Frozen chemistry:
Glaciers as archives of past environmental conditions
Mean annual temperature in Switzerland 1871-2022

Annual temperature – Switzerland – 1864-2022
departure from the mean 1961-1990

© MeteoSwiss
Glacier elevation change between 2000 and 2019 (Satellite data)

Hugonnet et al., 2021
800,000 years of temperature and CO₂

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
• **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

Ice cores allow to reconstruct

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

Raynaud et al., Paleoclimatology and Climate Change, 2020

Water - H₂O
(H₂¹⁶O, H₂¹⁸O, HDO)

Air
gases in air bubbles
(CO₂, ¹³CO₂, CH₄, ....)

Impurities
dust, sea salt, emissions from the biosphere, trace element pollution, volcanism,...
Ice on earth

**INTRODUCTION**

### Polar ice shields
- Global/Hemispheric signal

### High-alpine glaciers
- Closer to populated regions
- Closer to emission sources
- Local/regional signal

<table>
<thead>
<tr>
<th>Region</th>
<th>Ice volume (km³)</th>
<th>Instantaneous sea level rise (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaciers</td>
<td>180'000</td>
<td>0.45</td>
</tr>
<tr>
<td>Greenland</td>
<td>2'620'000</td>
<td>6.55</td>
</tr>
<tr>
<td>Antarctica</td>
<td>30'109'800</td>
<td>73.44</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>32'909'800</strong></td>
<td><strong>80.44</strong></td>
</tr>
</tbody>
</table>

*Image - https://earthobservatory.nasa.gov/images/83918/the-randolph-glacier-inventory/*
### Ice archives - alpine versus polar

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

**Δ thickness**  
**Δ accessible timescale**

*High-alpine glaciers*  
*Polar ice shields*
Alpine glaciers as natural archives

W.F. Ruddiman, *Earth’s Climate*
Alpine glaciers as natural archives

INTRODUCTION
INTRODUCTION

Population density

High alpine ice core locations

Proximity to emission sources

- allows investigation of short-lived atmospheric species.

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

High alpine ice core drill sites

PSI projects
Regional expression of climate change

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

High alpine ice core drill sites

IPCC, 2007
Ice core drilling on high-alpine glaciers

Colle Gniffeti, Switzerland (4450 m asl.)

Mercedario, Argentina (6100 m asl.)

Tsambagarav, Mongolia (4100 m asl.)

Illimani, Bolivia (6300 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.
Drilling equipment – lightweight, modular design

FELICS

Fast Electromechanical Lightweight Ice Coring System – deep drilling

Ginot et al., 2002
Drilling equipment – lightweight, modular design

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

FELICS
Fast Electromechanical Lightweight Ice Coring System – deep drilling

FELICS Thermal
for temperate ice conditions (warm & wet)

Melthead heated by hotspring coil heater

Ginot et al., 2002

Schwikowski et al., AoG, 2014
Ice core drilling at high altitudes

Intermediate Camp 5400 m asl., Illimani, Bolivia
Belukha drilling camp

© PSI - Theo Jenk
Analytical methods - from the ice core to the sample

- δ\(^{18}\)O
- \(\text{^{210}Pb}\) α-spectroscopy
- Cavity ring-down spectroscopy
- Soot (BC)
- Laser photometry SP2
- Accelerator mass spectrometry
- Cold room (-20 °C)
- Sampling resolution: 1 – 140 cm
- Trace element analysis
- CIM SF-ICP-MS
- (NH\(_4\)^+, Ca\(^{2+}\), SO\(_4^{2-}\), NO\(_3^{-}\)...)
Dating of ice cores from high-alpine glaciers

Annual layer counting (seasonality of signal)

Fiescherhorn (CH)
$\delta^{18}O$

Grenzgletscher (CH)

Black carbon
Illimani, Bolivia

$T_{JUN}$
$T_{GEB}$

warm
cold

Temperature

high concentration $\rightarrow$ summer

low concentration $\rightarrow$ winter

Mariani et al., 2014

Osmont et al., 2018

DATING 20
Dating of ice cores from high-alpine glaciers

Annual layer counting (seasonality of signal)

[Graph showing annual layer counting with seasonality of signal]
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

Ex-sulfate [μeq./L]

Tambora
1815

Krakatau
1883

Katmai
1912

Age [y]

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

$^{210}\text{Pb}$: half-life ($T_{1/2}$)* = 22.3 years
- environmental radionuclide
- member of the natural U / Th decay series ($^{238}\text{U}$)
- dating of lake sediments, peat bogs & ice cores
- dating range: present to around 150 years

NOTE:

$^{238}\text{U}$ (1.7 ppm) $>>$ $^{238}\text{U}$ (3 ppb)

$^{222}\text{Rn}$ (3.8 d) $\rightarrow$ $^{210}\text{Pb}$

*half-life ($T_{1/2}$): time after which 50% of $A_0$ has decayed
$t = \frac{-s}{\ln(2)} \cdot T_{1/2} \cdot x$

$t$: age since date of drilling, $s$: slope of the fit, $T_{1/2}$: half-life of $^{210}$Pb, $x$: depth in m w.e.

$^{210}$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)

Gäggeler et al., JoG, 2020
Limitations of annual layer counting

**Annual layer thinning with depth**

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

- 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)

\[ A(t) = A(0) \cdot e^{-\lambda t} \]
Unfortunately, ice contains carbon only in trace amounts.

CO₂ in air bubbles  In-situ ¹⁴C formation

Insect fragments, plant debris  Extremely rare
**Basic idea**

- **OC** (organic carbon), hydrocarbons of low to medium molecular weight
- **EC** (elemental carbon), highly polymerized hydrocarbons

**OC** & **EC**

**AEROSOL PHASE**

- **BIOGENIC EMISSIONS**
- **BIOMASS BURNING**

**DEPOSITION ON GLACIER**

**ICE CORE SAMPLES**

**OC/EC extraction**

**RADIOCARBON DATING**

Figure from Zapf et al., 2013
14C dating of ice using carbonaceous particles

**Analytical Method**

**WIOC (water insoluble organic carbon)**
- Cutting & decontamination
- Filtration, acid treatment

**DOC (dissolved organic carbon)**
- Controlled combustion - OC/EC separation

**Accelerator mass spectrometer (AMS)**
- Gas interface and 14C-AMS

**Evaluation & 14C-calibration**
- Jenk et al., 2007
- Uglietti et al., 2016

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**CO2**

**DOC extraction unit/ UV Oxidation**
- Fang et al., 2021
In pre-industrial times of...
Direct comparison with independently dated ice.

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

Uglietti et al., The Cryosphere, 2016
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.

Schwikowski et al., Pages Newsletter, 2013
Regional developments of temperature.

Tropical South America

Siberia

Kellerhals et al., 2010

Herren, 2013

Illimani

Results
Holocene neoglacialation in Tibet and the Alps

Tibetan Plateau

Alps

Hou et al., 2020
Bohleber et al., 2020
Recent fast retreat of high-altitude glaciers

Morteratsch glacier (Swiss Alps)

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

Sigl et al., TC, 2019
Impact of aerosols on climate remains poorly constrained.

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

Focus of this talk: Aerosols

Intergovernmental Panel on Climate Change (IPCC) 2022
IPCC; WG1AR6, Chapter07
Aerosol climate effects

Scattering & Absorption of radiative heat

Direct effect

Indirect effect

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

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

**Anthropogenic sources**
- Ammonium – Fertilization (agriculture)
- Nitrate – Traffic and Energy production
- Sulphate – Fossil fuel combustion

_Eichler et al., The Cryosphere, 2023_
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.

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

Human atmospheric pollution history

South America (Bolivia), Illimani (Andes)

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)

Colle Gnifetti

Brugger et al., Geophysical Research Letters, 2021
• **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 - Aletschgletscher (Switzerland)

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)
Ice lenses (IL) by refreezing of infiltrated meltwater: melt layers

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.
ICE MEMORY – international initiative

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

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

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

Long term storage in Antarctica under ICE MEMORY governance

Educate and train young researchers
Thank you for your attention

PSI - LUC (Laboratory of Environmental Chemistry)