Exercises #6

Sustainability, climate and energy

Today's goals

- Deeper dive into a proxy: strengths and limits of CO_2 measurements in ice cores.
    - Chemical and physical biases.
    - Corrections.
- EarthViewer app: maneuvering through geological time scales
- Quiz on the morning course.
- Discussion around a fictional article. Interview of Richard Malone, in EcoView Weekly, March 25th, 2025.

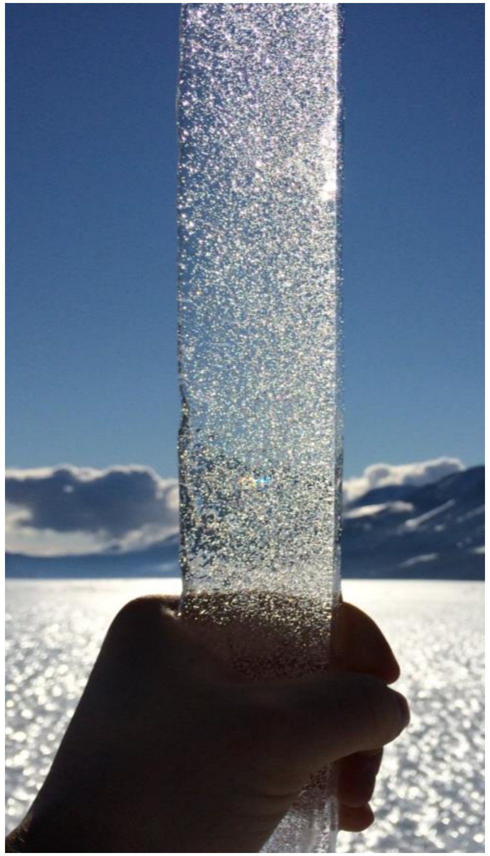
Today's goals

- **Deeper dive into a proxy: Strengths and limits of CO_2 measurements in ice cores.**
  - **Chemical and physical biases.**
  - **Corrections.**
- EarthViewer app: maneuvering through geological time scales
- Quiz on the morning course.
- Discussion around a fictional article. Interview of Richard Malone, in EcoView Weekly, March 25th, 2025.

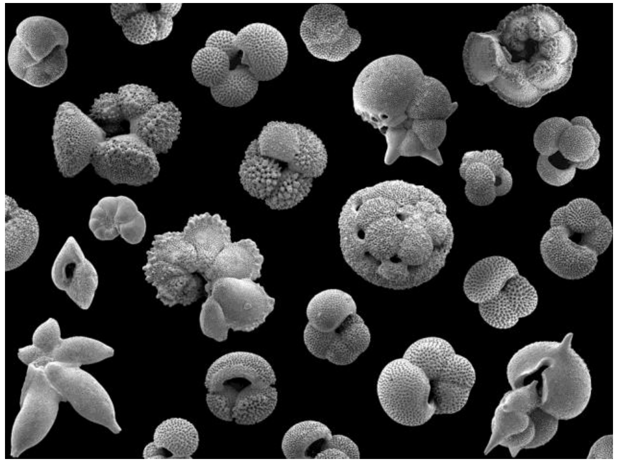
How to reconstruct past atmospheric CO_2 ?

- Only one direct method: measuring CO_2 in **air bubbles trapped in ice cores**. Valid so far back to 800'000 years (oldest ice ever drilled in Antarctica).

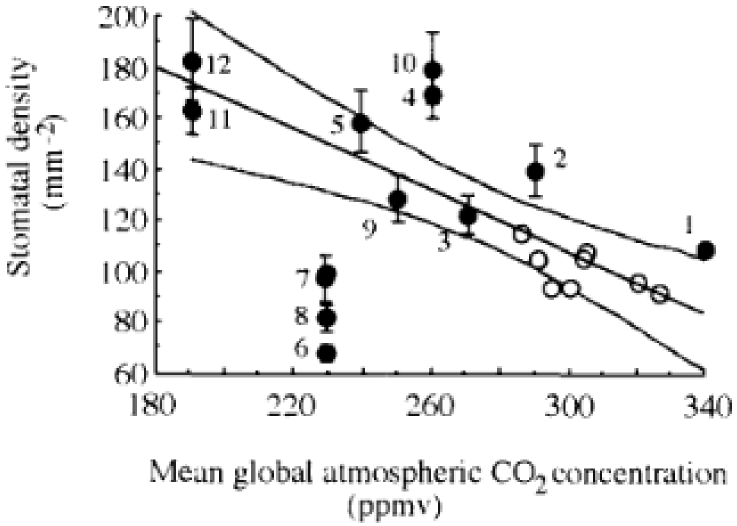
- Indirect methods:
  - **Boron isotopes**. Their ratio in marine carbonates depends on seawater pH and thus in part on dissolved CO_2 from the atmosphere. But needs other constraints on the carbonate chemistry.
  - **Carbon isotopes of alkenones**. Organic molecules produced by phytoplancton. $\delta^{13}C$ of alkenones depends on dissolved CO_2 (and other parameters like temperature).
  - **Stomatal density in fossil leaves**. If higher CO_2, fewer stomata (to limit water loss). Empirical method which supposes that the plant behaviour was like modern plants. Influenced by local CO_2 concentration.



Source: Peter Neff

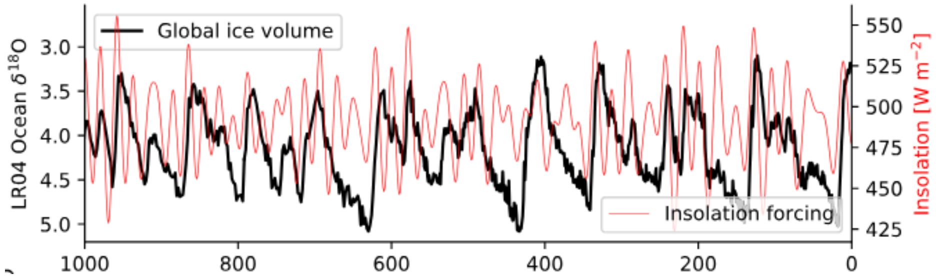


Source: Paul Pearson, Cardiff University

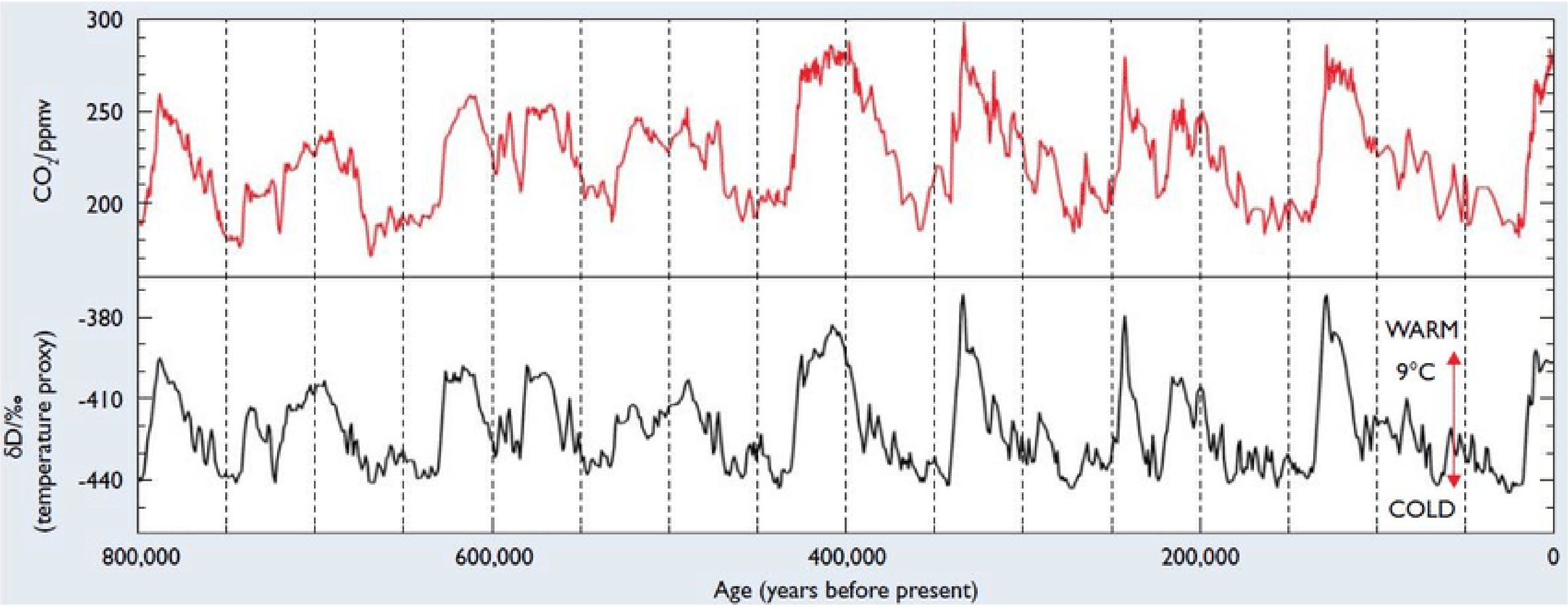


Source: Beerling and Chaloner, Rev. Palaeobotany & Palynology, 1994

Global ice volume: insolation and CO_2

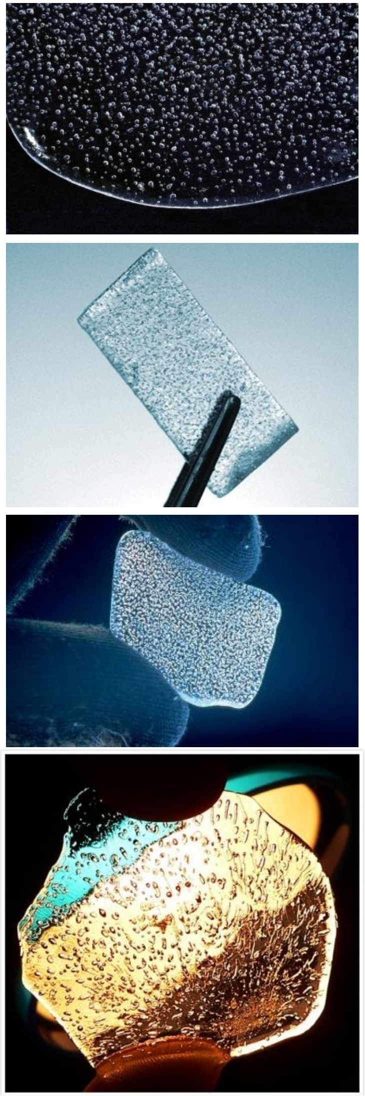


- CO_2 measured in Vostok and EPICA/Dome C ice cores from Antarctica.
- Minimum of ~180 ppm.
- Maximum of 300 ppm.



Source: Boers et al., Environ. Res. Lett. 2022 ; Lüthi et al., Nature 2008

How to reconstruct past atmospheric CO_2 ?

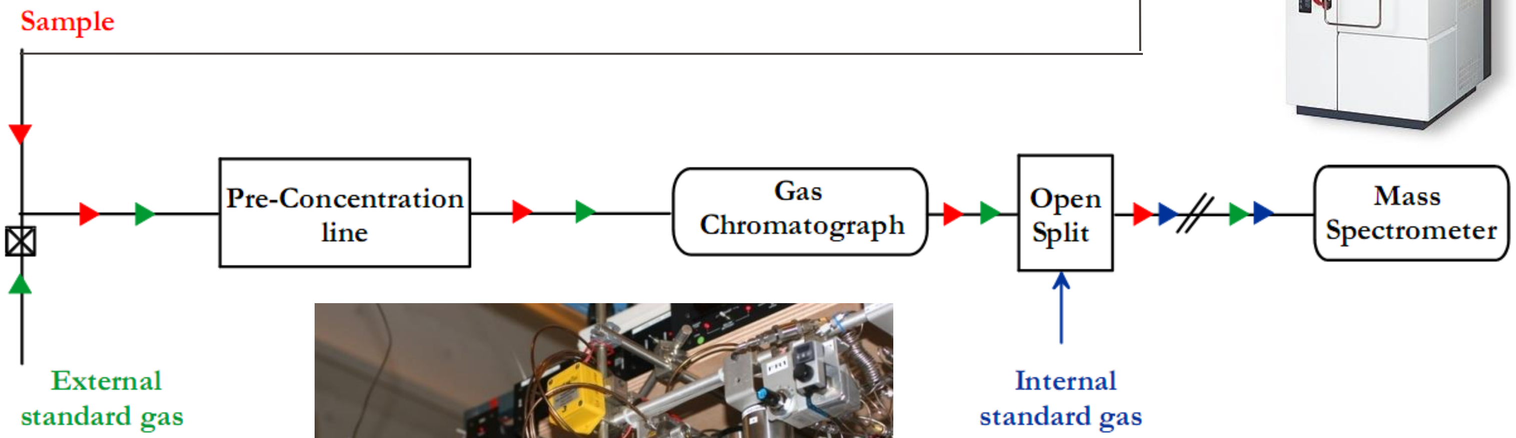


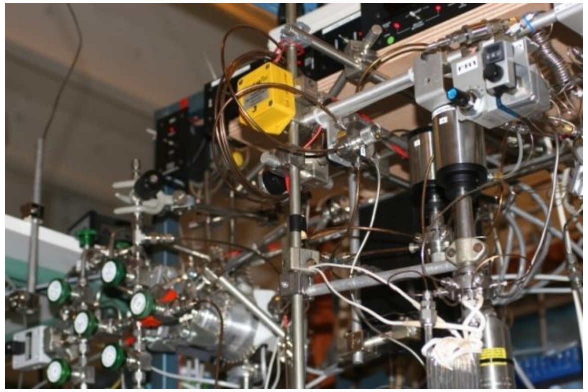
Crushing under vacuum

Gas transfer under vacuum or carrier gas

Gas extraction from the ice can also be by sublimation under vacuum

Typical sample size: 5 to 40 g





St. gas: 26 min

* 8

Sample: 28 min

* 3

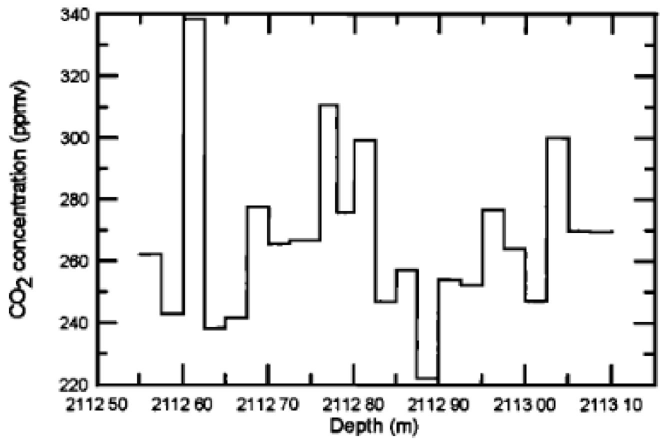
For stable carbon isotope analyses on trapped CO_2: **1 day per sample...**

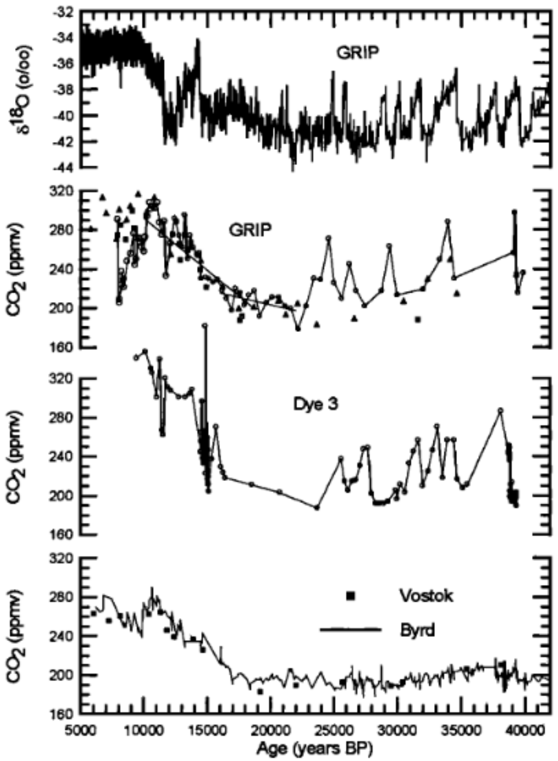
What potential biases do you anticipate when measuring CO_2 in ice cores ?

What potential biases do you anticipate when measuring CO_2 in ice cores ?

- First of all, remember about quantities!
- 280 ppm of CO_2 in ice containing 0.1 cm^3 of air per gram gives 55 nanograms of CO_2 per gram of ice !
- **Chemistry**:
  - Carbonate + acid reaction $\mathrm{CaCO_3}(s) + 2\mathrm{H}^+ \rightarrow \mathrm{Ca}^{2+} + \mathrm{CO_2}(g) + \mathrm{H_2O}$
  - Oxidation of organic matter $\mathrm{C_{org}} + O_2 \rightarrow \mathrm{CO_2}$

Source: *Anklin et al., J. Geophys. Res. 1997*





Right: Measured CO_2 anomalies (due to chemical artefacts) in Greenland ice cores (middle), compared with the Antarctic records (bottom).
Left: CO_2 anomalies at centimetric scale in Greenland ice.

What potential biases do you anticipate when measuring CO_2 in ice cores ?

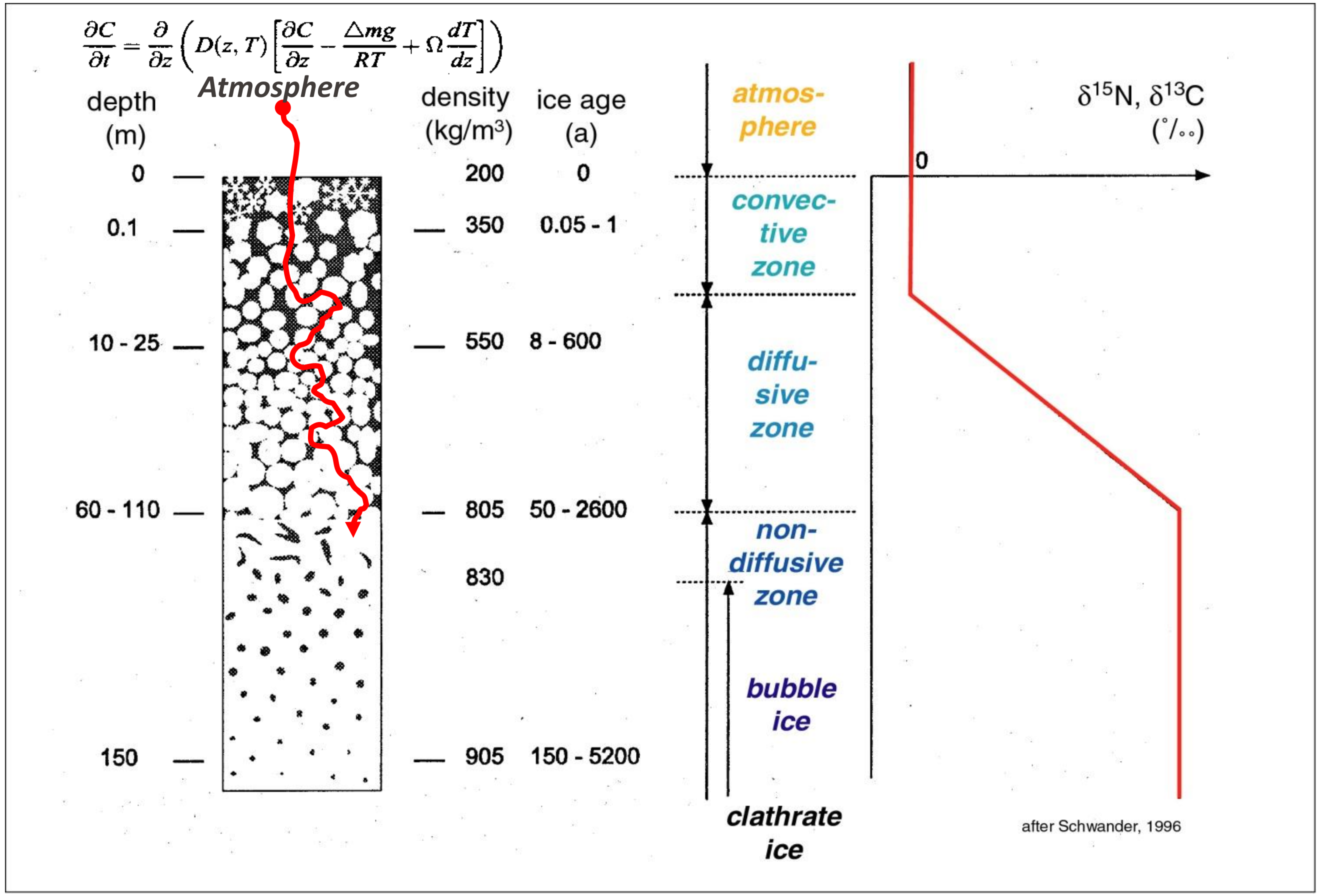
- First of all, remember about quantities!
- 280 ppm of CO_2 in ice containing 0.1 cm^3 of air per gram gives 55 nanograms of CO_2 per gram of ice !
- **Physics**:
- Diffusion through ice cracks. Careful about sample selection. Problem with ice containing gas hydrates. We leave the ice for one year in the field, to «relax».
- Gravitational fractionation.
- Thermal diffusion (negligible).
- Smoothing due to gas diffusion and progressive trapping of air bubbles.

Gas diffusion and gas trapping in polar firn and ice: advantages and limits of an archive

- Convection in upper layers, due to temperature gradients.
- Molecular diffusion under the influence of gravitation through the firn colum.
- Bubble enclosure in the so-called “lock-in” depths. A slow process.
- Gas age – ice age difference.

→ Trapped air = average of the atmospheric composition over 10 to 100’s of years

→ Firn air = large samples of the atmosphere over the last 10’s of years



How strong is the gravitational effect on CO_2 ?

Simplified calculation using the $^{15}N/^{14}N$ isotopic ratio of molecular nitrogen (which is constant in the atmosphere)

$$\mathrm{CO}_2^{\mathrm{corrected}} = \mathrm{CO}_2^{\mathrm{measured}} \left[1 - (M_{\mathrm{CO}_2} - M_{\mathrm{air}}) \times \delta^{15}\mathrm{N}_2\right]$$

- *M* are molar mass of CO_2 and of air.
- $\delta^{15}N$ of N_2 = 0.4 ‰ (valid today at Dome C in Antarctica)
- Assume CO_2 measured = 280 ppm

Calculate the gravitational correction on CO_2 in ppm.

-1,68 PPM

263.5 PPM

0.2PPM

278

278.32

278.31

-1.68PPM

17 PPM

2.78*10E-4

-17PPM DIFFERENCE

Solution

Simplified calculation using the $^{15}N/^{14}N$ isotopic ratio of molecular nitrogen (which is constant in the atmosphere)

$$\mathrm{CO_2^{corrected}} = \mathrm{CO_2^{measured}}\left[1 - (M_{\mathrm{CO_2}} - M_{\mathrm{air}}) \times \delta^{15}\mathrm{N_2}\right]$$

- *M* are molar mass of CO_2 and of air.
- $\delta^{15}N$ of N_2 = 0.4 ‰ (valid today at Dome C in Antarctica)
- Assume CO_2 measured = 280 ppm

Calculate the gravitational correction on CO_2 in ppm.

- $[CO_2]$corrected ≈ 280 x (1- (44 - 29) x 0.0004) = 278.32 ppm
- Correction of ~1.7 ppm
- Small but not negligible !

What difference of age between trapped CO_2 and surrounding ice ?

Simplication: we will assume that the difference of age is simply the ratio between the snow/firn column thickness *z* (converted into ice, in m) and the mean snow accumulation on site *A* (in m of water equivalent per year):

$$\Delta age = \frac{z}{A}$$

- We take a firn thickness of 100 m
- We consider an average snow density of 0.7
- Today's mean snow accumulation at Dome C in Antarctica is 3 cm per year

What is the difference of age between trapped CO_2 and the surrounding ice (in years) ?

2'333.333333333333333333333333333333...
4761.9 YEARS
4762 YR
2333
4762 YEARS
4761.9
4762
4761
233333 YEARS
2325 YEARS

Solution

Simplication: we will assume that the difference of age is simply the ratio between the snow/firn column thickness *z* (converted into ice, in m) and the mean snow accumulation on site *A* (in m of water equivalent per year):

$$\Delta age = \frac{z}{A}$$

- We take a firn thickness of 100 m
- We consider an average snow density of 0.7
- Today's mean snow accumulation at Dome C in Antarctica is 3 cm of water equivalent per year

What is the difference of age between trapped CO_2 and the surrounding ice (in years) ?

- Firn thickness *z* = 100 x 0.7 = 70 m of water equivalent
- Mean snow accumulation A = 0.03 m / yr
- Δage = 70 / 0.03 = ~2300 years !

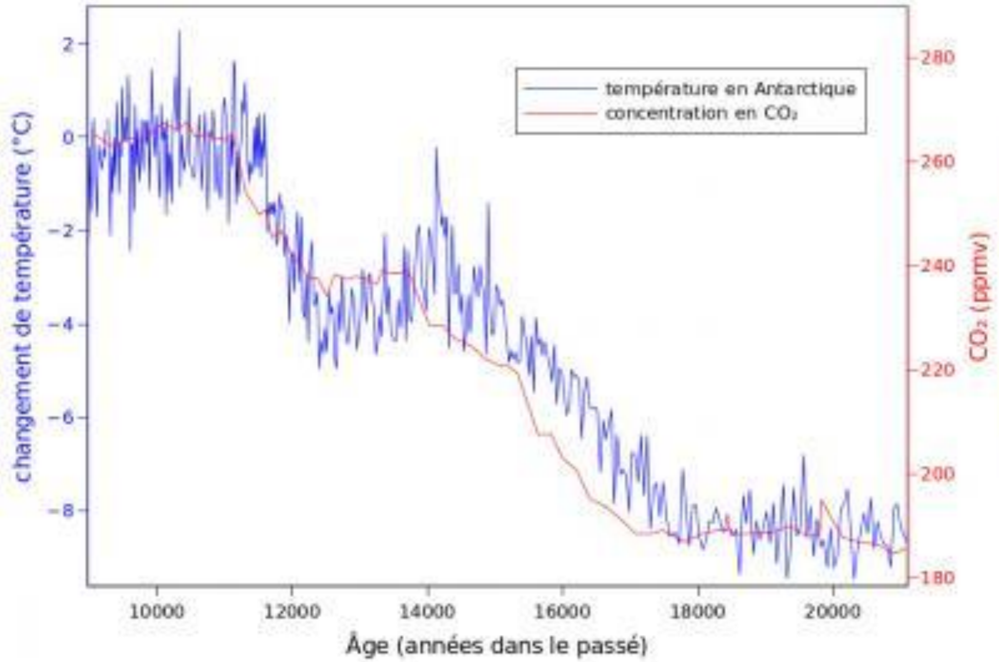
Can go up to 6000 years during glacial conditions (lower snow accumulation).

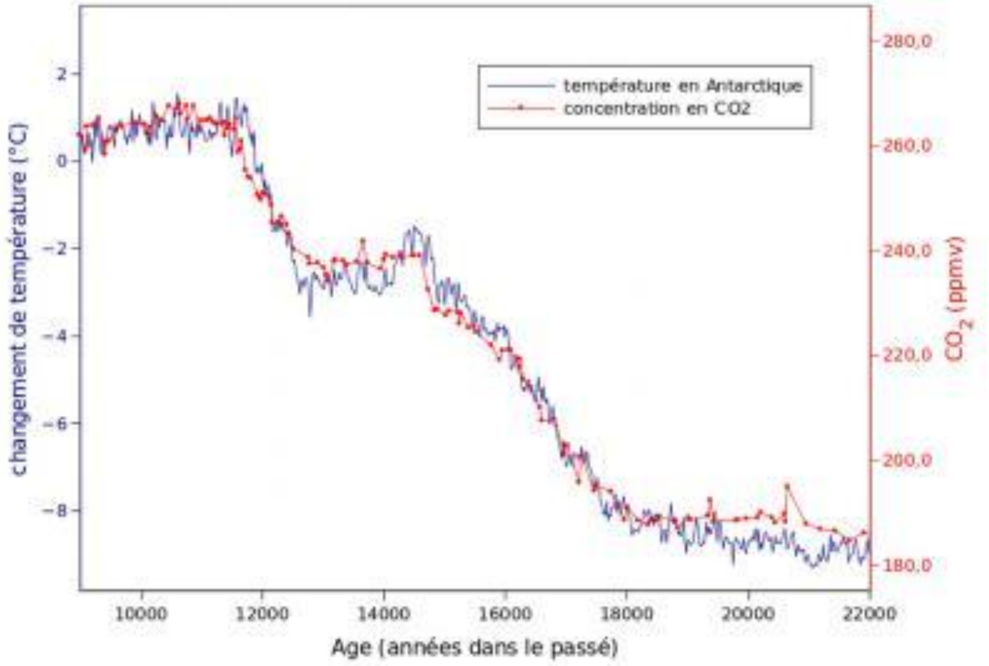
A major source of uncertainty when looking at the phase relationship between CO_2 and temperature changes.

It has been largely used by climate-skeptics to argue that CO_2 had no responsibility in glacial-interglacial transitions.

Ice age – gas age difference: a major challenge for ice core scientists

Joe Barton, represented Texas at the U.S. House of Representatives from 1985 to 2019: *«An article in Science magazine illustrated that a rise in carbon dioxide did not precede a rise in temperatures, but actually lagged behind temperature rises by 200 to 1000 years. A rise in carbon dioxide levels could not have caused a rise in temperature if it followed the temperature.”*





Adapted from Parrenin et al., Science 2013.
Left: time relationship published by Monnin et al. (Science 2001) and based on modelling of the age difference.
Right: new estimate using a continental reconstruction of Antarctic temperature and an age difference constrained by stable isotopes of N_2 and other markers.

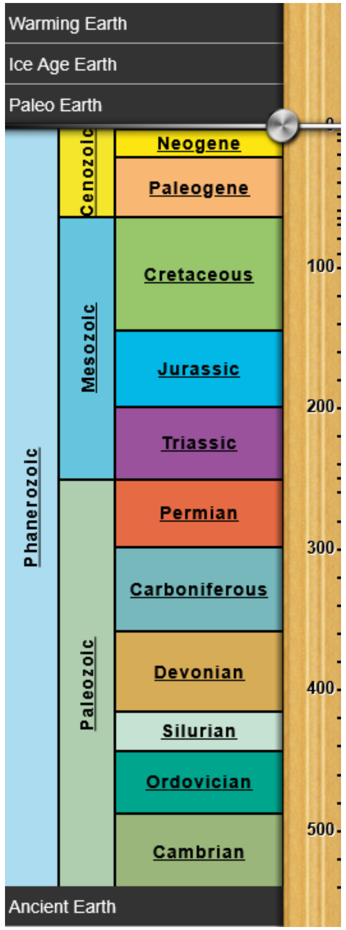
Today's goals

- Deeper dive into a proxy: strengths and limits of CO_2 measurements in ice cores.
    - Chemical and physical biases.
    - Corrections.
- **EarthViewer app: maneuvering through geological time scales**
- Quiz on the morning course.
- Discussion around a fictional article. Interview of Richard Malone, in EcoView Weekly, March 25th, 2025.

Maneuver through geological times and past climate !

- Connect to EarthViewer from BioInteractive
- https://media.hhmi.org/biointeractive/earthviewer_web/earthviewer.html
- Created by Howard Hughes Medical Institute.

- You can rotate the Earth to see different latitudes and longitudes.
- Click on the timeline on the left to select different geological era (ice age, paleo, ancient).
- Use the «charts» to show the evolution of different variables.
- Time, Oxygen and CO_2 appear in the upper left part, changing when you scrool through geological times.



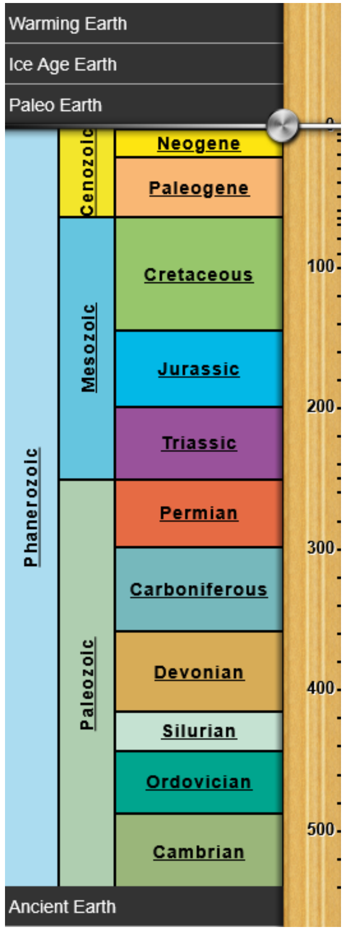
Maneuver through geological times and past climate !

- Scroll through time and look in particular what happens at the two poles. Ice sheets or sea ice are represented in white.

- Look at 500 Myr, 300 Myr, 100 Myr and 0:
  - Note temperature and CO_2
  - How do they compare ?
  - Why lower CO_2 at 300 Myr (look at the name of the geological period before) ?

- Look at «Ice Age Earth»:
  - Watch the evolution of boreal glaciation. When did eastern Canada become ice free ?
  - Watch Africa from the 21,000 years ago. What do you notice ?
  - Same question for Australia and southeast Asia.

Take notes. You'll give your answers in the succession of the following polls, question by question.



Look at 500 Myr, 300 Myr, 100 Myr and 0

Note temperature and CO_2
How do they compare ?

Look at 500 Myr, 300 Myr, 100 Myr and 0

Why lower CO_2 at 300 Myr (look at the name of the geological period before) ?

Look at «Ice Age Earth»

Watch the evolution of boreal glaciation. When did eastern Canada become ice free ?

Look at «Ice Age Earth»

Watch Africa from the 21,000 years ago. What do you notice ?

Look at «Ice Age Earth»

Same question for Australia and southeast Asia.

Today's goals

- Deeper dive into a proxy: strengths and limits of CO_2 measurements in ice cores.
  - Chemical and physical biases.
  - Corrections.
- EarthViewer app: maneuvering through geological time scales
- **Quiz on the morning course.**
- Discussion around a fictional article. Interview of Richard Malone, in EcoView Weekly, March 25th, 2025.

Which of the following sentences are true ?

A. The jet stream is an atmospheric current above the Atlantic Ocean circulating from east to west.

B. The El Niño Southern Oscillation (ENSO) is an example of external climate variability.

C. A positive phase of the North Atlantic Oscillation (NAO) typically brings wetter and warmer winters to northern Europe.

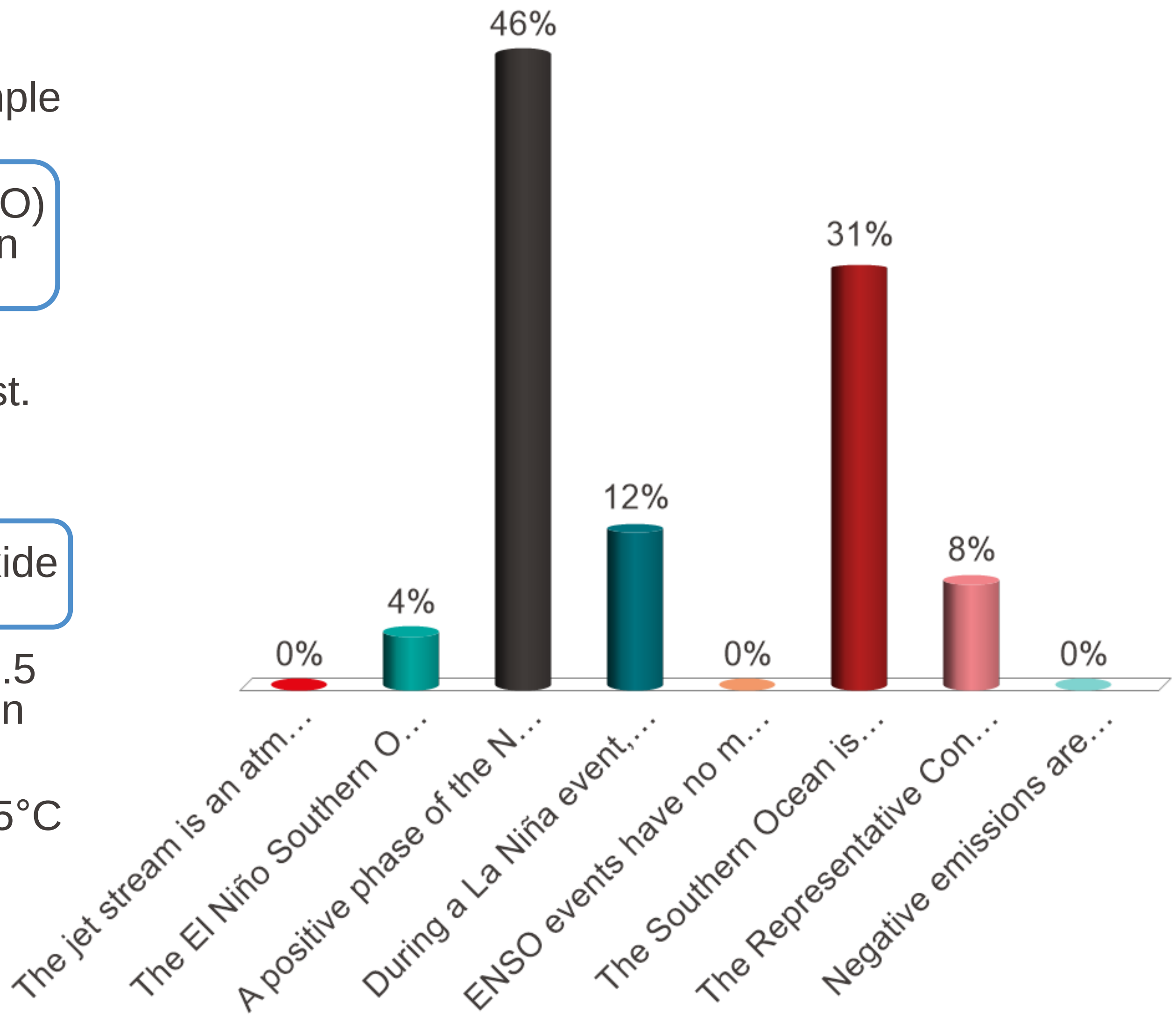
D. During a La Niña event, South America typically experiences increased rainfall along its western coast.

E. ENSO events have no measurable impact on renewable energy production.

F. The Southern Ocean is one of the major carbon dioxide (CO_2) sinks on the planet.

G. The Representative Concentration Pathway (RCP) 8.5 scenario corresponds to aggressive climate mitigation strategies.

H. Negative emissions are not required to meet the +1.5°C global warming target.



Which of the following sentences are true ?

A. The North Atlantic Oscillation (NAO) primarily affects climate conditions during the summer months.

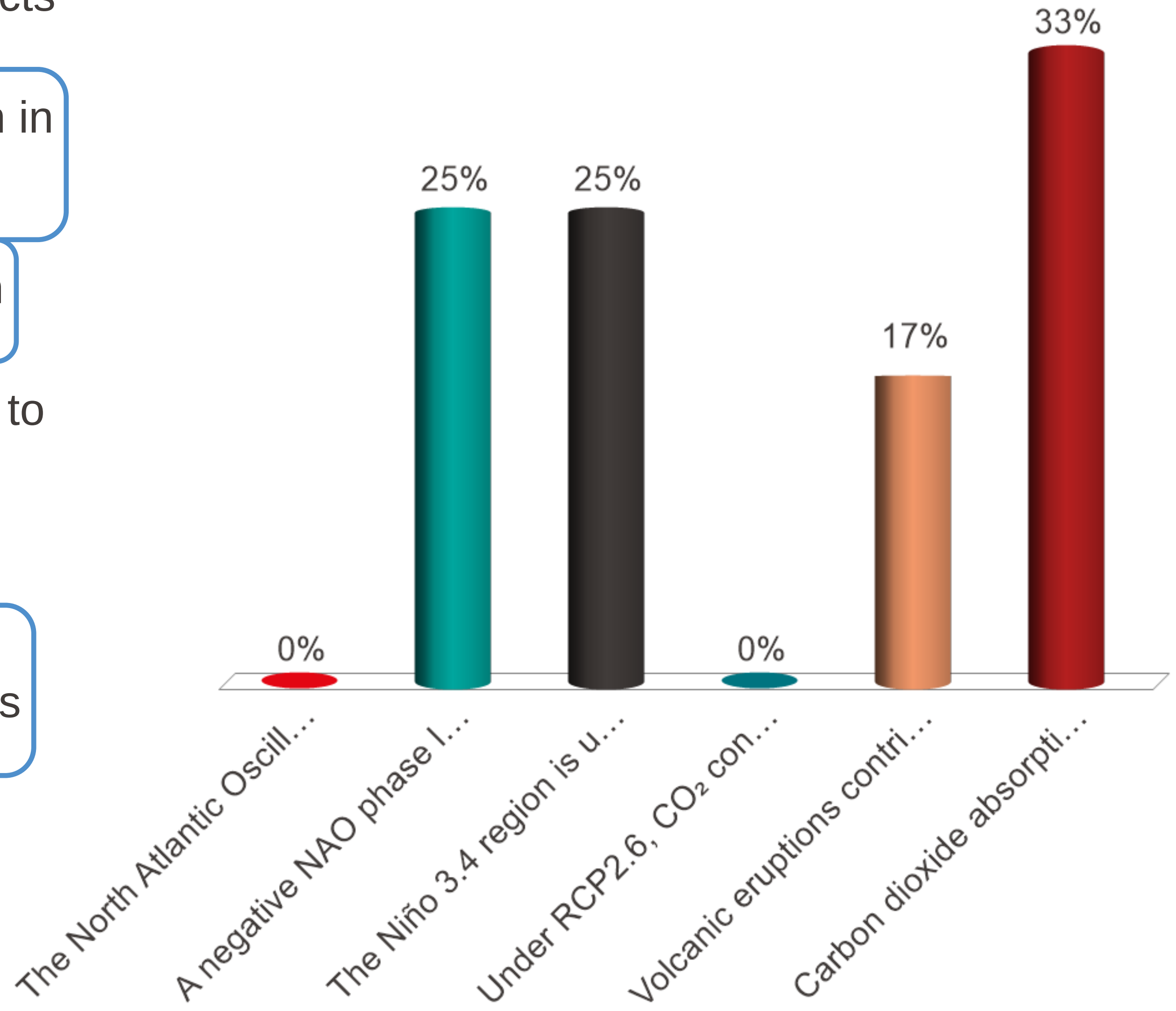
B. A negative NAO phase leads to more precipitation in southern Europe and drier conditions in northern Europe.

C. The Niño 3.4 region is used to monitor changes in sea surface temperature associated with ENSO.

D. Under RCP2.6, CO_2 concentrations are projected to stabilize around 1000 ppm by 2100.

E. Volcanic eruptions contribute to natural internal variability in the climate system.

F. Carbon dioxide absorption by the oceans is expected to decline under high-emission scenarios due to surface water saturation and stratification.



Today's goals

- Deeper dive into a proxy: strengths and limits of CO_2 measurements in ice cores.
    - Chemical and physical biases.
    - Corrections.
- EarthViewer app: maneuvering through geological time scales
- Quiz on the morning course.
- **Discussion around a fictional article. Interview of Richard Malone, in EcoView Weekly, March 25th, 2025.**

EPFL

Discussion around an interview

- Fictional interview of a geophysicist, Richard Malone, resembling in a way to Fred Singer.
- I would not be surprised that such an article could become a reality in the future…

https://moodle.epfl.ch/pluginfile.php/3432370/mod_resource/content/1/A%20fictional%20interview%20of%20a%20climate%20skeptic.pdf

EPFL

Your opinion / argument: Which of these statements are true ?

A. "Permafrost has been thawing and refreezing for millennia. It's no big deal."

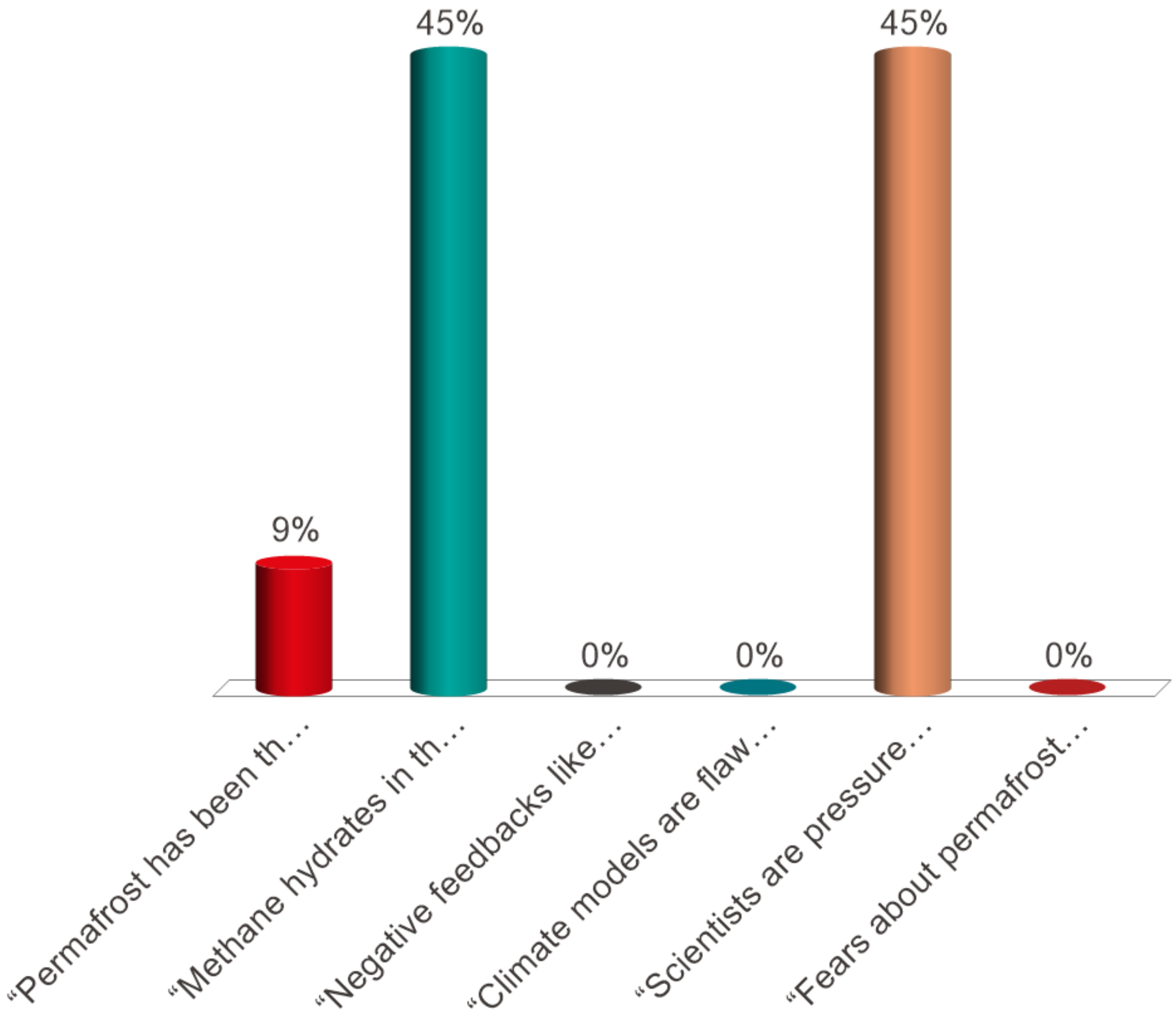
B. "Methane hydrates in the deep ocean are stable and not a concern."

C. "Negative feedbacks like increased plant growth will balance everything out."

D. "Climate models are flawed and exaggerate feedback loops."

E. "Scientists are pressured into supporting the consensus."

F. "Fears about permafrost carbon are Hollywood fiction."



EPFL

Your opinion / argument: Which of these statements are true ?

A. *“Permafrost has been thawing and refreezing for millennia. It’s no big deal.”*
B. *“Methane hydrates in the deep ocean are stable and not a concern.”*
C. *“Negative feedbacks like increased plant growth will balance everything out.”*
D. *“Climate models are flawed and exaggerate feedback loops.”*
E. *“Scientists are pressured into supporting the consensus.”*
F. *“Fears about permafrost carbon are Hollywood fiction.”*

- First part is true. But current rate of warming is new at the scale of the Holocene.
- True for deep ocean. Nearly all escaping methane is oxidized in the water column.
- The CO_2 fertilization effect can be counteracted by nutrient limitations, droughts, fires,… And by land-use.
- Most of the feedback loops are included, positive or negative. They are tested against recent observations.
- Consensus exists in science. Nobody contests the effect of gravitation. But group pressure is a reality.
- «Hollywood fiction» ONLY if we are on track to meet the SSP1-2.6 scenario !