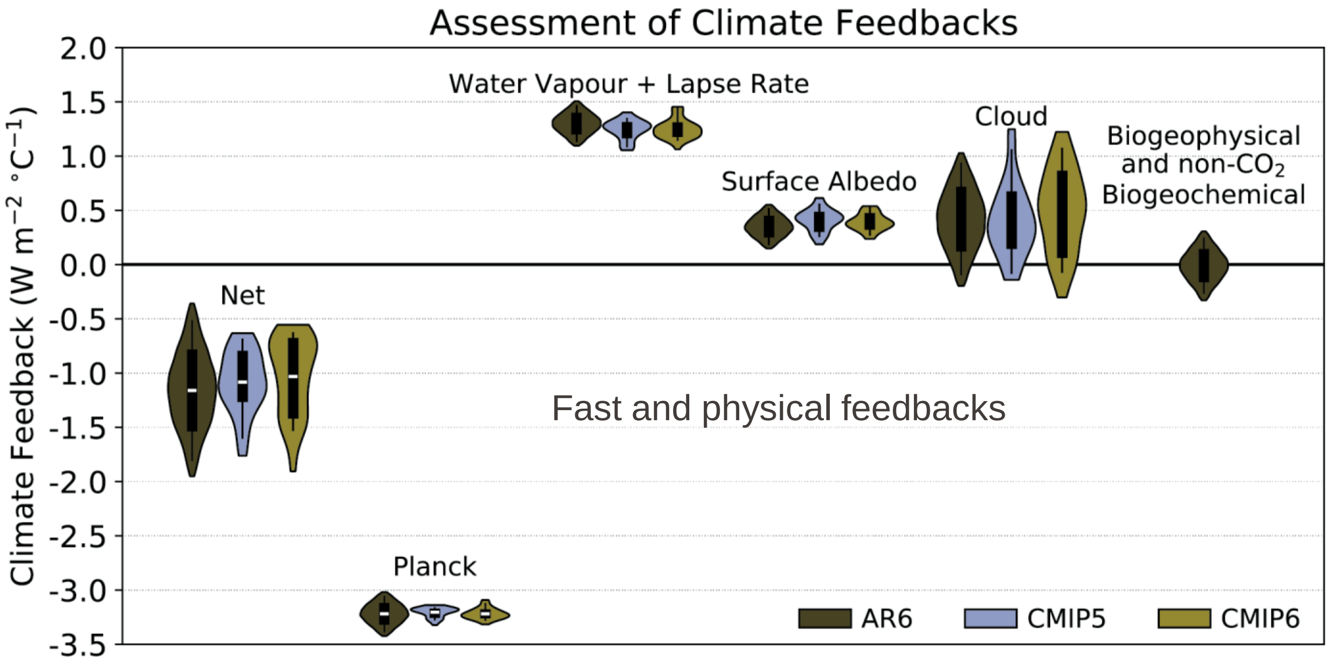
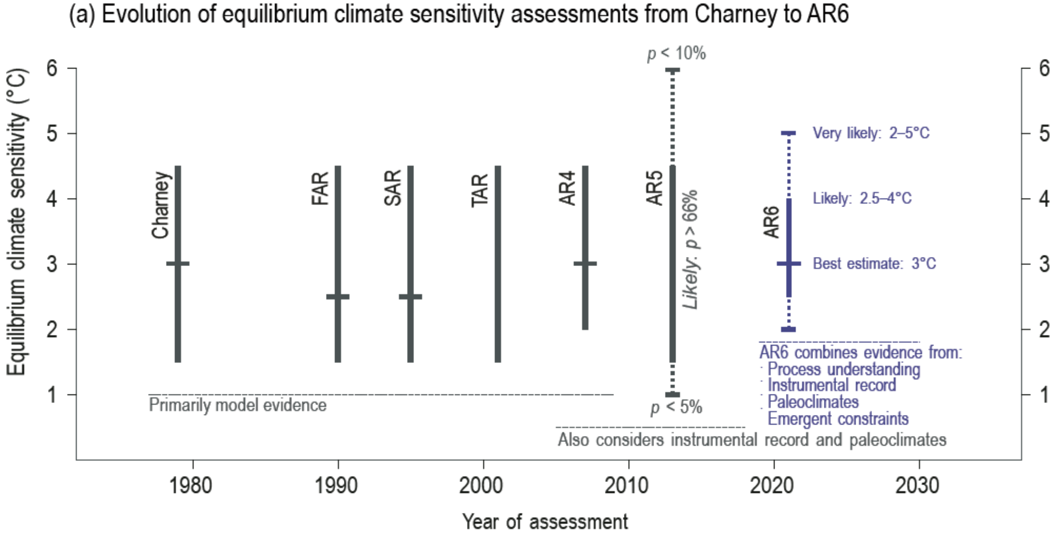
Recap from previous lecture



Evolution of climate sensitivity estimates



EPFL

Reading Task – «Energy transition»

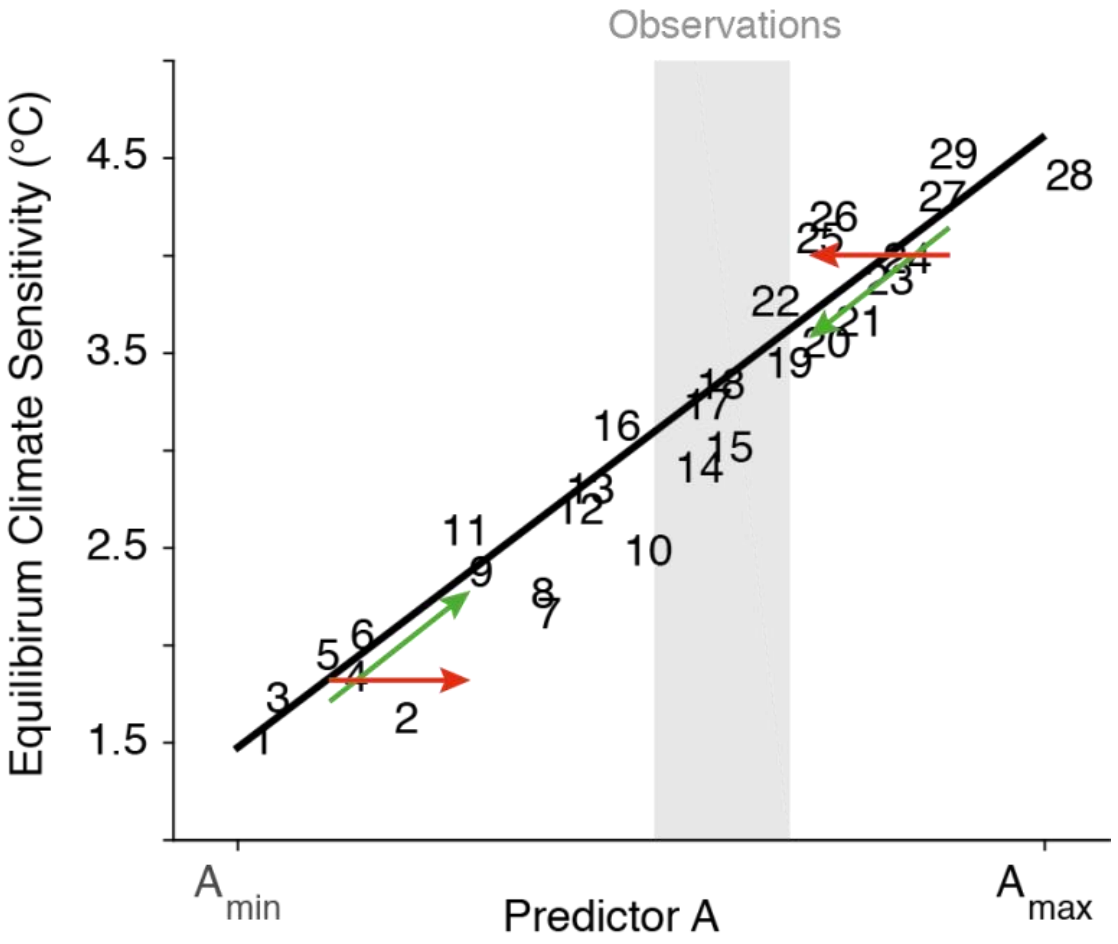
1. Trajectory of renewables: «Renewable energy passes 30% of world's electricity supply"
   - See moodle file: Reading_1_Guardian, or
   - https://www.theguardian.com/environment/article/2024/may/08/renewable-energy-passes-30-of-worlds-electricity-supply?CMP=Share_AndroidApp_Other
2. Trajectory of electricity consumption: Global Electricity Sources
   - See moodle file: Reading_1_NYT
3. Kerry gives scathing rating on climate action: 'Is there a letter underneath Z?'
   - See moodle file: Reading_1_Guardianb
   - https://www.theguardian.com/us-news/2024/sep/23/new-york-climate-week-al-gore-john-kerry-condemn-fossil-fuels?CMP=Share_AndroidApp_Other

- For the discussion on 31.10.2024, think about:
  - What are the good news?
  - What are the bad news?
  - What action is needed?

General outline

	No.	Date	Topics	Deadlines
Basics	1.	12.09.2024	Introduction	fill in Questionnaire in exercises (not graded)
	2.	19.09.2024	Climate System, Radiation, Greenhouse effect	
	3.	26.09.2024	Earth’s energy balance, Radiative transfer,	
	4.	03.10.2024	Aerosols & clouds, Radiative Forcing	Launch of poster assignment
	5.	10.10.2024	Feedback mechanisms, Climate Sensitivity	
	6.	17.10.2024	**Emergent Constraints, Paleoclimate**	submission of Poster proposal (01.11.2024)
Present and future Climate change	7.	31.10.2024	Climate variability	
	8.	07.11.2024	Paris Agreement, Emission Gap, IPCC – present day climate change	
	9.	14.11.2024	Extreme Events	
	10.	21.11.2024	Climate scenarios (RCPs, SSPs), Tipping elements, 1.5 vs 2.0°C	submission of Poster draft
	11.	28.11.2024	Carbon budget, carbon offsets, metrics	submission of assignment (graded)
Actions	12.	05.12.2024	Regional climate change	
	13.	12.12.2024	Mitigation and adaptation, Climate Engineering	**Poster Conference** (graded)
	14.	19.12.2024	Recapitulation of key points, questions and answers session	fill in Questionnaire in exercises (not graded)

Constraining with emergent constraints (the concept)



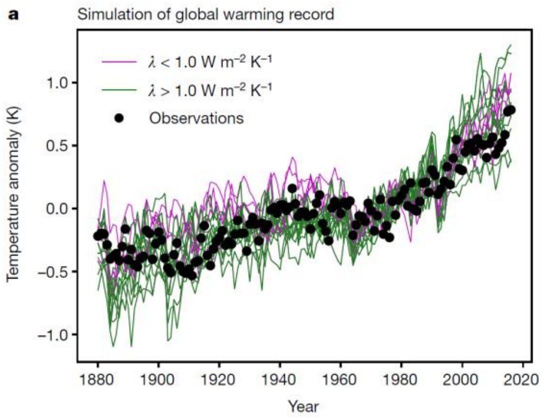
Hypothetical relationship between a predictor A and the equilibrium climate sensitivity (ECS) for 29 climate models.

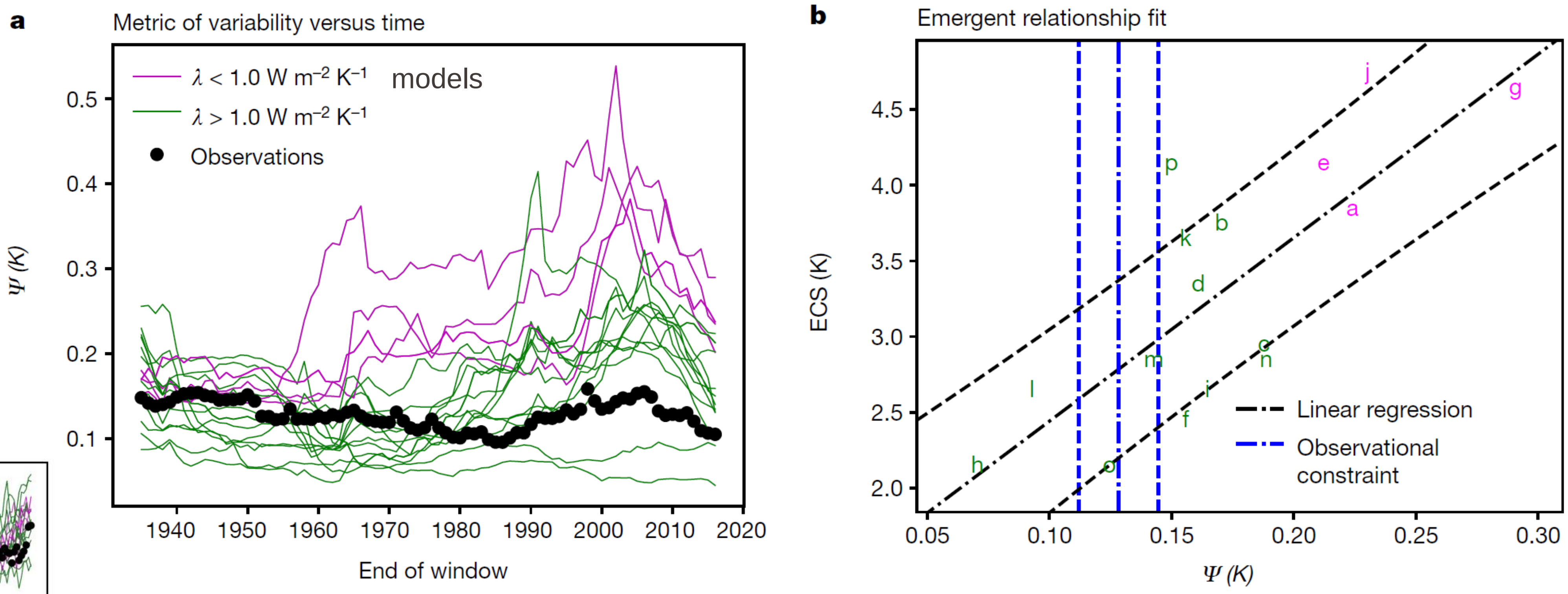
Predictor A may represent, for example, the variability of the surface temperature over time. On the y-axis, ECS may be replaced by any climate-change projection. The black line is the linear regression, and the grey vertical bar is the observed value of predictor A (with its uncertainty).
Arrows show the evolution of ECS after improving the representation of predictor A for two climate models having low (4) and high (24) ECS values.
If these climate models evolve following the red arrows, the relationship may have been found by chance. If they evolve following the green arrows, mechanisms underlying the relationship gain credibility.
Since predictor A can be observed, this relationship can be considered as an emergent constraint.

- https://climate-dynamics.org/reducing-uncertainties-in-climate-projections-with-emergent-constraints-part-1-concept/#more-1285

Constraining with emergent constraints

Temporal variability (Ψ) of the surface air temperature as observable metric to constrain ECS.





55 years as time windows to derive Ψ

Done for many time windows (not shown)

Reduces the probability of ECS being less than 1.5 degrees Celsius to less than 3 per cent, and the probability of ECS exceeding 4.5 degrees Celsius to less than 1 per cent.

- Cox et al., 2018, Nature, doi:10.1038/nature25450

Why larger range of ECS with the newest generation of climate models?

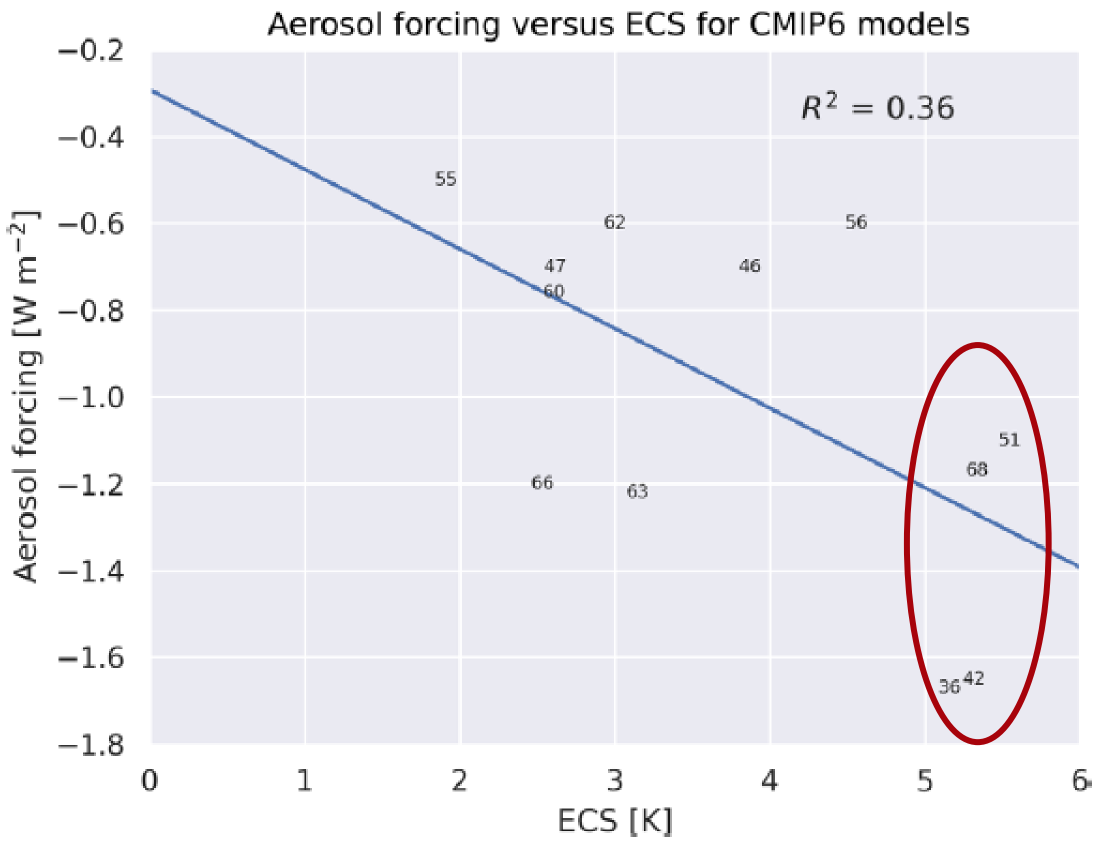


Fig. 4. Effective radiative forcing from aerosols versus ECS. Values supplied by the modeling groups (Table 3); black line is linear fit with R^2 of 0.36. The numbers denoting individual models are listed in Table 2.

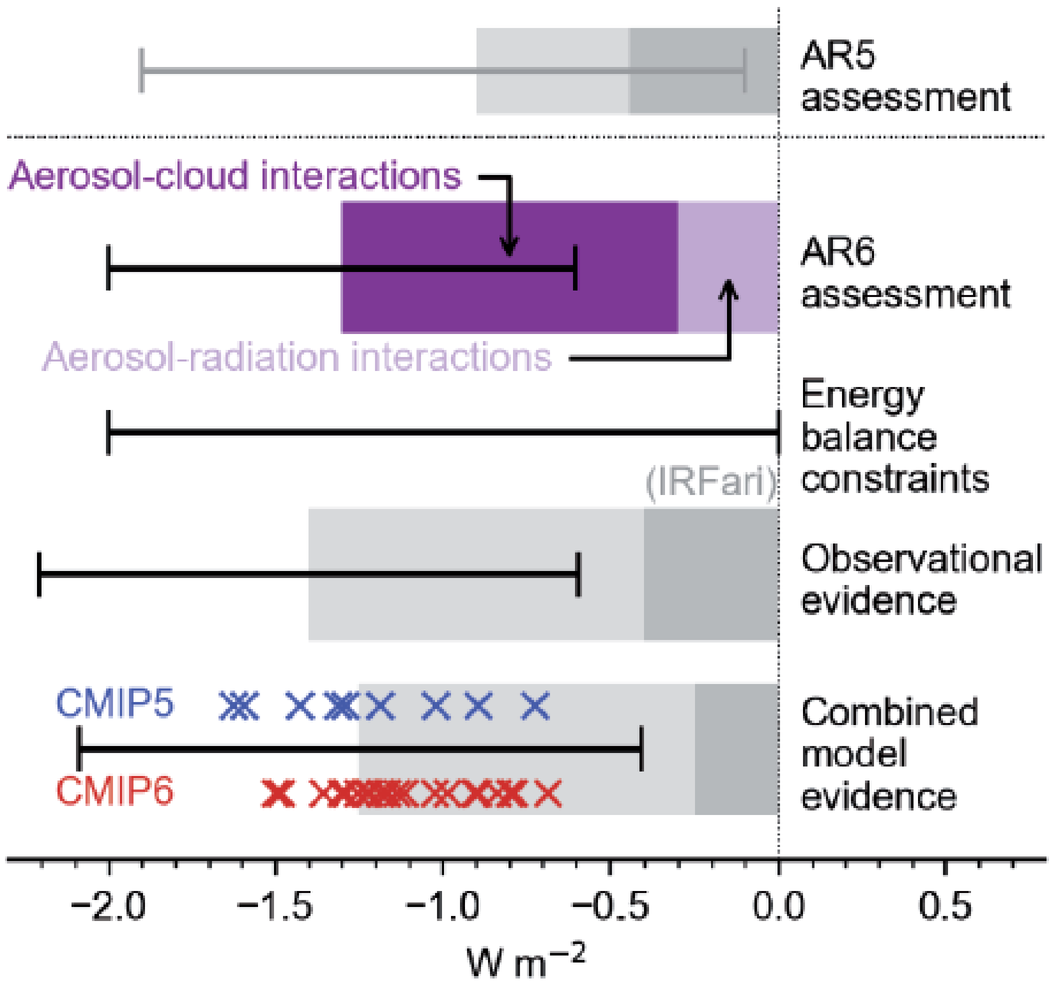
- Newer climate models include more complex treatment of aerosols.
- Aerosols interact with clouds which strongly influence the radiative forcing effect of aerosols.
- If the aerosol forcing is more negative, the climate sensitivity to CO_2 forcing needs to be higher to end up with the same rate of warming.
- However, CMIP6 models only show a week correlation ($R^2 = 0.36$).

Models with prognostic aerosol schemes and aerosol-cloud interactions.
It is difficult to pinpoint the exact feedback mechanisms in the models that lead to high ECS. But overall *”cloud feedbacks and cloud-aerosol interactions in models with prognostic aerosol schemes seem to be playing an important role”.*

Critical to research

- Meehl et al., Science Advances, 2021, https://advances.sciencemag.org/content/6/26/eaba1981/tab-pdf

Uncertainty from aerosols and clouds



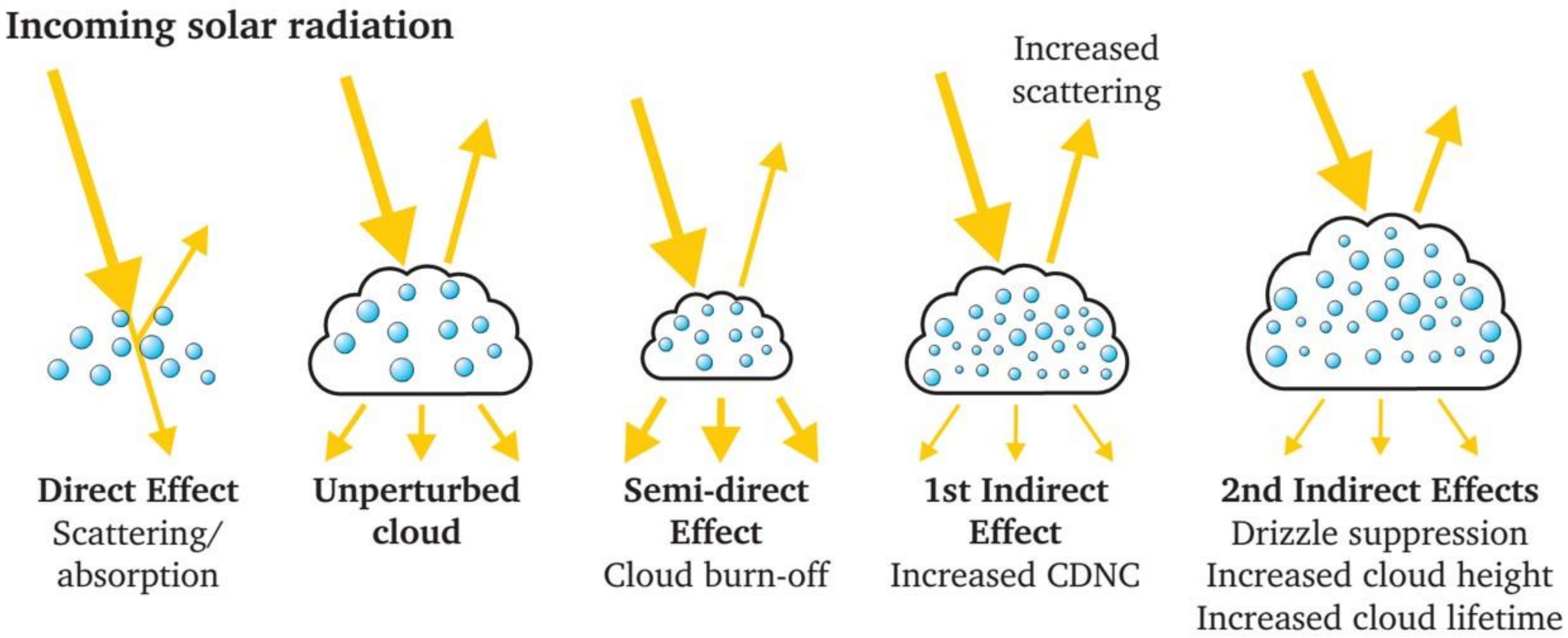
B. How can we reduce uncertainties from aerosol and cloud forcing?

defining the preindustrial

Cloud feedbacks and cloud-aerosol interactions are the most likely contributors to the high values and increased range of ECS in CMIP6.

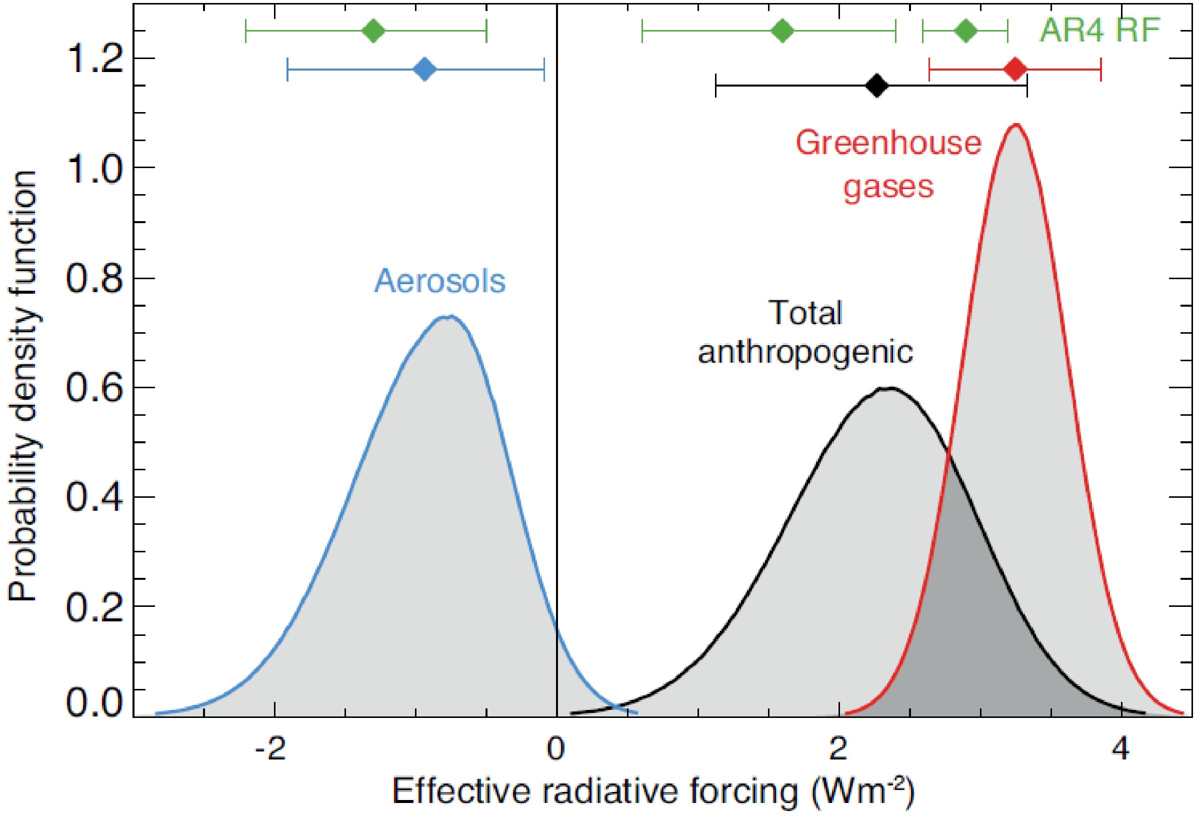
Meehl et al., Science Advances, 2021

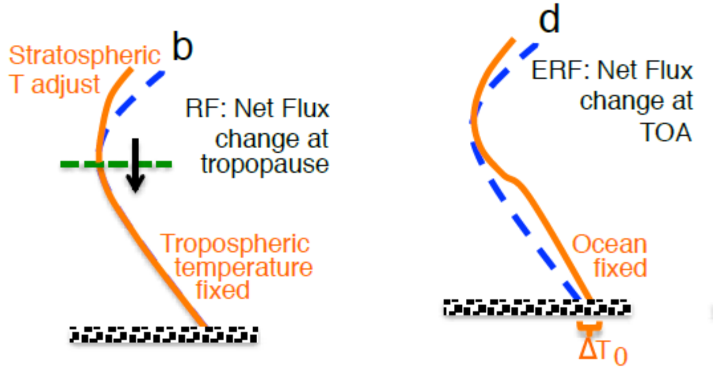
Aerosol-cloud interactions (ACI)



ERF from ARI and ACI

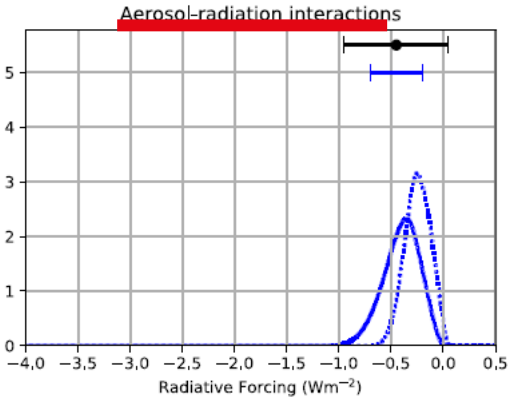
IPCC, 2013, chapter 8, Fig. 8.16

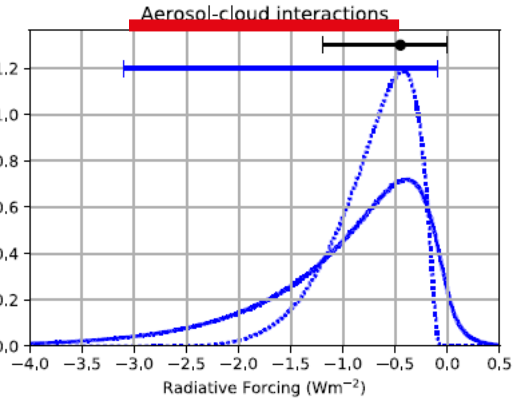


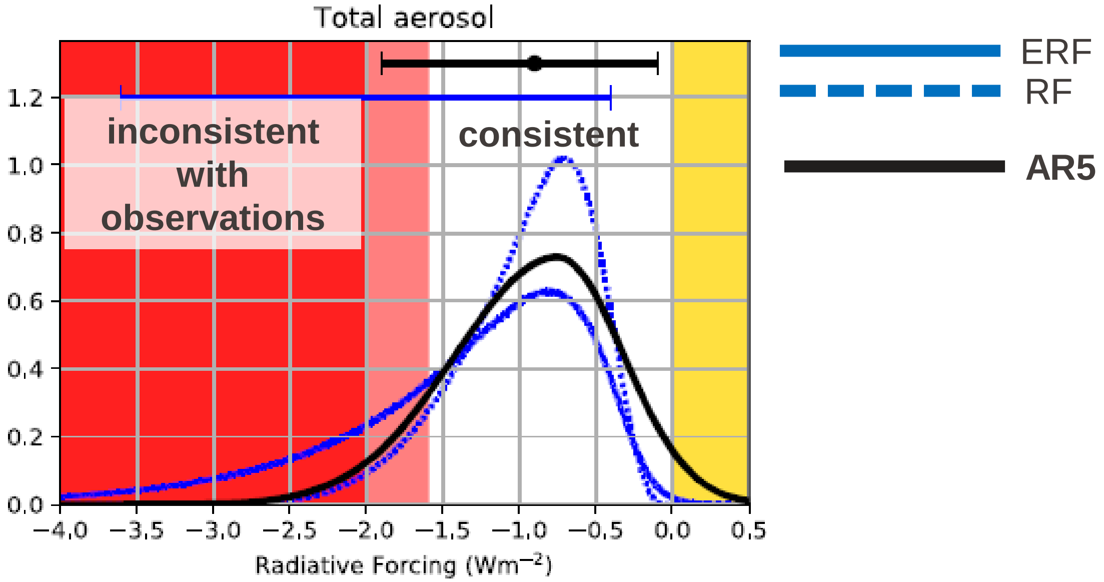


AR5 vs now:
better constrained
(less strong rapid adjustments)

AR5 vs now:
less constrained
(wider assessment of rapid adjustments)

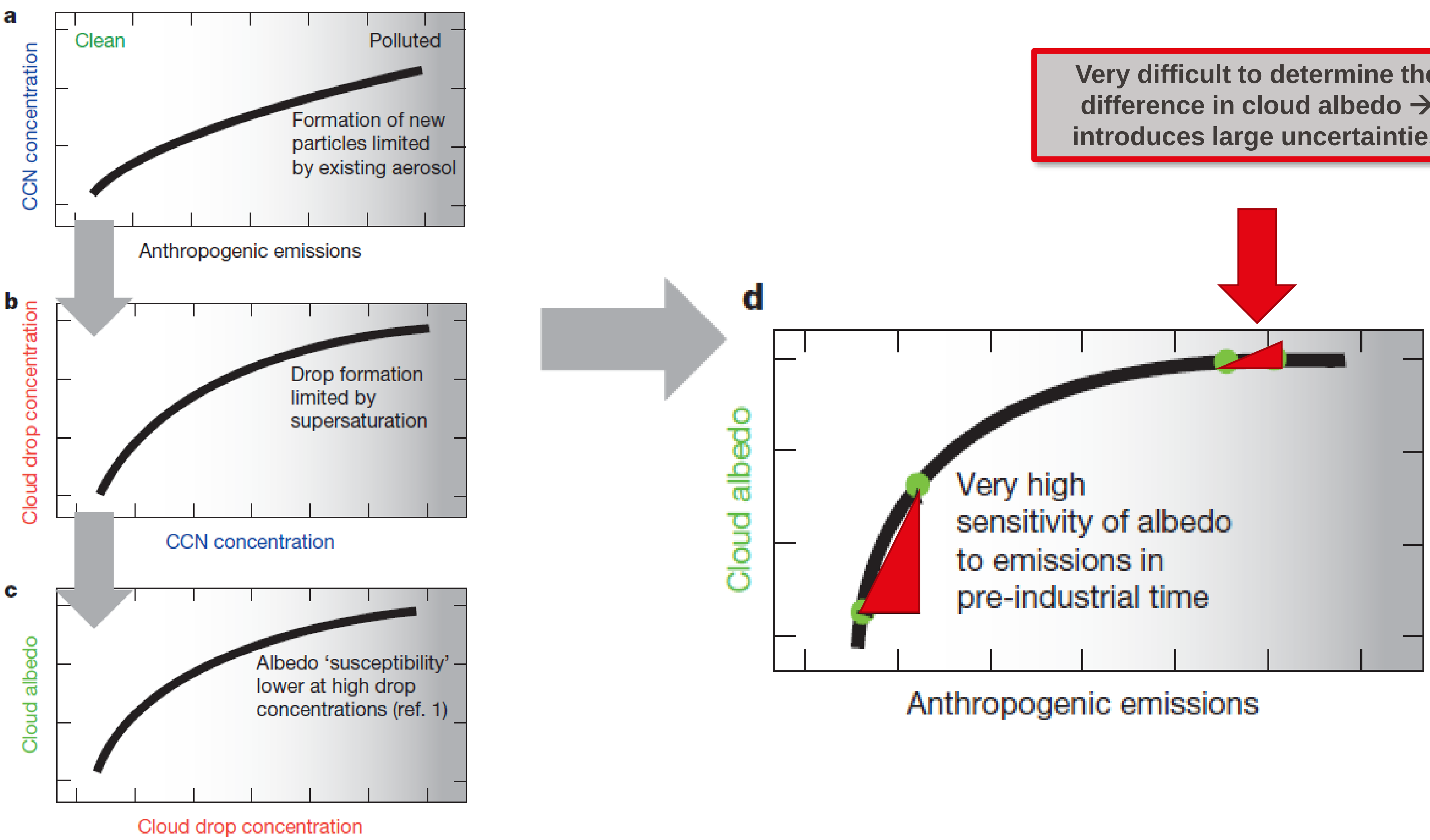






Bellouin et al., Rev. of Geophys., 2020

Determining the aerosol-cloud radiative effects



Very difficult to determine the difference in cloud albedo → introduces large uncertainties

CCN Cloud Condensation Nuclei

Carslaw et al., 2013, doi:10.1038/nature12674

The challenge of climate science: small relative quantities!

- We deal with small magnitudes of the changes in radiative fluxes and global temperature relative to the magnitudes of the initial, unperturbed quantities to determine current and future climate change.
- The observed change in global mean surface temperature of about 1.07 K represents a change of about 0.3% relative to the initial 287 K. Even the 2 K increase represents a change of less than 1%.
- The challenge to the climate change research community is to gain quantitative understanding of the changes in quantities influencing climate change and the expected response of the system to the accuracy necessary for informed decision making regarding prospective controls on future emissions of climate influencing substances.
- Such quantitative understanding is essential to answering “what if” questions regarding the consequences of future emissions of climate influencing substances.

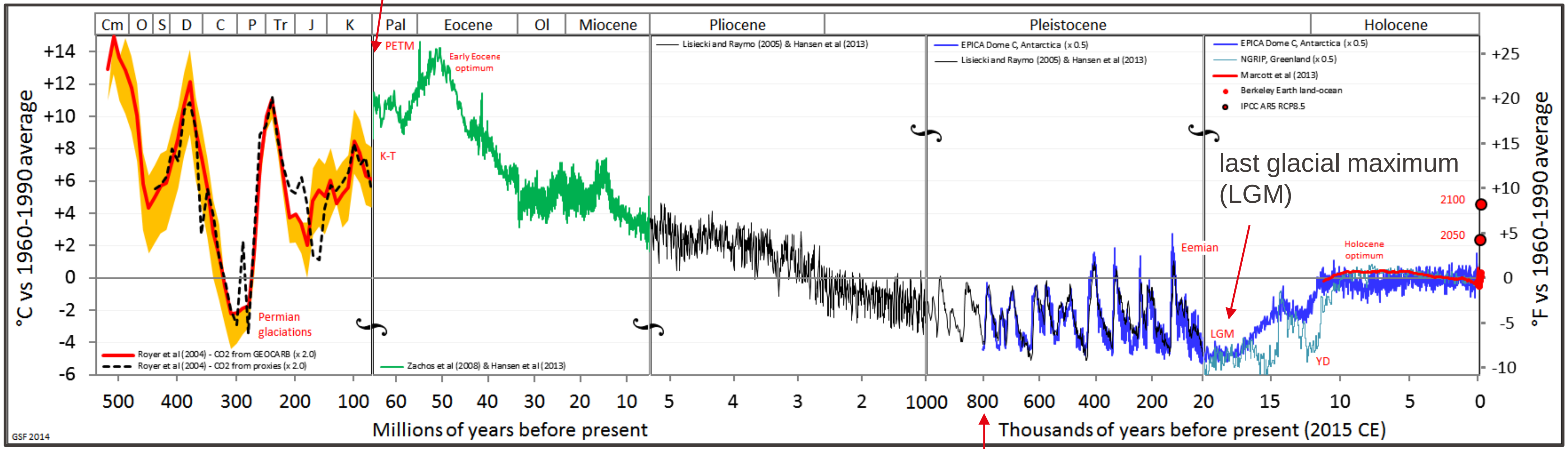
Paleoclimate – How does today's warming compare?

Temperature over the last 500 million years

Cretaceous-Paloecene
Dinosaurs extinction

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

100’000 year
glaciation cycles

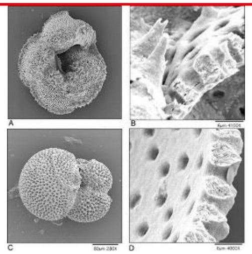


Time scale not linear!

uncertainty increases

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

- https://upload.wikimedia.org/wikipedia/commons/f/f5/All_palaeotemps.png, Zachos et al., Geology, 2006

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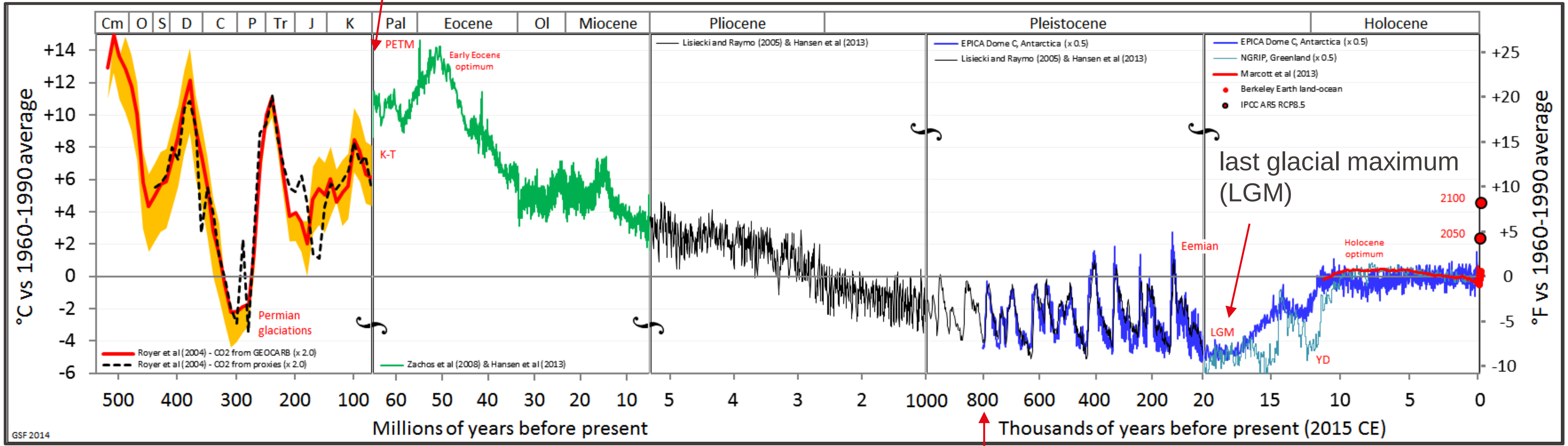

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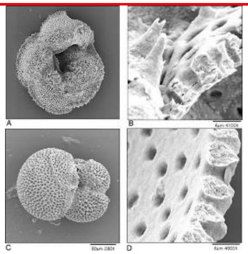
sea surface tropical temperature



stable oxygen isotope data from microscopic marine organisms

sea surface temperature

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

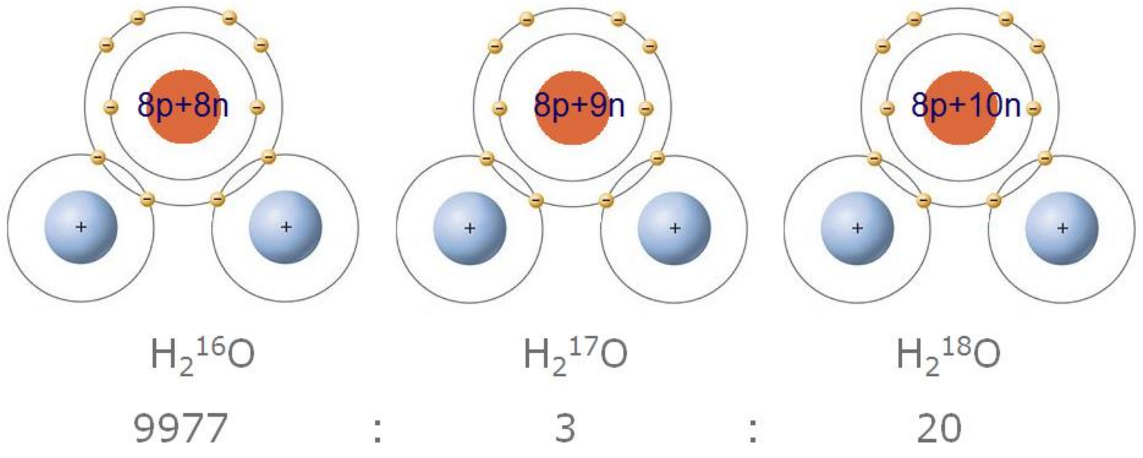
oxygen isotope measurements on the north Greenland ice core, from 1850 measured

polar temperature divided by 2 for polar amplification

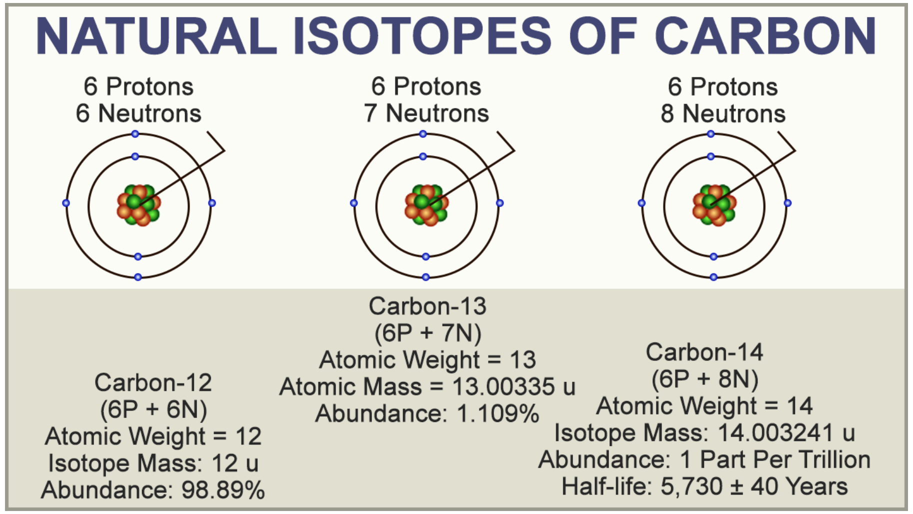
- https://upload.wikimedia.org/wikipedia/commons/f/f5/All_palaeotemps.png, Zachos et al., Geology, 2006

Isotopes

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 $H_2{}^{16}O$.
For each 10,000 water molecules in nature, only 3 are $H_2{}^{17}O$ and 20 are $H_2{}^{18}O$.

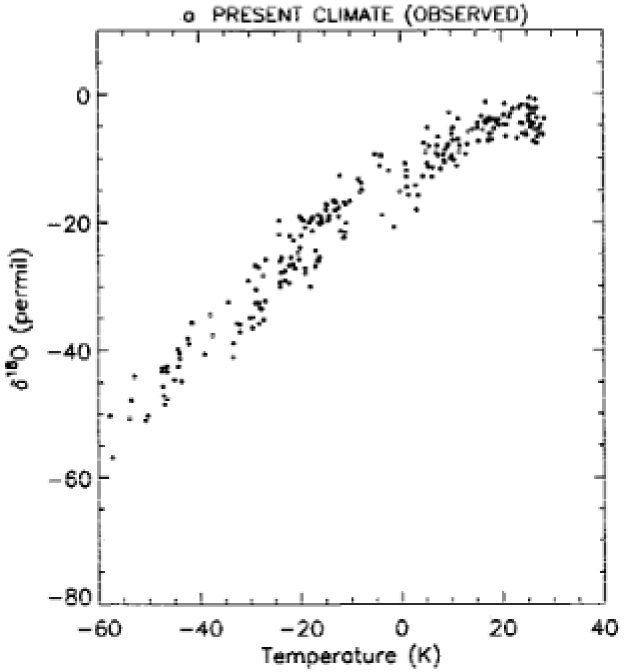


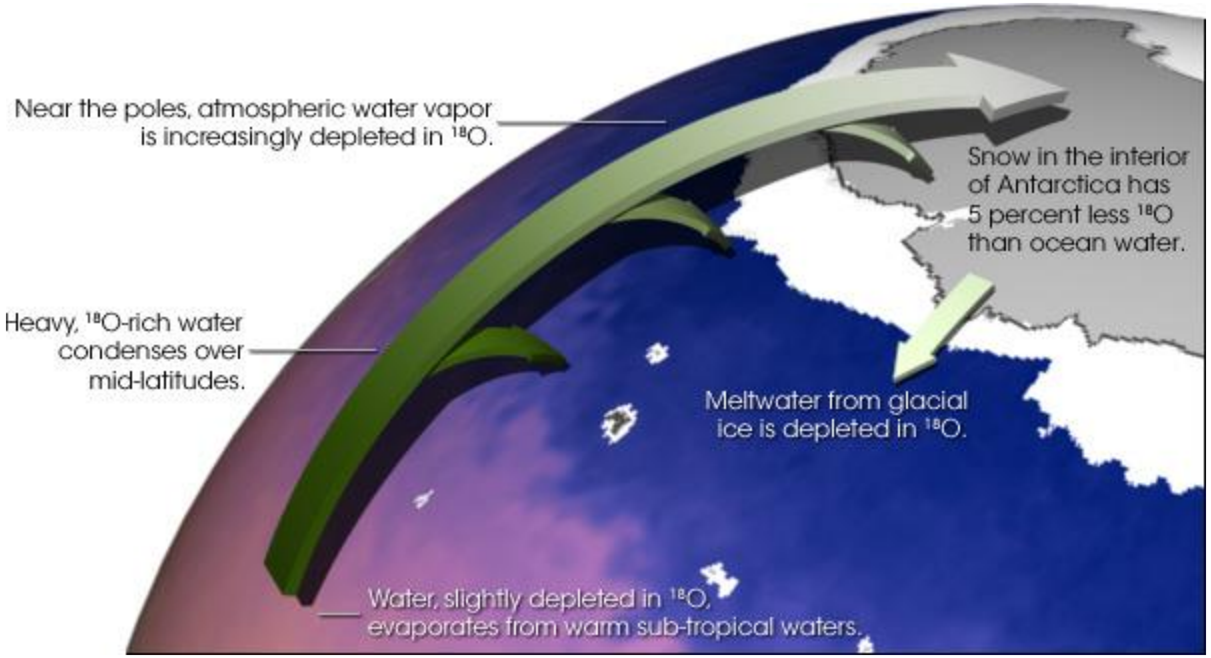
Carbon -14, Carbon-13, and Carbon-12 are isotopes of carbon, as C-14 has 8 neutrons, C-13 has 7 neutrons and C-12 has 6 neutrons, whereas, all of them have the same number of protons that is 6 and the same number of electrons that is 6.
Only C-14 is radioactive.

https://www.iceandclimate.nbi.ku.dk/research/past_atmos/past_temperature_moisture/

https://www.javatpoint.com/isotopes-and-isobars

Temperature reconstruction from oxygen isotopes



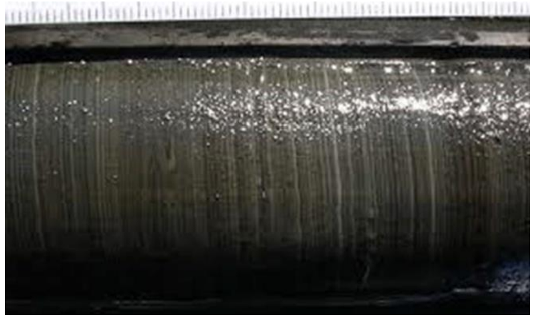


<u>During cold times</u>: enrichment of $\delta^{18}O$ near equator, strong depletion near poles
<u>During warm times</u>: less enrichment of $\delta^{18}O$ near equator, less depletion near poles.

- Jouzel, J., et al. *Journal of Geophysical Research, 1994*.

https://earthobservatory.nasa.gov/features/Paleoclimatology_OxygenBalance

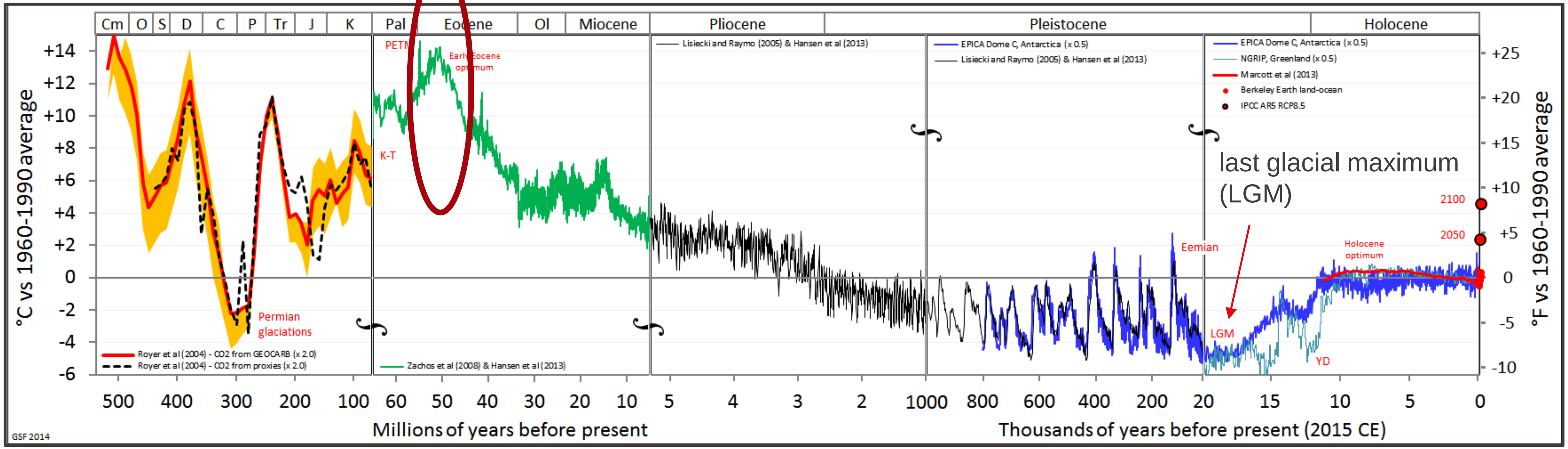
And how do we determine age?



- Direct methods
  - Counting of annual layers (sediments, corals…)
  - Counting of tree rings
- Radioisotope dating:
  - ^{14}C: $T_{1/2}$ (^{14}C) = 5.73 ka (maximum age 44 ka)
  - U-Th: $T_{1/2}$(^{230}TH) = 77 ka
  - K-Ar: $T_{1/2}$ (^{40}K) = 1.28 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

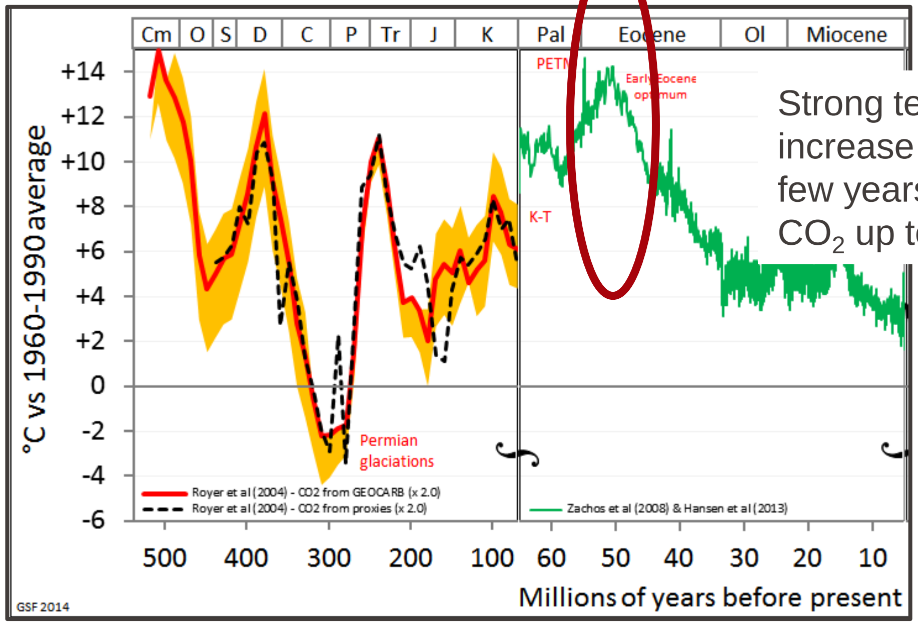
Reference temperature (avg. 1960-1990): +14 °C



- https://upload.wikimedia.org/wikipedia/commons/f/f5/All_palaeotemps.png, Zachos et al., Geology, 2006

Paleocene-Eocene Thermal Maximum (PETM)

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



Strong temperature increase in relatively few years

CO_2 up to 1700 ppm

- 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 ^{13}C-depleted carbon** into the carbon reservoirs at the Earth's surface, although the source remains an open issue. Biogenic carbon is depleted in ^{13}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.

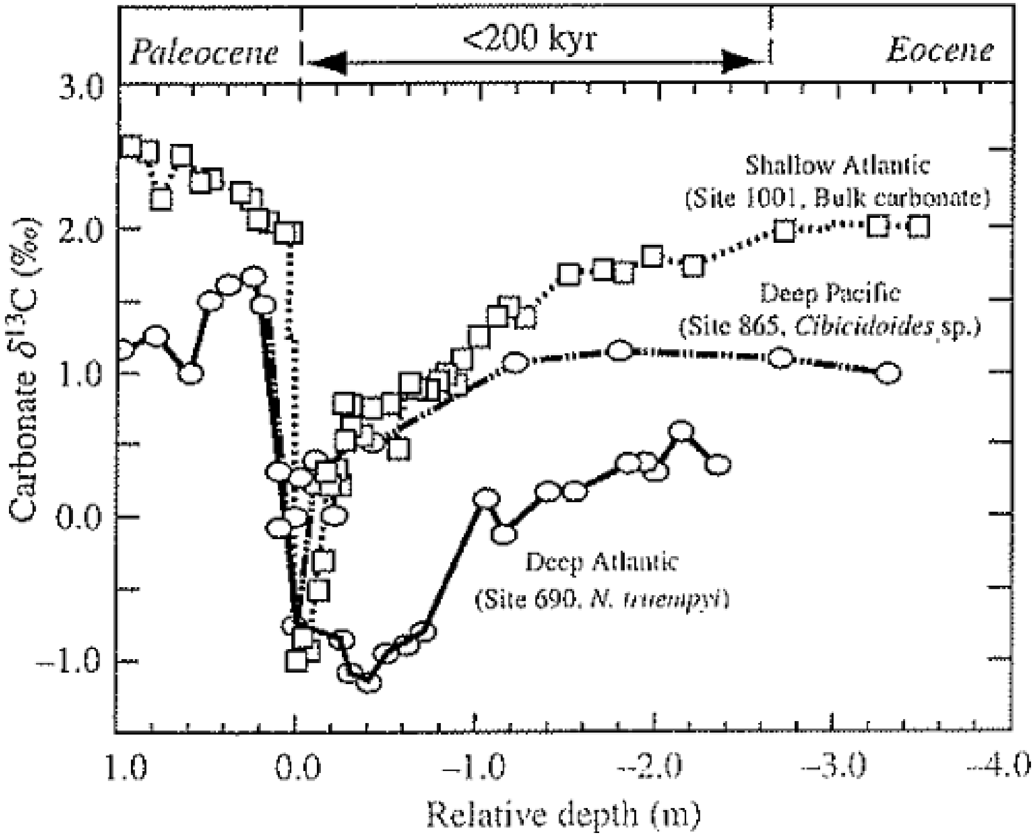
https://upload.wikimedia.org/wikipedia/commons/f/f5/All_palaeotemps.png

Zeebe et al., Nature Geoscience, 2009

Paleocene-Eocene Thermal Maximum (PETM)

- Sudden decrease in the $^{13}C/^{12}C$ ratio (normal around 1.1 permil)
- Biogenic carbon is depleted in ^{13}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.**
- Alterantively, release of methane-hydrates, requires less carbon to be released, because ^{13}C is strongly depleted in methane.

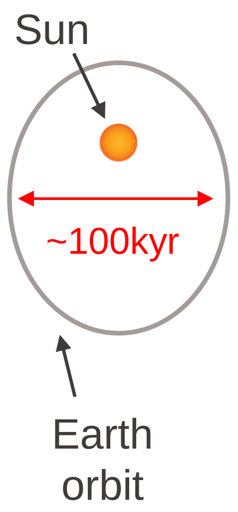
Still explanations are missing.

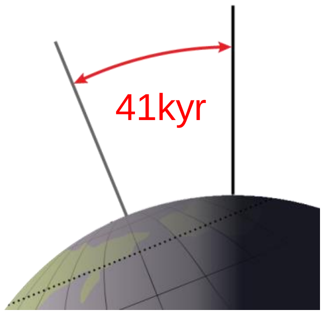


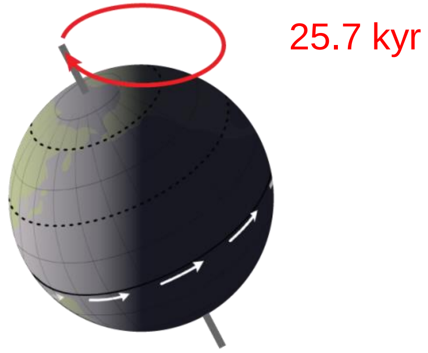
Carbon isotopic ratio from ocean sediment cores.
Depth ~ time

The Geologic History of the Carbon Cycle, Sundquist and Visser, 2003,
doi:10.1016/B0-08-043751-6/08133-0

Earth's Orbit







Eccentricitiy:
stronger change in radiation over the year

Obliquity:
axial tilt between 22.1° and 24.5°
Larger tilt means more insolation at poles.

Precession of the axis
1 ° 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:

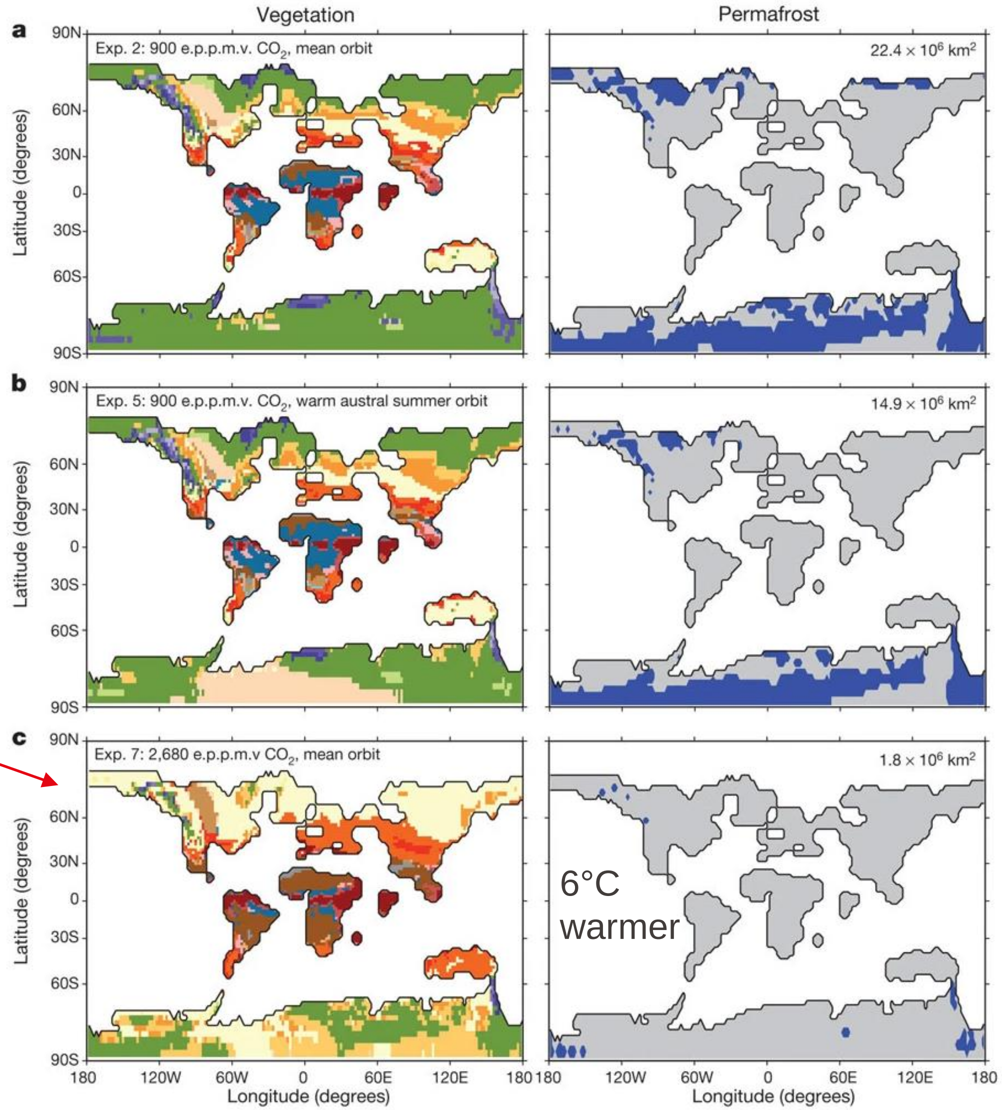
Coincidence of hyperthermals with combined **high-eccentricity** and **high-obliquity** forcing points to the **influence of polar latitudes**, where seasonal insolation is strongly affected by obliquity and precession during high-eccentricity orbits.

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

900 ppm CO_2, mean orbit

Initial release of carbon due to orbital forcing.

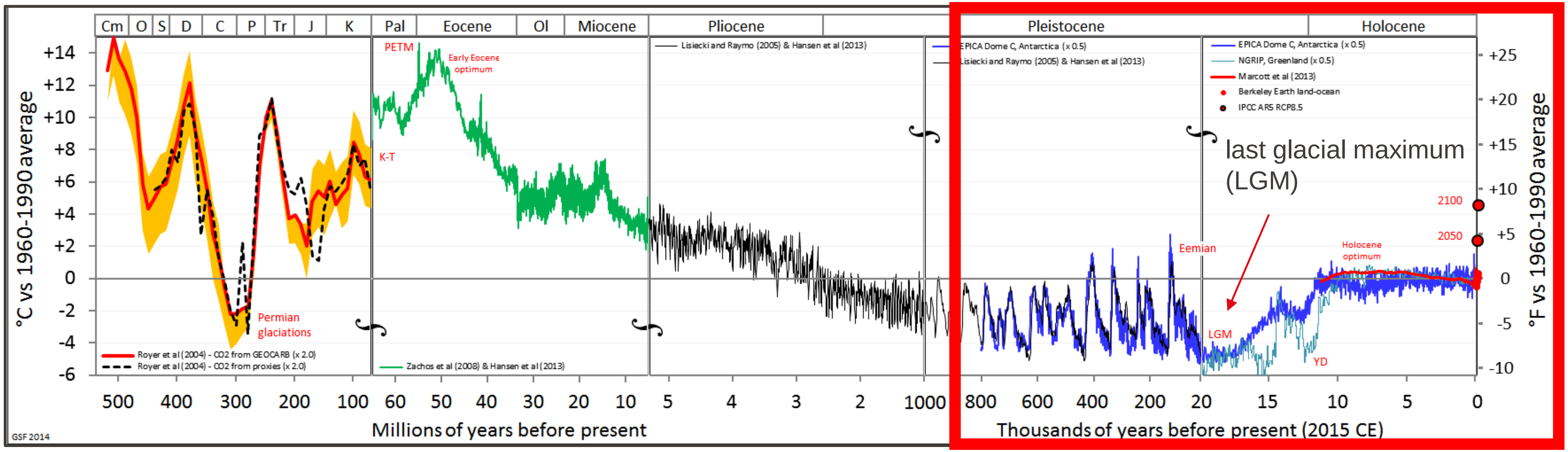
Run-away effect: 2680 ppm CO_2 and 6°C warmer



DeConto et al., Nature, 2012, https://doi.org/10.1038/nature10929

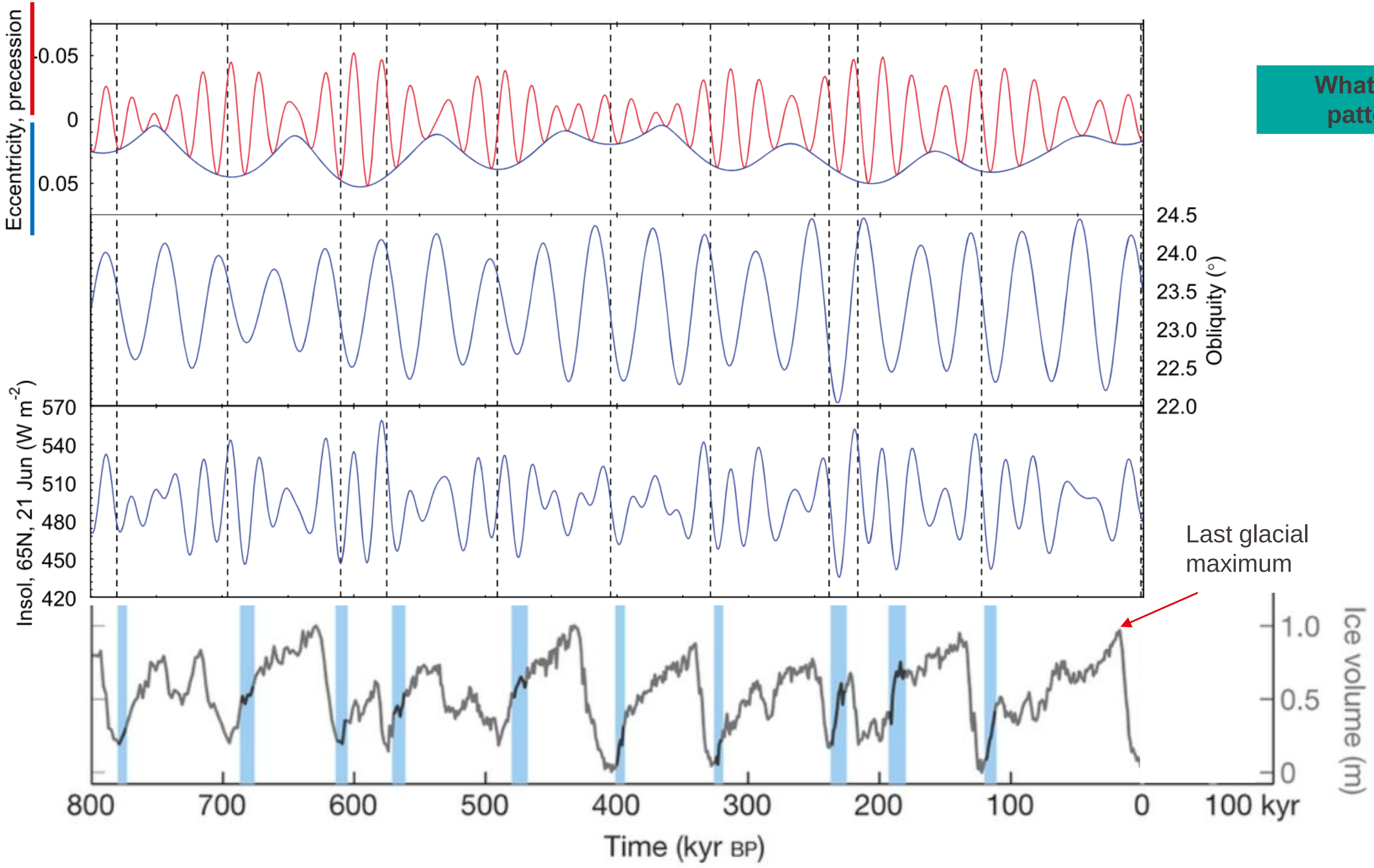
Glacials and interglacials

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



100’000 year glaciation cycles

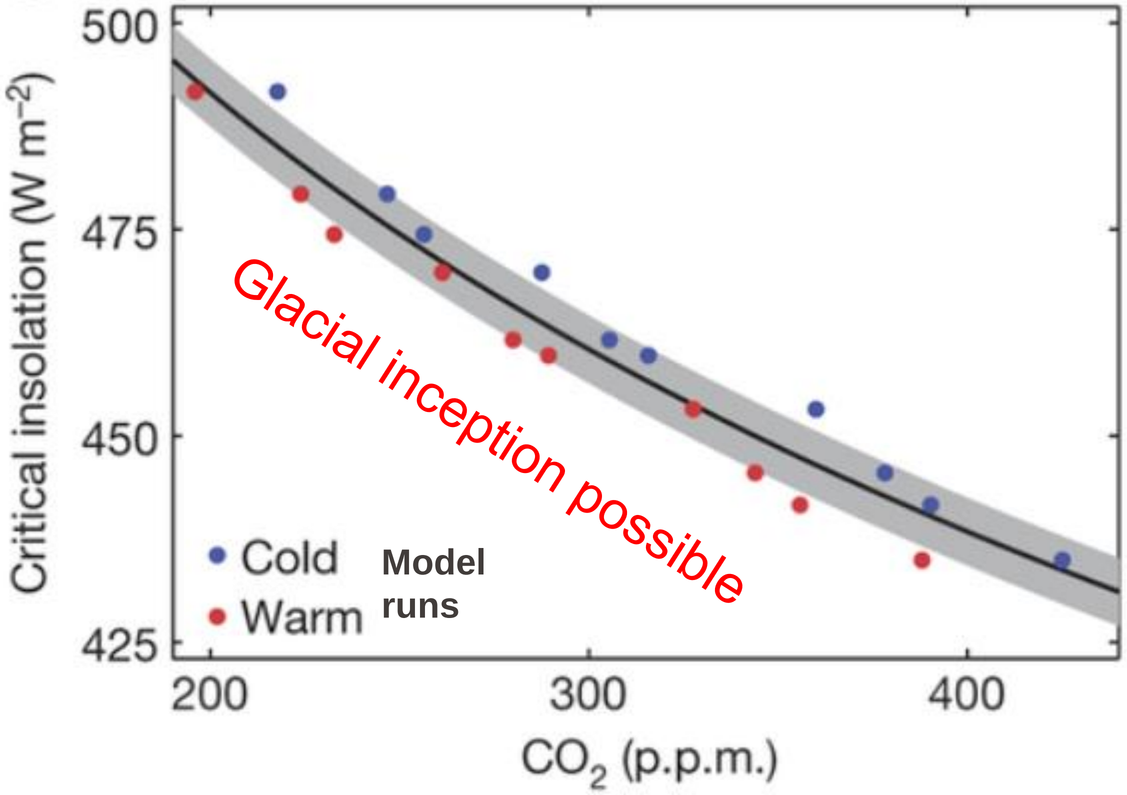
https://upload.wikimedia.org/wikipedia/commons/f/f5/All_palaeotemps.png



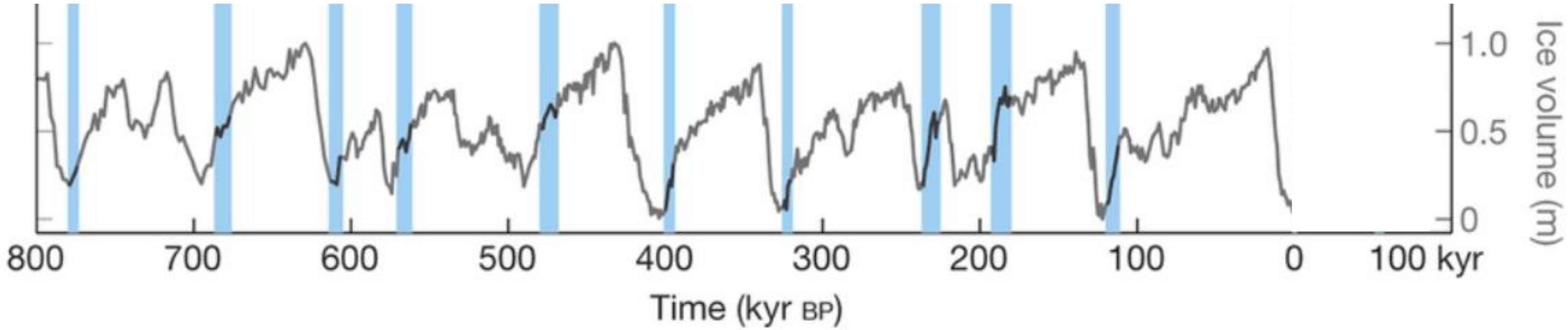
What's the pattern?

- Ganopolski et al. NAT, 2016 doi:10.1038/nature16494

PAGES, RoG, 2016 doi:10.1002/2015RG000482



Only a certain combinatin of insolation and CO_2 levels will allow for glacial periods.



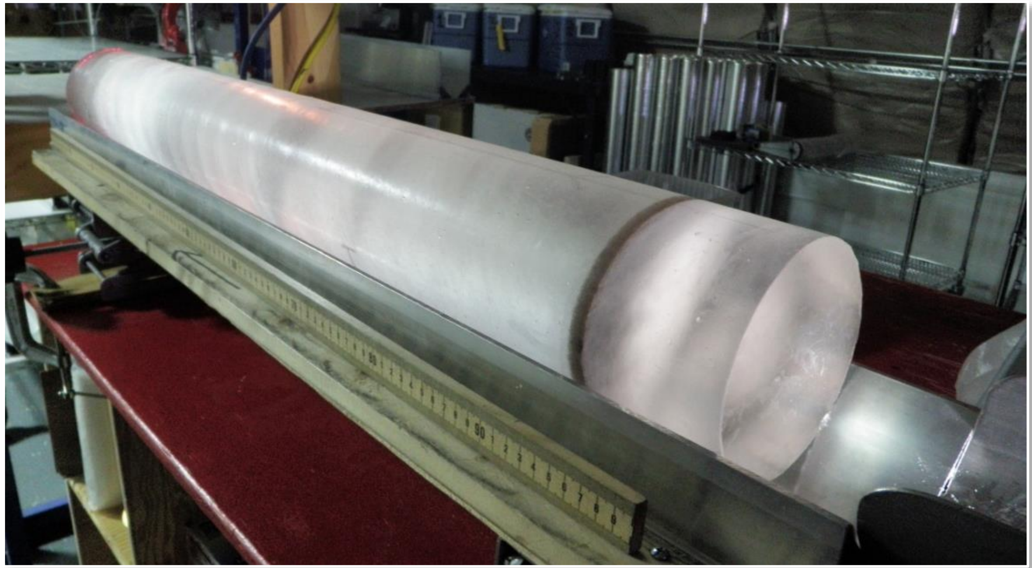
- Ganopolski et al. NAT, 2016 doi:10.1038/nature16494

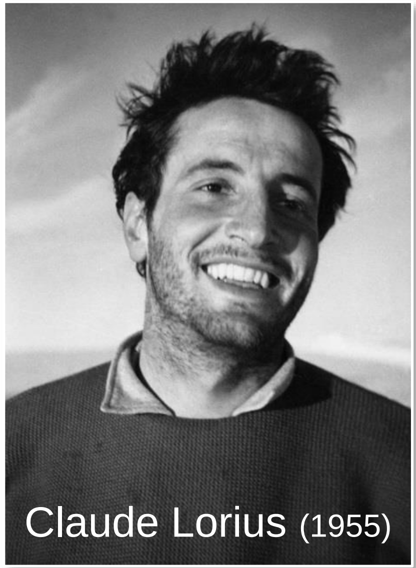
PAGES, RoG, 2016 doi:10.1002/2015RG000482

CO_2 concentrations from ice cores

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


Charcot Station (1957)



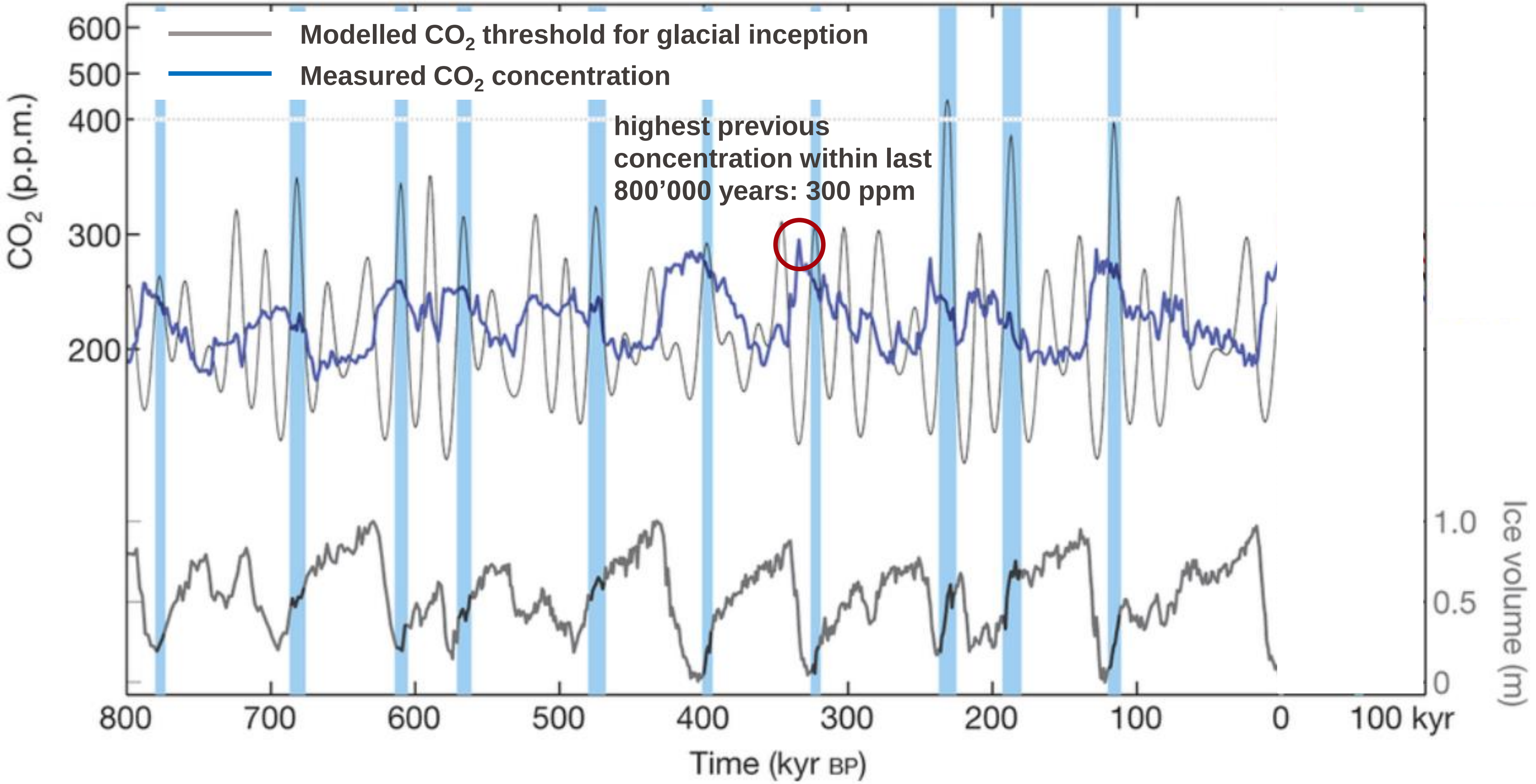

Claude Lorius (1955)

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.



- Ganopolski et al. NAT, 2016 doi:10.1038/nature16494

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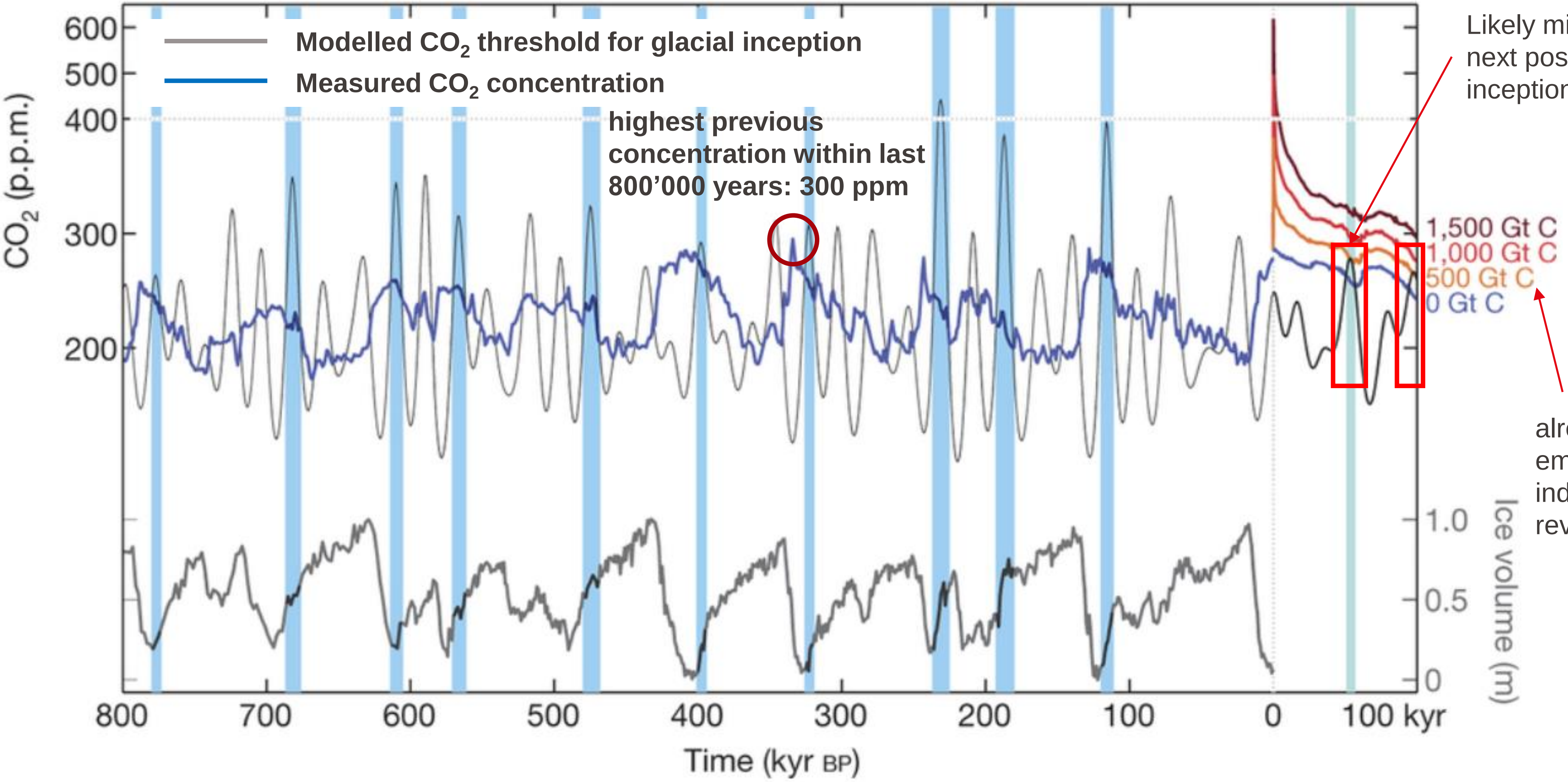


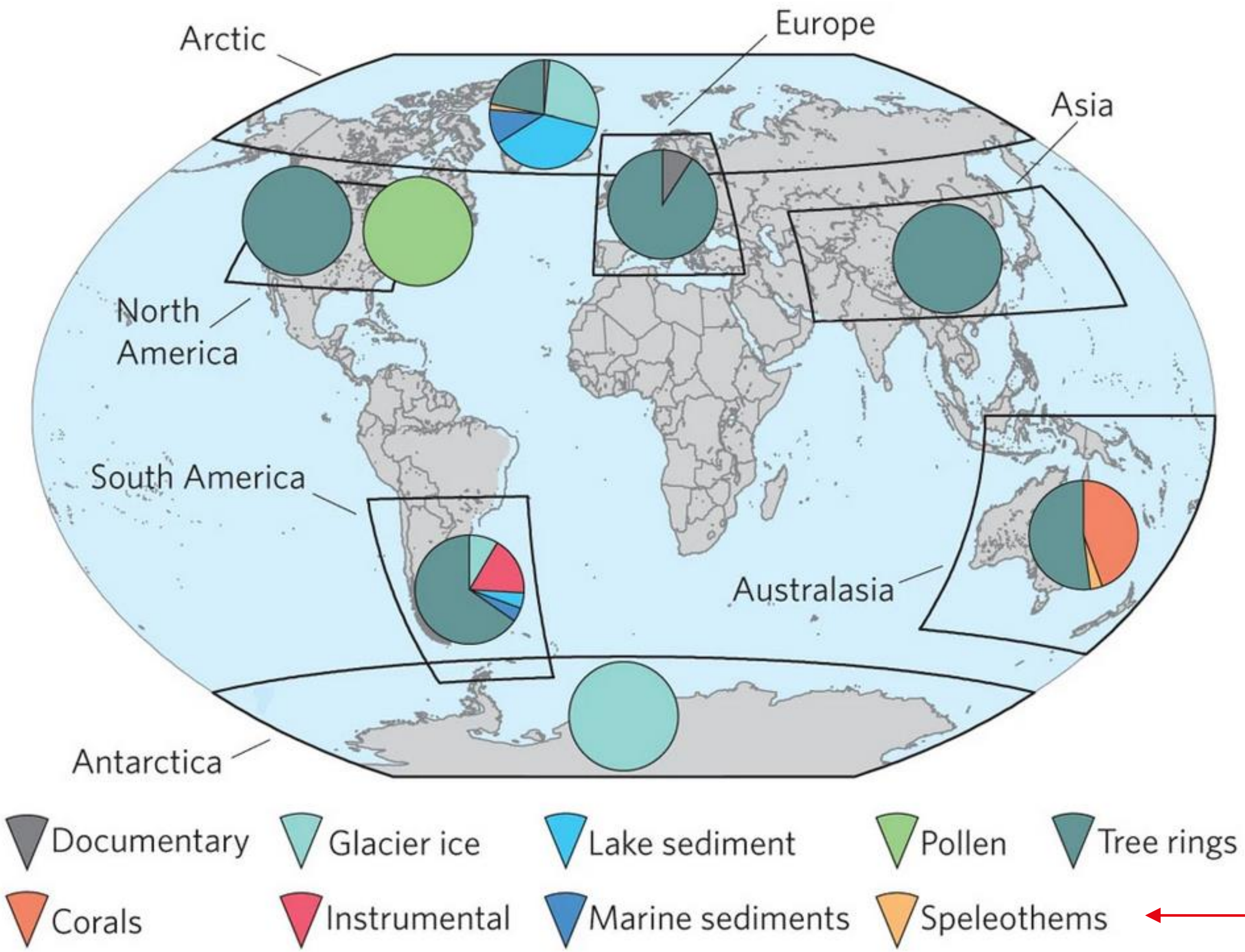
Likely missing the next possible glacial inceptions.

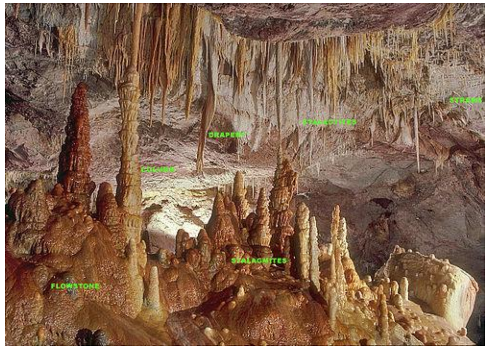
already emitted since industrial revolution

- Ganopolski et al. NAT, 2016 doi:10.1038/nature16494

PAGES, RoG, 2016 doi:10.1002/2015RG000482

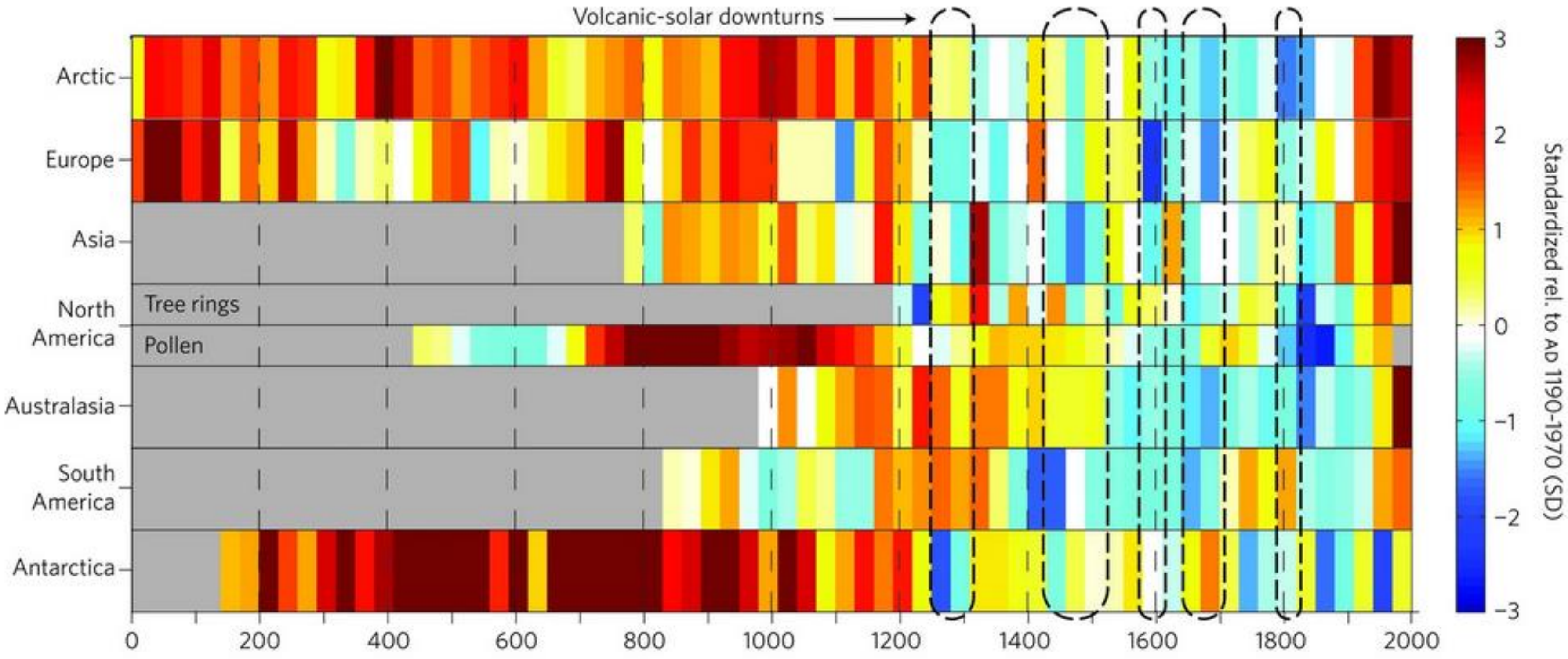
Regional differences over the last 2000 years





PAGES2K, 2013, https://www.nature.com/articles/ngeo1797

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.

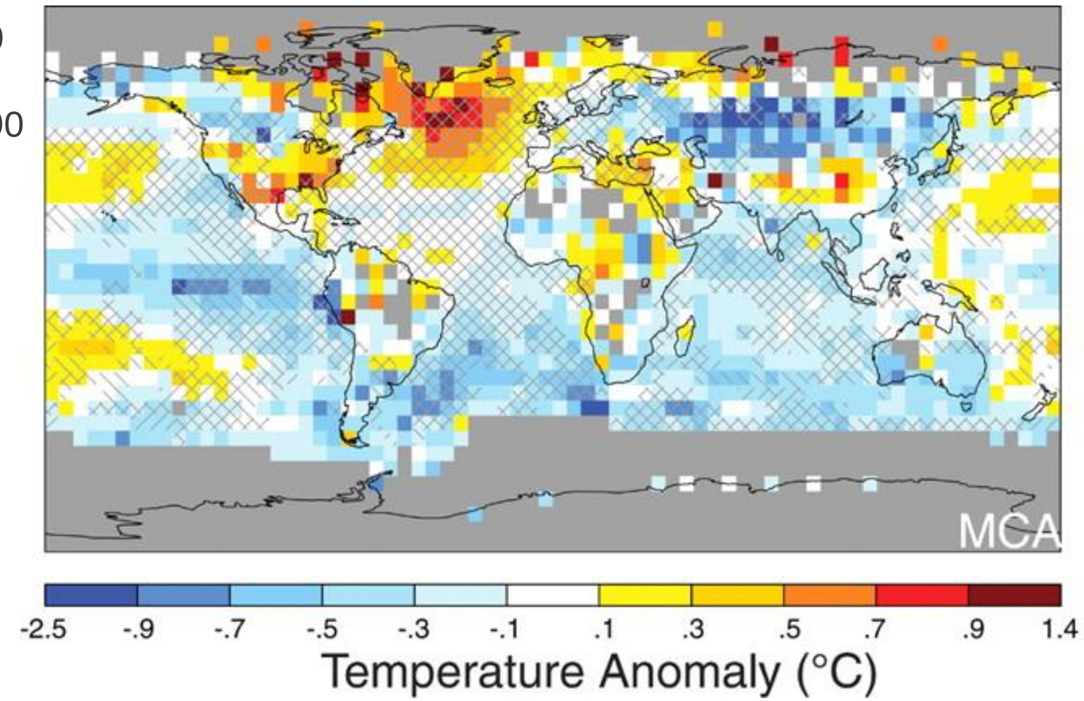
- PAGES2K, 2013, https://www.nature.com/articles/ngeo1797

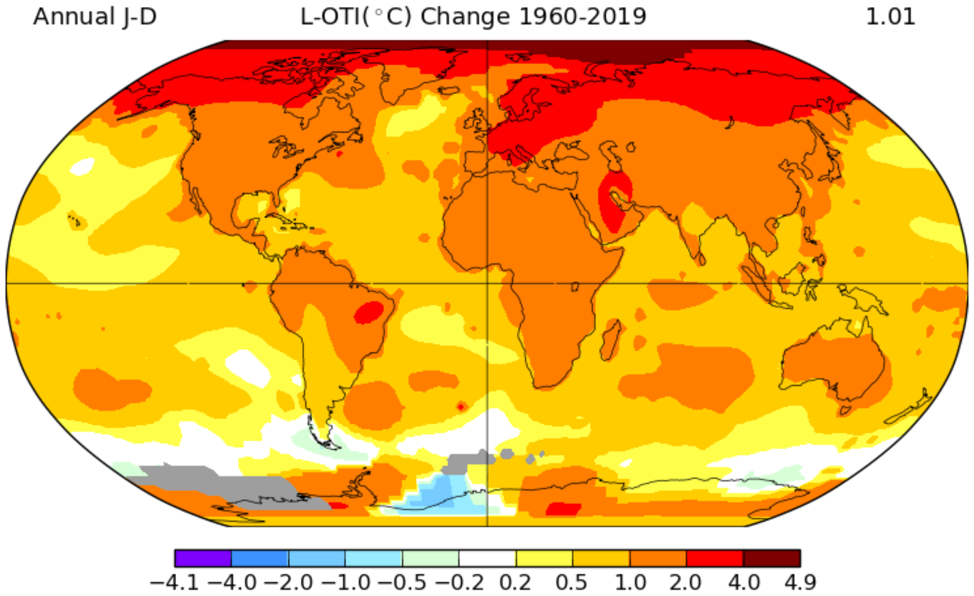
When was Greenland forested?

- There is evidence that southern Greenland was forested 130 to 116 thousand years ago, that is the last interglacial period. More likely it was 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.

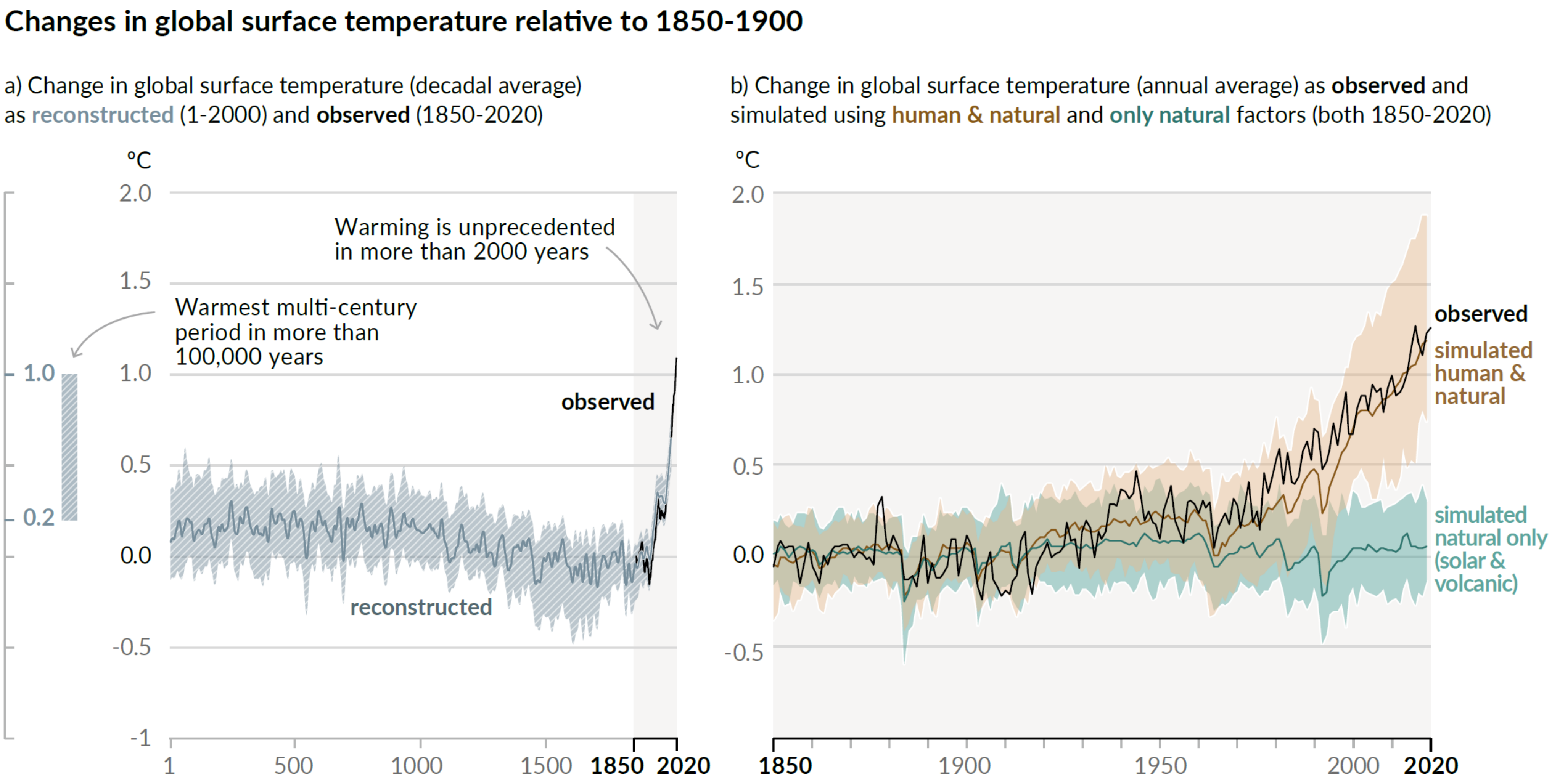
950 – 1250
vs
1961 – 1990





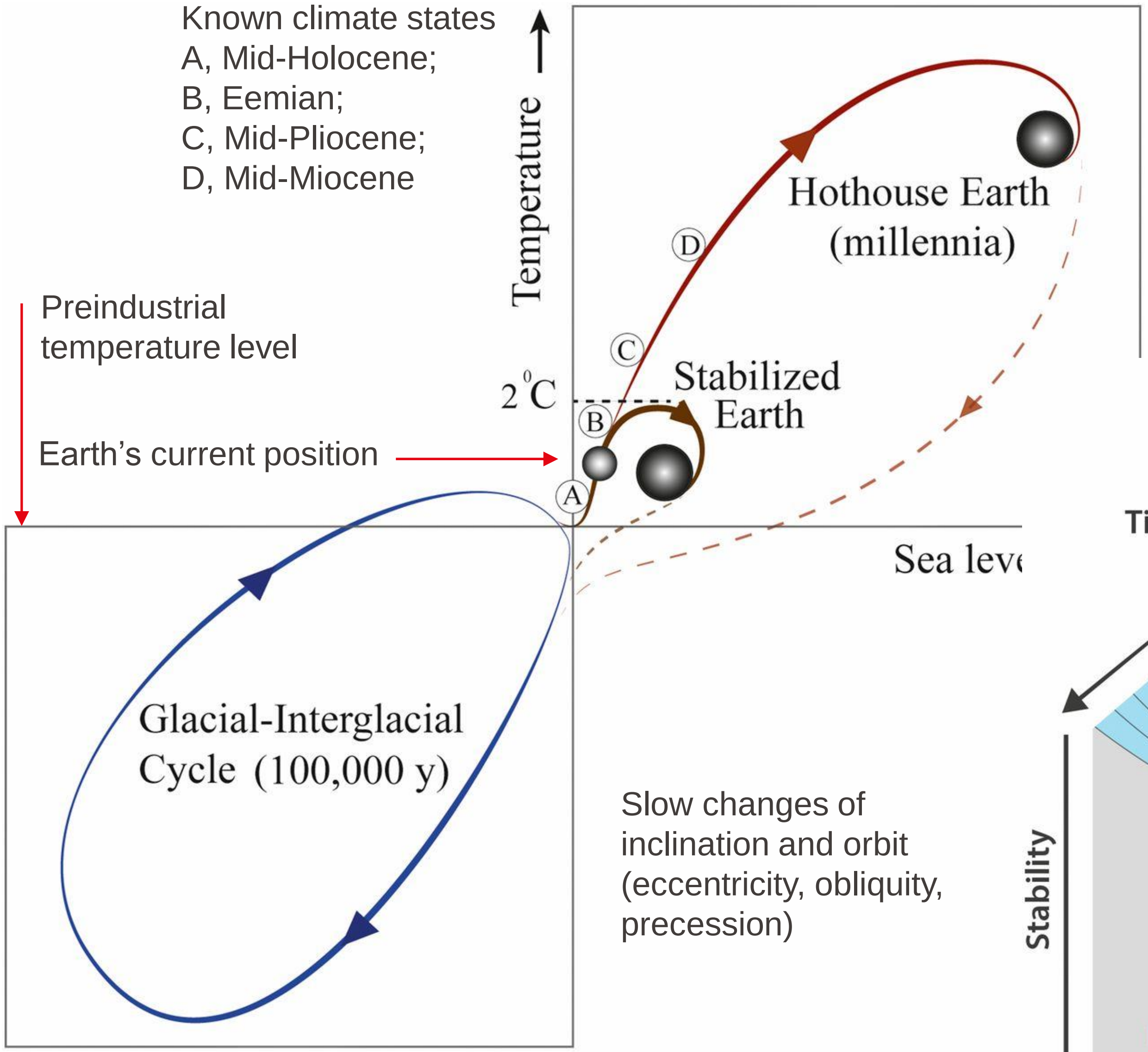
[1] https://www.science.org/doi/full/10.1126/science.1141758; [2] https://www.science.org/doi/10.1126/science.1177303

Today's temperature change

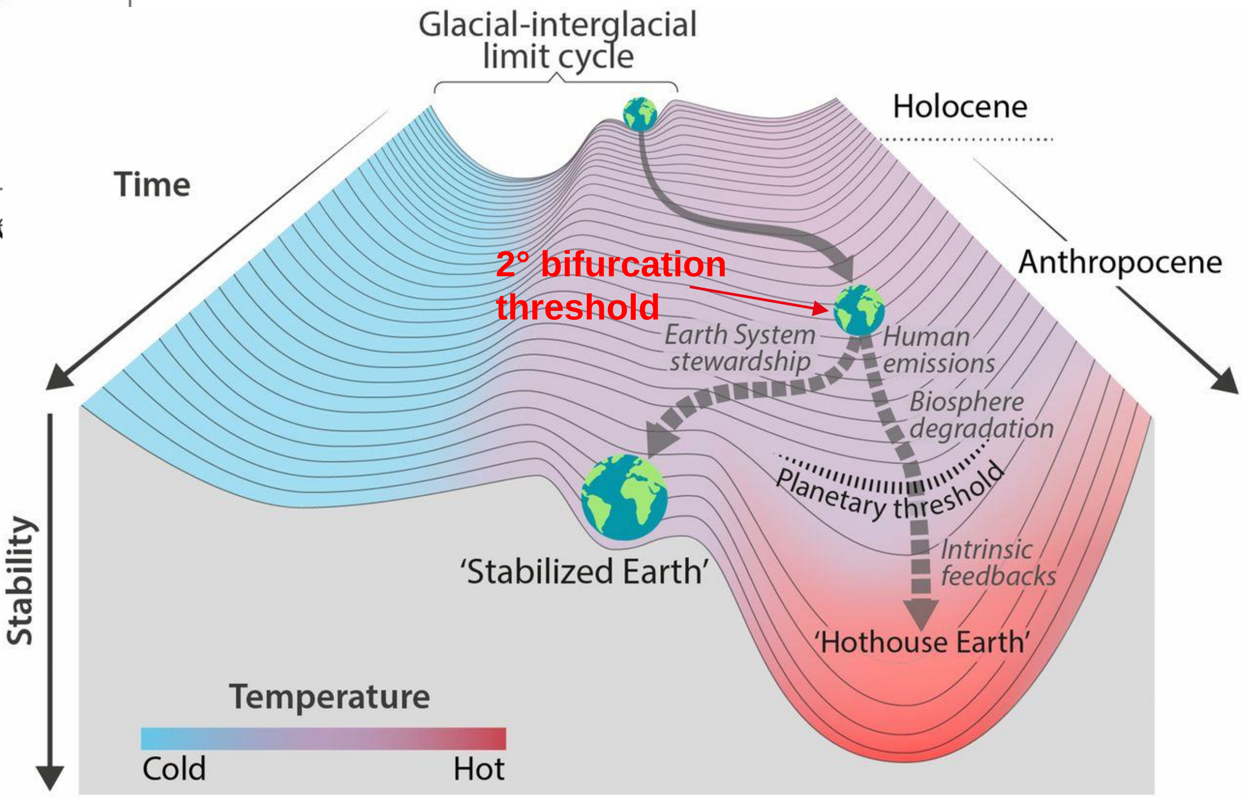


- IPCC, AR6, Figure SPM.1 (2021)

Which trajectory are we on: Ice or hot house?



- **What is forcing our climate and how much?**
- **(How sensitive is Earth to that forcing?)**



Stability landscape

- **Will Steffen et al. PNAS 2018;115:33:8252-8259**

Please watch for next time

- An introduction to atmospheric circulation:

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

See moodle