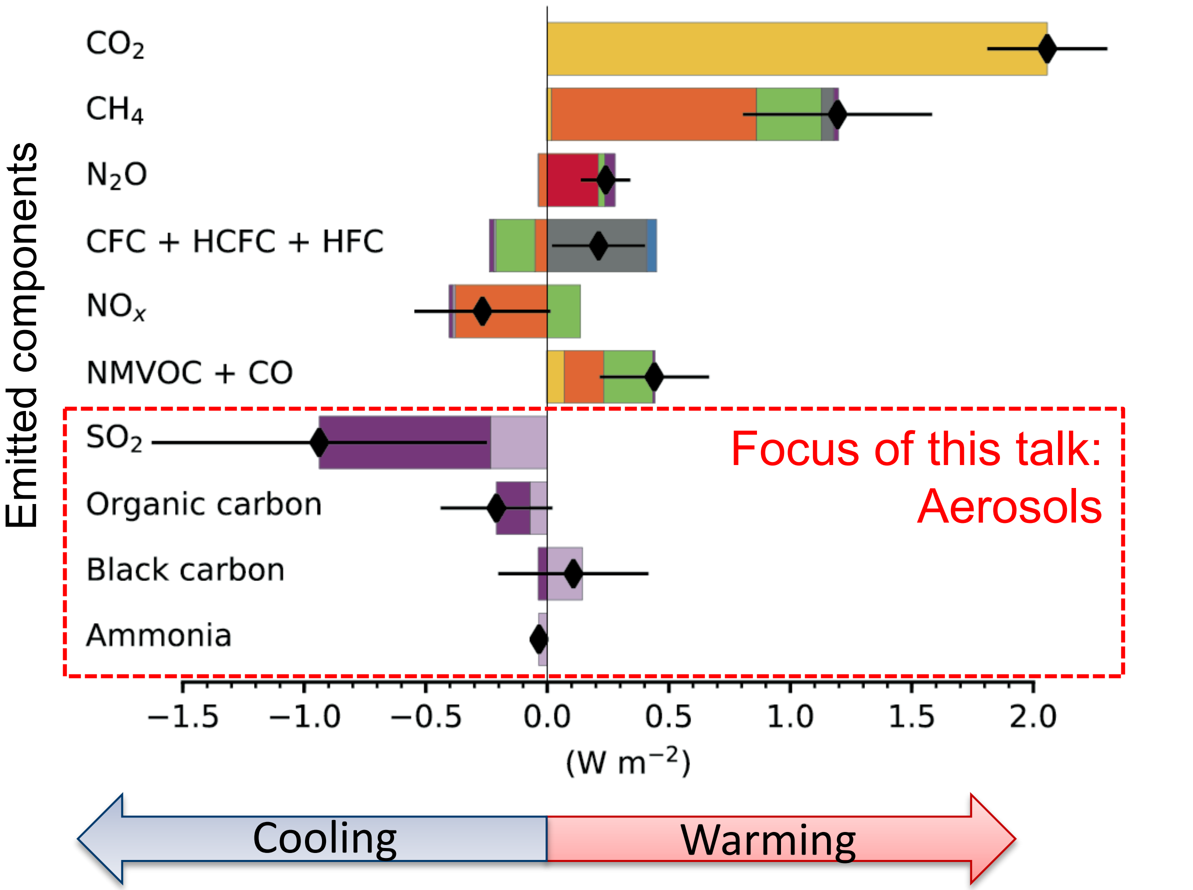


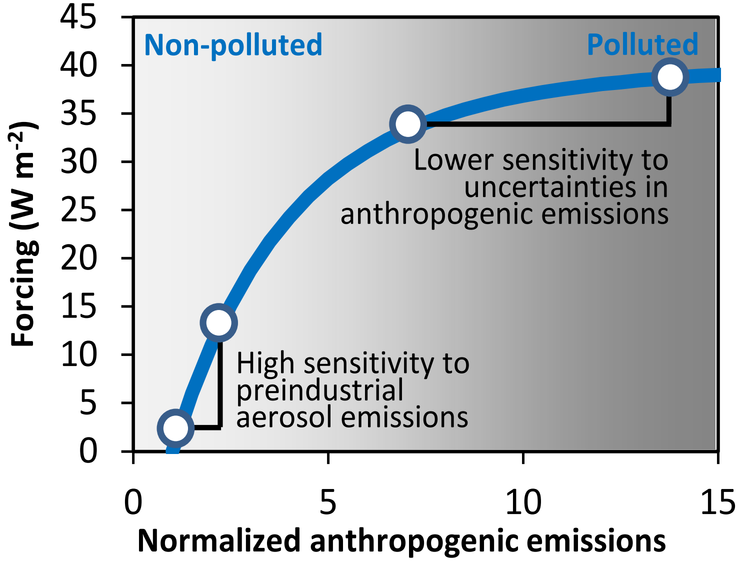
Sigl et al., TC, 2019

Atmospheric aerosol pollution – why do we care?

Impact of aerosols on climate remains poorly constrained.

Effective radiative forcing, 2019 relative to 1750 (pre-industrial)





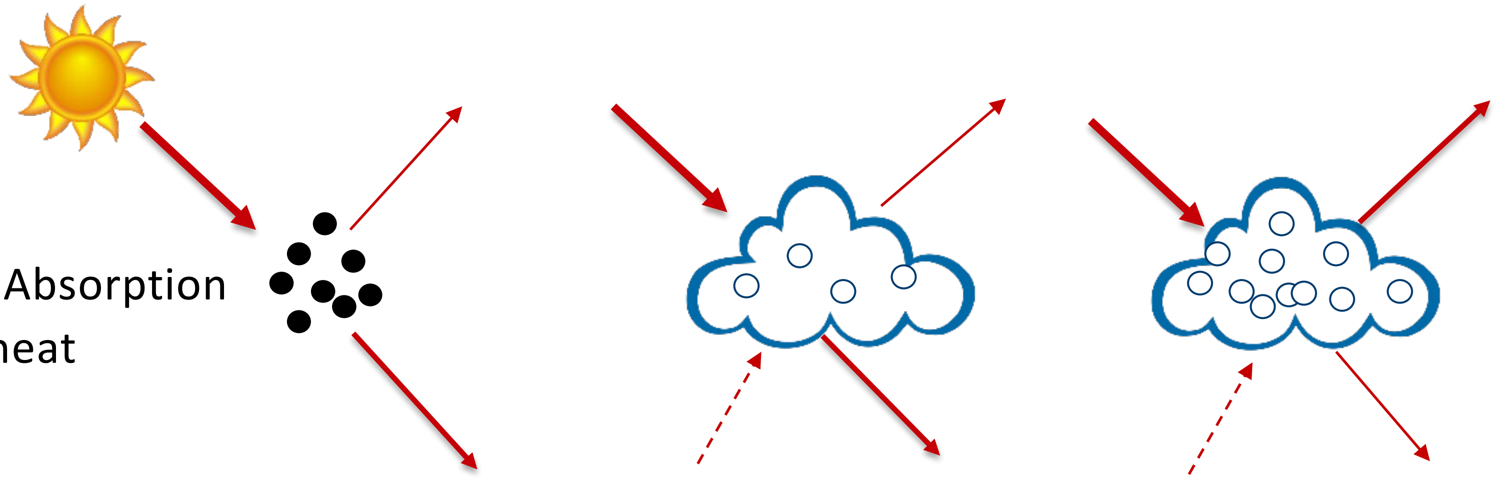
Carslaw et al., 2013

Intergovernmental Panel on Climate Change (IPCC) 2022

IPCC; WG1AR6, Chapter07

Aerosol climate effects

Scattering & Absorption
of radiative heat



Cloud albedo changes
by affecting cloud properties
(cloud condensation nuclei)

Direct effect

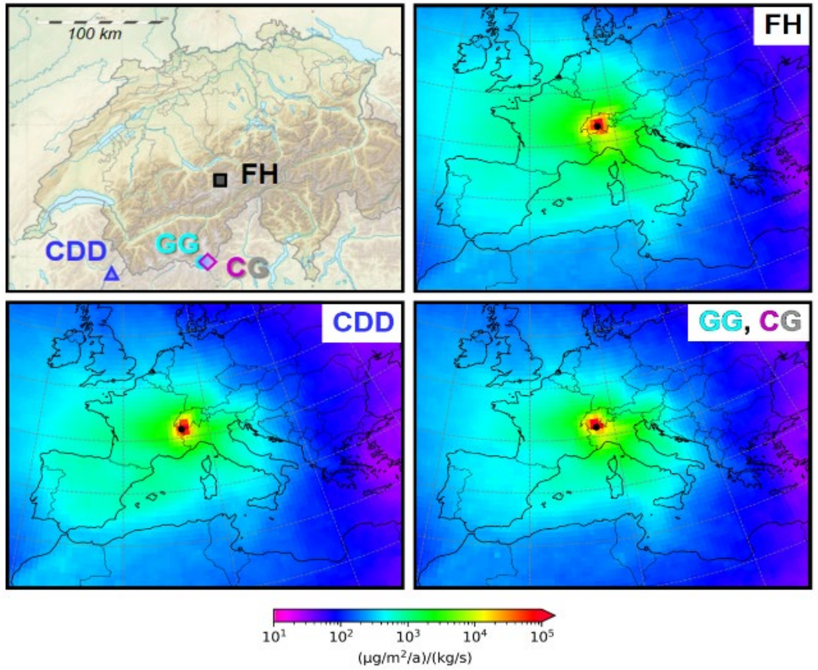
Indirect effect

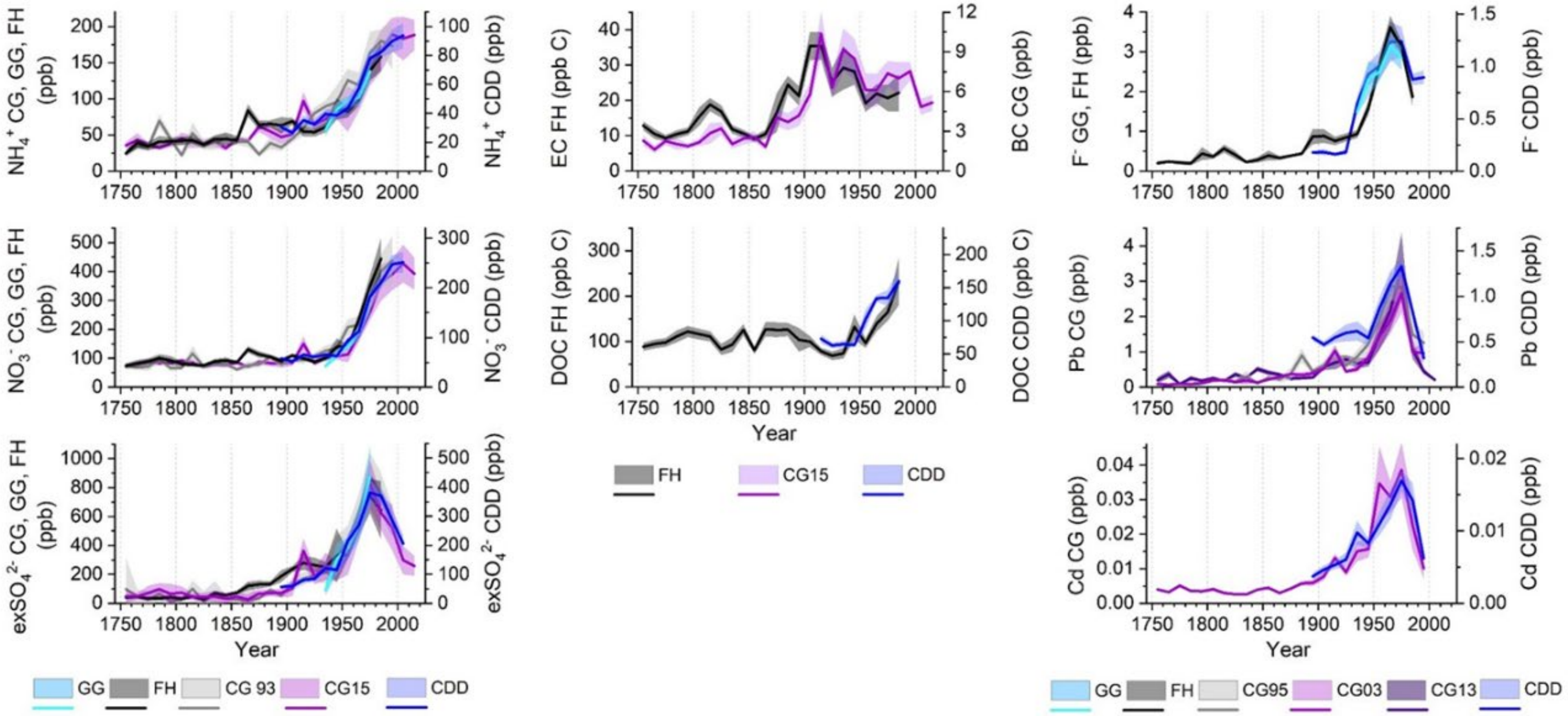
e.g. Kiehl and Briegleb, 1993; Maria et al., 2004; DeMott et al., 2010

European air pollution

(how representative is a record from one single ice core?)

- Four different glaciers: Col du Dôme (CDD), Colle Gnifetti (CG 2x +), Grenzgletscher (GG), Fiescherhorn (FH)
- Two different laboratories





Eichler et al., The Cryosphere, 2023

anthropogenic sources

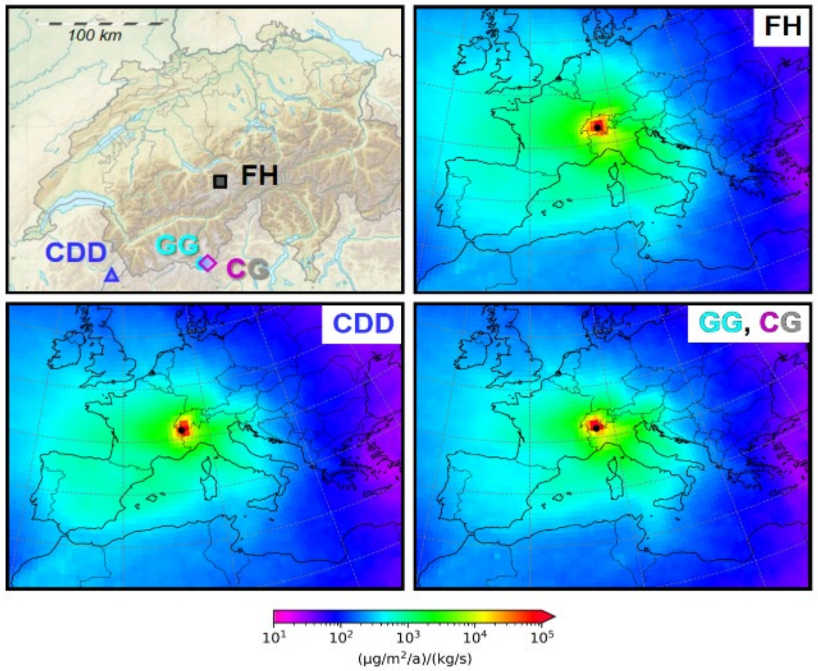
Ammonium – Fertilization (agriculture)
Nitrate – Traffic and Energy production
Sulphate – Fossil fuel combustion

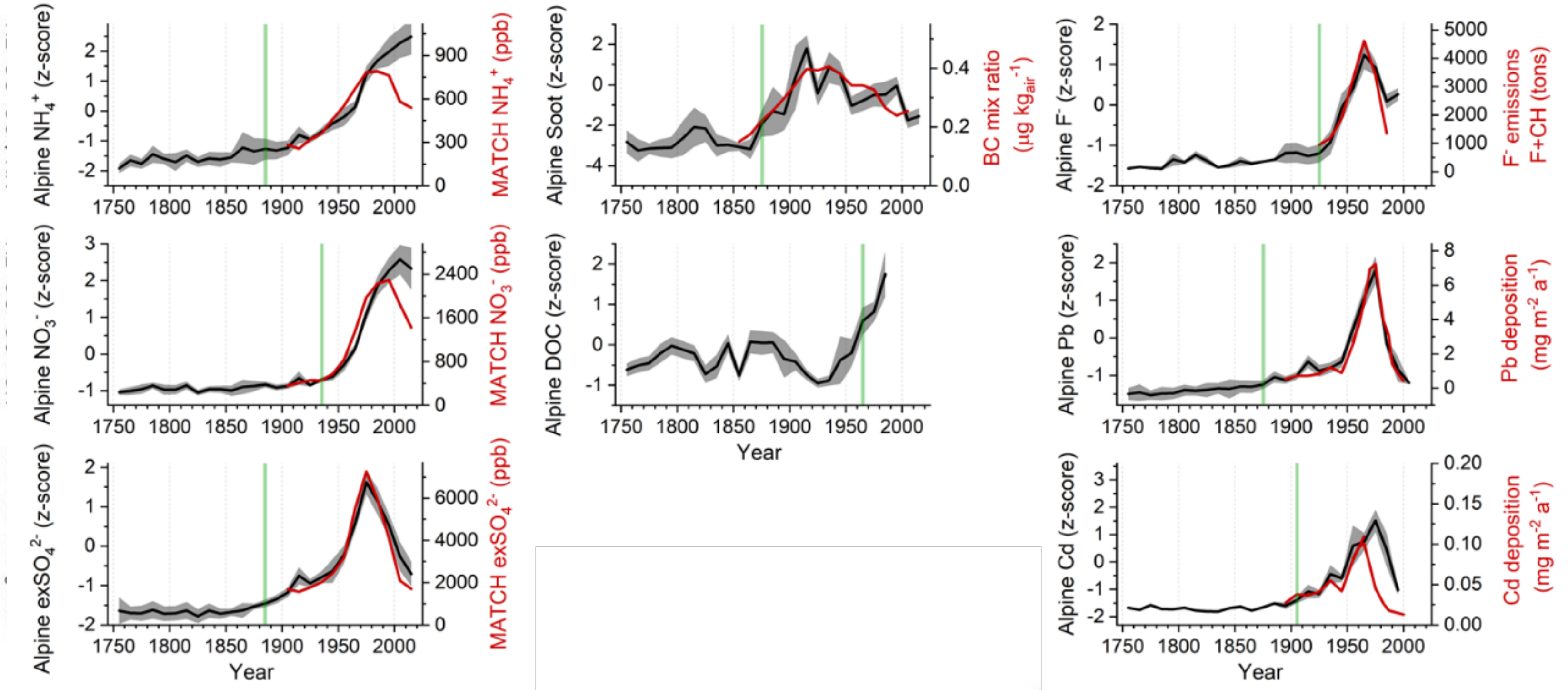
European air pollution

(agreement with bottom-up emission estimates)

- Composite of records from four different glaciers (z-score)

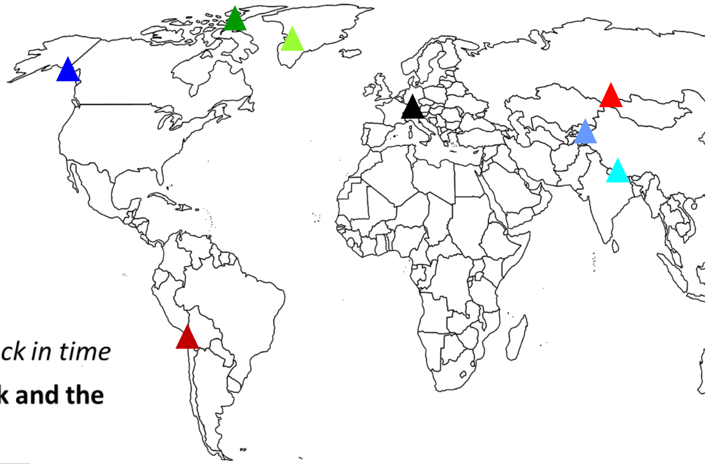
  …compared to estimated emissions from national reports of European OECD countries.





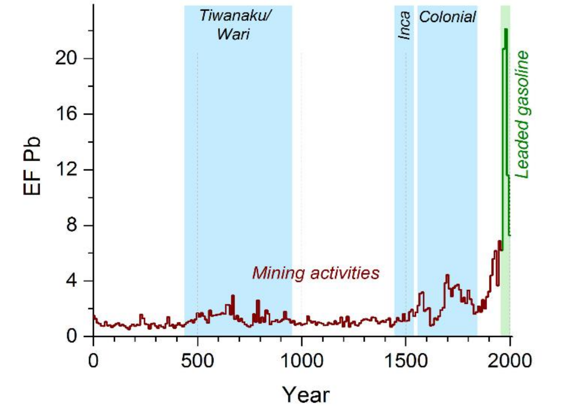
Eichler et al., The Cryosphere, 2023

Regional differences in the trends of lead (Pb)
Sources: mining, coal combustion, leaded gasoline

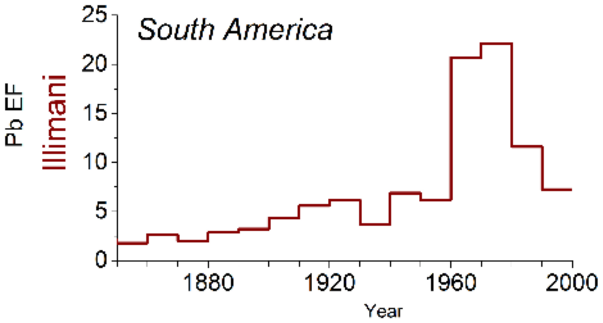


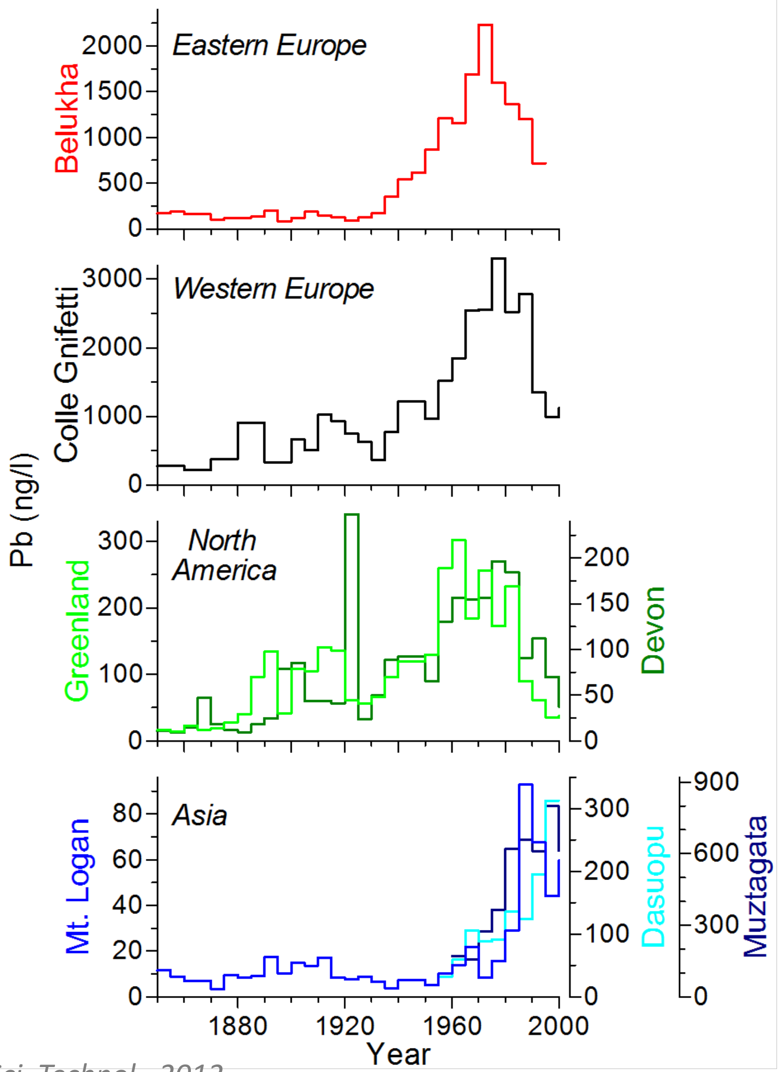
South America (Illimani) – record extended back in time

Early lead pollution, the leaded gasoline peak and the effect of "clean air" measures.



Eichler et al., Sci. Adv., 2015

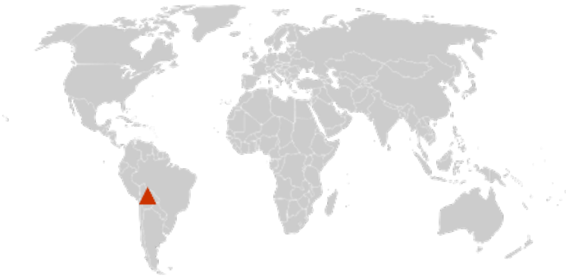




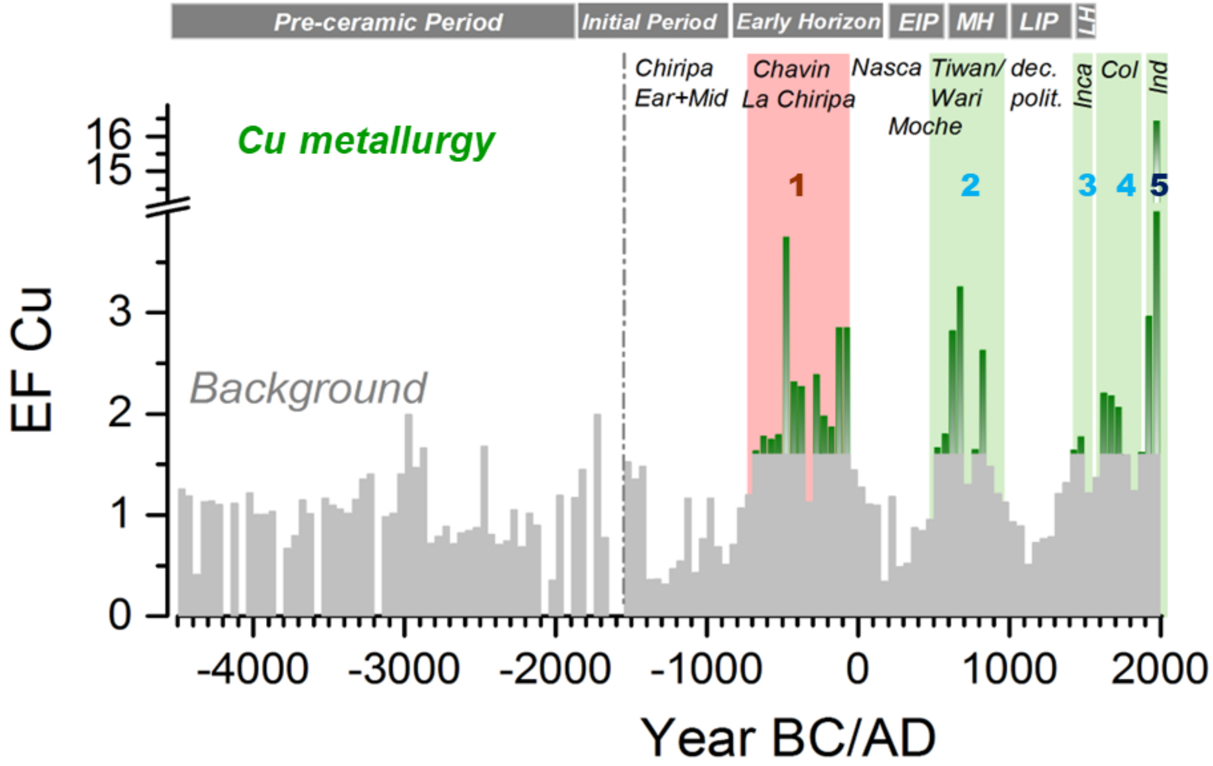
Eichler et al., Environ. Sci. Technol., 2012

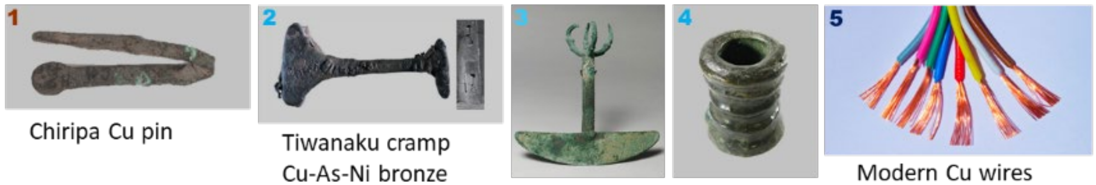
Human atmospheric pollution history

Earliest extensive Cu metallurgy in the Andes during Chavin and Chiripa Cultures, 2700 years ago.



South America (Bolivia), Illimani (Andes)





Chiripa Cu pin

Tiwanaku cramp Cu-As-Ni bronze

Inca tumi Sn bronze

Signal cannon Colonial bronze

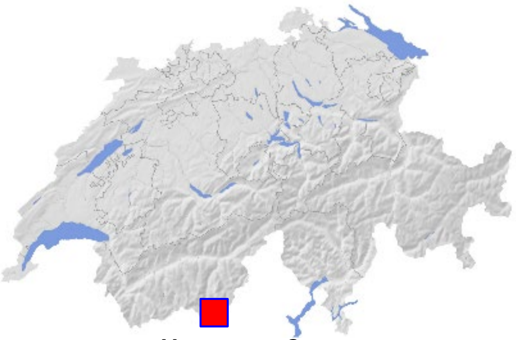
Modern Cu wires

Eichler et al., Nat. Sci. Rep., 2017

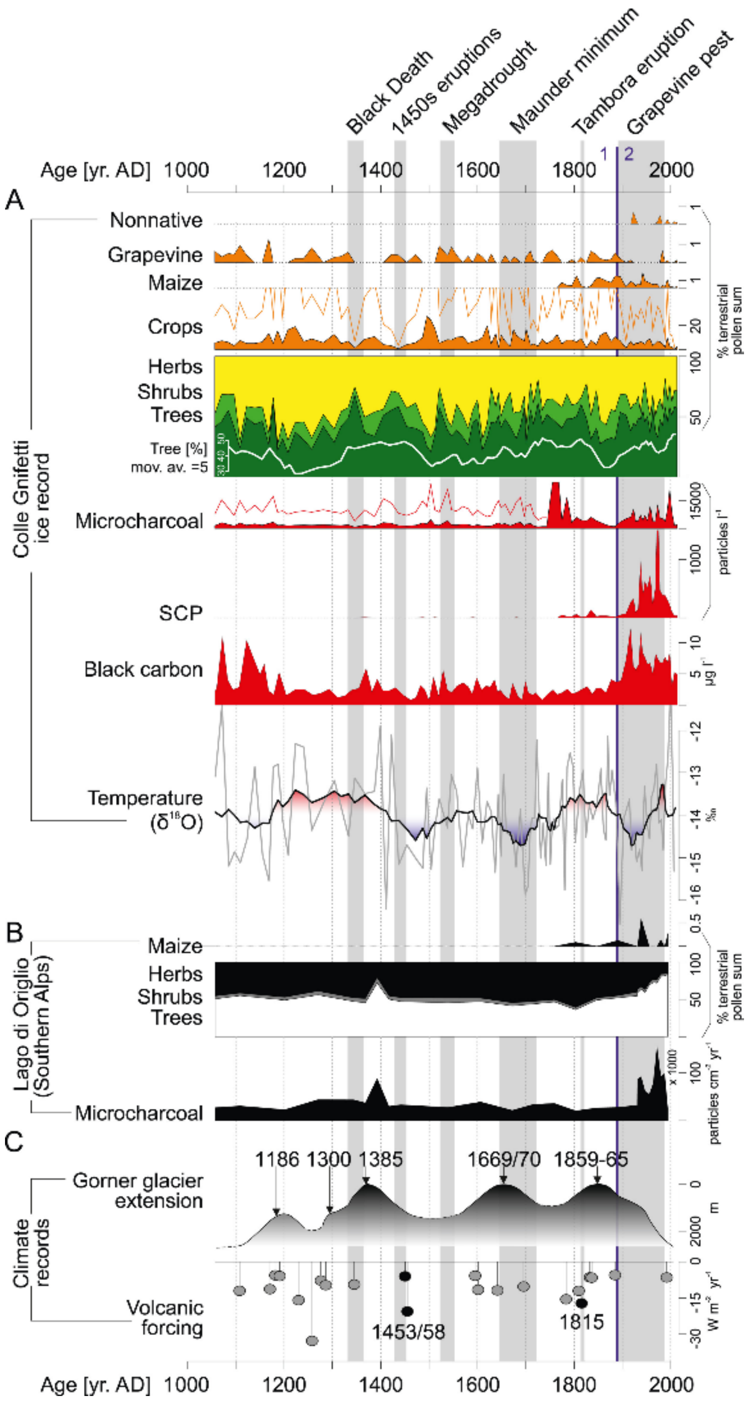
PAUL SCHERRER INSTITUT PSI

Interaction of climate and societies and the responses of ecosystems - the last millennium

“Europe’s Triumphs and Troubles Are Written in Swiss Ice“
(17.9.2018) The New York Times



Colle Gnifetti



Brugger et al., Geophysical Research Letters, 2021

HUMAN HISTORY

Outlook

- **Organics in ice** (non-target screening of the thousands of different organic molecules)

  SNF project, M Schwikowski; close collaboration with LAC-PSI

- **European Alps: Minimal glacier extent during the Holocene warm period** (the last ~10 kyrs)

  SNF project, TM Jenk

- **Ancient DNA (aDNA) in ice**

  in collaboration with the Globe Institute, University of Copenhagen, Denmark

The future of high-alpine glaciers

An endangered heritage - Aletschgletcher (Switzerland)

swisseduc.ch

swisseduc.ch

Predicted by 2100

Lenght: -80%

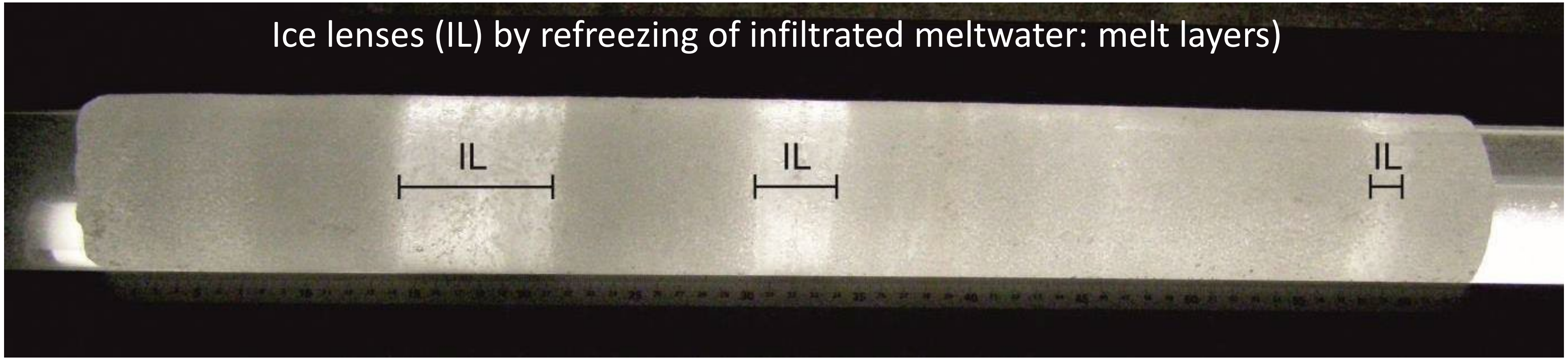
Area: -50%

Volume: -75%

relative to 2017 under RCP4.5 climate scenario

Modified picture based on simulations from Jouvet and Huss, 2019 (RCP 4.5 scenario)

The *book* is melting

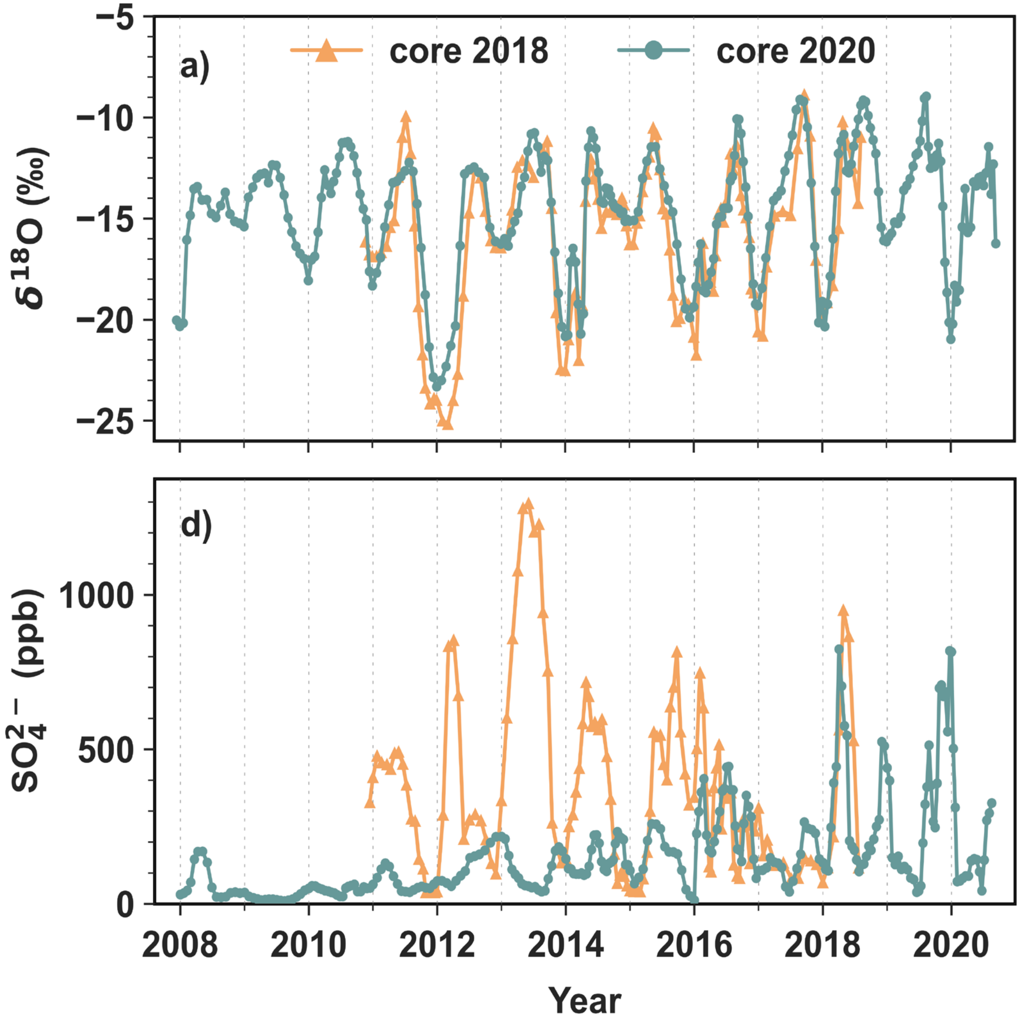


The *book* is melting fast – loss of recorded proxy signal

Signal in an ice core drilled in 2018 and 2020, respectively - Grand Combin, Switzerland (4200 m asl.)

$\delta^{18}O$

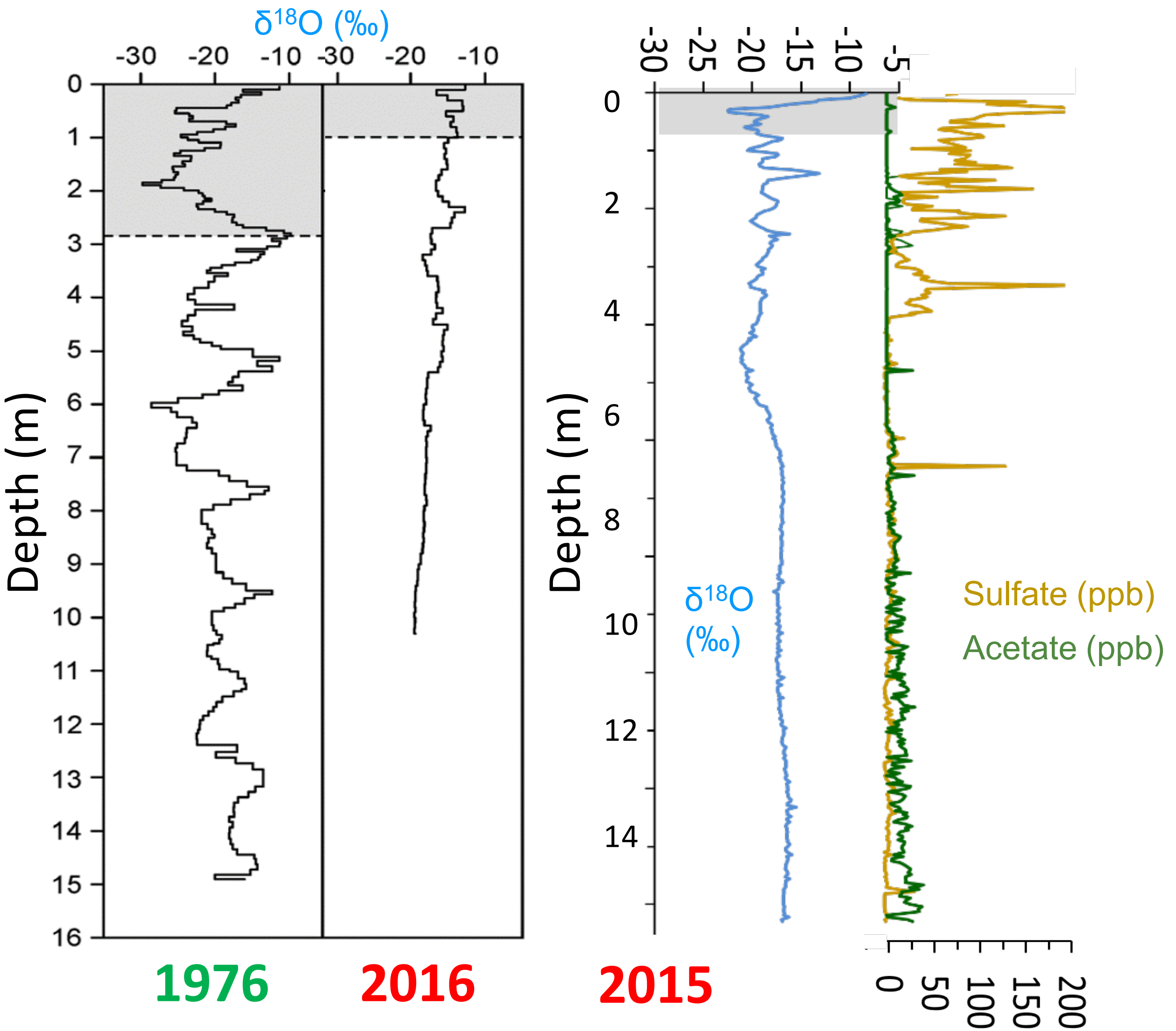
Sulfate



Huber et al., Science Communication, 2023

The *book* is melting fast – loss of recorded proxy signal

Quelccaya ice cap, Peru (5670 m asl.)



Thompson et al., JGR, 2017 *PSI core, Jenk, unpublished*

ICE MEMORY – international initiative

1. **Collect ice cores** from selected glaciers of scientific and cultural interest and still **mostly unaffected by melting**

2. **Analyze the ice cores** for present and future scientists as well as build an **open database for today and tomorrow** *(reference core)*

3. Donation to humanity: **heritage core to be studied by the next generation of scientists**

4. **Long term storage in Antarctica** under ICE MEMORY governance

5. Educate and train young researchers

Thank you for your attention

PSI - LUC (Laboratory of Environmental Chemistry)