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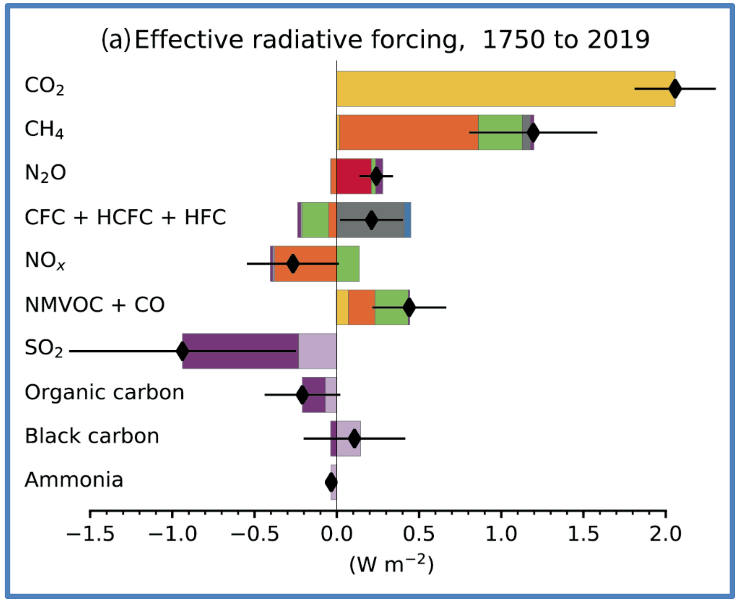
Sustainability, climate and energy

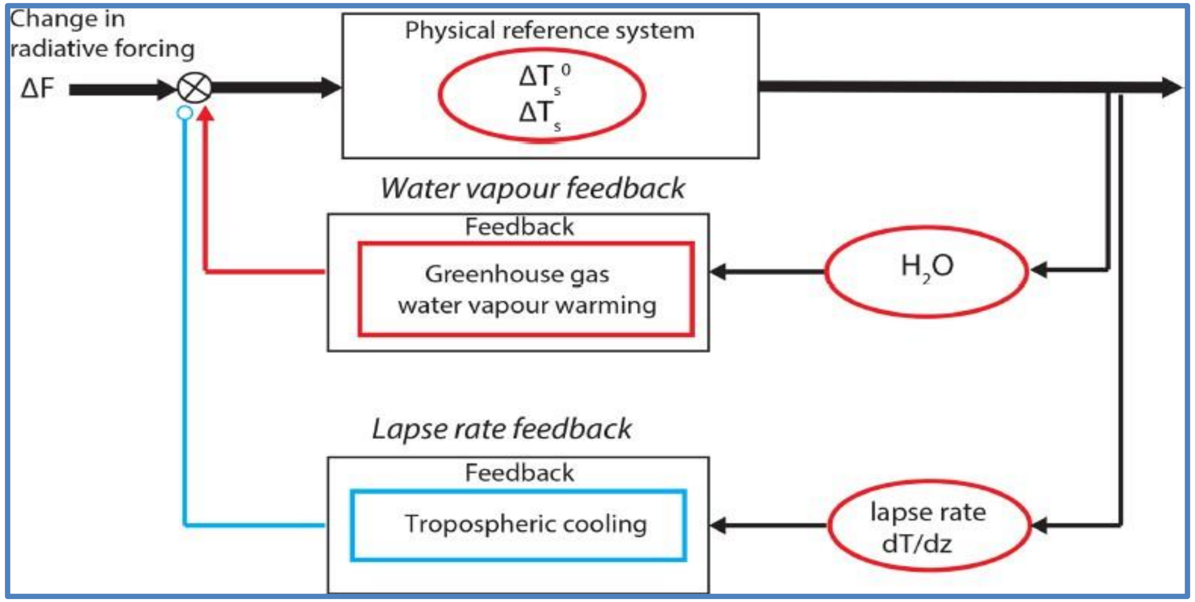
ENV-421
Jérôme Chappellaz, Jonas Schnidrig

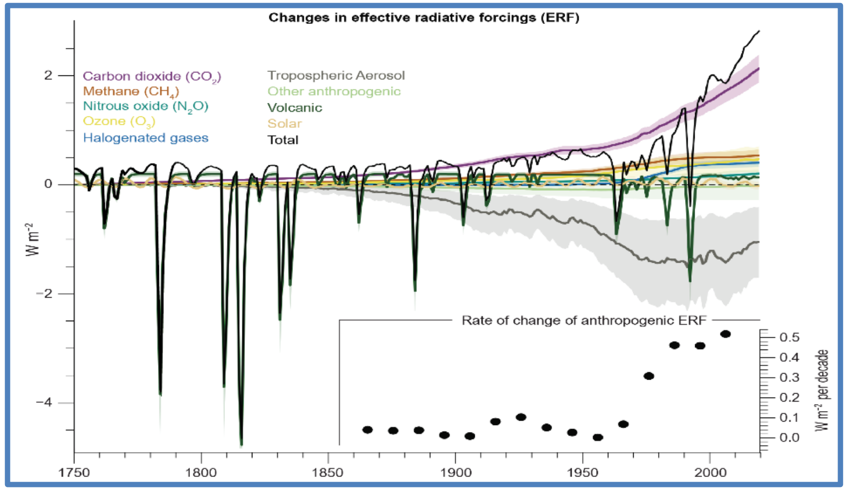
Recap from Week 2: Lecture



Radiative forcing due to GHG and aerosols

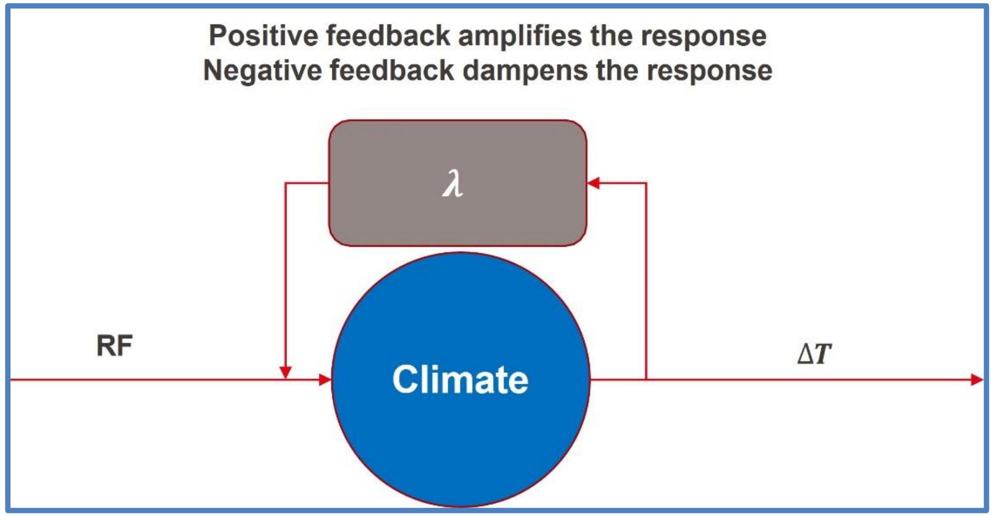
Fast physical feedbacks



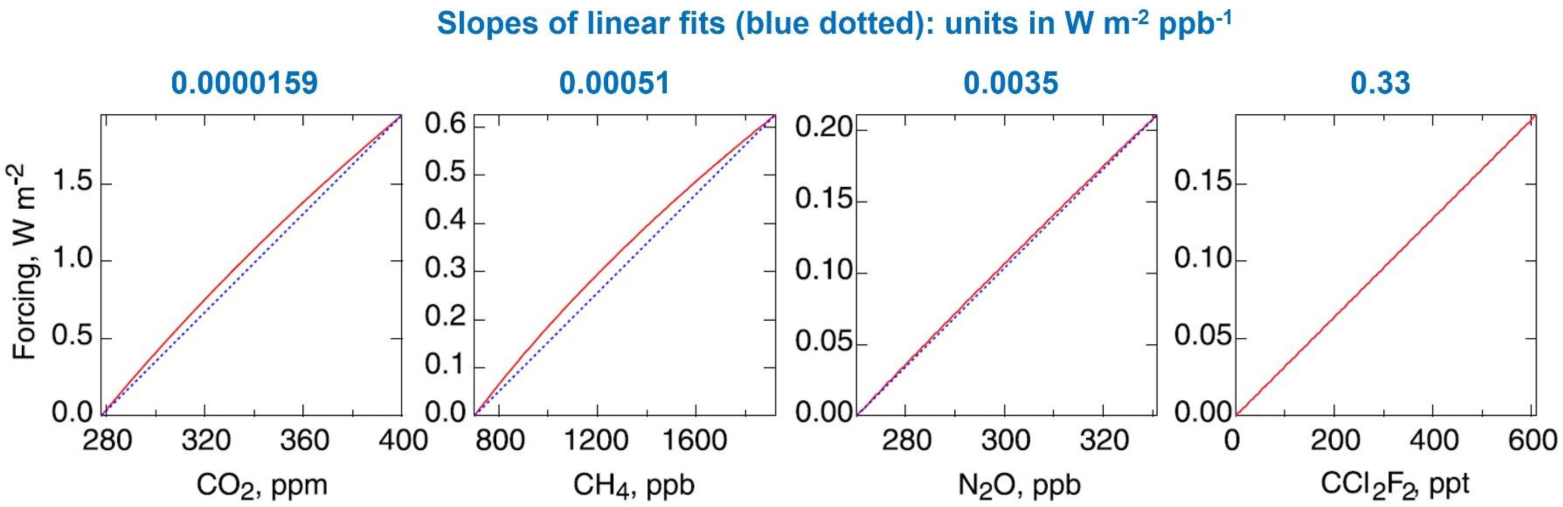


Combined radiative forcing including natural ones

Climate sensitivity



Recap from Week 2: Exercises



- Radiative forcing: mathematical expression and linear fit.
- Water vapor and Clausius-Clapeyron equation: +6.6% for a 1°C warming. $\frac{\Delta e_s}{\Delta T} = \frac{e_s L_v}{T^2 R_v}$
- Feedback factor $\lambda = -\frac{RF}{\Delta T}$

Can we constrain climate sensitivity from observations?

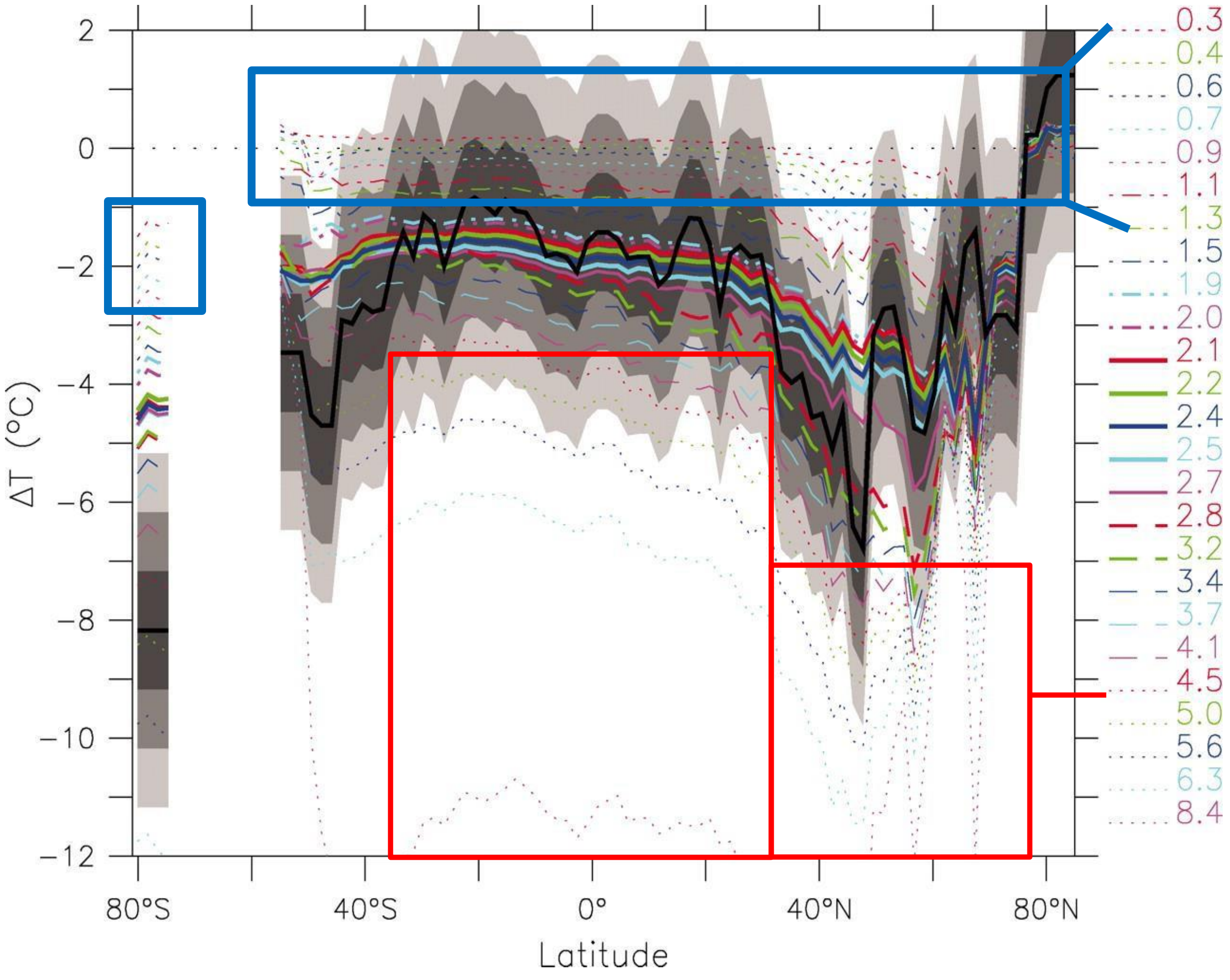
- Changes of the climate system between equilibrium states with different radiative forcing provide in principle the best estimate of climate sensitivity.

- However, the mean climate state and the nature of the forcing (both affecting feedbacks) should be close to the current one.

- Examples: different positions of the continents, meteorite impacts, snowball Earth,… are not so pertinent for climate sensitivity of the next decades / centuries. They allow to test feedbacks under extreme conditions.

- Constraints from observations:
  - Observed warming over the instrumental record.
  - Process-understanding of feedbacks (e.g. satellite and reanalysis products for cloud and water vapor feedback).
  - Short-term climate response to volcanic eruptions (but does not include slow feedbacks).
  - **Paleoclimate records, in particular the Last Glacial Maximum, 20,000 years ago (CO_2~ ≈ 185 ppm).**
  - Observed trends in recent climate variations (emergent-constraint approach).

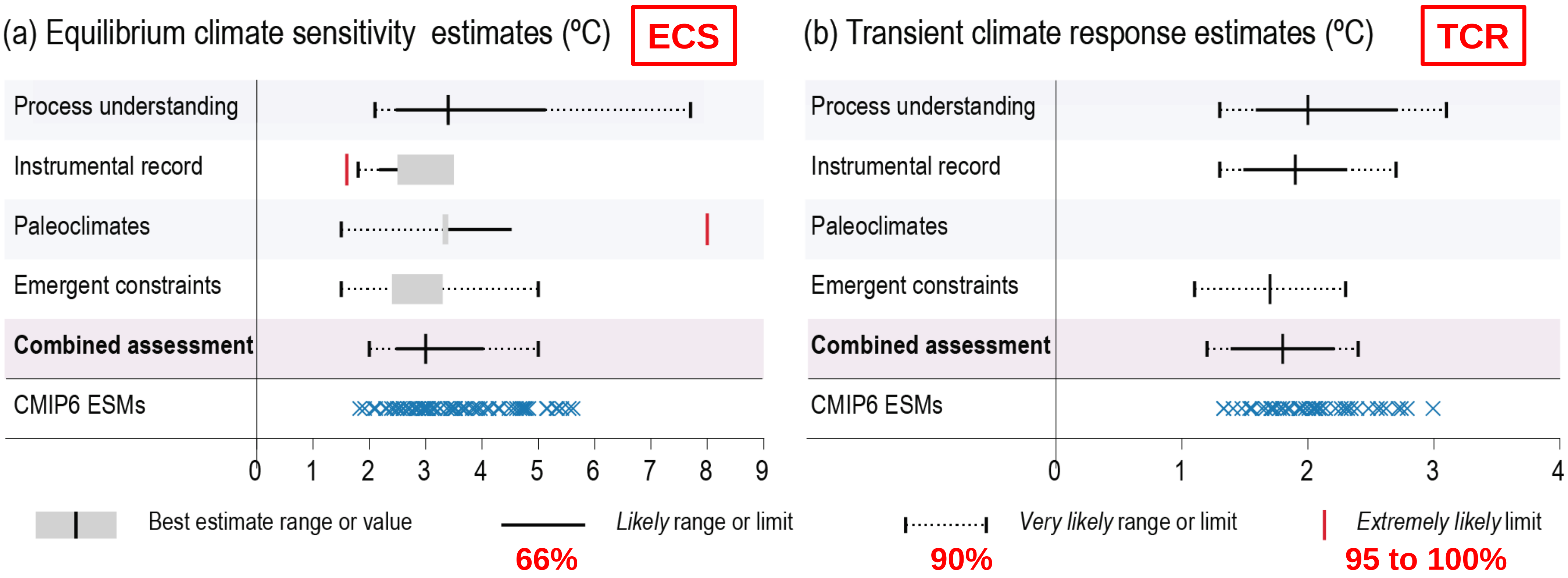
Using the Last Glacial Maximum



- Zonally average surface temperature change between the Last Glacial Maximum (LGM) and preindustrial times.
- Black line = observations.
- Colored lines = different model simulations, with different climate sensitivity ECS.
- Models with ECS_{2xCO2} < 1.3°C underestimate the LGM cooling nearly everywhere, in particular at mid-latitudes and over Antarctica.
- Models with ECS_{2xCO2} > 4.5°C overestimate the cooling almost everywhere, in particular at low latitudes.
- 95% range: 1.4 to 2.8°C.
- IPCC AR6: new paleoclimatic data and improved models. Likely ECS range of **2.5 to 4.0°C**

Source: Schmittner et al., Science 2011

Current state of knowledge about ECS and TCR



Emergent constraints: statistical methods to narrow down the ECS from models and to rule out unrealistic ECS values.

See Caltech Climate Dynamics Group for more explanation

- IPCC AR6: **~2.5 to 4°C** per doubling of CO_2 (**best estimate: 3°C**)

- IPCC AR6: **1.4°C to 2.2°C** (less than ECS because ocean heat uptake is a slow process),

Source: IPCC AR6, Fig. 7.18

Summary: Radiative forcing, feedbacks, climate sensitivity

- They are three fundamental aspects of climate science. Usually referenced **with respect to pre-industrial state**.
- **Time matters !** There are different speeds among radiative forcing factors and different response time of the climate system.
- Solar forcing currently accounts for **0.15 W.m^{-2}**. Volcanic forcing can reach several W.m^{-2} but is limited in time.
- The effective **radiative forcing** of greenhouse gases since 1750 amounts to **3.84 W.m^{-2}**.
- It is strongly muted (but with large uncertainties) by aerosols (including impact on clouds). Total ERF of **2.72 W.m^{-2}** since 1750. Difficult to measure at top of the atmosphere…
- The **fast physical feedback factors** amount to **-1.16 W.m^{-2}.°C^{-1}**. Slow feedbacks (deep ocean, ice sheets,…) will add on over millennial time scales.
- **Climate sensitivity** is calculated based on a doubling of atmospheric CO_2. It depends on the time scale being considered, which impacts the involved feedbacks.
- For the 21st century, it ranges typically between **1.5 and 4°C**.
- **Our future climate depends on climate sensitivity. But even more on emission scenarios for greenhouse gases and aerosols !**

General outline

Basics

Applications

No.	Date	Topics	Remarks
1.	18.02.2025	Introduction to the climate system. Earth energy balance. Greenhouse gases and aerosols	
2.	25.02.2025	Introduction to energy systems. Energy balance fundamentals	
3.	04.03.2025	Radiative forcing. Feedback mechanisms. Climate sensitivity	
4.	11.03.2025	Overview of energy technologies	
5.	18.03.2025	**Climate archives: geological to millennial time scales**	Conf. Michael Sigl + QCM evaluation (graded)
6.	25.03.2025	Climate variability. Climate change scenarios. Carbon cycle feedbacks.	
7.	01.04.2025	Technologies' impacts	Conf. Alexis Quentin
8.	08.04.2025	Tipping points. Extreme events. Regional climate change	
9.	15.04.2025	Climate change impacts on renewable energy systems. Impact of RES on climate	J. Castella (Watted) : PowerPlay game
10.	29.04.2025	Field visit : floating solar platform + dam (Romande Energie)	
11.	06.05.2025	Intro to systemic approach on local scale climate/energy engineering	Start of group work
12.	13.05.2025	Group work on chosen case study	
13.	20.05.2025	Group work on chosen case study	
14.	27.05.2025	Presentation of group reports	Reports are graded

Exam session between 16.06.2025 and 05.07.2025

Climate archives

Why do we need a long temporal framework of observations ?

- Changes in slow climate processes are not well covered by the instrumental time scale.
- Statistics on extreme events and on the role of external forcings require a longer time scale.
- Our confidence in climate model outputs is reinforced when they are are tested against past climate events.
- Indirect evaluation of climate sensitivity under similar or different boundary conditions.

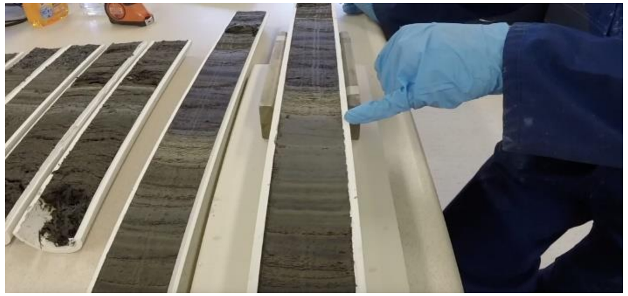
Source: Nnadir Mimouni, Saatchi Art

Quizz : which archives are available to document past climate changes ?

Examples:
- Ice cores
- Tree rings
- Lake sediments

Provide at least two more…

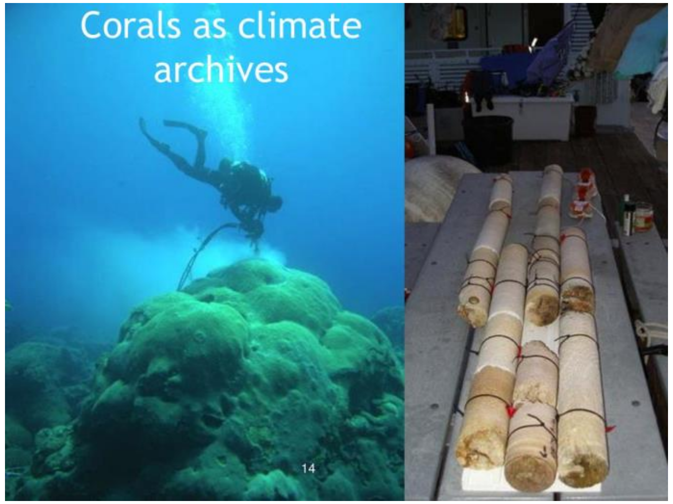




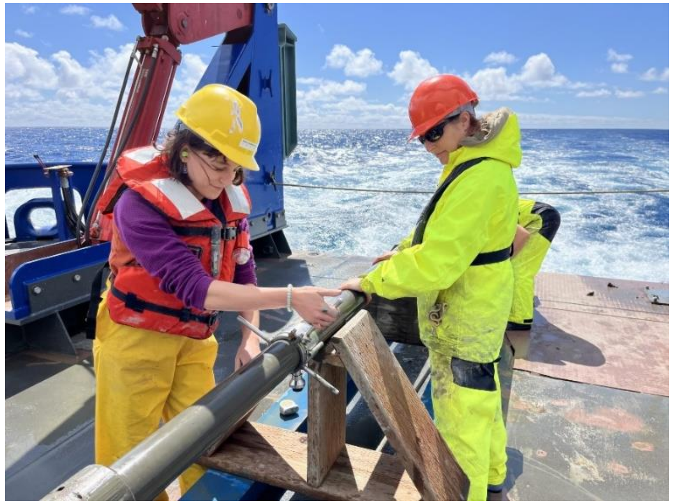
FEDERAL DOCUMENT, ROCKS, BOTTOM OF OCE...
ROCKS LAYERS, ROCKS WITH WATER LEVEL
FOSSILS SOILS ROCKS CAVE PAINTINGS ?
OXYGEN ISOTOPES
LAYERS IN SEDIMENTARY ROCKS
FOSSILES ISOTOPES

Archives of past climate

Corals

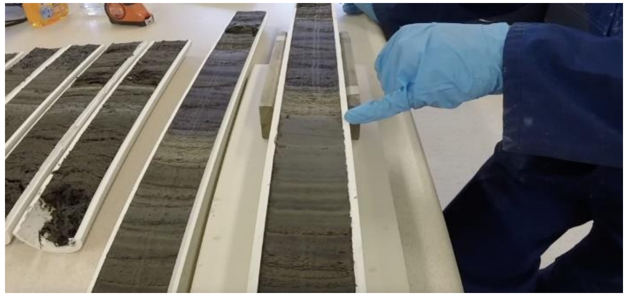


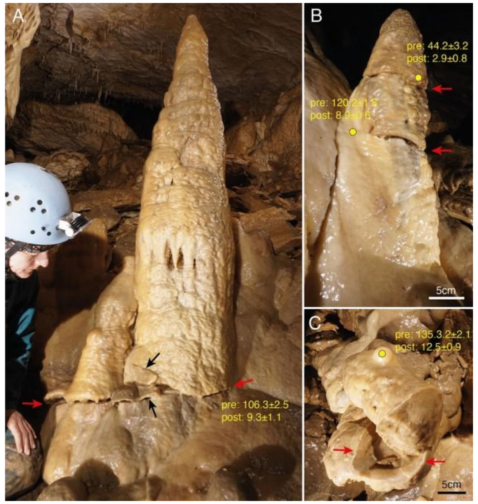
Marine sediments



Examples:
- Ice cores
- Tree rings
- Lake sediments

Provide at least two more…





Speleothems

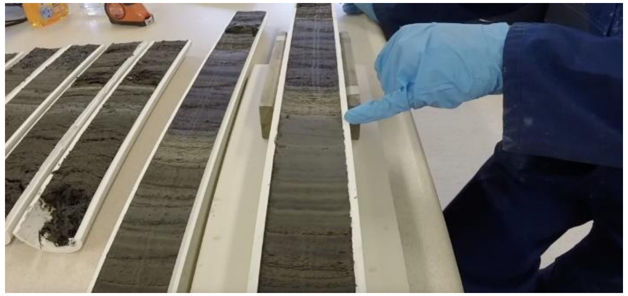
Historical records

Archives of past climate

Examples:
- Ice cores
- Tree rings
- Lake sediments

Provide at least two more…





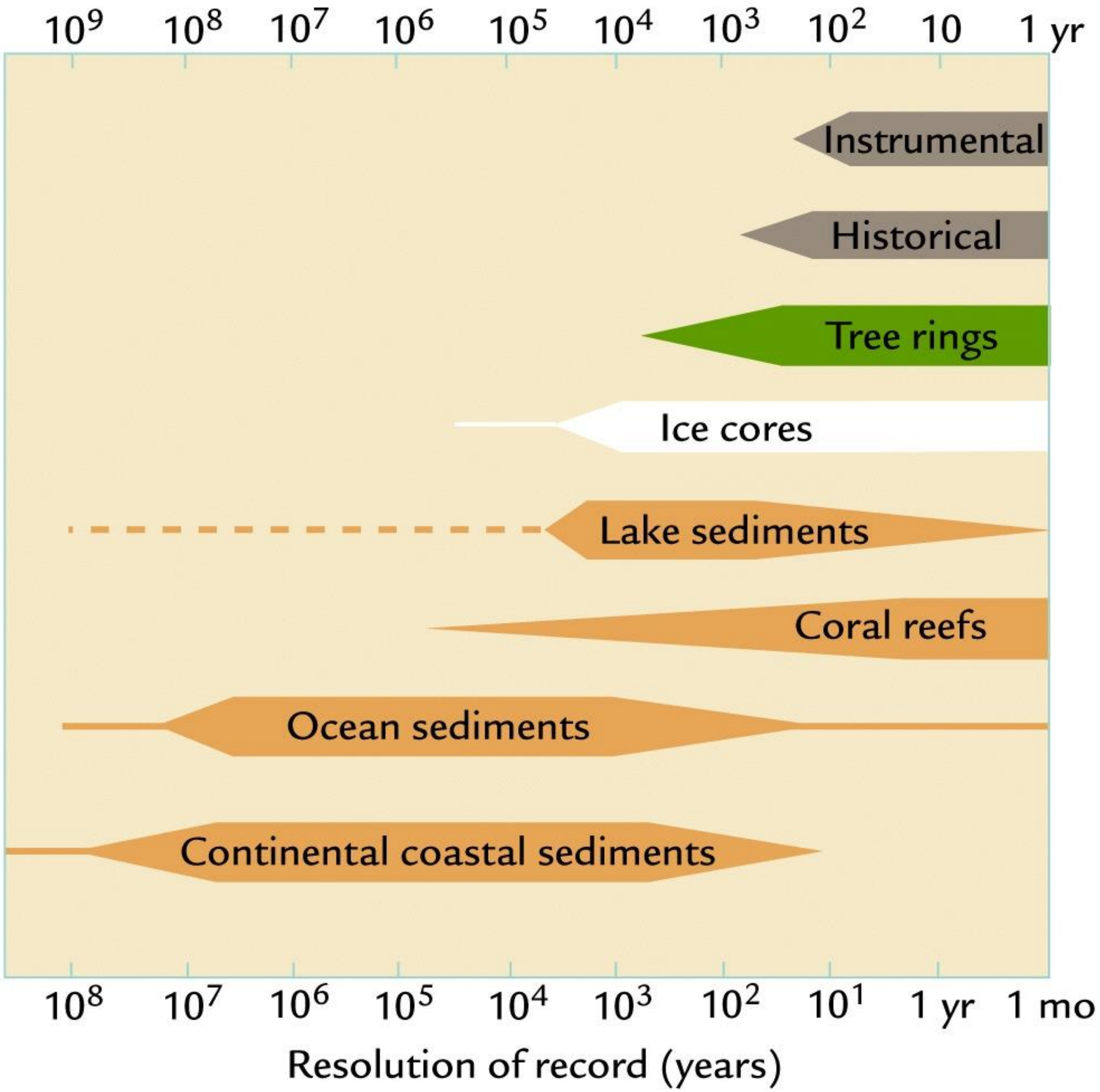
Rocks and fossils

Fossil leaves from deciduous trees in Clarkia Lake, USA, dated ~16 million years ago.

Ice-rafted debris in sediments of Namibia, dated ~635 million years ago.

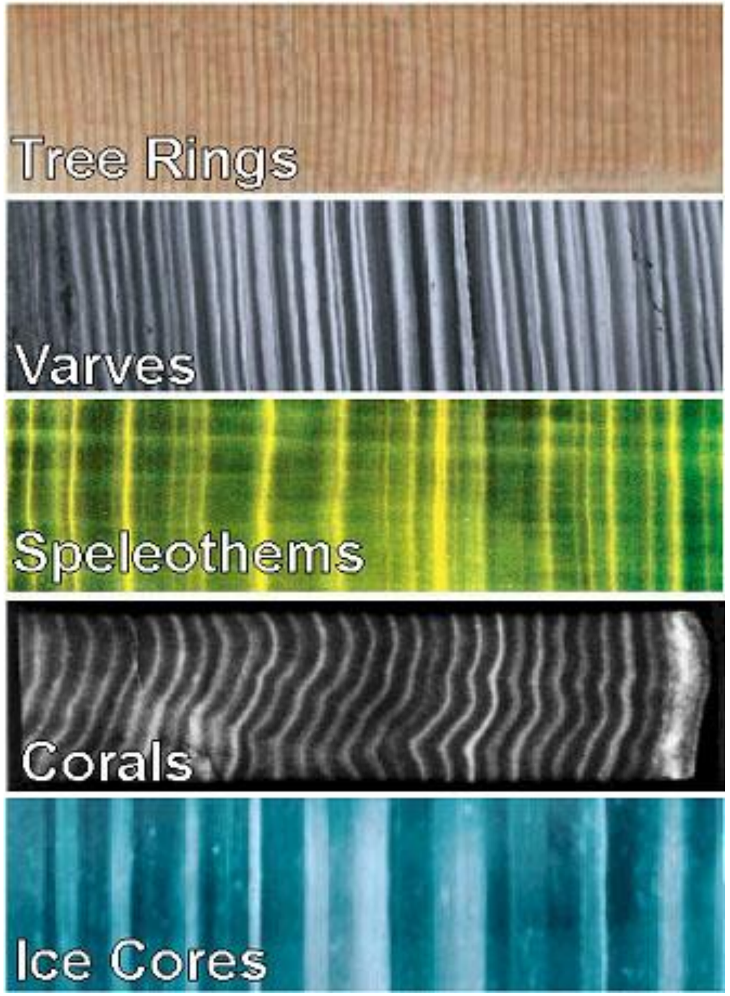
Sources: Dr. Yige Zhang ; Paul Hoffman

Archives of past climate: time scale and resolution



Source: Ruddiman, Earth's climate, past and future

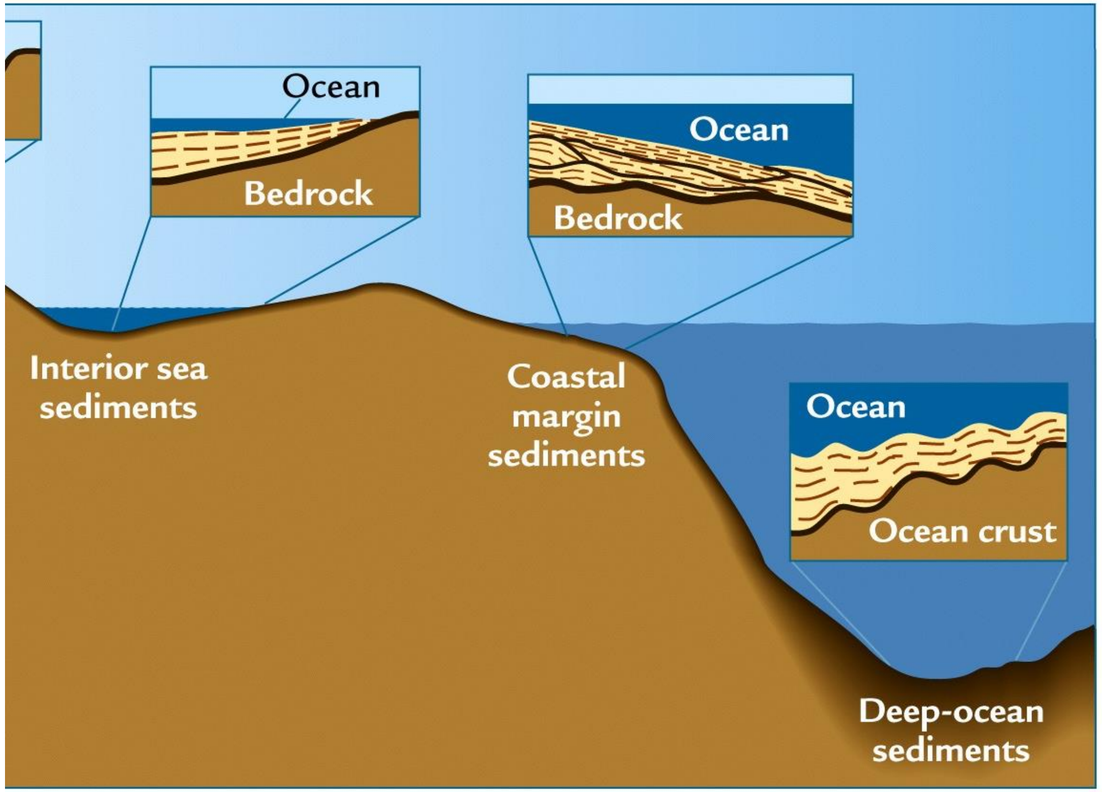
Laminated archives: physical or biological processes leading to annual resolution.



Source: PAGES Newsletter, october 2003

Marine sediments

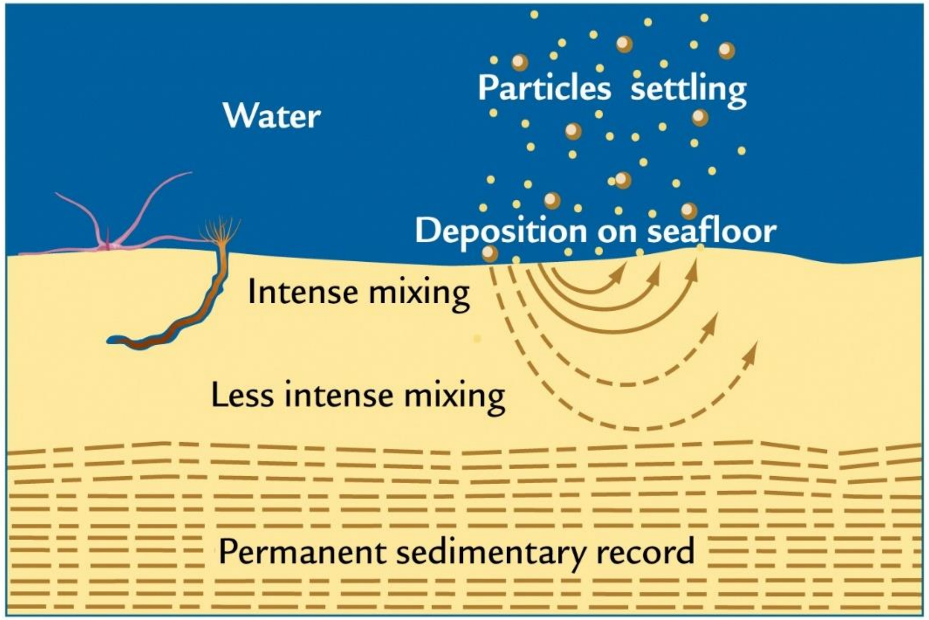
- Covers a large part of geological time scales.
- Back to 170 million years in the western Pacific !
- Sediment material results from :
  - Continental erosion and usually river transport.
  - Sedimentation of marine biota.
  - Atmospheric fallout (meteorites, volcanic ash).
  - Minor contribution from subsea volcanoes.



Source: Ruddiman, Earth's climate, past and future

Marine sediments – Pros and cons

Pros:
- Time scale.
- Long stratigraphic sequences.
- Multiple tracers related with ocean physics, biology, dynamics.

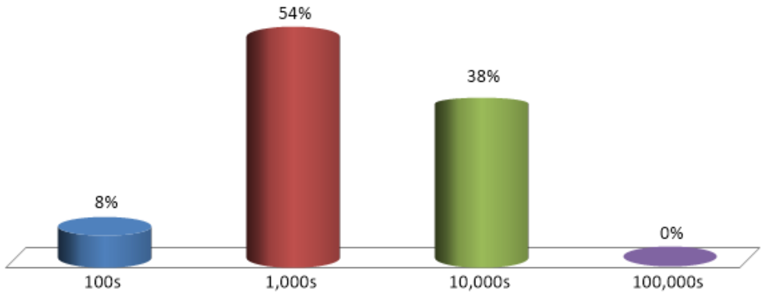


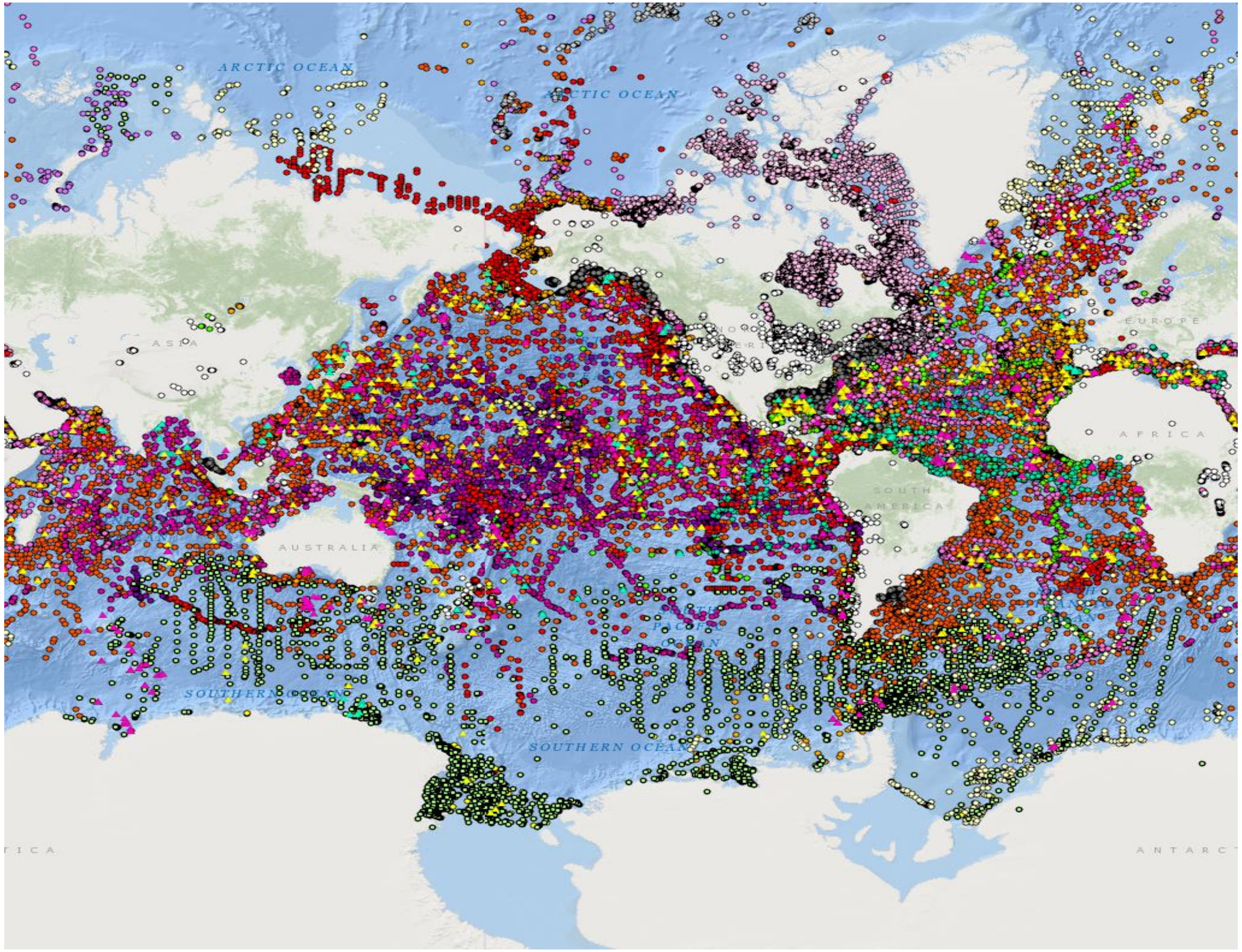
Cons:
- Usually low temporal resolution (a few mm per 1’000 years in deep oceans).
- Post-deposition disturbances due to:
  - Bioturbation.
  - Diagenesis (i.e. dissolution of calcite at depth below ~4’500 m).
  - Marine slumps.
- Often complex transfer function between the proxy being measured and the climate-related signal.

Source: Ruddiman, Earth’s climate, past and future

How many marine sediment cores have been drilled throughout the world's oceans and seas ?

A. 100s
B. 1,000s
C. 10,000s
D. 100,000s





Source: NOAA Marine and Lacustrine Geological Samples

Marine sediments – what information ?

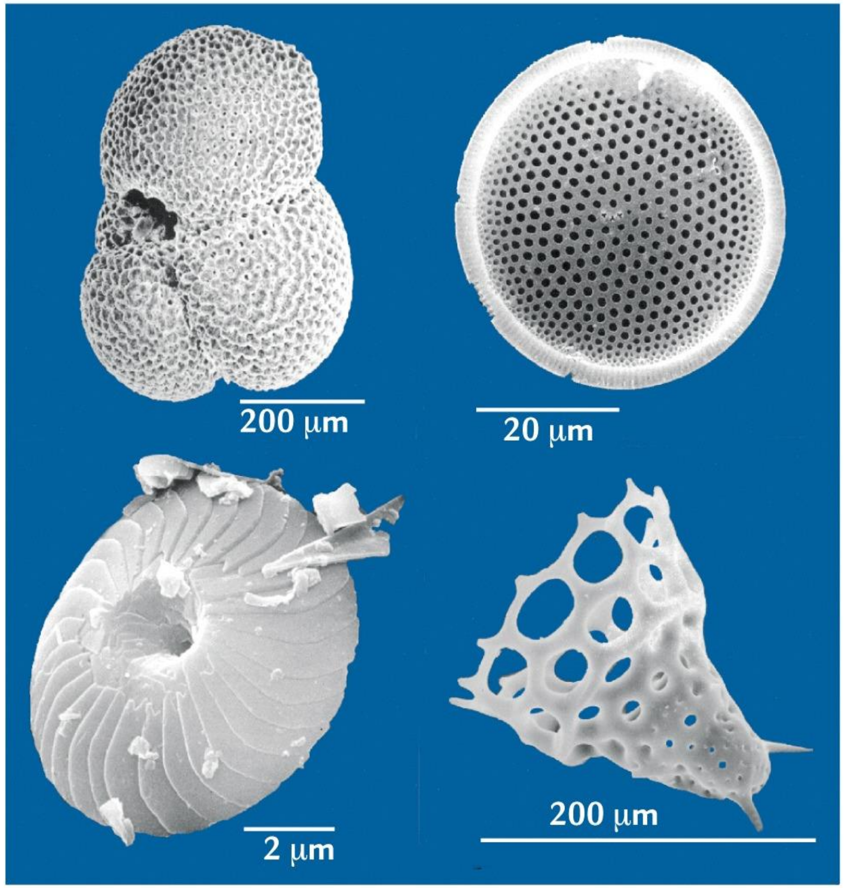
- Assemblages of fossil shells of microorganisms, living at the ocean surface (planktic) or in deep water (benthic).

- Marine conditions can be species-specific. Examples:
  - *Globigerinoides ruber* (foraminifera) is specific of warm tropical waters.
  - *Fragilariopsis cylindrus* (diatom) is specific of sea-ice conditions at the surface.

- But the main use of these shells goes through isotopic measurements of the shells (oxygen, carbon, boron,…) or elemental ratios (such as magnesium / calcium).

Foraminifera ($CaCO_3$)

Diatoms (SiO_2)

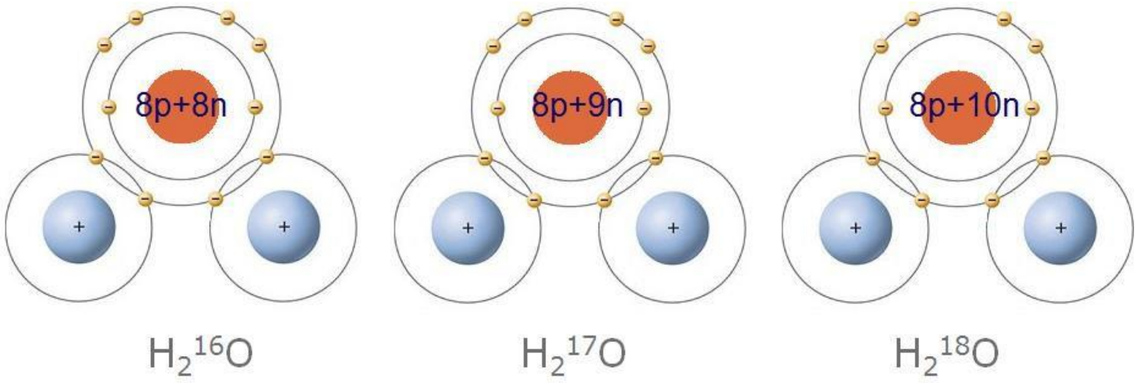


Coccoliths ($CaCO_3$)

Radiolar (Opal: $SiO_2.nH_2O$)

Isotopes

- Isotopes: **atoms** of an element **with the same atomic number but different atomic masses**.
- Same number of protons and electrons but **different number of neutrons**.
- **Isotopologues**: refers to **molecules** having different isotopic compositions.



Abundance: 9977 : 3 : 20

$$\delta^{18}O = \left(\frac{(^{18}O/^{16}O)_{\text{sample}}}{(^{18}O/^{16}O)_{\text{standard}}} - 1 \right) \times 1000$$

- Three different water molecules with different oxygen isotopes.
- The most common form is $H_2{}^{16}O$.
- For each 10,000 water molecules in nature:
  - only 3 are $H_2{}^{17}O$.
  - 20 are $H_2{}^{18}O$.

- Because the changes of relative abundance of the «heavy» isotopologue versus the «light» one in nature are very small, we use the delta-notation with respect to a standard.

- For oxygen, the standard made by the International Atomic Energy Agency IAEA is called «Vienna Standard Mean Ocean Water» (VSMOW) and is set to 0 ‰.

Source: Ice and climate

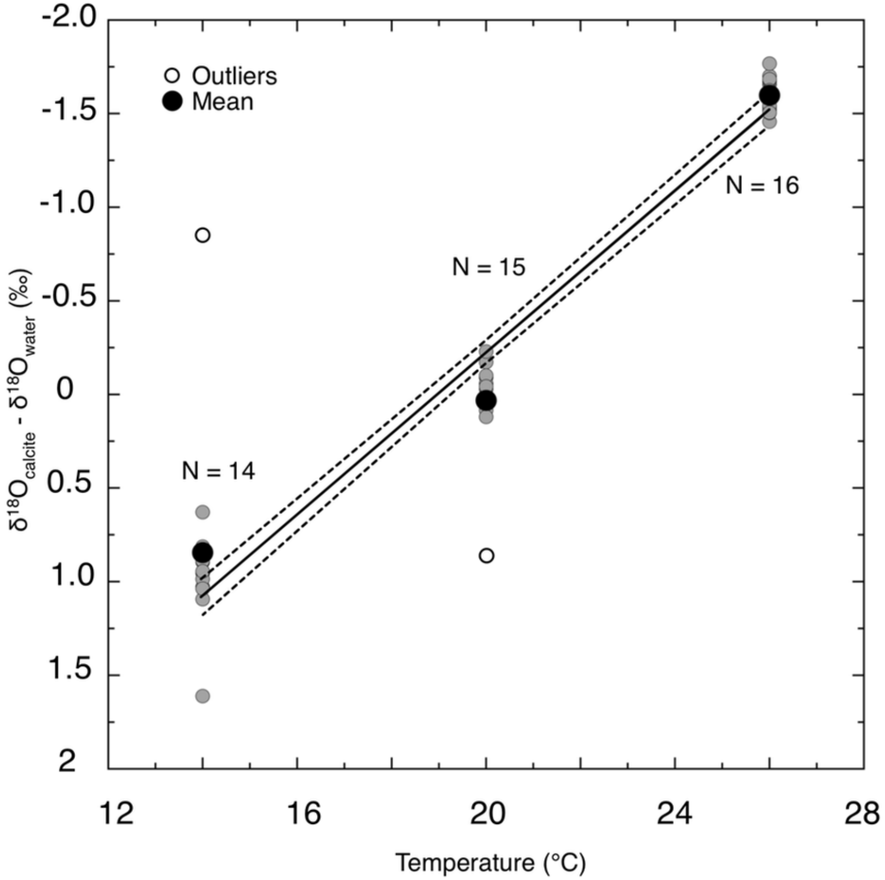
Oxygen isotopes of calcite

Source: Al-Qattan et al. AGU Advances, 2023

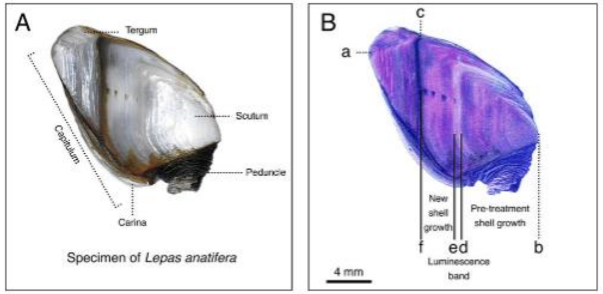
- The oxygen isotopic composition of calcite in the shells of microorganisms depends on:
  - Water temperature.
  - The seawater isotopic composition.
- Empirical equation based on laboratory experiments and natural observations:

$$T(^\circ C) = 16.9 - 4.38(\delta^{18}O_{calcite} - \delta^{18}O_{water}) + 0.1(\delta^{18}O_{calcite} - \delta^{18}O_{water})^2$$

- Colder (warmer) temperatures lead to higher (lower) $\delta^{18}O$ of calcite.
- But $\delta^{18}O$ of seawater is strongly affected by changes in global ice volume on continents.
- In addition: use the magnesium / calcium Mg/Ca ratio in shells of foraminifera: warmer water increases Mg incorporation in their shells.



Barnacles found on the MH370 flaperon of Malaysian Airline, disappeared on March 2014

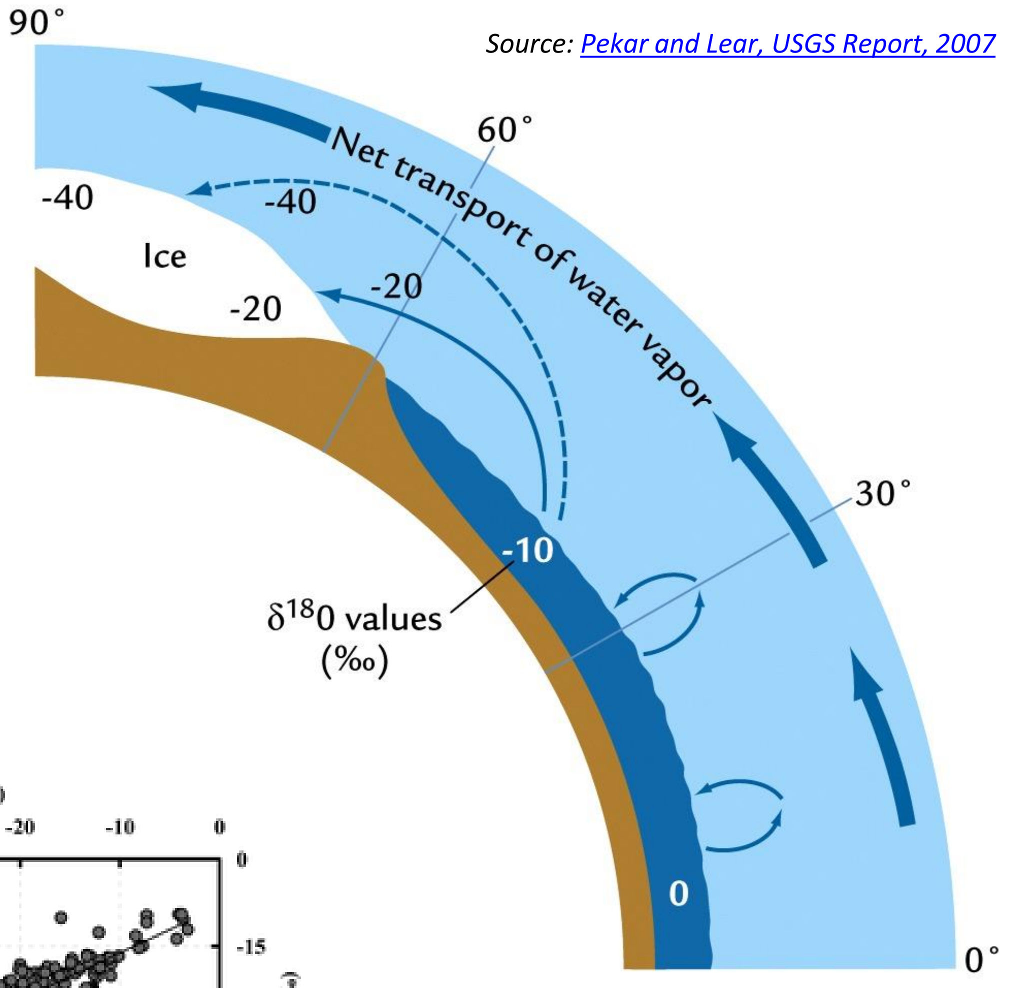


Water isotopes as paleo-thermometer

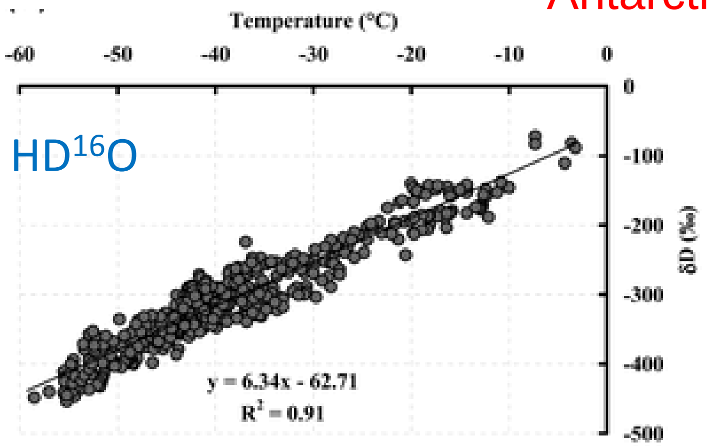
<u>**Global water cycle**</u>:

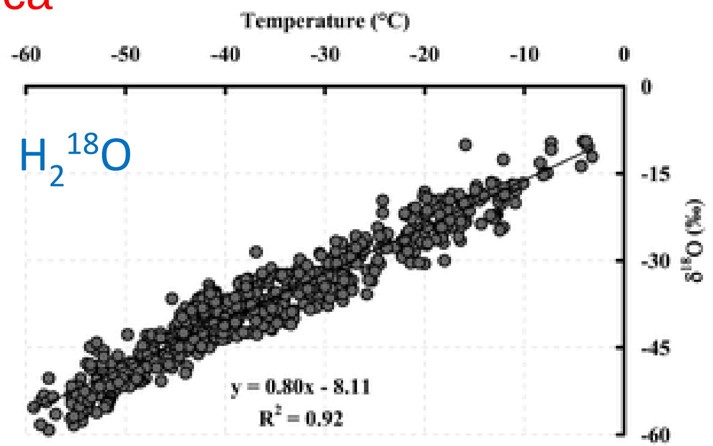
- Ocean evaporation followed by atmospheric transport.
- The colder the air, the less water vapor content.
- Progressive depletion of heavy isotopologues ($H_2{}^{18}O$, $HD^{16}O$) during consecutive precipitation events (phase change).
- This so-called **"Rayleigh distillation"** leads to a linear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

Source: *Pekar and Lear, USGS Report, 2007*



Antarctica



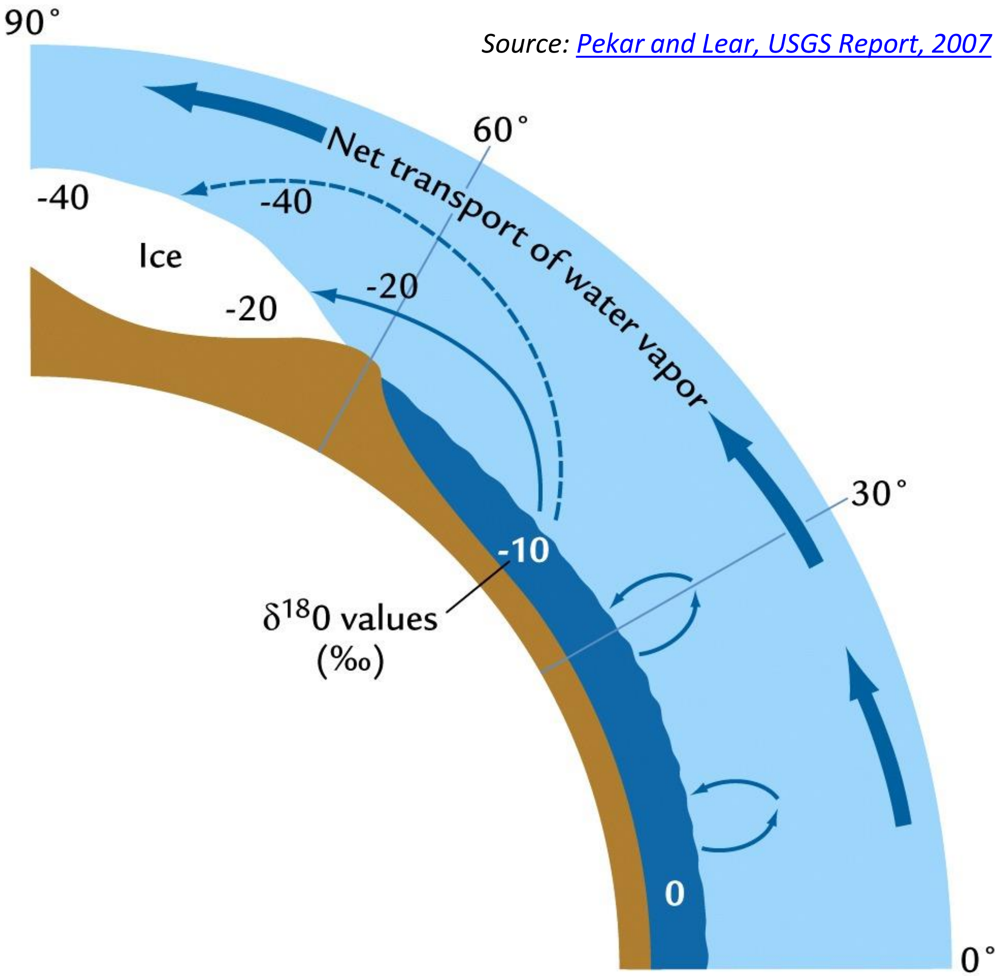


Source: *Masson-Delmotte et al., Journal of Climate, 2008*

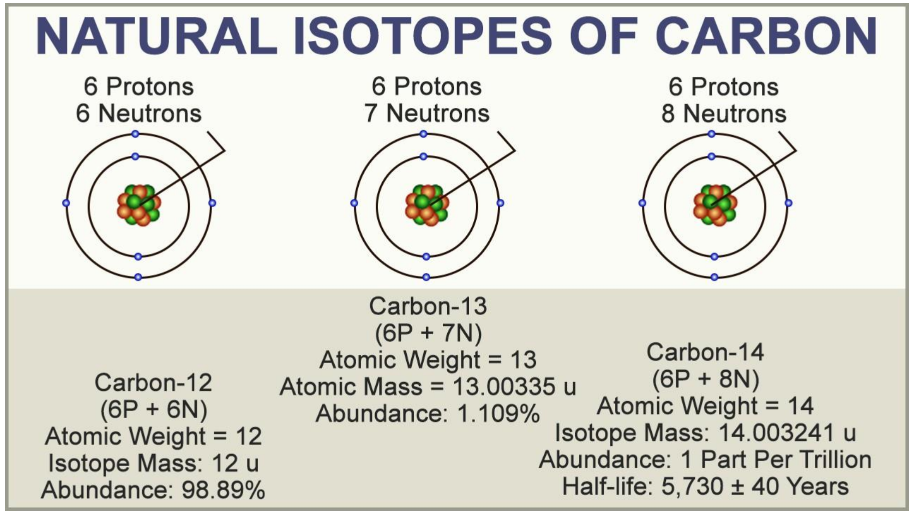
Water isotopes as paleo-thermometer

Source: Pekar and Lear, USGS Report, 2007

- Water isotopes (oxygen and hydrogen) of snow and ice provide **past surface temperature of polar ice sheets**.
- Oxygen isotopes of fossil microorganisms in marine sediments are a mix of **past ocean temperature and past global ice volume.**
- The differential use of planktic and benthic foraminifera is a way to distinguish the two variables. Deep water temperature is much more stable than surface waters.



Carbon isotopes



- Carbon-14, Carbon-13, and Carbon-12 are isotopes of carbon.
- C-14 has 8 neutrons, C-13 has 7 neutrons and C-12 has 6 neutrons.
- All of them have the same number of protons (6) and the same number of électrons (6).
- Only C-14 is radioactive, with a half-life of 5,730 years.

Different use in paleoclimatology. In particular:

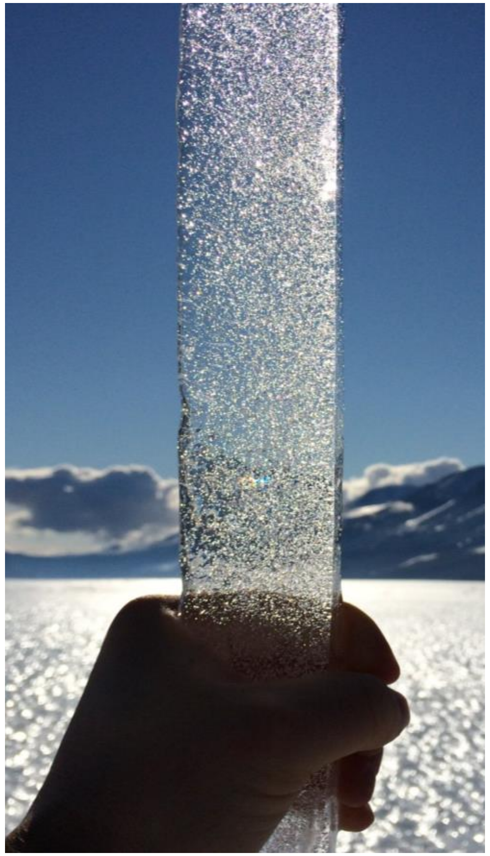
- $\delta^{13}C$ (delta notation for the ratio $^{13}C/^{12}C$) of benthic foraminifera (living in the deep ocean) is low when ocean stratification is more important.
- On continents, $\delta^{13}C$ of soil carbonates will depend on the type of vegetation (C4 («grass») or C3 («trees») plants).

Source: [Hasan Al-Khshemawee]

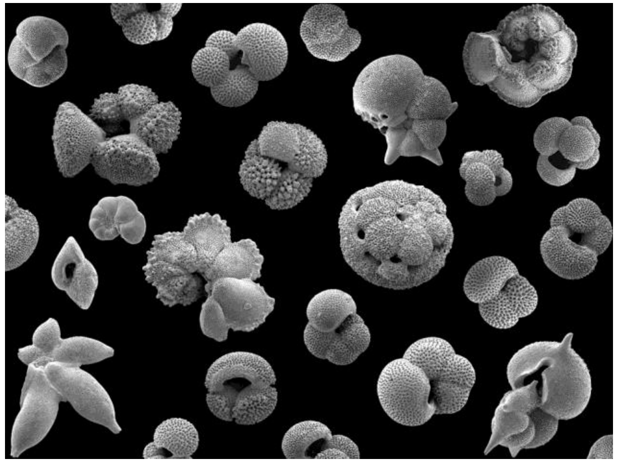
How to reconstruct past atmospheric CO_2 ?

- 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).

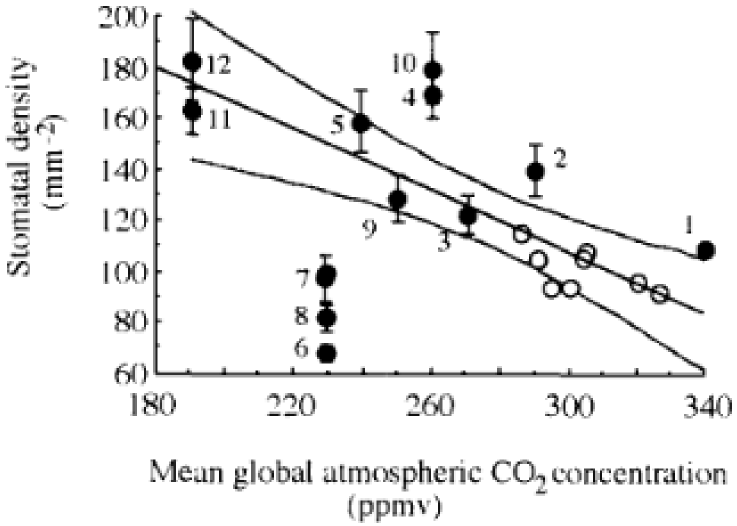
- Indirect methods:
  - **Boron isotopes**. Their ratio in marine carbonates depends on seawater pH and thus in part on dissolved CO_2 from the atmosphere. But needs other constraints on the carbonate chemistry.
  - **Carbon isotopes of alkenones**. Organic molecules produced by phytoplancton. $\delta^{13}C$ 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

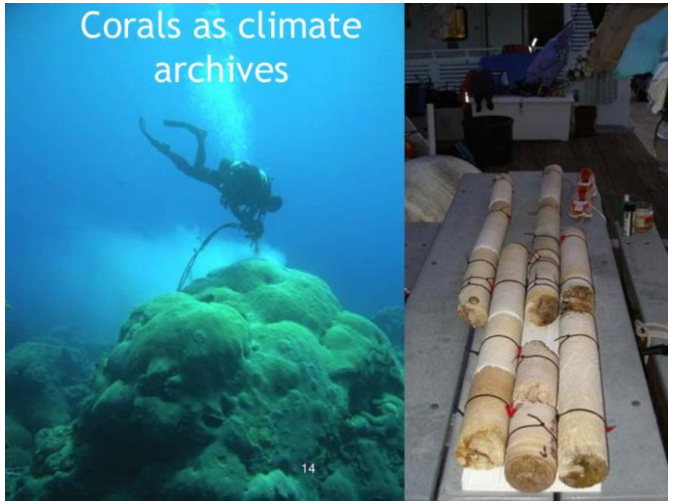
Climate proxies in other archives like tree rings

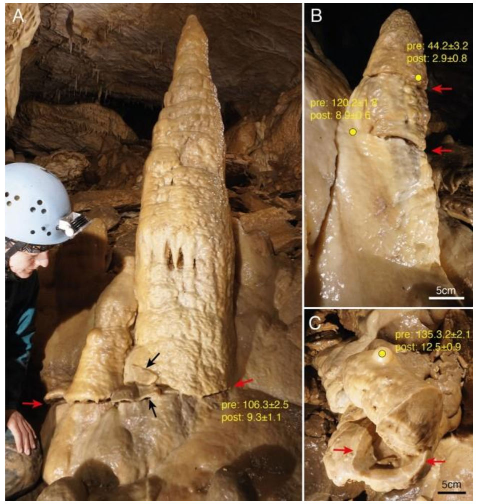
<u>Usual signals</u>:

- Width of annual rings.
- Example for tree rings: wide rings mean unusually warm and wet conditions.

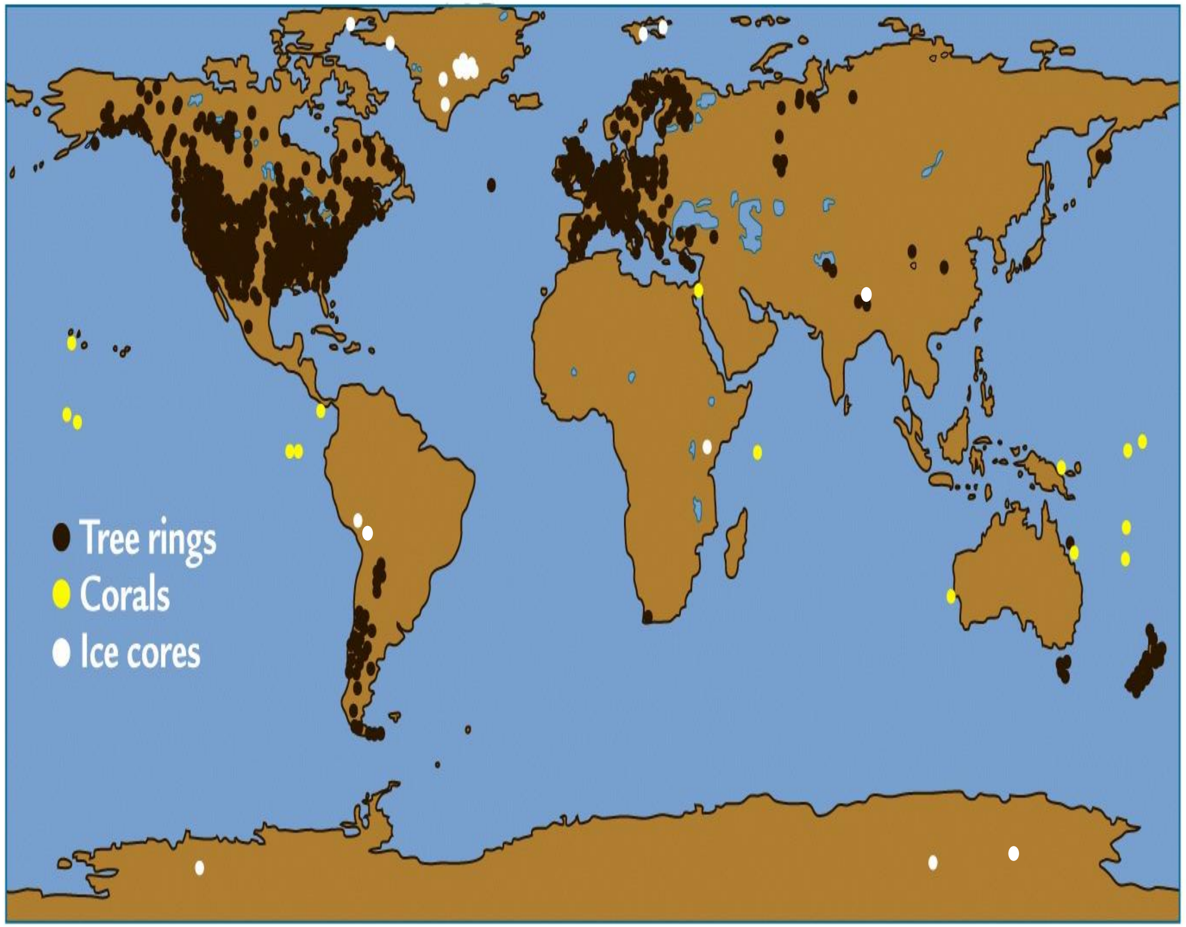
- Oxygen and carbon isotopes.

- <u>Extreme events</u>:
  - Fire scars on tree rings.
  - Cyclone impact on coral growth.
  - Interruption of growth for speleothems (drought).





An uneven distribution in space



Source: Ruddiman, Earth's climate, past and future

- Strong bias on Europe and North America for tree rings.
- Ice cores mostly in Greenland and Antarctica.
- Corals in equatorial regions.

Historical archives

- Qualitative perception of temperature, wind, rain, clouds, based on reports, novels,…
- Occurrence of extreme events (storms, floods), freezing of rivers, snow cover…
- Official records of types and yield of crops (taxes), dates of grape harvest.
- Punctual and rarely on an absolute scale. But useful to depict natural variability and extremes under conditions similar to today.
- Limited to Europe and China.

"Le piège à oiseaux", Pieter Brueghel l'ancien (1565)

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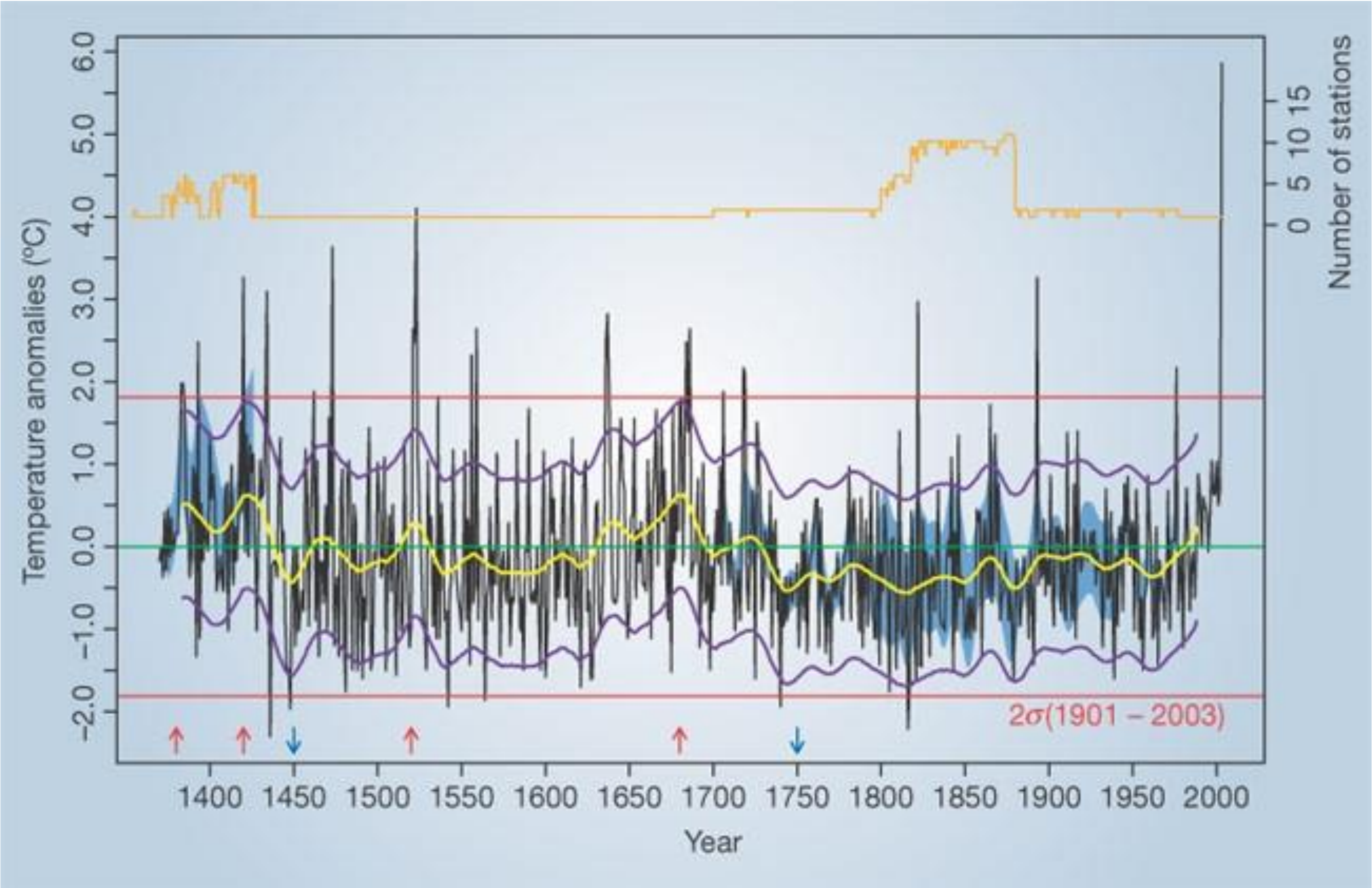
- Official records of types and yield of crops (taxes), dates of grape harvest.
- Punctual and rarely on an absolute scale. But useful to depict natural variability and extremes under conditions similar to today.
- Limited to Europe and China.
- Illustration with summer temperature anomalies in Burgundy (France) reconstructed from harvest dates (using a phenological model of Pinot noir grapes)

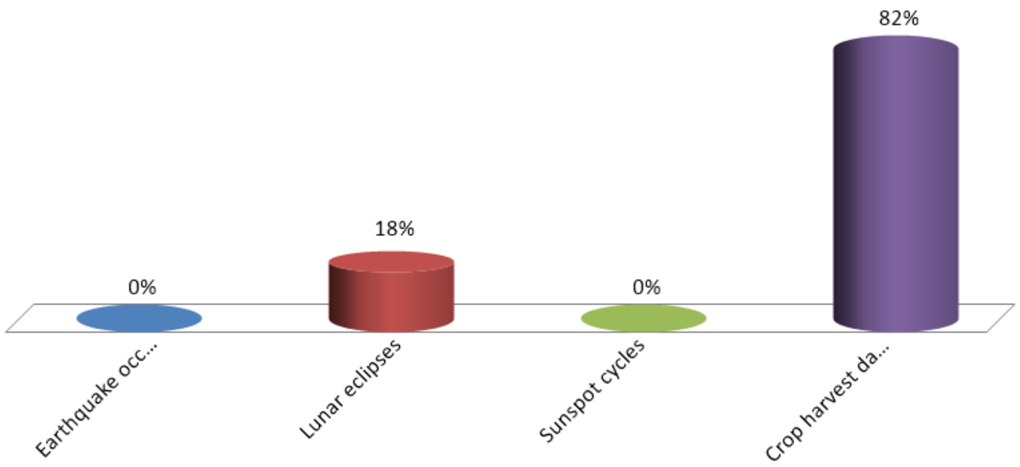


Source: [Chuine et al., Nature 2004]

Monastery archives

What record from monastery archives allows to constrain past climate changes ?

A. Earthquake occurrence
B. Lunar eclipses
C. Sunspot cycles
D. Crop harvest dates



Dating

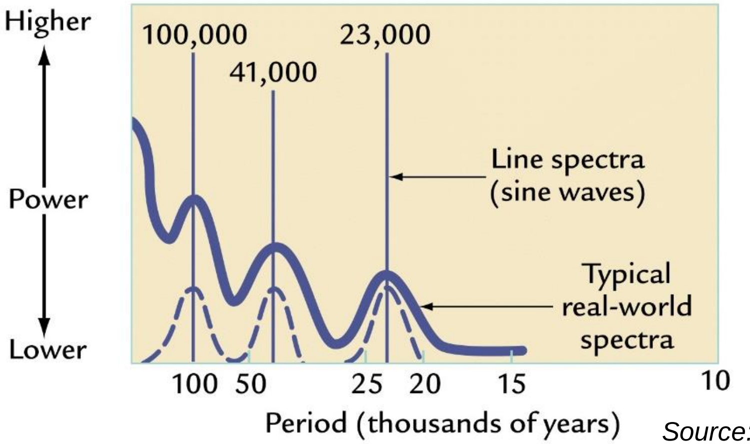
- Direct method: counting annual layers.
- Radiochronological dating based on radioactive tracers.
- Indirect methods:
  - Event matching (tephra layers of well-known volcanic eruptions)
  - Orbital tuning (fit of climatic features on orbital periodicities)
  - Model-based dating. Example: modeling the ice flow of an ice sheet (ice core dating).

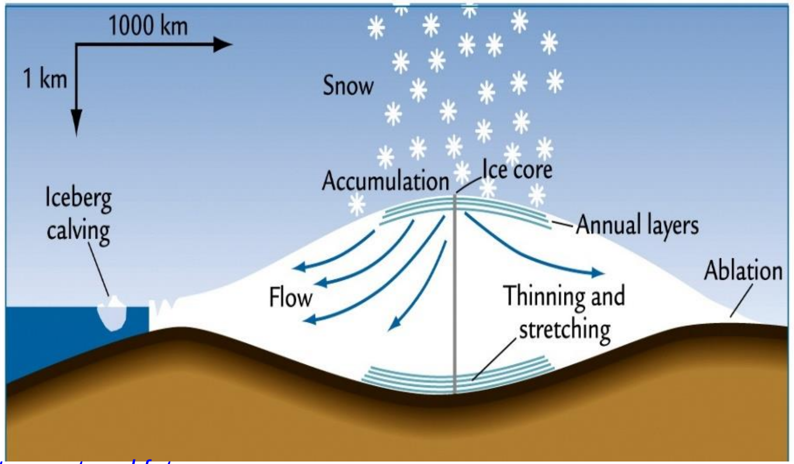
Source: Ruddiman, Earth's climate, past and future

TABLE 3-1 Radioactive Decay Used to Date Climate Records

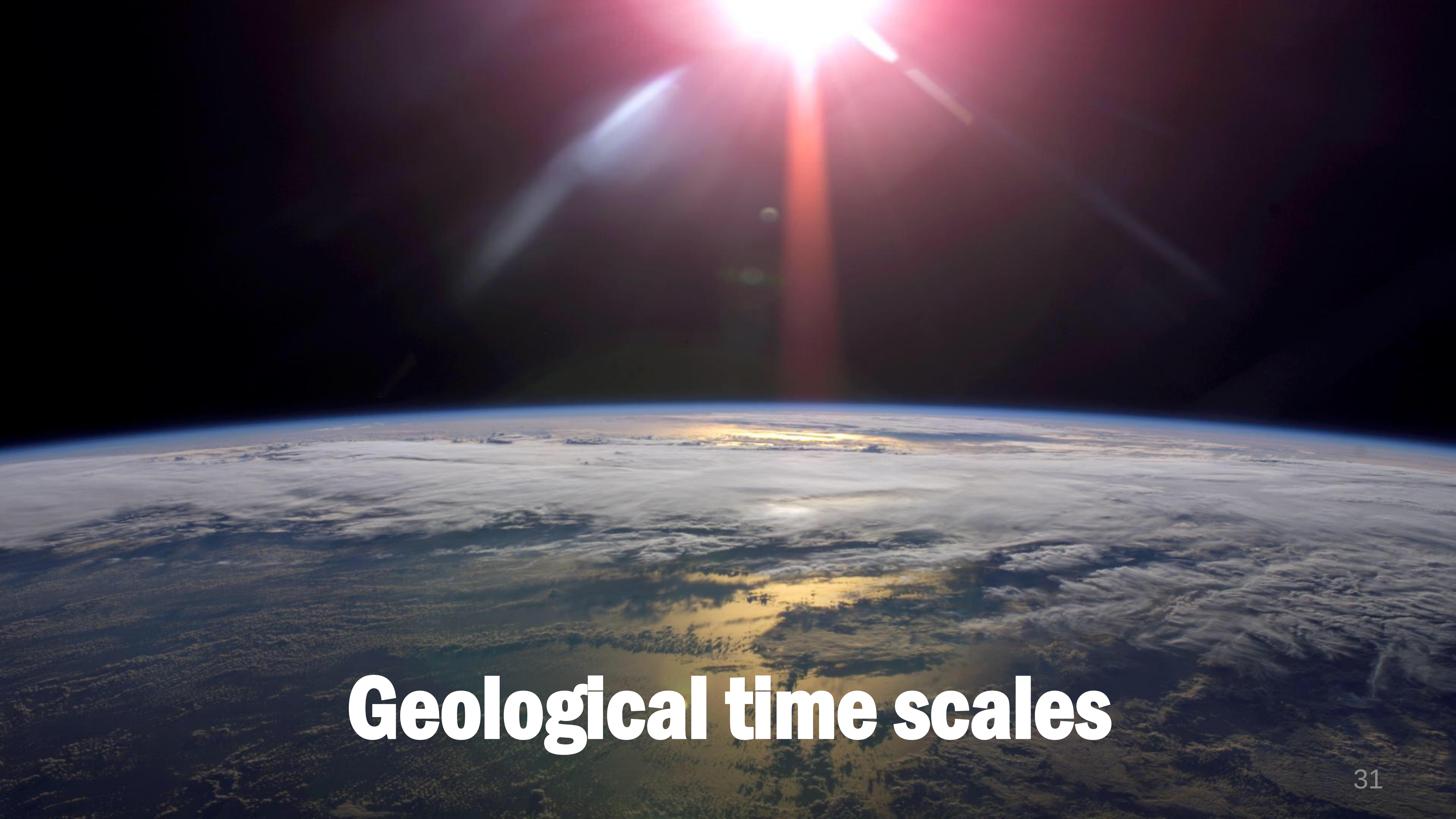
Parent isotope	Daughter isotope	Half-life	Useful for ages:	Useful for dating:
Rubidium-87 (^{87}Rb)	Strontium-87 (^{87}Sr)	47 Byr	100 Myr	Granites
Uranium-238 (^{238}U)	Lead-206 (^{206}Pb)	4.5 Byr	>100 Myr	Many rocks
Uranium-235 (^{235}U)	Lead-207 (^{207}Pb)	0.7 Byr	>100 Myr	Many rocks
Potassium-40 (^{40}K)	Argon-40 (^{40}Ar)	1.3 Byr	>100,000 years	Basalts
Thorium 230 (^{230}Th)	Radon-226* (^{226}Ra)	75,000 years	<400,000 years	Corals
Carbon-14 (^{14}C)	Nitrogen-14* (^{14}N)	5,780 years	<50,000 years	Anything that contains carbon

Daughter is a gas that has escaped and cannot be measured.



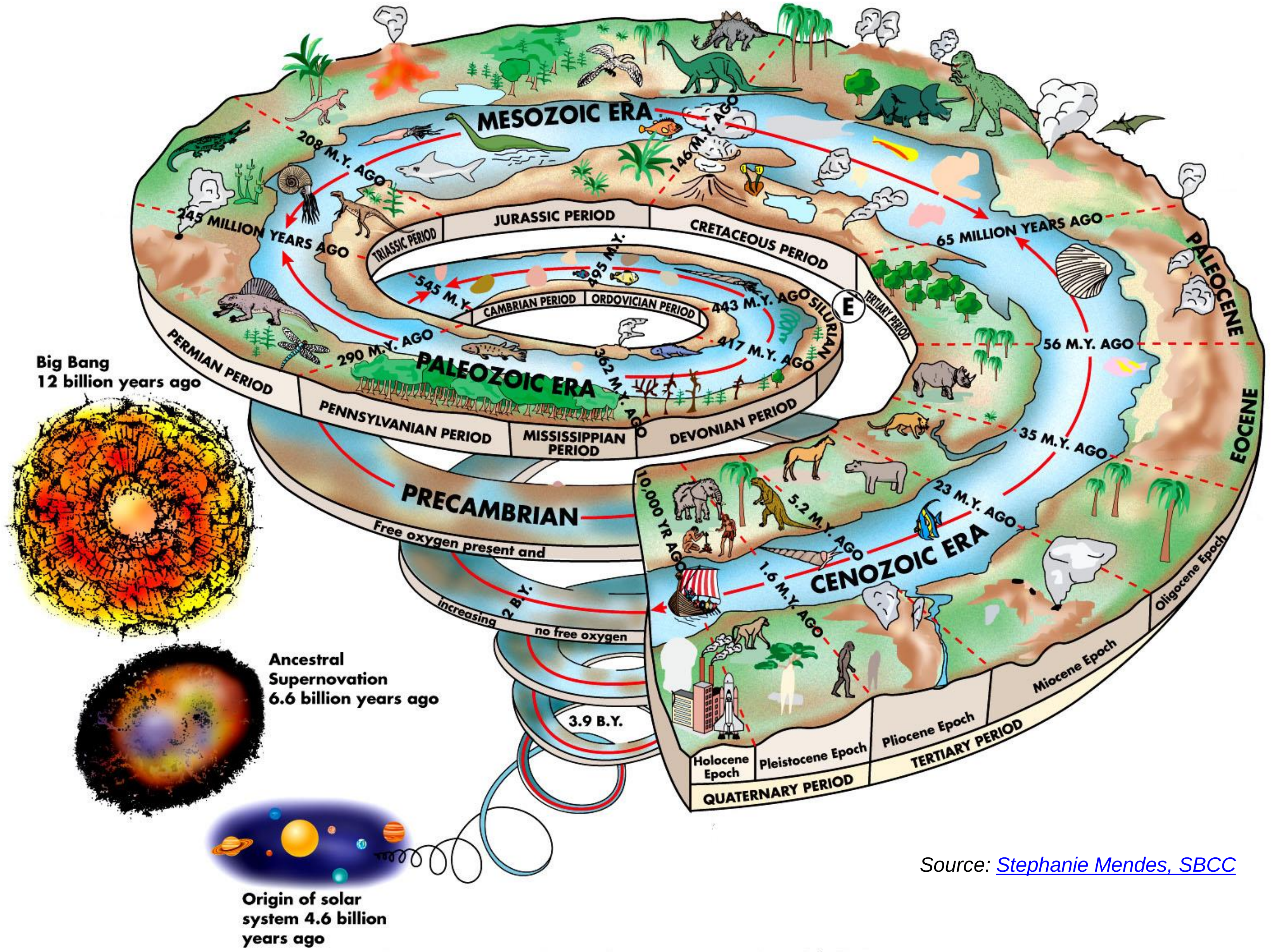


Source: Ruddiman, Earth's climate, past and future



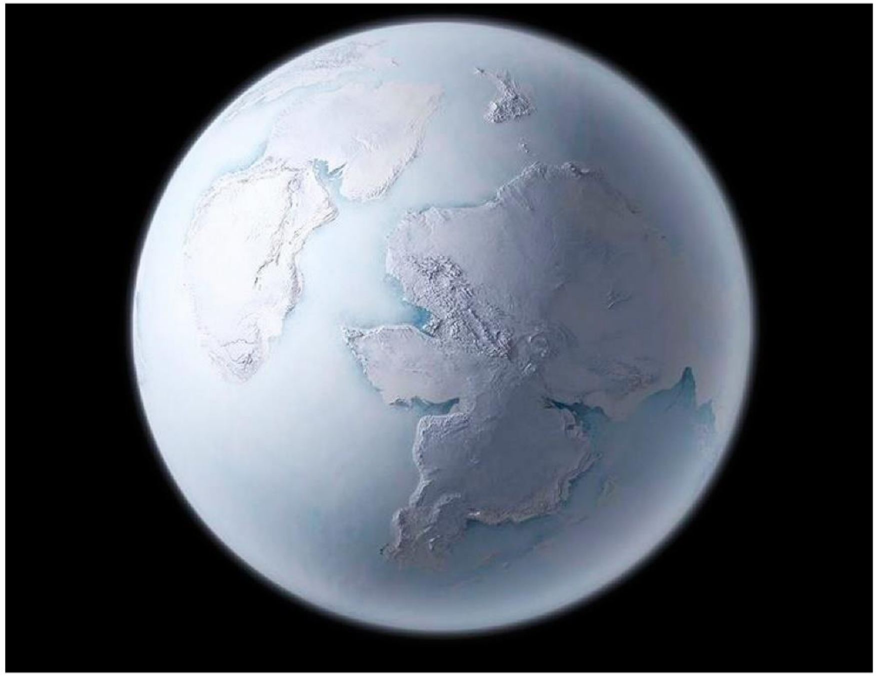
Geological time scales

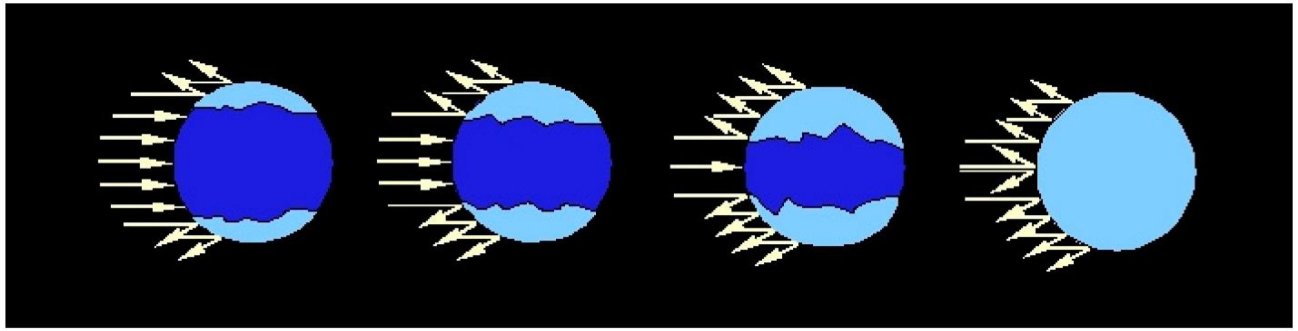
The spiral of geological times

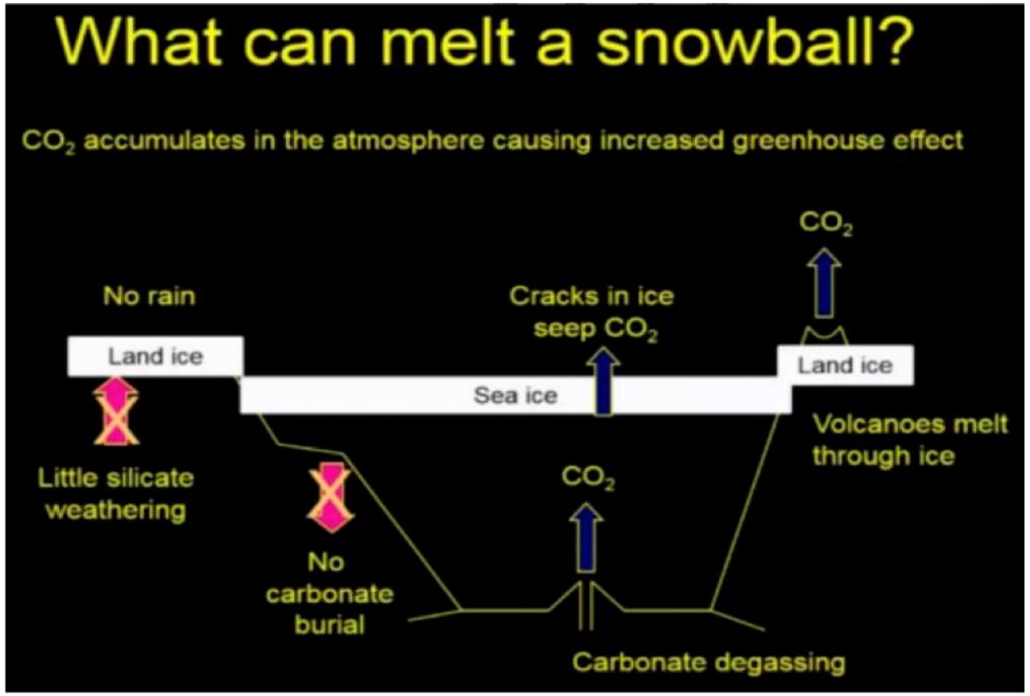


Source: Stephanie Mendes, SBCC

Periods of extremes: the «Snowball» Earth





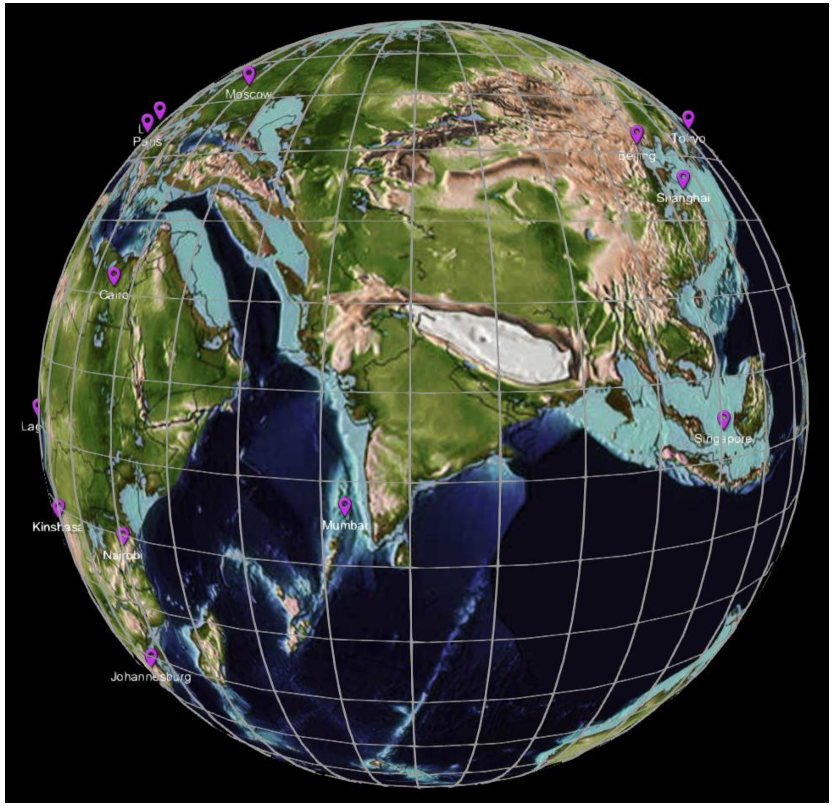


- Between ~720 and ~635 million years ago.
- Evidences of global-scale glaciations, with ice sheet potentially reaching the Equator.
- Could have lasted several million years.
- Probably ended by increased CO_2 from volcanic activity.

Source: Siozos et al., Env. Sci. Proceedings 2023

The main drivers: tectonics and volcanism

300 million years: Pangea supercontinent



50 million years: Himalayan uplift

Source: [BioInteractive Earth Viewer]

Examples:

- Pangea supercontinent (~300-200 Myr): extreme deserts.
- Himalayan uplift (~50 Myr): chemical weathering, reduction of atmospheric CO_2, long-term cooling.
- Continents close to the poles: albedo effect and cooling.
- Opening of the Drake Passage (between 41 and 34 Myr ago): Antarctic circumpolar current and Antarctic glaciation.

Paleo-geography

How the position of continents is determined in the past ?

A. Magnetic measurements in rocks
B. Modeling changes of the Earth gravity
C. Fossil and geological correlations
D. Magnetic field along the ocean floors
E. Glacial or coal deposits
F. All of the methods above

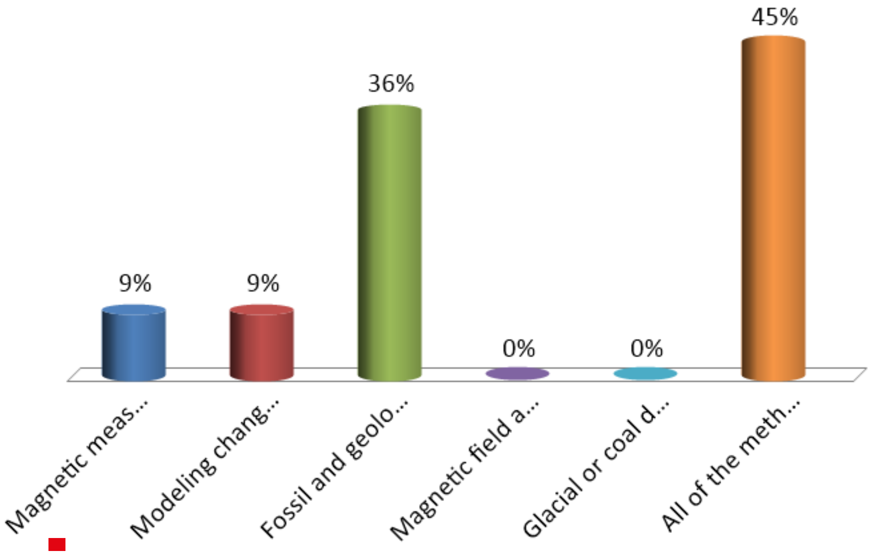


Illustration with paleomagnetism of Laurentia and SW Baltica

Source: *Kulakov et al. Precambrian Research 2022*

Tectonics and continental weathering

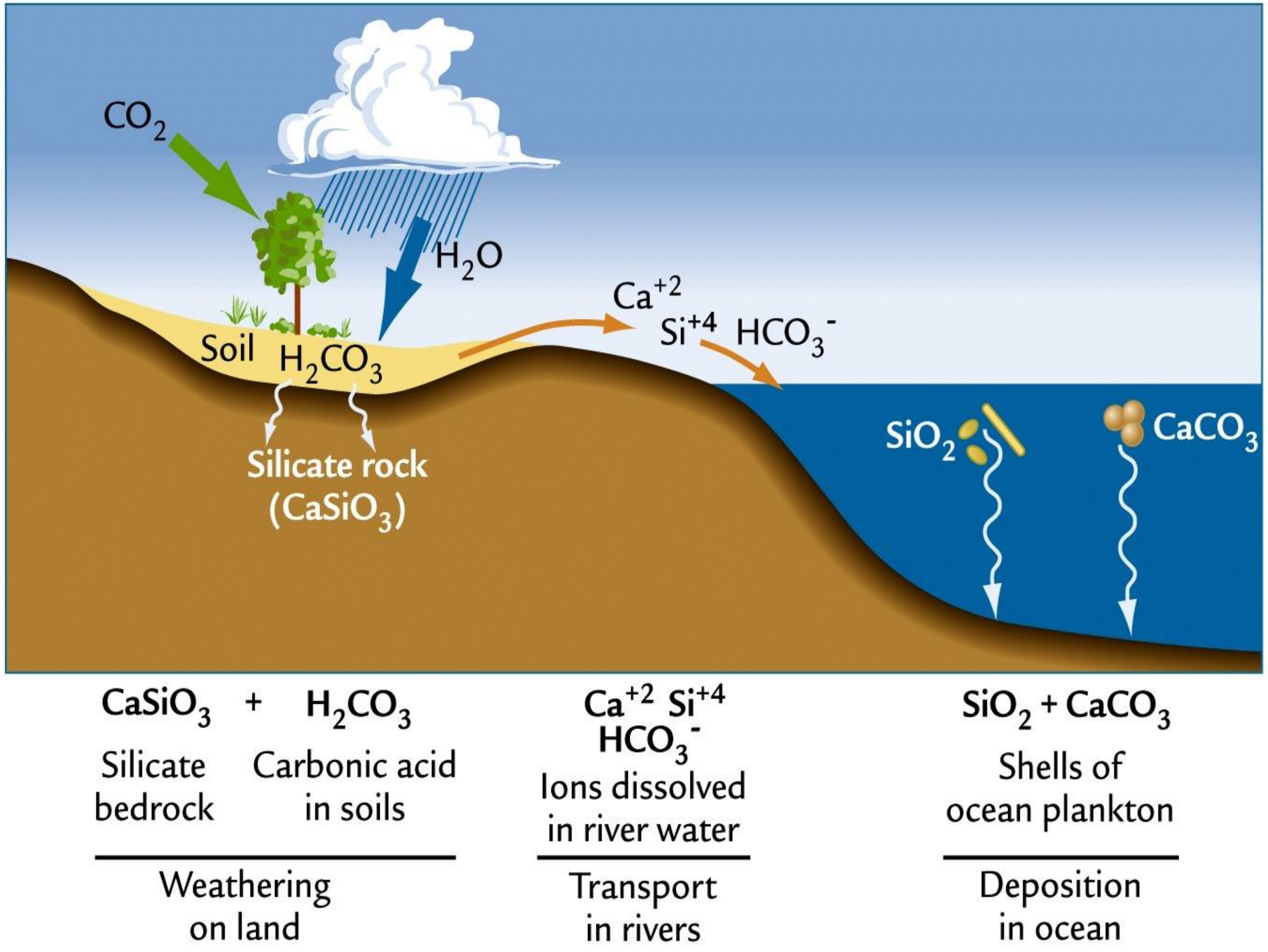
- Atmospheric CO_2 dissolves in rainwater, forming carbonic acid H_2CO_3:

  $H_2O + CO_2 \rightarrow H_2CO_3$

  $CaSiO_3 + H_2CO_3 \rightarrow CaCO_3 + SiO_2 + H_2O$

- Net transfer of a carbon atom from the atmosphere to river water and toward the ocean (deposition in sediments).

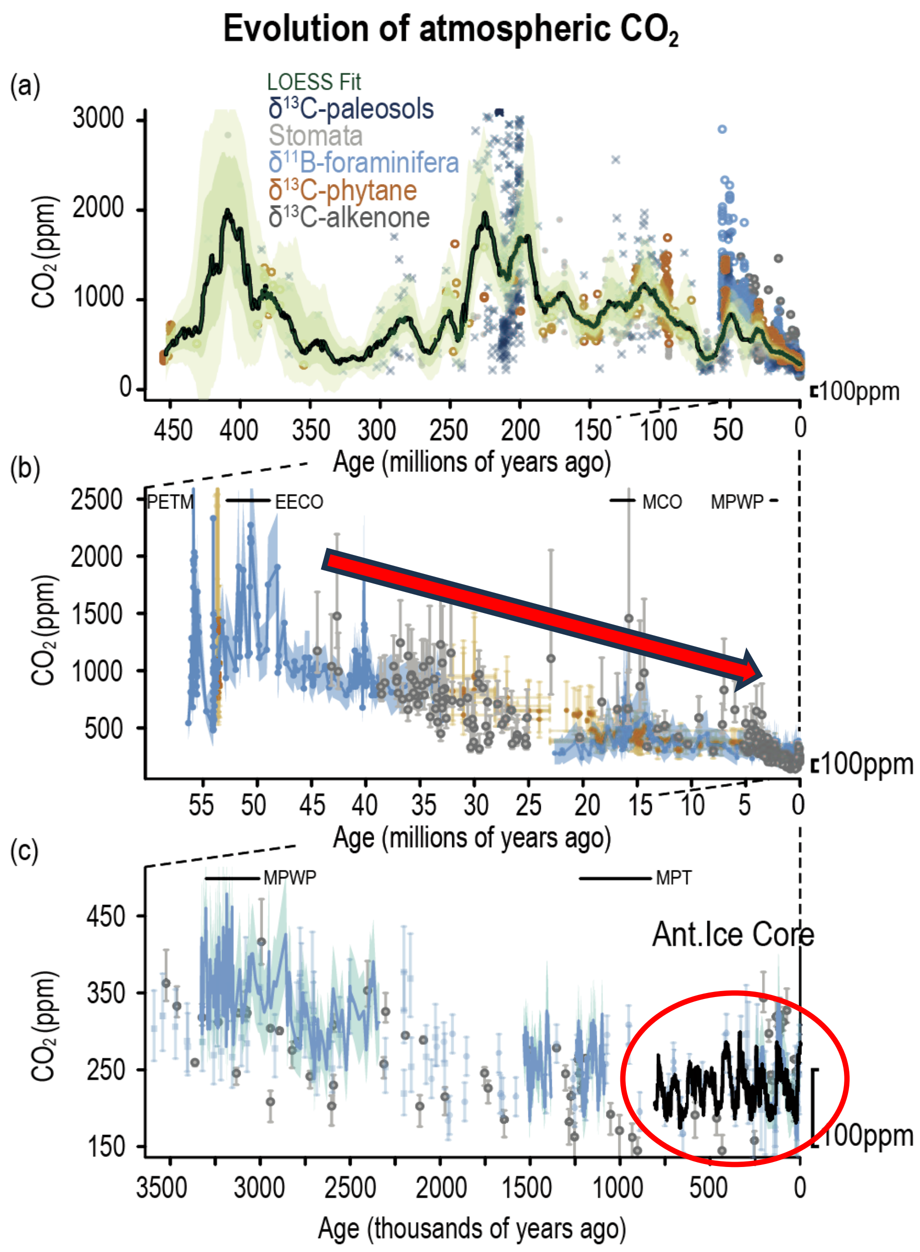
- Continental weathering is intensified by wet climate and mountain uplift.



Source: Ruddiman, Earth's climate, past and future

Evidences of large CO_2 changes in the past

- Multi-proxy evaluation of atmospheric CO_2 from various tracers.
- Periods when CO_2 was as high as 3,000 ppm (today: 420).
- Decline since ~45 Myr towards present.
- Most precise measurements: last 800,000 years from bubbles in Antarctic ice cores.



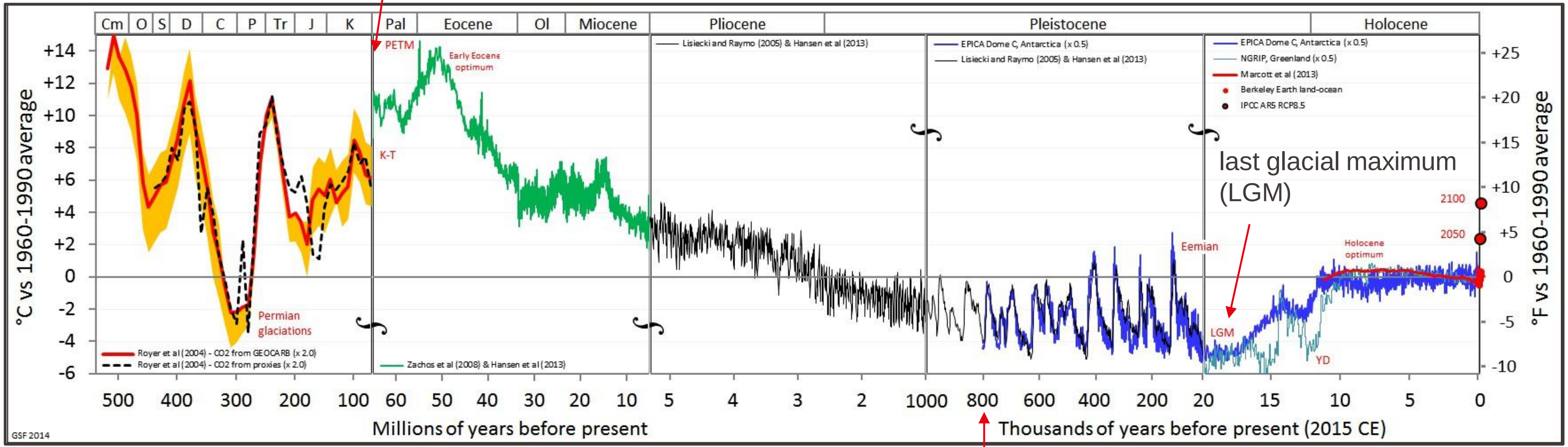
Source: IPCC AR6 WG1, Fig. 2.3

Temperature over the last 500 million years

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

Cretaceous-Paloecene
Dinosaurs extinction

100'000 year
glaciation cycles



Time scale not linear!

uncertainty increases

Source: Wikimedia

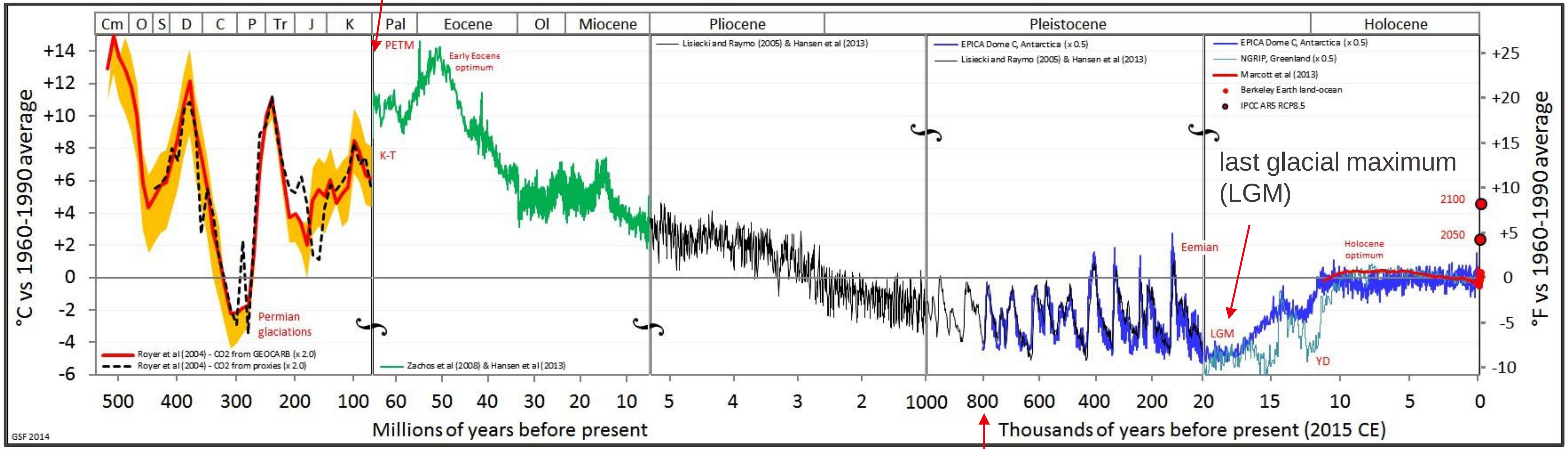
Temperature over the last 500 million years

Cretaceous-Paloegene
Dinosaurs extinction

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

100’000 year
glaciation cycles

last glacial maximum
(LGM)

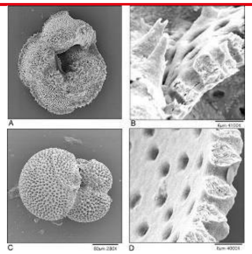


Time scale not linear!

uncertainty increases

about the data

δ18O of shells of macroscopic marine organisms



δ18O of marine organisms

D/H isotopic ratio of ice from the EPICA Dome C ice core, Antarctica

δ18O of ice from Greenland ice core

sea surface tropical temperature

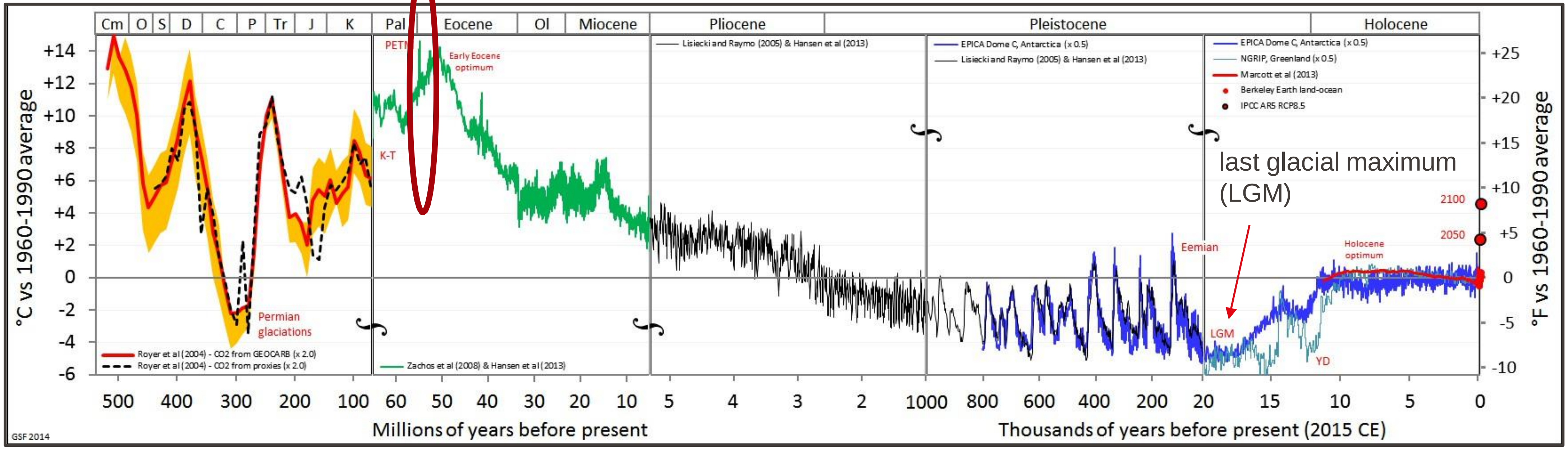
sea surface temperature

polar temperature divided by 2 for polar amplification

Source: Wikimedia

Temperature over the last 500 million years

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

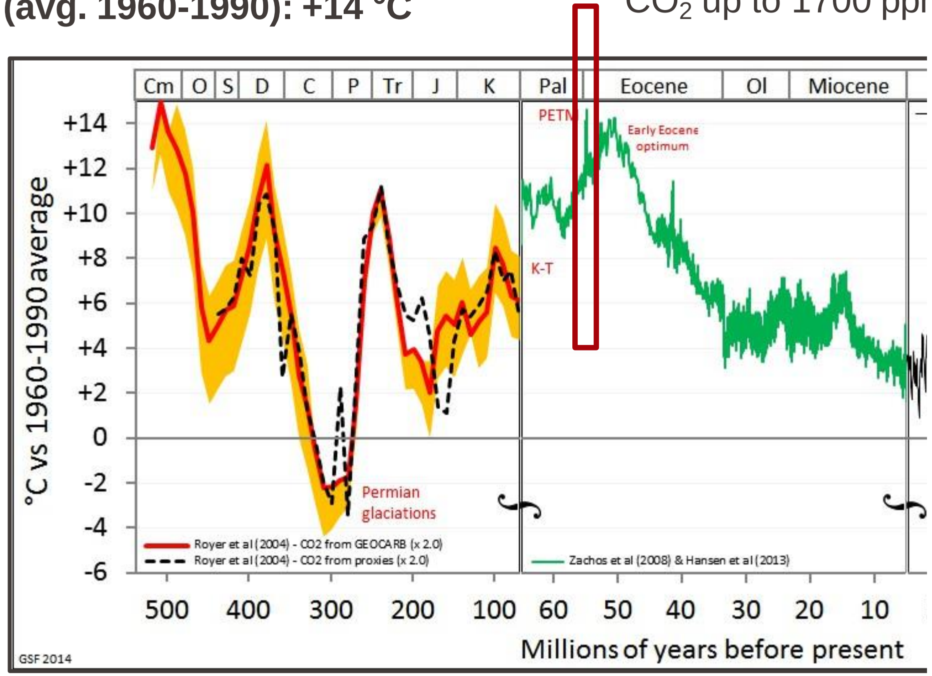


Source: Wikimedia

Paleocene-Eocene Thermal Maximum (PETM)

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

Strong temperature increase in 3,000 to 10,000 years
CO_2 up to 1700 ppm



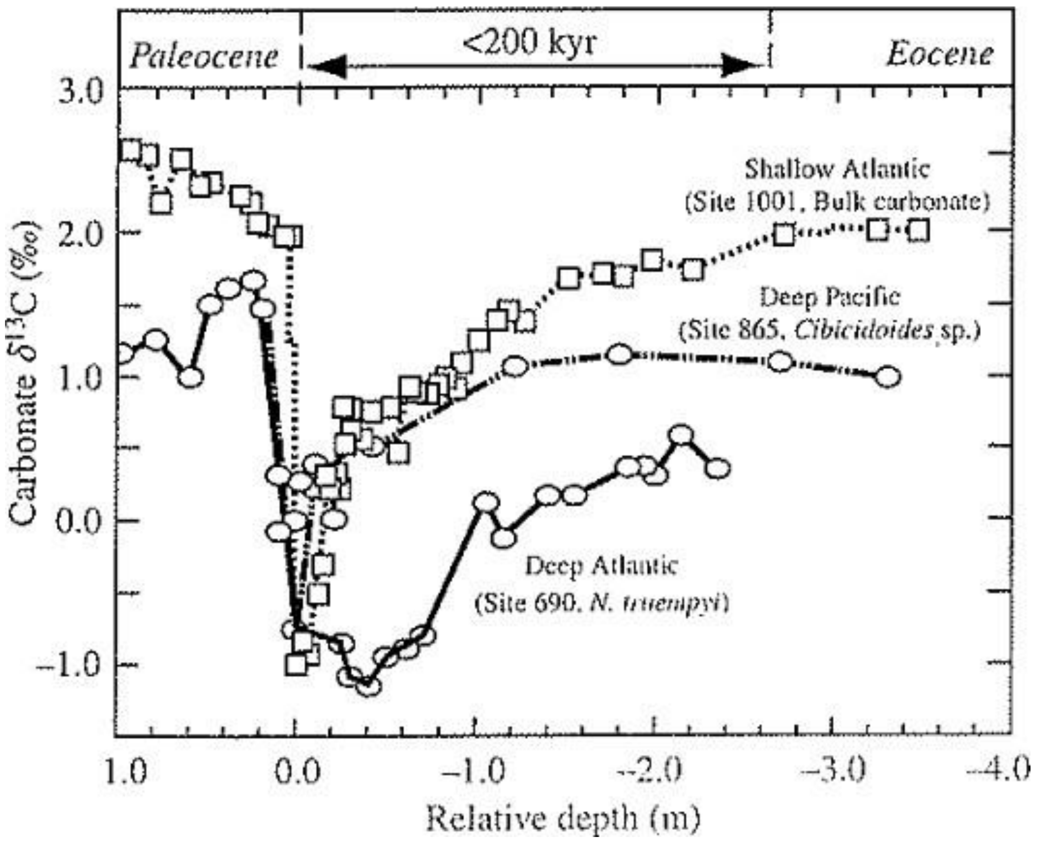
- Paleocene-Eocene Thermal Maximum (PETM), ~56 Myr ago, is one of the most prominent and abrupt climate anomaly in Earth history.
- It represents a possible analogue for the future. It may provide insights into climate sensitivity and feedbacks to large carbon release.
- Key feature: **release of a large mass of ^{13}C-depleted carbon** into the carbon reservoirs at the Earth' surface. Its source remains debated but should be biogenic (biogenic carbon is strongly depleted in ^{13}C).
- CO_2 was up to **1700 ppm**. Rate of increase comparable to modern times.
- **From the CO_2 and T increases, a climate sensitivity of 5 to 9°C is estimated, much larger than today's estimates.**
- What feedbacks ?

Source: *Wikimedia*

Paleocene-Eocene Thermal Maximum (PETM)

Strong temperature increase
in 3,000 to 10,000 years
CO_2 up to 1700 ppm

- Before the event, $\delta^{13}C$ of carbonate around 1 to 2 ‰ (normal value).
- Then, sudden decrease of $\delta^{13}C$ by 2 to 3 ‰, followed by a progressive recovery.
- Hypothesis: large transfer of terrestrial biogenic carbon to the atmosphere and oceans.
- **However, mass balance calculations give a transfer equivalent to today's terrestrial biosphere + permafrost ! (~ 2,000 Gt of C)**
- Other hypothesis: Decomposition of methane hydrates in sea sediments and permafrost (it has a very depleted $\delta^{13}C$).



$\delta^{13}C$ of carbonate in 3 different marine cores.
Relative depth in the core

Source: Paleoclimatology, 2020

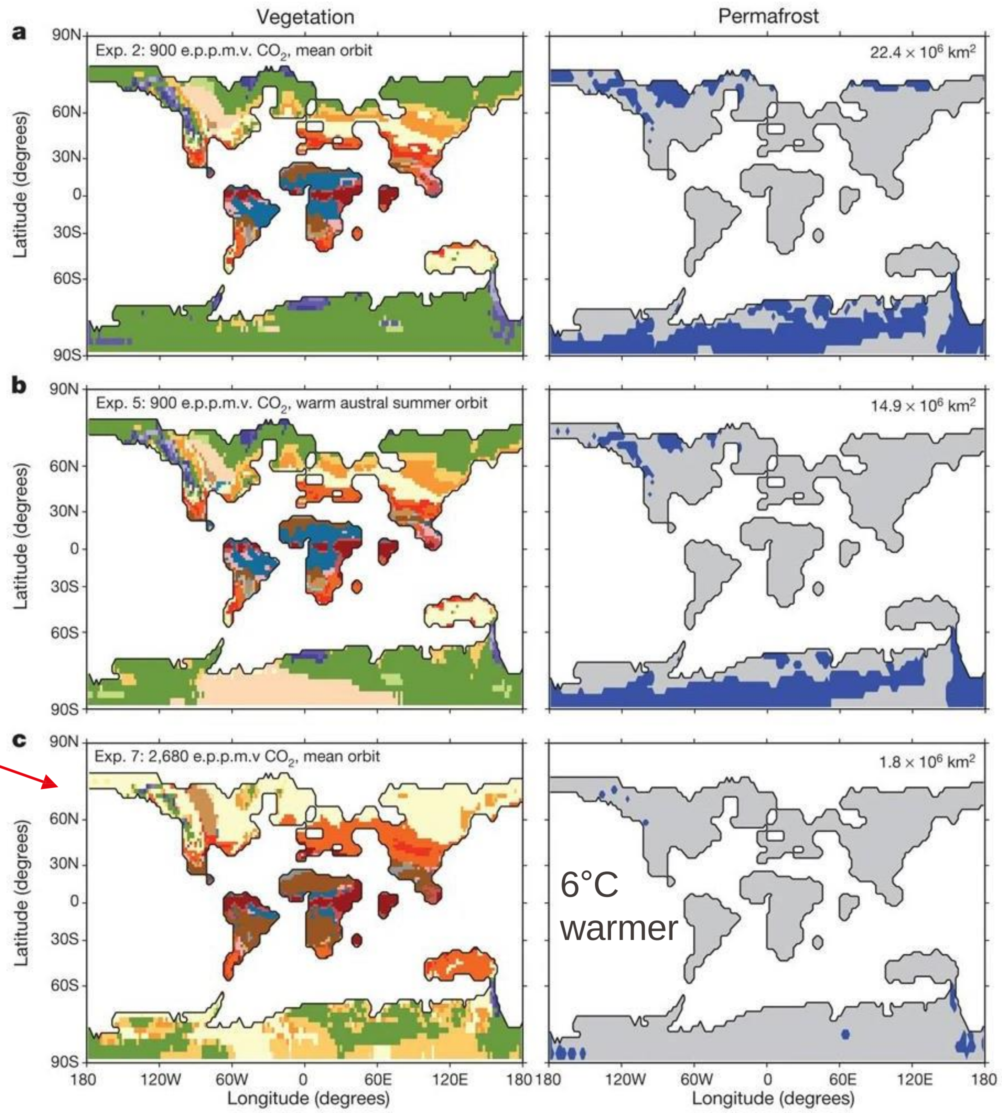
Paleocene-Eocene Thermal Maximum (PETM)

- Where does the terrestrial carbon come from ?!
- Earth orbit characterized by **strong eccentricity** and **high obliquity at the inception of PETM** → Large insolation anomaly at high latitudes.
- 56 Myr ago, Antarctica was not glaciated. Mostly polar forest and permafrost. In a lesser extent, similar at boreal latitudes. Huge carbon pool.
- Current permafrost carbon pool is much smaller but could lead to increased climate sensitivity.

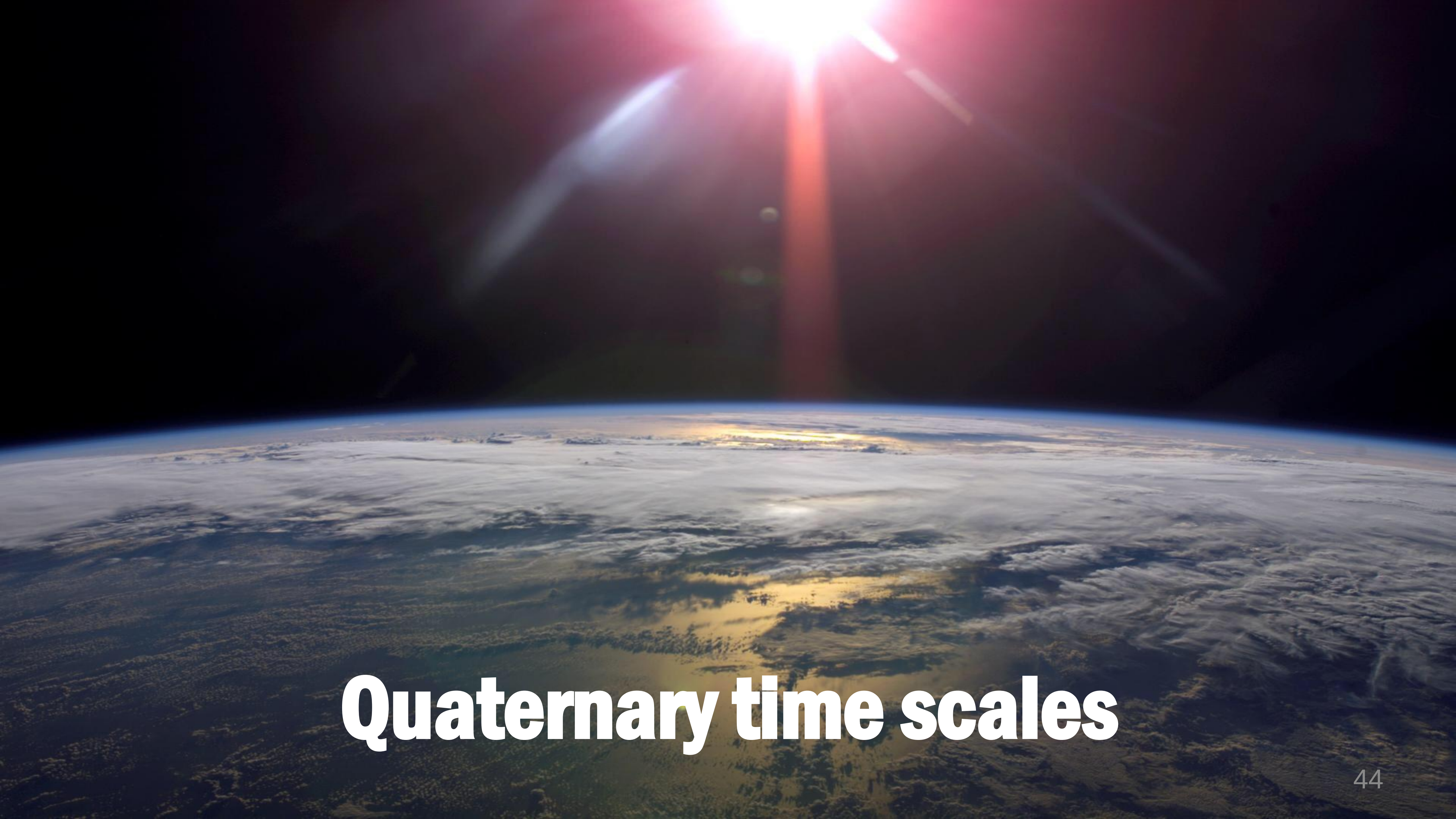
Start model simulation: 900 ppm CO_2, mean orbit

Initial release of carbon due to orbital forcing.

Reinforced forcing due to 2680 ppm CO_2 ; 6°C warmer

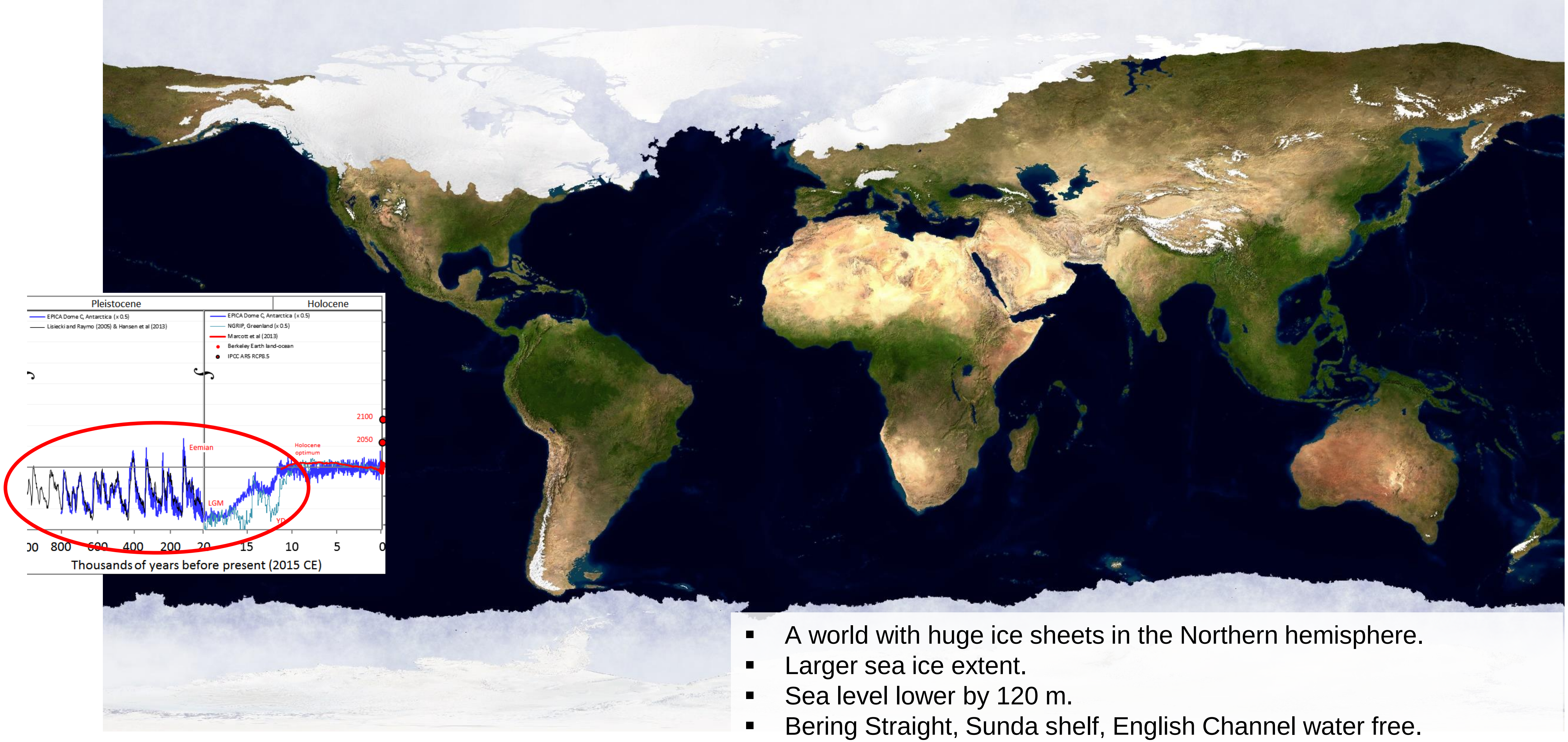


Source: DeConto et al., Nature, 2012



Quaternary time scales

Glaciations and interglacial periods



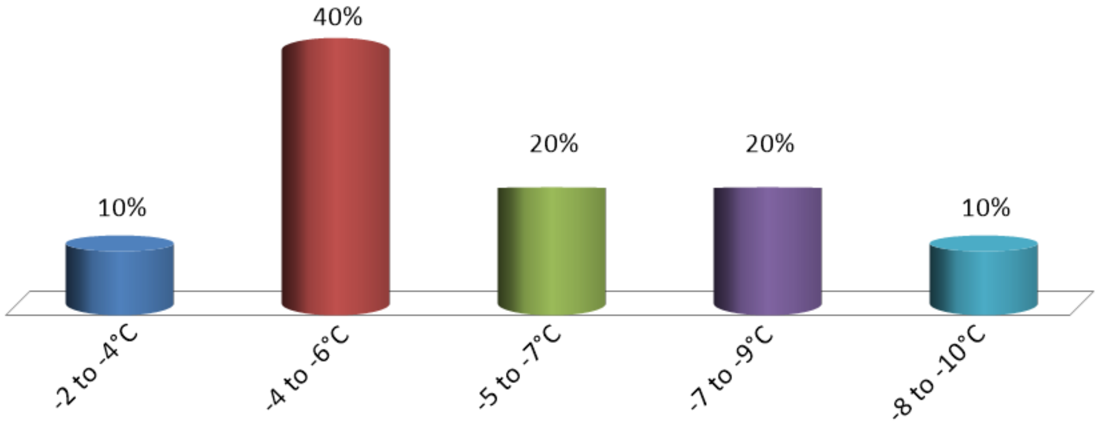
- A world with huge ice sheets in the Northern hemisphere.
- Larger sea ice extent.
- Sea level lower by 120 m.
- Bering Straight, Sunda shelf, English Channel water free.
- Steppe and dry grassland in Europe.
- Last occurrence: Last Glacial Maximum (LGM), 20,000 years ago.

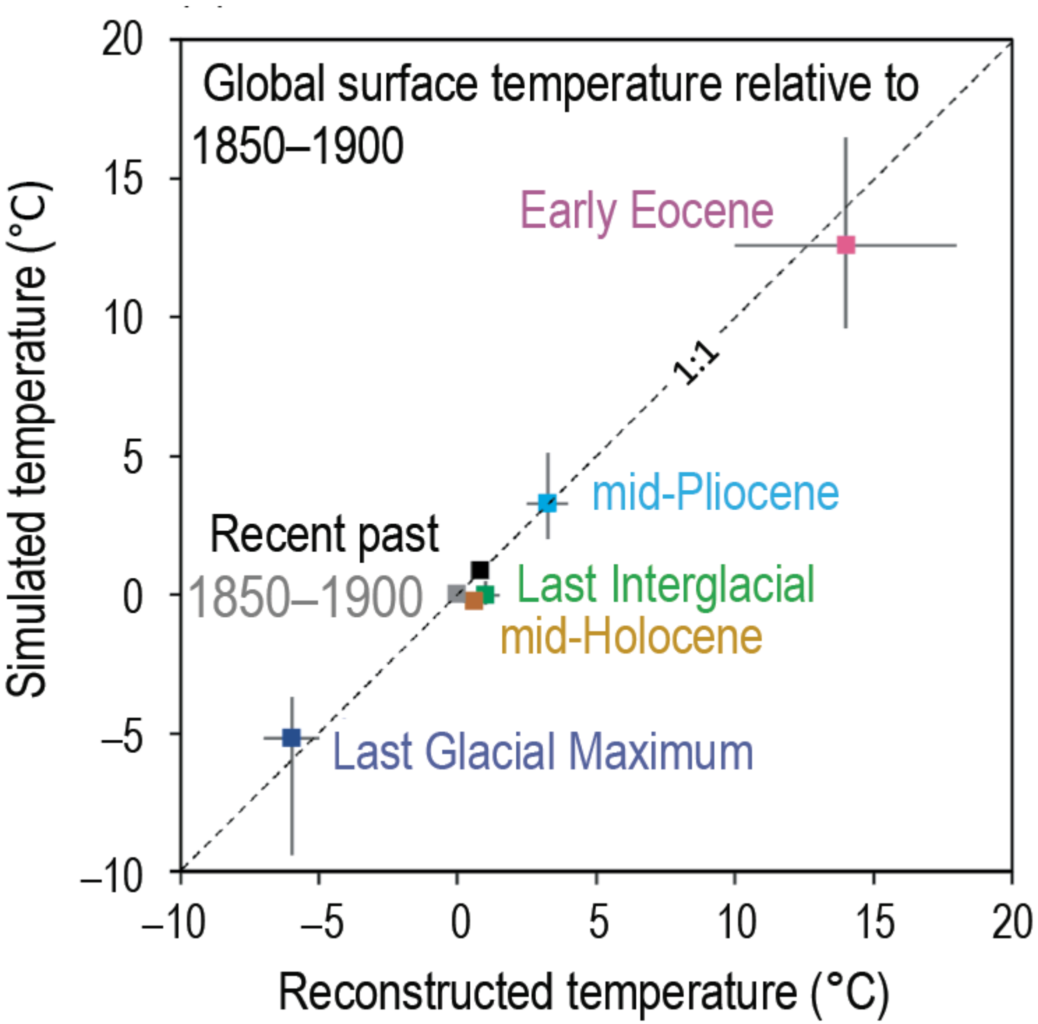
Source: [Reddit]

What is the mean global temperature decrease during the Last Glacial Maximum compared to preindustrial times ?

A. -2 to -4°C
B. -4 to -6°C
C. -5 to -7°C
D. -7 to -9°C
E. -8 to -10°C

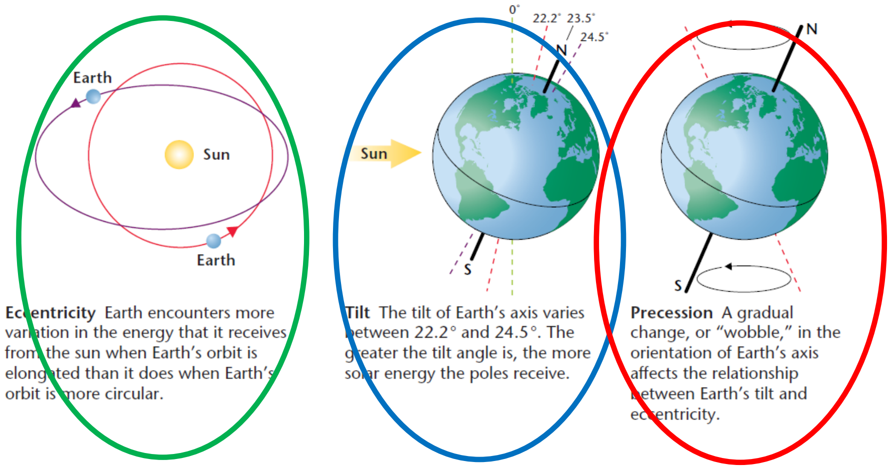
Polar amplification: 10 to 15°C cooler at the poles…





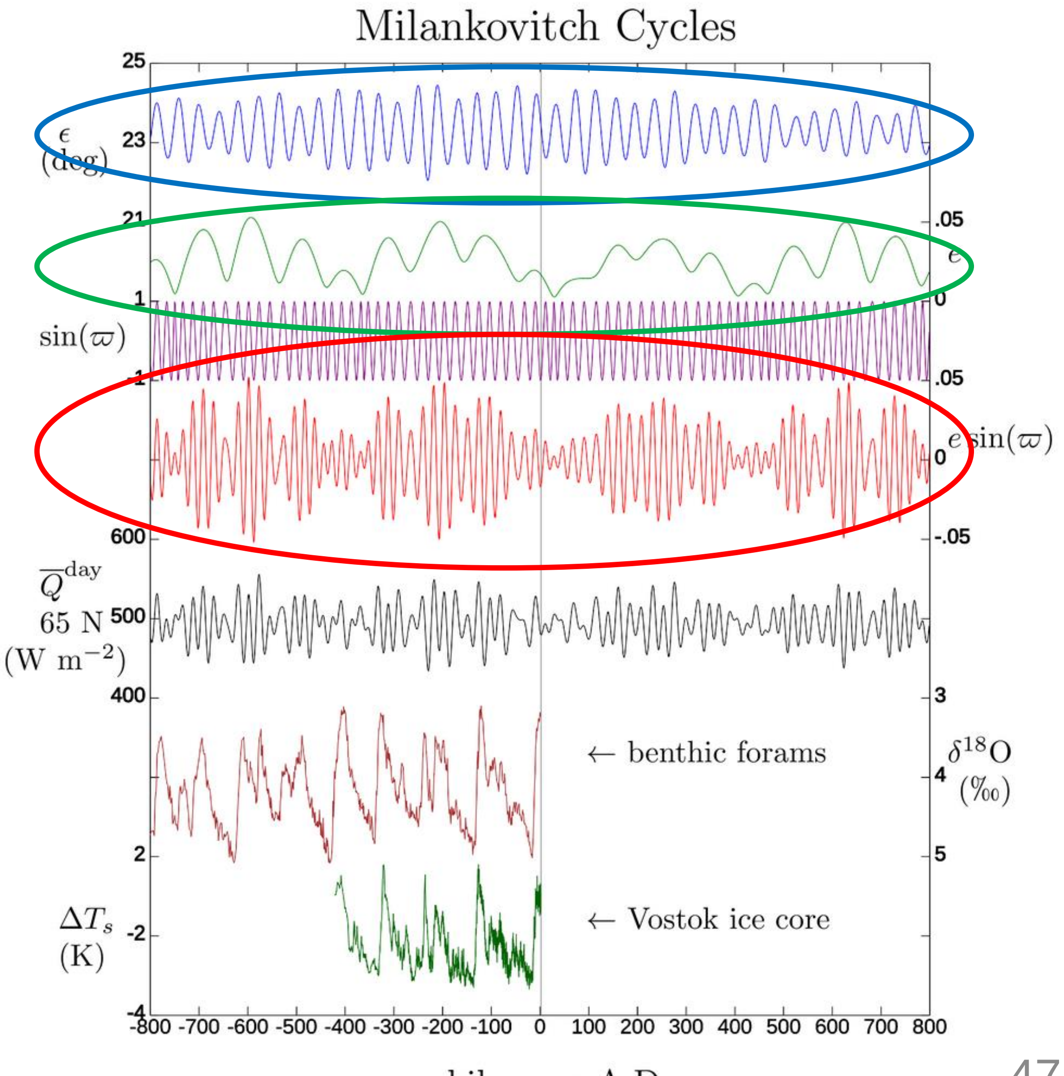
Source: IPCC AR6 WG1, Box TS2 Fig. 2

Natural external forcing factors: Earth's orbit



Periodicities: 100,000 yr / 400,000 yr — 41,000 yr — 19,000 yr / 23,000 yr

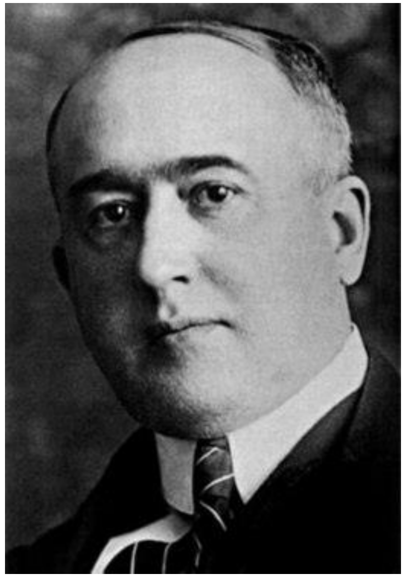
<u>Important</u>: Changes of the Earth's orbit do not affect the global annually averaged incoming solar radiation. They modify the seasonal and latitudinal distribution.



Source: http://gulfcoastcommentary.blogspot.com/2013/11/what-causes-ice-ages.html

Source: Wikipedia

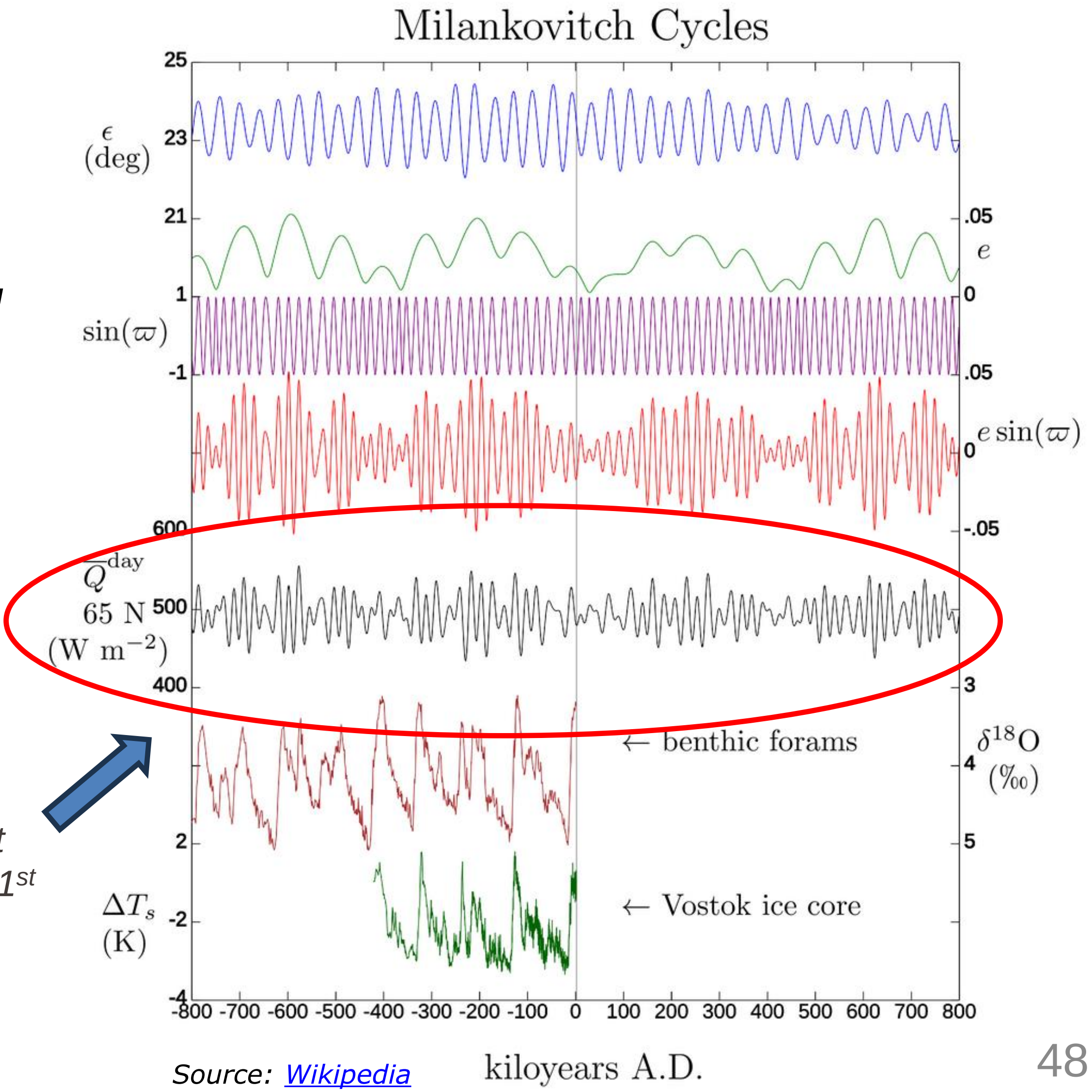
Milankovitch theory



Milutin Milankovitch
(1879-1958)

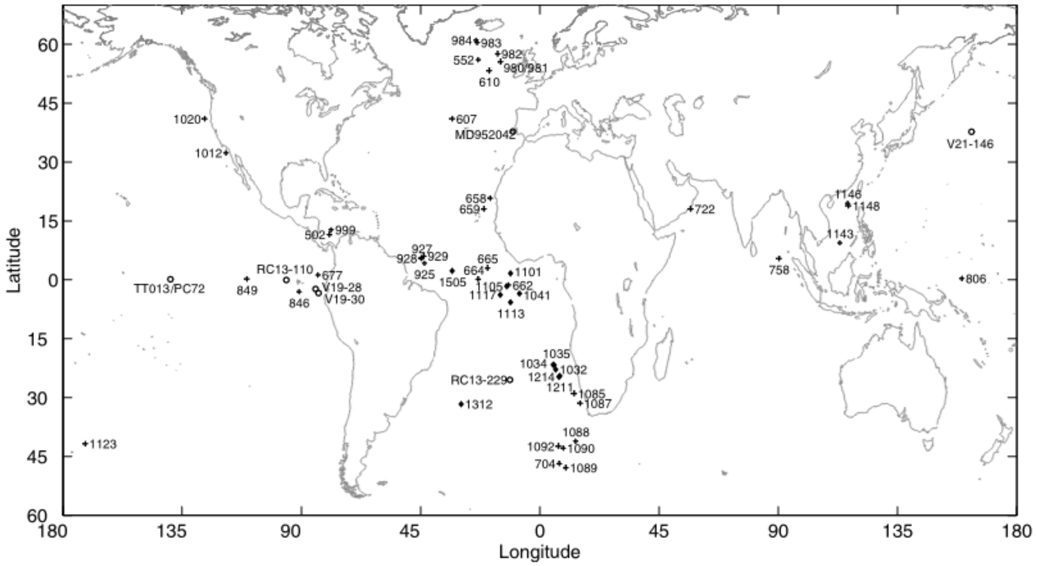
- Astronomic theory of ice ages, published in 1941.
- He tested the original idea of John Murphy (Irish astronomer, 1876):
  - *«A long, cool summer and a short, mild winter in boreal regions are the most favorable to glacial inception.»*
- Calculations of insolation changes with latitudes and seasons + simple energy balance model including albedo feedback.

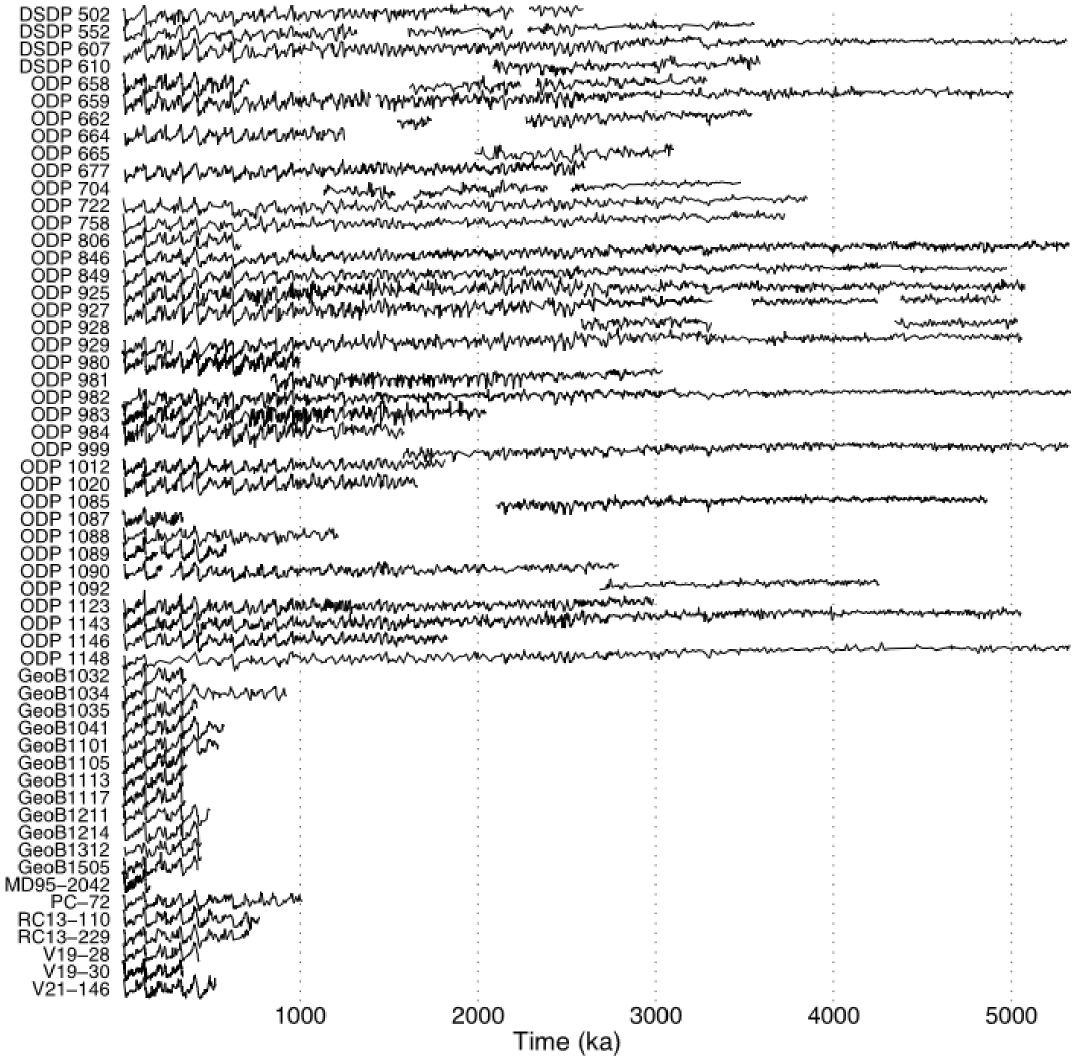
Illustration with insolation changes at the top of the atmosphere on June 21st (summer solstice) at 65°N.



Source: [Wikipedia]

A history of global ice volume over 5 Myr

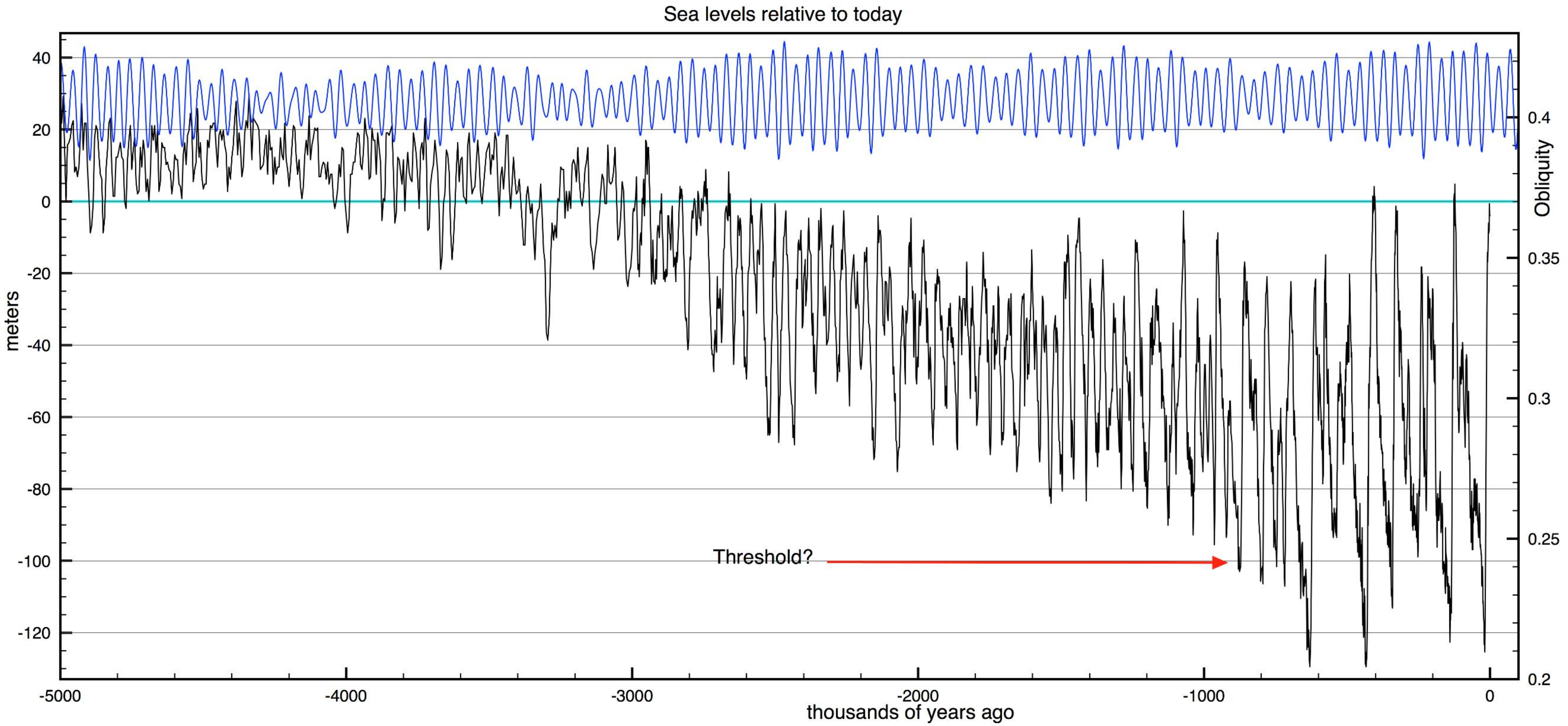




- 57 marine cores stacked over 5 Myr
- Assumes that a 1 ‰ increase of $\delta^{18}O$ of benthic foraminifera corresponds to a 120 meter decrease of mean sea level.

Source: *Lisiecki and Raymo, Paleoceanography 2005*

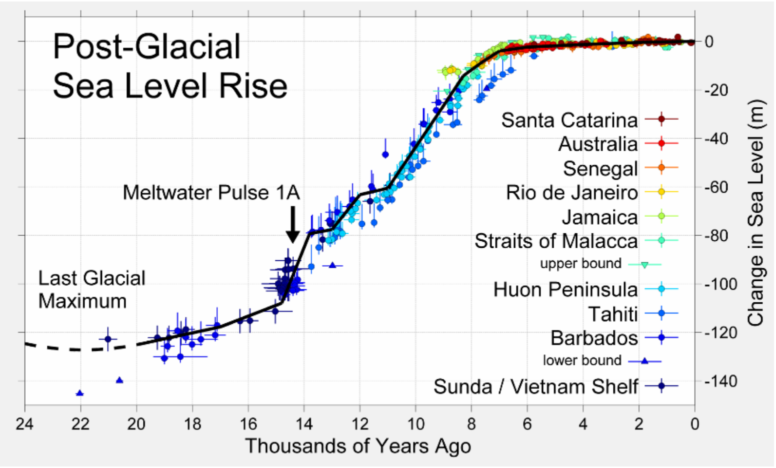
A history of global sea level (ice volume) over 5 Myr



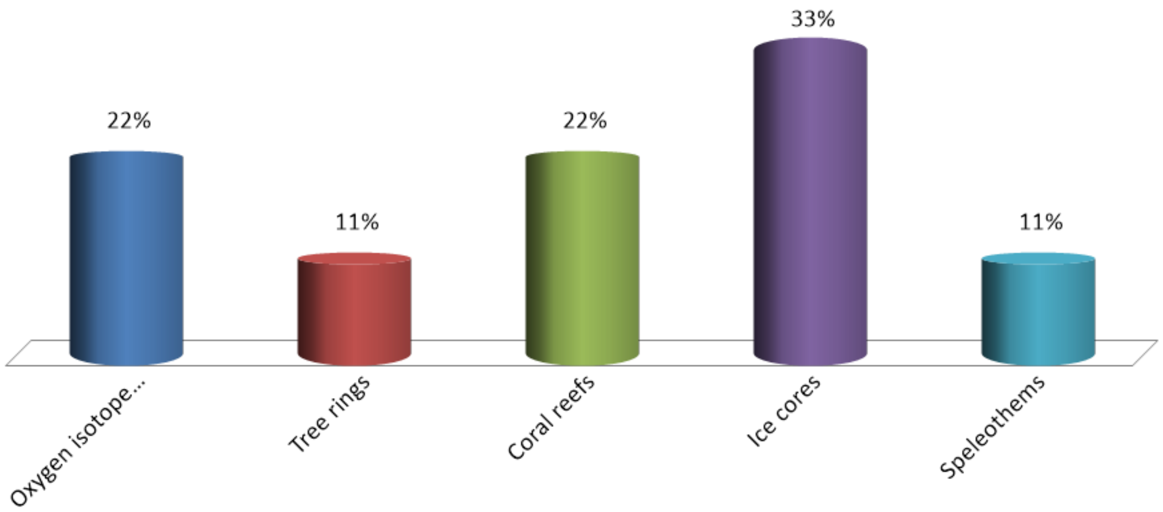
Source: [Lisiecki and Raymo, Paleoceanography 2005](#) ; [adapted by Clive Best](#)

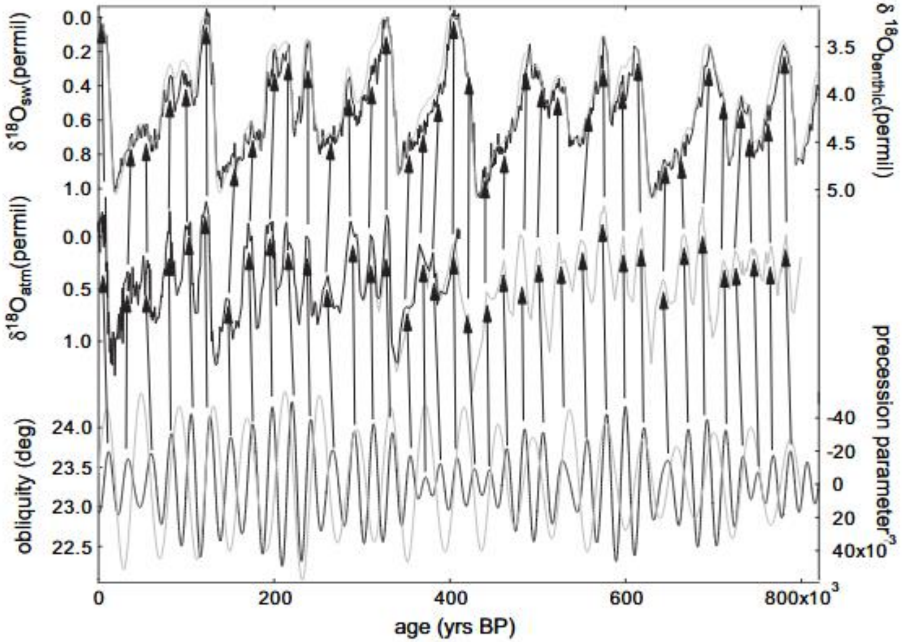
Which archives can document sea-level changes ?

A. Oxygen isotopes in marine sediments
B. Tree rings
C. Coral reefs
D. Ice cores
E. Speleothems



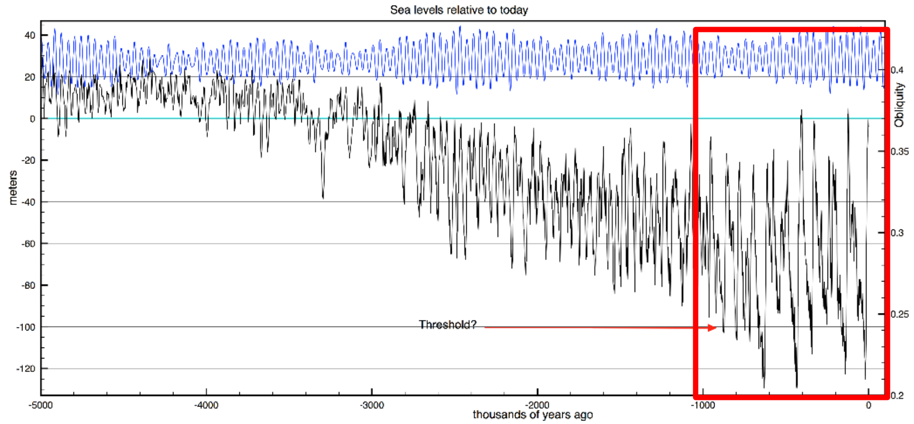
Source: Fleming et al., Earth. Planet. Sci. Lett. 1998



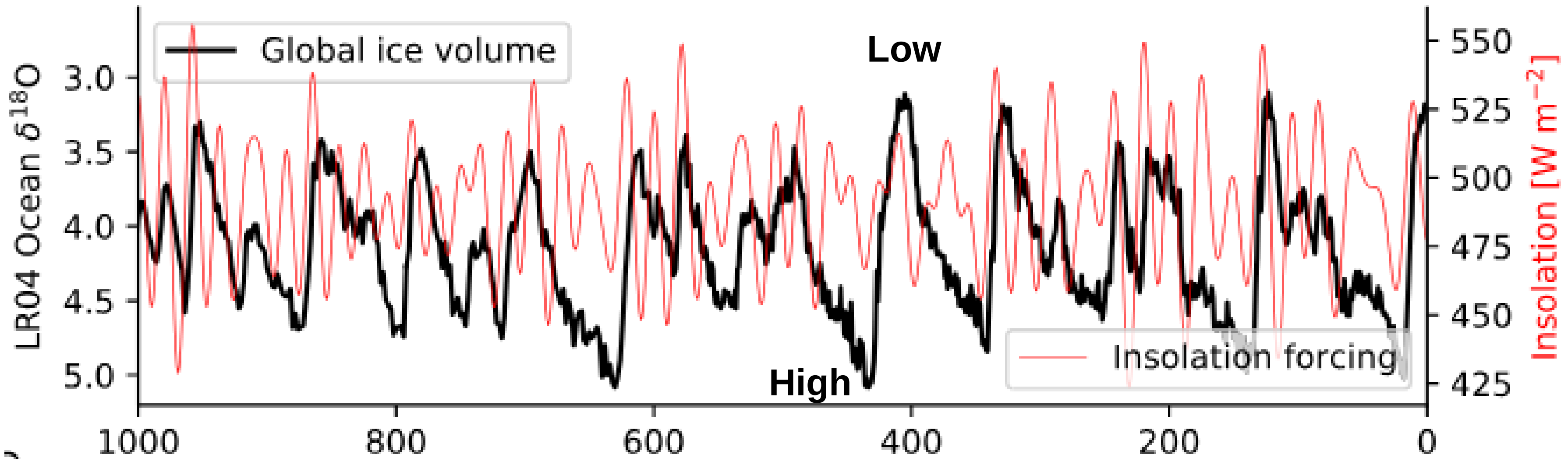


Source: Landais et al., Quaternary Sci. Rev. 2010

A history of global ice volume: the last Myr

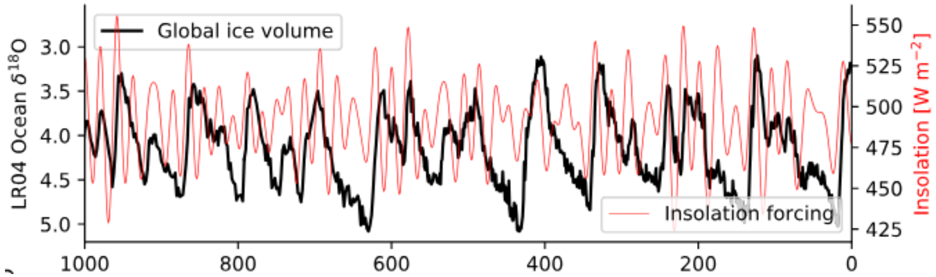


- What do you observe ?

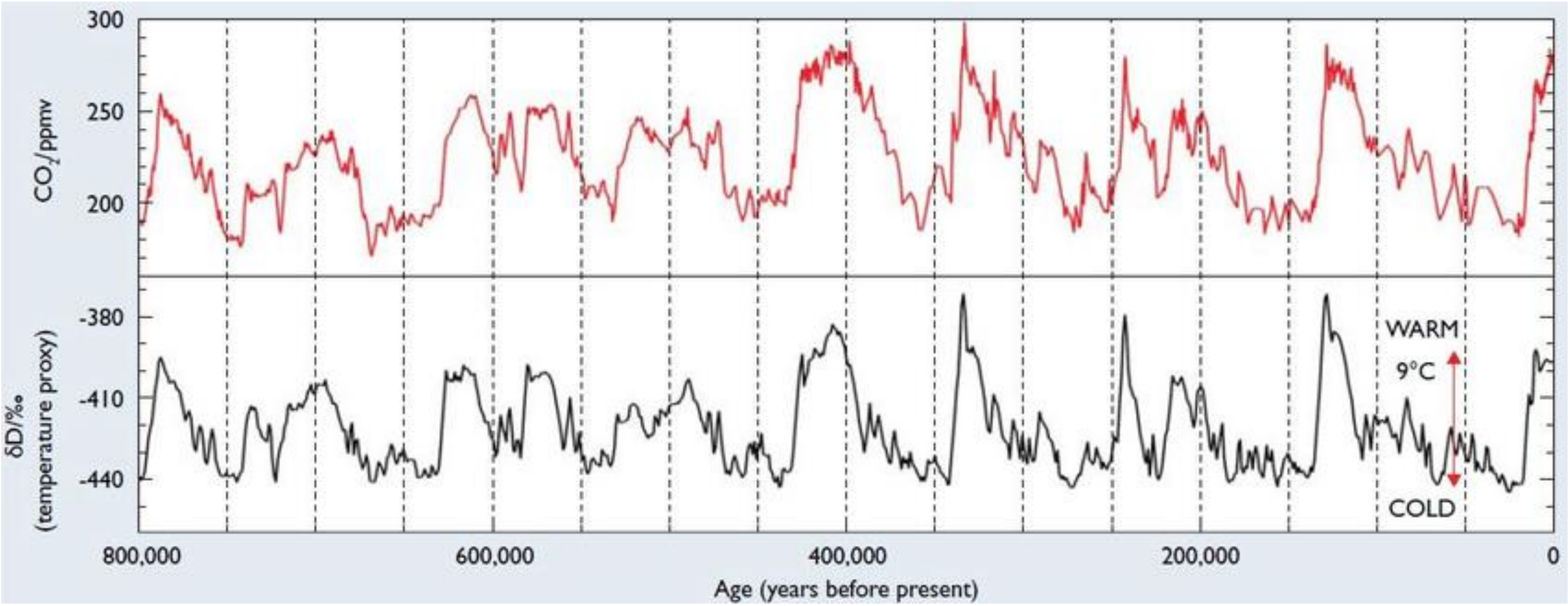


Source: Lisiecki and Raymo, Paleoceanography 2005 ; Boers et al., Environ. Res. Lett. 2022

Global ice volume: insolation and CO_2



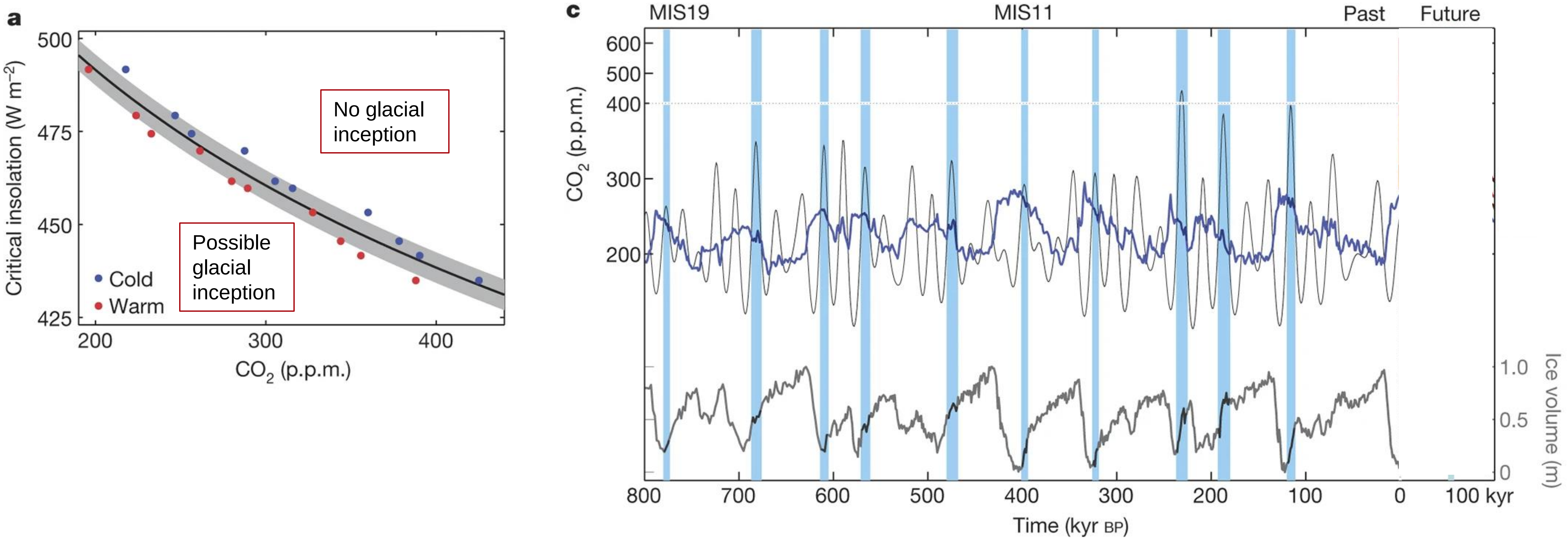
- CO_2 measured in Vostok and EPICA/Dome C ice cores from Antarctica.
- Minimum of ~180 ppm.
- Maximum of 300 ppm.



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

A history of global ice volume: the last Myr

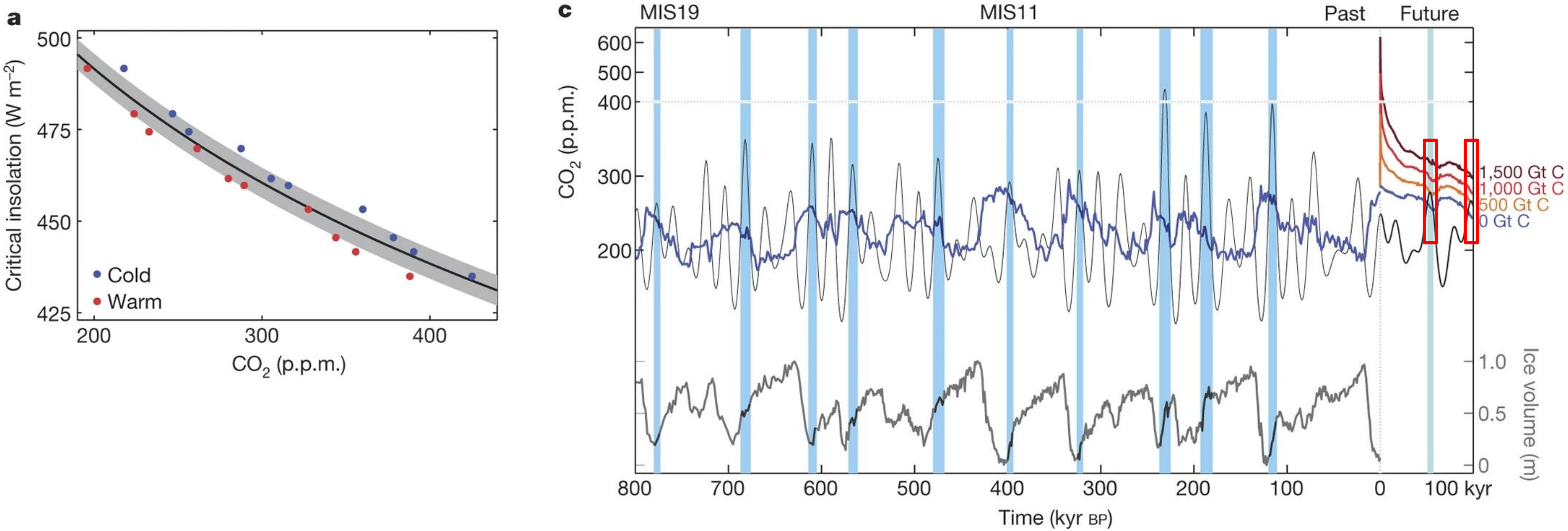
When the blue line is below the grey line, glacial inception is possible.



Source: Ganapolski et al., Nature 2016

- Based on a climate model of intermediate complexity.
- A critical threshold of atmospheric CO_2, combined with a critical summer insolation at 65°N, is necessary to generate a glacial inception.

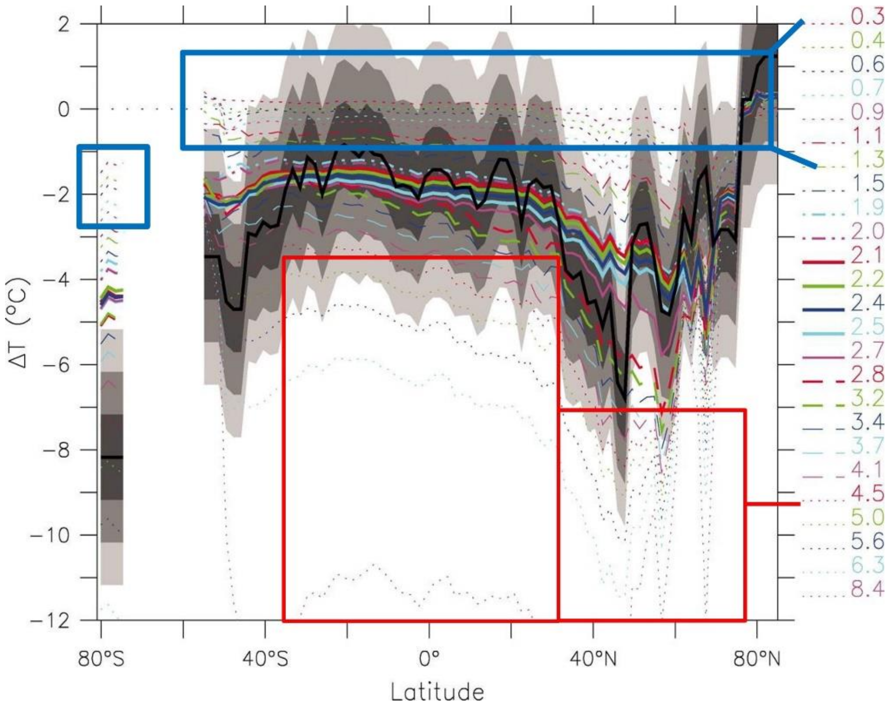
Global ice volume: the future



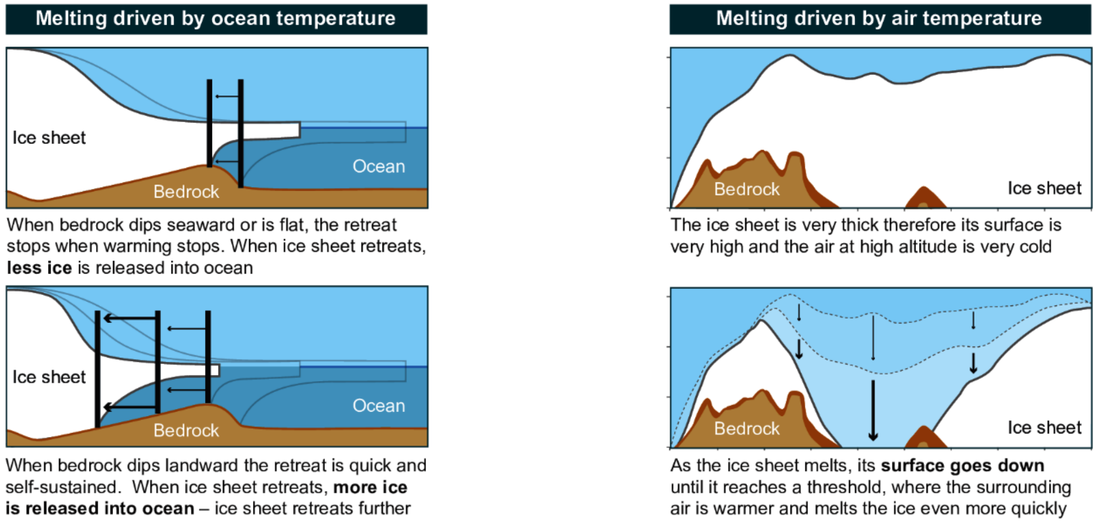
Source: *Ganapolski et al., Nature 2016*

- If no anthropogenic CO_2, next glacial inception expected in ~50,000 years.
- CO_2 emissions of 1000 to 1500 Gt of carbon will postpone the next glacial inception to 100,000 years.

Quaternary time scales and model validation

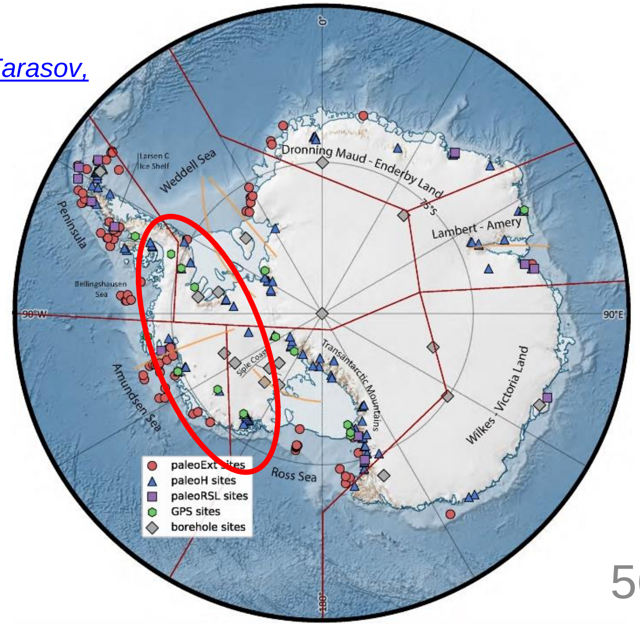


Source: Schmittner et al., Science 2011



Source: IPCC AR6 WG1, Fig. 9.1

Source: Lecavalier and Tarasov, The Cryosphere, 2025



- IPCC AR6: new paleoclimatic data and improved models. Likely ECS range of **2.5 to 4.0°C**

- Evaluating model capacities to generate an instability of the West Antarctic ice sheet during the last interglacial period.
- Critical for future sea level changes (potential of +3 to +5 m).

Last millennia

Climate change over the last 2000 years

Why is it particularly important ?

- Description of climate variability on a longer time scale than 150 years. Helps to put current trends into perspective.
- Background climatic conditions similar to early industrial times (glacier extent, Earth orbit, land cover, ocean circulation,…). Best to test global climate models.

Paintings of the series «The Months» by Pieter Bruegel the Elder, Dutch Renaissance painter, 1565.
January on the left. August on the right.

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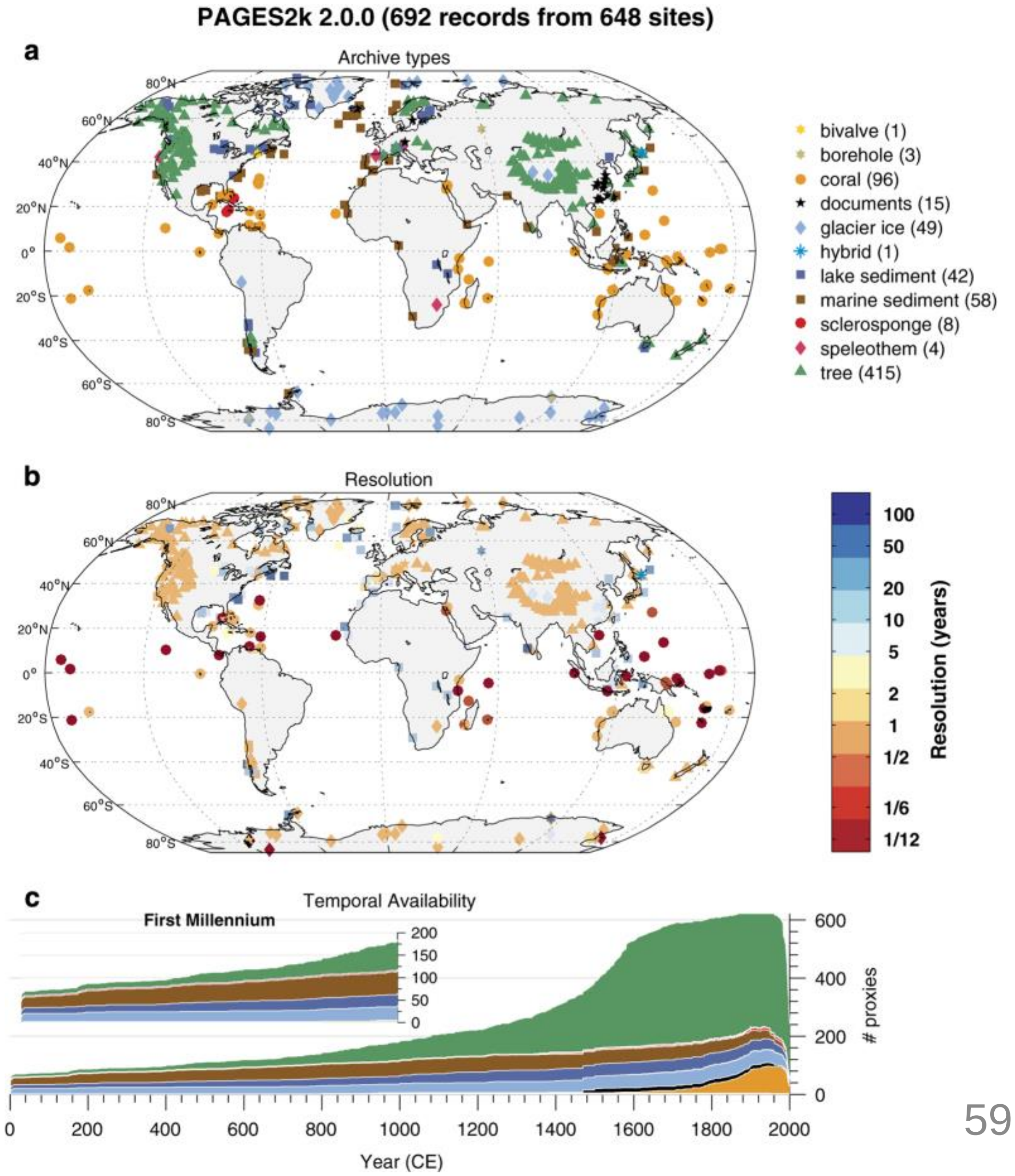
- Maximum density of different archives, allowing to discuss regional features.



Source: [PAGES2k Consortium, Nature Scientific Data, 2017]

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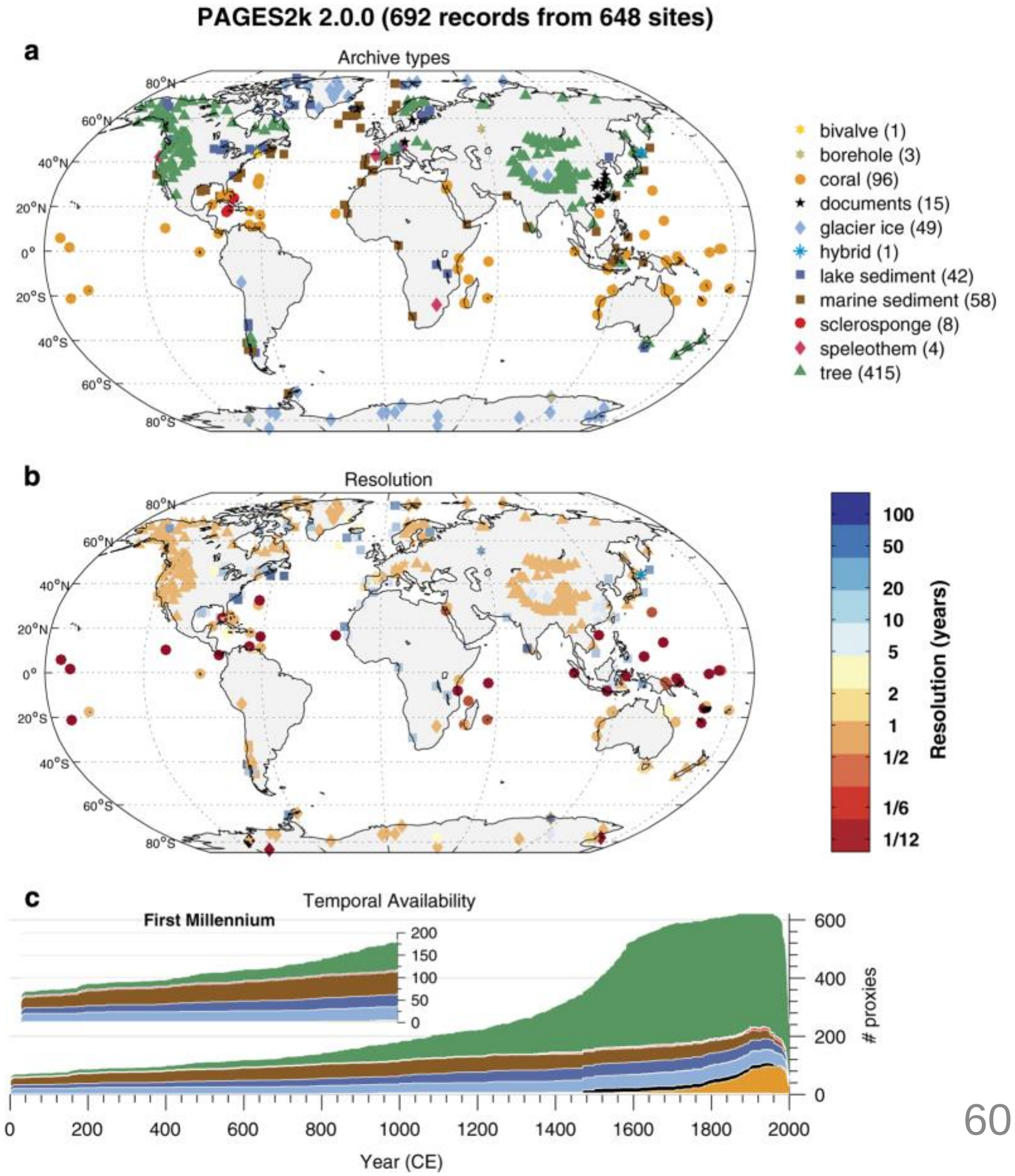
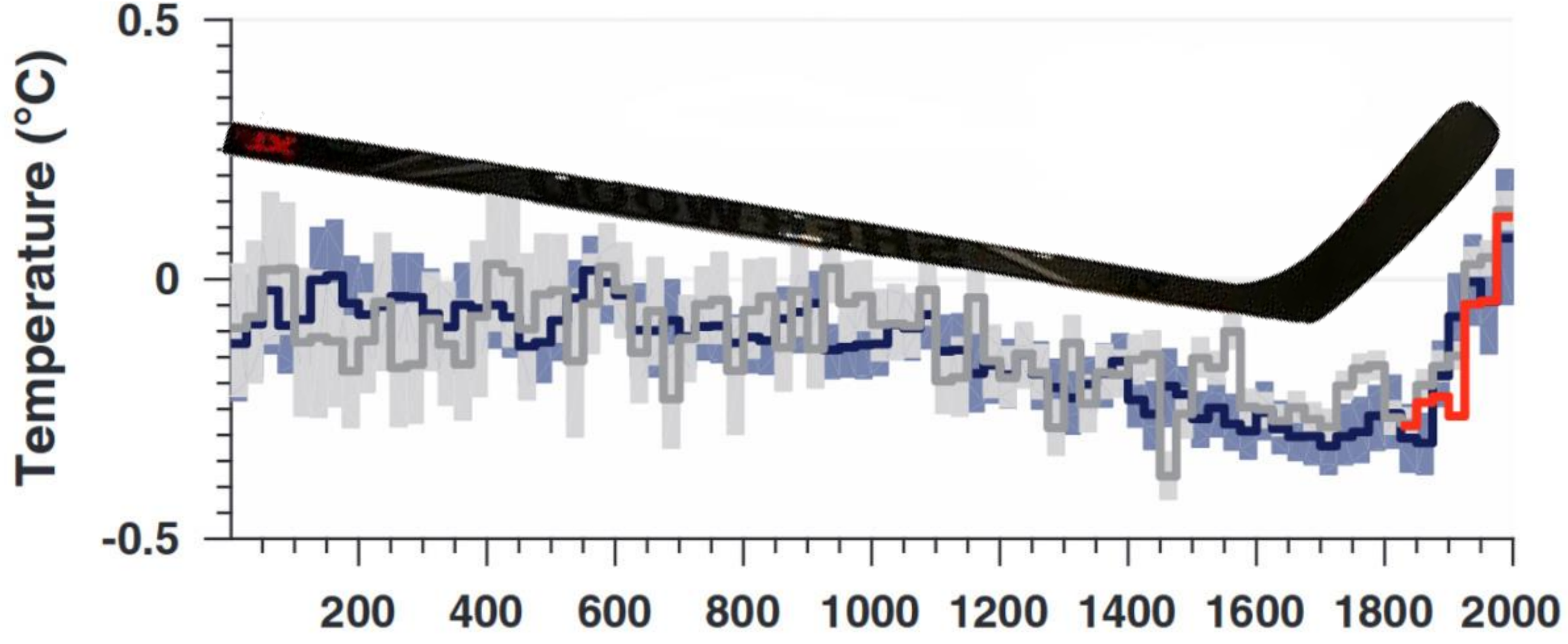
- Maximum density of different archives, allowing to discuss regional features.
- Allows to evaluate the impact of natural climate change on civilizations.



Source: [PAGES2k Consortium, Nature Scientific Data, 2017]

Trends over the last 2000 years



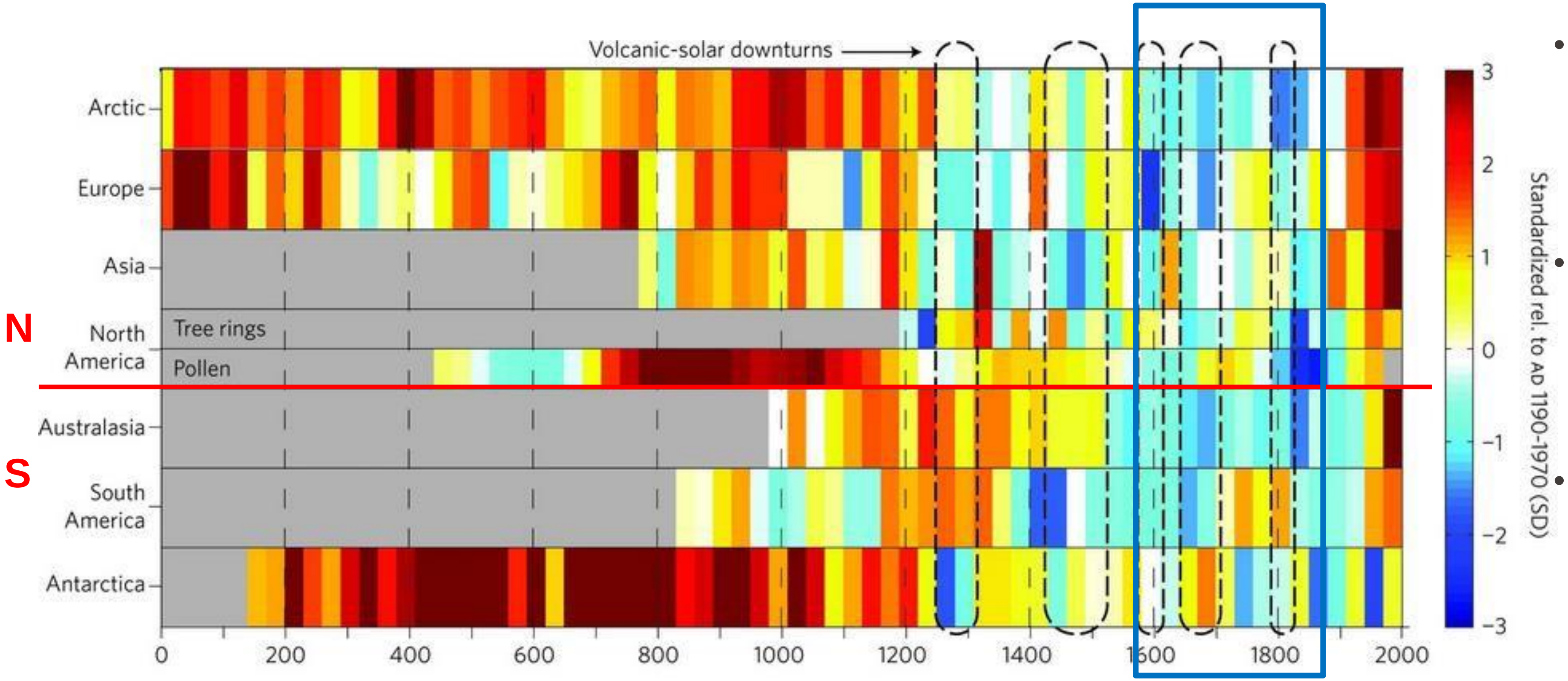
Grey: archives with temporal resolution < 5 years.
Blue: archives with temporal resolution > 5 years.
Light grey and blue: uncertainties.
Red: instrumental observations.
All curves = average over 25 years.

- On global average, long-term cooling trend, which ended late in the 19th century.
- «Hockey stick» curve.
- Global mean temperature change of less than 0.5°C.

Recent warming reversed the long-term cooling.

Source: PAGES2k Consortium, Nature Scientific Data, 2017

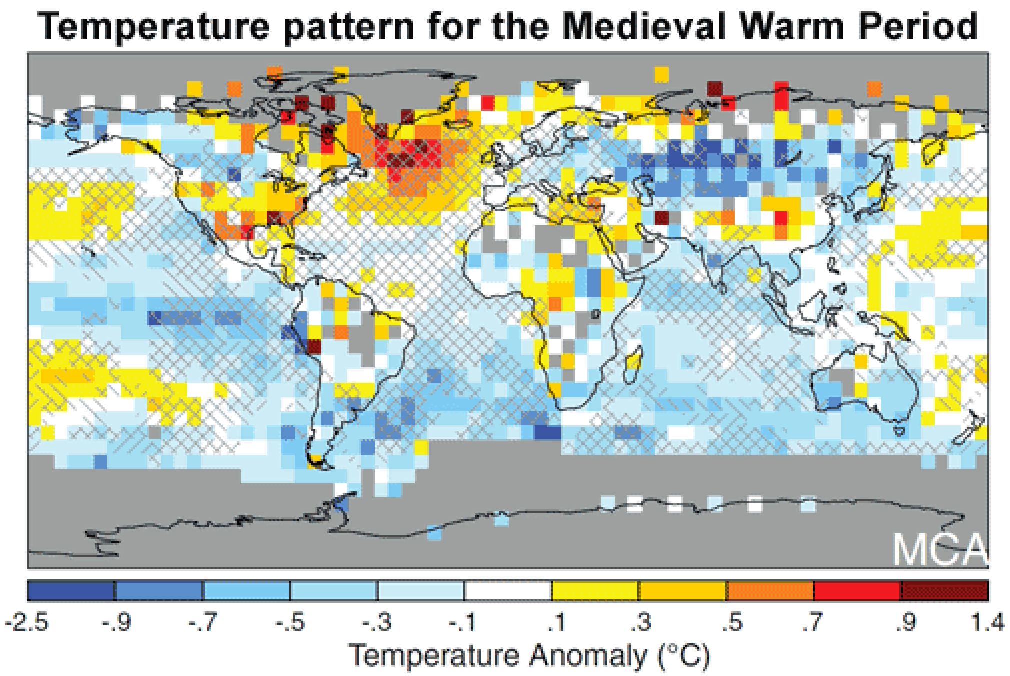
Regional differences over the last 2000 years

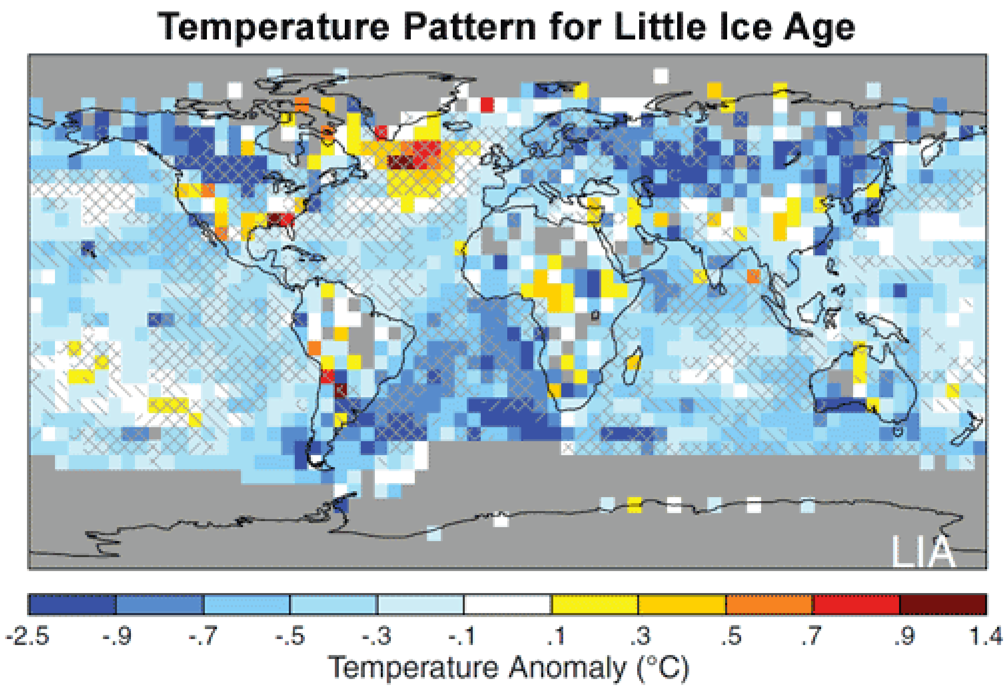


Source: PAGES2k Consortium, Nature Geoscience, 2013

- Multi-decadal to centennial scale regional temperature variability. more similarity within each hemisphere than between them.
- No globally synchronous warm or cold intervals that would define a worldwide Medieval Climate Anomaly and a Little Ice Age.
- But cold conditions in several regions between 1580 CE and 1880 CE.

Regional differences over the last 2000 years

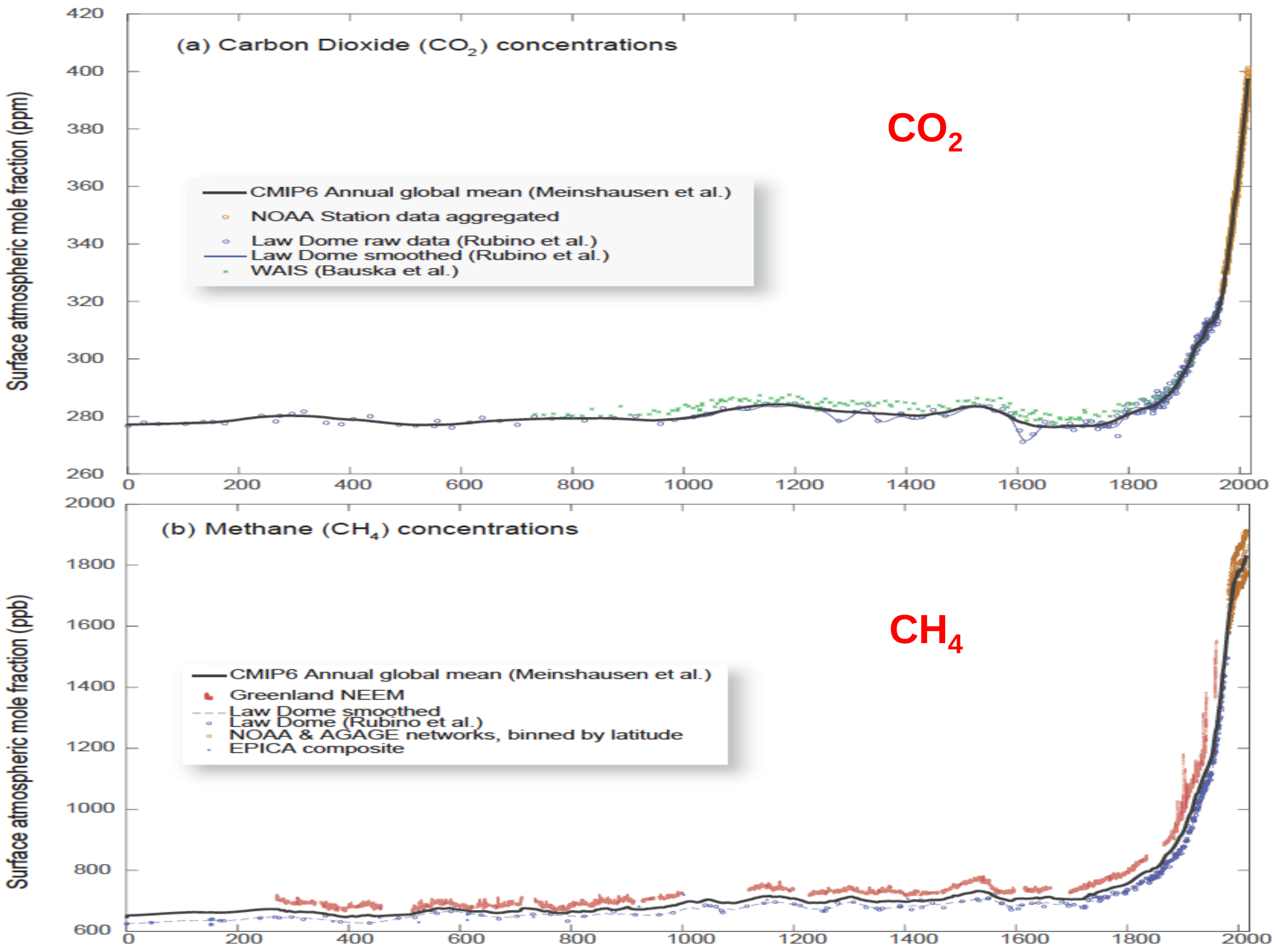




Source: *Mann et al., Science, 2009*

- Medieval Climate Anomaly: ~900 CE to ~1,300 CE (Common Era)
- Little Ice Age: ~1,400 CE to ~1,850 CE
- Warmer summers and less sea ice in the North Atlantic helped Vikings to settle in Greenland.

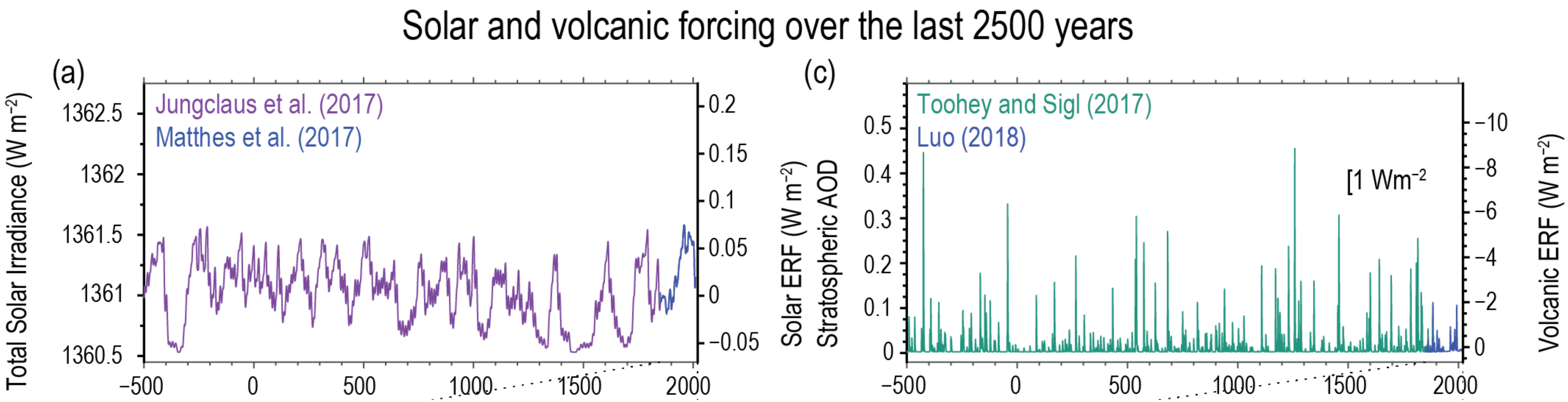
What causes ? Greenhouse gases ?



- Very limited changes prior to 1800 CE.
- ~10 ppm maximum for CO_2 (4%)
- ~100 ppb maximum for CH_4 (10%)

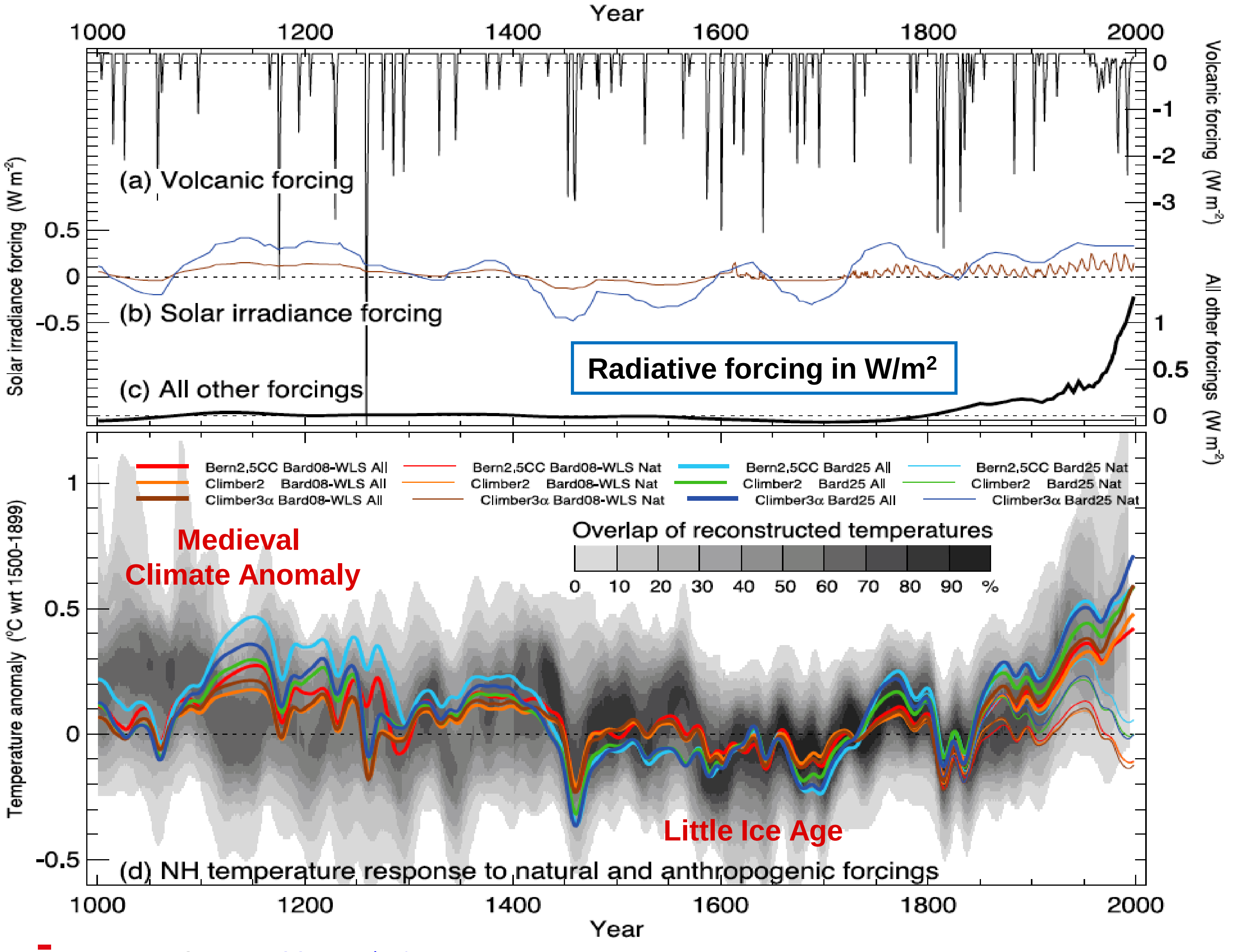
Source: Jungclaus et al., Geophys. Model. Dev. 2017

What causes ? Solar and volcanic variability ?



Source: IPCC AR6 Fig. 2.2.

What causes ? Solar and volcanic variability ?



Source: *IPCC AR4 Fig. 6.14.*

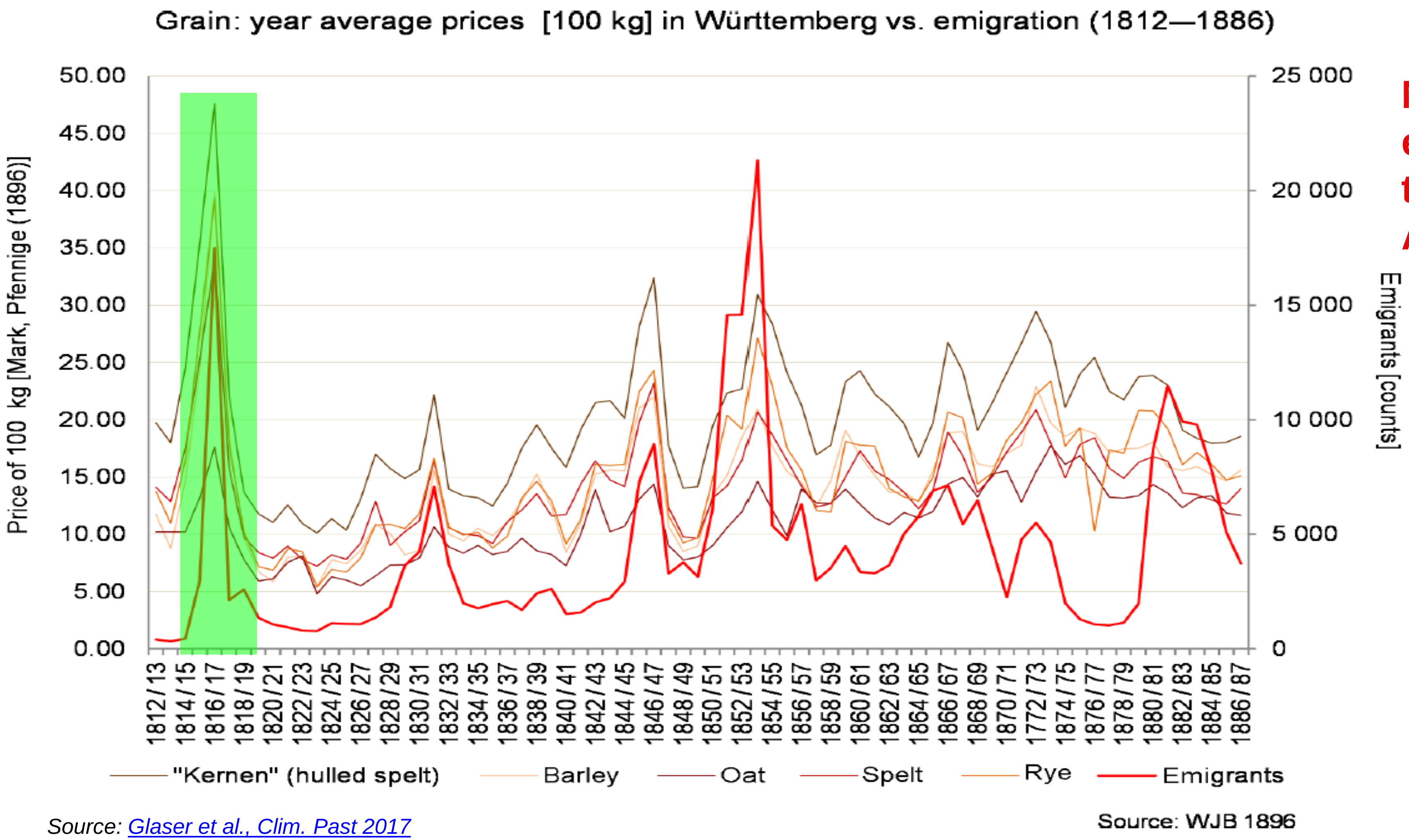
- Reasonable agreement between the annual mean Northern Hemisphere temperature reconstruction and model simulations, using strong (blue) or weak (brown) solar irradiance variations.
- It points out the difficulty of estimating past irradiance changes from proxies such as sunspot number and cosmonucleides produced by cosmic rays (^{14}C, ^{10}Be, ^{36}Cl), recorded in tree rings and ice cores.

Tambora eruption in 1815:
2016, the year without summer

Impact of the Tambora eruption on European emigration

- Data from Western Germany.
- But it’s not all about climate forcing. 1845-1852: the European Potato failure.

Grain price (Marks/100kg)



Number of emigrants to North America

Source: *Glaser et al., Clim. Past 2017*

Summary: Climate archives, geological to millennial time scales

- Past climate observations and testing of climate models against them are important to evaluate our understanding of climate processes and model accuracy.
- There is **a whole suite of climate archives**, qualitative (like species distribution) or quantitative (isotopic tracers, ice core gases).
- Depending on the archive, spatial coverage and time resolution usually decline with increasing age.
- **Geological times scales**: Climate is regulated by the balance between plate tectonics, volcanism and silicate weathering, modulating atmospheric CO_2 levels.
- **Quaternary time scales** (last 2.6 million years): great to test models regarding external forcing (orbital parameters) and slow internal feedbacks (ocean circulation, ice sheet dynamics). Climate change mainly driven by orbital forcing and CO_2. Confirmation of a medium climate sensitivity of 2.5 to 4°C. Important to constrain future ice sheet decay.
- **Millennial time scales** (last 2,000 years): internal variability of the climate system (Medieval Climate Anomaly, Little Ice Age) constrained by volcanic and solar forcings, superimposed on a long-term cooling.
- Climate models behave reasonably well in reproducing the most recent patterns. Bur regional uncertainties remain.
- **The warming of the industrial Era due to greenhouse gas increases has changed the game.**