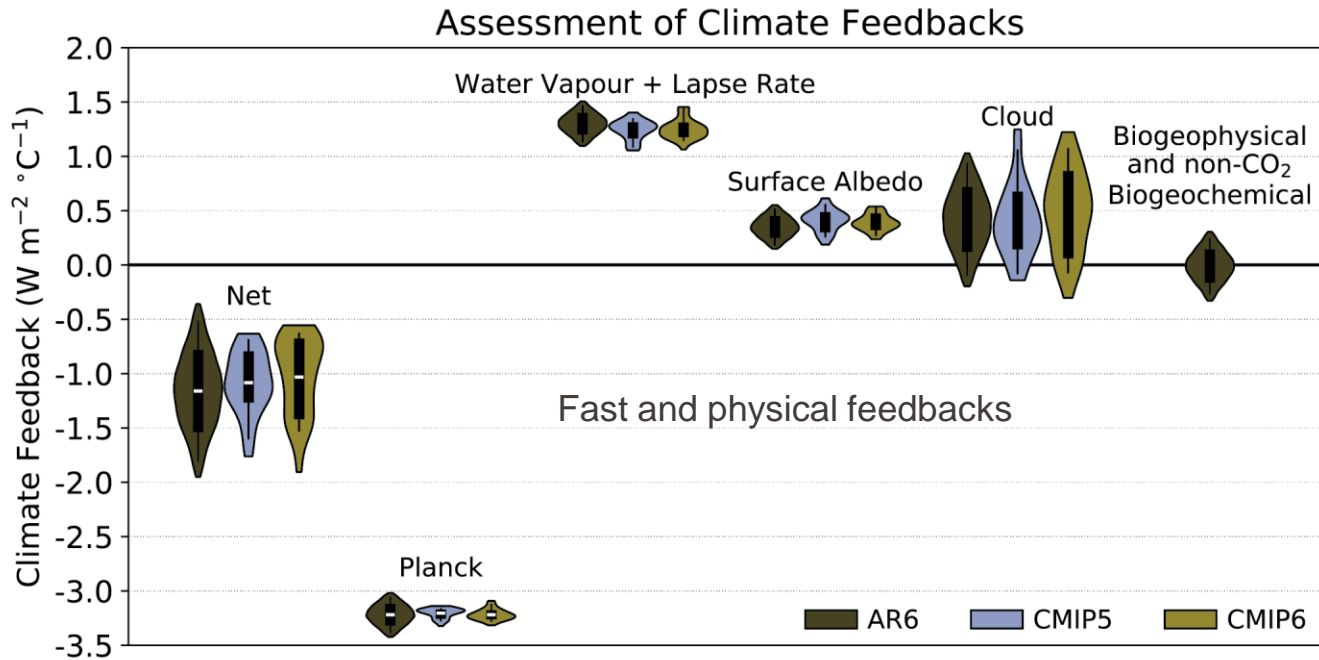
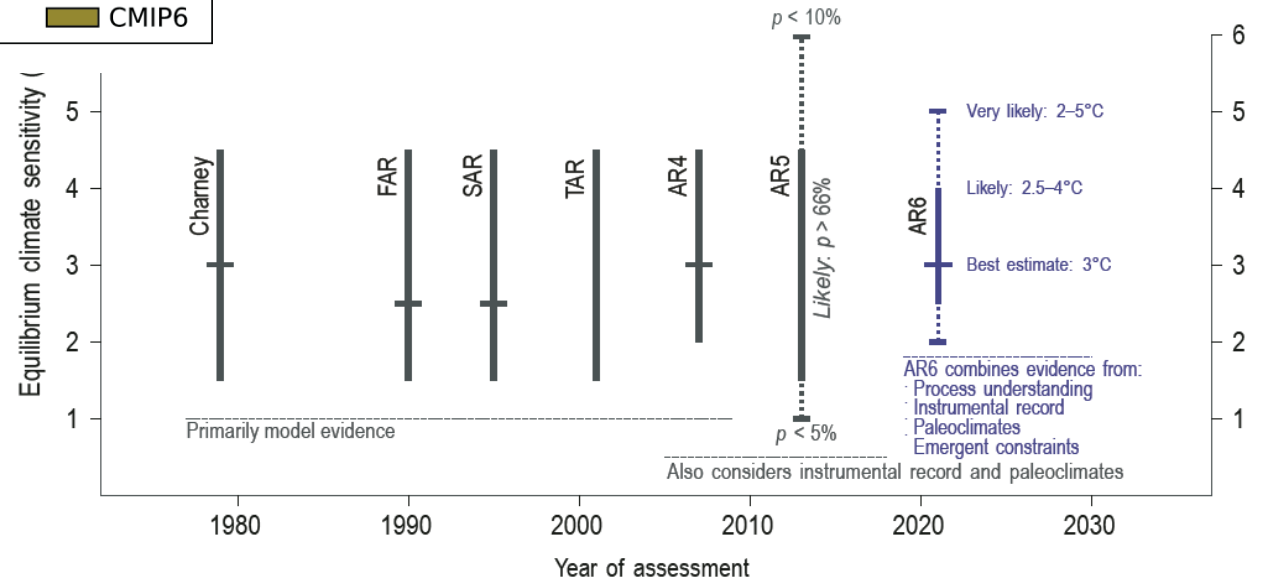


# Recap from previous lecture



### Evolution of climate sensitivity estimates

of equilibrium climate sensitivity assessments from Charney to AR6



# Reading Task till next lecture

- World's major cities hit by 25% leap in extremely hot days since the 1990s
- <https://www.theguardian.com/environment/2025/sep/30/worlds-major-cities-hit-by-25-leap-in-extremely-hot-days-since-the-1990s>
- Focus on:
  - What has been calculated?
  - What's the main finding and why is it important?
  - Why 35°C?

	No.	Date	Topics	Deadlines / tentative
Basics	1.	11.09.2025	Introduction to the climate system	Questionnaire (not graded)
	2.	18.09.2025	Climate System, Radiation	
	3.	25.09.2025	Radiation, Earth's Energy balance, Greenhouse effect	launch of first assignment
	4.	02.10.2025	Aerosols & clouds, Radiative Forcing	Launch of poster project
	5.	09.10.2025	Feedback mechanisms, Climate Sensitivity	
	6.	16.10.2025	Paleoclimate	submission of Poster proposal (graded)
Present and future Climate change	7.	30.10.2025	Climate variability	
	8.	06.11.2025	Paris Agreement, IPCC – report, Climate scenarios (RCPs, SSPs),	
	9.	13.11.2025	Tipping elements, 1.5 vs 2.0°C vs warmer, Emissions, Carbon budget, Emissions Gap	submission of Poster draft (graded)
	10.	20.11.2025	Carbon budget, Emissions Gap, Metrics	
	11.	27.11.2025	Metrics, Extreme Events	submission of assignment (graded)
Actions	12.	04.12.2025	Polar climate change	
	13.	11.12.2025	Mitigation measures	Poster Conference (graded)
	14.	18.12.2025	Climate engineering, questions and answers session	fill in Questionnaire in exercises (not graded)

# Paleoclimate – How does today's warming compare?



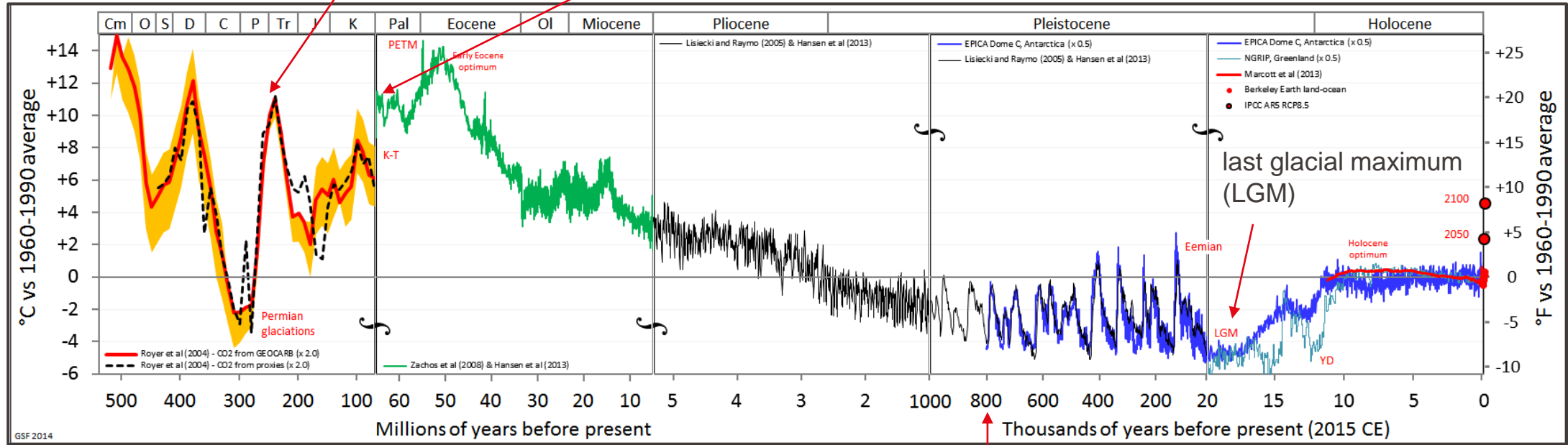
# Temperature over the last 500 million years

Reference temperature (avg. 1960-1990): +14 °C

Mass extinction, due to volcanic eruptions → GHG atmosphere

Cretaceous-Paleocene  
Dinosaurs extinction

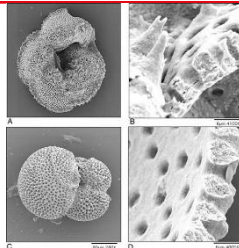
100'000 year  
glaciation cycles



Time scale not linear!

about the data

stable oxygen isotope measurements from the shells of macroscopic marine organisms



stable oxygen isotope data from microscopic marine organisms

stable hydrogen isotope measurements from the EPICA Dome C ice core from central Antarctica

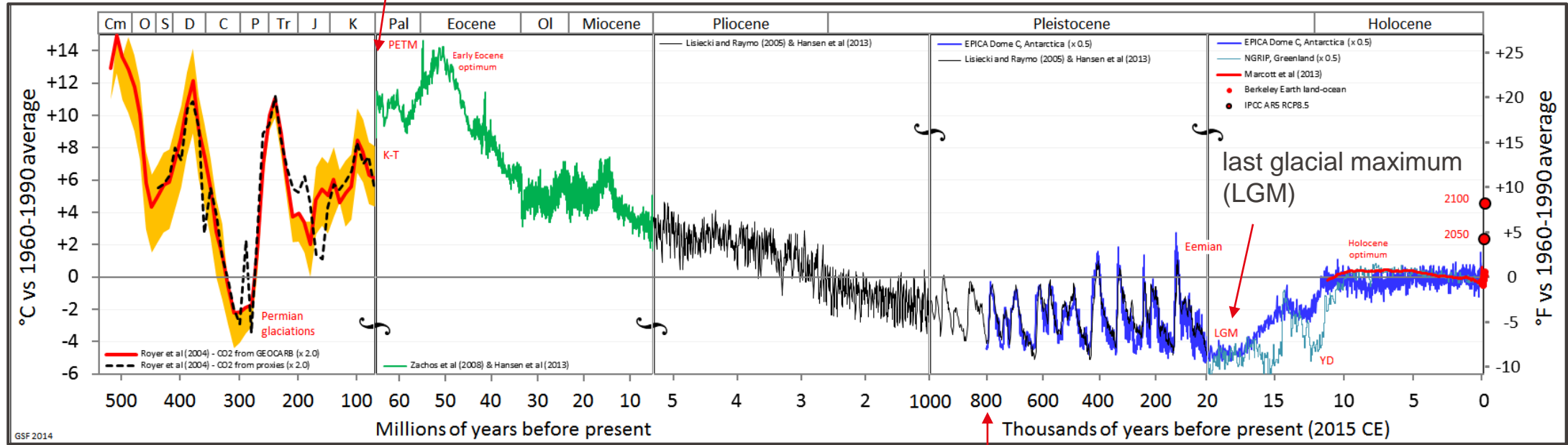
oxygen isotope measurements on the north Greenland ice core, from 1850 measured

# Temperature over the last 500 million years

Reference temperature  
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Cretaceous-Palaeogene  
Dinosaurs extinction

100'000 year  
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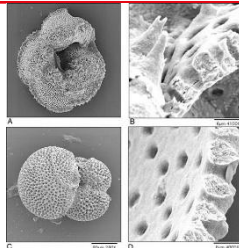


Time scale  
not linear!

about the data

← uncertainty increases

stable oxygen isotope  
measurements from  
the shells of  
macroscopic marine  
organisms



stable oxygen isotope  
data from microscopic  
marine organisms

sea surface tropical temperature

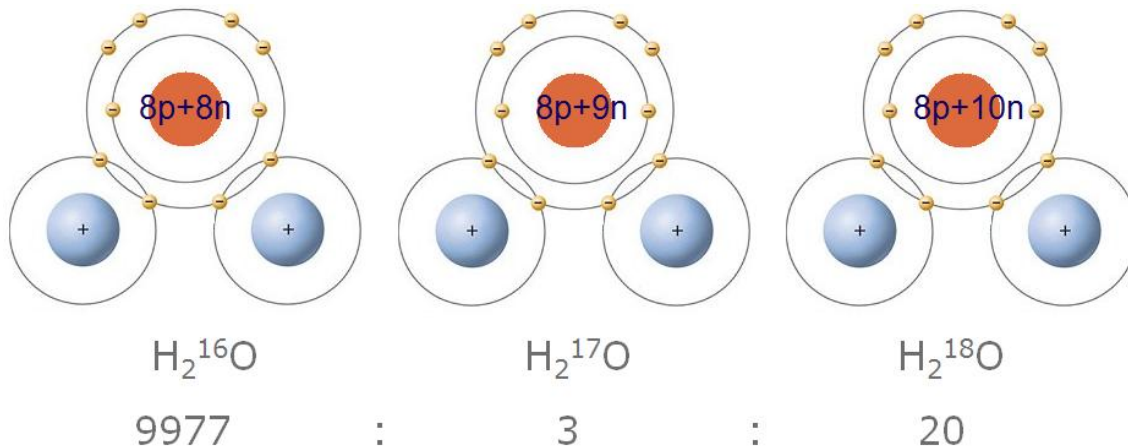
sea surface temperature

stable hydrogen isotope  
measurements from the  
EPICA Dome C ice  
core from central  
Antarctica

oxygen isotope  
measurements on the  
north Greenland ice  
core, from 1850  
measured

polar temperature divided  
by 2 for polar amplification

Isotopes refer to the *different atoms or forms of an element with the same atomic number but different atomic masses*. So, they contain the same number of protons and electrons but **differ in the number of neutrons**.



Three different water molecules formed from 2 hydrogen atoms and different oxygen isotopes (similar, but with different number of neutrons in the nucleus).

The most common form is  $\text{H}_2^{16}\text{O}$ .

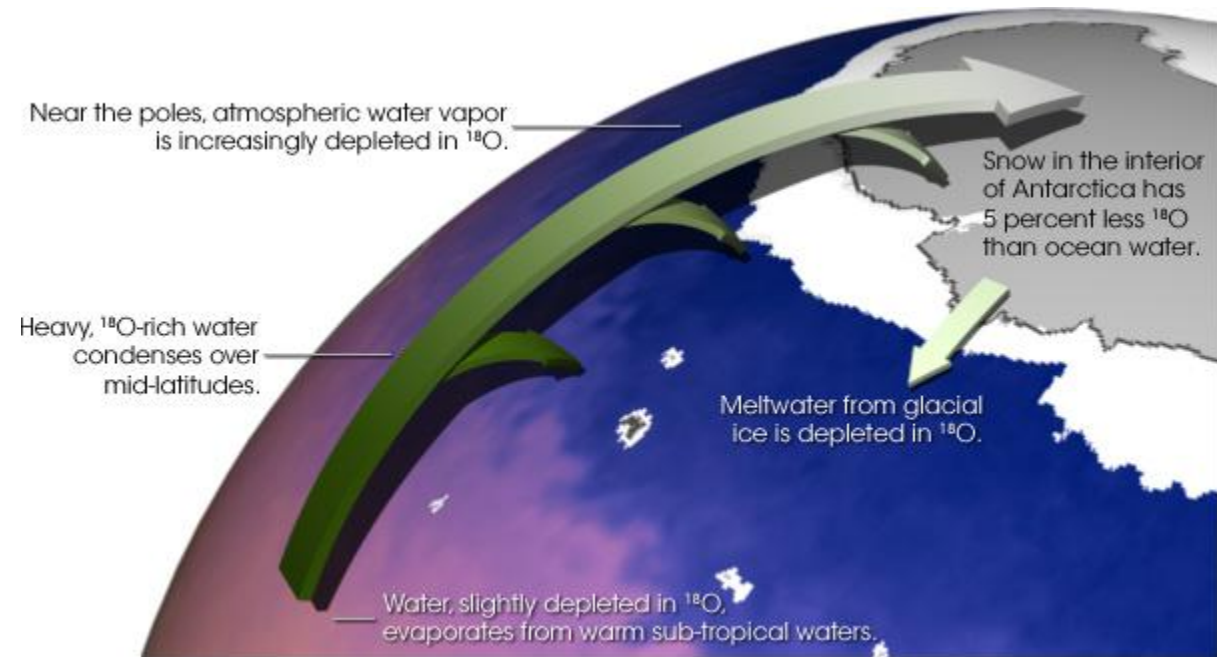
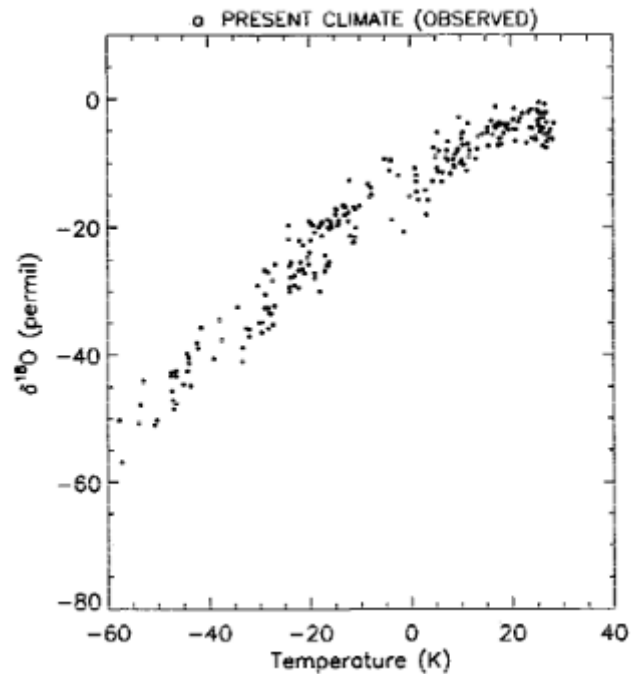
For each 10,000 water molecules in nature, only 3 are  $\text{H}_2^{17}\text{O}$  and 20 are  $\text{H}_2^{18}\text{O}$ .

## NATURAL ISOTOPES OF CARBON

<p>6 Protons 6 Neutrons</p>	<p>6 Protons 7 Neutrons</p>	<p>6 Protons 8 Neutrons</p>
<p>Carbon-12 (6P + 6N) Atomic Weight = 12 Isotope Mass: 12 u Abundance: 98.89%</p>	<p>Carbon-13 (6P + 7N) Atomic Weight = 13 Atomic Mass = 13.00335 u Abundance: 1.109%</p>	<p>Carbon-14 (6P + 8N) Atomic Weight = 14 Isotope Mass: 14.003241 u Abundance: 1 Part Per Trillion Half-life: 5,730 ± 40 Years</p>

Carbon -14, Carbon-13, and Carbon-12 are isotopes of carbon, as C-14 has 8 neutrons, C-13 has 7 neutrons and C-12 has 6 neutrons, whereas, all of them have the same number of protons that is 6 and the same number of electrons that is 6. Only C-14 is radioactive.

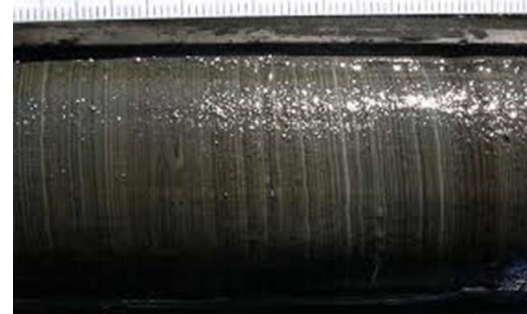
# Temperature reconstruction from oxygen isotopes



During cold times: enrichment of  $\delta^{18}\text{O}$  near equator, strong depletion near poles  
During warm times: less enrichment of  $\delta^{18}\text{O}$  near equator, less depletion near poles.

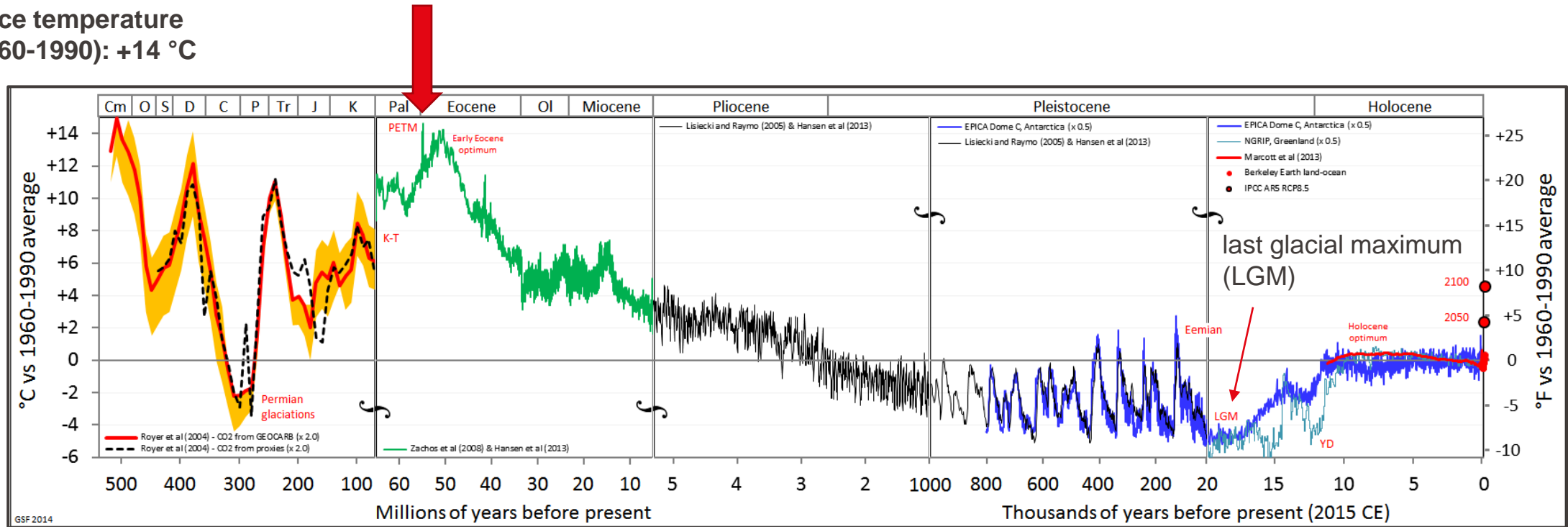
# And how do we determine age?

- Direct methods
  - Counting of annual layers (sediments, corals...)
  - Counting of tree rings
- Radioisotope dating:
  - $^{14}\text{C}$ :  $T_{1/2} (^{14}\text{C}) = 5.73 \text{ ka}$  (maximum age 44 ka)
  - U-Th:  $T_{1/2} (^{230}\text{Th}) = 77 \text{ ka}$
  - K-Ar:  $T_{1/2} (^{40}\text{K}) = 1.28 \text{ Ga}$
- Indirect dating methods:
  - «event matching» (volcanic eruptions – tephra layers, atomic tests, ...)
  - «orbital tuning» (frequency fit to insolation)
  - Model-based dating (e.g., ice flow modeling)

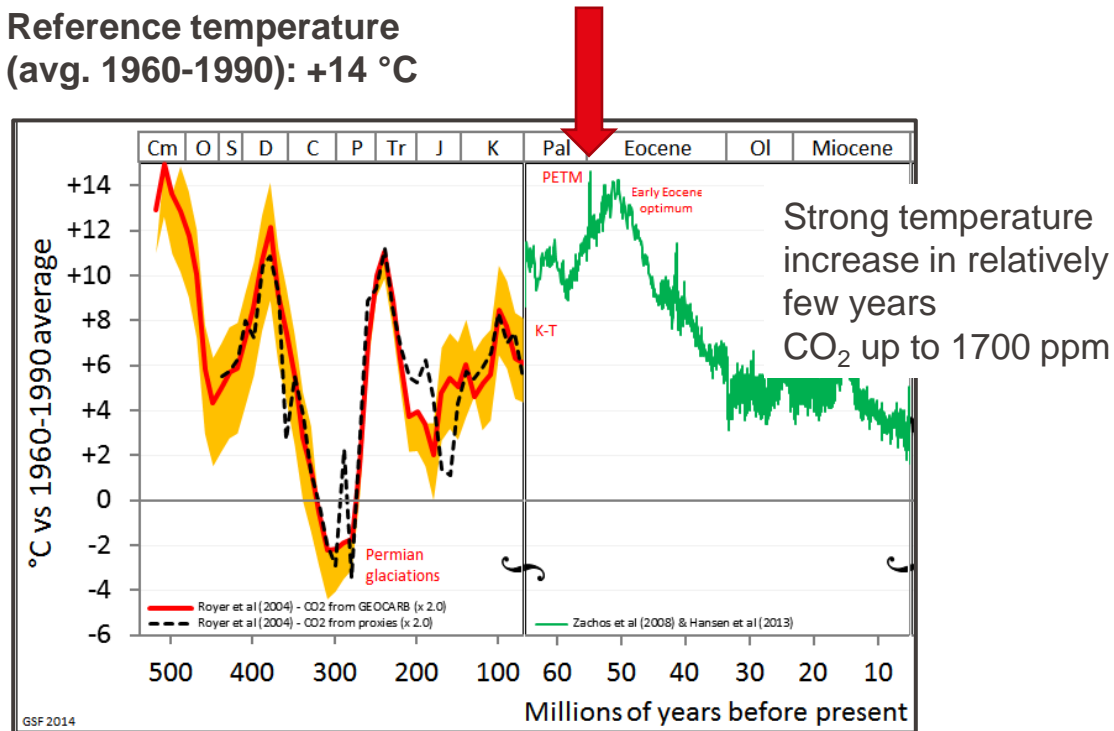


# Temperature over the last 500 million years

Reference temperature  
(avg. 1960-1990): +14 °C



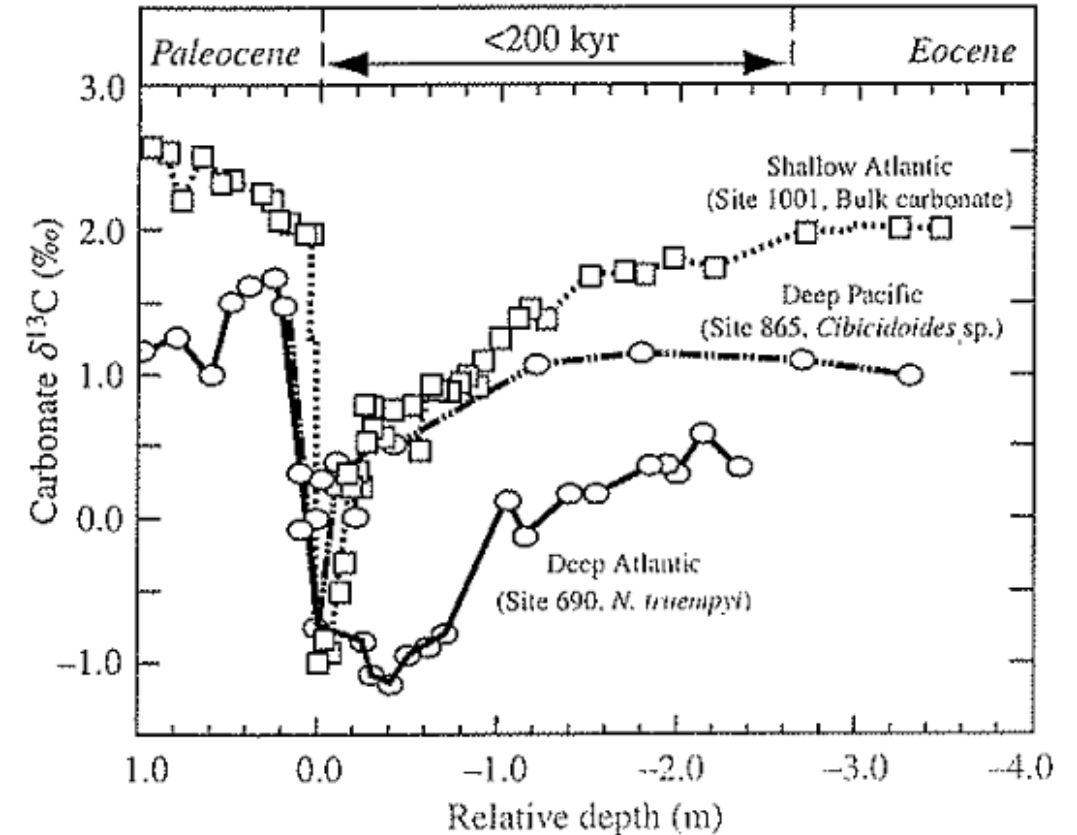
Reference temperature  
(avg. 1960-1990): +14 °C



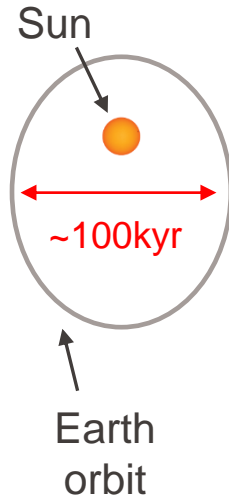
- Paleocene-Eocene Thermal Maximum (PETM) represents one of the more **prominent and abrupt climate anomalies** in Earth history.
- Interesting to study, because **represents a possible analogue** for the future and thus may provide insight into climate system sensitivity and feedbacks (similar amount of carbon release in the first 50 years of event compared to today).
- The key feature of this event is the **release of a large mass of <sup>13</sup>C-depleted carbon** into the carbon reservoirs at the Earth's surface, although the source remains an open issue. Biogenic carbon is depleted in <sup>13</sup>C.
- Carbon levels increased by < 70% compared to pre-event levels.
- **With given climate sensitivity this leads to 1 – 3.5°C warming only. But 5-9°C are inferred.**
- Other drivers unclear.

- Sudden decrease in the  $^{13}\text{C}/^{12}\text{C}$  ratio (normal around 1.1 permil)
- Biogenic carbon is depleted in  $^{13}\text{C}$ : The hypothesis is that terrestrial biogenic carbon was transferred to the atmosphere and ocean. (atmosphere-ocean equilibrium, sea sediment cores)
- **However, the amount of carbon would have been similar to today's total terrestrial biosphere plus soil carbon.**
- Alternatively, release of methane-hydrates, requires less carbon to be released, because  $^{13}\text{C}$  is strongly depleted in methane.

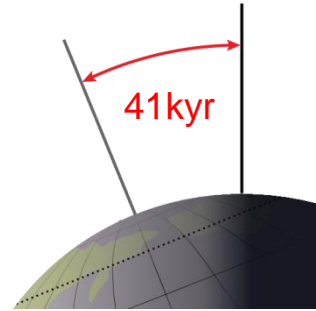
Still explanations are missing.



Carbon isotopic ratio from ocean sediment cores.  
Depth ~ time



**Eccentricity:**  
stronger change in radiation  
over the year



**Obliquity:**  
axial tilt between  $22.1^\circ$  and  
 $24.5^\circ$   
Larger tilt means more  
insolation at poles.



**Precession of the axis**  
 $1^\circ$  each 72 years

**Milankovic Cycles:** Variations in eccentricity, precession and obliquity lead to varying solar insolation on Earth.  
→ Orbital forcing with an effect on Earth's climate.

# Paleocene-Eocene Thermal Maximum (PETM)

Earth's orbit played a role:

Coincidence of hyperthermals with combined **high-eccentricity** and **high-obliquity** forcing points to the **influence of polar latitudes**, where seasonal insolation is strongly affected by obliquity and precession during high-eccentricity orbits.

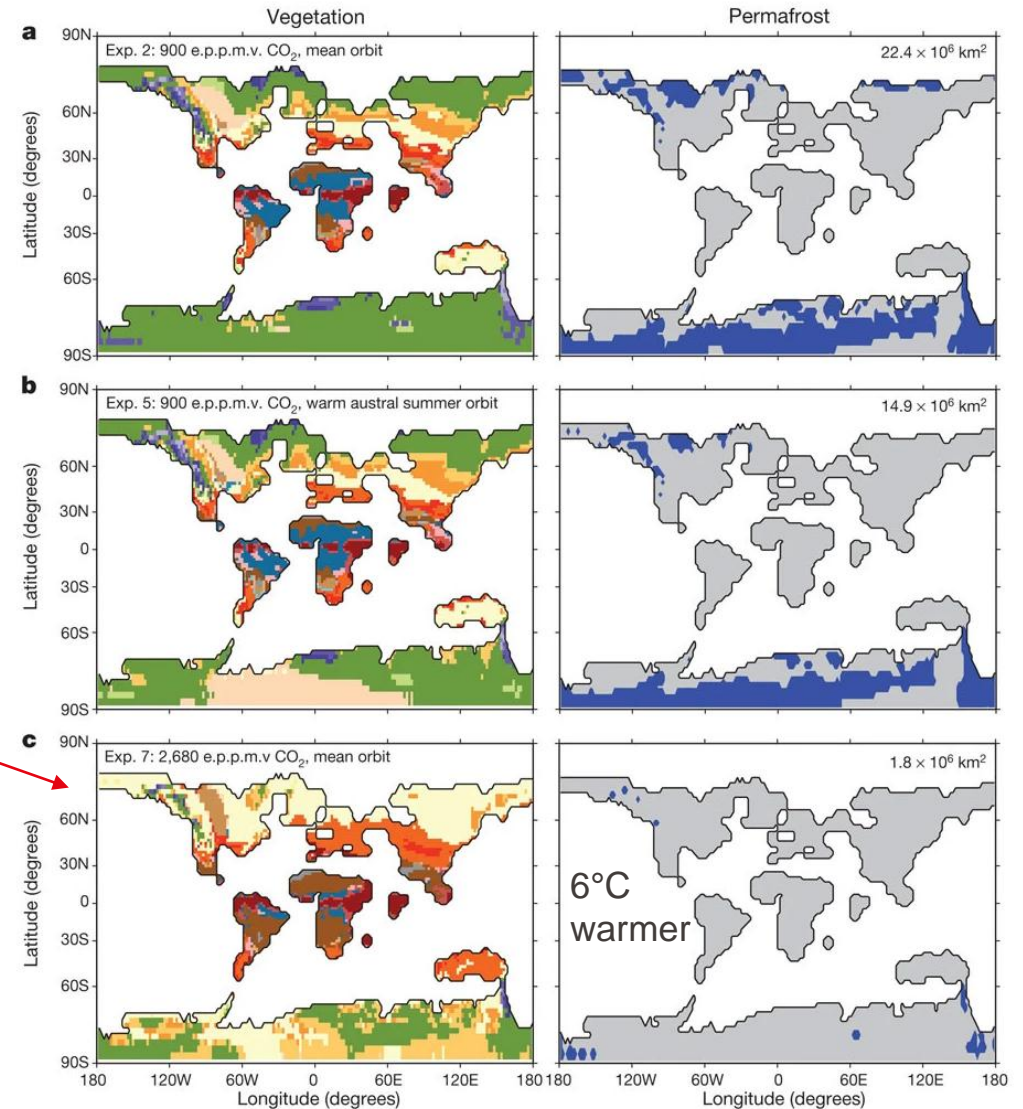
→ High-latitude orbital forcing through carbon-cycle feedbacks involving permafrost soil carbon (Antarctica only became glaciated 34 Myrs ago).

**900 ppm CO<sub>2</sub>, mean orbit**

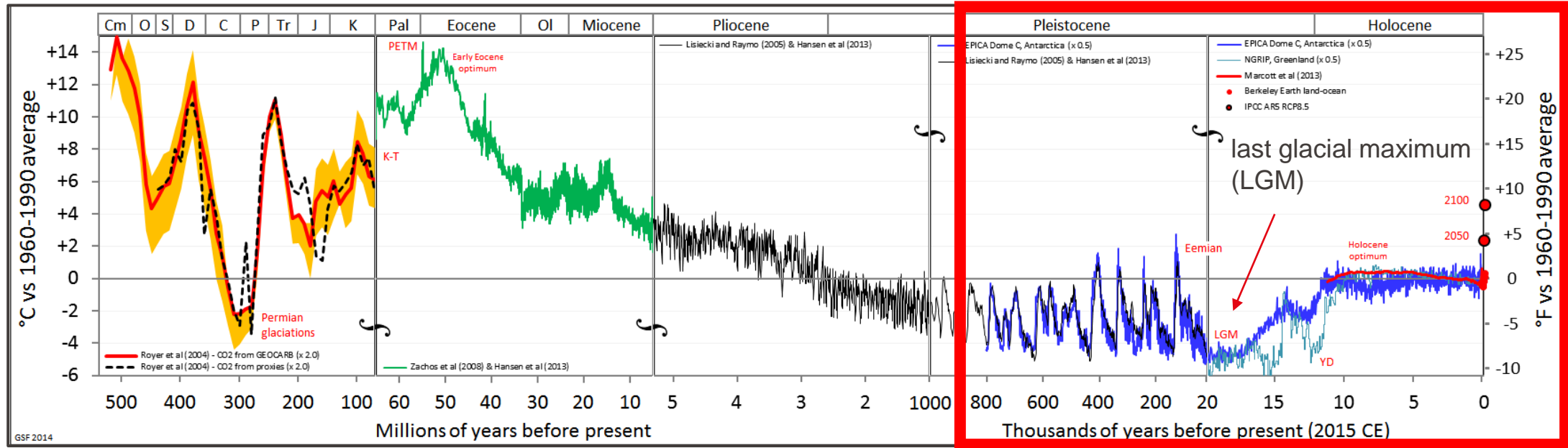
**Initial release of carbon due to orbital forcing.**

**Run-away effect: 2680 ppm CO<sub>2</sub> and 6°C warmer**

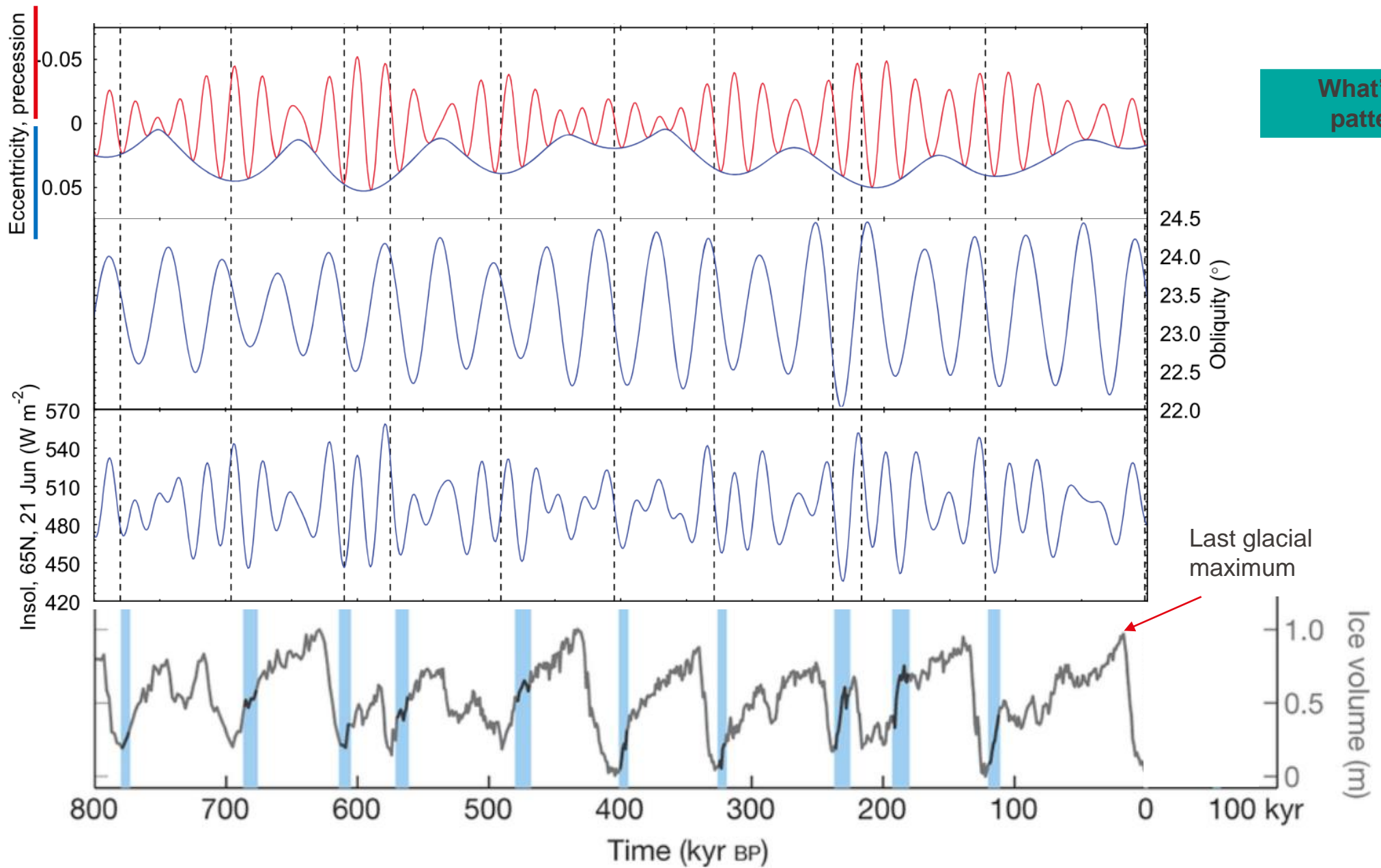
- |   |  |   |
|---|--|---|
| <p><b>Tropical forest</b></p> <ul style="list-style-type: none"> <li>■ Tropical deciduous broadleaf forest and woodland</li> <li>■ Tropical semi-evergreen broadleaf forest</li> <li>■ Tropical evergreen broadleaf forest</li> </ul> <p><b>Temperate forest</b></p> <ul style="list-style-type: none"> <li>■ Temperate deciduous forest</li> <li>■ Cold mixed forest</li> <li>■ Warm mixed forest</li> <li>■ Temperate conifer forest</li> <li>■ Barren</li> <li>■ Desert</li> </ul> | <p><b>Savanna and dry woodland</b></p> <ul style="list-style-type: none"> <li>■ Boreal parkland</li> <li>■ Temperate sclerophyll woodland and shrubland</li> <li>■ Temperate evergreen needleleaf open woodland</li> <li>■ Temperate deciduous broadleaf savanna</li> <li>■ Tropical savanna</li> </ul> <p><b>Grassland and dry shrubland</b></p> <ul style="list-style-type: none"> <li>■ Temperate grassland</li> <li>■ Tropical grassland</li> <li>■ Temperate xerophytic shrubland</li> <li>■ Tropical xerophytic shrubland</li> </ul> | <p><b>Polar forest</b></p> <ul style="list-style-type: none"> <li>■ Cold deciduous forest</li> <li>■ Cold evergreen needle-leaf forest</li> </ul> <p><b>Tundra</b></p> <ul style="list-style-type: none"> <li>■ Cushion-forb tundra</li> <li>■ Prostrate dwarf-shrub tundra</li> <li>■ Erect dwarf-shrub tundra</li> <li>■ Low and high shrub tundra</li> <li>■ Graminoid and forb tundra</li> </ul> <p><b>Permafrost</b></p> |
|---|--|---|



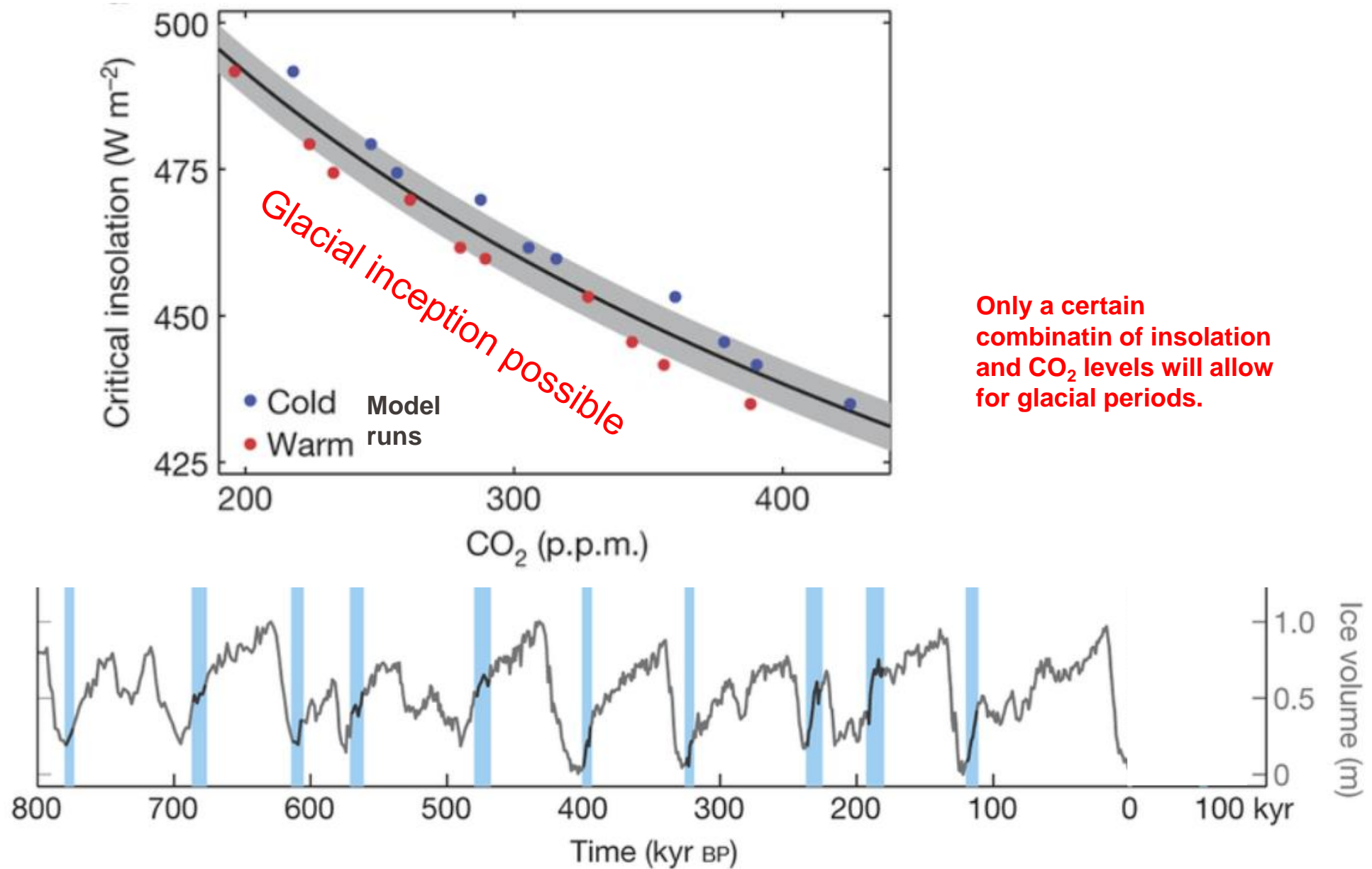
Reference temperature  
(avg. 1960-1990): +14 °C



100'000 year  
glaciation cycles

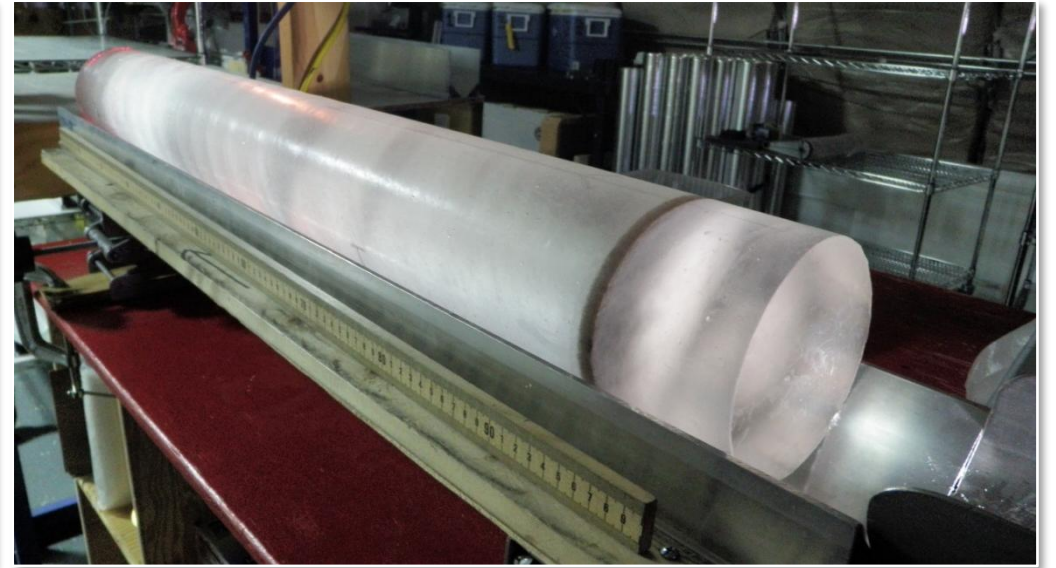


What's the pattern?

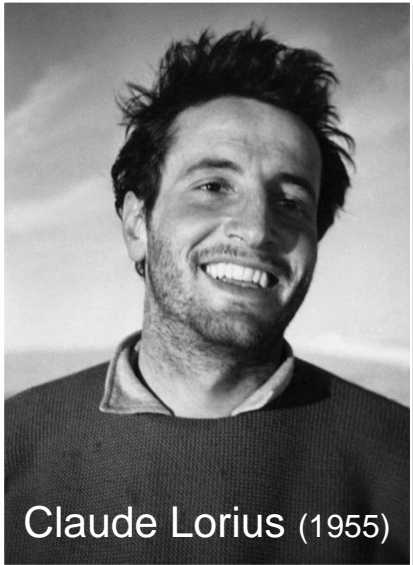




Charcot Station (1957)



Documentary “Ice and the sky”  
 (“Le glace et le ciel” by Luc Jacquet, 2015)



Claude Lorius (1955)



Ice is crushed in a cold vacuum container.  
The air is then expanded into a measurement  
device (e.g., gas chromatograph)

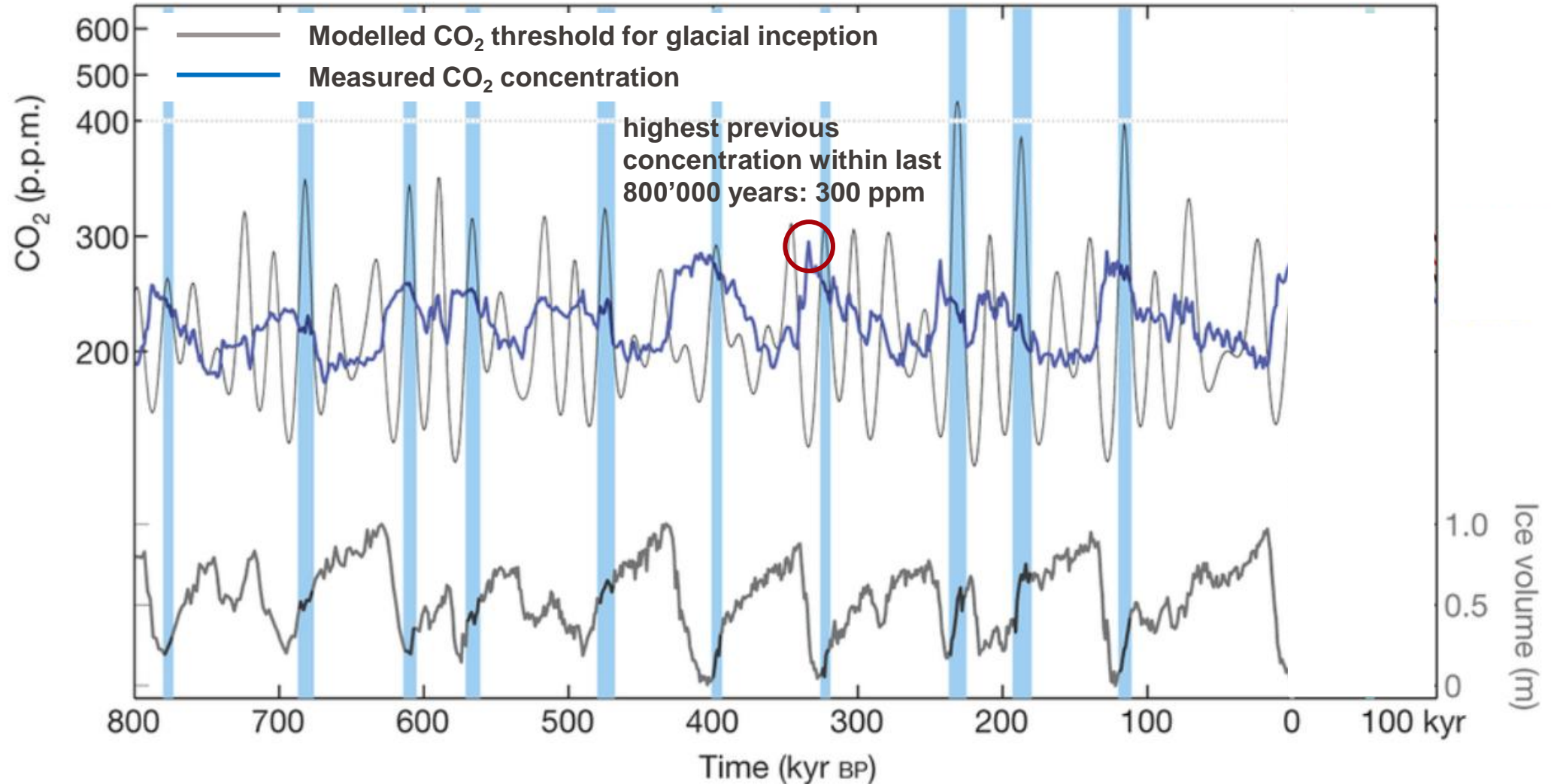
Method published in 1980 by Robert J. Delmas,  
Jean-Marc Ascencio & Michel Legrand:

<https://www.nature.com/articles/284155a0>

Other methods explored in the 1960s and 70s were  
not successful.

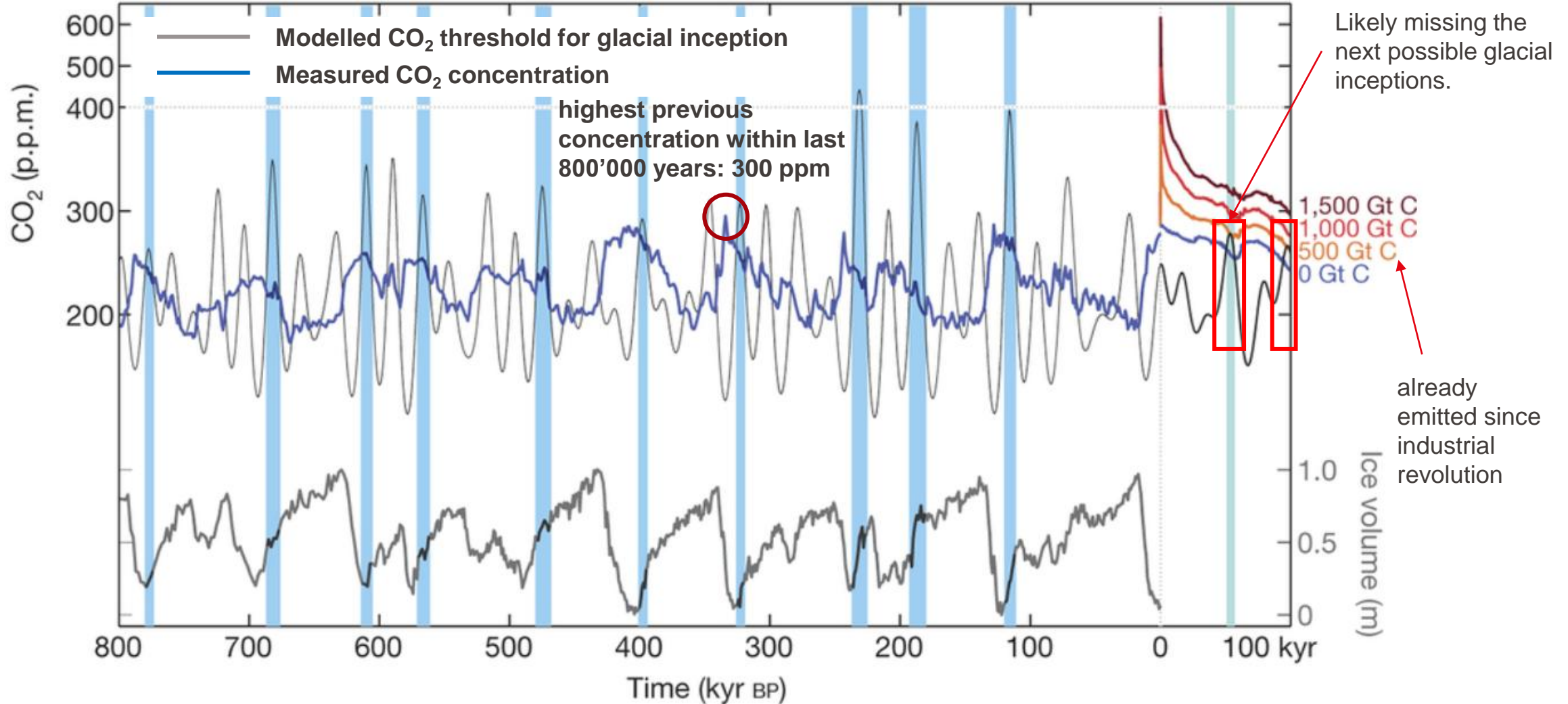
# Glacials and interglacials

When the blue line is below the grey line, glacial inception is possible.



# Glacials and interglacials

When the blue line is below the grey line, glacial inception is possible.



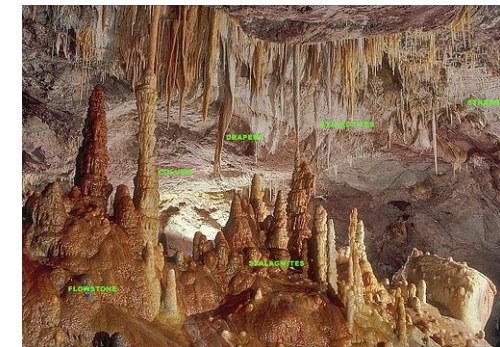
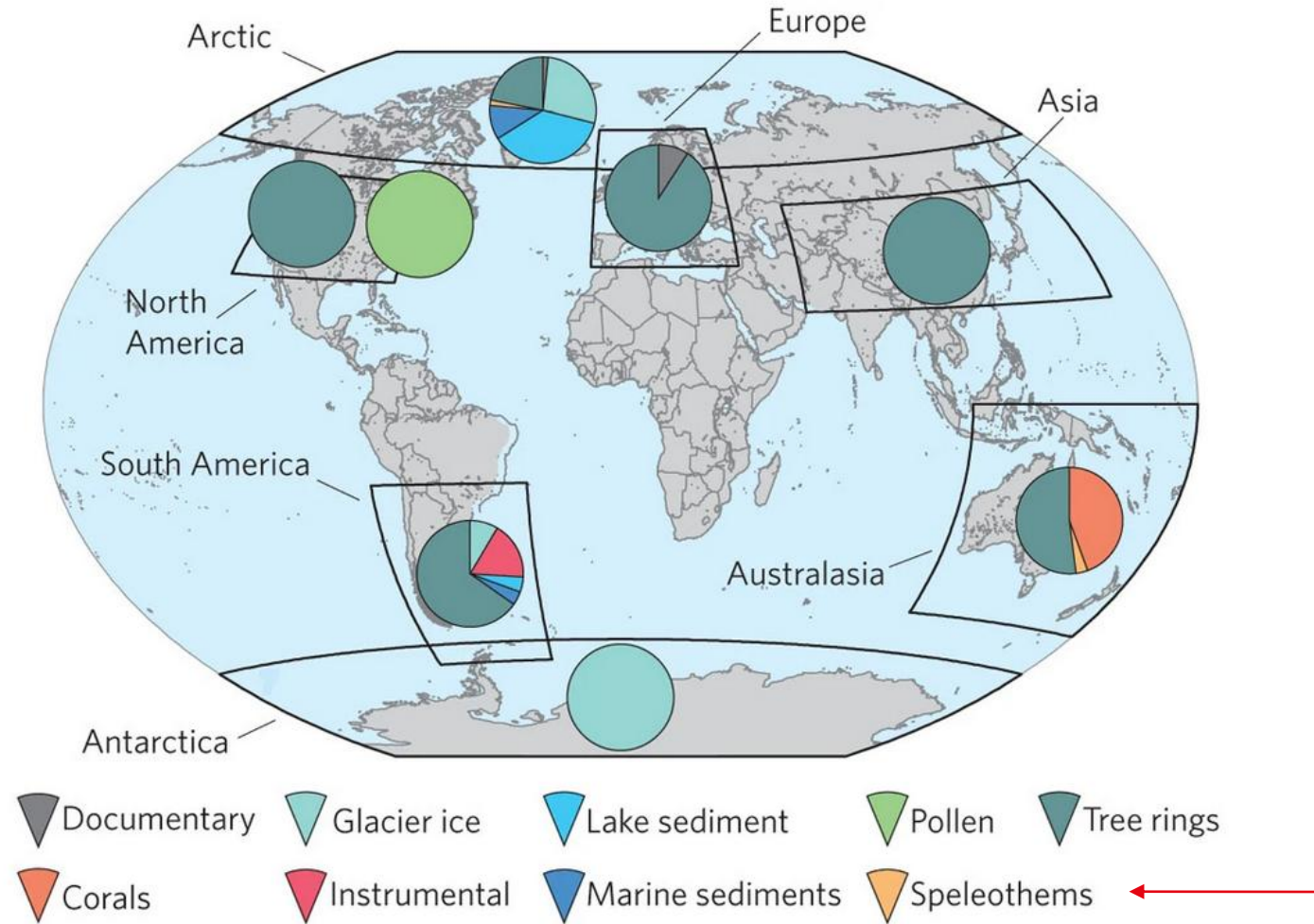
## Media Relations

[Services](#)[Media releases](#)[Staff news](#)[Facts and Figures](#)[< 2025](#)

### Antarctica: Historic Drilling Campaign Reaches more than 1.2-Million-Year-Old Ice

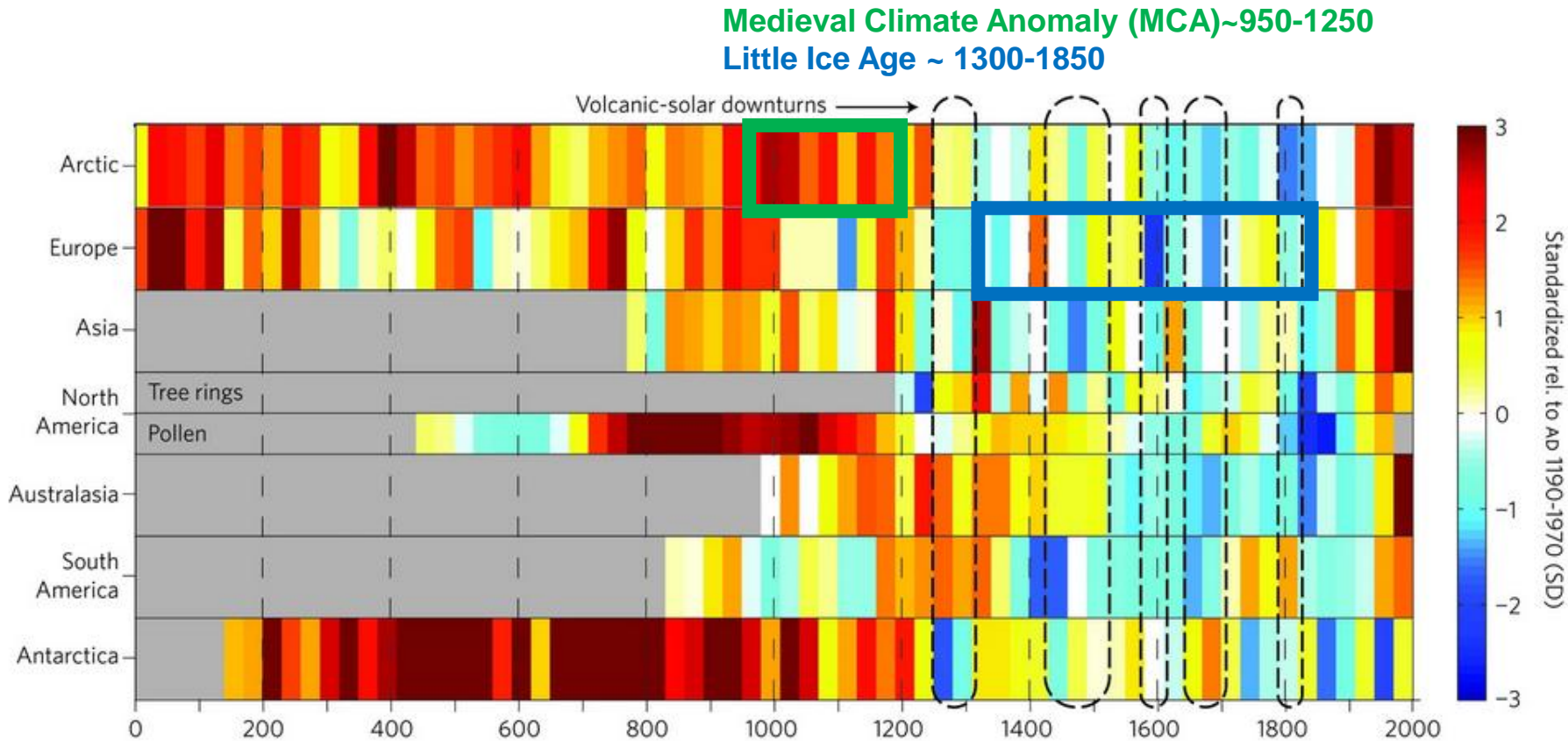
The fourth Antarctic campaign of the “Beyond EPICA - Oldest Ice” project, funded by the European Commission, has achieved a historic milestone for climate science. An international team of scientists with participation of the University of Bern successfully drilled a 2,800-meter-long and over 1.2 million years old ice core, reaching the bedrock beneath the Antarctic ice sheet.

# Regional differences over the last 2000 years



PAGES2K, 2013,  
<https://www.nature.com/articles/ngo1797>

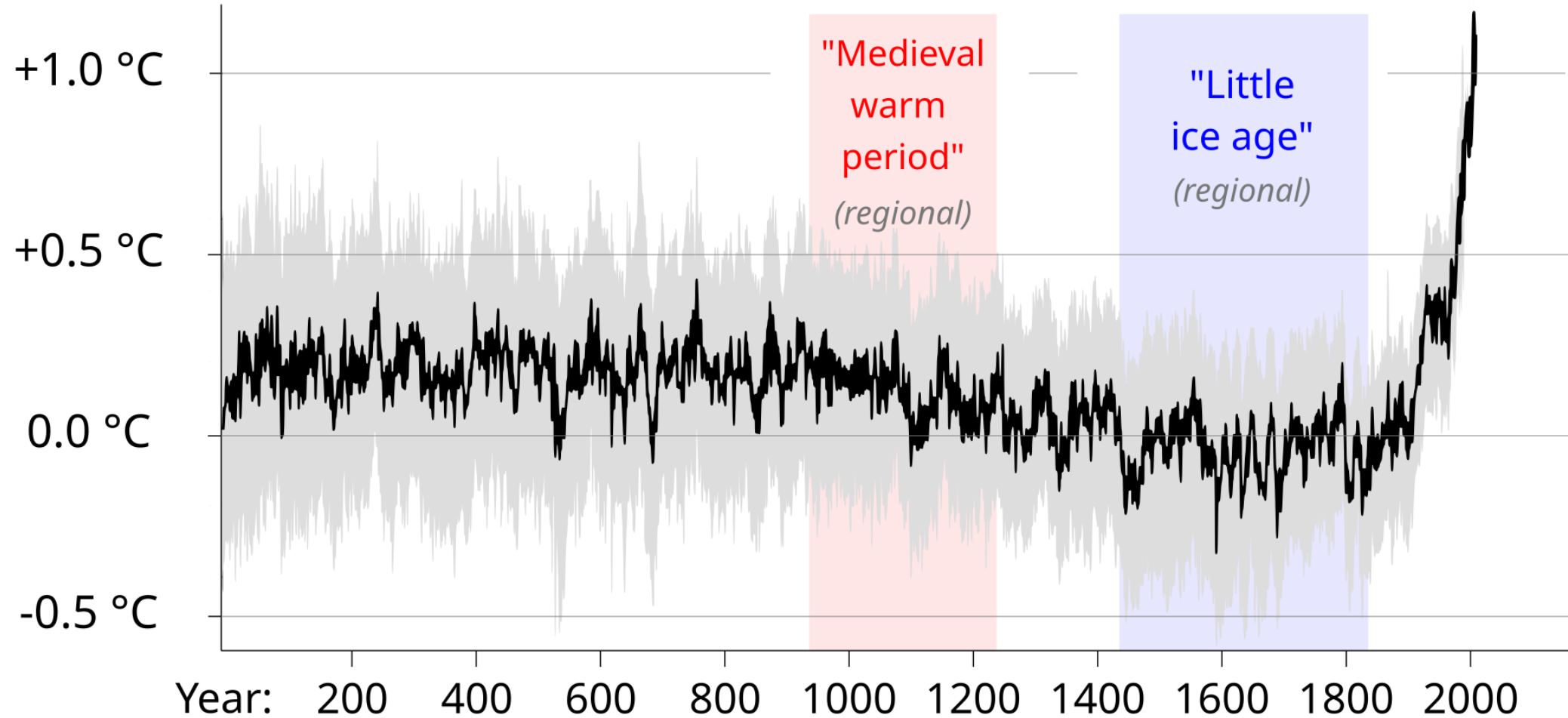
# Regional differences over the last 2000 years



- In nearly all regions: long-term cooling trend, which ended late in the nineteenth century.
- Multi-decadal to centennial scales: temperature variability shows distinctly different regional patterns, more similarity within each hemisphere than between them.
- There were no globally synchronous multi-decadal warm or cold intervals that define a worldwide Medieval Warm Period or Little Ice Age, but all reconstructions show generally cold conditions between ad 1580 and 1880.
- The transition to these colder conditions occurred earlier in the Arctic, Europe and Asia than in North America or the Southern Hemisphere regions.

Recent warming reversed the long-term cooling: during the period ad 1971–2000, the area-weighted average reconstructed temperature was higher than any other time in nearly 1,400 years.

## Global Average Temperature Change



# Medieval Climate Anomaly (MCA) and Little Ice Age (LIA)

- Both were regional events across some parts of the northern hemisphere, rather than global climate change.
- MCA was likely caused by enhanced sun activity (more insolation), less volcanic eruptions and internal climate variability (ocean-atmosphere coupling).
- During the LIA, there was lower solar activity - Spörer Minimum (1450–1550) and Maunder Minimum (1645–1715), more volcanic activity (e.g., Kuwae ~1450, Huaynaputina 1600, Tambora 1815), and potentially snow-albedo feedback.



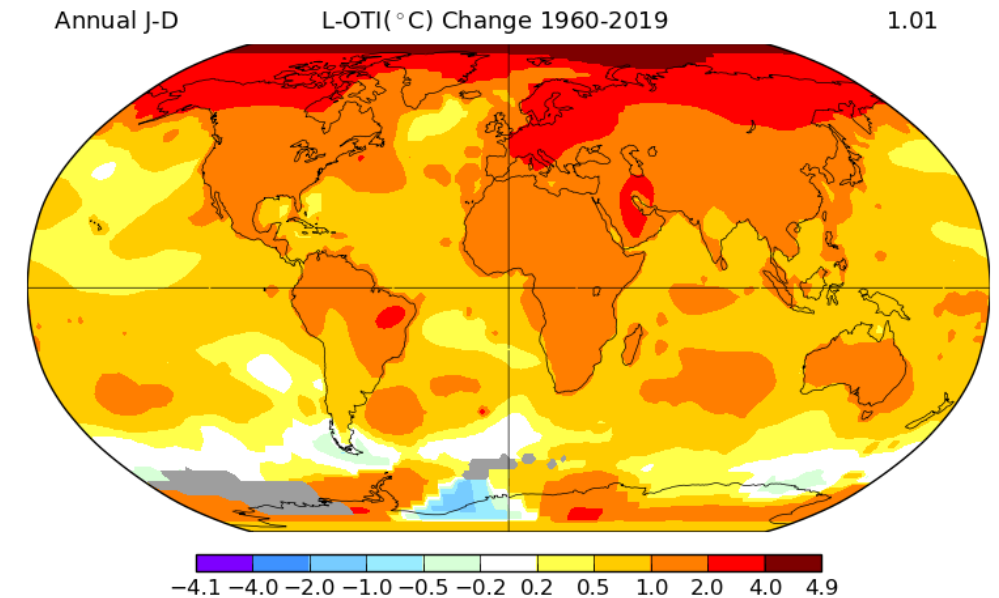
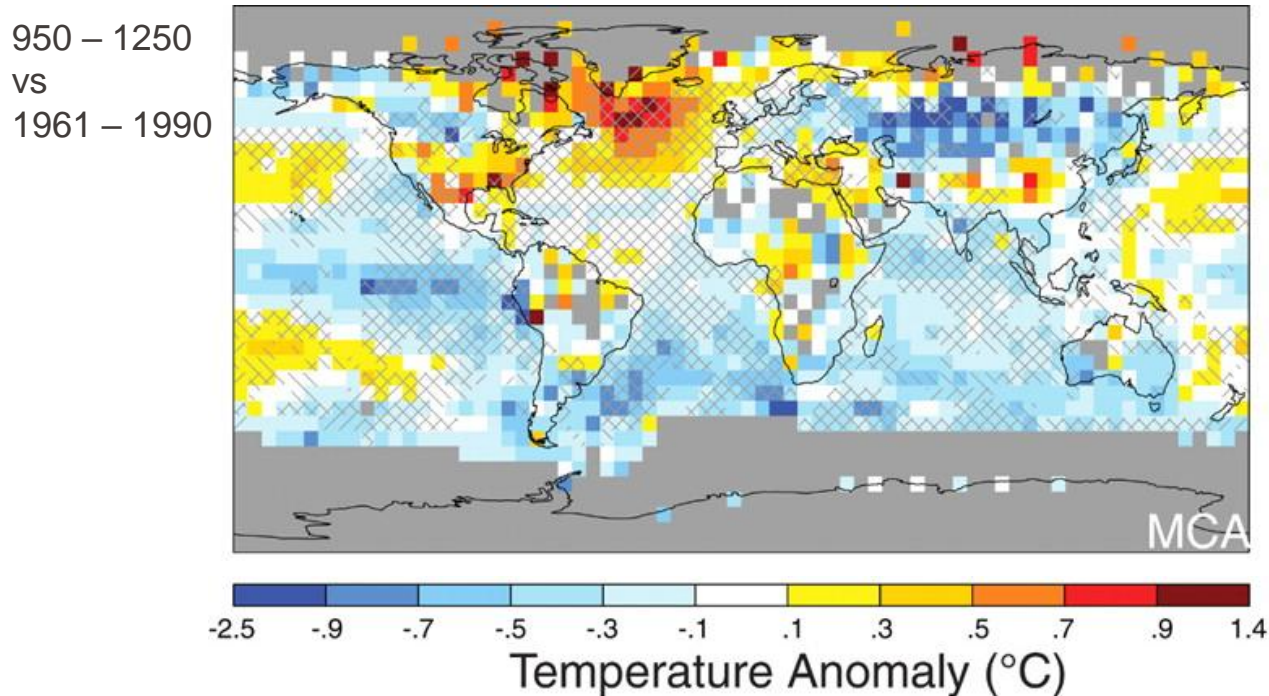
The Fair on the Thames, February 4th 1814, by Luke Clenell. These events happened in 1684, 1716, 1740, 1789, and 1814.

Credit: Wiki Commons

# When was Greenland forested?

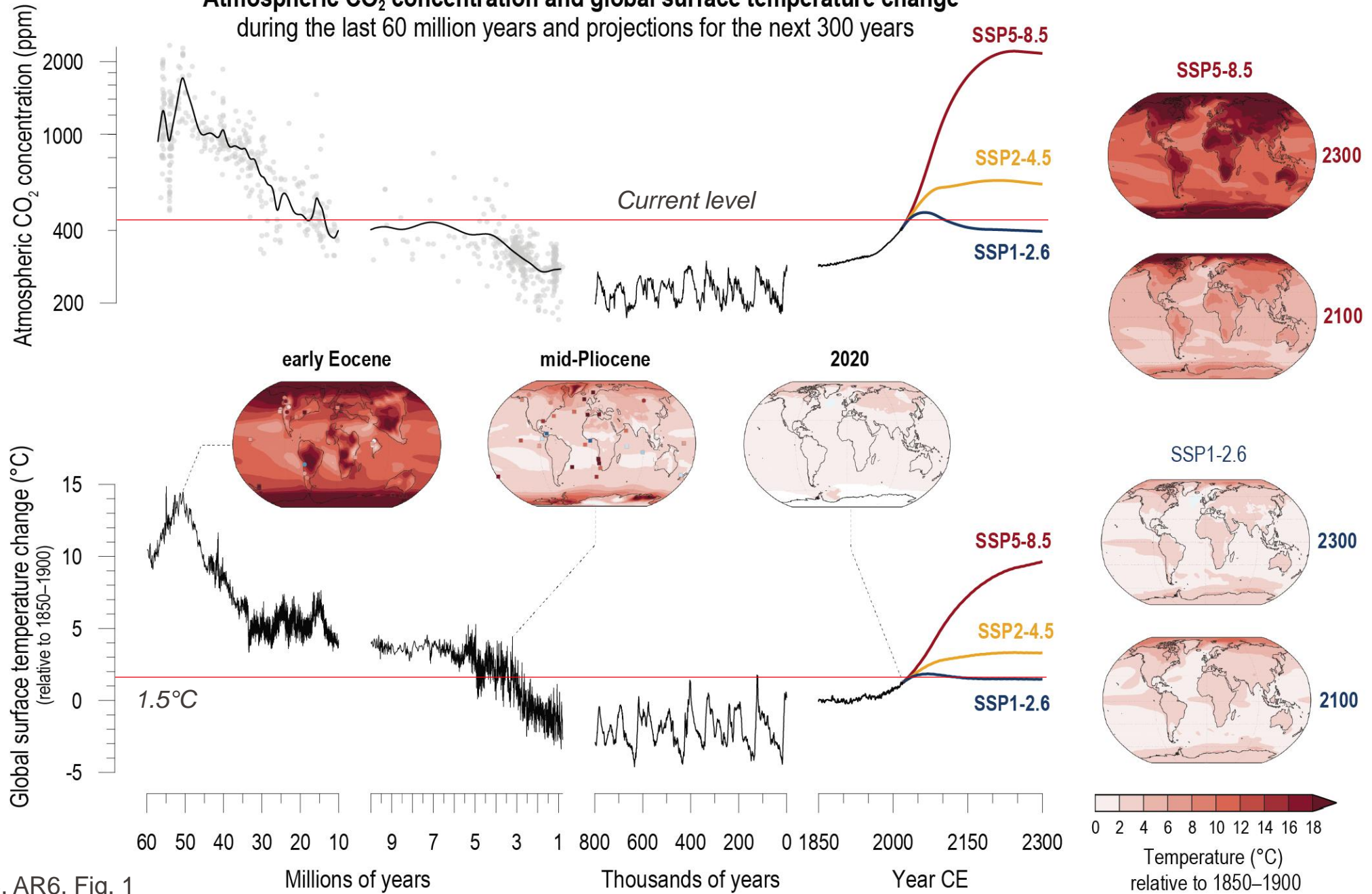
- There is evidence that southern Greenland was forested 130 to 116 thousand years ago, that is the last interglacial period. More likely it was older 450 – 800 thousand years ago. [1]
- More recently, during the medieval warm period, Greenland was warmer, but still covered with the ice sheet. [2]

In the medieval time, there was no global warming, but regional only. Today there is global warming.



- [1] <https://www.science.org/doi/full/10.1126/science.1141758>; [2] <https://www.science.org/doi/10.1126/science.1177303>

### Atmospheric CO<sub>2</sub> concentration and global surface temperature change during the last 60 million years and projections for the next 300 years

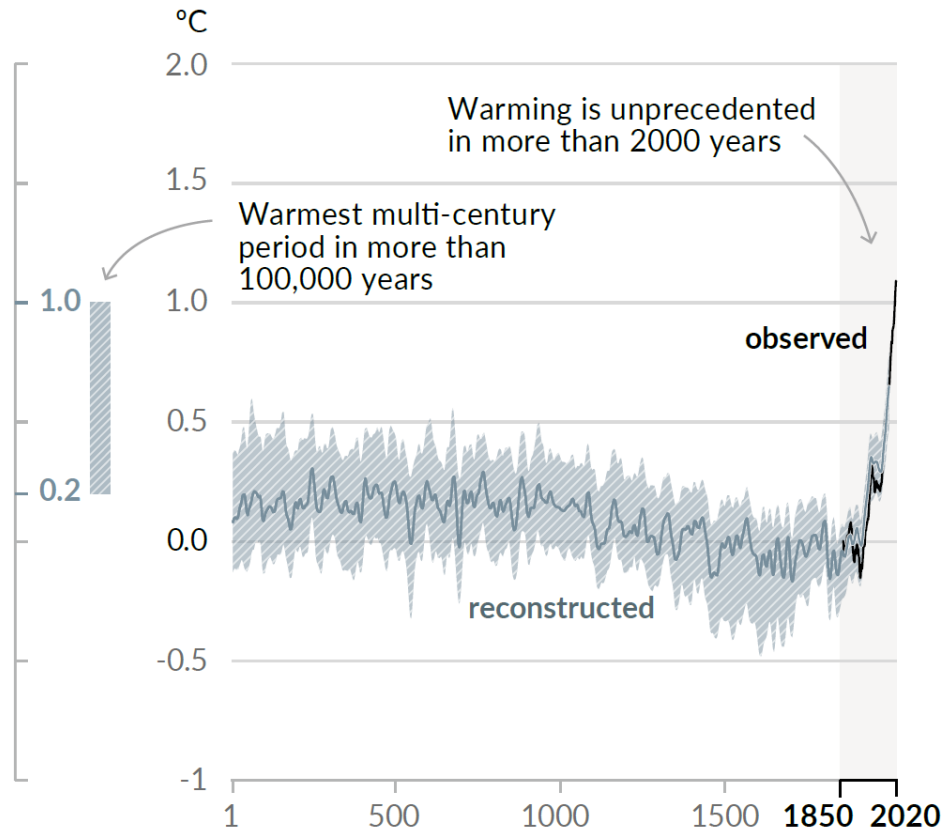


■ IPCC, AR6, Fig. 1  
Technical summary

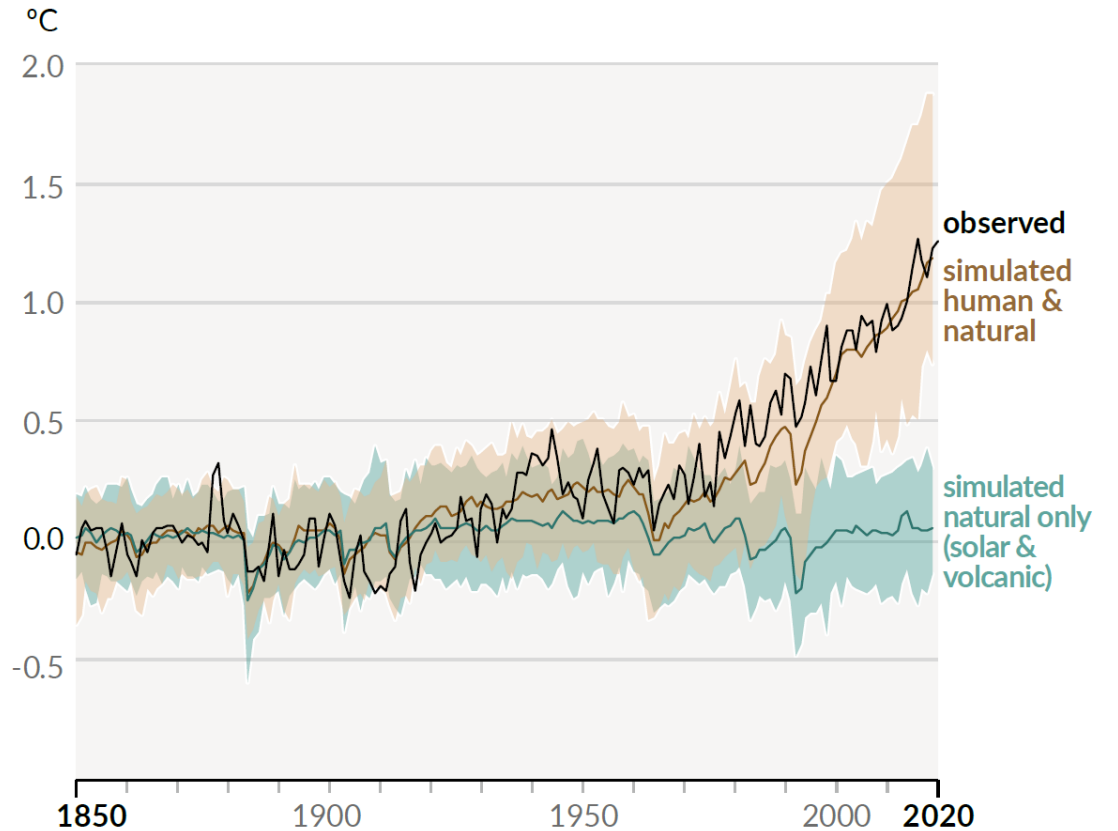
# Today's temperature change

## Changes in global surface temperature relative to 1850-1900

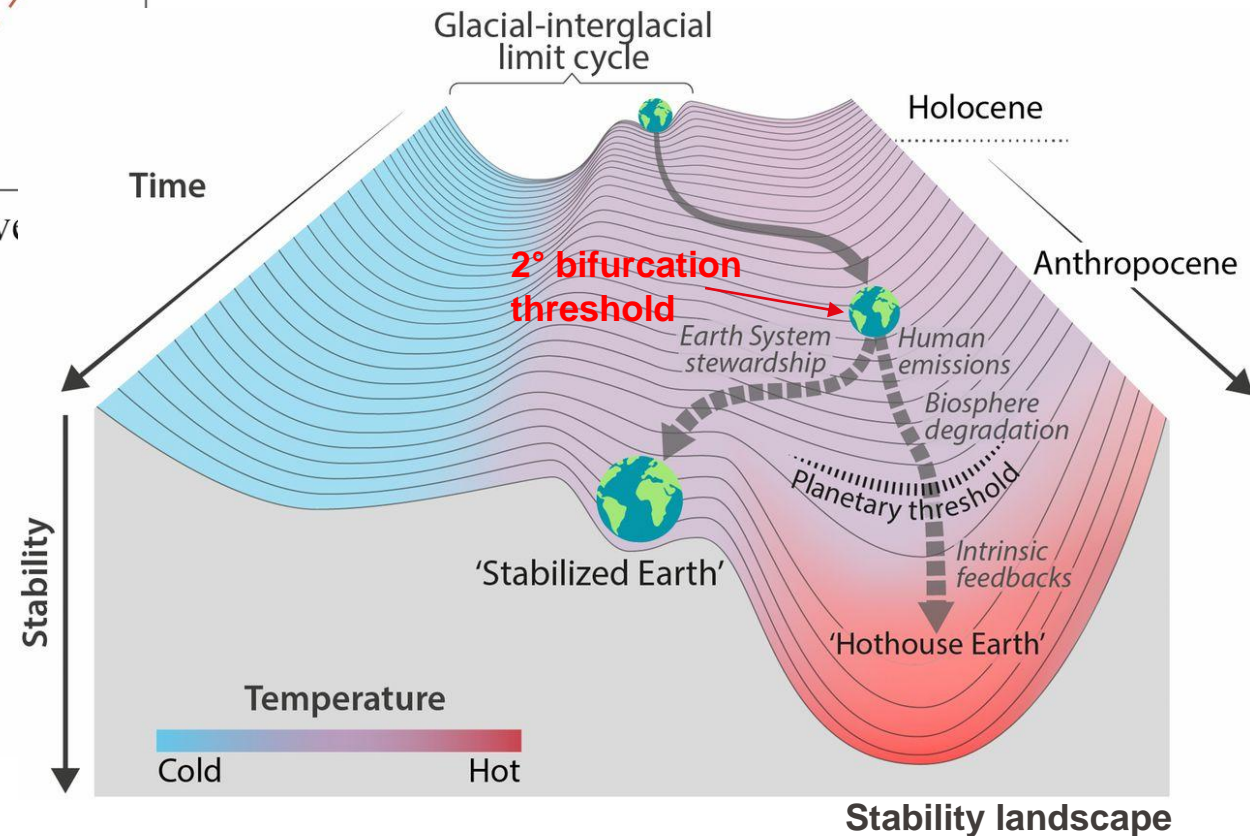
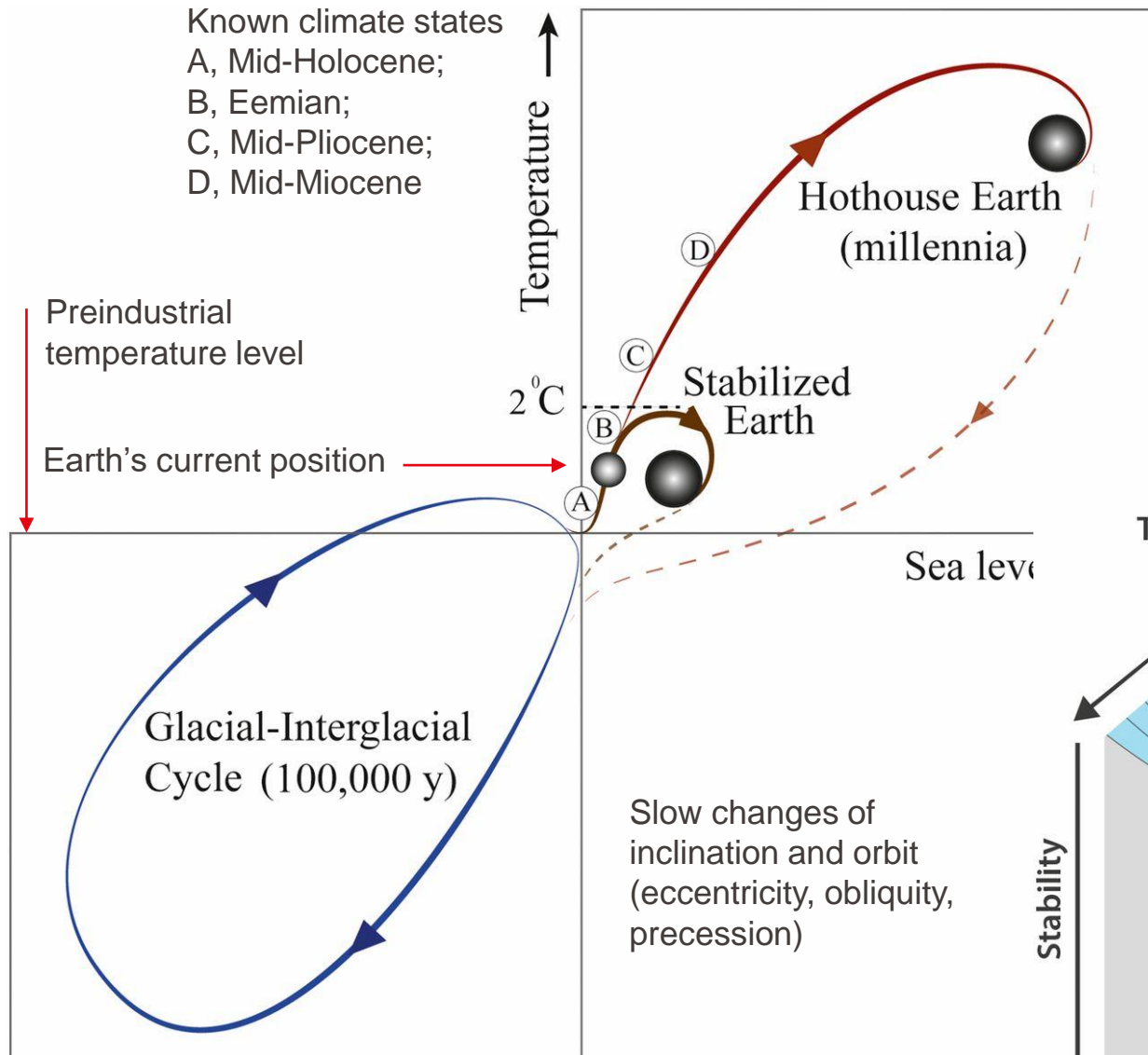
a) Change in global surface temperature (decadal average) as **reconstructed** (1-2000) and **observed** (1850-2020)



b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850-2020)



# Which trajectory are we on: Ice or hot house?



# Please watch for next time

- An introduction to atmospheric circulation:

<https://www.youtube.com/watch?v=Lg91eowtfbw>

See moodle