Photo: IPEV

Science at the poles — An ice core illustration

Prof. Jérôme CHAPPELLAZ

EPFL-ENAC-IIE-SENSE

Ferring Pharmaceuticals Margaretha Kamprad Chair in environmental sciences

FERRING PHARMACEUTICALS

Photo: Sarah del Ben

A brief personal introduction

- Researcher at CNRS (France) during 32 years
- Specialized in past climate and greenhouse gases (ice core analyses)
- Director of the French polar Institute IPEV between 2018 and 2022
- Professor at EPFL since ~2 years ; head of SENSE research unit
- Development of sensors for aquatic environments

Digging a snow trench at Concordia station, Antarctica. Photo: O. Alemany

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Outline of the introduction

- **1st part**
  - What scientific challenges at the poles ?
  - How engineering can contribute ?
- **Pause of 15 min**
- **2nd part**
  - A more detailed illustration through ice core studies
  - What future for such science and for the icy memory of the planet ?

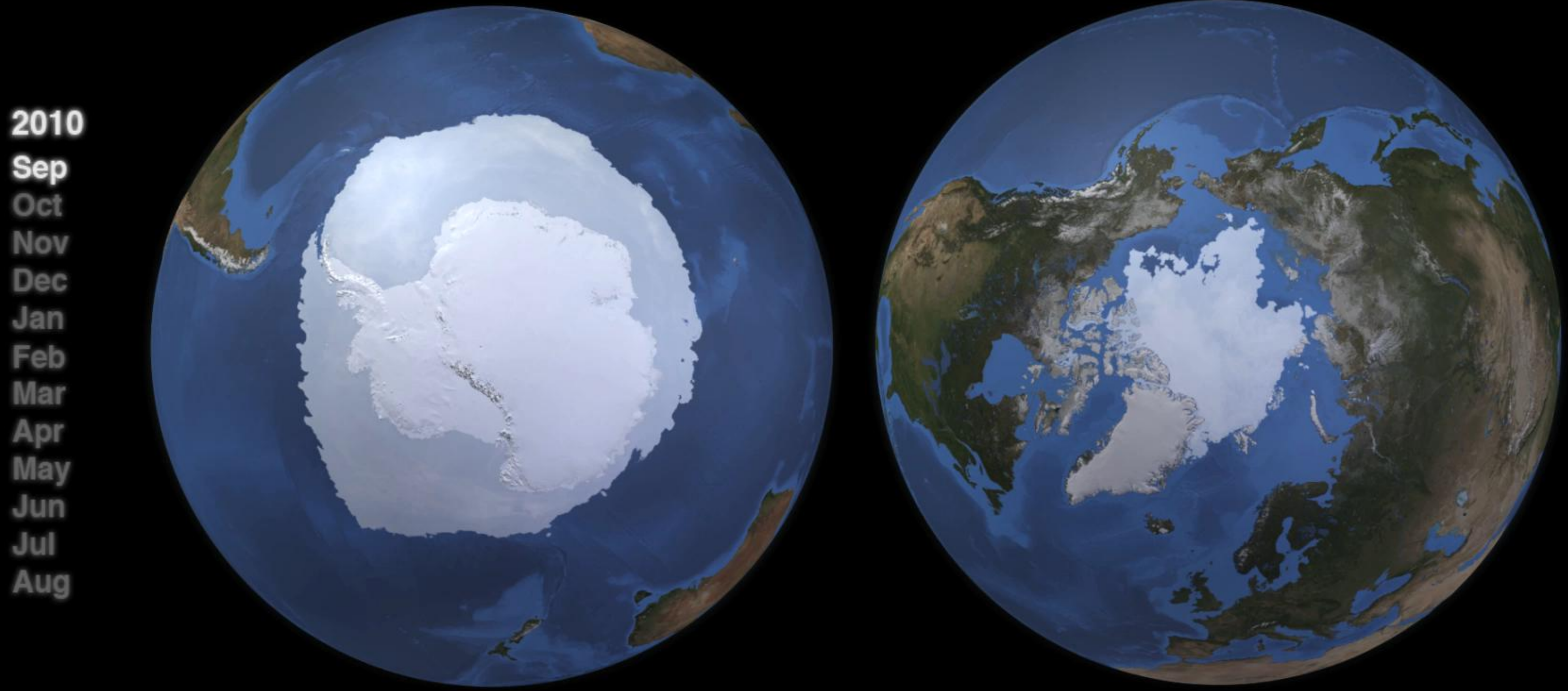
MOSAiC expedition: the Polarstern icebreaker in Arctic winter. Photo: J. Stroeve

Who already crossed the Arctic or the Antarctic Circle ?

Photo: British Antarctic Survey

Who already saw a polar bear in its environment ?

Photo: Caters News Agency



Source: NASA visualization studio.
AMSR-E and MODIS satellite imagery

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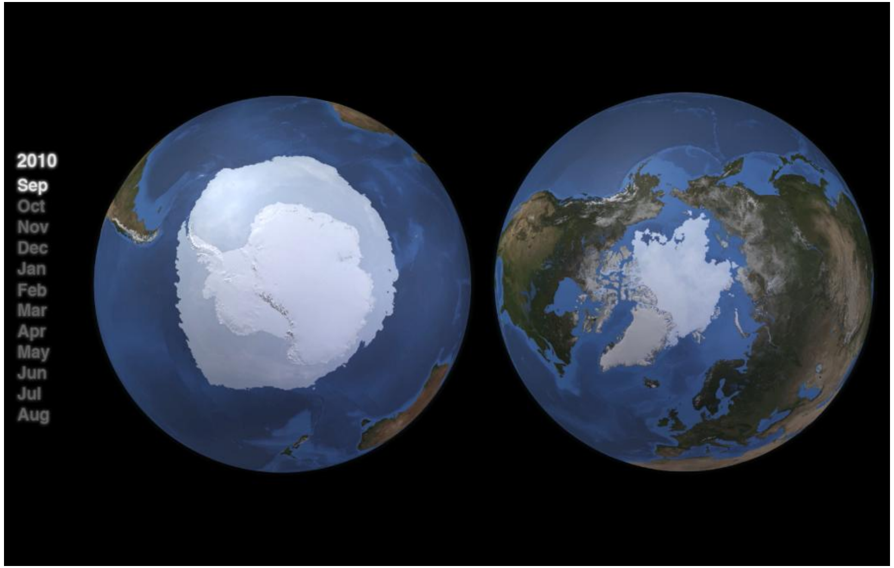
The poles : Kingdom of the cryosphere

- **Climate**: glaciers, sea ice and snow reflect a large part of the incoming solar radiation → Hendrik Huwald, Sept. 10th
- **Atmosphere**: a specific chemistry (ozone hole, Arctic haze) → Julia Schmale, Nov. 10th
- **Oceans**: large impact on global ocean circulation
- **Land**: lots of organic matter stored in frozen soils
- **Sea level**: huge ice bodies lying on bedrock
- **Biology**: endemic species, resources
- **A planetary memory**: ice cores

→ Stay tuned ! In one hour



Main science disciplines at the poles

<u>Geosciences</u>:

- Climate science
- Glaciology
- Oceanography
- Atmospheric physics and chemistry
- Biogeochemistry (cycle of main elements)
- Geology and resources (energy, minerals)

Main science disciplines at the poles

Life sciences:

- Biodiversity
- Ecology
- Dynamics of ecosystems
- Impact of acidification/pollutions
- Adaptability
- Resources (fishing,…)

Main science disciplines at the poles

Human and social sciences:

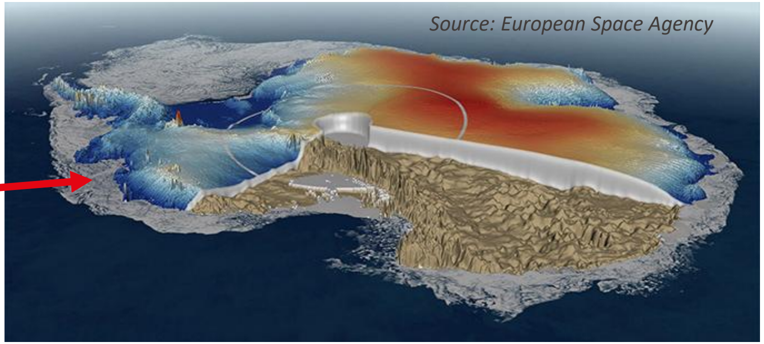
- Impact and adaptation to climate and environmental changes
- Human health
- Anthropology
- Economy
- Geopolitics

Other: Engineering, astronomy/astrophysics, biomedecine

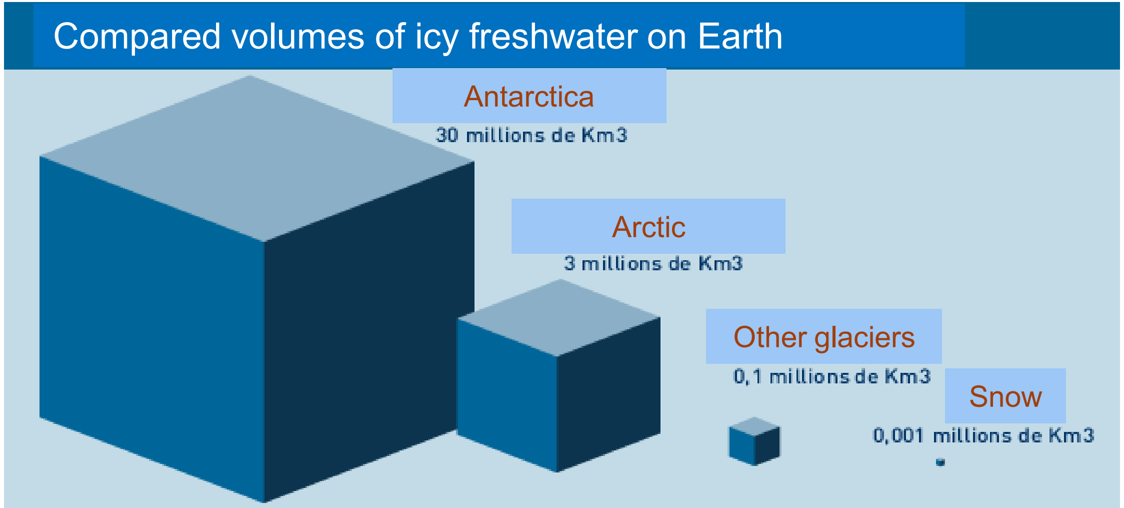
What future sea level ?

- **Antarctica**: potential for **~60 m** of sea-level increase
- «Short term»: Thwaites and Pine Island glaciers ; potential of **~3 m** in a few centuries
- **Greenland**: potential of **~7 m**

Antarctic ice thickness



- United Nations expect **~1 billion people** leaving in low-lying coastal regions by 2050



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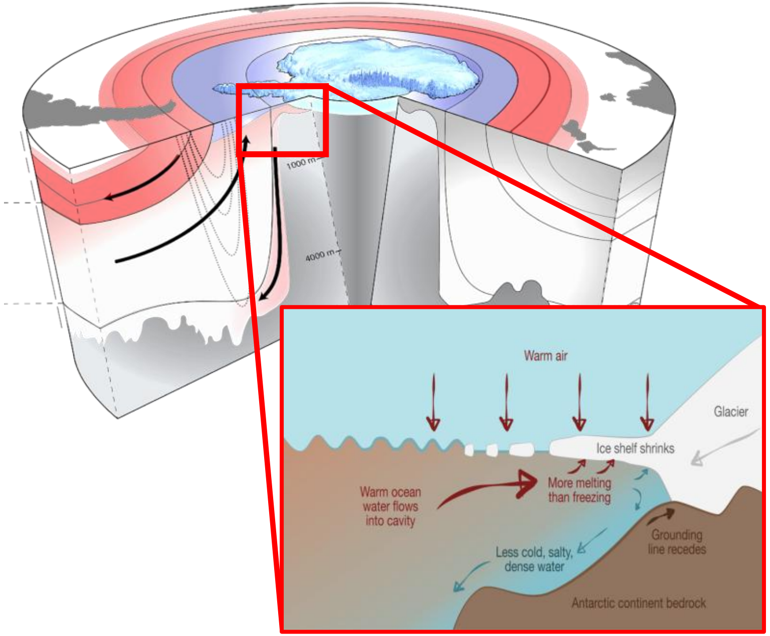
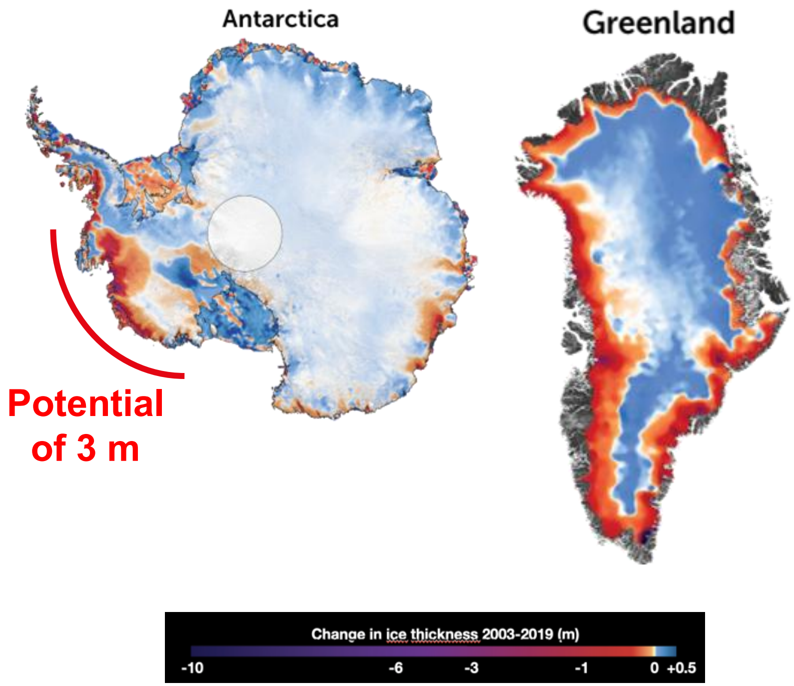
What future sea level ?

Source :
JB Sallée, Oceanography 2018



Change in ice thickness as measured by satellites between 2003 and 2019

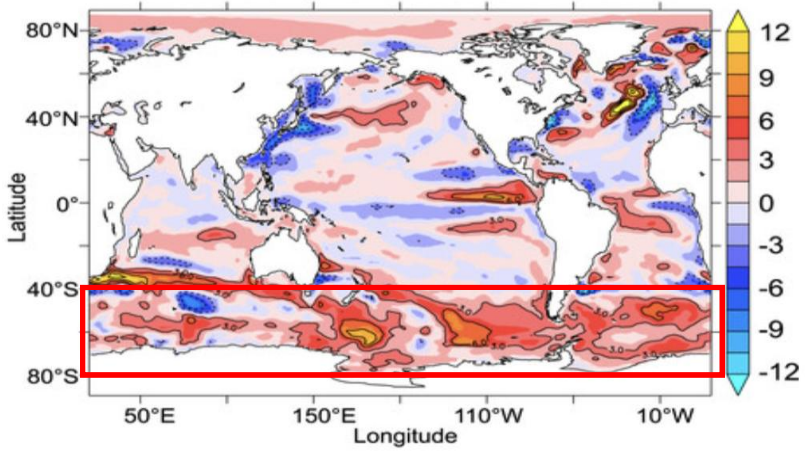


Key mechanism: Interactions between the Austral ocean and floating ice shelves

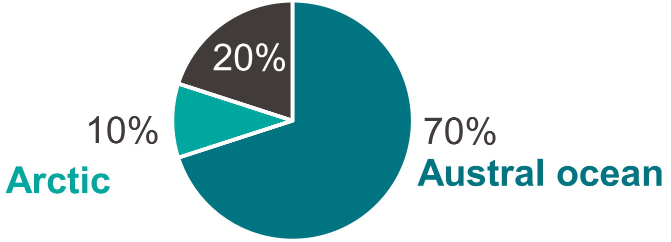
Source :
Smith et al., Science 2020

Polar oceans: Energy and carbon traps

- 90% of the excess energy in the atmosphere/land/ocean system due to anthropogenic activities is stored in the oceans
- Out of these 90%, **70%** is stored in the Austral ocean surrounding Antarctica



Source : Frölicher et al., J. of Climate 2015



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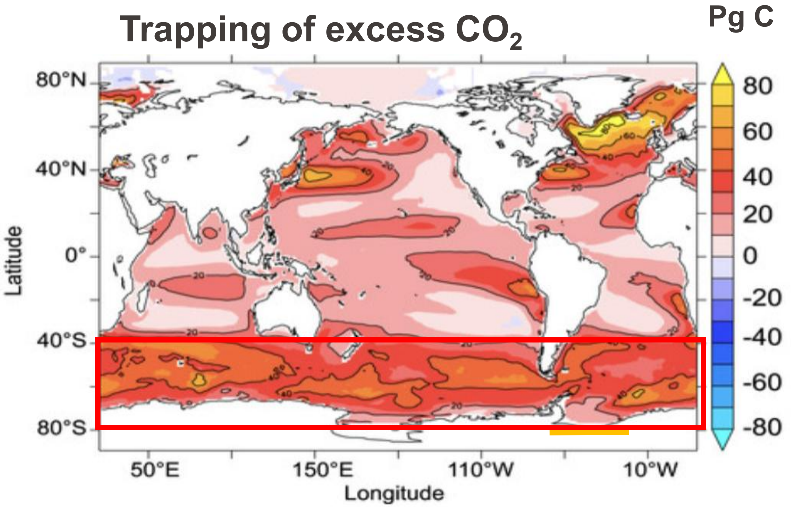
Polar oceans: Energy and carbon traps



Source :
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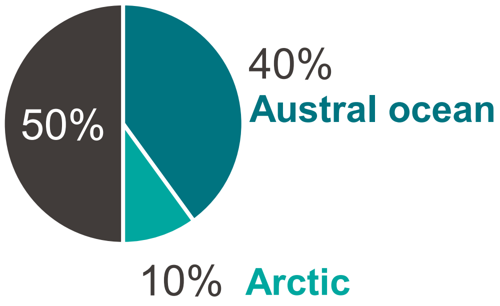
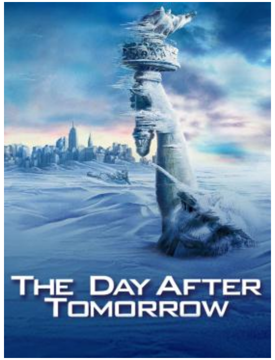


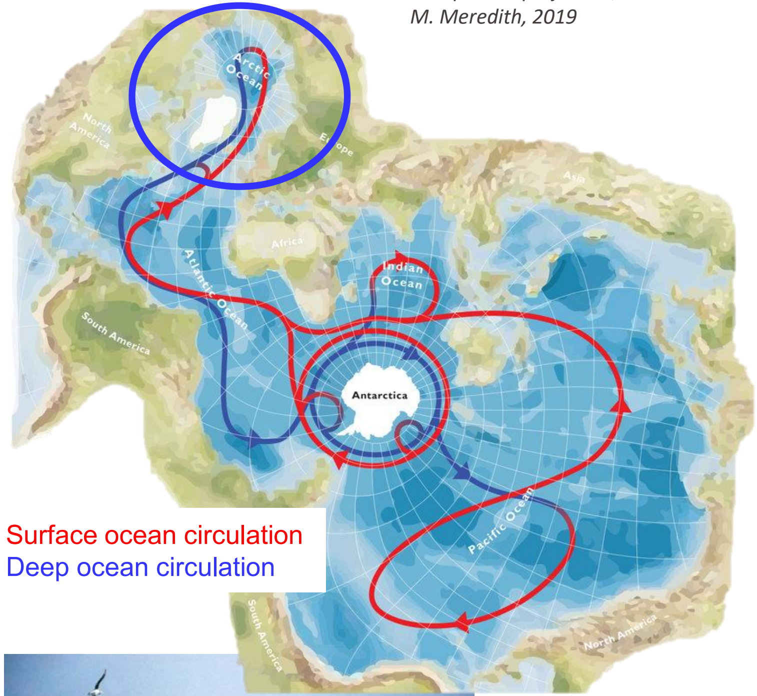
- About 25 to 30% of excess CO_2 due to human activities are absorbed by the oceans (a number equivalent to the continental biosphere)
- Out of these 25 to 30%, **40%** are stored in the Austral ocean surrounding Antarctica

« The day after tomorrow »: fiction or reality ?



- Increased freshwater fluxes in the Arctic (from rivers and Greenland melting) could increase ocean stratification and reduce heat transfer in the North Atlantic
- **Regional cooling**
- Models do not agree on timing and strength of the phenomenon: could be a reduction of 6 to 8 Sv* in the coming centuries, compared with a flux of ~30 Sv today

Source : Spilhaus projection, M. Meredith, 2019



Source : The Daily Digest

* 1 Sv (Sverdrup) = 1 million m^3 of water flow / sec

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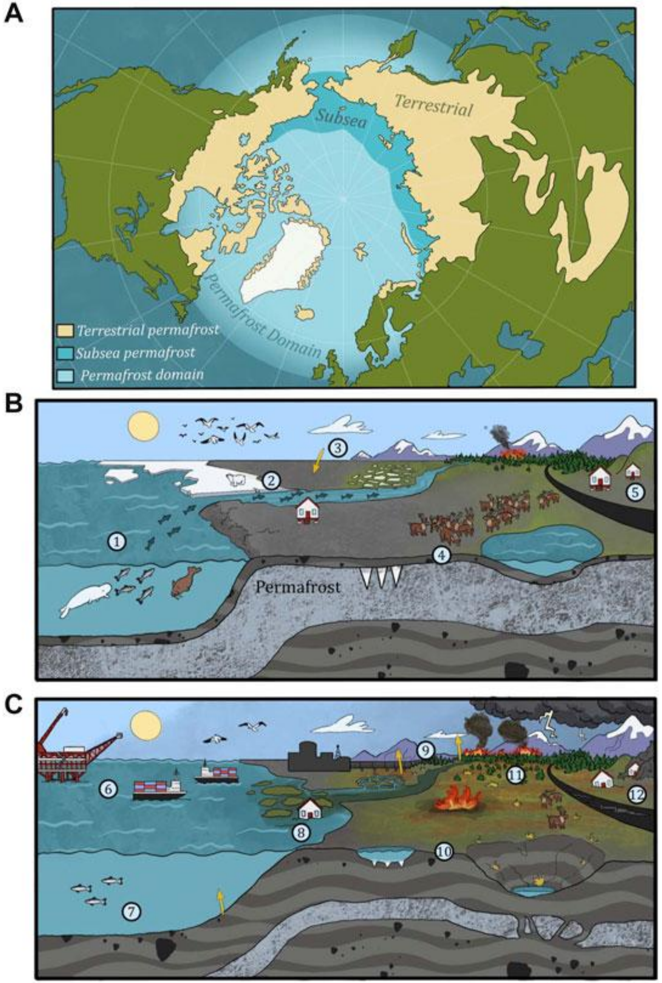
Carbon release from permafrost

- Include twice the amount of carbon of the atmosphere
- Increased melting + forest wildfires
- Can generate additional greenhouse gases CO_2 or CH_4 (depending on local hydrology)
- Even with a mean global warming of +1,5°C, one expects **100 to 200 Gigatons*** of extra CO_2 in the atmosphere from this process

** Current anthropogenic emissions : ~40 Gt of CO_2 / year*

Source : US Geological Survey



Source : Abbott et al., Front. Environ. Sci. 2022

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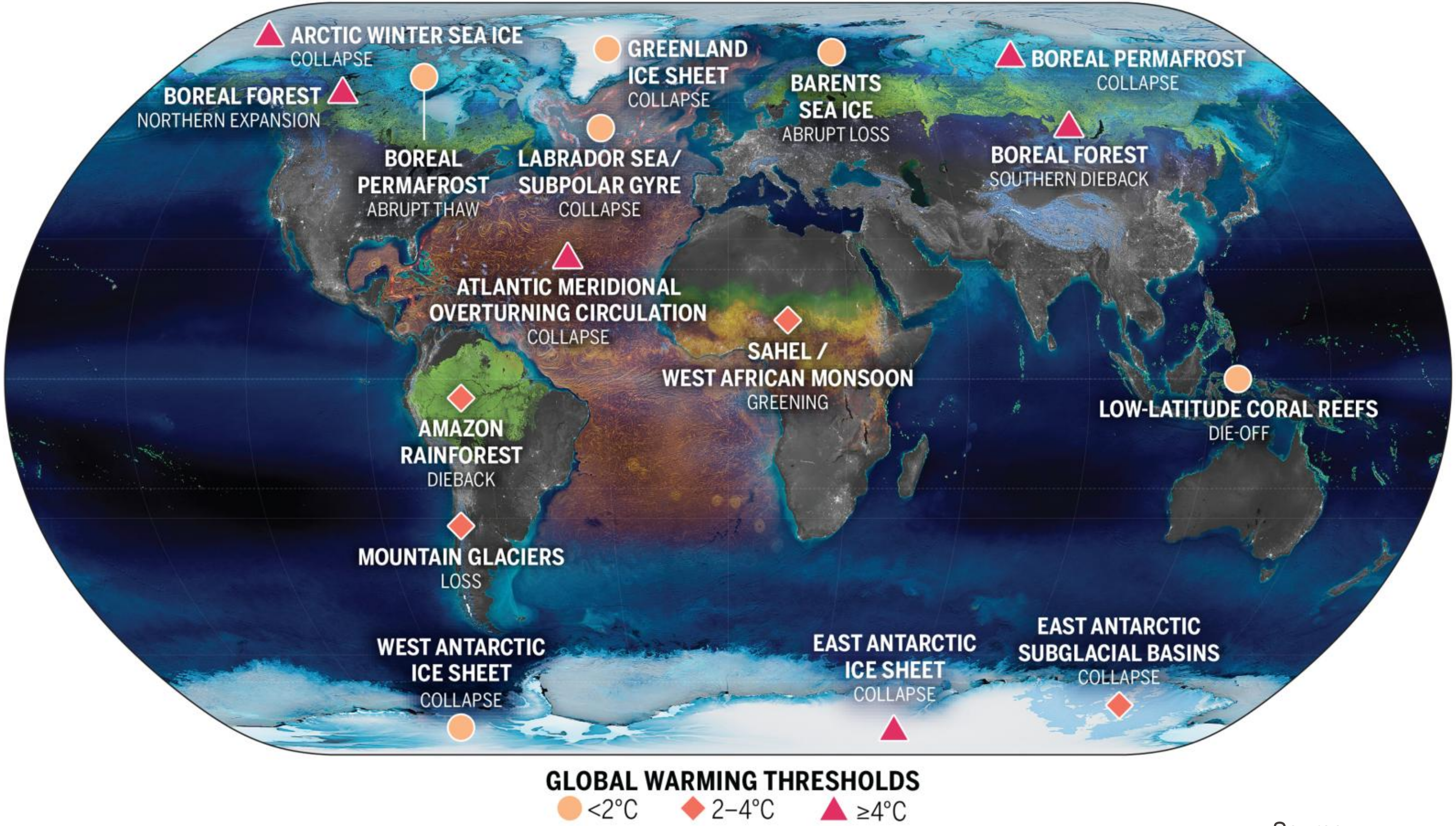
Climate tipping points: the poles do matter…



Source:
Armstrong McKay et al., Science 2022

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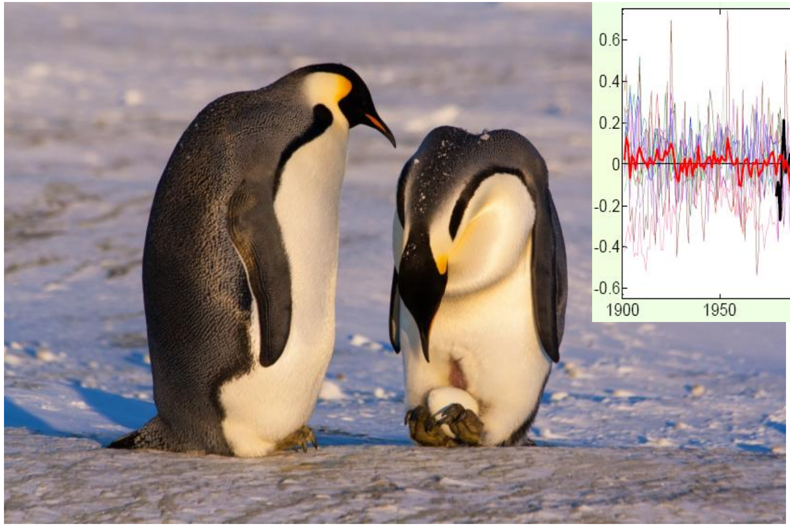
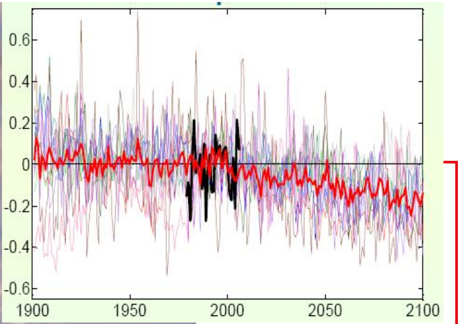
Pressure on biodiversity

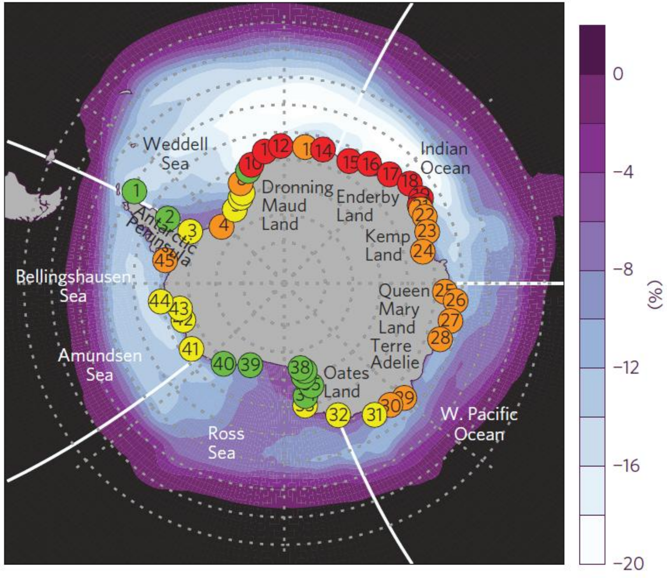
Photo: IPEV



IPCC scenarios (future of Antarctic sea ice)



Projection of Emperor penguin colonies for 2100



Source : Jenouvrier et al., Nature 2014

- Due to overuse of resources (fishing), to pollution (air, land, water), to land use (Arctic), to climate change
- Example: Many colonies of Emperor penguins could disappear by 2100

Outline of the introduction

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  - A more detailed illustration through ice core studies
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MOSAiC expedition: the Polarstern icebreaker in Arctic winter. Photo: J. Stroeve

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How engineering can contribute ?

- Science at the poles is largely a science of **observation**
- Satellites are great but not enough: one needs **ground-truthing**
- **Sensors** to document the physics, chemistry and biology of the polar environments
- **Vectors** to move around the sensors
- AI and **machine-learning** to get the maximum out of data
- Toward more citizen science (in the Arctic)

Photo: J. Chappellaz, GreenFjord expedition 2024

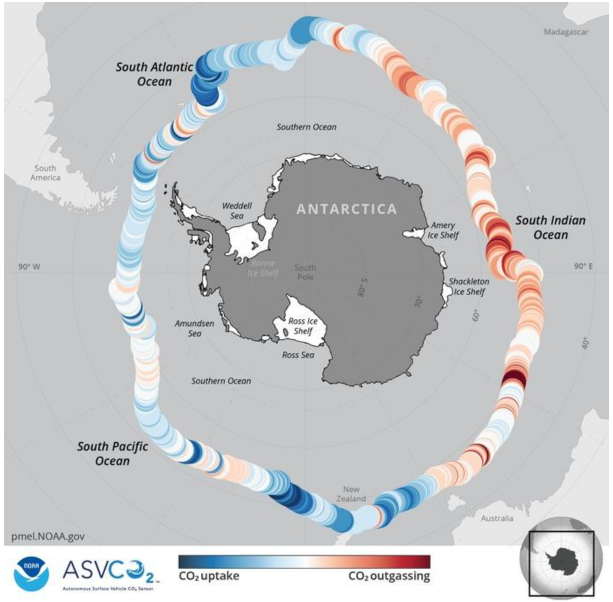
Robotics : example of Saildrone

SAILDRONE

Robotics : example of Saildrone

SAILDRONE

CO_2 fluxes in the Austral ocean over 196 days of self-navigation



Source : NOAA PMEL Carbon Program

How to document processes below ice shelves ?

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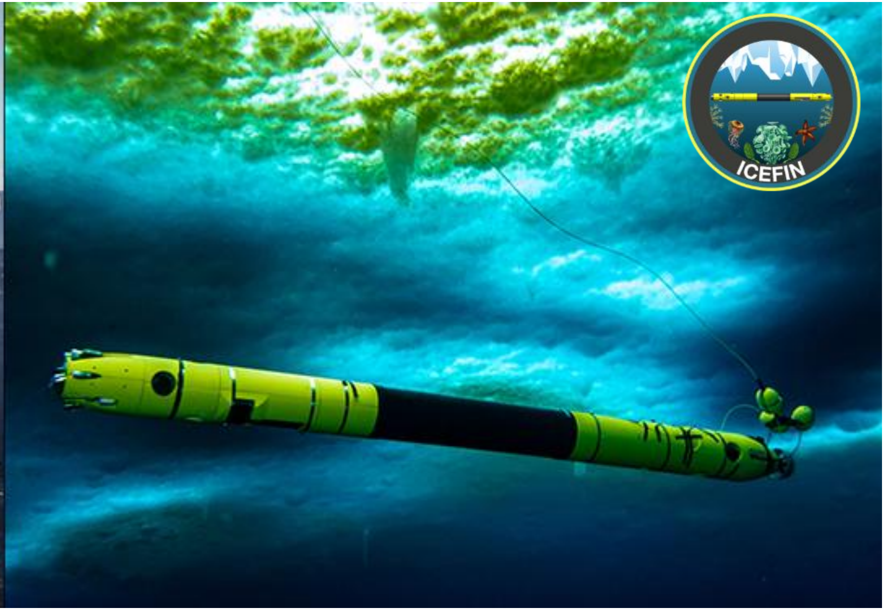
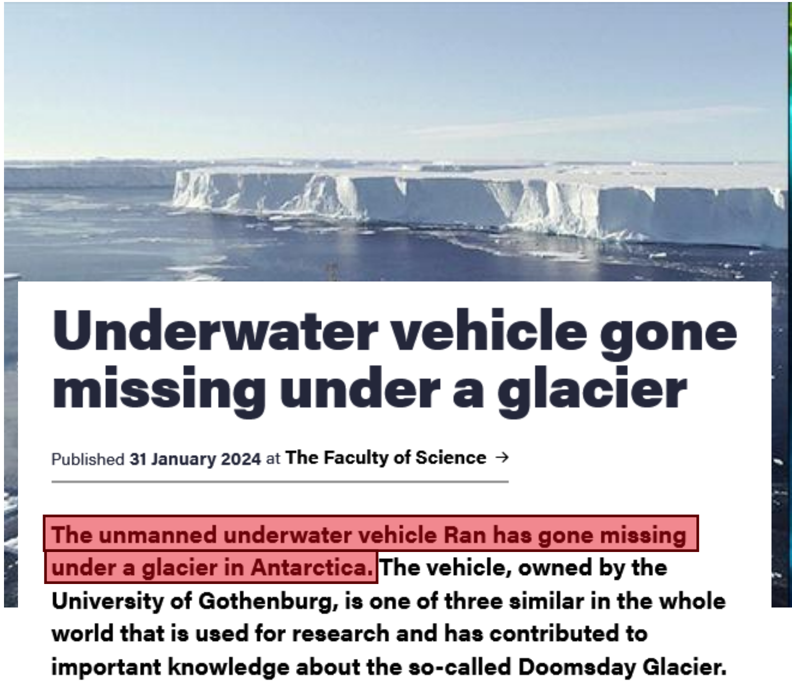


- Need for autonomous submarines with embedded sensors

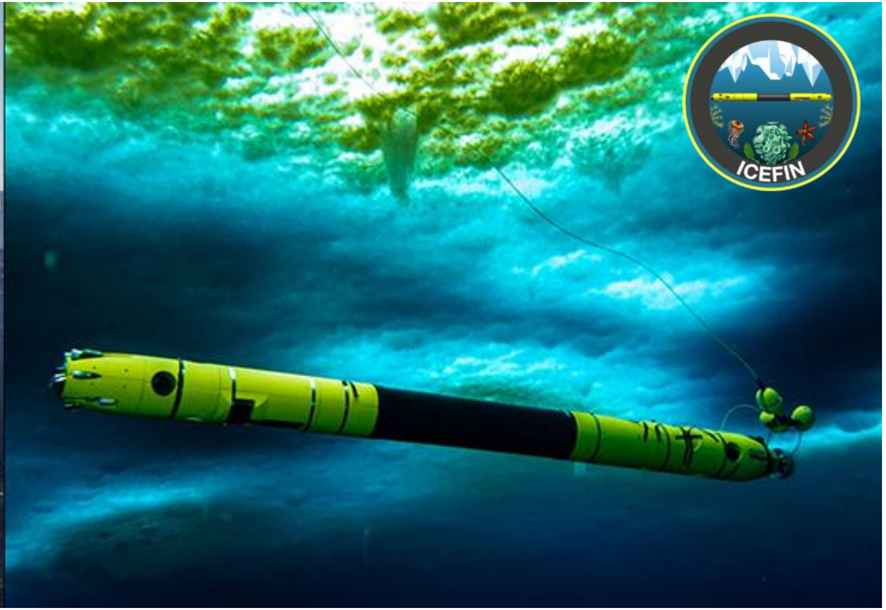
  Which can be recovered…

How to document processes below ice shelves ?


Underwater vehicle gone missing under a glacier

Published 31 January 2024 at The Faculty of Science →

The unmanned underwater vehicle Ran has gone missing under a glacier in Antarctica. The vehicle, owned by the University of Gothenburg, is one of three similar in the whole world that is used for research and has contributed to important knowledge about the so-called Doomsday Glacier.



- Need for autonomous submarines with embedded sensors

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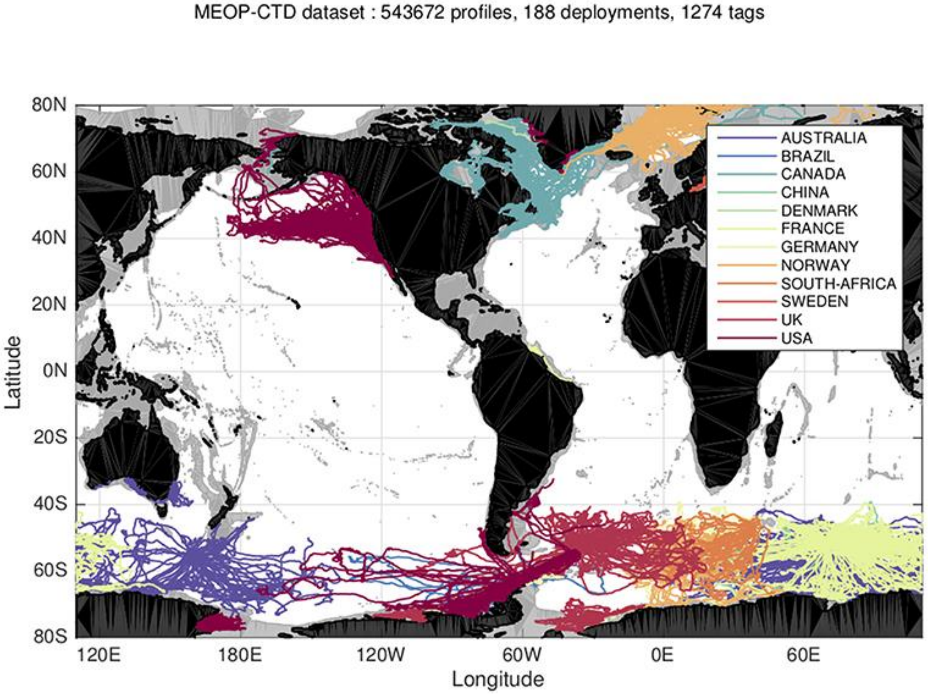
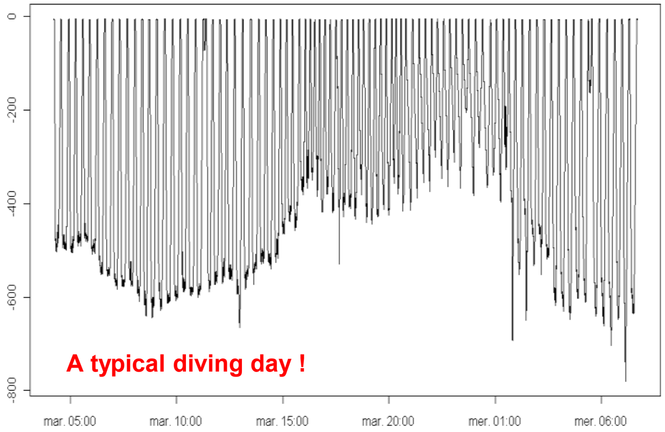
Animal-borne telemetry : double-win (oceano & ecology)

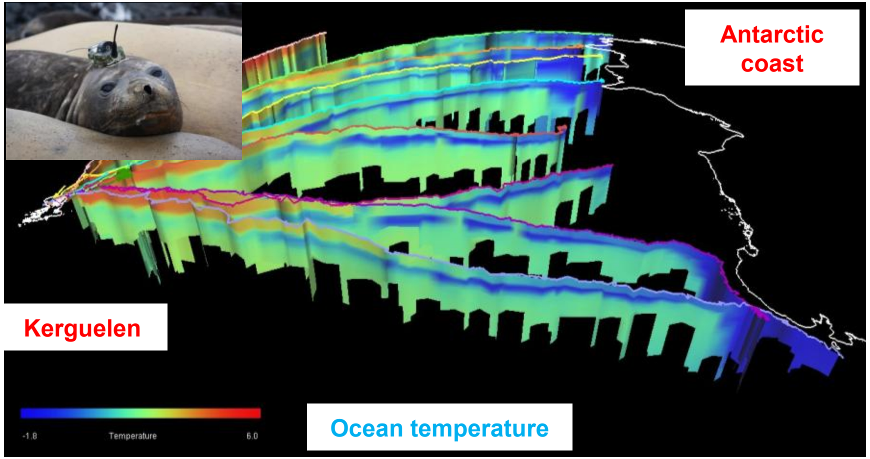


- Make profit of marine mammals and seabirds
- Get important data in the ocean while better understanding their behavior

Source: Harcourt et al., Frontiers in Marine Science 2019

Animal-borne telemetry

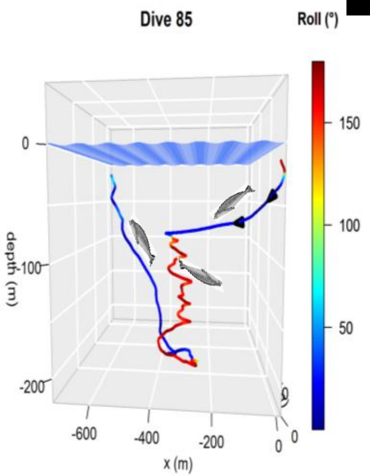




Source: *CEBC / CNRS*

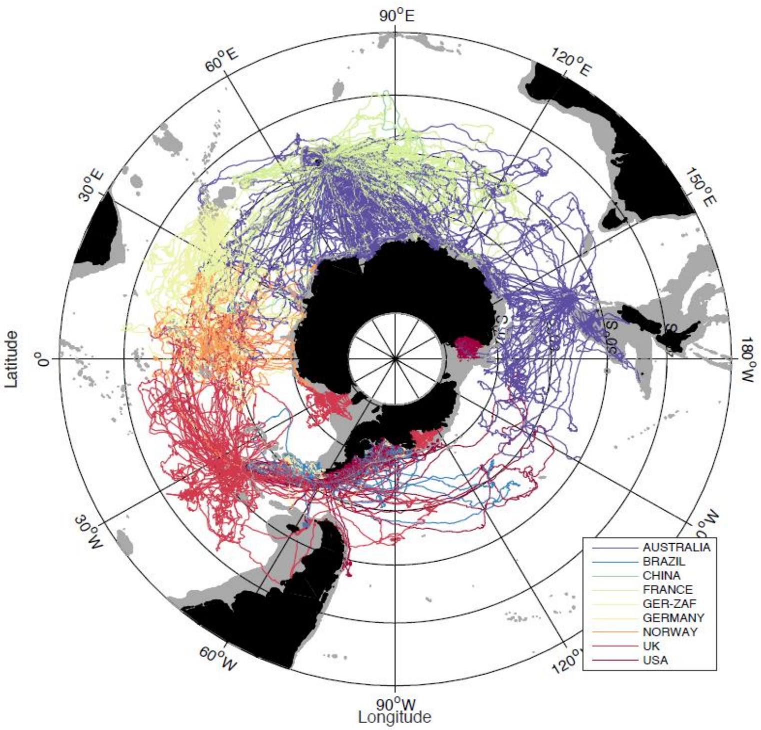
Elephant seals

- Mean Diving Depth: 500m (max 2000 m)
- Mean Diving Duration: 21 mn
- Mean Surface Interval: 2-3 mn

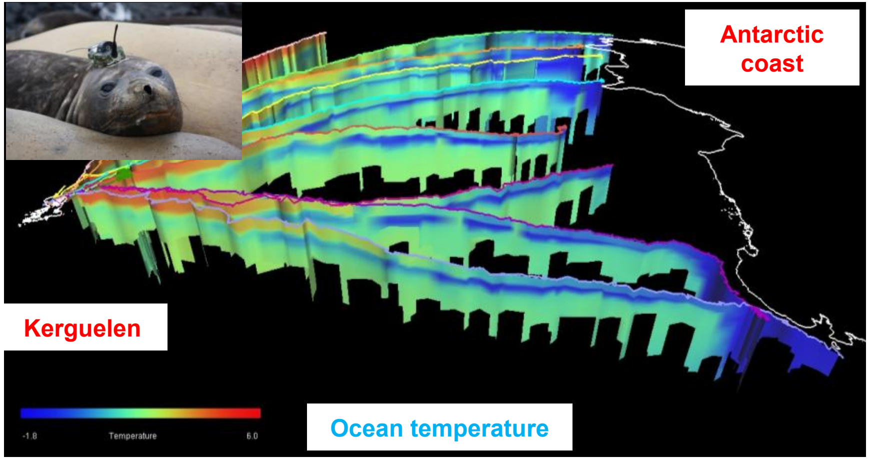


- A remarkable source of marine information in the Austral ocean !

Animal-borne telemetry



Source: MEMO Observatory, CNRS



Source: CEBC / CNRS

- A remarkable source of marine information in the Austral ocean !
- **80%** of oceanographic profiles South of 60°S
- **98%** of oceanographic profiles under Antarctic sea-ice !

Animal-borne telemetry : what's next ?

Source: University of St Andrews, Scotland

What is measured today by these tags ?

Biotelemetry : Argos Transmitted (2-4 profiles/day), Real time

- Depth
- Temperature
- Salinity (1Hz)
- (Fluorescence)
- Dissolved oxygen

Biologging : Archived **(the tag needs to be recovered)**

- Depth (1Hz)
- Temperature (1Hz)
- Salinity (1Hz)
- Fluorescence, (1Hz 4/profiles per day)
- Dissolved oxygen (1 Hz, 4 profiles per day)
- **Light** (1 Hz)
- **Accelerometer** (12Hz)

Constraints:

- Size
- Limited energy supply
- Cold environment
- Pressure

Optimization of data acquisition, processing and transfert

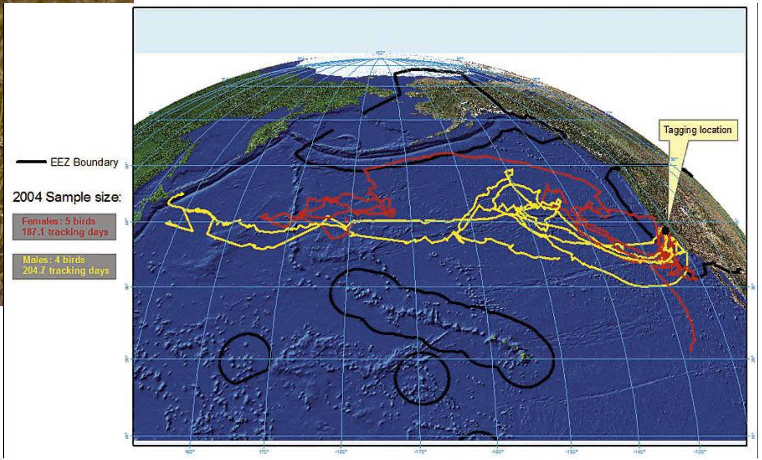
Animal-borne telemetry : what's next ?

Photo: A. Corbeau, CEBC, CNRS

Loggers on albatross:

- Track radar signals from unsignaled boats
- Combined with GPS, help to localize illegal fishing

- Next: e.g., document Dimethyl sulfide concentration in marine boundary layer ?!



Source: US National Marine Sanctuaries


Photo: C. Guinet, CEBC, CNRS


Photo: J.B. Pons, CEBC, CNRS

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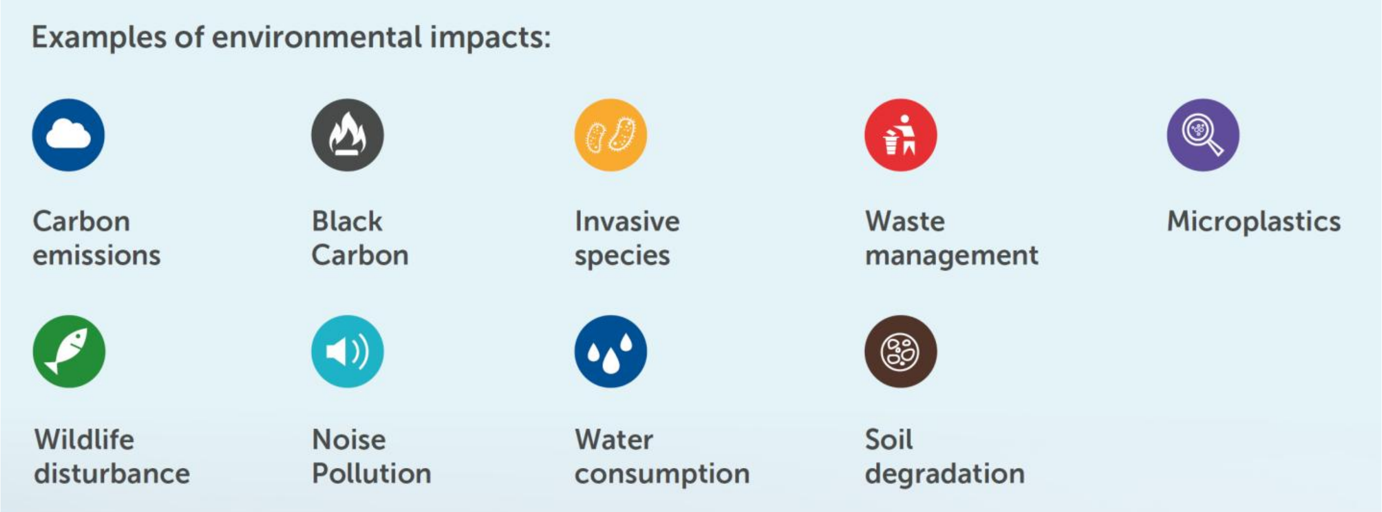
How engineering can contribute to greening polar science ?

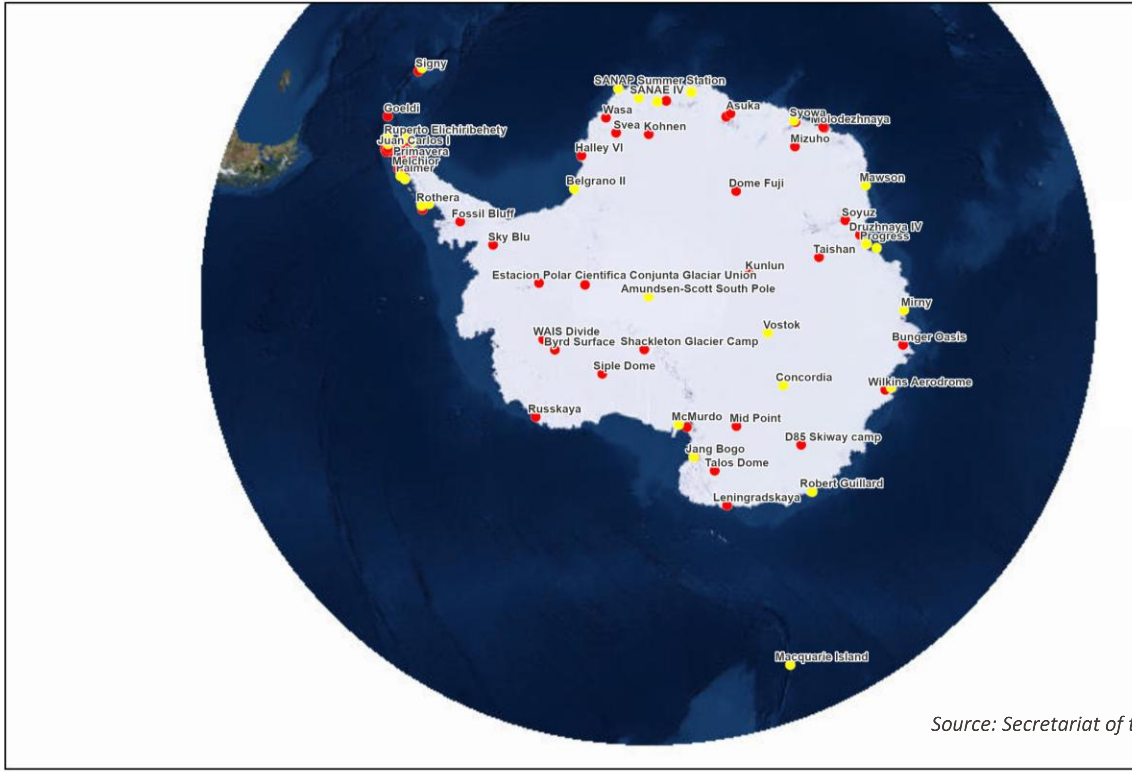


Source: Elshout, Chappellaz et al., European Polar Board Report
DOI: 10.5281/zenodo.7907235

- Working in polar regions is challenging and has a significant environmental impact
- Engineering needs for cleaner research stations and logistics


MARINE
MELCAL
P800

Today's science in Antarctica



Source: Secretariat of the Antarctic Treaty

- 68 operational stations
- 40 working all-year round
- Population:
  - ~1000 in winter
  - ~5000 in summer

29/11/2023 18:00:02

Facilities (Updated 16/02/2023)

- Seasonal
- Year-Round

1:48,570,801

0 500 1,000 2,000 mi

0 500 1,000 2,000 km

Source: Earthstar Geographics

COMNAP

Source: Earthstar Geographics |

More sustainability : automated stations

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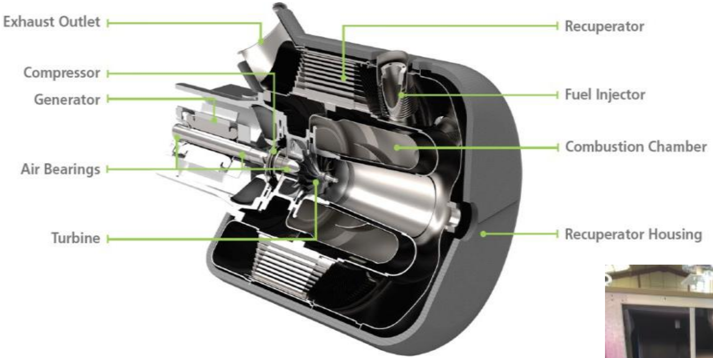
Example : Halley VI winter-over station in Antarctica

Fully automated station built by the British Antarctic Survey

Automated ozone measurements



Containerised Capstone C30 Micro-turbine

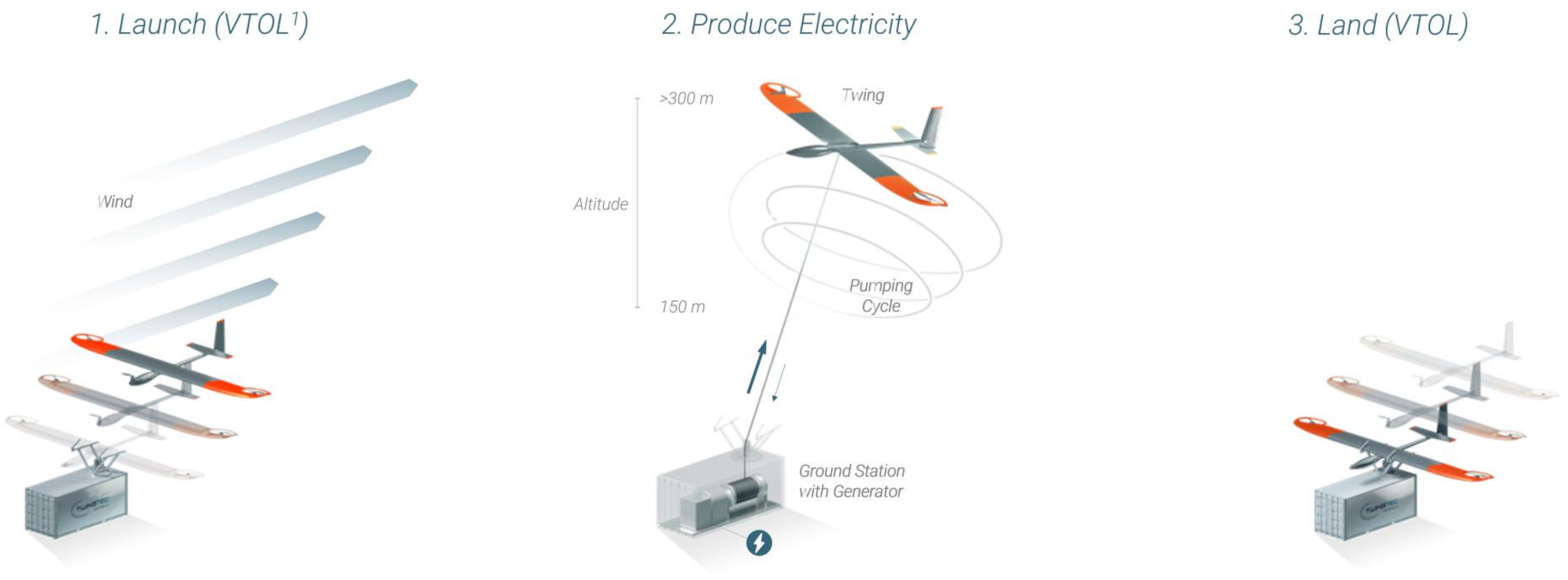
Space weather, atm. chemistry, meteorology, GPS stations

From J. Eager, COMNAP Meeting 2019

Clean and mobile energy : A Swiss startup

Courtesy : Rolf Luchsinger, co-founder

Clean and mobile energy : A Swiss startup



Courtesy : Rolf Luchsinger, co-founder

Take-home messages

- Science in polar regions matters a lot for society: future climate, sea level, ocean circulation, carbon cycle, biodiversity, Indigenous People and knowledge
- One needs more observations in these demanding environments, through smarter sensors and vectors
- One needs greener science at the poles
- There is an exciting future for engineers motivated by such extreme (and fascinating !) environments

MOSAiC expedition: the Polarstern icebreaker in Arctic winter. Photo: J. Stroeve

PAUSE of 15 minutes !

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Science at the poles

—

An ice core illustration

Photo: *Sarah Del Ben*

Prof. Jérôme CHAPPELLAZ

EPFL-ENAC-IIE-SENSE

Ferring Pharmaceuticals Margaretha Kamprad Chair in environmental sciences

Former President

of the Ice Memory Fondation

ICE MEMORY
Sheltered by UGA Foundation Foundation

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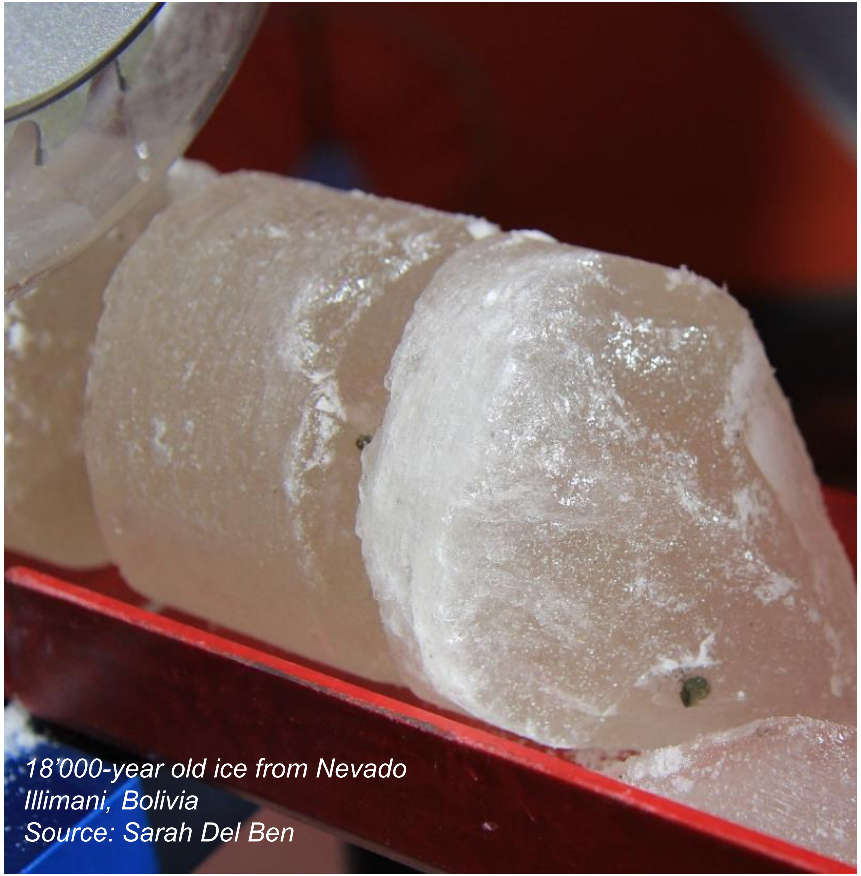
Who already heard about ice cores ?

Photo: Ricardo Selvatico

Who already had a chance to visit an ice core lab ?

Photo: Sarah Del Ben

Ice from glaciers: a unique memory of the planet



18'000-year old ice from Nevado Illimani, Bolivia
Source: Sarah Del Ben

Earth and human history recorded in ice cores

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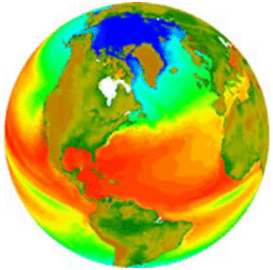


CLIMATE

$\delta^{18}O$ and δD of H_2O, CH_4 , CO_2, N_2O, $\delta^{15}N$ in NO_3^-

CONTINENTAL DUST, DRY EVENTS

Dust, ions, trace metals …

BIOMASS BURNING

Black Carbon, K^+, organic acids, sugars …

VOLCANISM

SO_4^{2-}, pH, particles, $\Delta^{33}S$ & $\Delta^{17}O$ in SO_4^{2-}

INDUSTRIAL POLLUTION

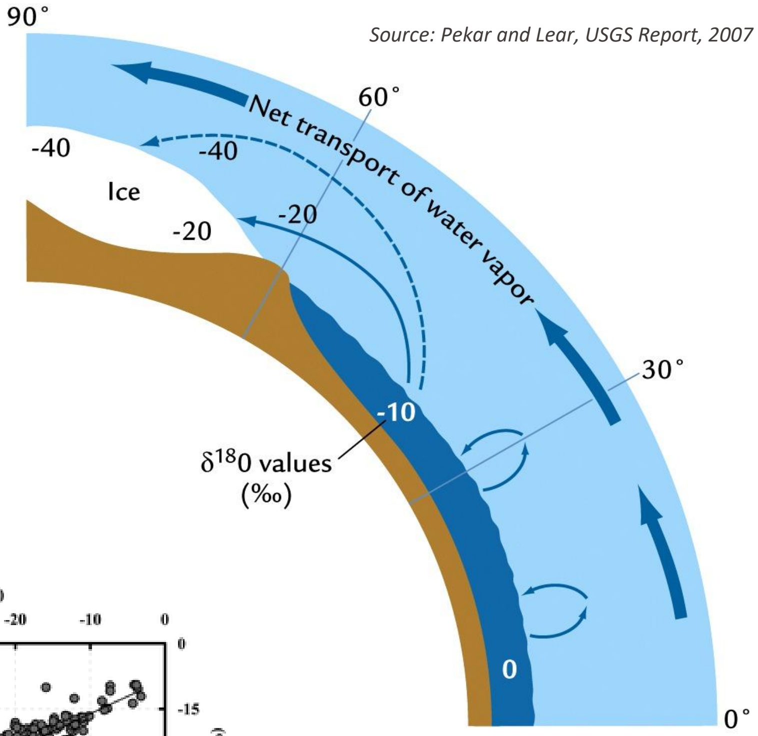
SO_4^{2-}, NO_3^- trace metals, radioactivity, S-N-O isotopes …

BACTERIA ? VIRUS ? OTHER ?

How polar glaciers record past temperature changes ?

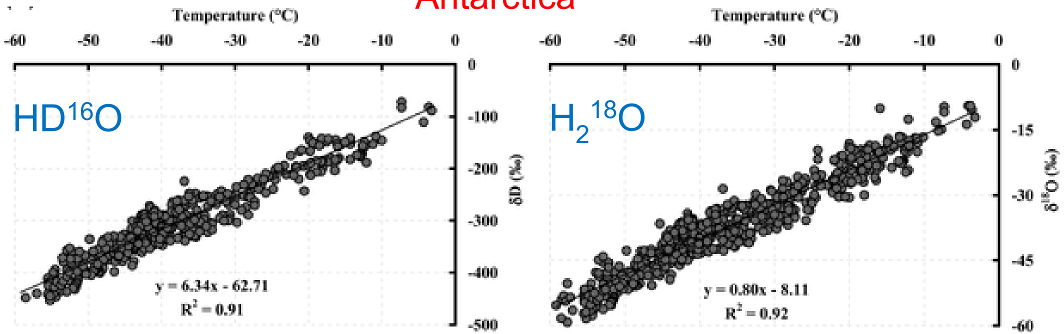
Global water cycle:

- Ocean evaporation followed by atmospheric transport
- The colder the air, the less water vapor content
- Progressive depletion of heavy isotopologues ($H_2{}^{18}O$, $HD^{16}O$) during consecutive precipitation events (phase change)
- This so-called **"Rayleigh distillation"** leads to a linear relationship between the snow/ice isotopic composition and surface air temperature



Source: Pekar and Lear, USGS Report, 2007

Antarctica



Source: Masson-Delmotte et al., Journal of Climate, 2008

Air bubbles in polar ice: a reliable recorder of past atmospheres

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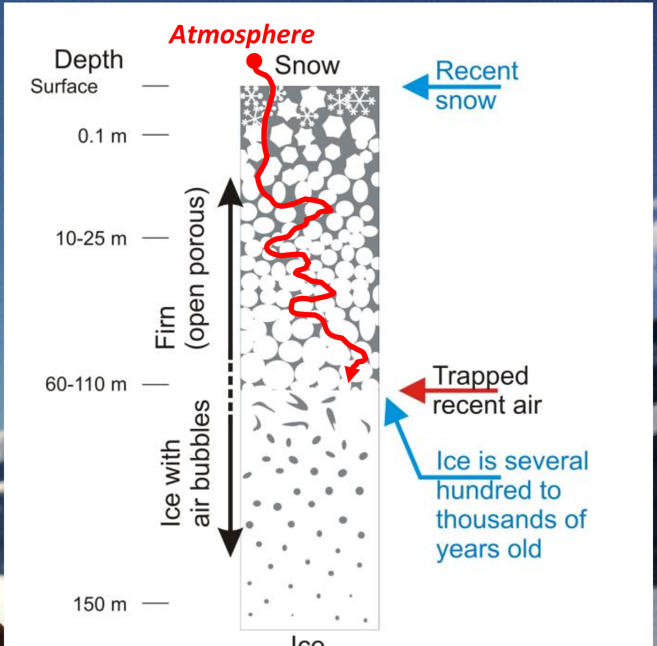
- Air molecules diffuse through the porous snow and firn
- Get trapped into bubbles when firn transforms into ice
- **1 kg of ice** contains **~100 cm^3 of air**



Source: J. Aagaard, 2015

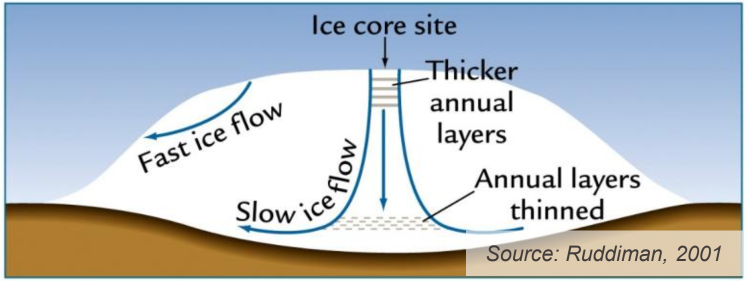
Photo: Peter Neff

Going back in time: ice flow and ice core drilling

- Glaciers are made of consecutive snow falls
- Ice flow is zero at domes: only vertical component (thinning)
- Thick glacier + small annual snow accumulation rate

  → Ancient ice
- Oldest ice core drilled so far: European drilling EPICA at Concordia station (Antarctica):

  → **800’000 years**



Source: Ruddiman, 2001


Photo: Rob Mulvaney

Photo: Peter Neff

20 years of deep drilling operations in Antarctica and Greenland

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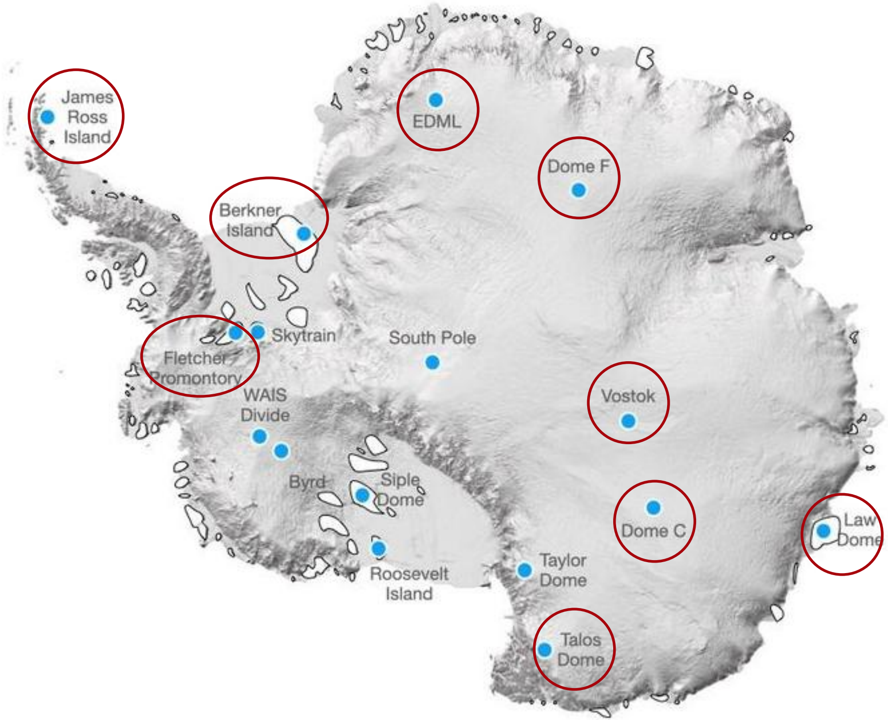
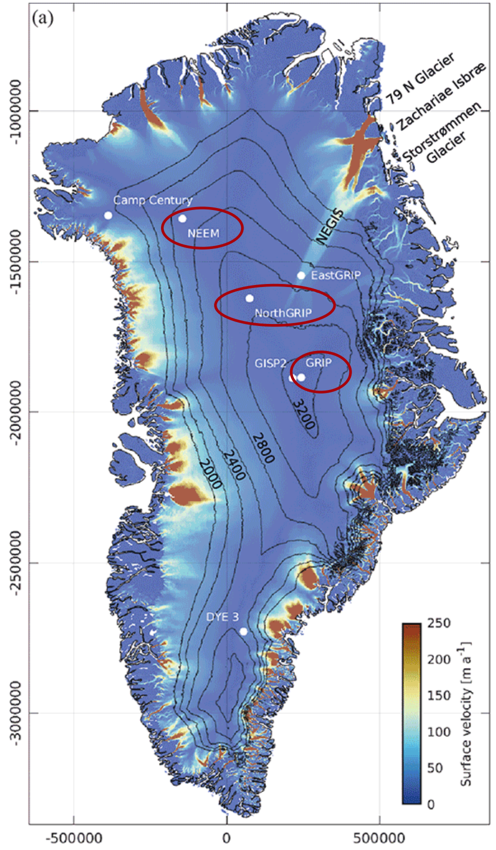
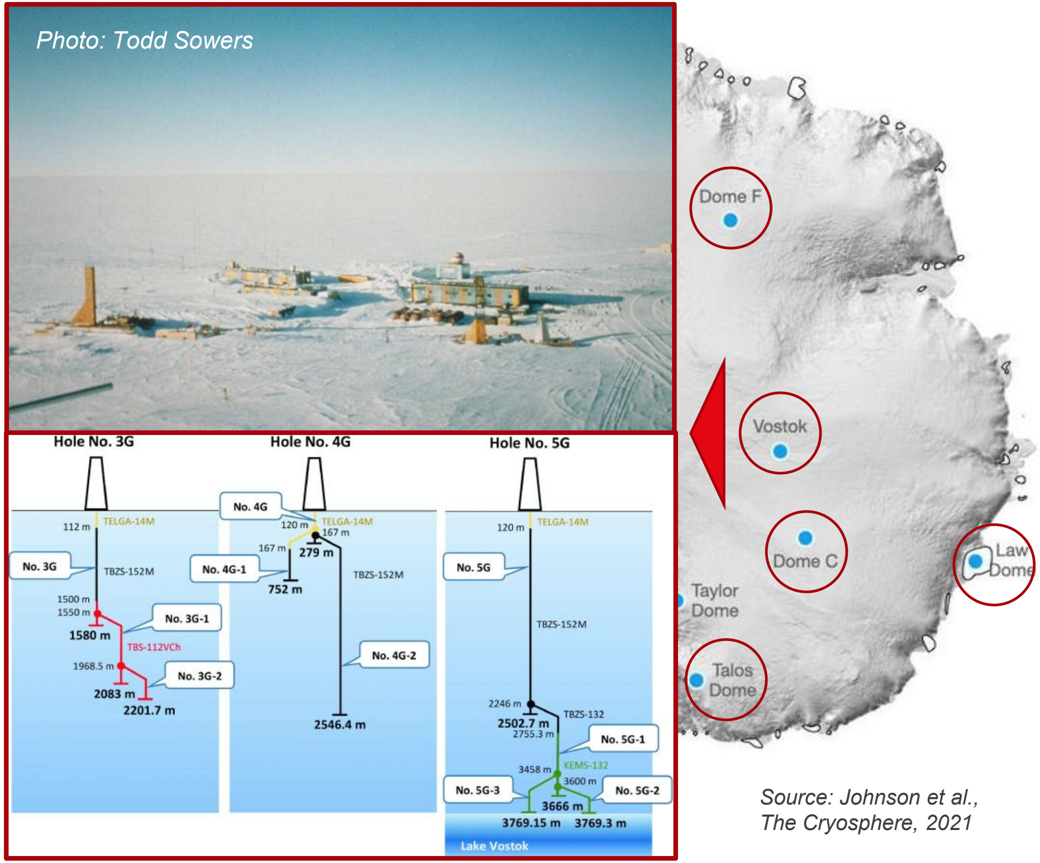


Source: Johnson et al., The Cryosphere, 2021

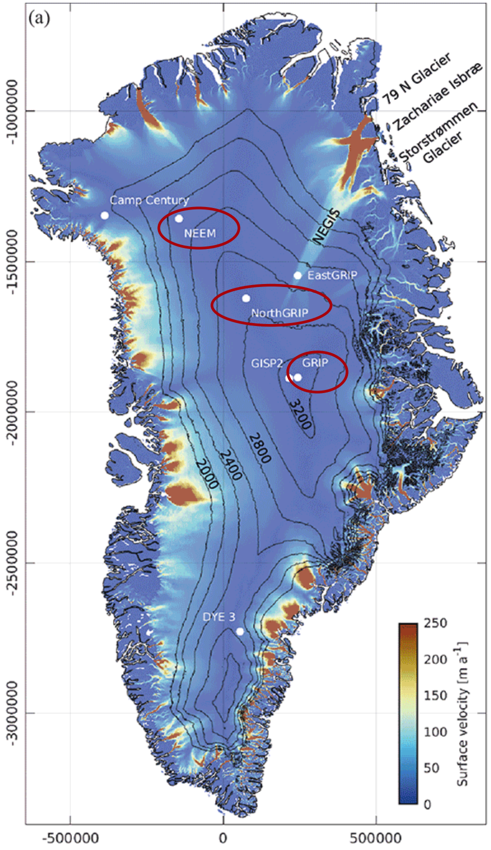


Source: Nagler et al., Remote Sensing, 2015

20 years of deep drilling operations in Antarctica and Greenland

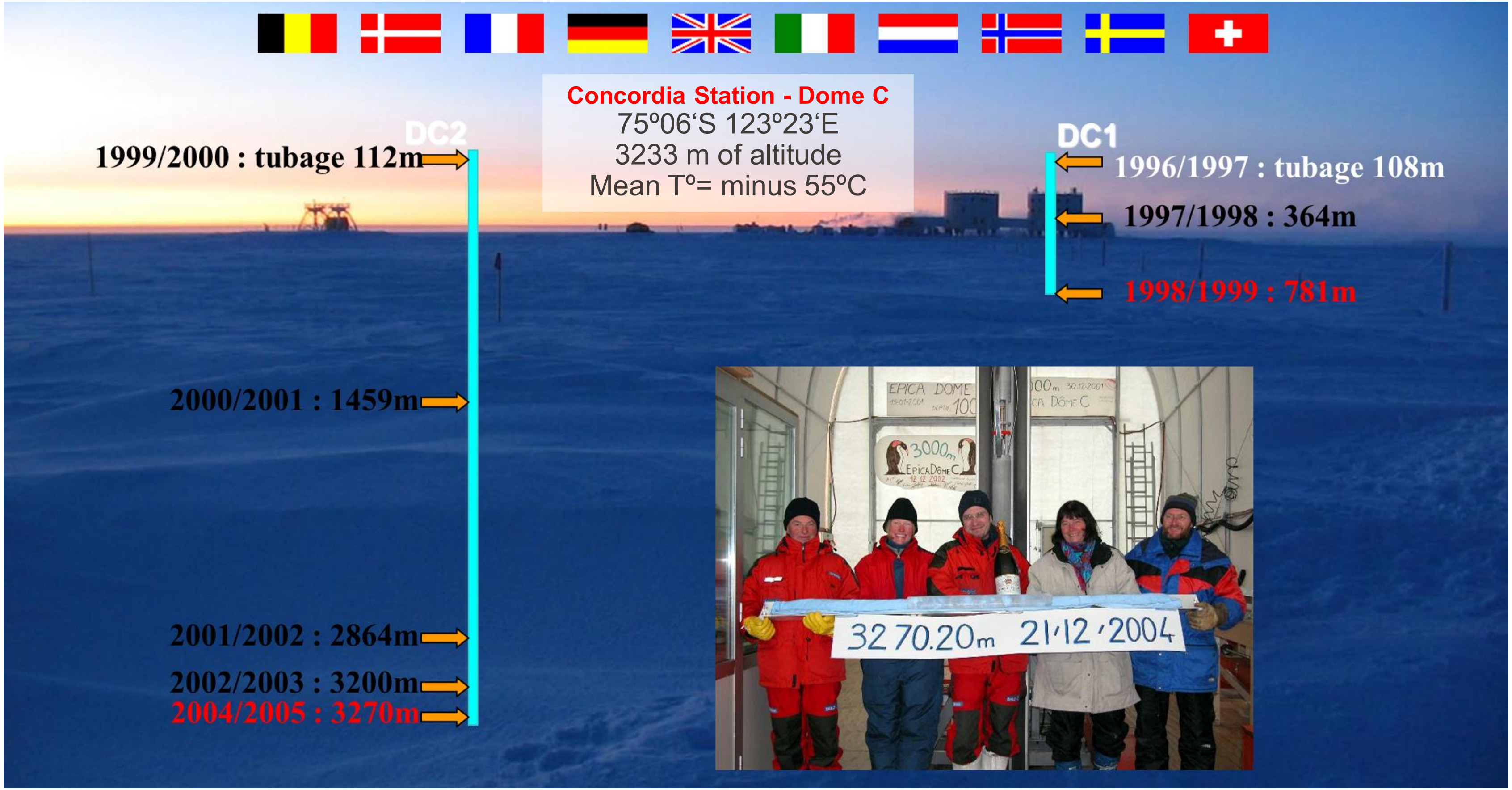


Source: Johnson et al., The Cryosphere, 2021

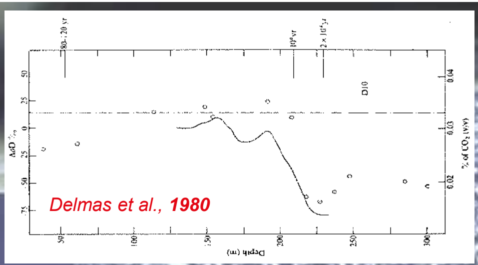


Source: Nagler et al., Remote Sensing, 2015

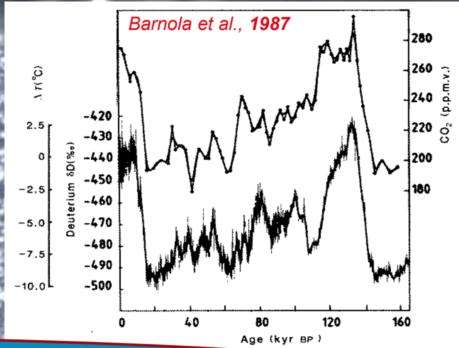
European Project for Ice Coring in Antarctica (EPICA)



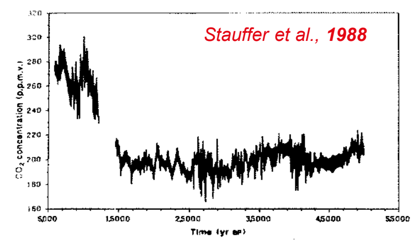
Greenhouse gases: Swiss and French analytical breakthrough in the 1980s



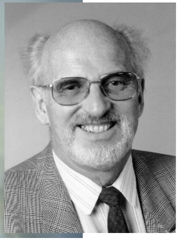
Delmas et al., 1980



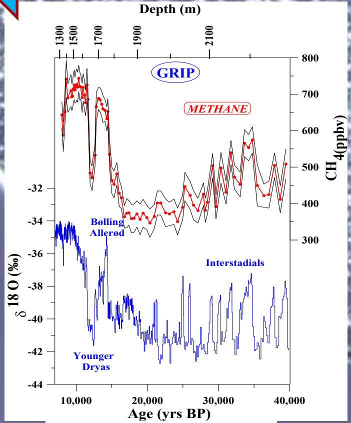
Barnola et al., 1987



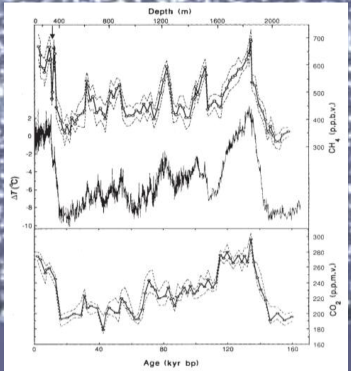
Stauffer et al., 1988


Hans Oeschger

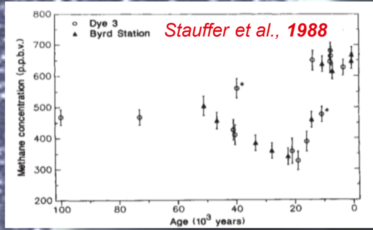

Claude Lorius



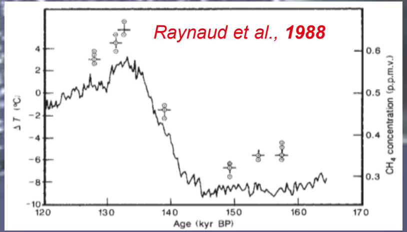
Chappellaz et al., 1993



Chappellaz et al., 1990



Stauffer et al., 1988

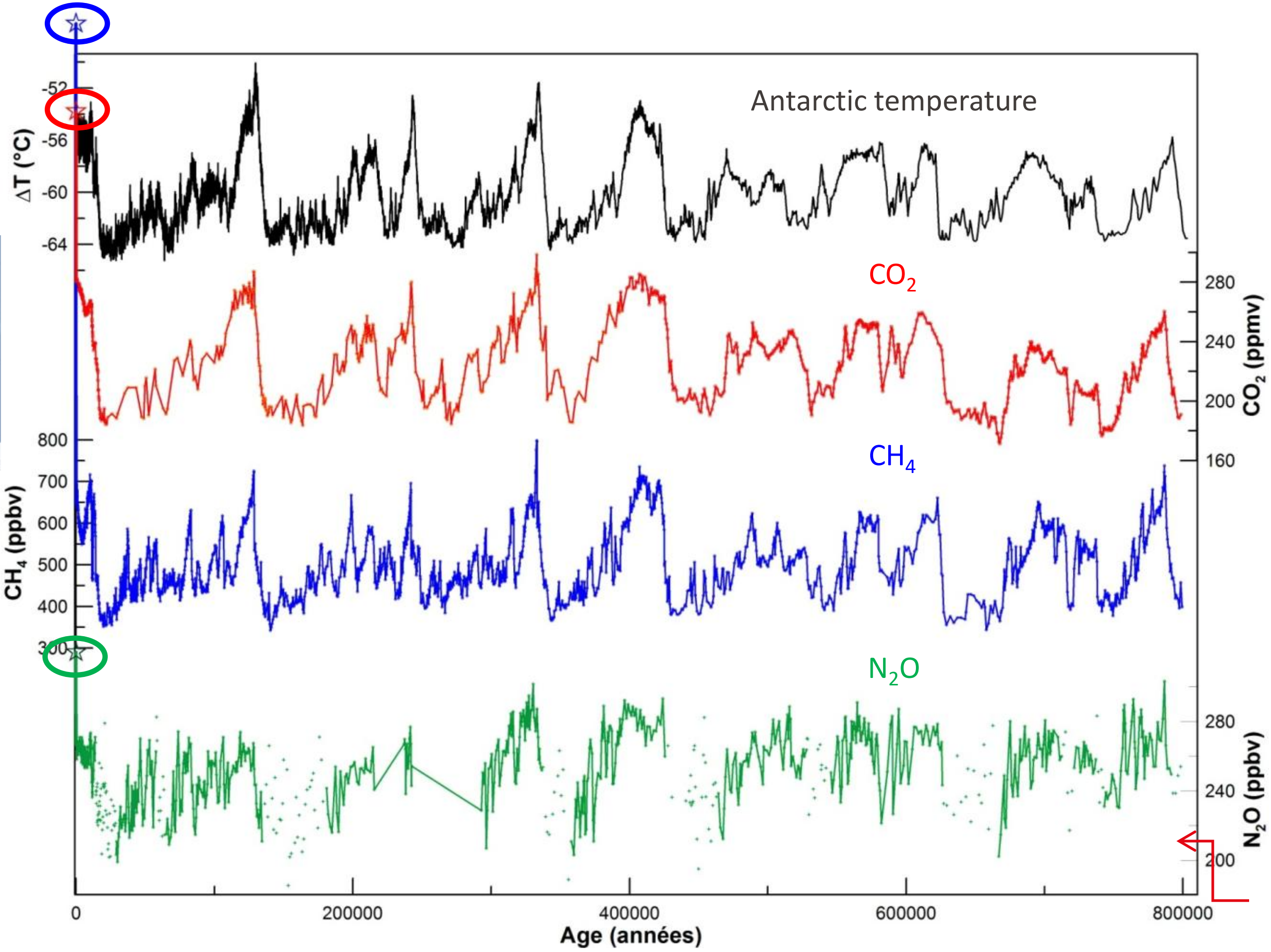


Raynaud et al., 1988

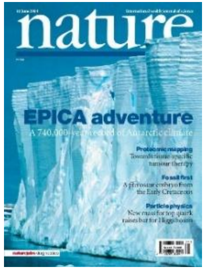
J. Chappellaz

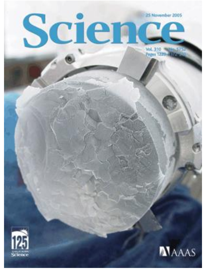
EPICA project : 800,000 years of greenhouse gas history

J. Chappellaz



3200 m of depth



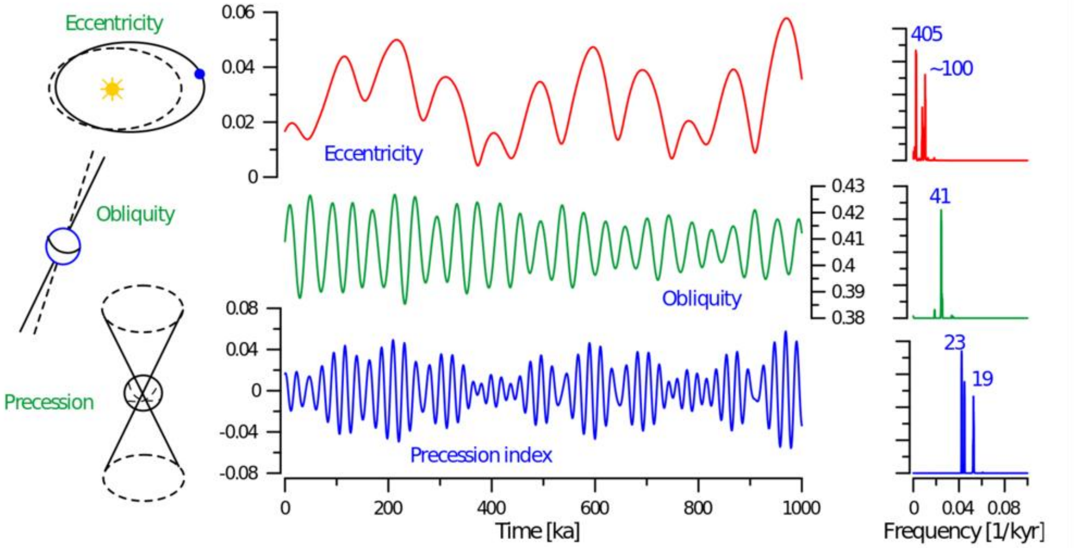


Jouzel et al., Science 2007
Lüthi et al., Nature 2008
Loulergue et al., Nature 2008
Schilt et al., EPSL 2010

Ice cores + climate models: deciphering past climate dynamics

Quaternary climate change:

- Solar radiation redistribution with seasons and latitudes (pacemaker at high northern latitudes)
- **+2.6 ± 0.5 W/m²** between glacial and interglacial periods from the combined effect of CO_2, CH_4 and N_2O
- **+3.5 ± 1 W/m²** from the albedo effect (snow, ice and vegetation)
- **+0.5 ± 1 W/m²** from dust and aerosols

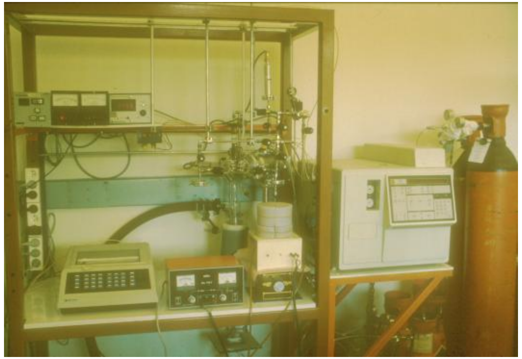


Source: https://www.cyclostratigraphy.org

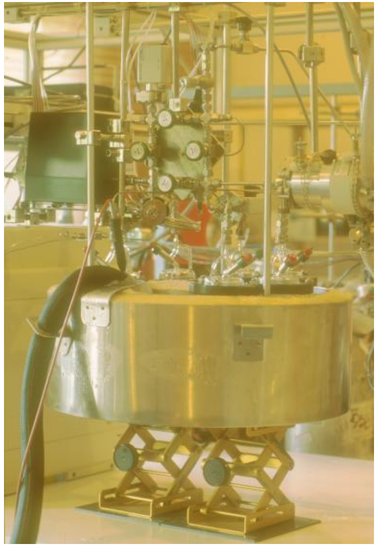
An important contribution to IPCC reports since 1990

ipcc WMO UNEP

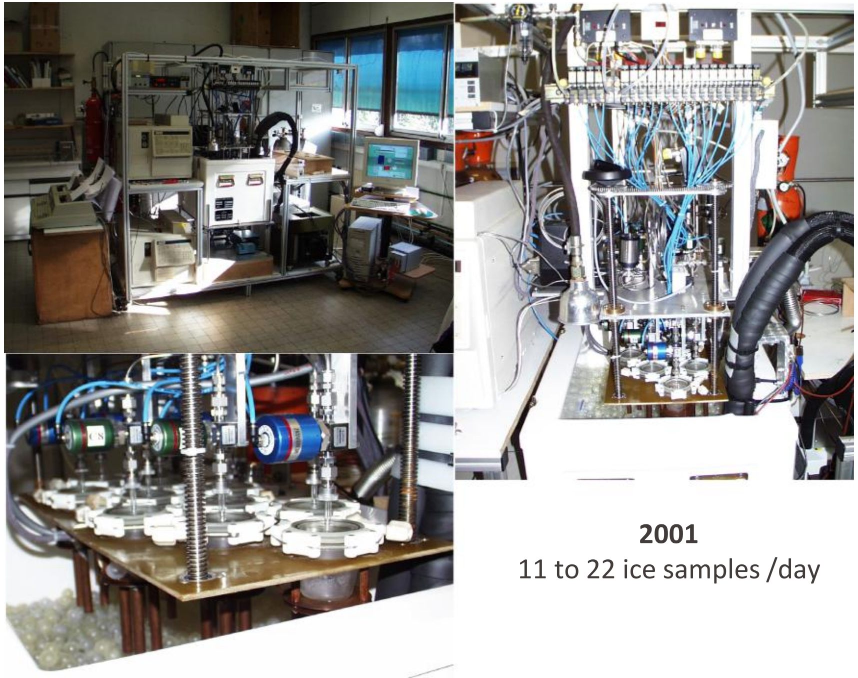
Some engineering work: improving sample throughput and precision



1988
2 ice samples / day



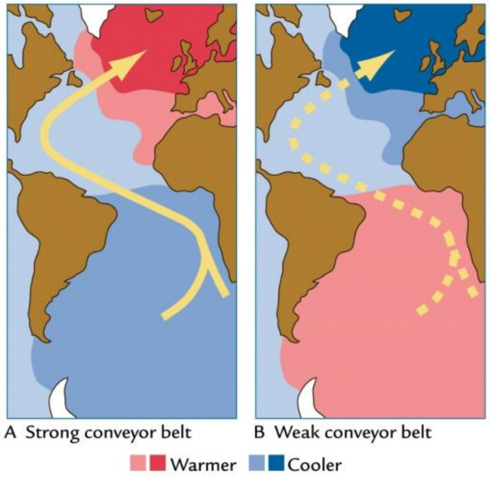
1995
7 ice samples / day



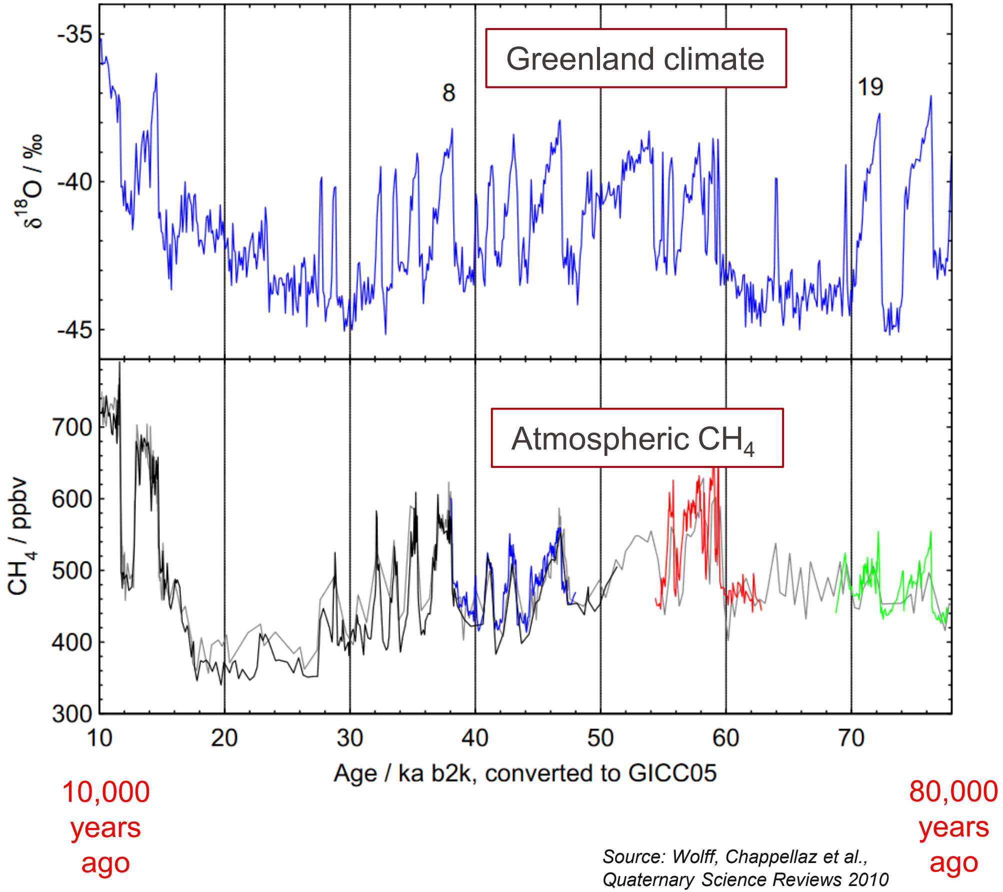
2001
11 to 22 ice samples /day

Photos: J. Chappellaz

Rapid climate change and atmospheric methane : a time resolution problem



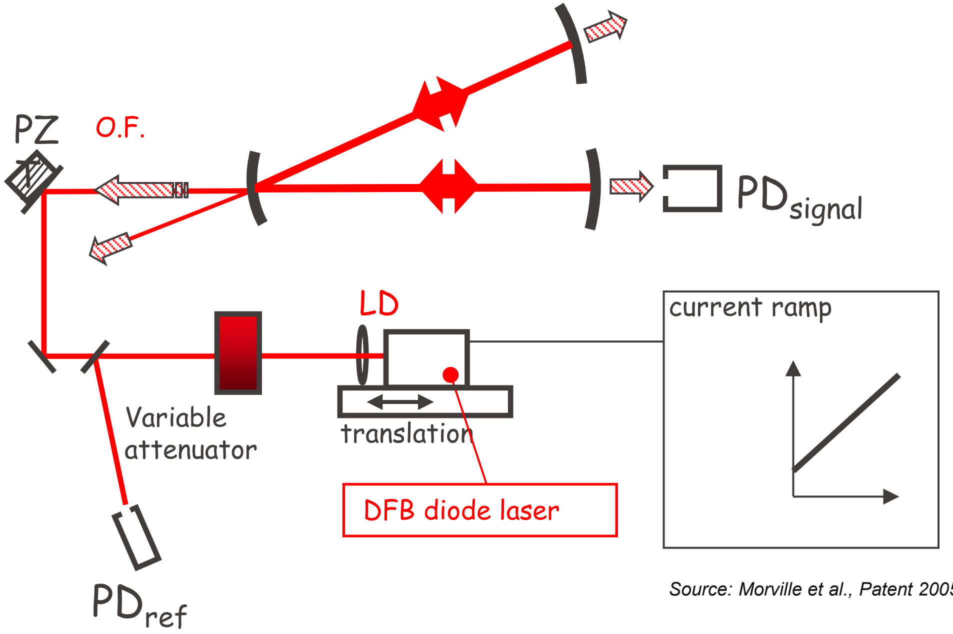
Source: Rahmstorf, Nature 2002



Source: Wolff, Chappellaz et al., Quaternary Science Reviews 2010

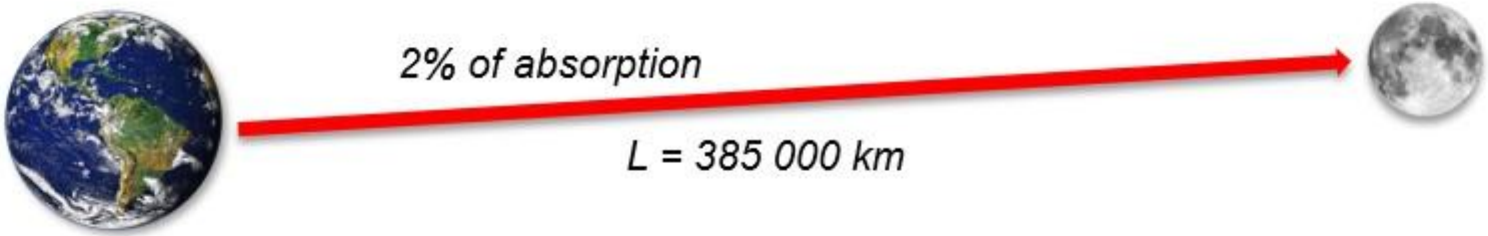
- CH_4 covaries with Greenland temperature swings during the last glaciation
- What amplitude ?
- What timing with respect to Greenland T° ?
- What speed of change ?

New technological approach : laser spectroscopy + membrane extraction

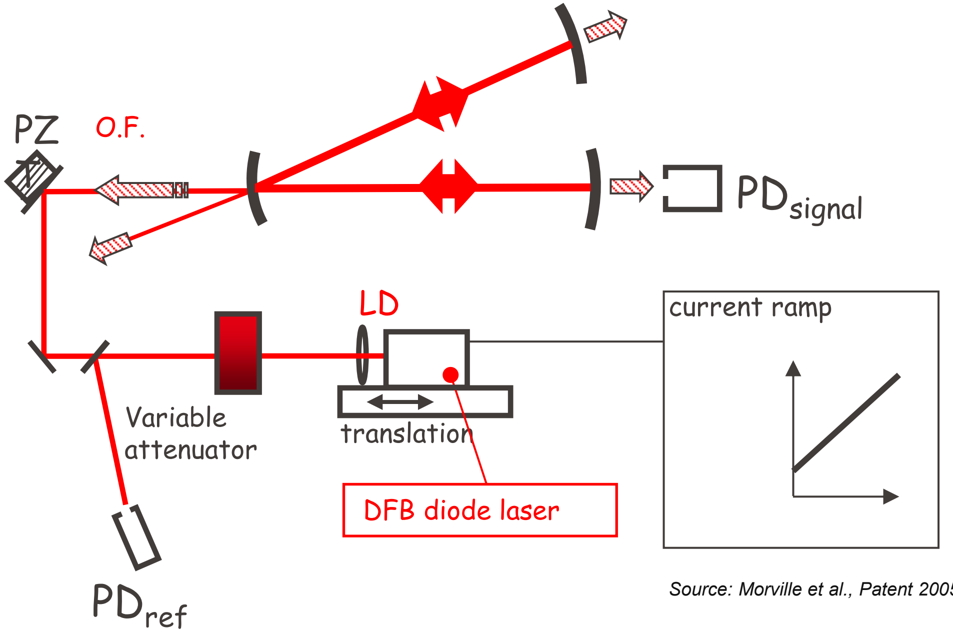


Source: Morville et al., Patent 2005

- Optical Feedback Cavity Enhanced Absorption Spectroscopy (OF-CEAS)
- Sensitivity of ~10^{-9} per cm !
- Small optical cavity (~ 10 cm^3), small sample size
- Custom-made interface to continuously extract air bubbles from a 32x32 mm ice slice



New technological approach : laser spectroscopy + membrane extraction



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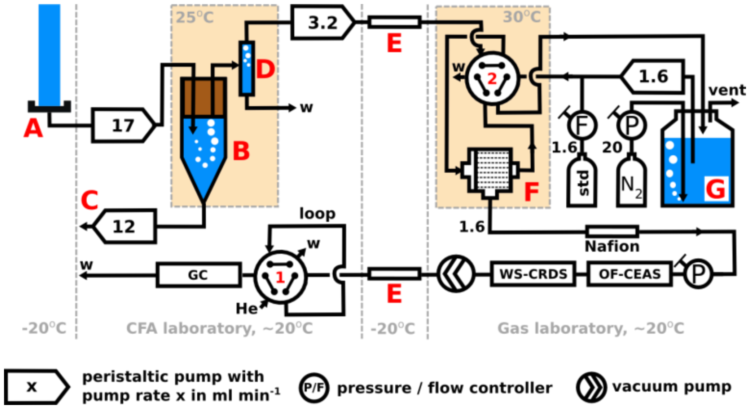
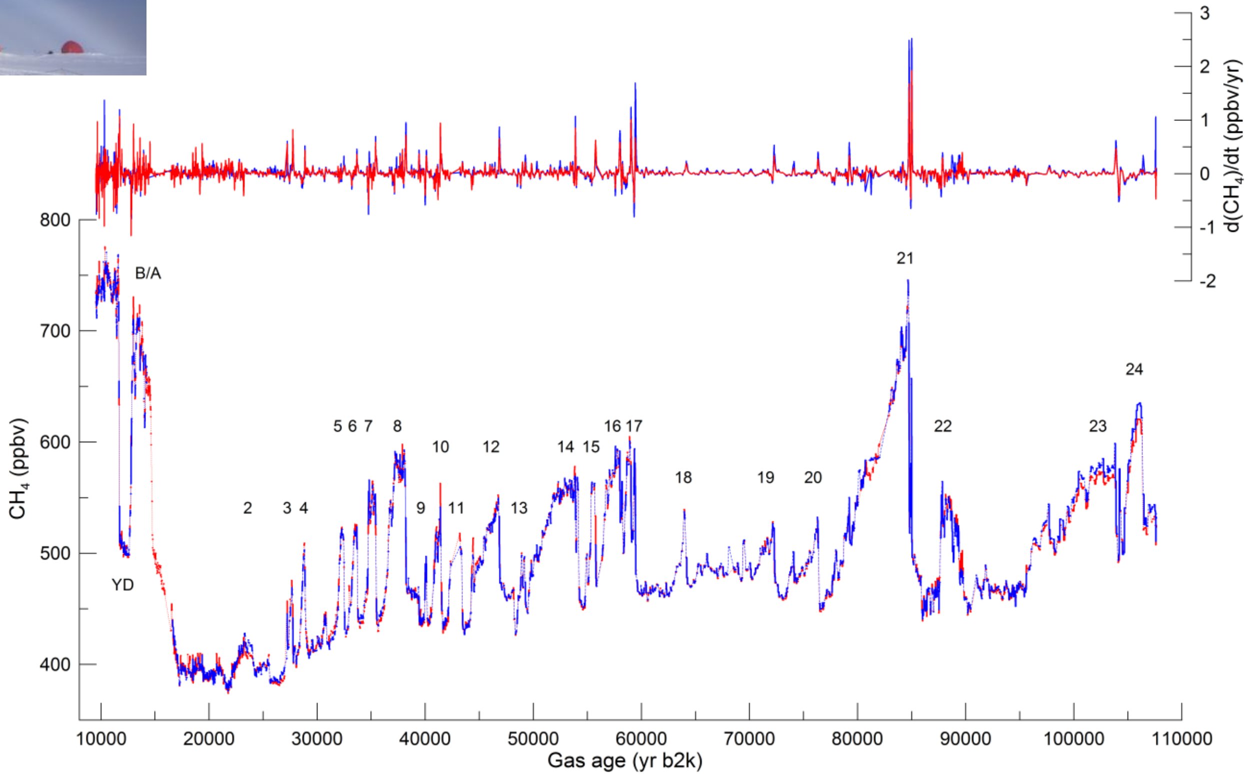


Source: Chappellaz et al., CP 2013

Laser spectroscopy applied to CH_4 measurements in ice

J. Chappellaz



Source: Chappellaz et al., CP 2013

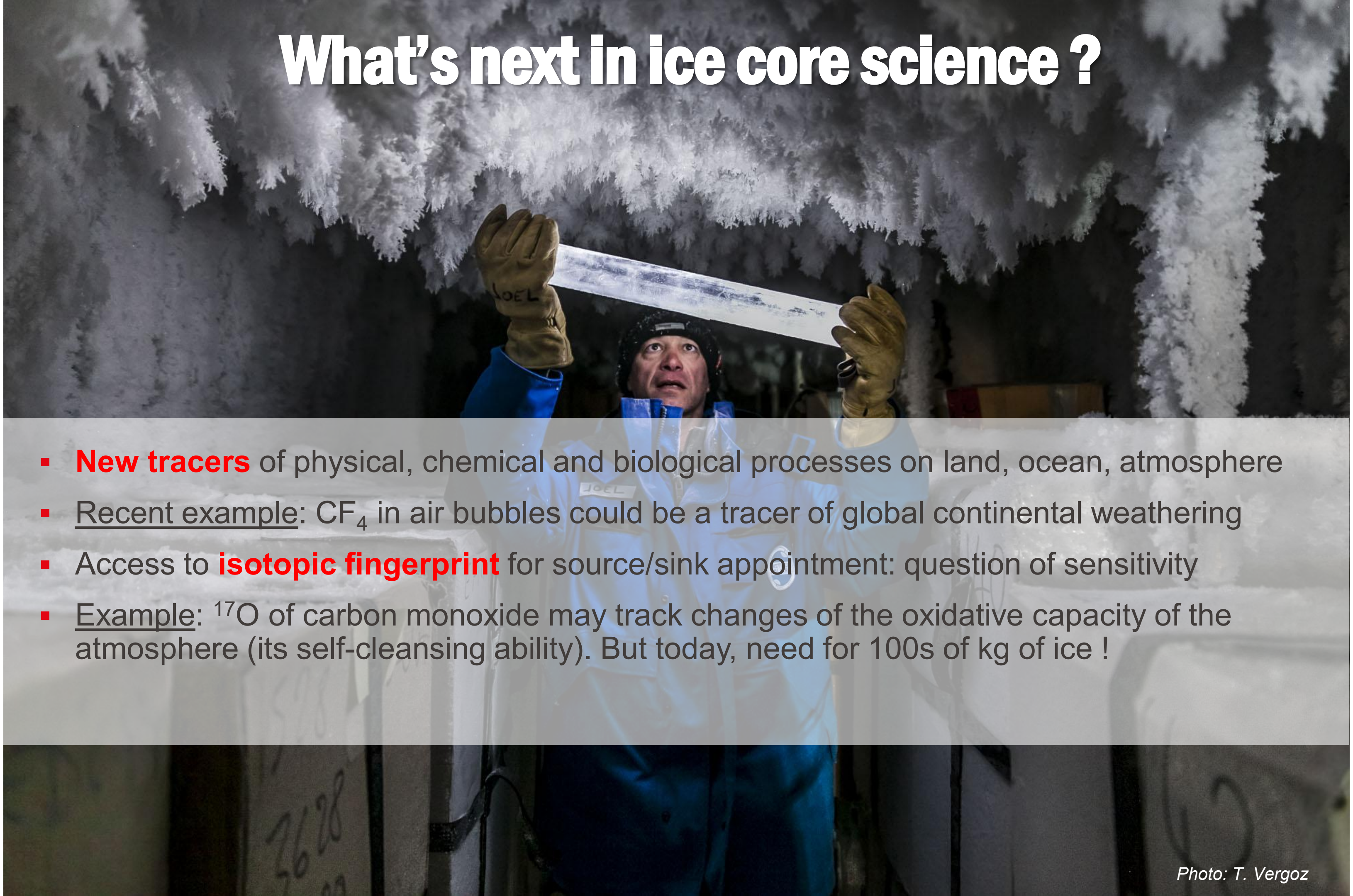
- June-July 2010 at the NEEM camp : One million data points over 900 m of freshly drilled ice core !
- Sensitivity of the CH_4 cycle: 5 to 18 ppb increase of CH_4 per °C
- Rate of change up to 2.5 ppb per year *(~ direct atmospheric observations between 2000 and 2005)*

Outline of the introduction

- **1st part**
  - What scientific challenges at the poles ?
  - How engineering can contribute ?
- **Pause of 15 min**
- **2nd part**
  - A more detailed illustration through ice core studies
  - **What future for such science and for the icy memory of the planet ?**

MOSAiC expedition: the Polarstern icebreaker in Arctic winter. Photo: J. Stroeve

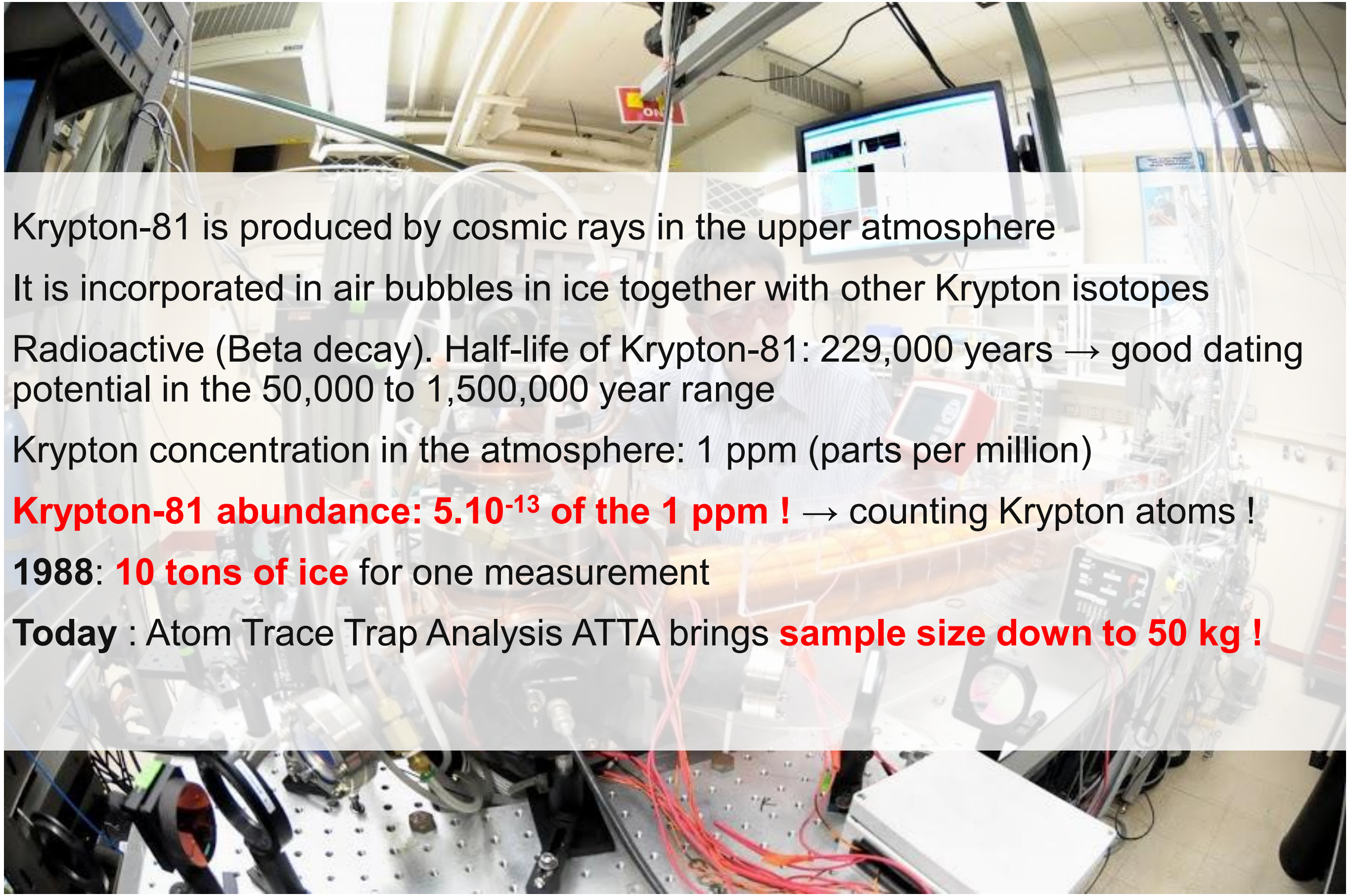
What's next in ice core science ?



- **New tracers** of physical, chemical and biological processes on land, ocean, atmosphere
- Recent example: CF_4 in air bubbles could be a tracer of global continental weathering
- Access to **isotopic fingerprint** for source/sink appointment: question of sensitivity
- Example: ^{17}O of carbon monoxide may track changes of the oxidative capacity of the atmosphere (its self-cleansing ability). But today, need for 100s of kg of ice !

Photo: T. Vergoz

An example: Krypton-81 and ice core dating



- Krypton-81 is produced by cosmic rays in the upper atmosphere
- It is incorporated in air bubbles in ice together with other Krypton isotopes
- Radioactive (Beta decay). Half-life of Krypton-81: 229,000 years → good dating potential in the 50,000 to 1,500,000 year range
- Krypton concentration in the atmosphere: 1 ppm (parts per million)
- **Krypton-81 abundance: 5.10^{-13} of the 1 ppm !** → counting Krypton atoms !
- **1988**: **10 tons of ice** for one measurement
- **Today** : Atom Trace Trap Analysis ATTA brings **sample size down to 50 kg !**

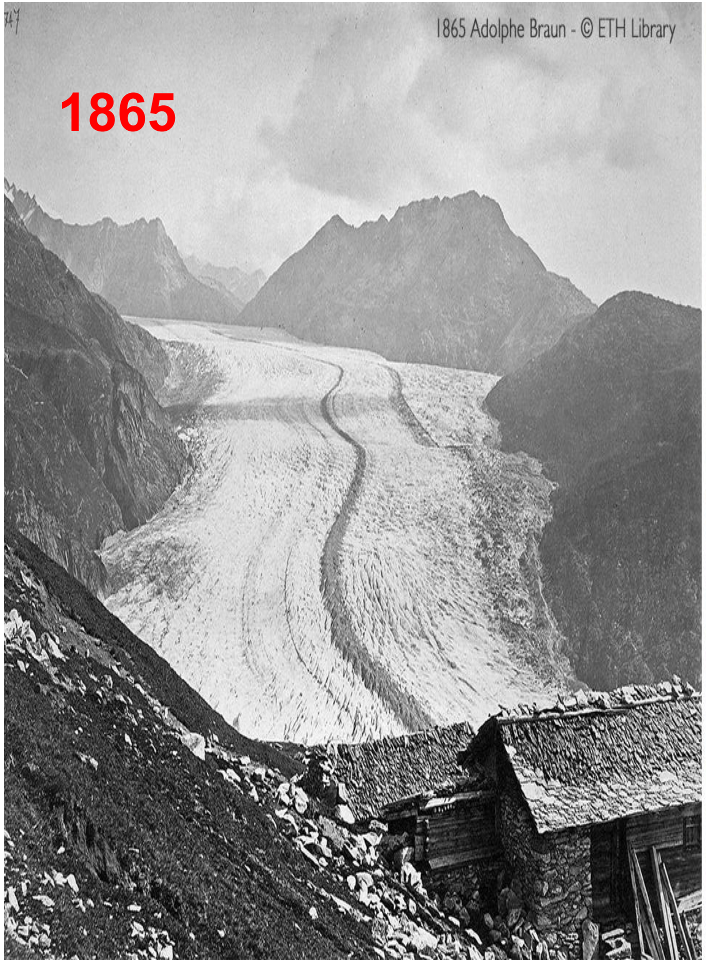
Photo: Argonne National Labs

What's next in ice core science ?

- **New tracers** of physical, chemical and biological processes on land, ocean, atmosphere
- Recent example: CF_4 in air bubbles could be a tracer of global continental weathering
- Access to **isotopic fingerprint** for source/sink appointment: question of sensitivity
- Example: ^{17}O of carbon monoxide may track changes of the oxidative capacity of the atmosphere (its self-cleansing ability). But today, need for 100s of kg of ice !
- **There is ample work for engineering development !**

Photo: T. Vergoz

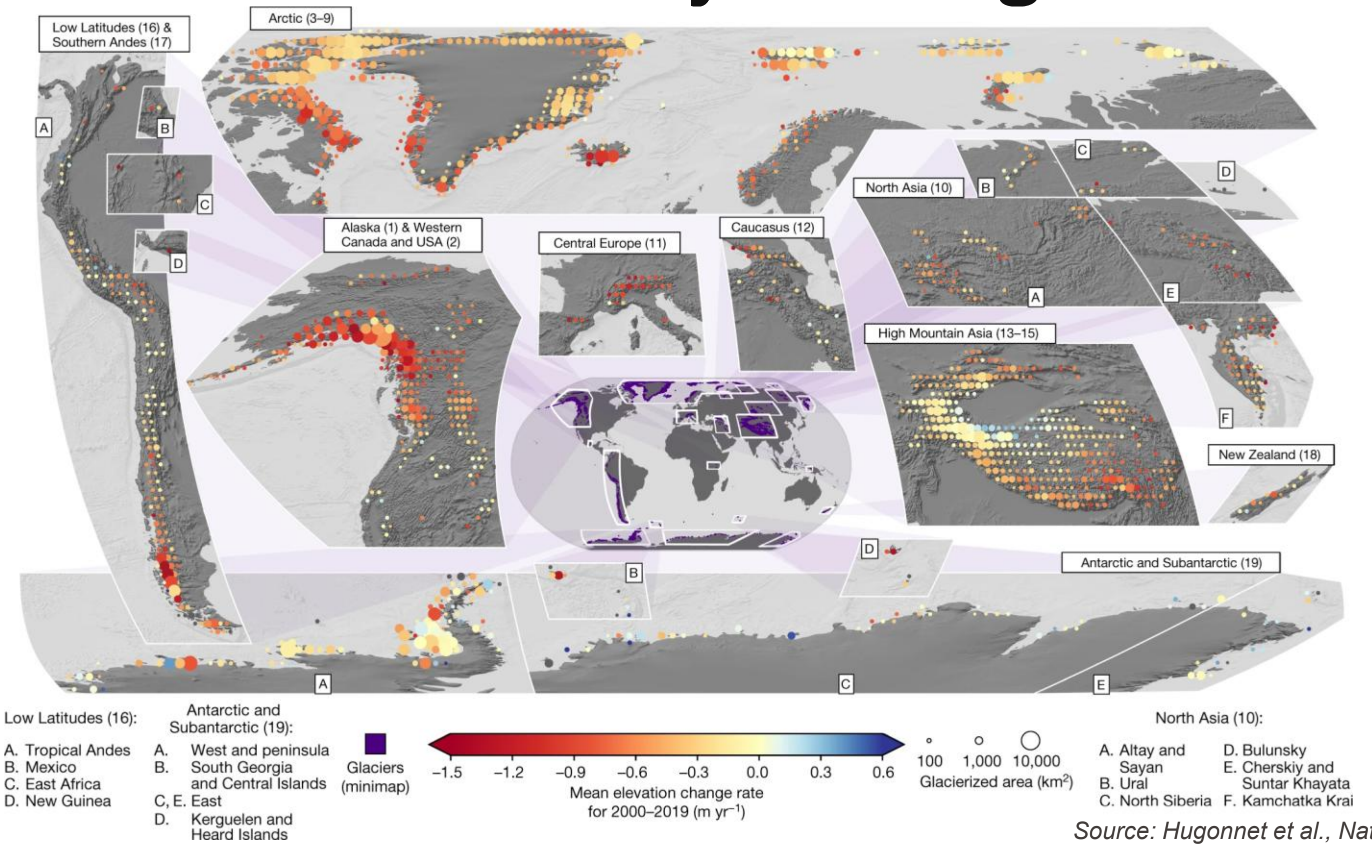
But the library is burning…



Aletsch Glacier

Switzerland

But the library is burning…



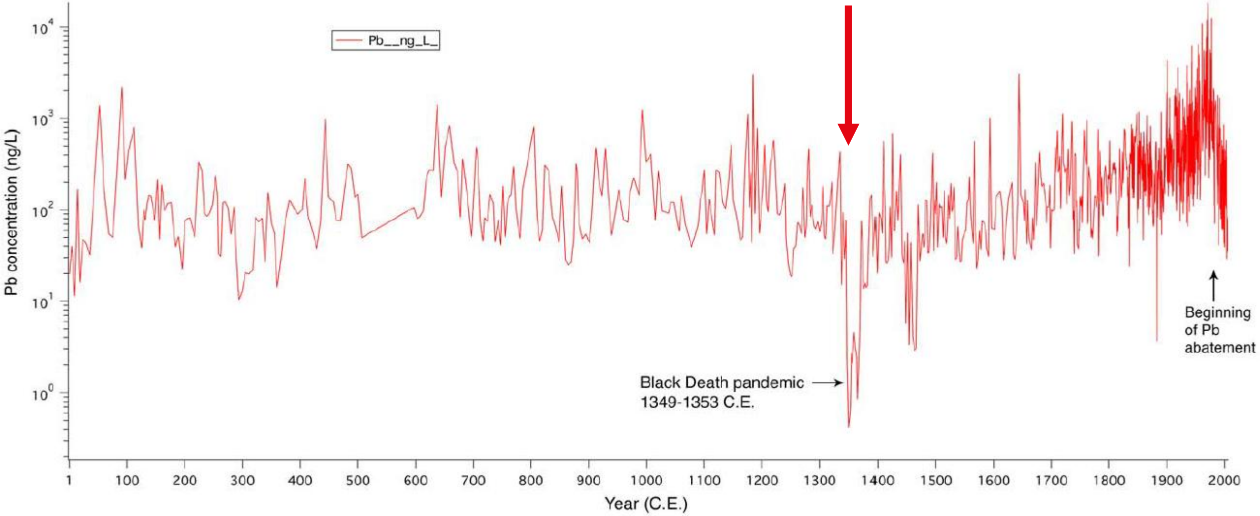
Source: Hugonnet et al., Nature, 2021

Altitude loss of glaciers between 2000 and 2019

Mountain glaciers are important for regional information

Log scale…

Illustration with **atmospheric lead (Pb) in the Alps**: Colle Gnifetti (Monte Rosa, Switzerland) ice core record over the last 2000 years



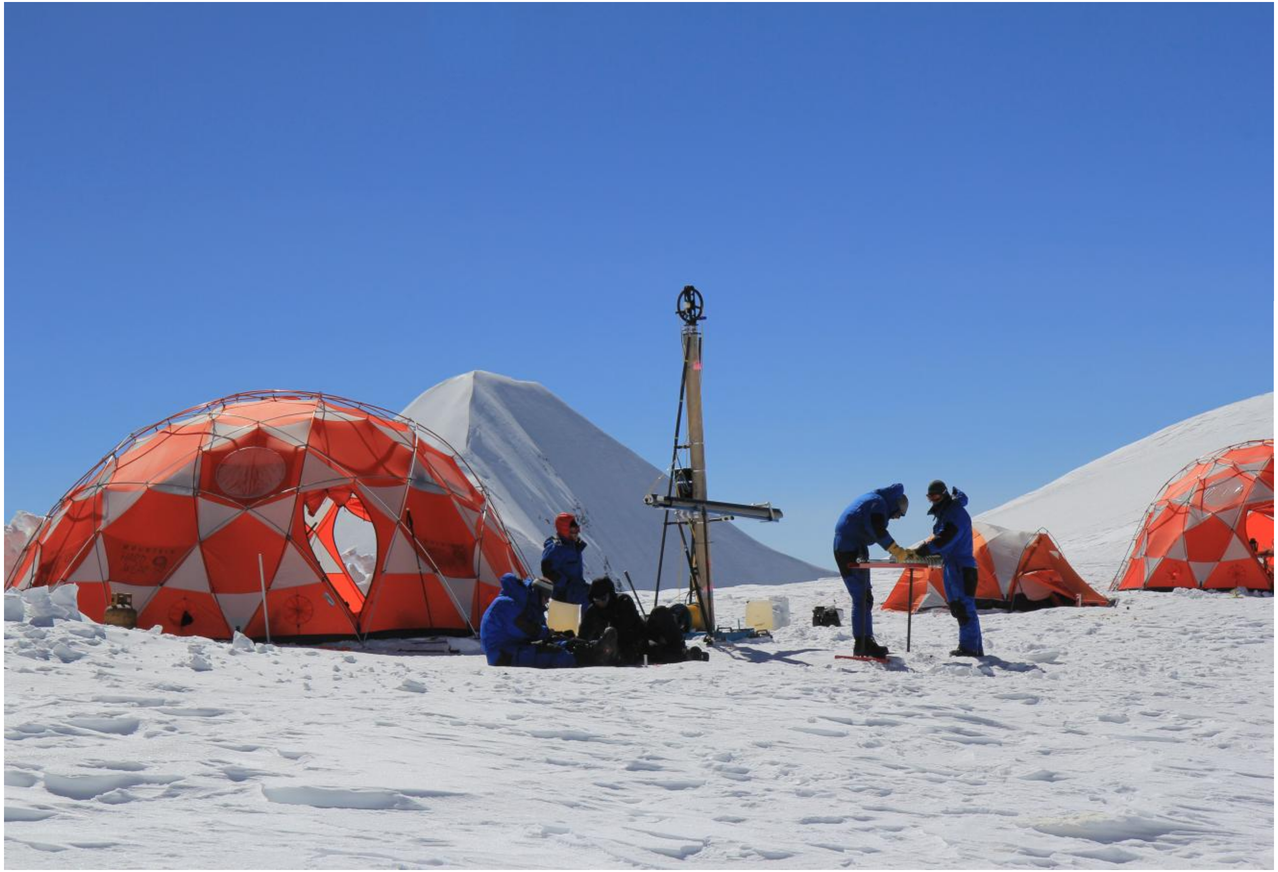
Source: *More et al., GeoHealth, 2017*

Preserve
the **Ice Memory**
for future generations

Ice Memory objective:
Collect ice cores from 20 endangered glaciers in 20 years

J. Chappellaz

ICE MEMORY
Sheltered by UGA Foundation Foundation



Drilling at Nevado Illimani, Bolivia

6300 m of altitude

Photo: Sarah del Ben

Ice Memory objective:
Create a dedicated sanctuary in Antarctica for generations to come

ICE MEMORY Sheltered by UGA Foundation Foundation

The best natural freezer in the world !

Photos: Rocco Ascione

Ice Memory: success so far, but more to come

ICE MEMORY
Sheltered by UGA Foundation
Foundation

J. Chappellaz

EPFL

Take-home messages

- Glaciers are a **memory book** of our planet
- Those in **polar** regions provide fundamental information about **natural climate changes** and their mechanisms on long time scales
- Those from **mountains** (shorter time scale) complement the regional information, in particular for tracers having a short atmospheric lifetime: key to constrain, e.g., the amplitude of **anthropogenic pollutions**
- Glaciers (including at the poles) are **under threat** and we will loose forever this unique environmental memory book
- We need a new generation of scientists and engineers to develop the **analytical methodologies of tomorrow**

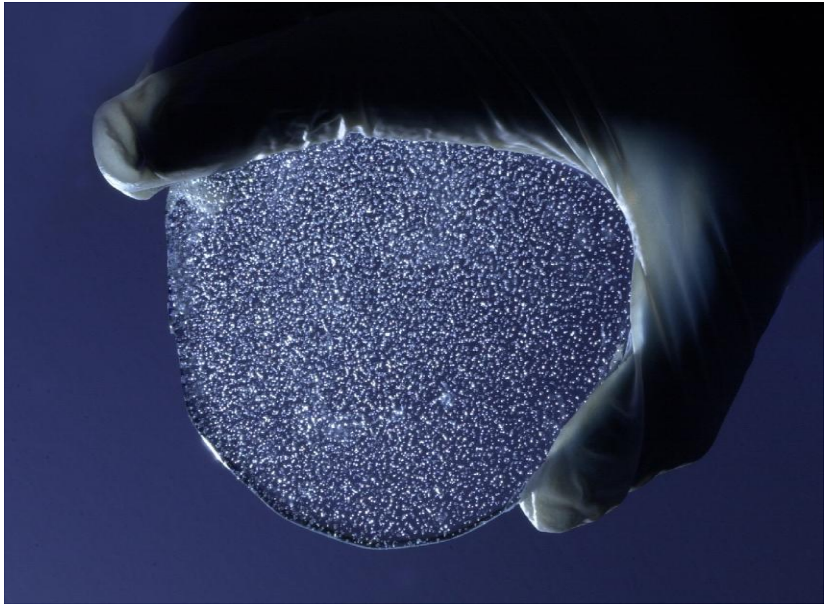
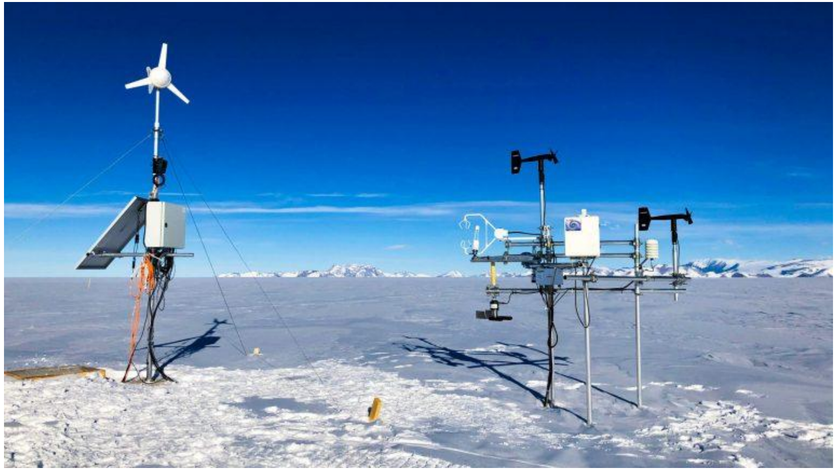


Photo: British Antarctic Survey

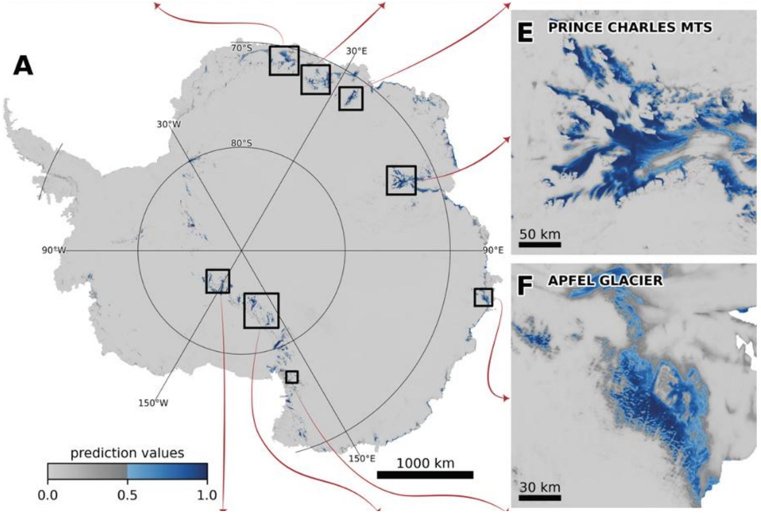
Photo: X. Faïn, Taylor Glacier, Antarctica

IIE / ALPOLE and Antarctica



CRYOS (Michi Lehning) :

- atmosphere / snow physical processes, surface mass balance
- SNOWPACK model coupled to climate models



ECEO (Devis Tuia) :

- Location of Antarctic blue ice areas
- Multi-sensor satellite observations and deep learning algorithm

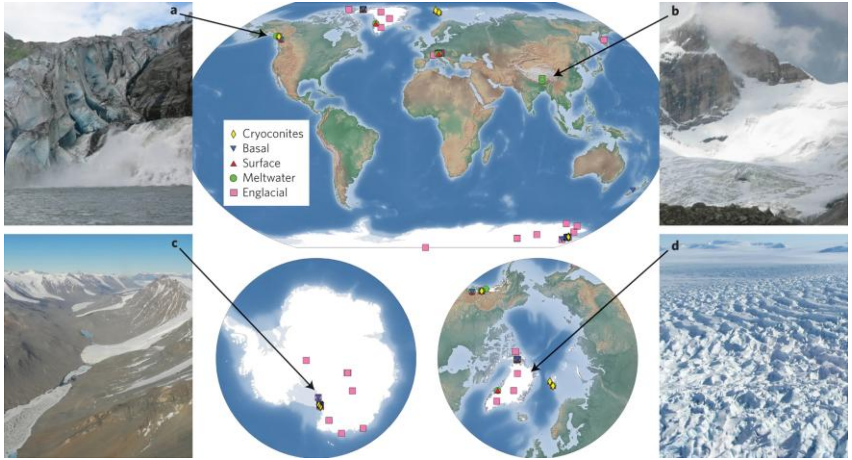
IIE / ALPOLE and Antarctica

EERL (Julia Schmale) :

- Atmospheric physical and chemical processes
- ACE circum-Antarctic expedition 2016-2017
- ORACLES project (2023-2028) Swiss NSF : role of cloud particles on Antarctic surface temperature warming

RIVER (Tom Battin) :

- Organic carbon storage under the Antarctic ice sheet and its loss through glacier calving

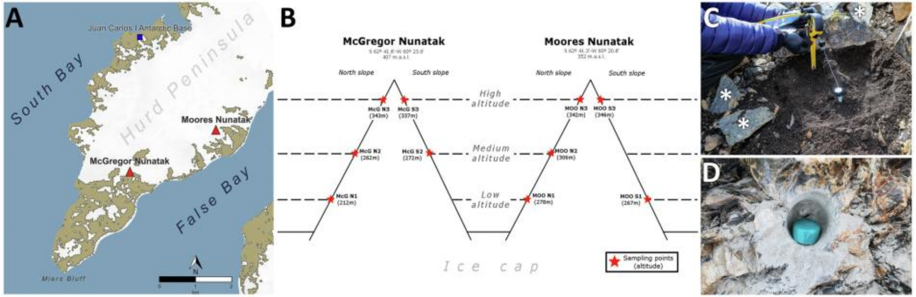


IIE / ALPOLE and Antarctica

J. Chappellaz

MACE (Ianina Altshuler) :

- Microbial communities of Antarctic nunataks, as analogs of past environmental conditions on Mars



SENSE (Jérôme Chappellaz) :

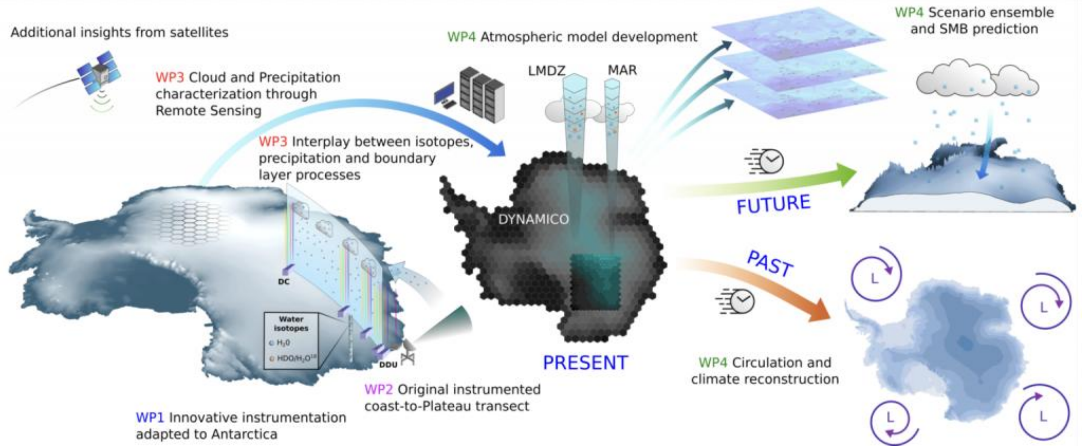
- Ice Memory initiative to safeguard ice cores in Antarctica, from vanishing glaciers worldwide (endorsed by UNESCO)

ICE MEMORY
Sheltered by UGA Foundation
Foundation

ENAC / IIE and Antarctica

LTE (Alexis Berne) :

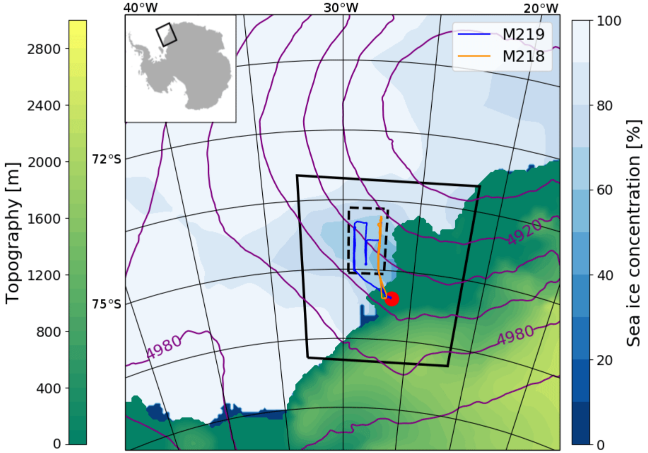
- ERC Synergy Grant AWACA (2021-2026) : Antarctic precipitation
- Autonomous stations inland for in-situ observations

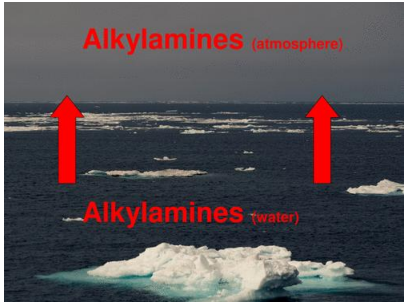


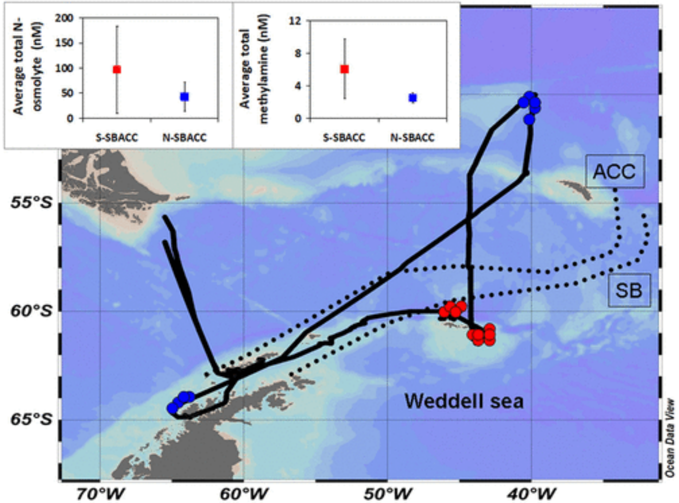
ENAC / IIE and Antarctica

LAPI (Athanasios Nenes) :

- Ice crystal nucleation in summer clouds along the Antarctic coast :
    - Flights in the Weddell Sea
- Measurements of alkylamines from seawater and in the atmosphere along the Antarctic peninsula







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