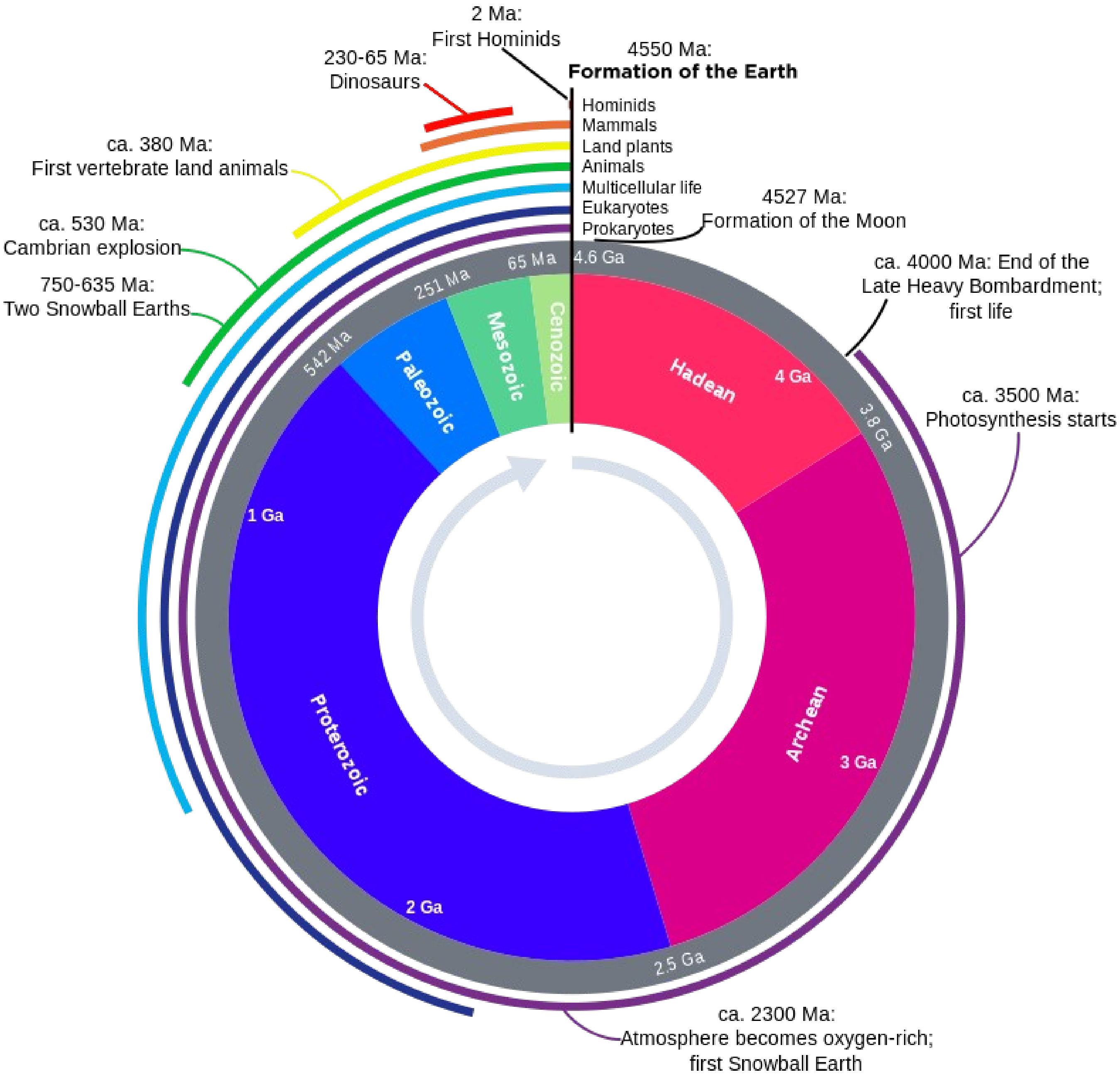
Global warming - physicist's perspective - 03

Szymon P. Malinowski

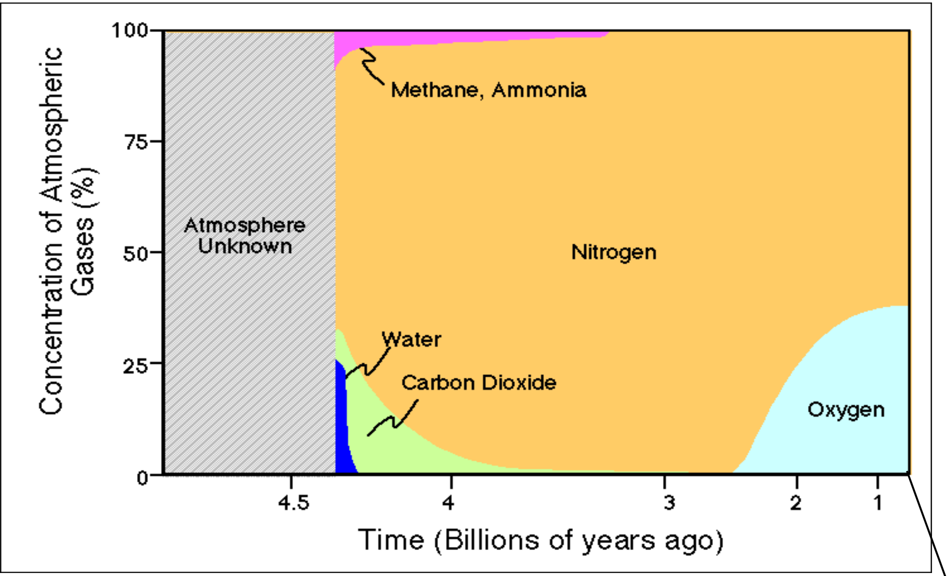
University of Warsaw, Faculty of Physics, Institute of Geophysics

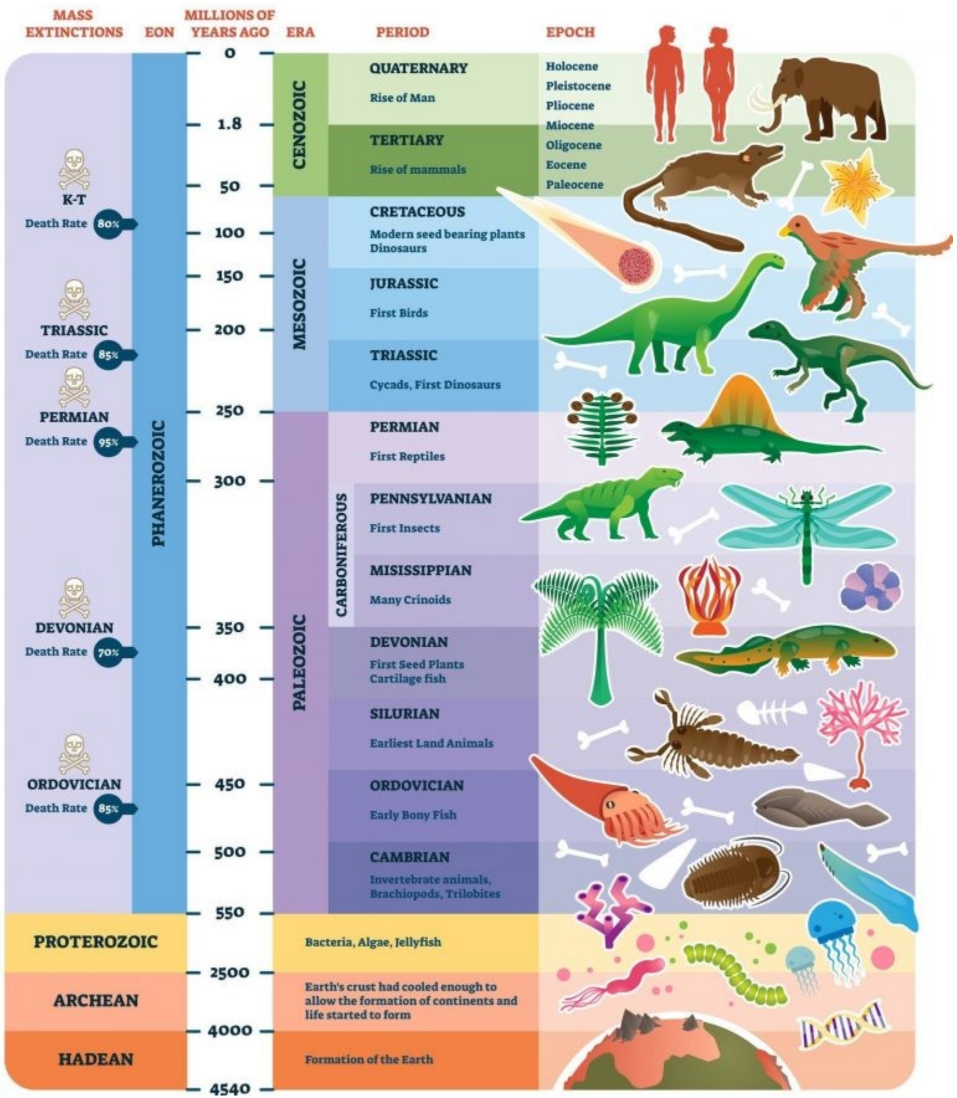
NAUKA O KLIMACIE
DLA SCEPTYCZNYCH

UNIVERSITY
OF WARSAW


2 Ma:
First Hominids
230-65 Ma:
Dinosaurs
4550 Ma:
Formation of the Earth
Hominids
Mammals
Land plants
Animals
Multicellular life
Eukaryotes
Prokaryotes
4527 Ma:
Formation of the Moon
ca. 380 Ma:
First vertebrate land animals
ca. 530 Ma:
Cambrian explosion
750-635 Ma:
Two Snowball Earths
ca. 4000 Ma: End of the
Late Heavy Bombardment;
first life
ca. 3500 Ma:
Photosynthesis starts
ca. 2300 Ma:
Atmosphere becomes oxygen-rich;
first Snowball Earth
65 Ma
4.6 Ga
251 Ma
542 Ma
Cenozoic
Mesozoic
Paleozoic
Hadean
4 Ga
3.8 Ga
Archean
3 Ga
2.5 Ga
Proterozoic
1 Ga
2 Ga

Changes in atmospheric composition and

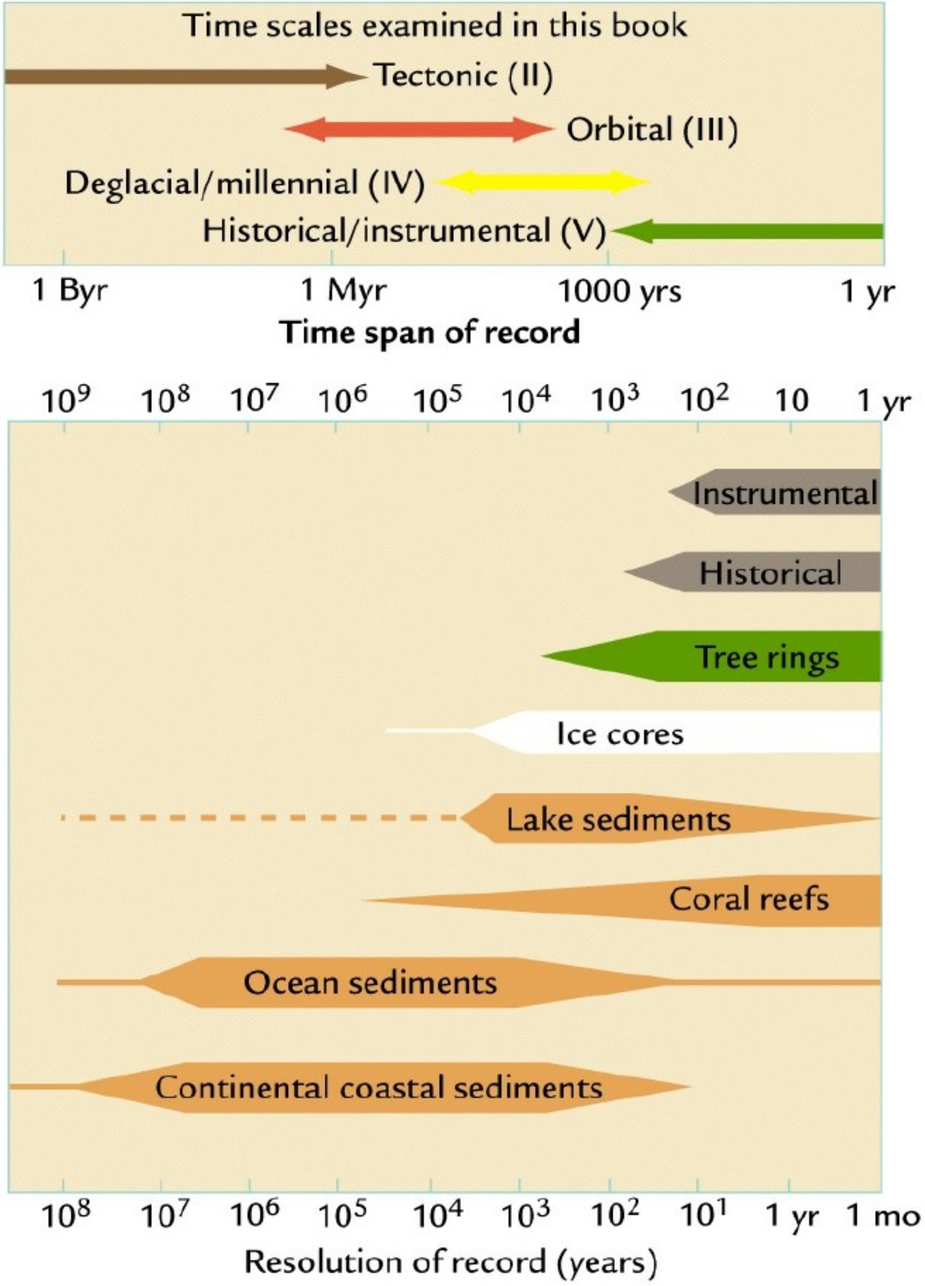




Paleolclimatic data

Dating methods

- 1.1 Radiometric dating
- 1.2 Fission-track dating
- 1.3 Cosmogenic nuclide geochronology
- 1.4 Luminescence dating
- 1.5 Incremental dating
- 1.6 Paleomagnetic dating
- 1.7 Magnetostratigraphy
- 1.8 Chemostratigraphy
- 1.9 Correlation of marker horizons



Radiometric dating

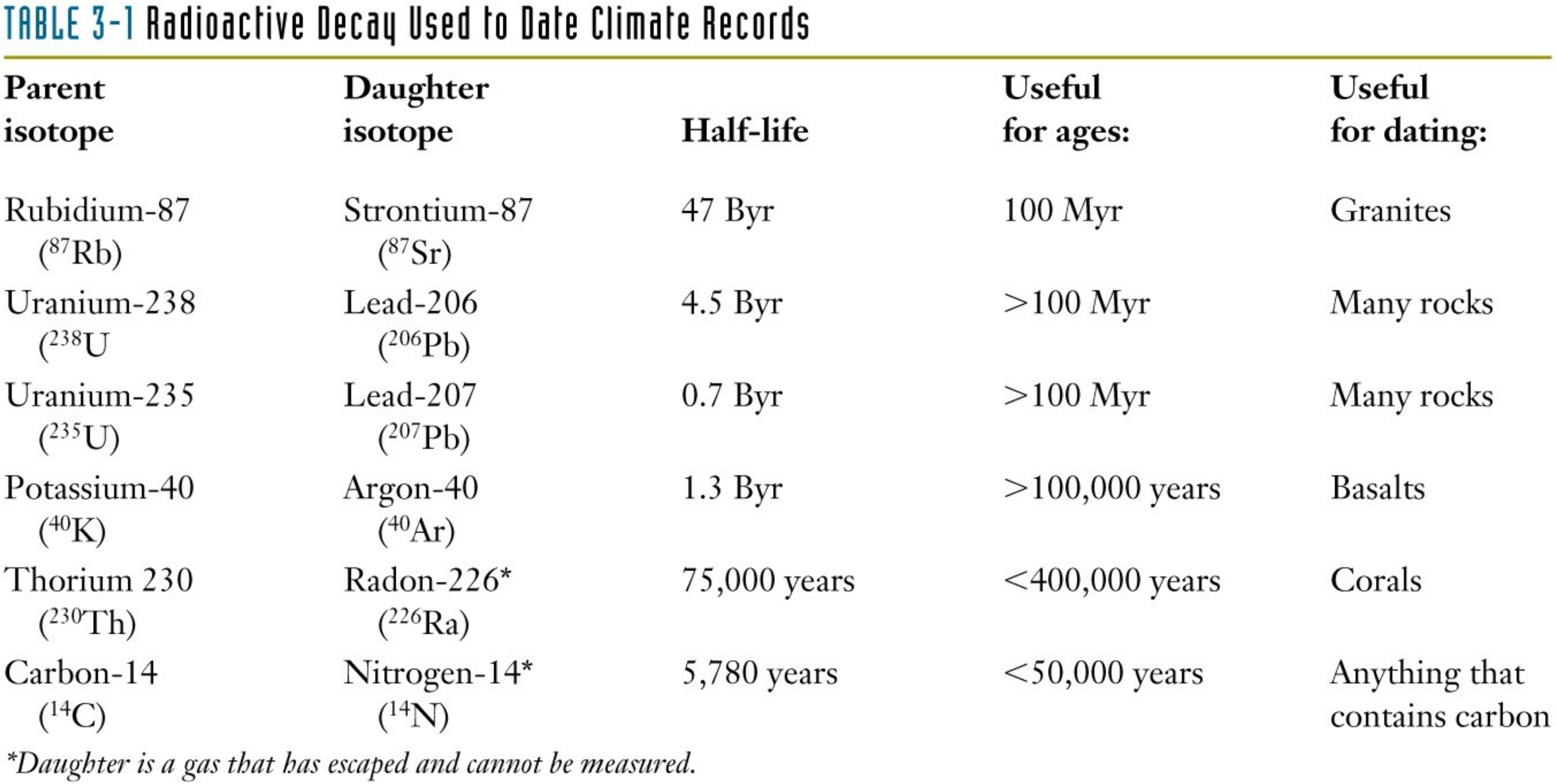


TABLE 3-1 Radioactive Decay Used to Date Climate Records

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

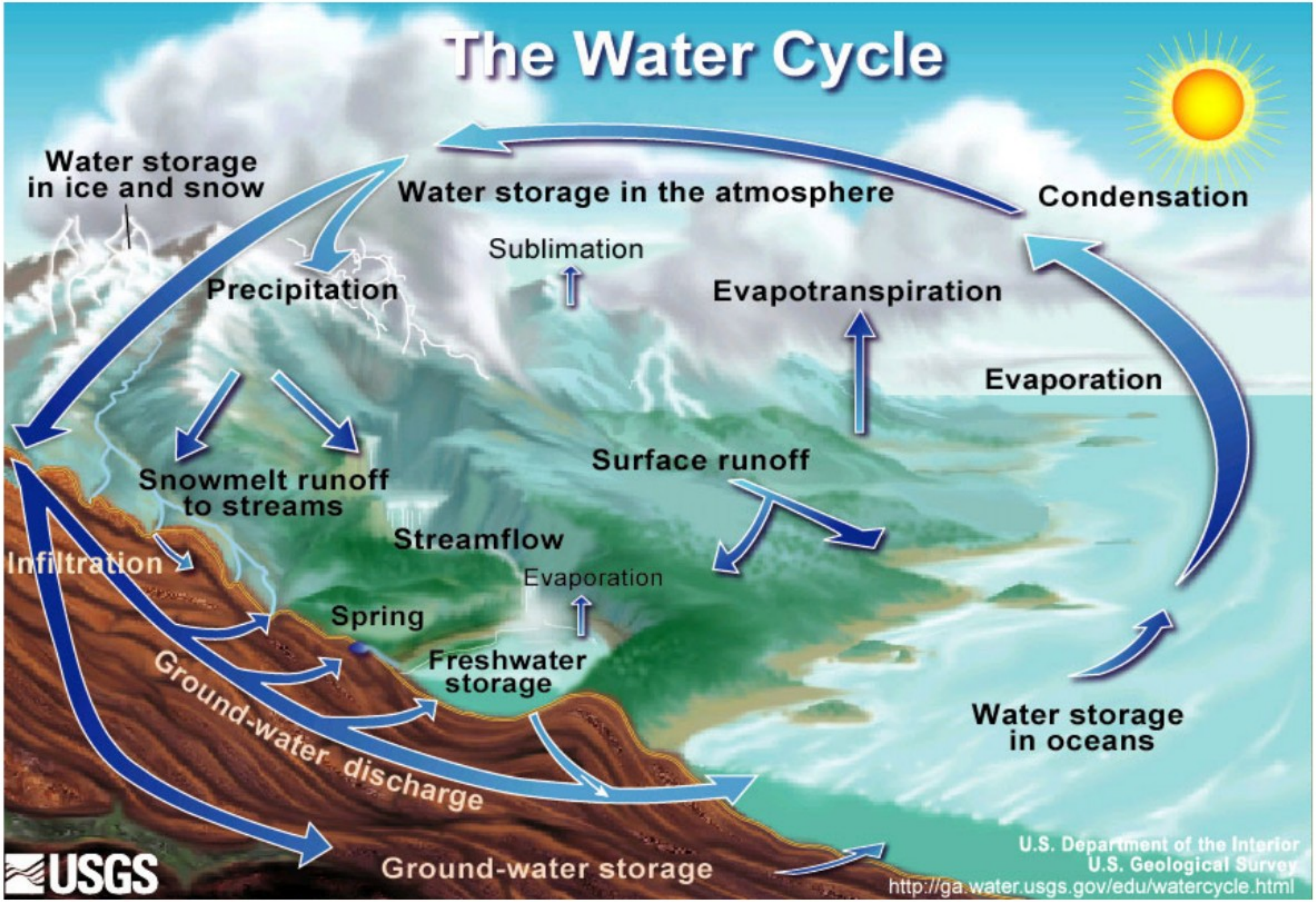
**Daughter is a gas that has escaped and cannot be measured.*

Isotope systematics in the hydrological cycle:

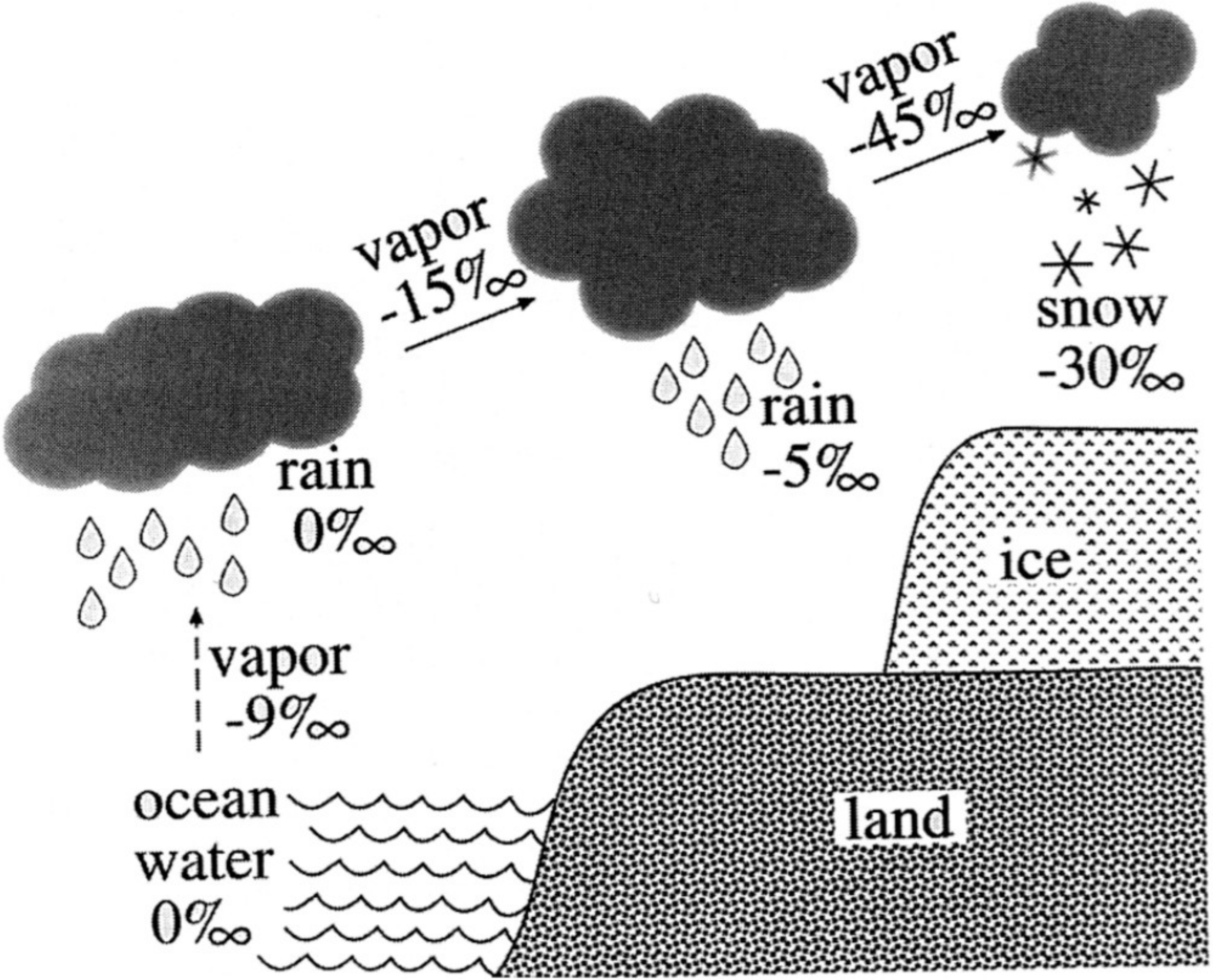
The isotope composition of natural meteoric waters (which form the main reservoirs of freshwater on earth, ice caps, lakes, rivers and groundwater) is determined by three main factors.

- 1) The isotopic composition of the source of the moisture i.e. the ocean, the largest water reservoir on earth.
- 2) Processes of fractionation during evaporation from the ocean.
- 3) Fractionation processes during condensation in the cloud and precipitation to the ground.

δ^{18}O - Tracer of the water cycle



Isotope water cycle

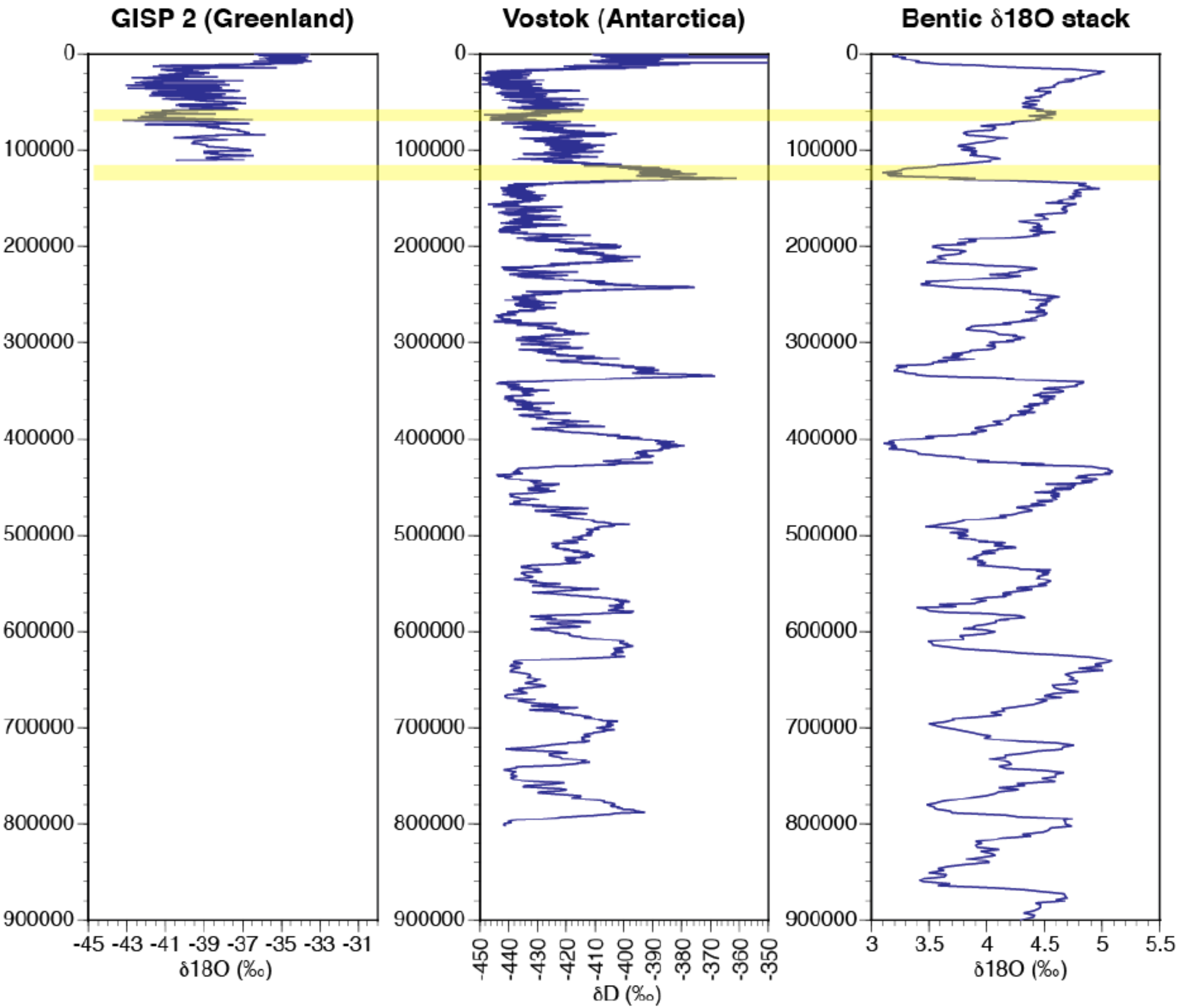


$\delta^{18}O$ signal in different climate archives

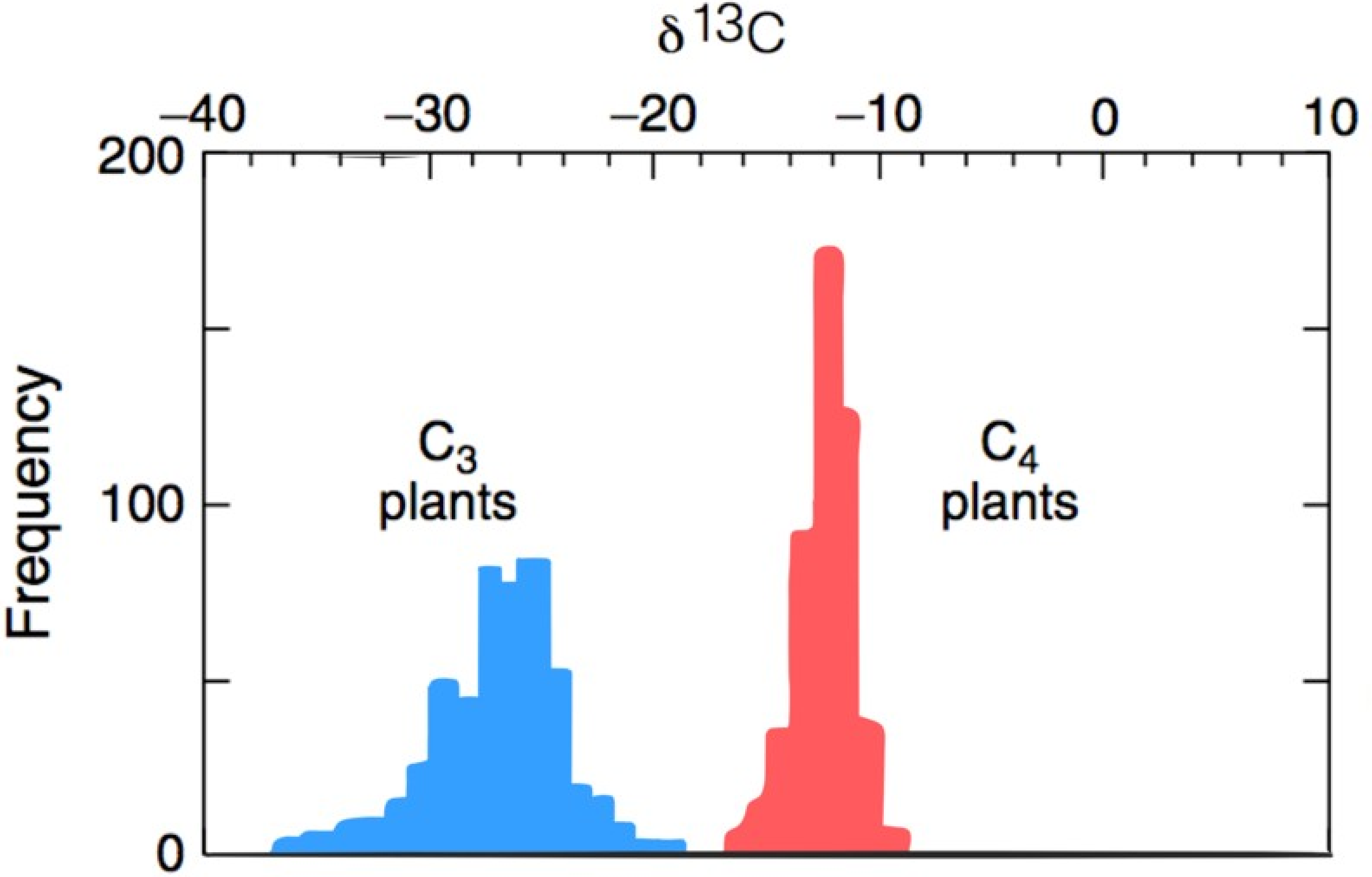
- $H_2{}^{16}O$

Abundance:

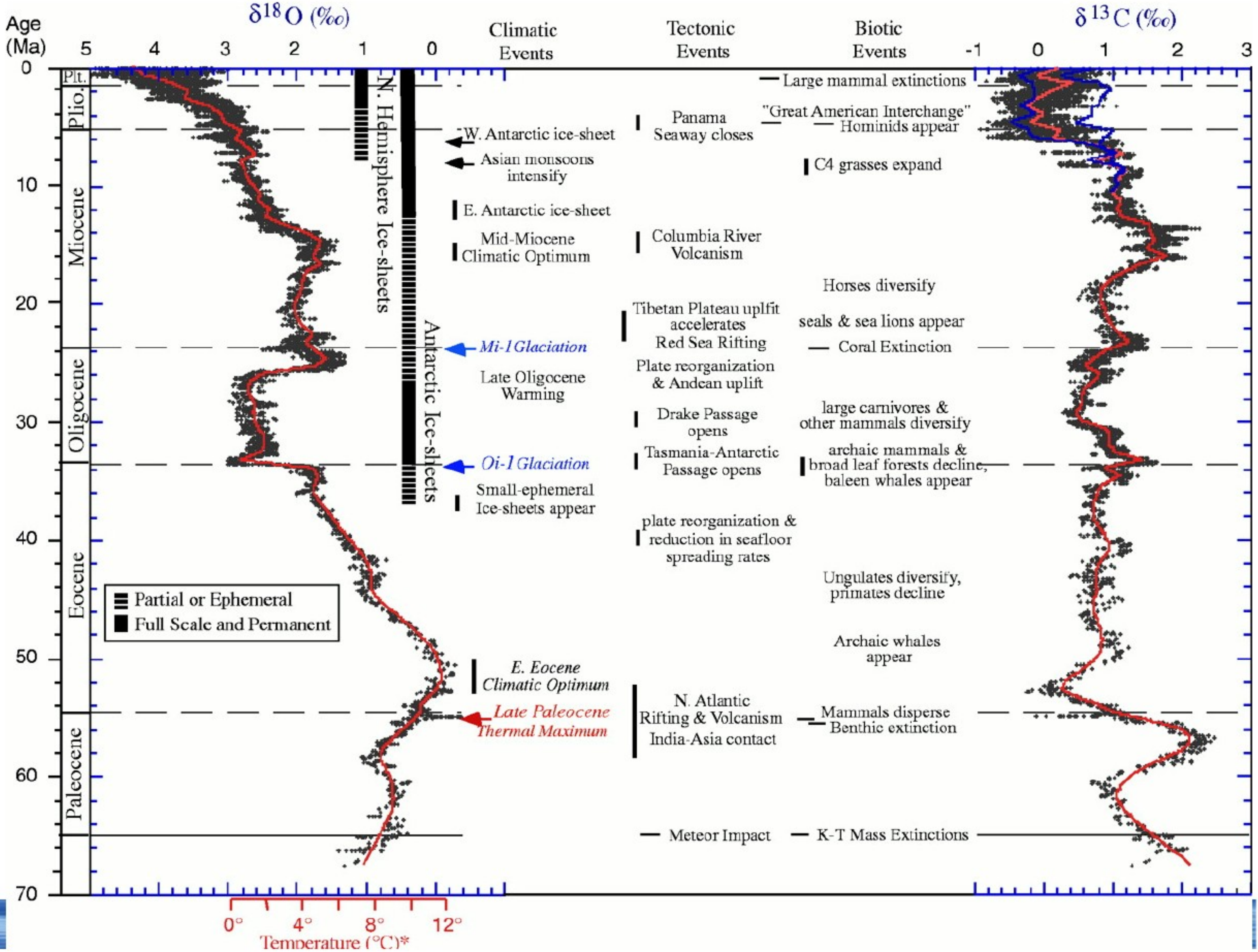
- ^{16}O = 99.7621
  ^{17}O = 0.03790
  ^{18}O = 0.20004
- H = 99.9844
  D = 0.01557



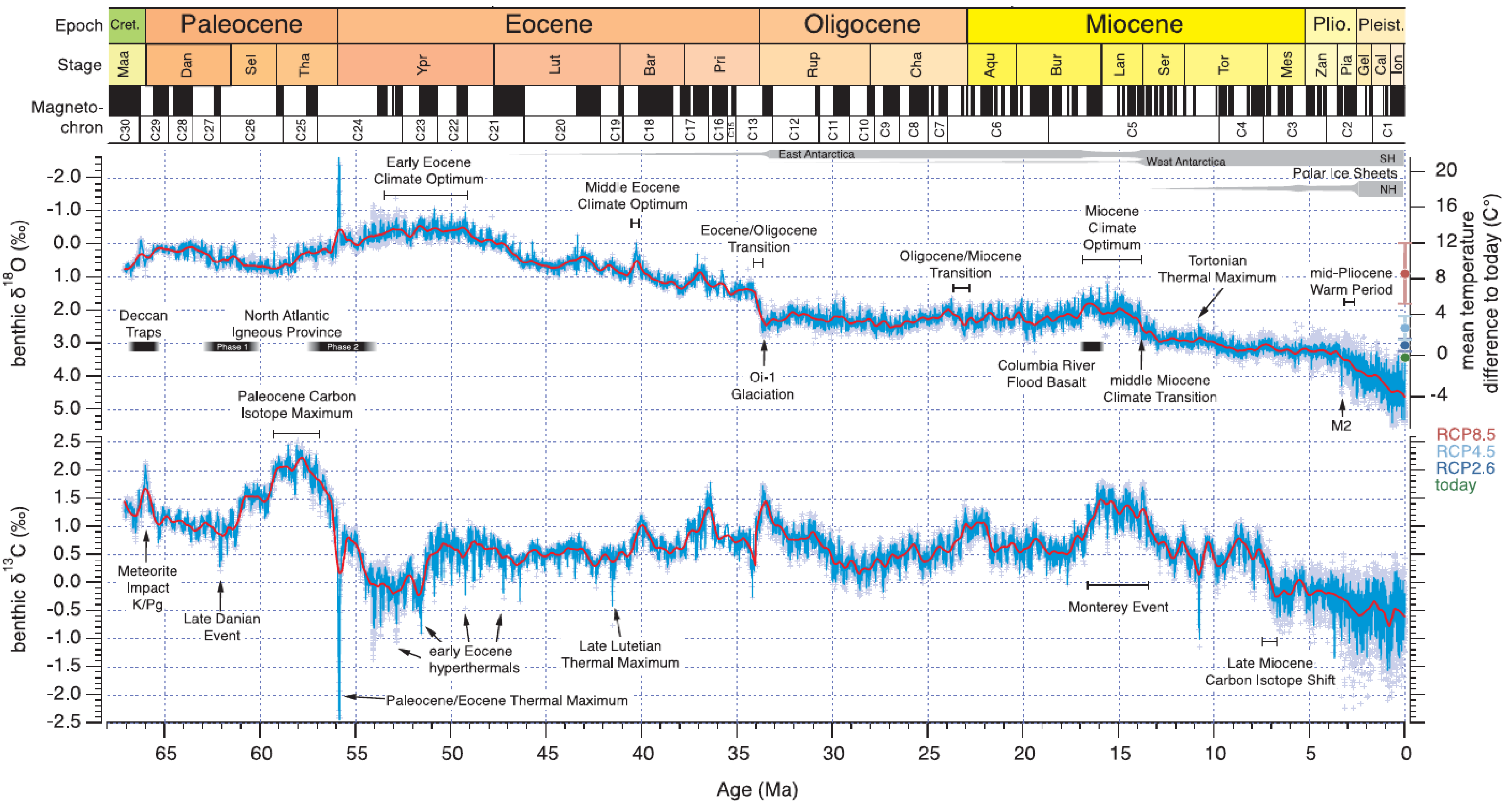
Reduced amount of carbon stable isotope ^{13}C in plants depending on photosynthesis type.



Long-term $\delta^{18}O$ evolution



Zachos et al, 2001, Science, v.292, p.686



Westerhold, T., N Marwan, AJ Drury, D Liebrand, C Agnini, E Anagnostou, JSK Barnet, SM Bohaty, D Vleeschouwer, F Florindo, T Frederichs, DA Hodell, AE Holbourn, D Kroon, V Lauretano, K Littler, LJ Lourens, M Lyle, H Pälike, U Röhl, J Tian, RH Wilkens, PA Wilson, JC Zachos, 2020, An astronomically dated record of Earth's climate and its predictability over the last 66 Million Years, Science, v. 369, Issue 6509, pp. 1383-1387. DOI: 10.1126/science.aba6853

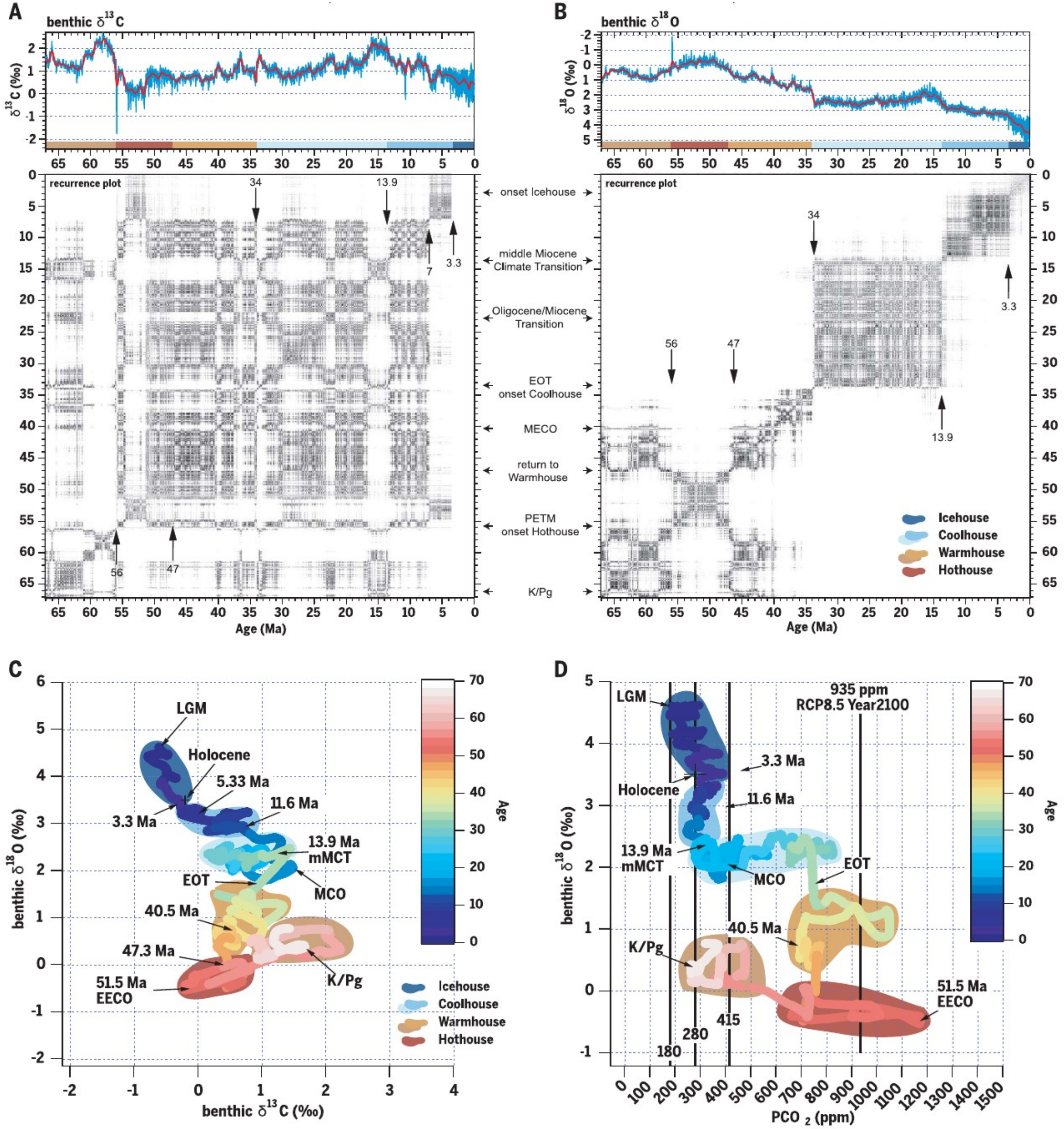
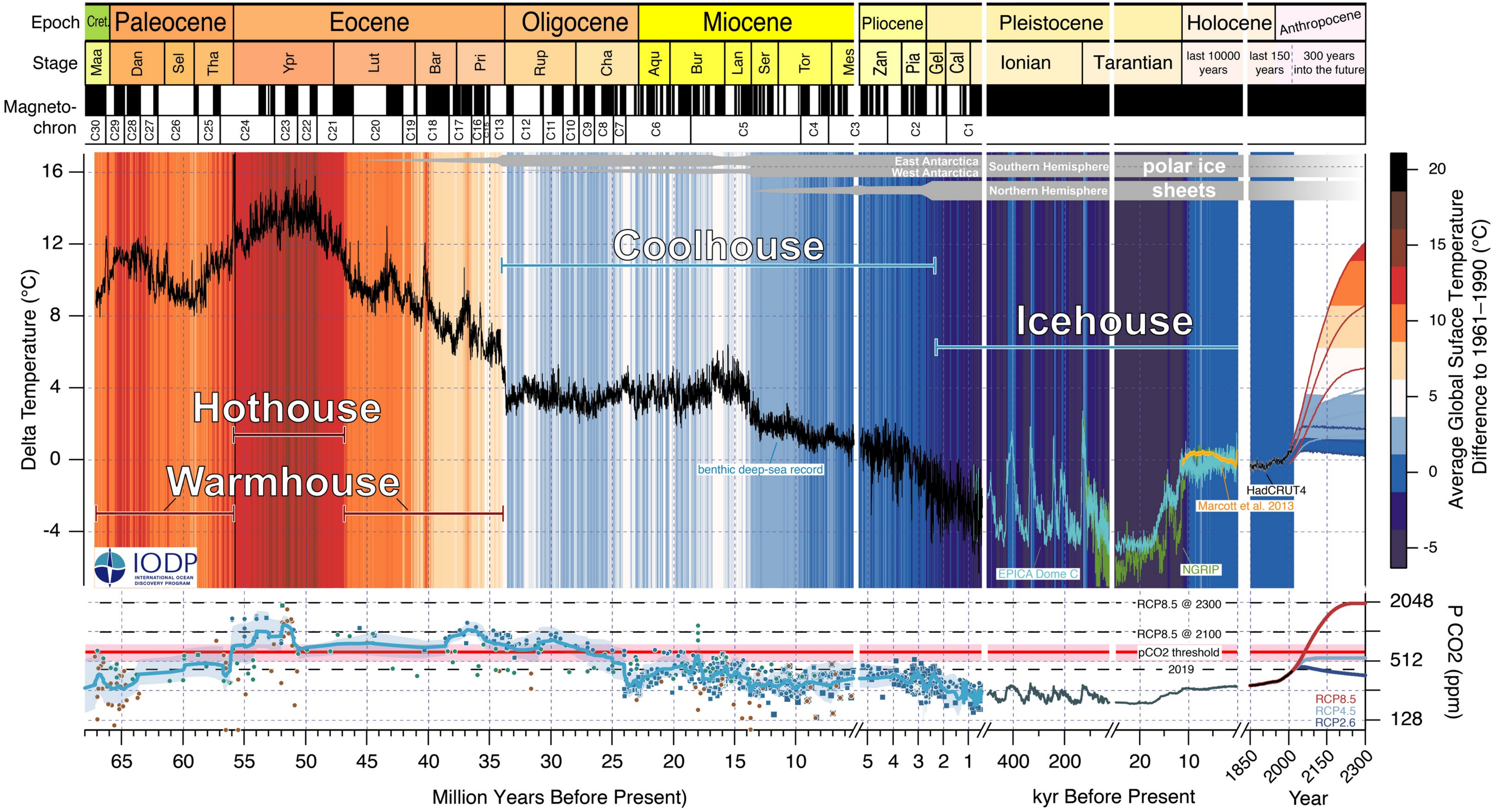
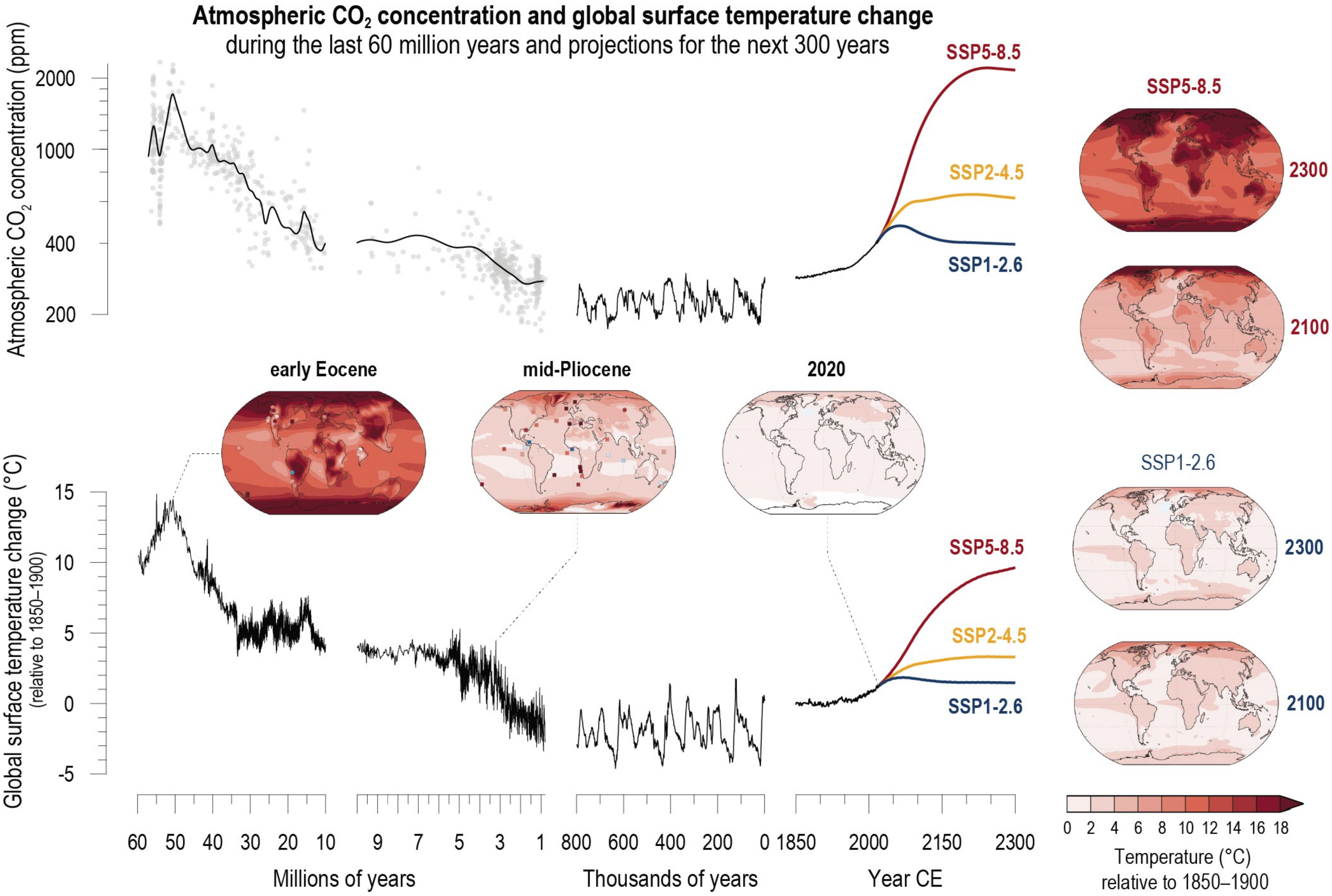


Fig. 2. Climate states of the Cenozoic. Deep-sea benthic foraminifer high-resolution carbon (A) and oxygen (B) isotope records and the respective recurrence plots as well as scatterplots of long-term benthic foraminifer carbon versus oxygen values (C) and oxygen values versus atmospheric CO2 concentrations (D).



https://websites.pmc.ucsc.edu/~jzachos/images/CENOGRID_Cartoon_withProjection_alternate.png



Atmospheric CO_2 concentration and global surface temperature change
during the last 60 million years and projections for the next 300 years

https://www.ipcc.ch/report/ar6/wg1/figures/technical-summary

RESEARCH ARTICLE | PALEOCLIMATE

A 485-million-year history of Earth's surface temperature

EMILY J. JUDD, JESSICA E. TIERNEY, DANIEL J. LUNT, ISABEL P. MONTAÑEZ, BRIAN T. HUBER, SCOTT L. WING, AND PAUL J. VALDES Authors Info & Affiliations

SCIENCE • 20 Sep 2024 • Vol 385, Issue 6715 • DOI: 10.1126/science.adk3705

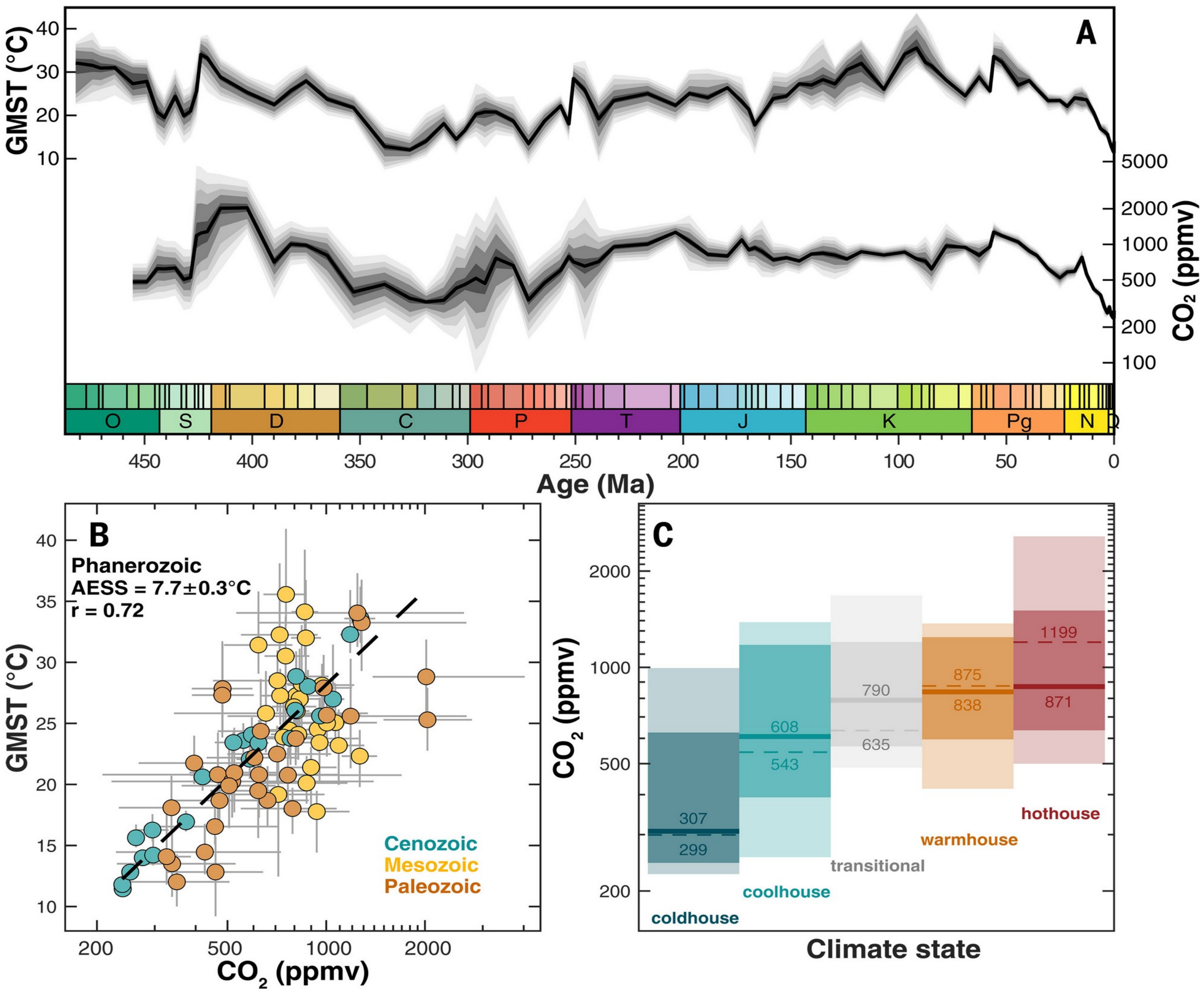


Fig. 4. The relationship between Phanerozoic temperature and atmospheric CO2.

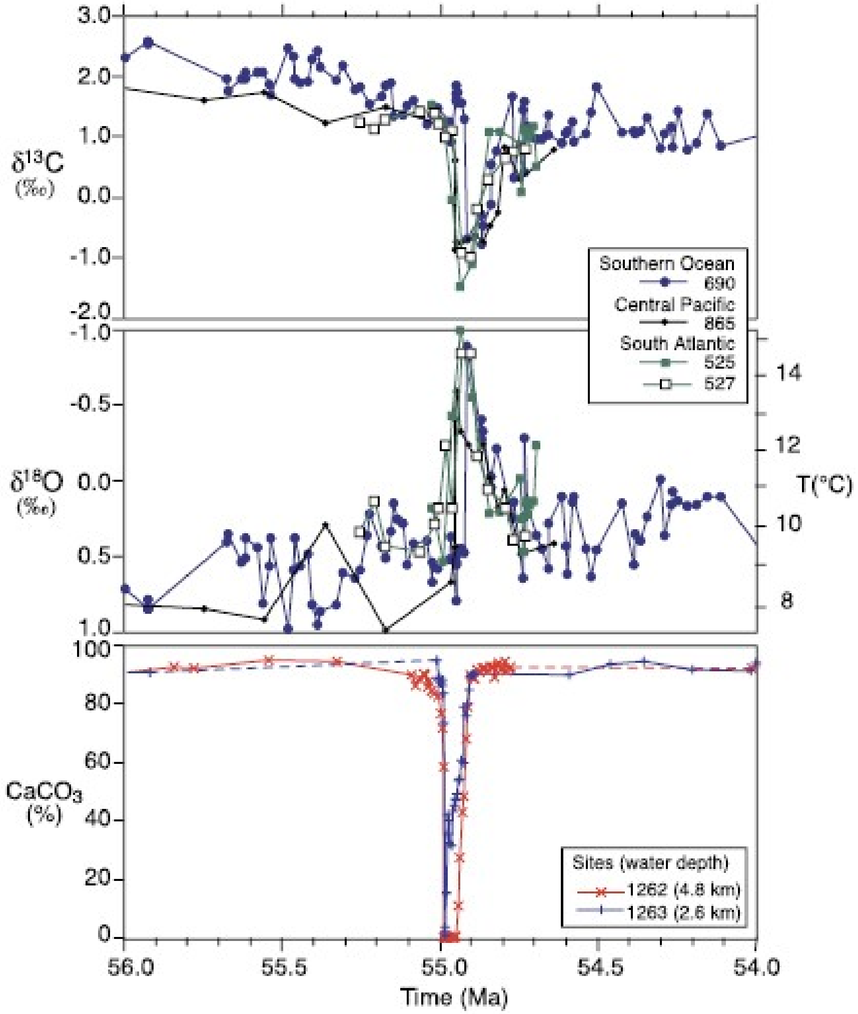
(A) PhanDA GMST (top) and reconstructed atmospheric CO2 (bottom), resolved at the stage level. The CO2 reconstruction (29) is largely based on the data from Foster et al. (2017) (78) in the Paleozoic and Mesozoic, and the data from Rae et al. (2021) (80) in the Cenozoic. Shading reflects percentiles.

(B) PhanDA GMST versus CO2, color-coded by geologic era. The York regression (86), which accounts for uncertainty in both the predictor and response variables, is shown by the black dashed line.

(C) CO2 ranges for each of the climate states defined in Fig. 3. Light and dark bands show the 5th to 95th and 16th to 84th percentiles, respectively. The thick solid line shows the median value, and the dashed line shows the median, excluding data from the Mesozoic, where CO2 is more uncertain.

- Long-term (> 10s of millions of years to 4.6Gyr) climate history information can come from geology.
- Oxygen isotopes ($\delta^{18}O$) from carbonate ($CaCO_3$) can be used as a paleotemperature proxy.
- Can also use similar techniques to measure ancient carbon dioxide levels.
- Earth has only had polar ice for ~15% of its history; frequently there is sufficient equator-to-pole heat transport to allow palm trees at the poles.
- Specific example: Snowball Earth, when Earth froze over 600 Myr ago.
- Snowball Earths are reversed by build up of carbon dioxide, and are followed by global hothouses when the ice melts.
- Earth's climate history is a total roller coaster on 10 million year to billion year timescales.

Abrupt Climate Change – example: PETM

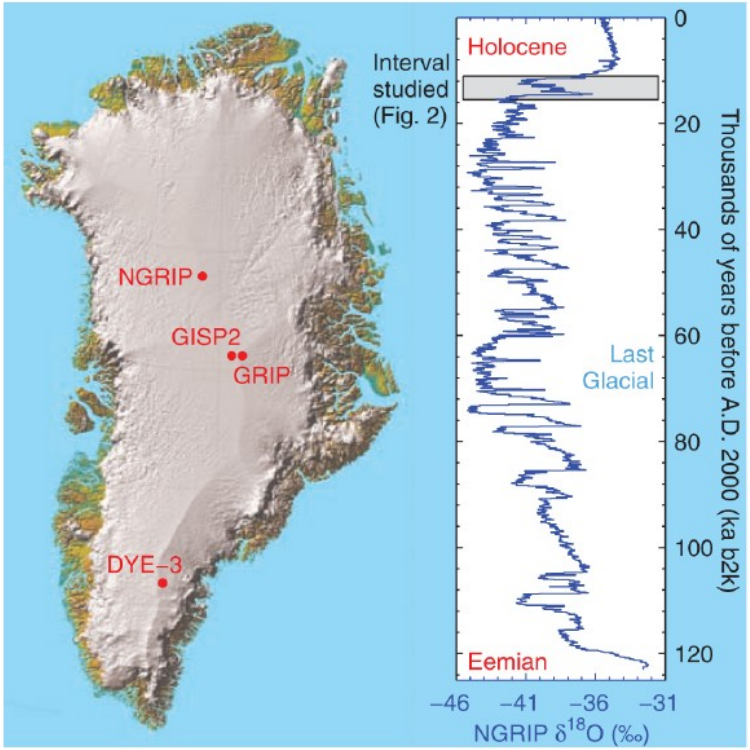


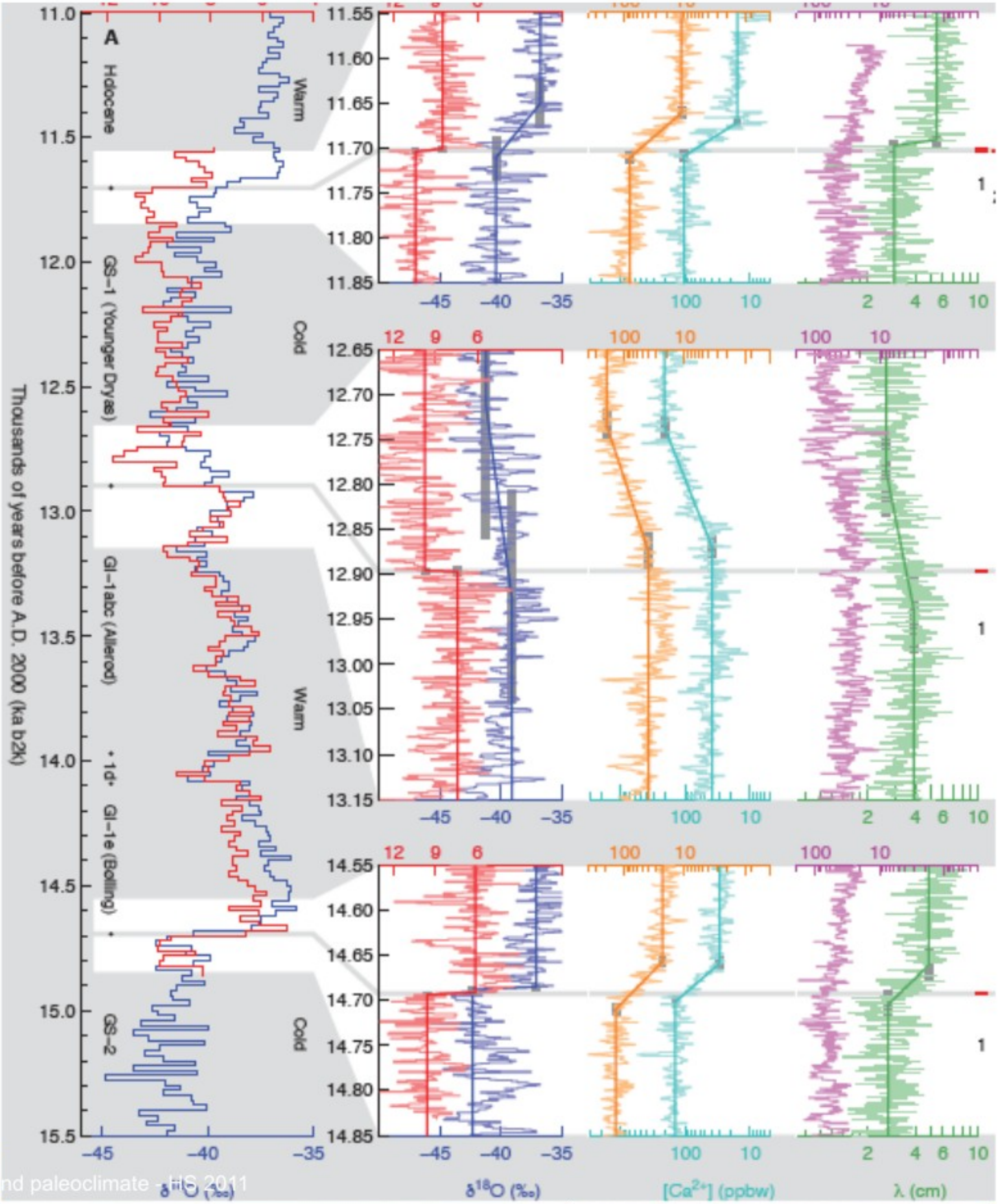
The Palaeocene-Eocene Thermal Maximum as recorded in benthic (bottom dwelling) foraminifer (Nuttallides truempyi) isotopic records from sites in the Antarctic, south Atlantic and Pacific (see Zachos et al., 2003 for details). The rapid decrease in carbon isotope ratios in the top panel is indicative of a large increase in atmospheric greenhouse gases CO2 and CH4 that was coincident with an approximately 5°C global warming (centre panel). Using the carbon isotope records, numerical models show that CH4 released by the rapid decomposition of marine hydrates might have been a major component (~2,000 GtC) of the carbon flux (Dickens and Owen, 1996).

IPCC 2007

Application in ice cores
Abrupt climate change

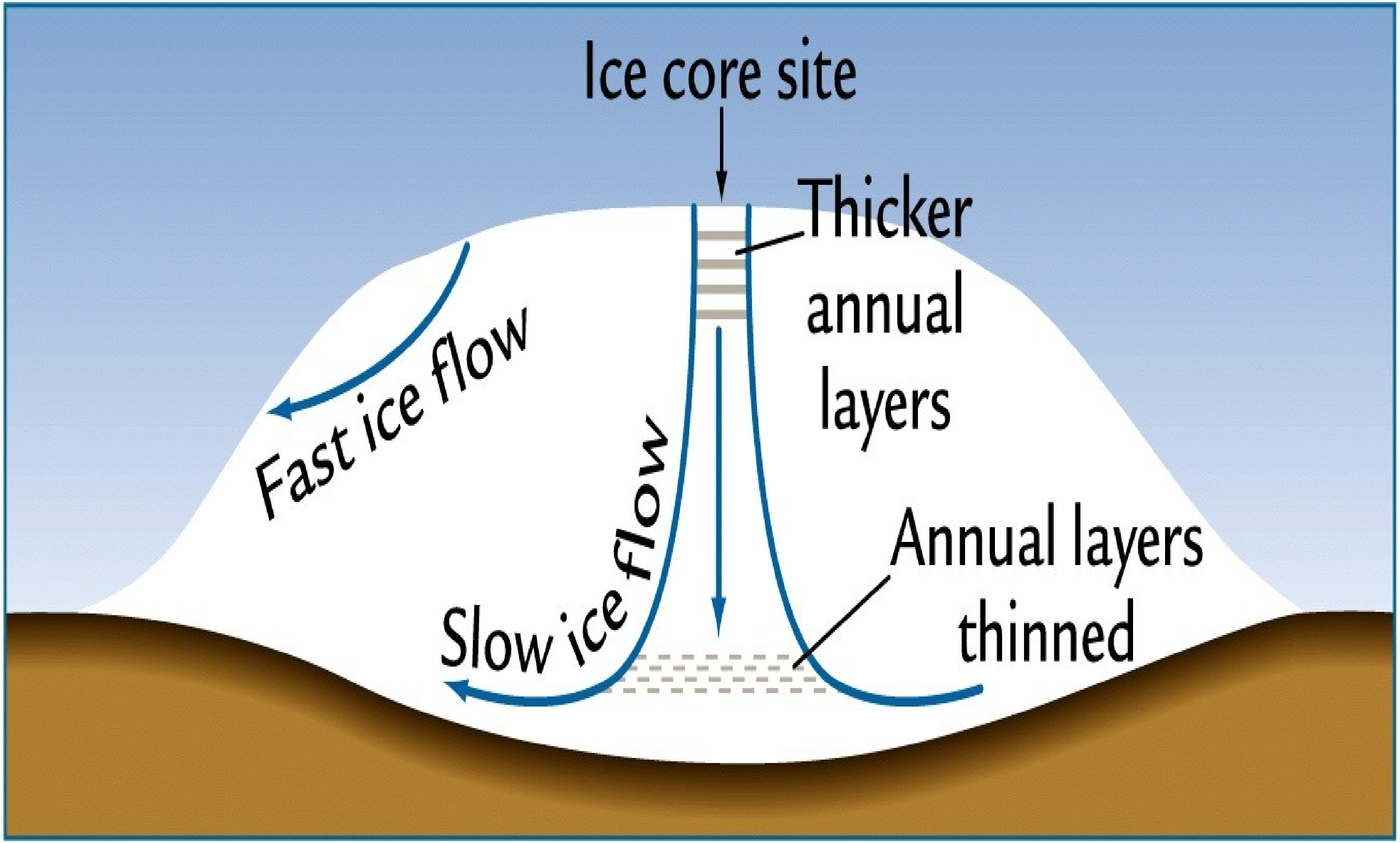
- Study the long ice record in Greenland

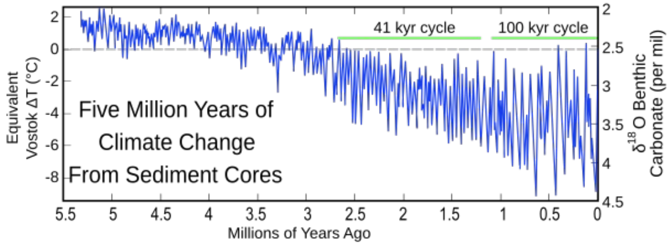




Steffensen et al, Science, 321, 1. August 2008

Ice Cores and Ice Sheet Flow





MIS - marine Isotopic Stages,
minima of $\delta^{18}O$

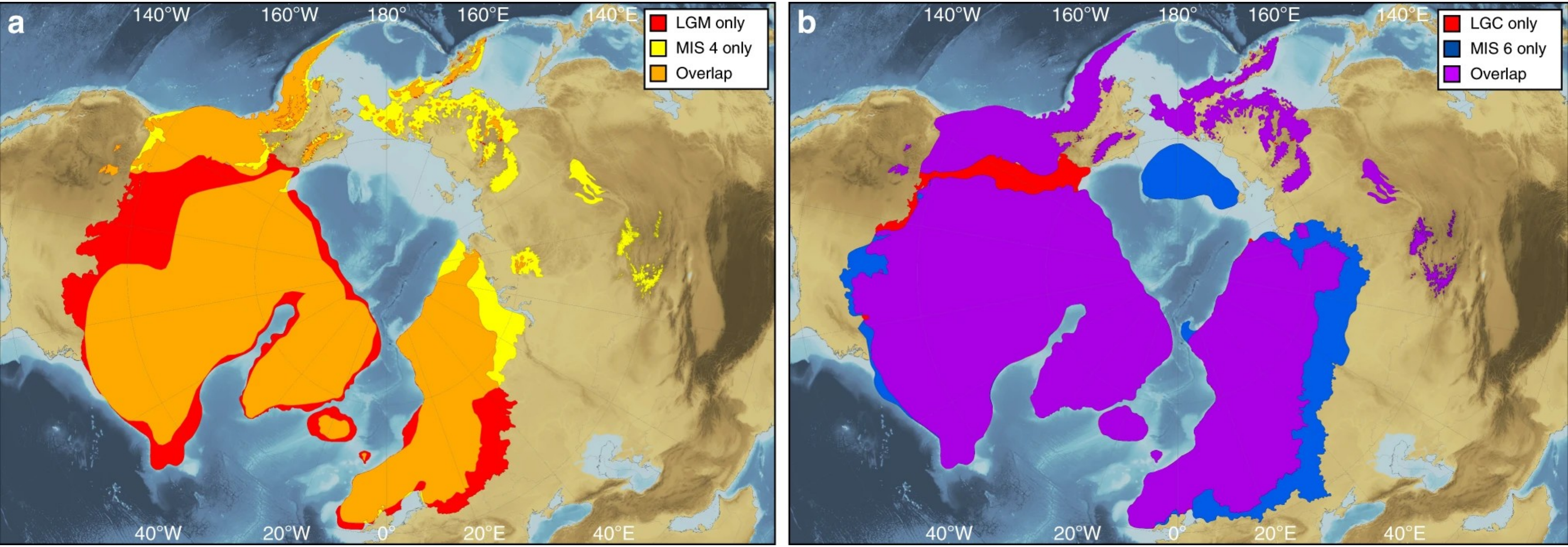

nature › nature communications › articles › article

Article | Open access | Published: 16 August 2019

The configuration of Northern Hemisphere ice sheets through the Quaternary

Christine L. Batchelor, Martin Margold, Mario Krapp, Della K. Murton, April S. Dalton, Philip L. Gibbard, Chris R. Stokes, Julian B. Murton & Andrea Manica

Nature Communications **10**, Article number: 3713 (2019) | Cite this article

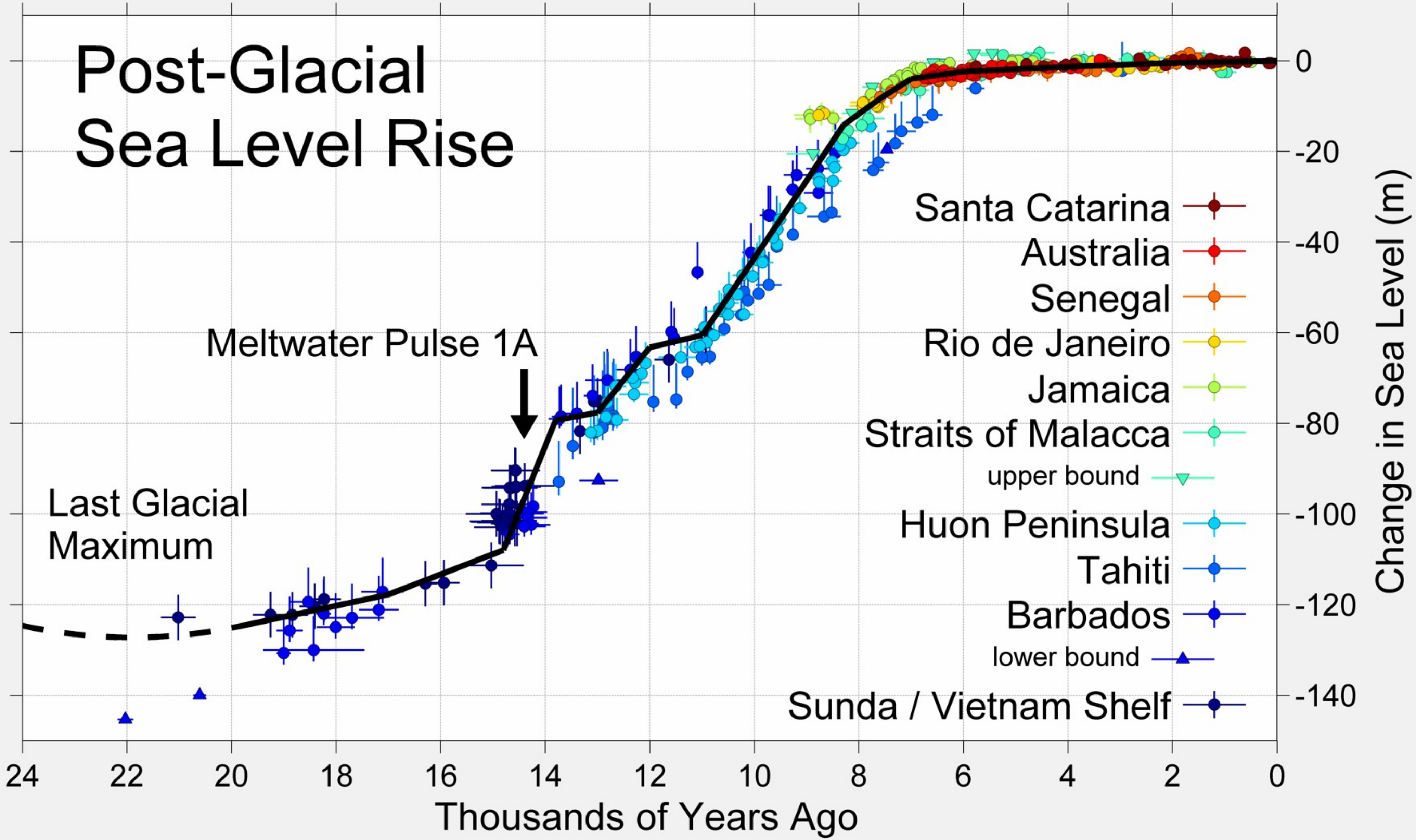


Comparison of NH ice-sheet extent during the last glacial cycle and MIS 6.

a shows a comparison of the reconstructed ice-sheet extent during the LGM and MIS 4.

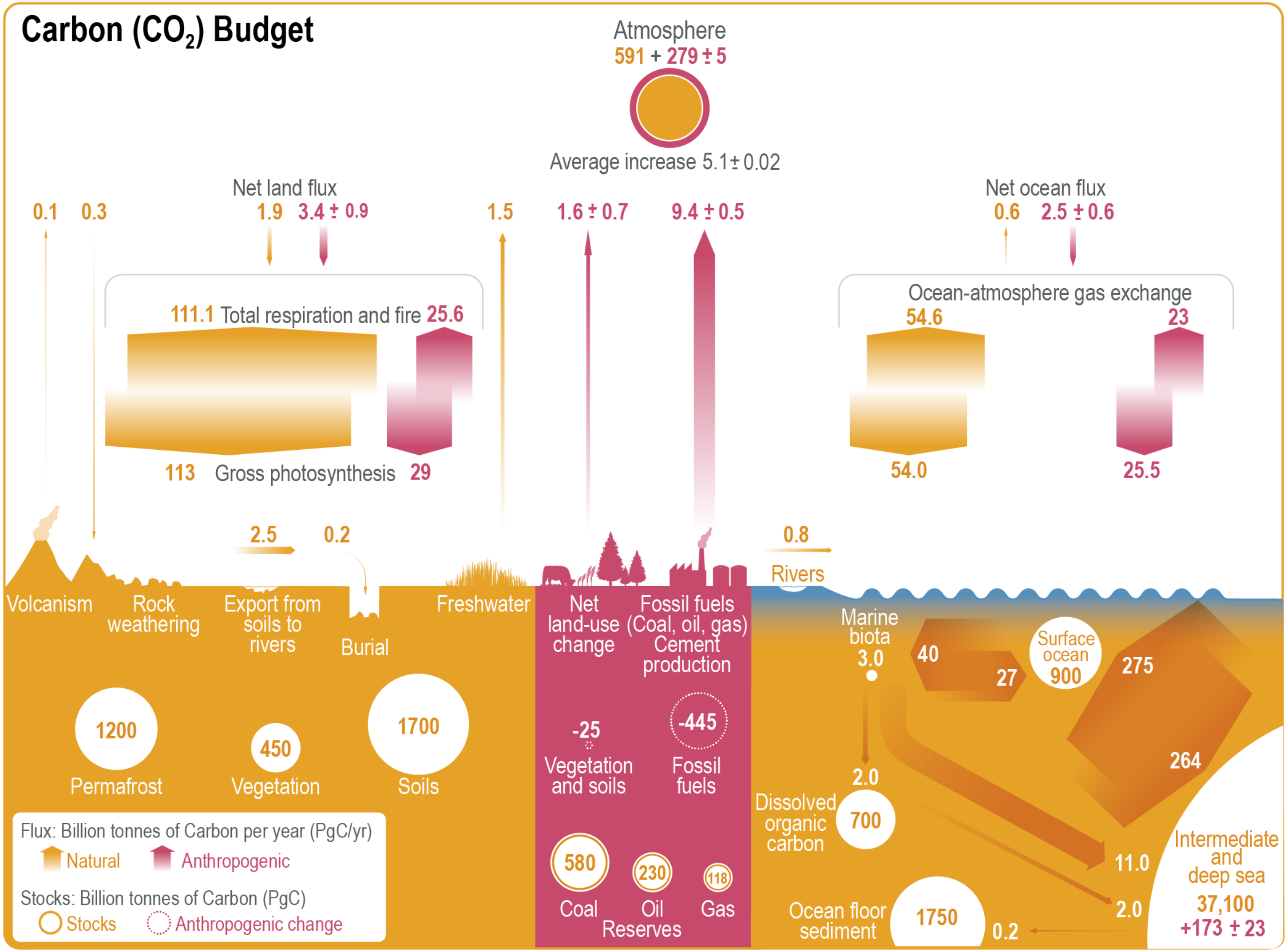
The orange fill shows areas that were covered by ice sheets during both the LGM and MIS 4.

b shows a comparison of the reconstructed geographical maximum ice-sheet extent during the last glacial cycle (MIS 2–5d) and MIS 6. The purple fill shows areas that were covered by ice sheets during both the last glacial cycle (LGC) and MIS 6. Background is ETOPO1 1 arc-minute global relief model of the Earth’s surface[72]


Post-Glacial
Sea Level Rise
Meltwater Pulse 1A
Last Glacial
Maximum
Santa Catarina
Australia
Senegal
Rio de Janeiro
Jamaica
Straits of Malacca
upper bound
Huon Peninsula
Tahiti
Barbados
lower bound
Sunda / Vietnam Shelf
0
-20
-40
-60
-80
-100
-120
-140
Change in Sea Level (m)
24
22
20
18
16
14
12
10
8
6
4
2
0
Thousands of Years Ago

Carbon in climate system

(IPCC 2021)



Volcanic C
Global Ca

Sustainable and Rene
Occasional Publicati

5 Present day volcanic carbon flux estimates

Terrestrial volcanism occurs within both the hydrosphere and atmosphere. Submarine and subaerial volcanism originate almost entirely within different tectonic environments (as outlined above), tapping different, although not entirely exclusive volatile sources, shown schematically in Figure 2, below.

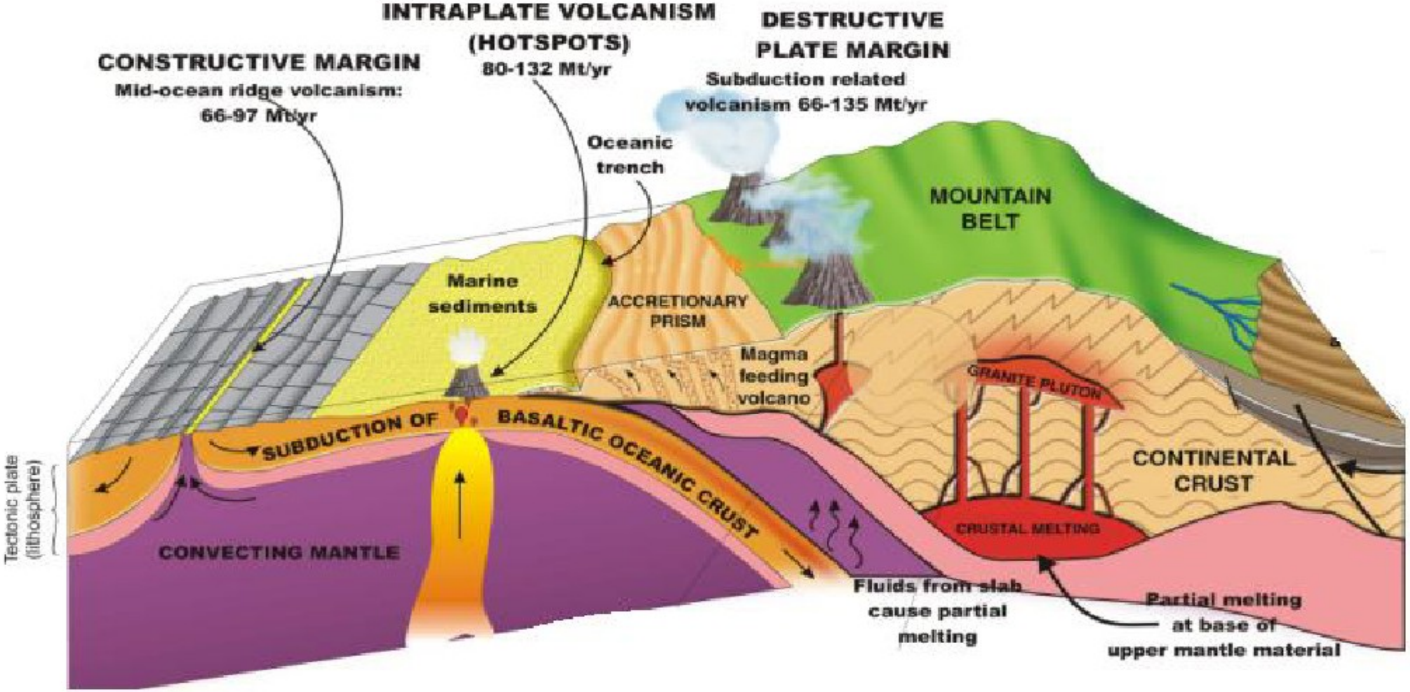
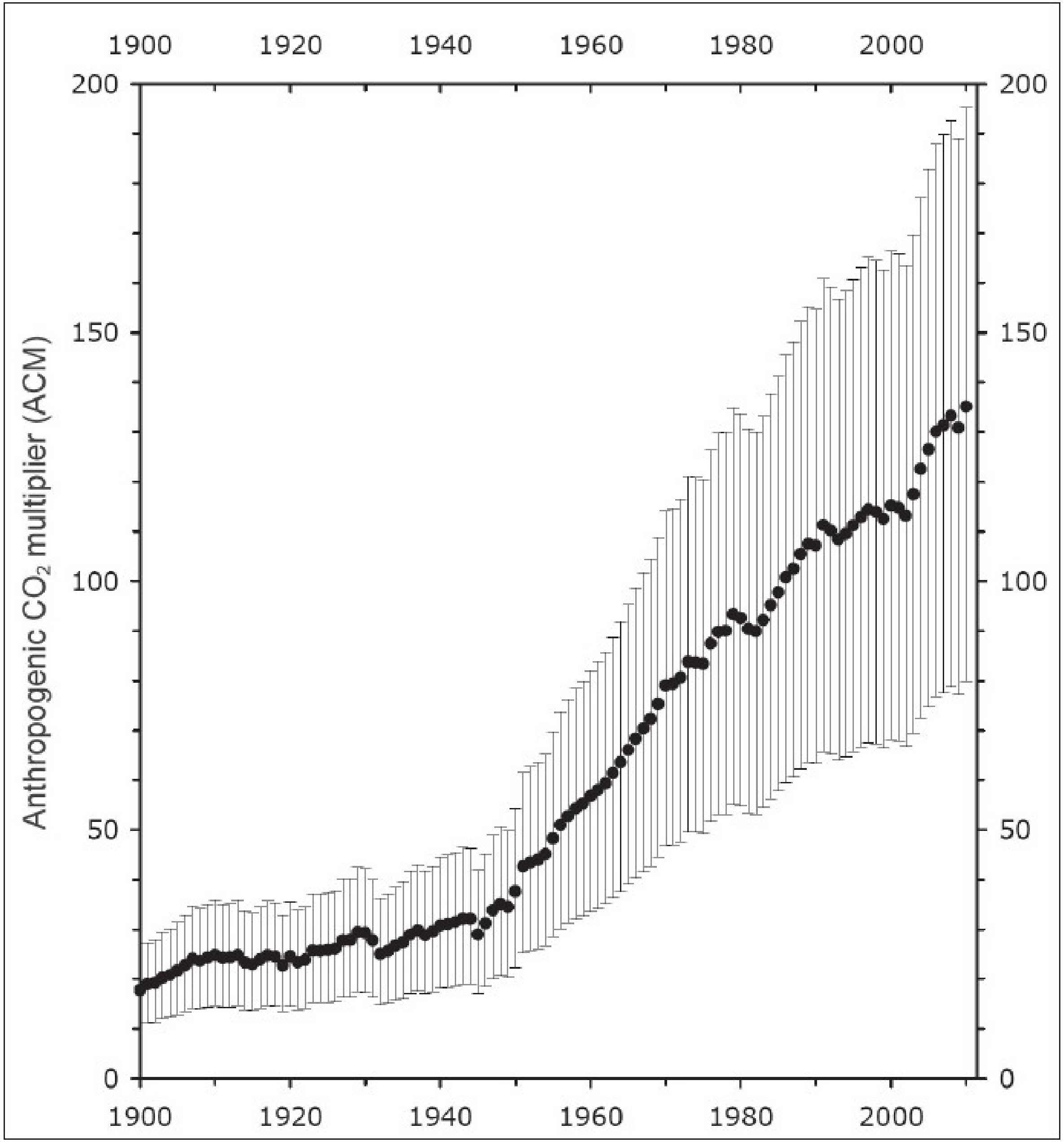
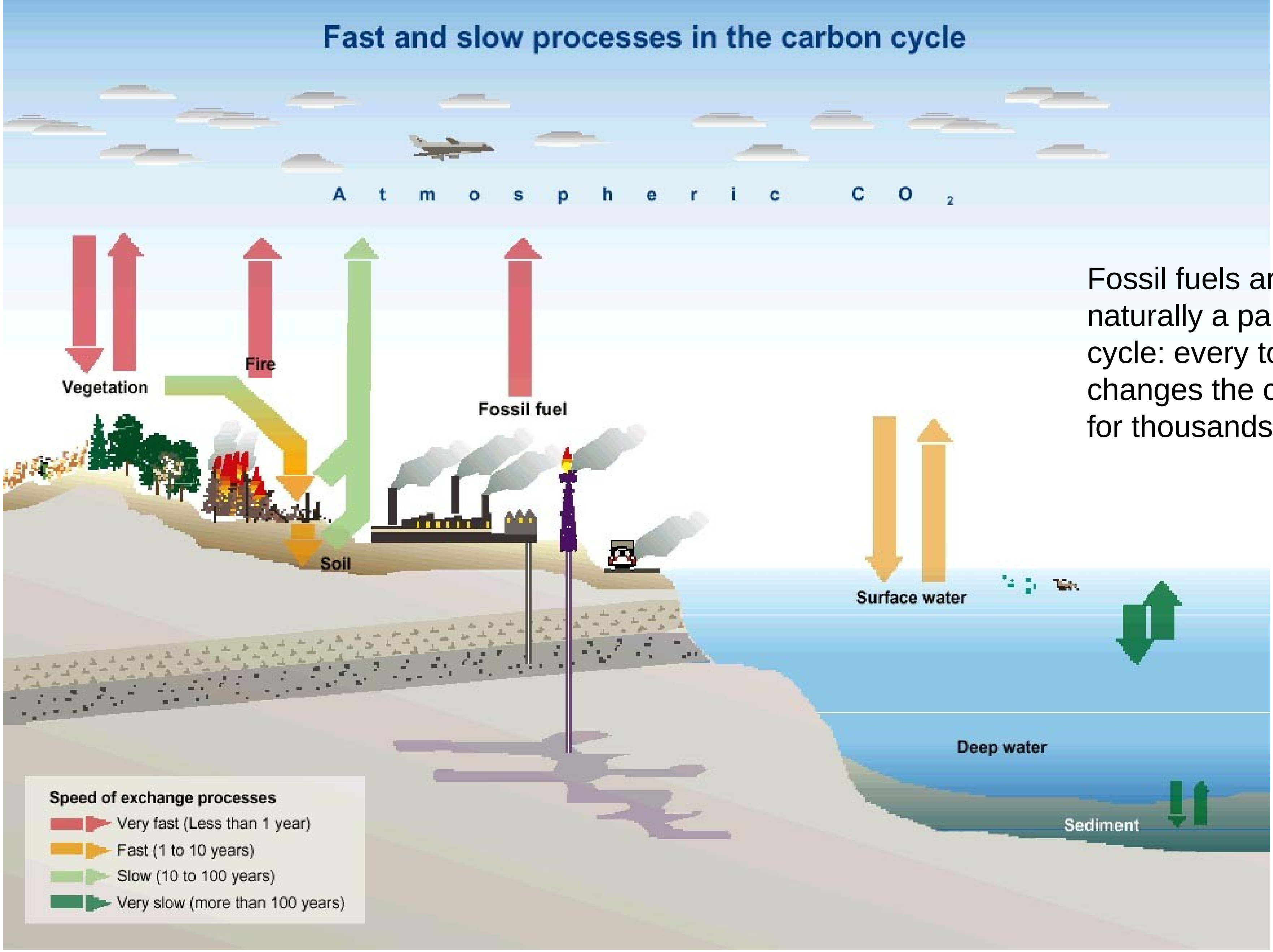


Figure 2. Diagrammatic representation of the different volcanic environments with estimates of CO_2 emission rates and their relationship to plate tectonic environment.

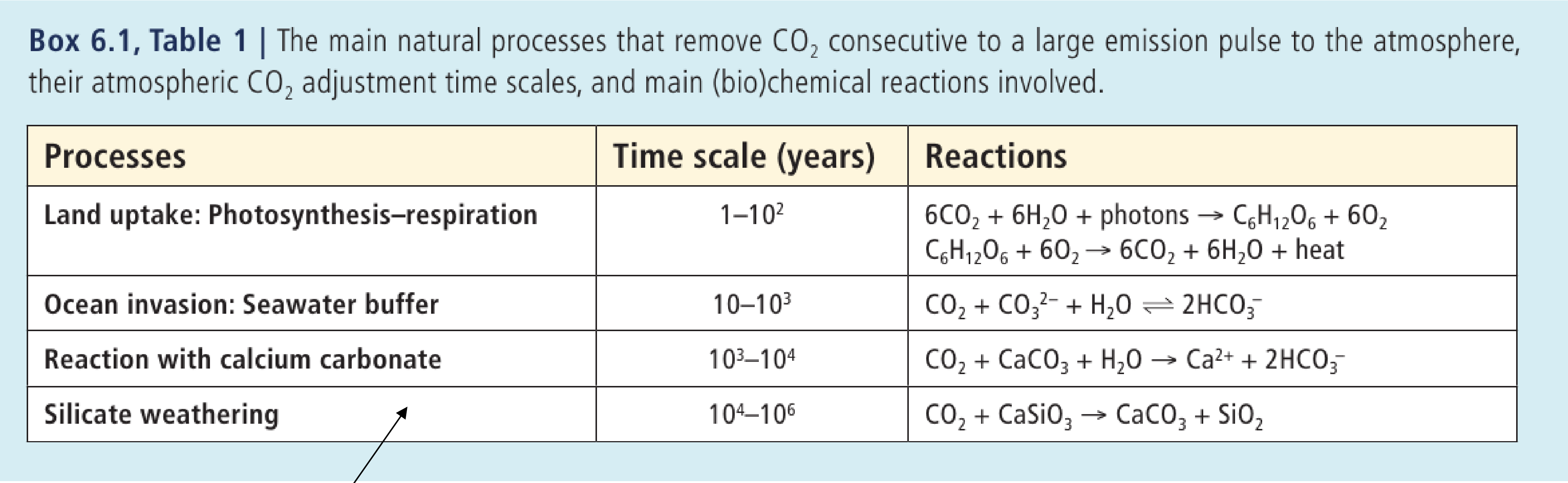


Antropogenic vs. volcanic CO_2 emissions.

Gerlach, T. (2011): "Volcanic Versus Anthropogenic Carbon Dioxide", EOS, Trans. AGU, 92:24, 201-208



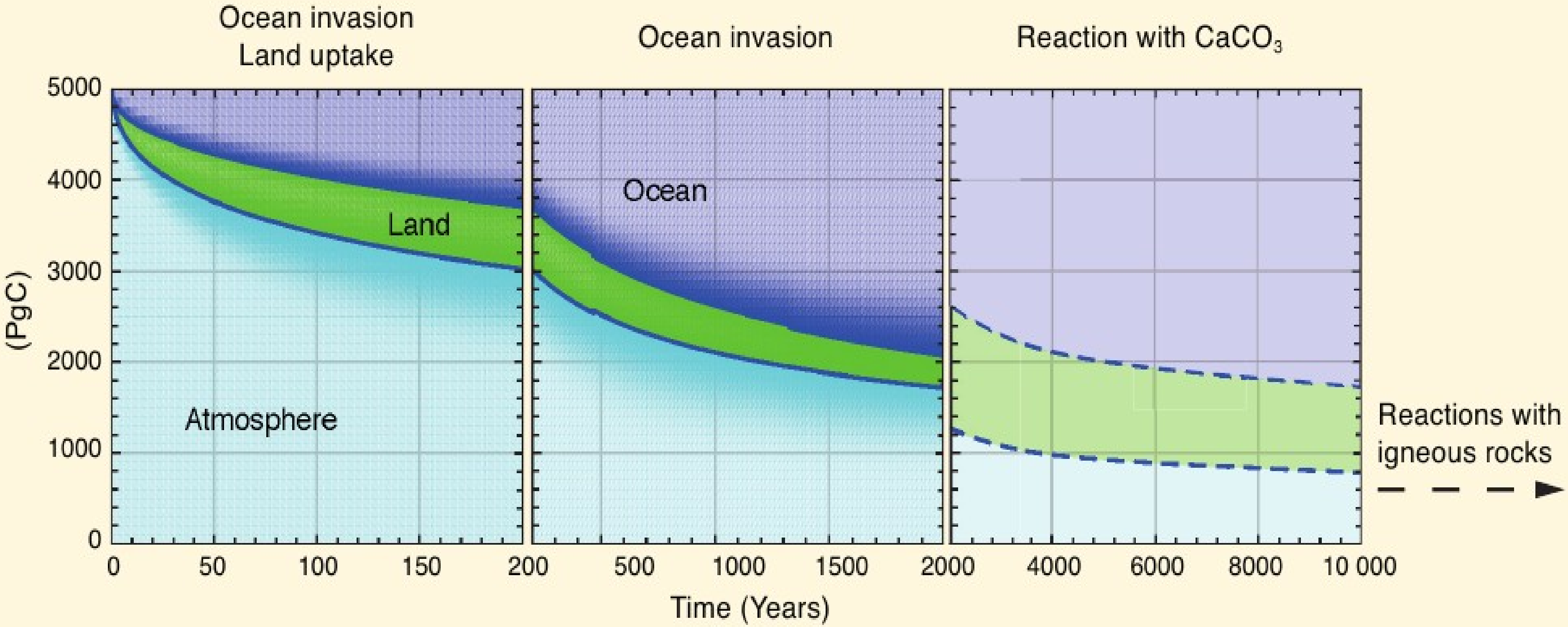
Fossil fuels are not naturally a part of the fast cycle: every ton emitted changes the carbon cycle for thousands of years



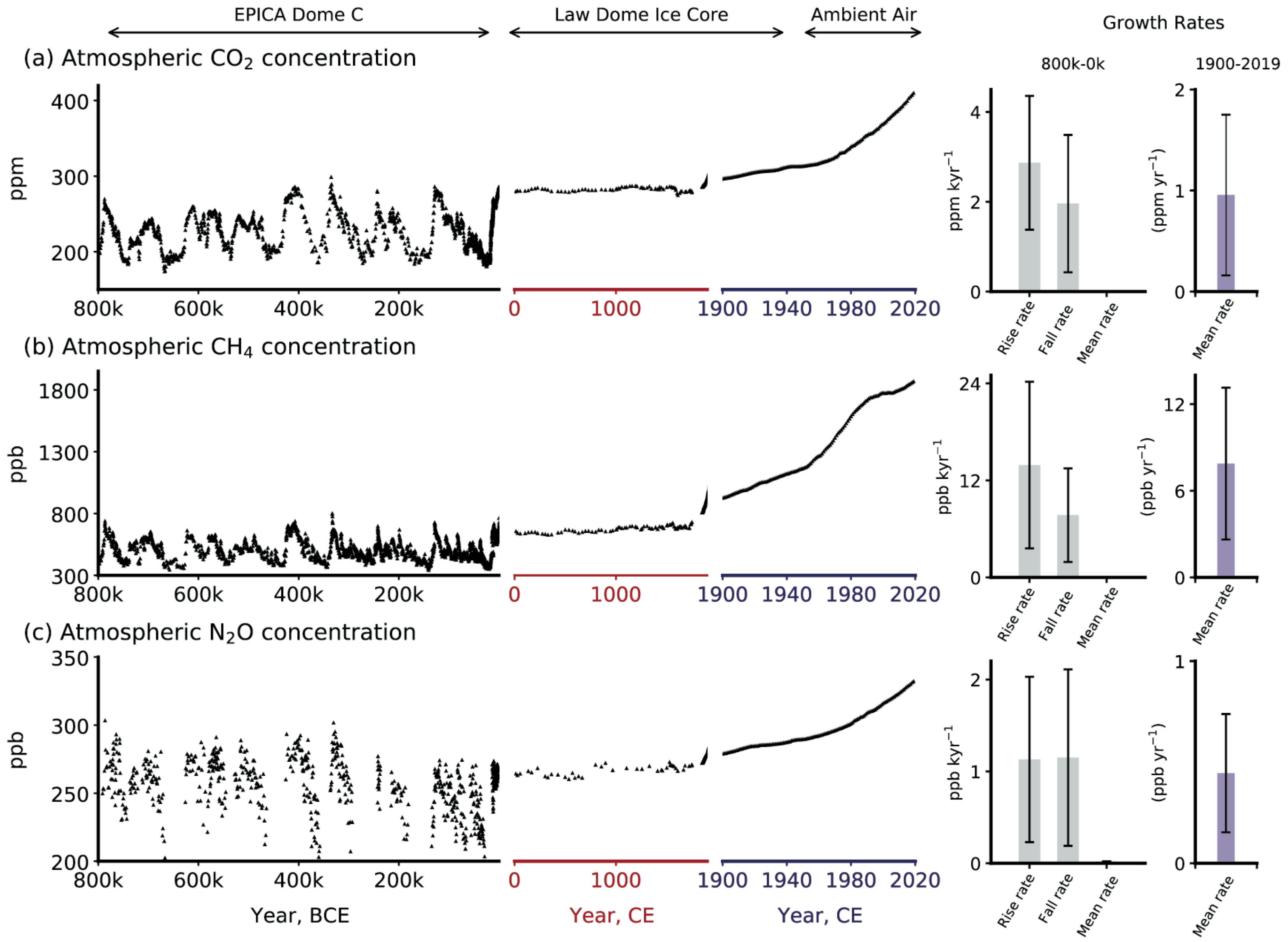
Box 6.1, Table 1 | The main natural processes that remove CO_2 consecutive to a large emission pulse to the atmosphere, their atmospheric CO_2 adjustment time scales, and main (bio)chemical reactions involved.

Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	$1–10^2$	$6CO_2 + 6H_2O + \text{photons} \rightarrow C_6H_{12}O_6 + 6O_2$ $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$
Ocean invasion: Seawater buffer	$10–10^3$	$CO_2 + CO_3^{2-} + H_2O \rightleftharpoons 2HCO_3^-$
Reaction with calcium carbonate	$10^3–10^4$	$CO_2 + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$
Silicate weathering	$10^4–10^6$	$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

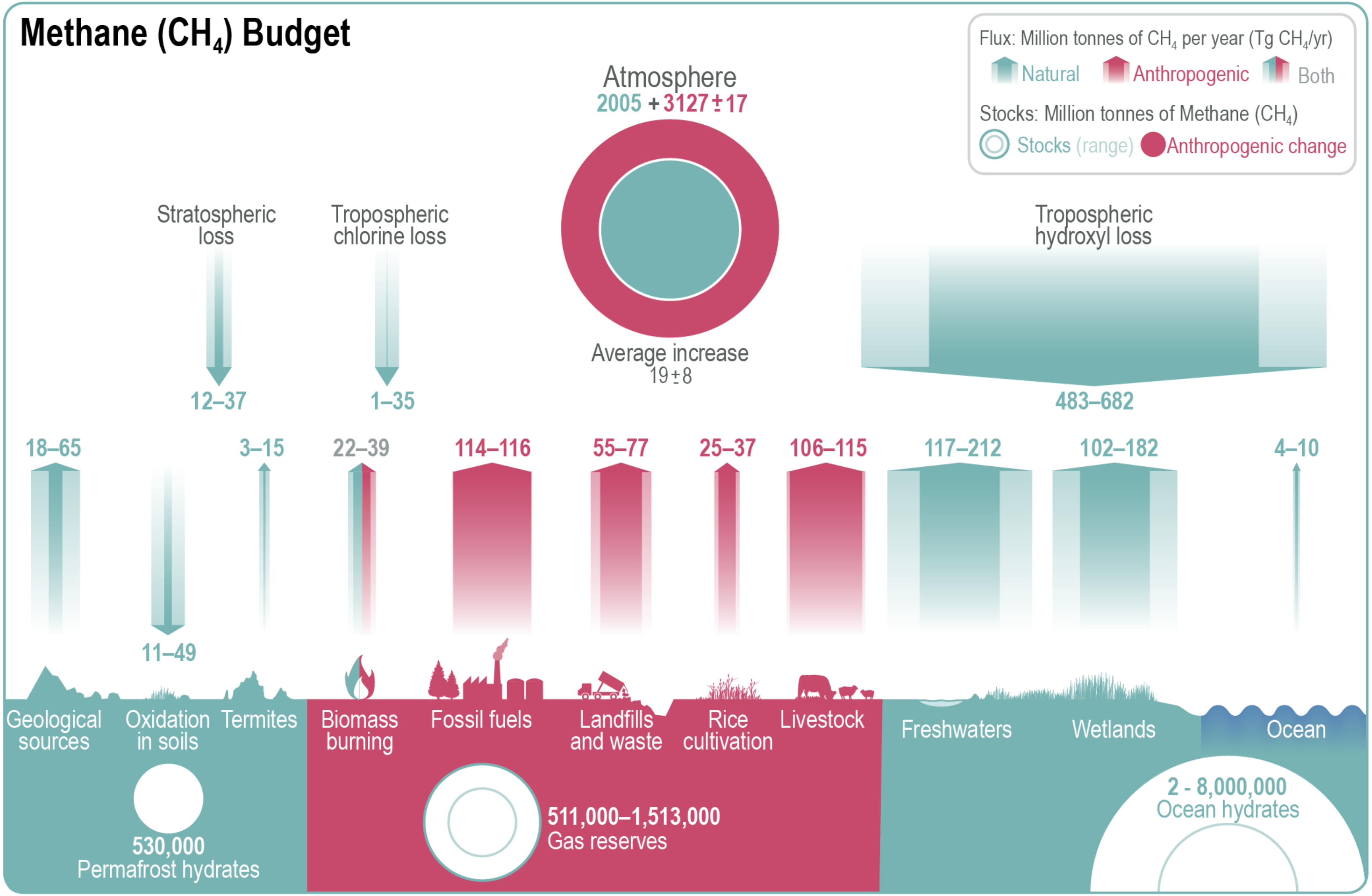
Timescales of carbon removal.



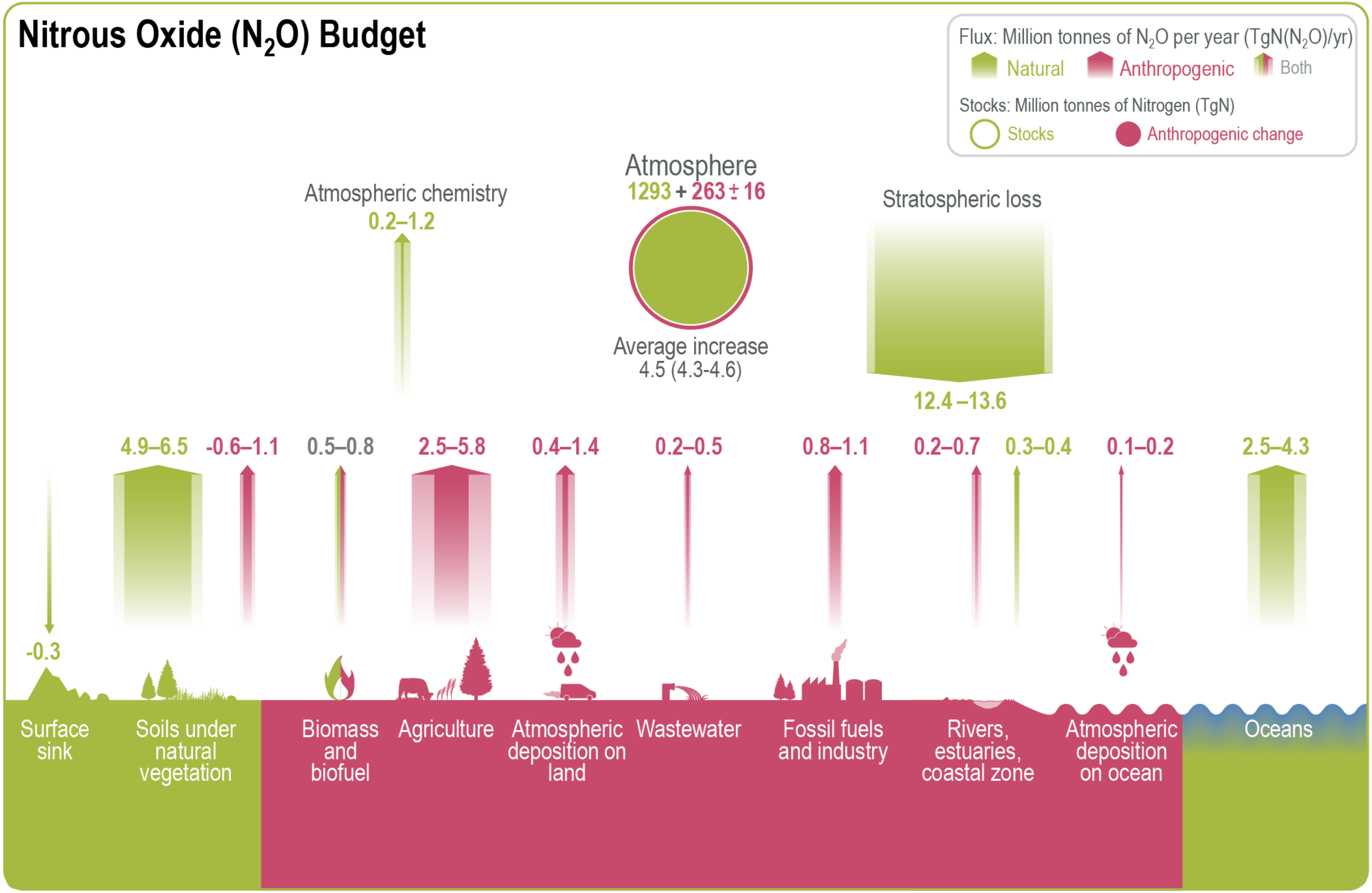
FAQ 6.2, Figure 2 | Decay of a CO_2 excess amount of 5000 PgC emitted at time zero into the atmosphere, and its subsequent redistribution into land and ocean as a function of time, computed by coupled carbon-cycle climate models. The sizes of the colour bands indicate the carbon uptake by the respective reservoir. The first two panels show the multi-model mean from a model intercomparison project (Joos et al., 2013). The last panel shows the longer term redistribution including ocean dissolution of carbonaceous sediments as computed with an Earth System Model of Intermediate Complexity (after Archer et al., 2009b).


EPICA Dome C
Law Dome Ice Core
Ambient Air
Growth Rates
(a) Atmospheric CO_2 concentration
800k-0k
1900-2019
ppm
400
300
200
800k
600k
400k
200k
0
1000
1900
1940
1980
2020
ppm kyr^{-1}
4
2
0
(ppm yr^{-1})
2
1
0
Rise rate
Fall rate
Mean rate
Mean rate
(b) Atmospheric CH_4 concentration
ppb
1800
1300
800
300
800k
600k
400k
200k
0
1000
1900
1940
1980
2020
ppb kyr^{-1}
24
12
0
(ppb yr^{-1})
12
6
0
Rise rate
Fall rate
Mean rate
Mean rate
(c) Atmospheric N_2O concentration
ppb
350
300
250
200
800k
600k
400k
200k
0
1000
1900
1940
1980
2020
Year, BCE
Year, CE
Year, CE
ppb kyr^{-1}
2
1
0
(ppb yr^{-1})
1
0
Rise rate
Fall rate
Mean rate
Mean rate

CH_4 in climate system



N_2O in climate system



Perspective

Journal of the Geological Society

https://doi.org/10.1144/jgs2020-239 | Vol. 178 | 2020 | jgs2020-239

Geological Society of London Scientific Statement: what the geological record tells us about our present and future climate

Caroline H. Lear[1*], Pallavi Anand[2], Tom Blenkinsop[1], Gavin L. Foster[3], Mary Gagen[4], Babette Hoogakker[5], Robert D. Larter[6], Daniel J. Lunt[7], I. Nicholas McCave[8], Erin McClymont[9], Richard D. Pancost[10], Rosalind E.M. Rickaby[11], David M. Schultz[12], Colin Summerhayes[13], Charles J.R. Williams[7] and Jan Zalasiewicz[14]

Geology is the science of how the Earth functions and has evolved and, as such, it can contribute to our understanding of the climate systemand how it responds to the addition of carbon dioxide (CO2) to the atmosphere and oceans. Observations from the geological record show that atmospheric CO2 concentrations are now at their highest levels in at least the past 3 million years. Furthermore, the current speed of human-induced CO2 change and warming is nearly without precedent in the entire geological record, with the only known exception being the instantaneous, meteorite-induced event that caused the extinction of non-bird-like dinosaurs 66 million years ago. In short, whilst atmospheric CO2 concentrations have varied dramatically during the geological past due to natural processes, and have often been higher than today, the current rate of CO2 (and therefore temperature) change is unprecedented in almost the entire geological past.

The geological record shows that changes in temperature and greenhouse gas concentrations have direct impacts on sea-level, the hydrological cycle, marine and terrestrial ecosystems, and the acidification and oxygen depletion of the oceans…

The geological record provides powerful evidence that atmospheric CO2 concentrations drive climate change, and supports multiple lines of evidence that greenhouse gases emitted by human activities are altering the Earth’s climate. Moreover, the amount of anthropogenic greenhouse gases already in the atmosphere means that Earth is committed to a certain degree of warming. As the Earth’s climate changes due to the burning of fossil fuels and changes in land-use, the planet we live on will experience further changes that will have increasingly drastic effects on human societies. An assessment of past climate changes helps to inform policy decisions regarding future climate change. Earth scientists will also have an important role to play in the delivery of any policies aimed at limiting future climate change

Summary:

Modern paleoclimatology is based on physical/chemical/biological analysis of past climate footprints present in sediments and remnants from the past. Paleoclimatology gives insight into past climates.

Paleoclimatological analysis increases our understanding of climate forcings and feedbacks, affecting distortions of carbon cycle and other biogeochemical cycles.

Alterations of carbon cycle and changes within this cycle due to feedbacks in climate system are explaining climate variability in last ~500 millions of years.