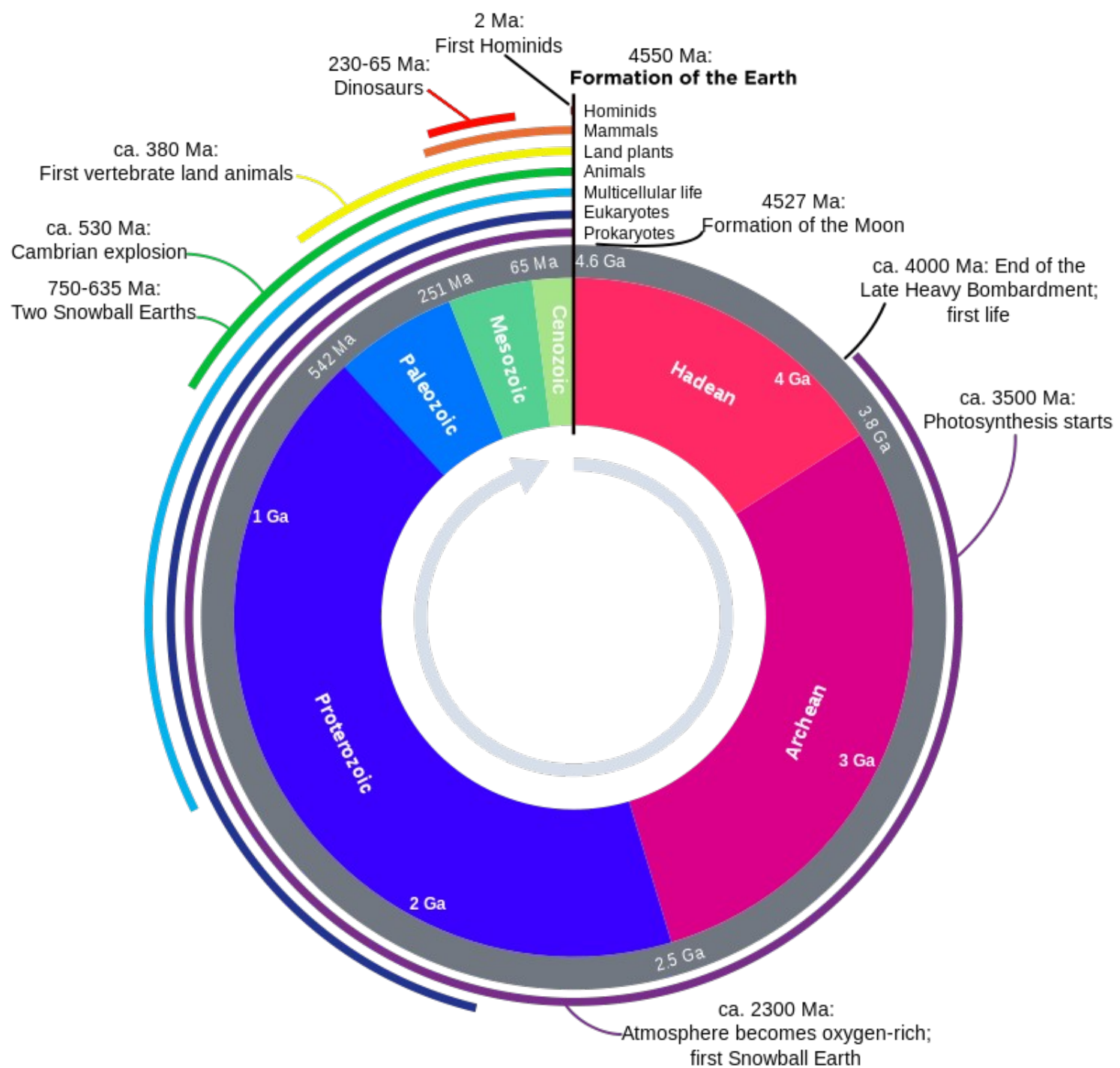


Fizyka Procesów Klimatycznych Paleoklimatologia

prof. dr hab. Szymon Malinowski
Instytut Geofizyki, Wydział Fizyki
Uniwersytet Warszawski
malina@igf.fuw.edu.pl

dr hab. Krzysztof Markowicz
Instytut Geofizyki, Wydział Fizyki
Uniwersytet Warszawski
kmark@igf.fuw.edu.pl

Wykorzystano slajdy dr Aleksandry Kardaś

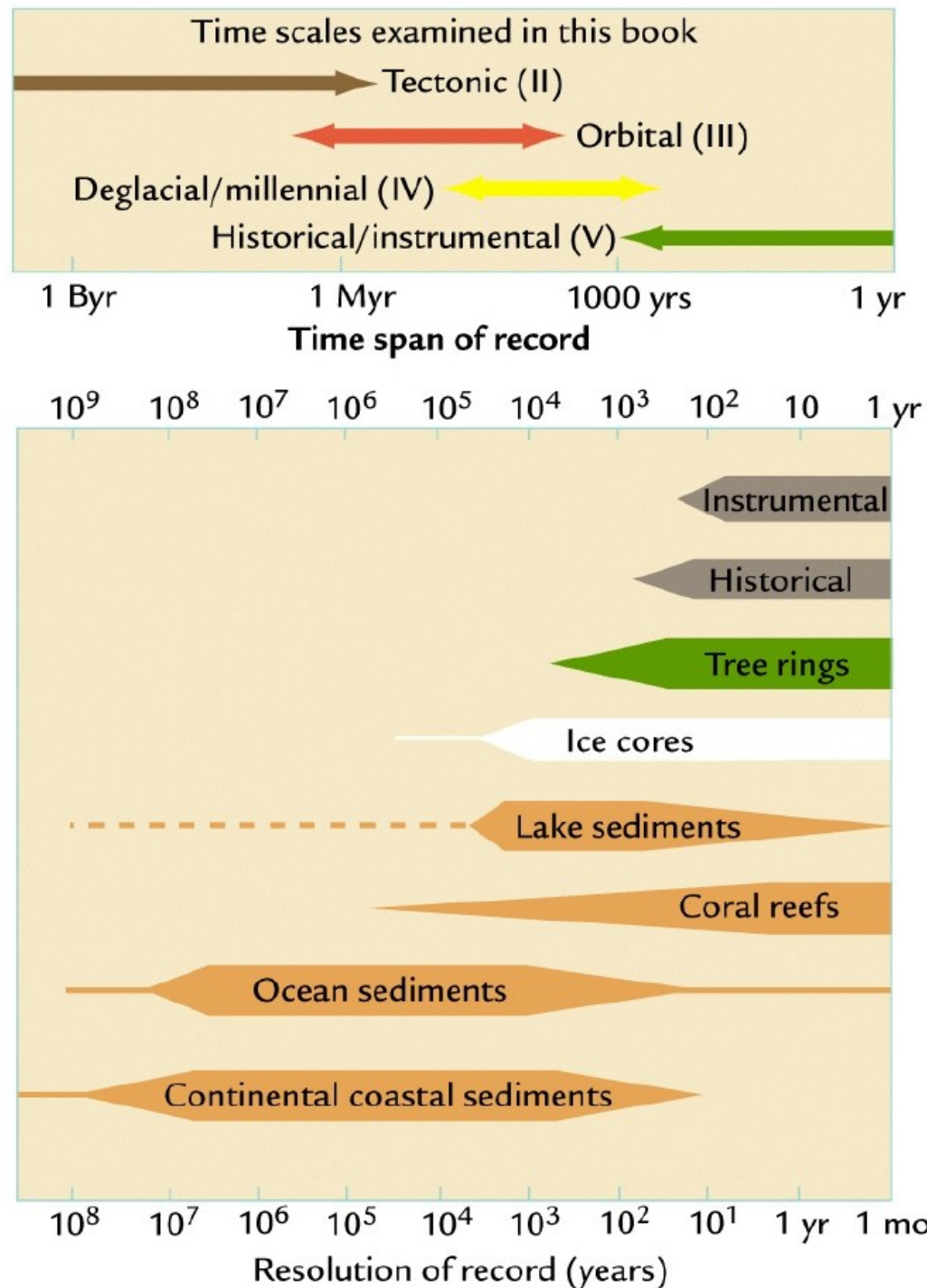


Dane z przeszłości:

- z pomiarów

- z zapisków historycznych

- proxy



Paleoclimatology Datasets



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

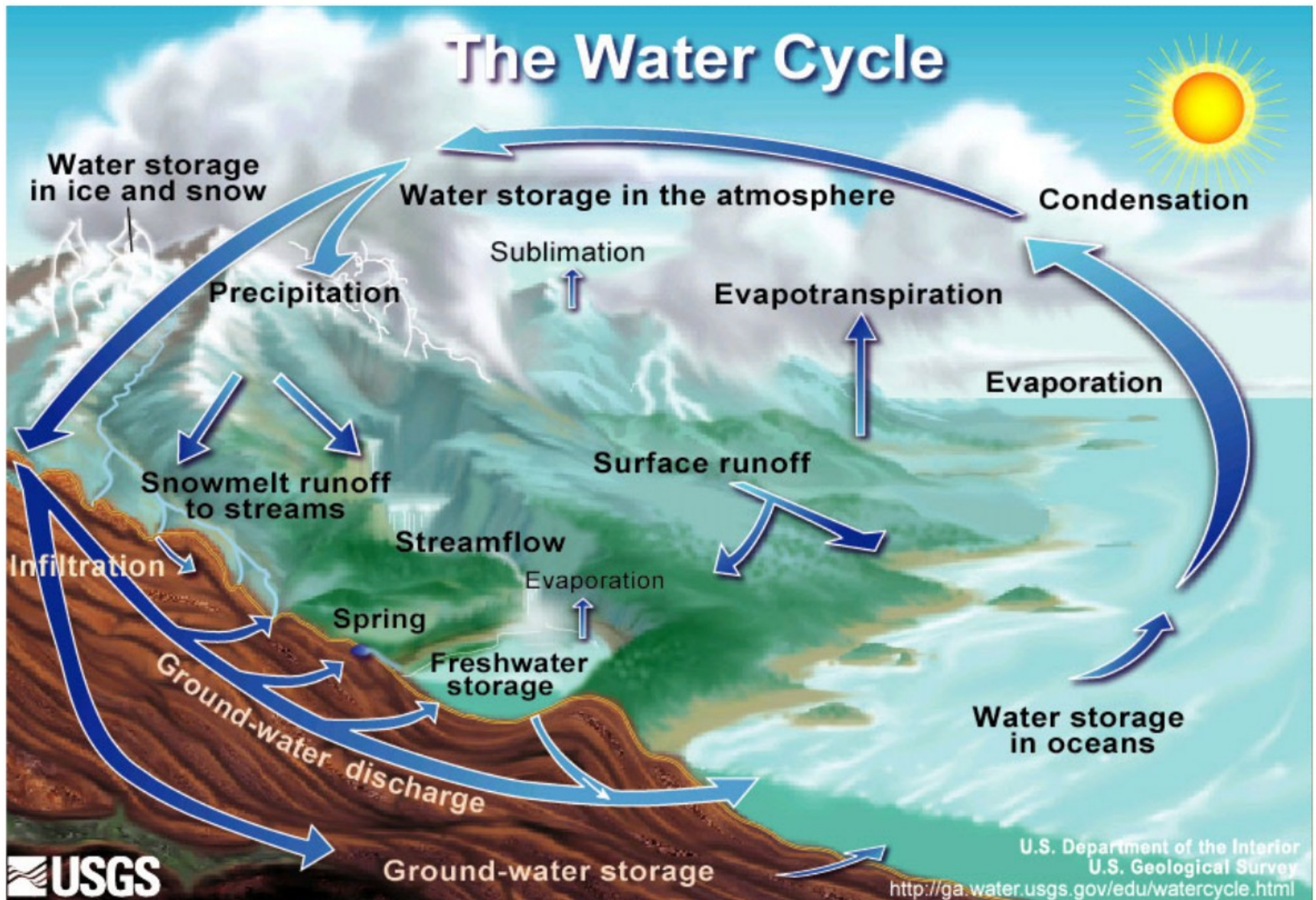
Radiometric dating

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.*

$\delta^{18}\text{O}$ - Tracer of the water cycle



$\delta^{18}\text{O}$ - Tracer of the water cycle

- Delta notation:

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

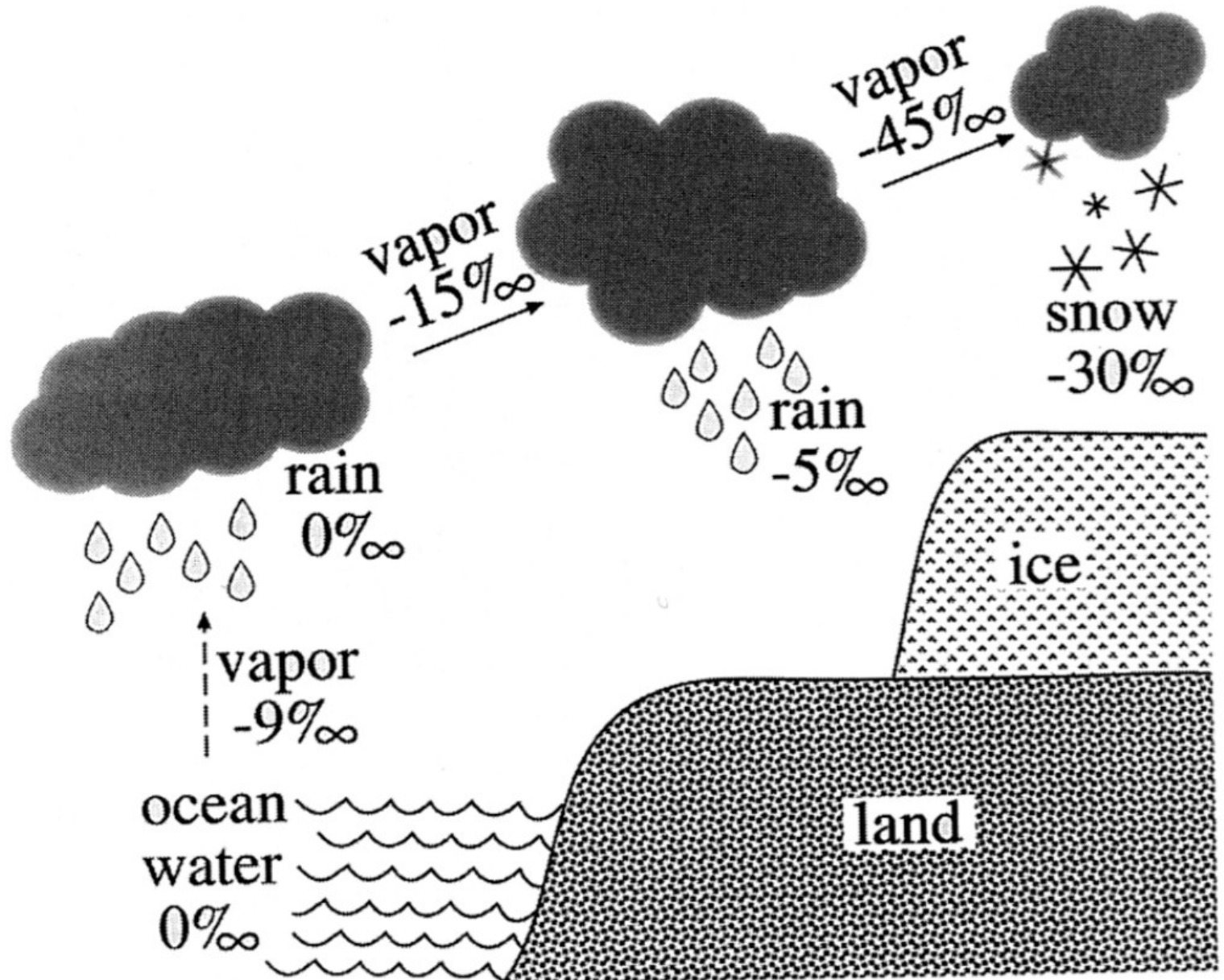
- A positive δ value means that the ratio of the heavy to the light isotope is higher in the sample than it is in the standard
- Units reported as “per mil” or ‰
- Standard:
V-SMOW: Vienna-Standard mean ocean water
or
V-PDB: Vienna - Pee Dee Belemnite

Isotope systematics in the hydrological cycle:

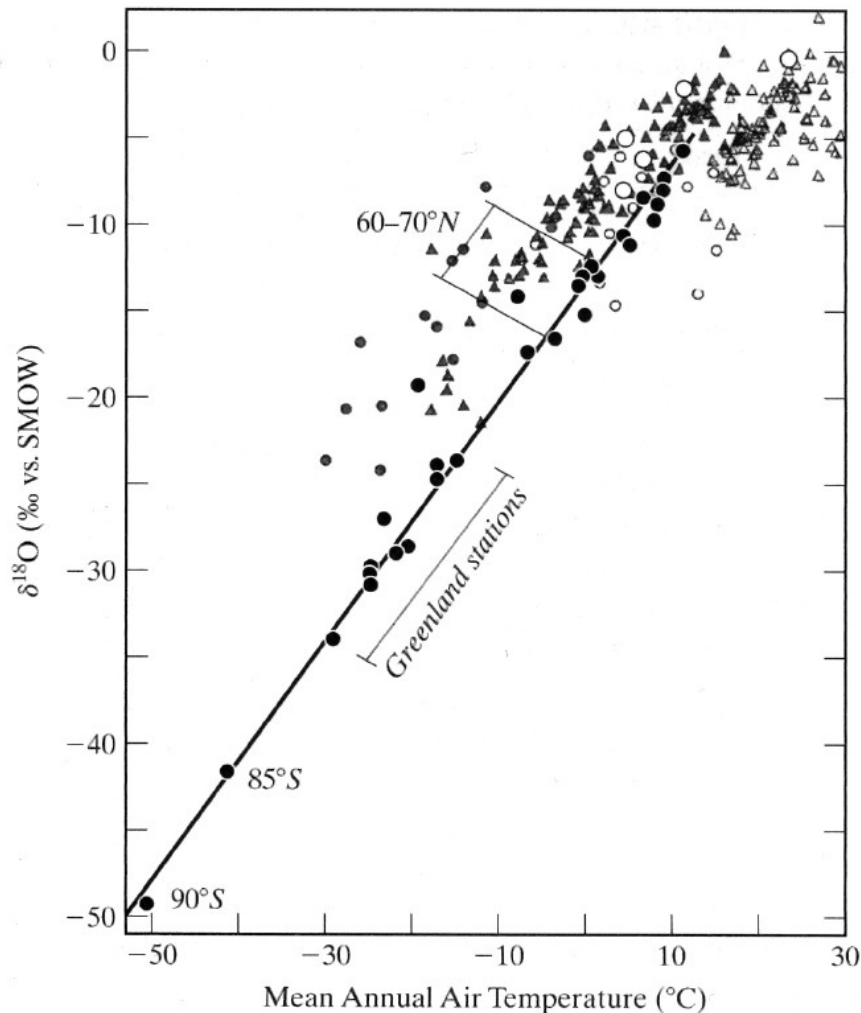
The isotope composition of natural meteoric waters (which form the main reservoirs of freshwater on earth, ice caps, lakes, rivers and groundwater) is determined by three main factors.

- 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.

Isotope water cycle



Temperature effect

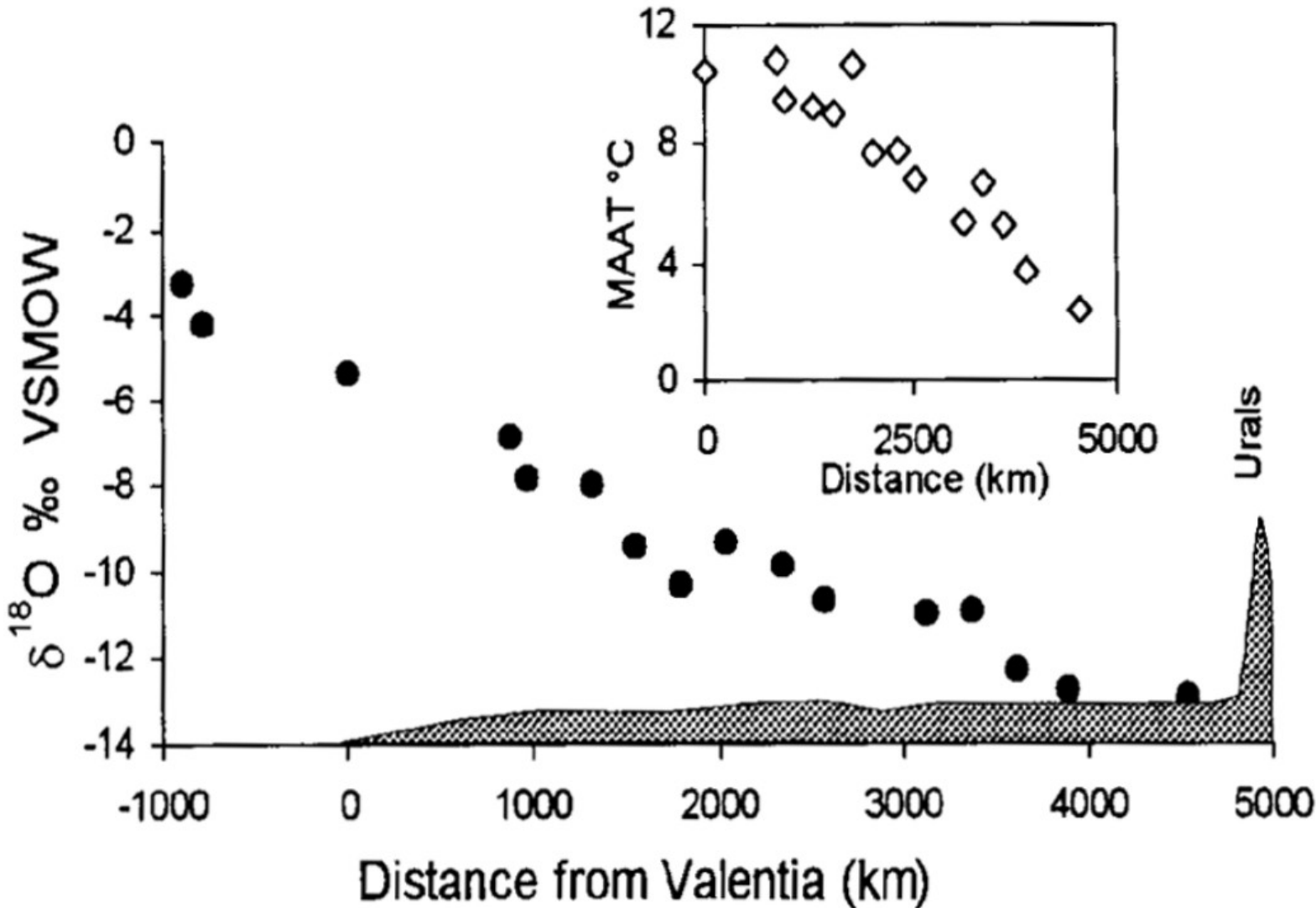


- Strong overall $\delta^{18}\text{O}$ - surface temperature relationship for locations in the extra-tropics
- Can be used for calibrating the $\delta^{18}\text{O}$ record in ice cores

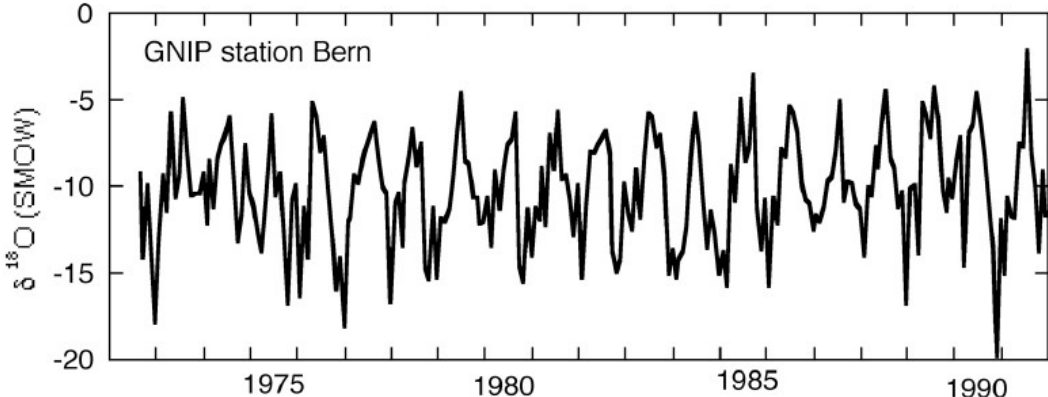
FIGURE 4.12: Effect of mean annual air temperature on the oxygen isotope composition of meteoric precipitation. The effect is largest and most linear at high latitudes, where condensation occurs close to the land surface. Circles are annual data from Dansgaard (1964); open diamonds are summer data, closed diamonds winter data, from Fricke and O'Neil (1999).

From Zachery Sharp, 2007, Principles of stable isotope geochemistry

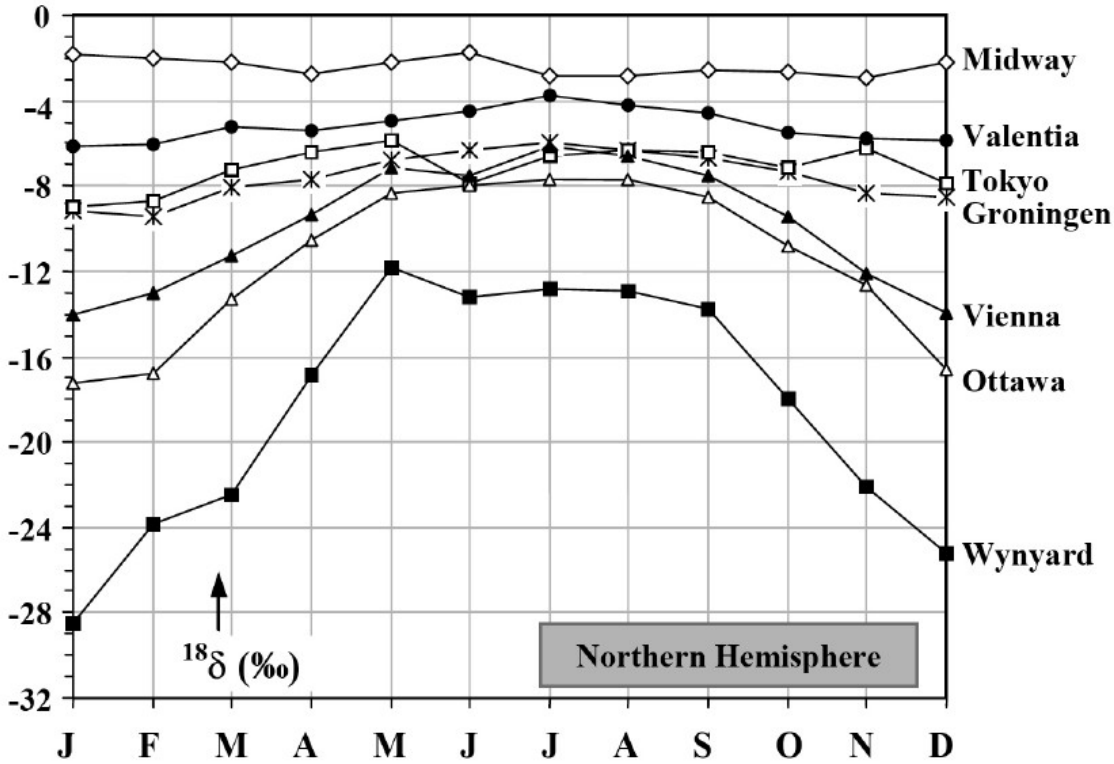
Continental effect



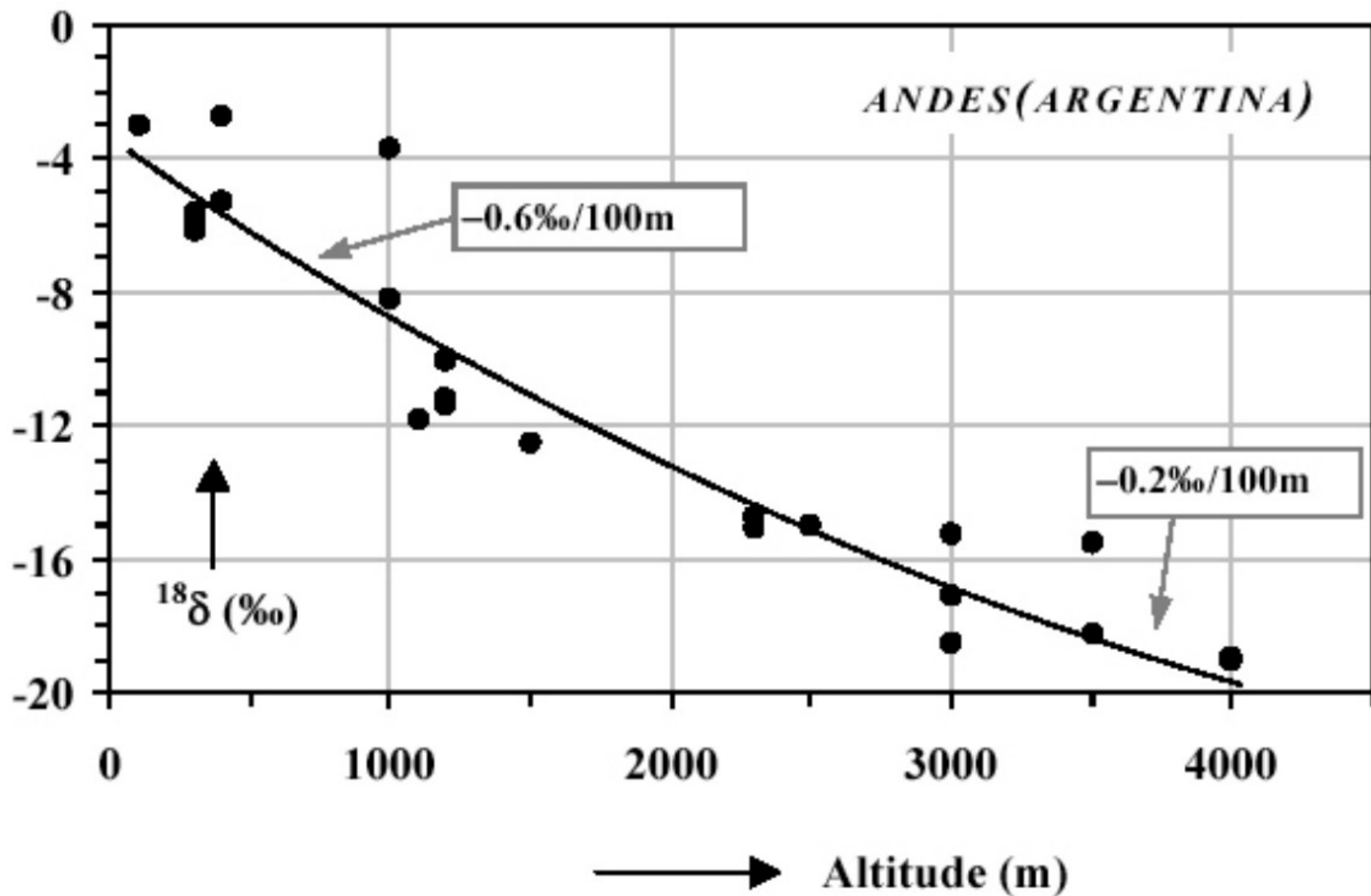
Seasonal effect



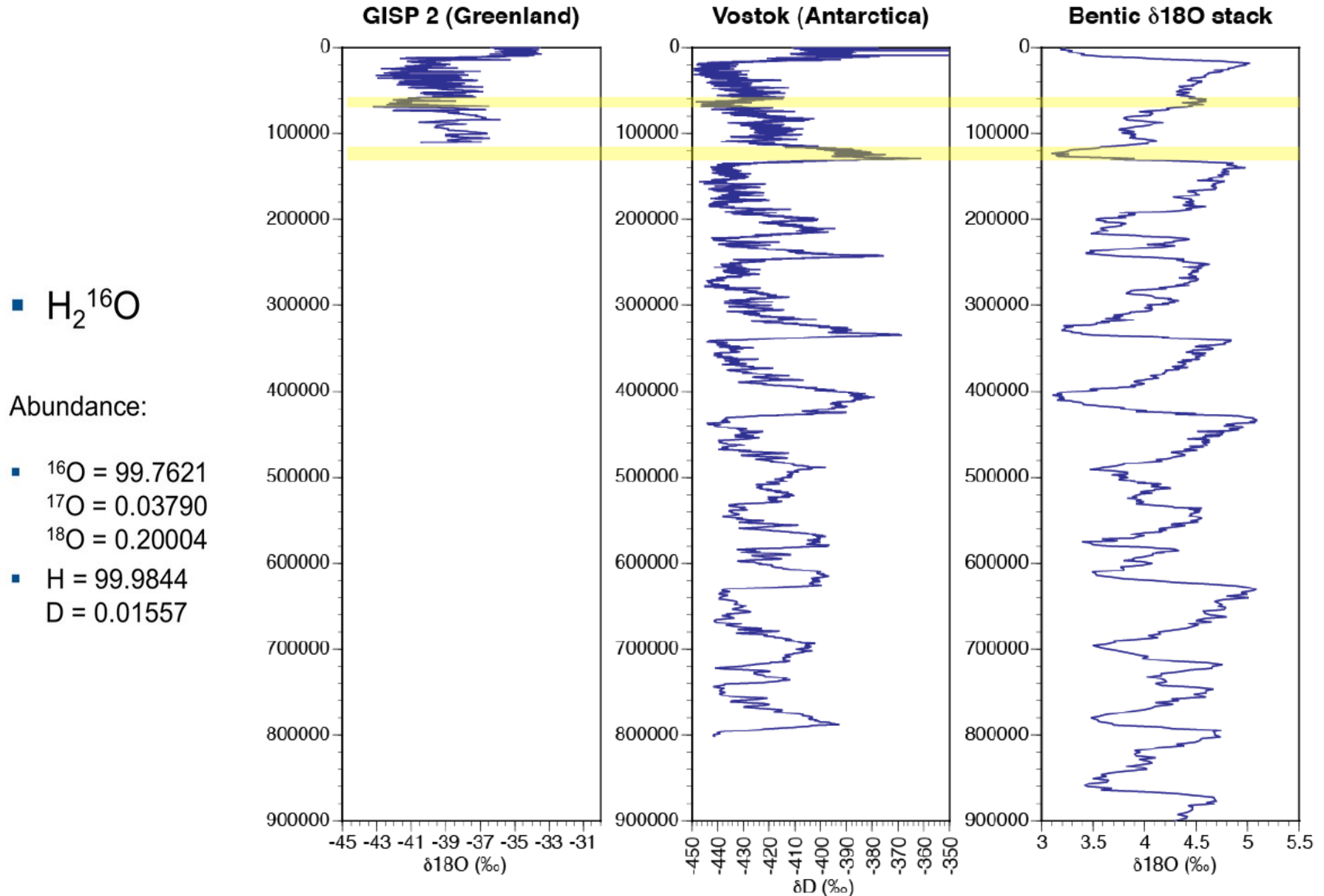
A



Altitude effect



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



$\delta^{18}\text{O}$: Temperature dependence

- Shell material from marine organisms like mussels, brachiopods and snails in different water temperature
- Empirical relationship
- $T(^{\circ}\text{C}) = 16.9 - 4.2(\delta^{18}\text{O}_C - \delta^{18}\text{O}_W) + 0.13 (\delta^{18}\text{O}_C - \delta^{18}\text{O}_W)^2$
- $T(^{\circ}\text{C}) = 16.5 - 4.80(\delta^{18}\text{O}_{\text{calcite}} - \delta^{18}\text{O}_{\text{water}})$
- 1 per mil shift in $\delta^{18}\text{O}$ (under equilibrium conditions) is equal $\sim 4^{\circ}\text{C}$ temperature shift

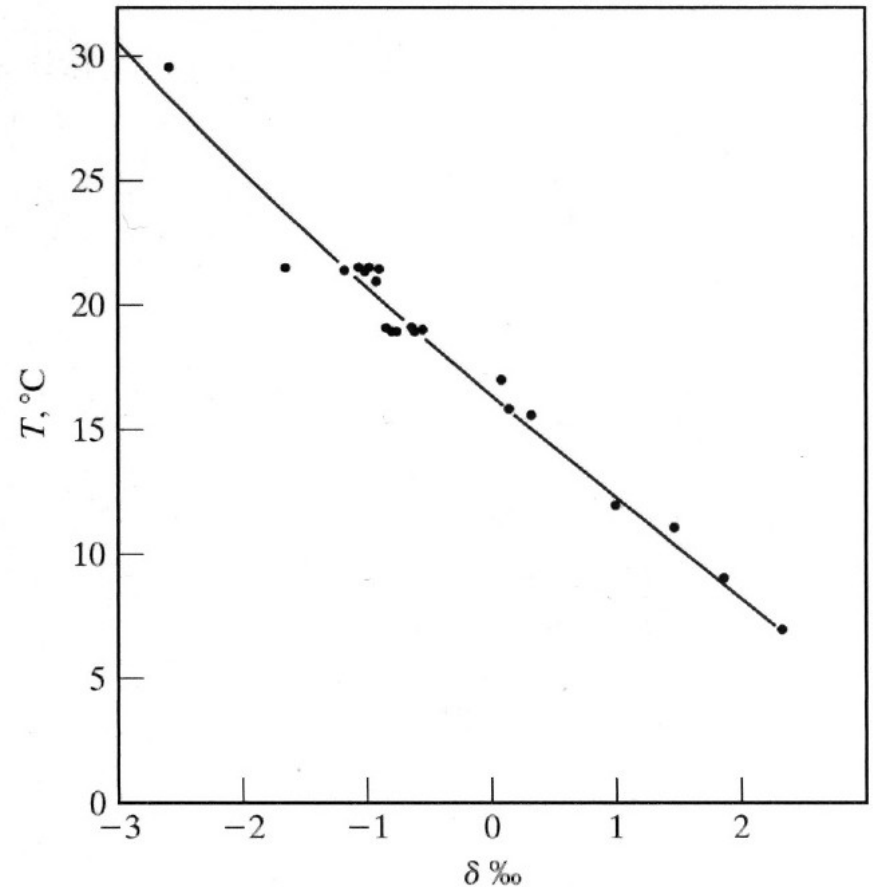


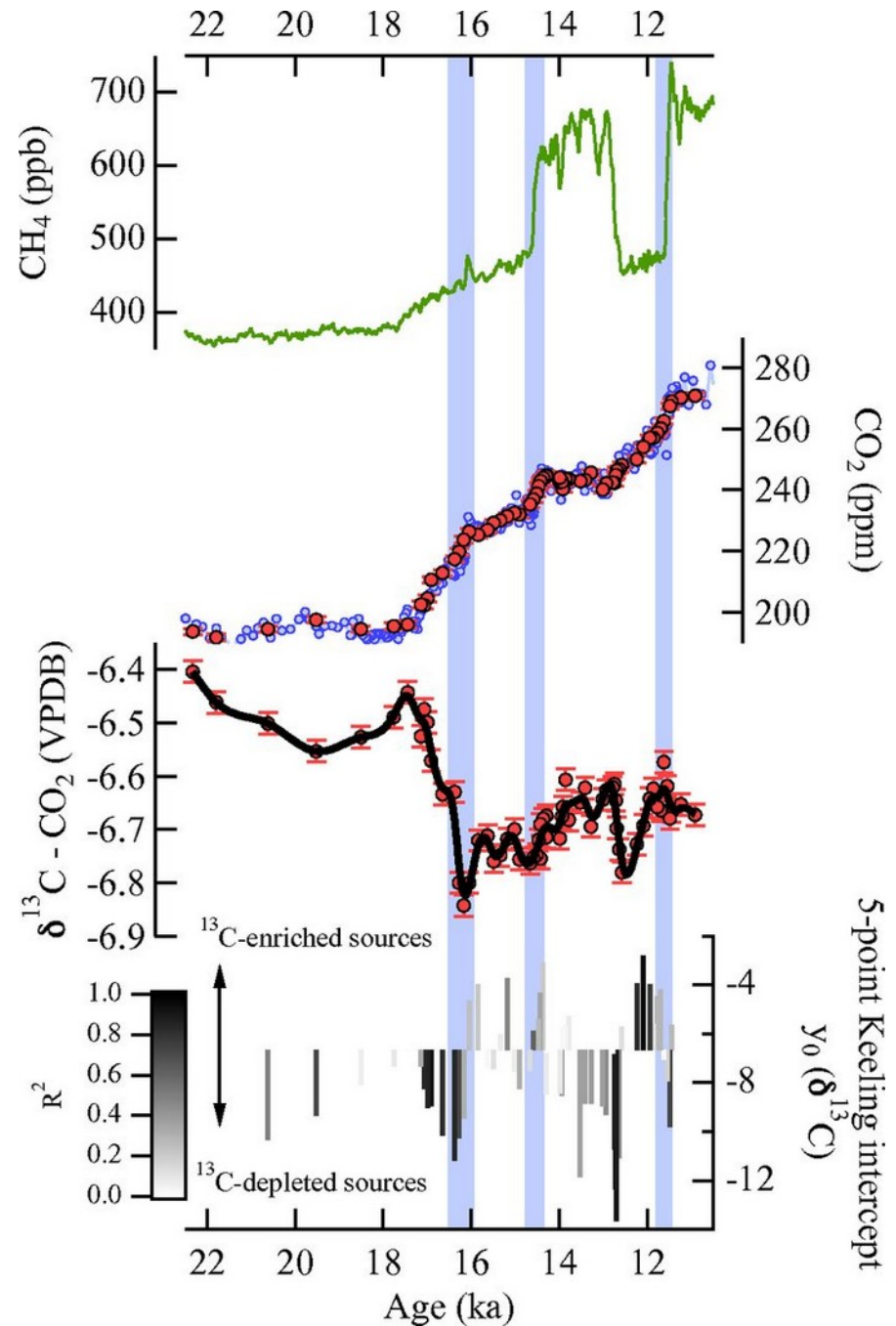
FIGURE 6.2: Plot of Epstein et al.'s (1953) corrected data set for determining the fractionation factor for carbonate–water. The x -axis ($\delta\text{‰}$) refers to the $(\delta_c - \delta_w)$ of equation (6.4), while $T(^{\circ}\text{C})$ is the measured water temperature. Reprinted with permission from the Geological Society of America.

Carbon isotopes characterize rapid changes in atmospheric carbon dioxide during the last deglaciation

Thomas K. Bauska, Daniel Baggenstos, Edward J. Brook, Alan C. Mix, Shaun A. Marcott, Vasil...
 + See all authors and affiliations

PNAS March 29, 2016 113 (13) 3465-3470; first published March 14, 2016; <https://doi.org/10.1073/pnas.1513868113>

$$\delta^{13}\text{C} = \left(\frac{\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{sample}}}{\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{standard}}} - 1 \right) \times 1000 \text{ ‰}$$



[Home](#) ▶ [For Scientists](#) ▶ [Publications](#)

Scientific Publications



The IODP Publications page (publications.iodp.org) includes links to:

- Scientific prospectus
- Preliminary reports
- Proceedings

for each Integrated Ocean Drilling Program (2003-2013) and International Ocean Discovery Program (2013-2023) expedition.

The IODP Publications page also contains links to:

- [Deep Sea Drilling Program \(DSDP\) Publications](#)
- [Ocean Drilling Program \(ODP\) Publications](#)
- [Scientific Drilling](#), the journal for the IODP and the International Continental Scientific Drilling Program (ICDP)

as well as a downloadable copy of the Statement on IODP Publications and Reports.

Scientific Drilling is an open-access multi-disciplinary program journal delivering peer-reviewed reports on science, technology, and engineering from ocean, continental, lake and ice drilling scientific research projects. It is designed to enhance communication between and among IODP, the [International Continental Scientific Drilling Program](#), and other scientific drilling communities.

The IODP Digital Reference for Smear Slide Analysis of Marine Mud. Part 1: Methodology and Atlas of Siliciclastic and Volcanogenic Components (IODP Technical Note 1) is available in a variety of formats at the [IODP TECHNICAL NOTES](#) site.

ODP legacy information is available at the [ODP Legacy](#) site, and a database of publication citation records related to the Deep Sea Drilling Project, Ocean Drilling Program, and Integrated Ocean Drilling Program is available at the [Ocean Drilling Citation Database](#).

Finally, the [SELECTED PUBLICATIONS](#) page contains a list of representative articles appearing in the journals Science, Nature, and Nature Geoscience based on scientific ocean drilling program expeditions beginning in 2003.

For Scientists

[DRILLING PROPOSALS](#)

[SITE SURVEY DATA BANK](#)

[ACCESS SAMPLES AND DATA](#)

[APPLY TO SAIL](#)

[ACRONYMS](#)

[KML DATA](#)

[EXPEDITION EXPLORER](#)

[PUBLICATIONS](#)

[WORKSHOPS](#)

[FORMER PROGRAM 2003-2013](#)

[IODP Council](#)

[Meeting Reports](#)

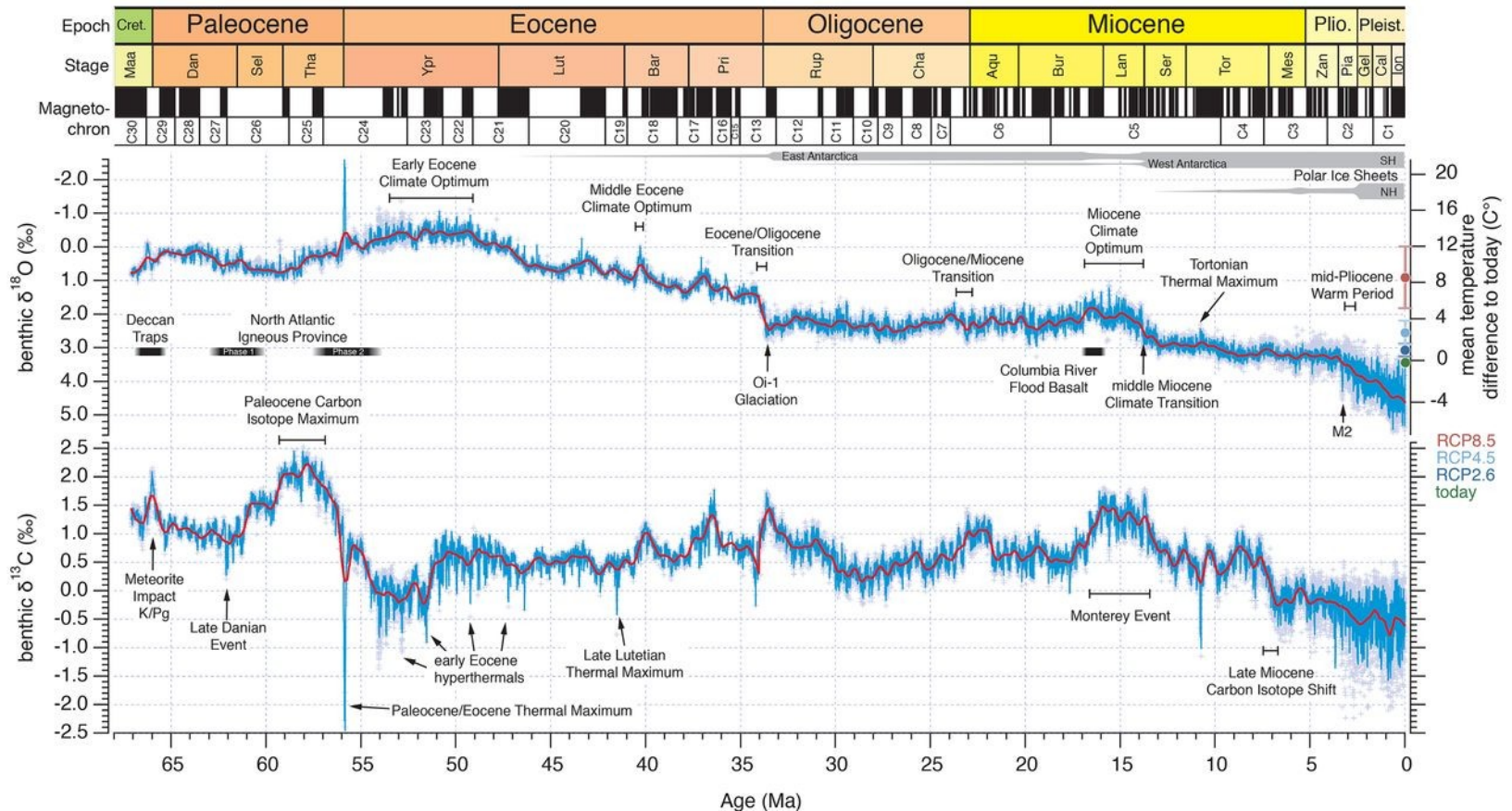
[Meeting Schedule](#)

[Policies and Guidelines](#)

[Science Advisory Structure](#)

[Task Forces](#)

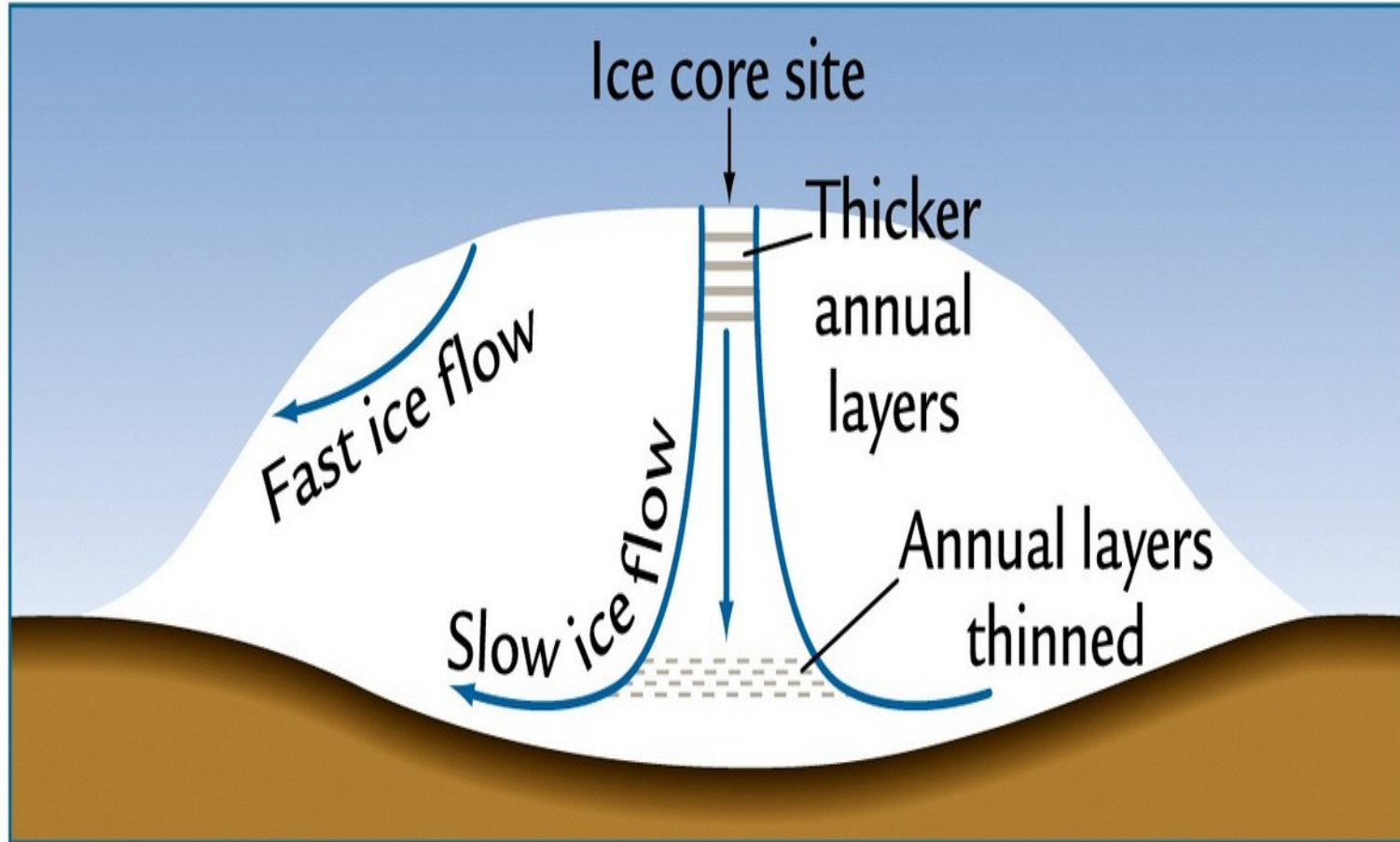
Fig. 1 Cenozoic Global Reference benthic foraminifer carbon and oxygen Isotope Dataset (CENOGRID) from ocean drilling core sites spanning the past 66 million years.



Thomas Westerhold et al. *Science* 2020;369:1383-1387



Ice Cores and Ice Sheet Flow



Age of Ice: annual layers (Greenland) and ice flow models (Antarctica)

Porównanie zmian średniej temperatury globu i koncentracji CO₂ w atmosferze od czasów dinozaurów (65 milionów lat temu) do teraz z możliwym antropogenicznym globalnym ociepleniem (450 lat).

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

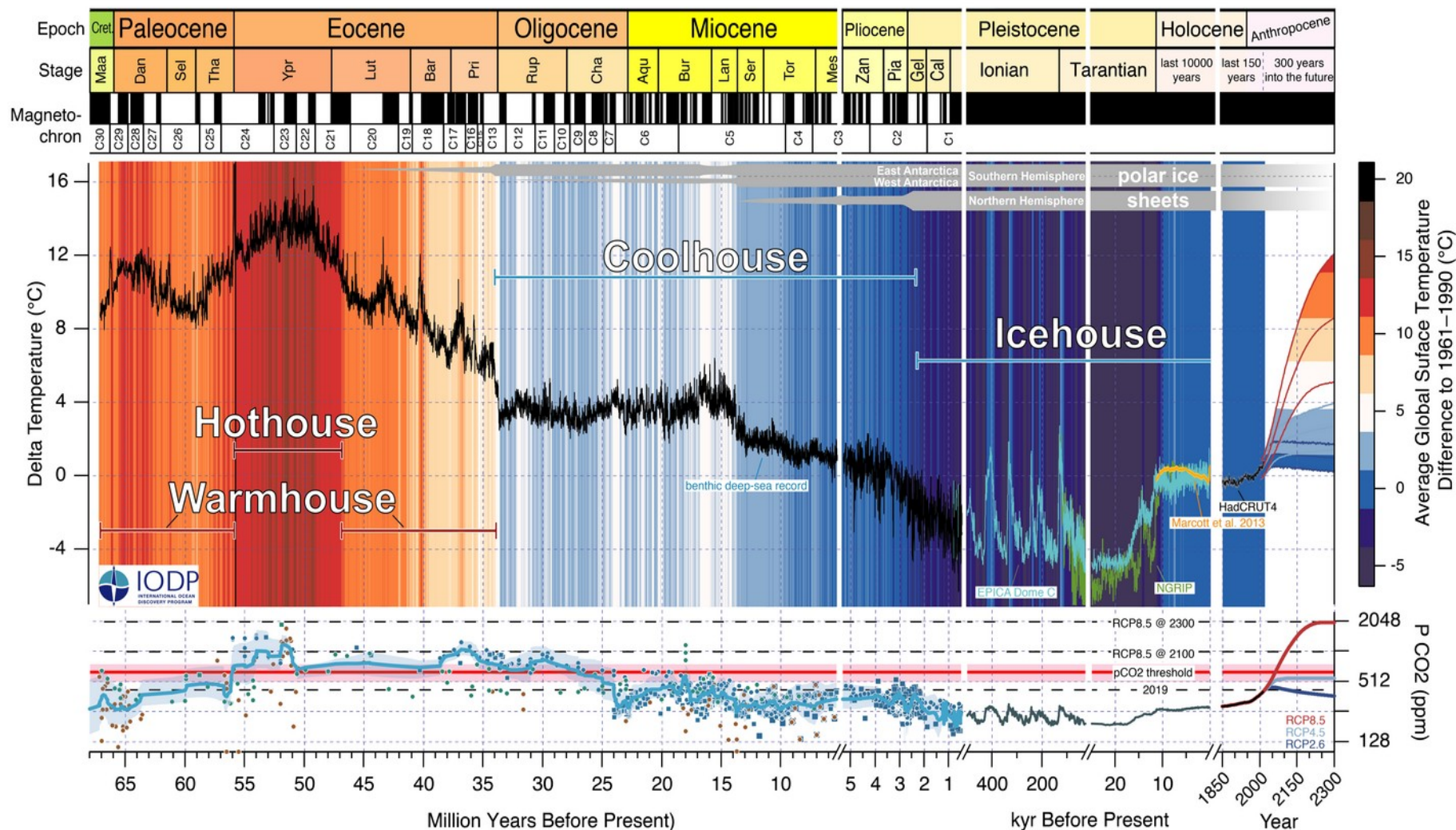
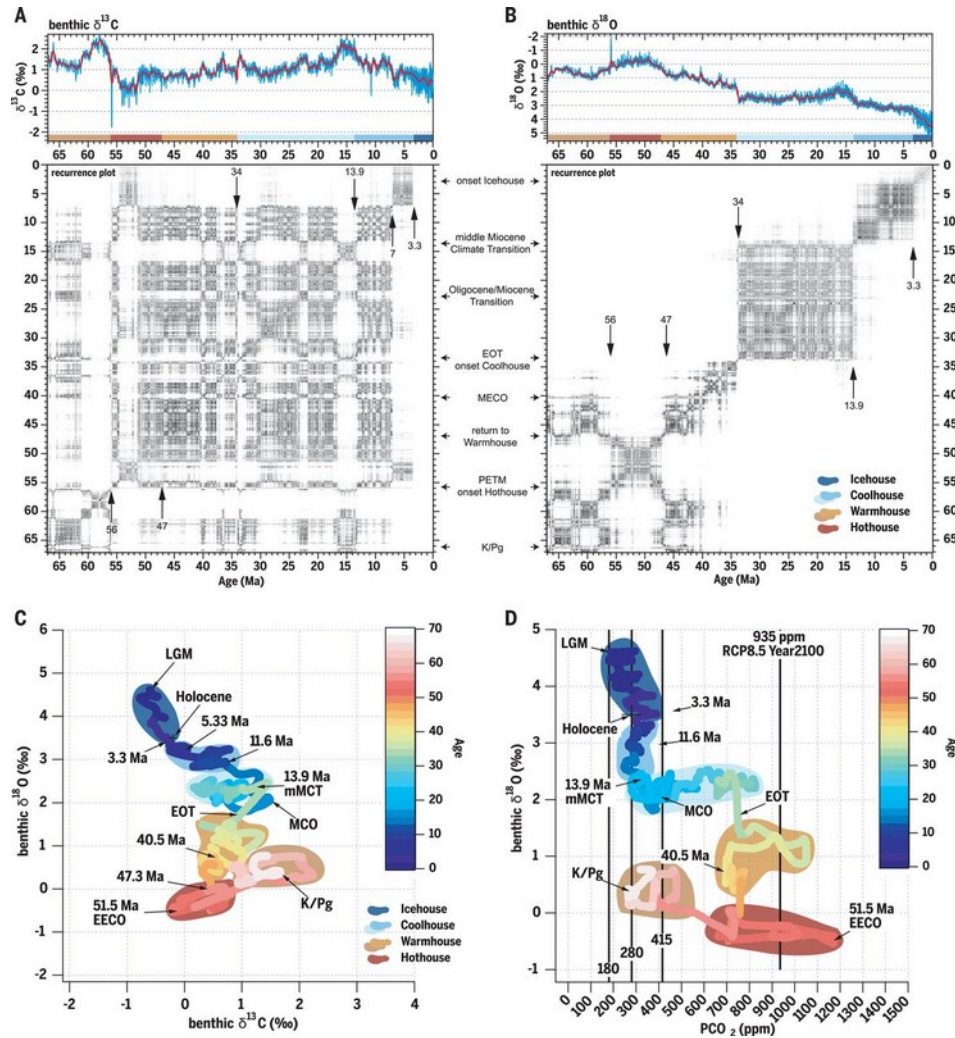
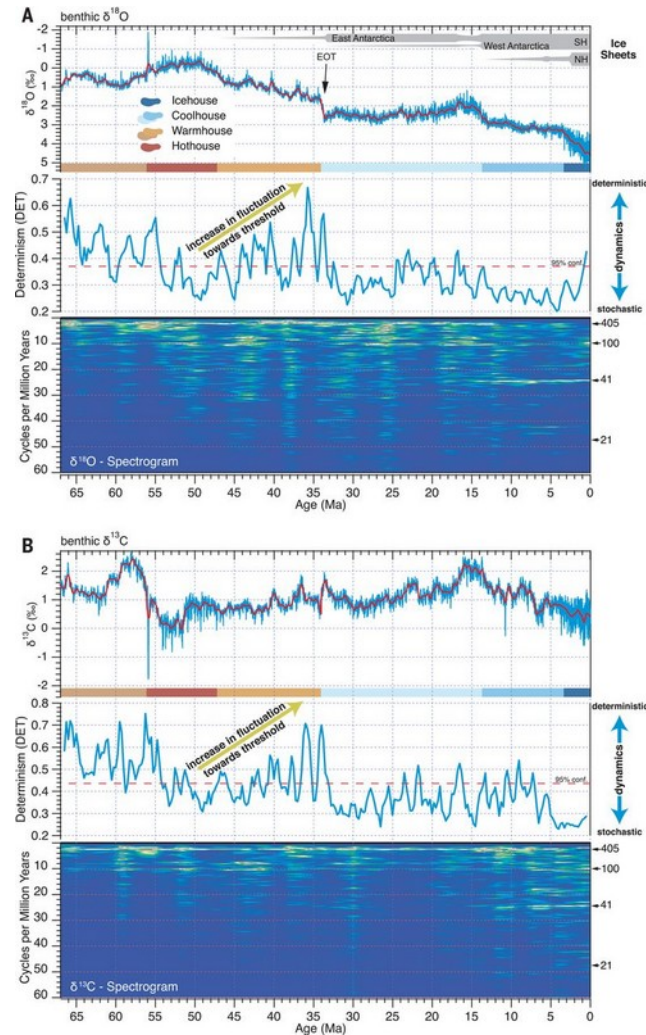


Fig. 2 Climate states of the Cenozoic.

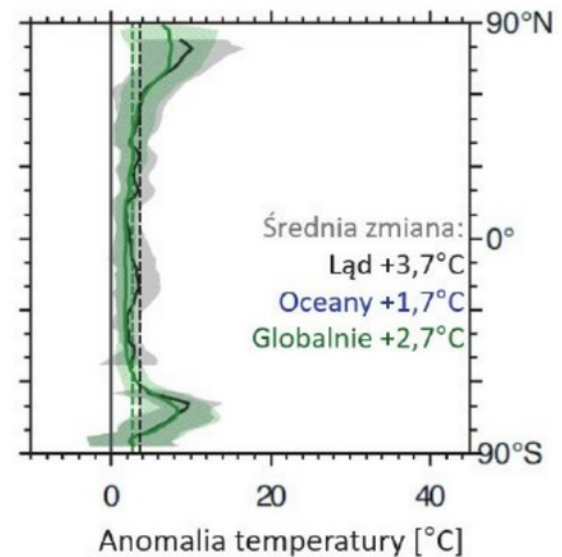
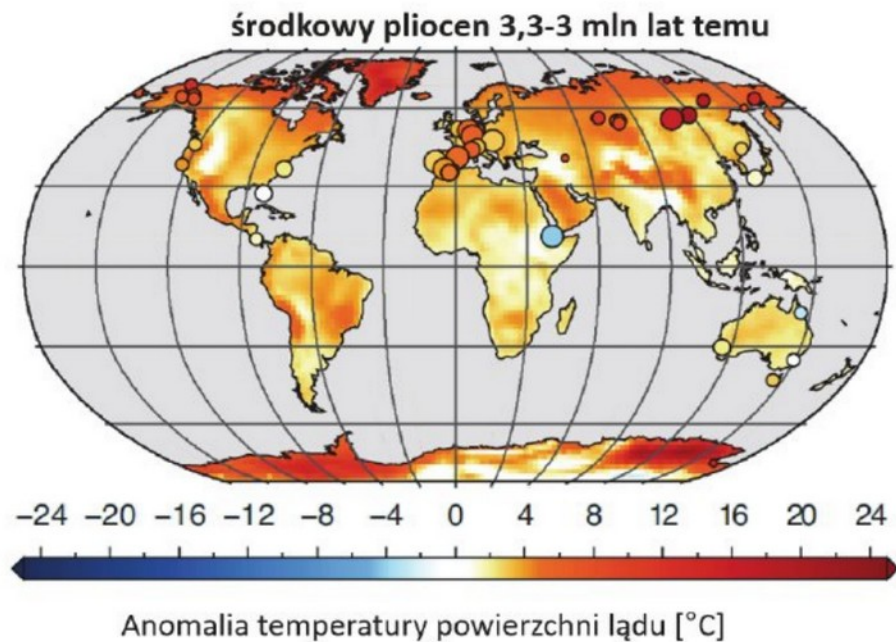


Thomas Westerhold et al. Science 2020;369:1383-1387

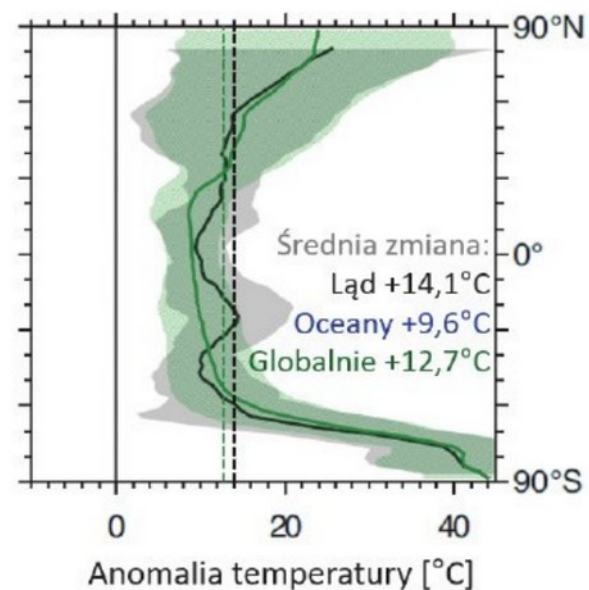
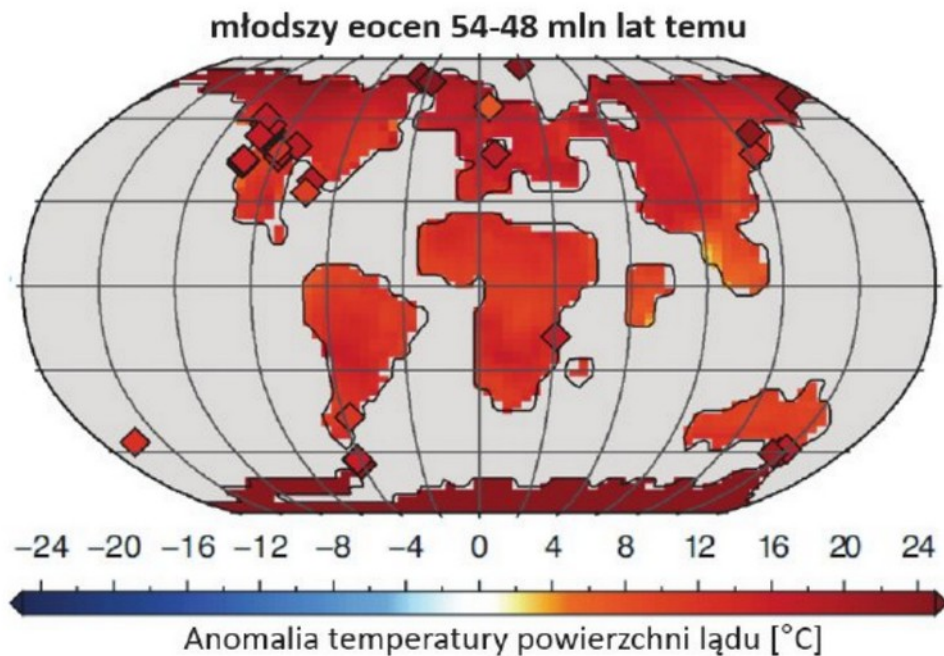
Quasi-periodic changes and determinism in the global reference carbon cycle and oxygen isotope record.



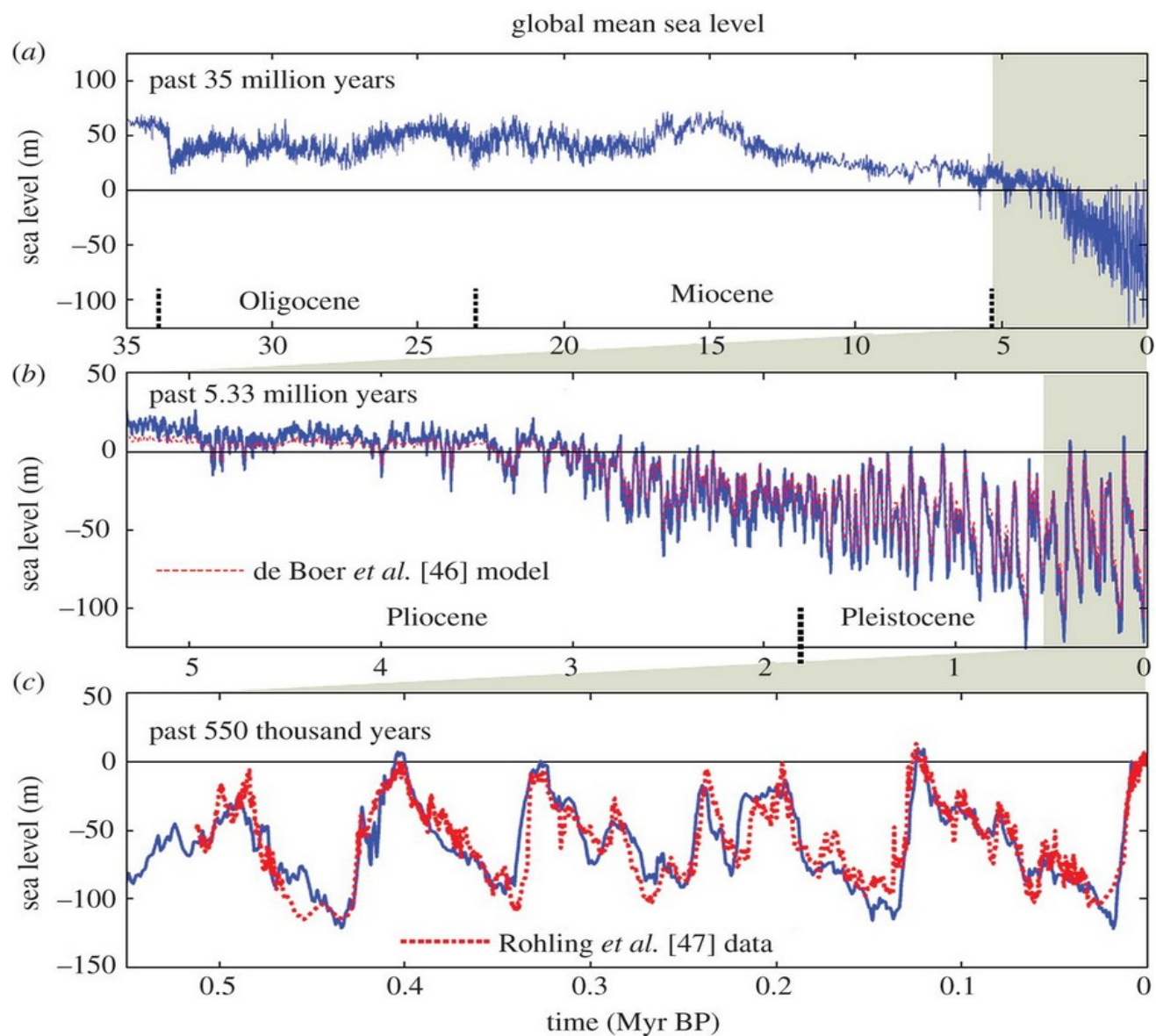
Thomas Westerhold et al. *Science* 2020;369:1383-1387



Ilustracja 3.2.2. Anomalie temperatury w środkowym pliocenie, na krótko przed powstaniem lądolodu Grenlandii, względem poziomu z epoki przedprzemysłowej. Na wykresie po prawej stronie czarna linia pokazuje najbardziej prawdopodobne anomalie temperatur na różnych szerokościach geograficznych nad lądami, a zielona globalne; rozmyte pasy pokazują przedział ufności 2σ (prawdopodobieństwo 95%).



Ilustracja 3.2.3. Anomalie temperatury w młodszym eocenie względem poziomu z epoki przedprzemysłowej. Na wykresie po prawej czarna linia pokazuje najbardziej prawdopodobne anomalie temperatur na różnych szerokościach geograficznych nad lądami, a zielona – nad lądami i oceanami łącznie; rozmyte pasy pokazują przedział ufności 2σ .

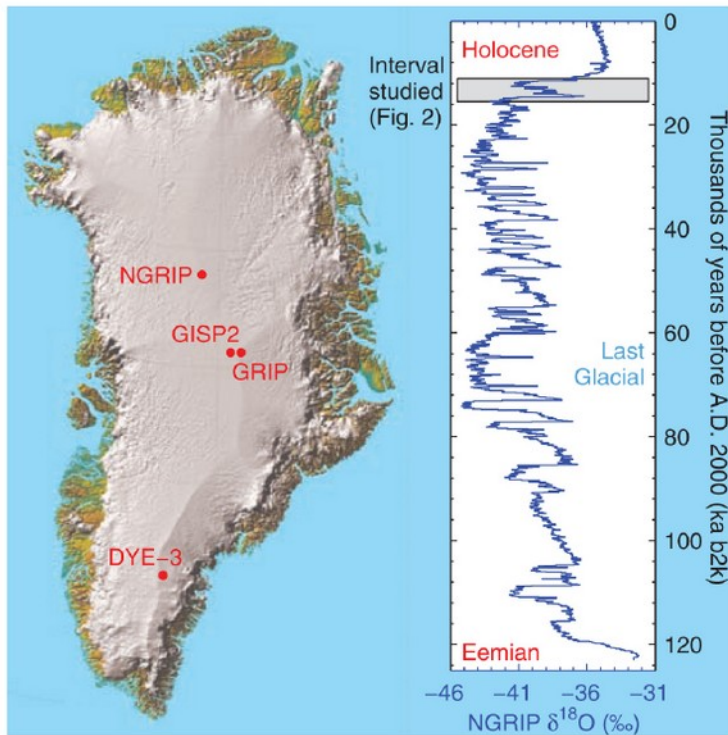


Deep ocean temperature in (a) the Pliocene and Pleistocene and (b) the last 800 000 years. High-frequency variations (black) are five-point running means of the original data [4], whereas the blue curve has a 500 kyr resolution. The deep ocean temperature for the entire Cenozoic era is in figure 1b.

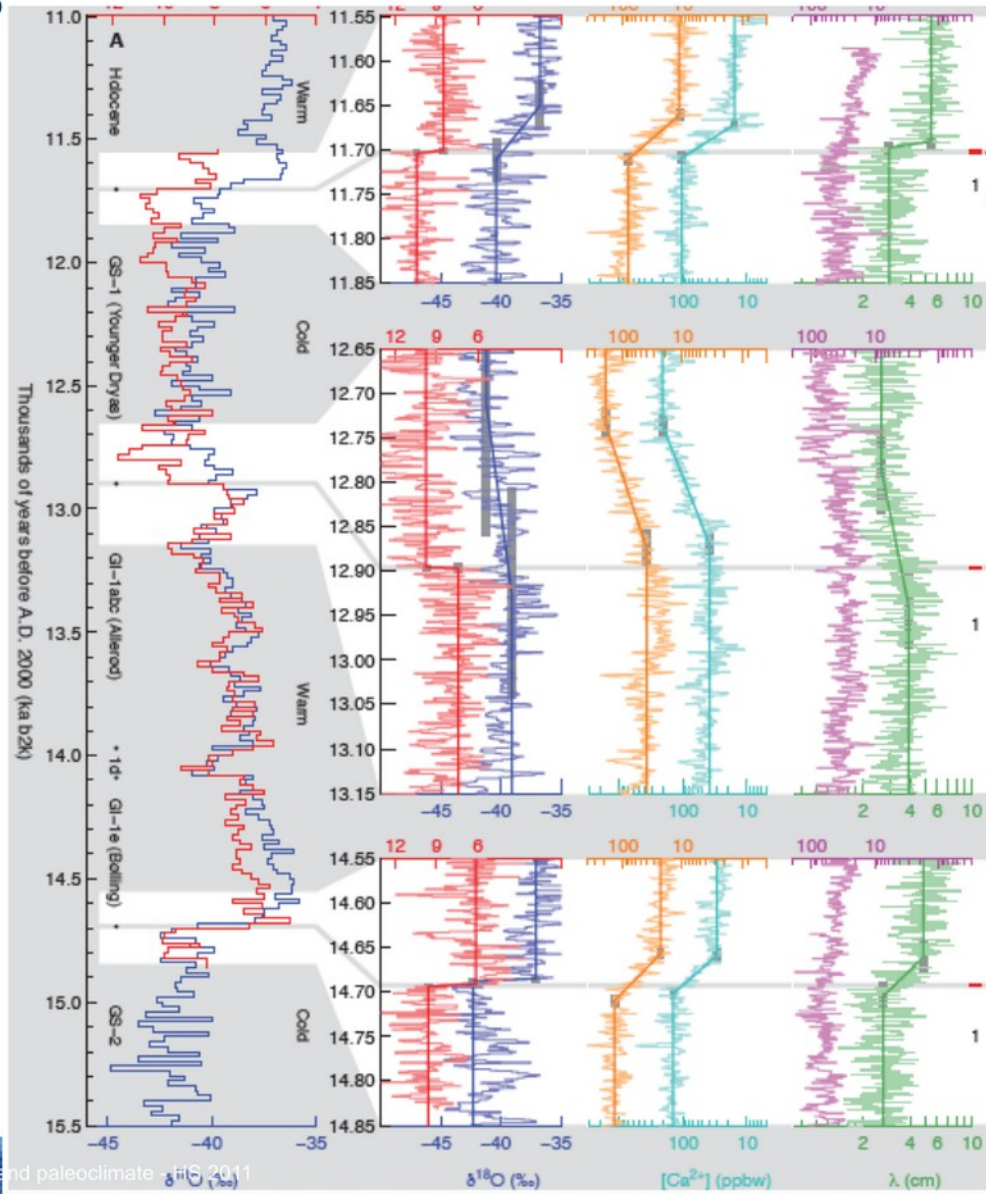
Application in ice cores

Abrupt climate change

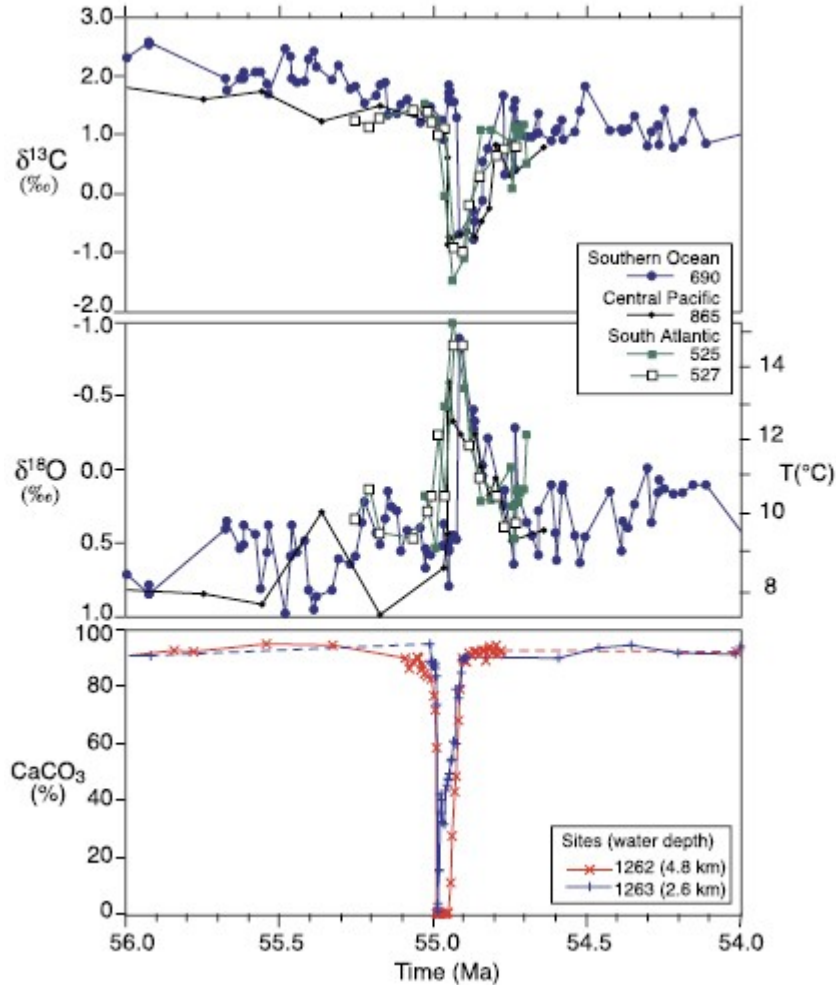
- Study the long ice record in Greenland



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



Abrupt Climate Change – przykład: 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 CO_2 and CH_4 that was coincident with an approximately 5°C global warming (centre panel). Using the carbon isotope records, numerical models show that CH_4 released by the rapid decomposition of marine hydrates might have been a major component ($\sim 2,000$ GtC) of the carbon flux (Dickens and Owen, 1996).

IPCC 2007

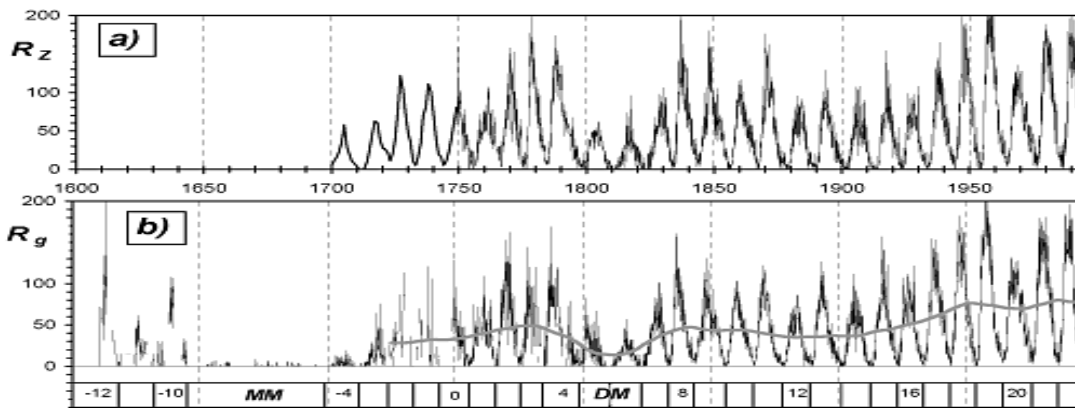


Figure 1: Sunspot numbers since 1610. a) Monthly (since 1749) and yearly (1700 – 1749) Wolf sunspot number series. b) Monthly group sunspot number series. The grey line presents the 11-year running mean after the Maunder minimum. Standard (Zürich) cycle numbering as well as the Maunder minimum (MM) and Dalton minimum (DM) are shown in the lower panel.

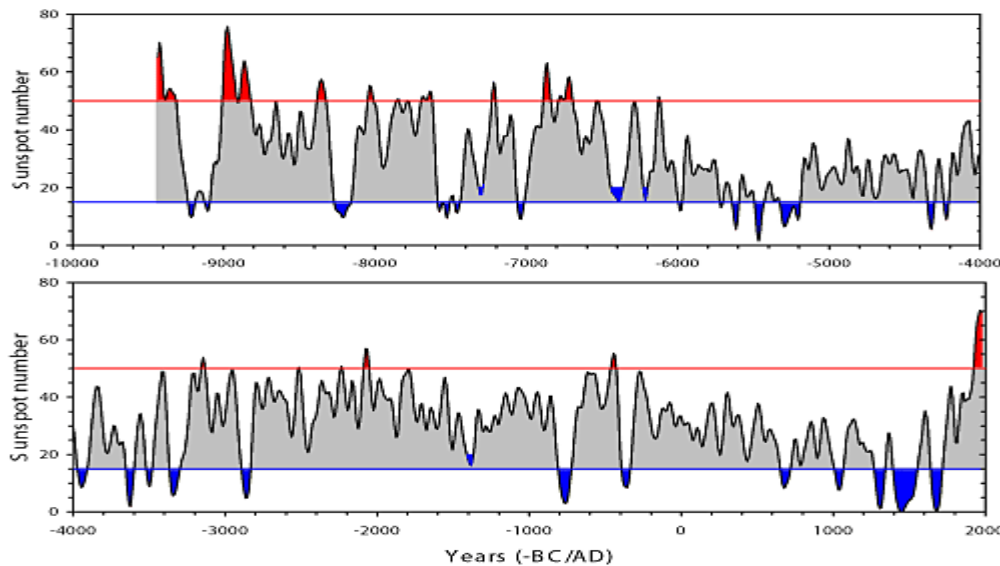


Figure 17: Sunspot activity (over decades, smoothed with a 12221 filter) throughout the Holocene, reconstructed from ^{14}C by Usoskin *et al.* (2007) using geomagnetic data by Yang *et al.* (2000). Blue and red areas denote grand minima and maxima, respectively.]

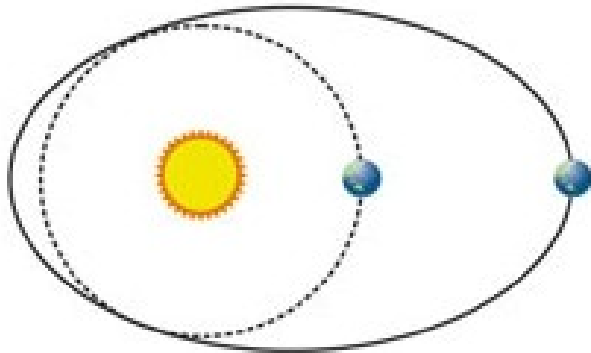
PLAMY NA SŁOŃCU

I.G. Usoskin "A History of Solar Activity over Millennia"
 Publication URI:

<http://www.livingreviews.org/lrsp-2008-3>

Cykle orbitalne

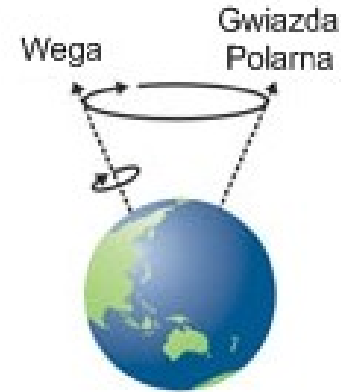
Cykle Milankowicia



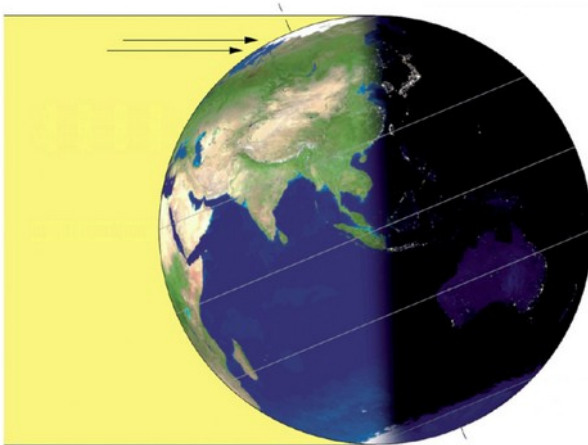
mimośród



nutacja



precesja



Lato na półkuli północnej. Kiedy północna półkula Ziemi otrzymuje latem więcej energii (czemu sprzyjają dwie niezależne sytuacje – mniejsza od średniej odległość Ziemi od Słońca oraz większe nachylenie osi obrotu Ziemi), lata w Arktyce są cieplejsze, co prowadzi do zaniku czapy polarnej.

Problem nachylenia osi:

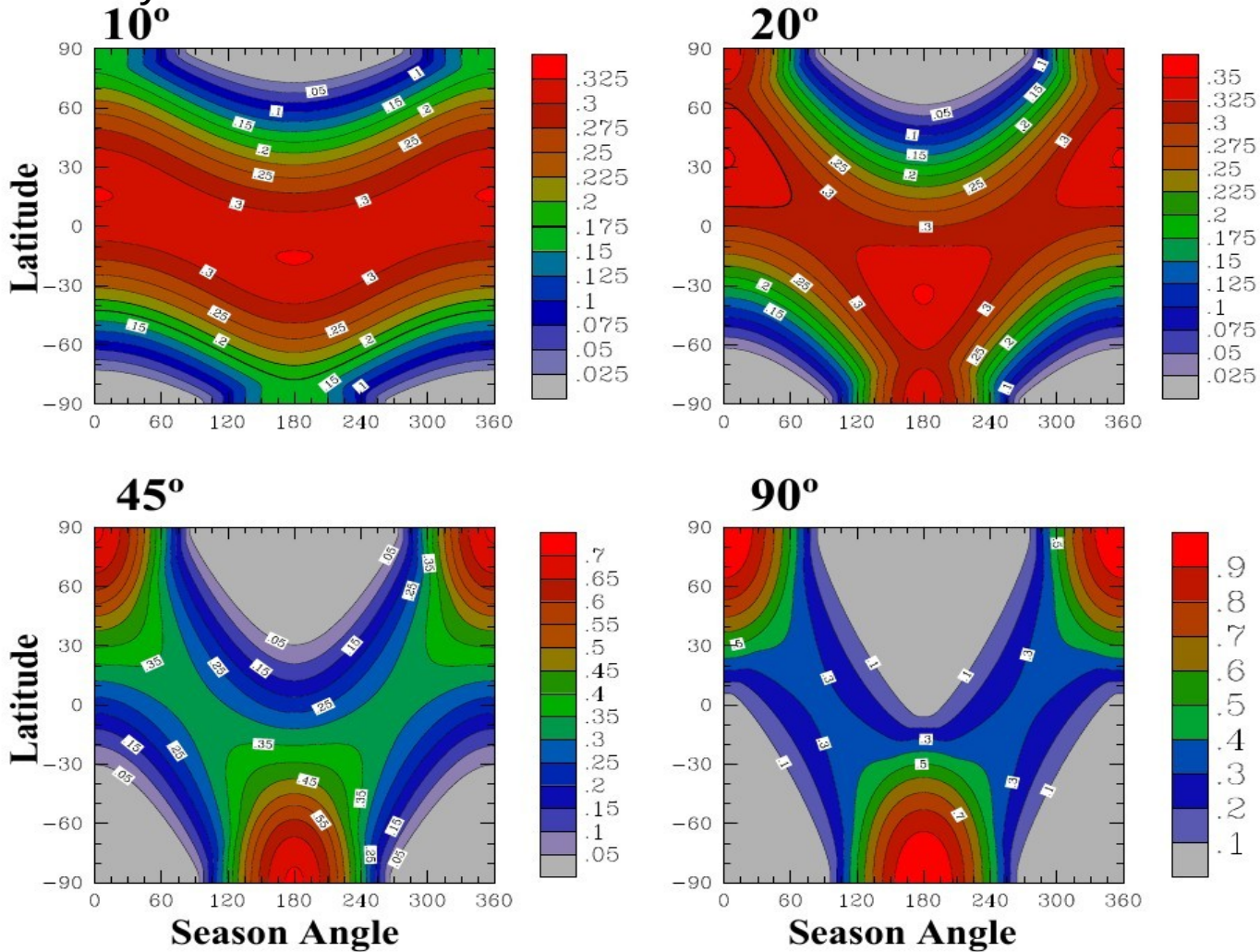
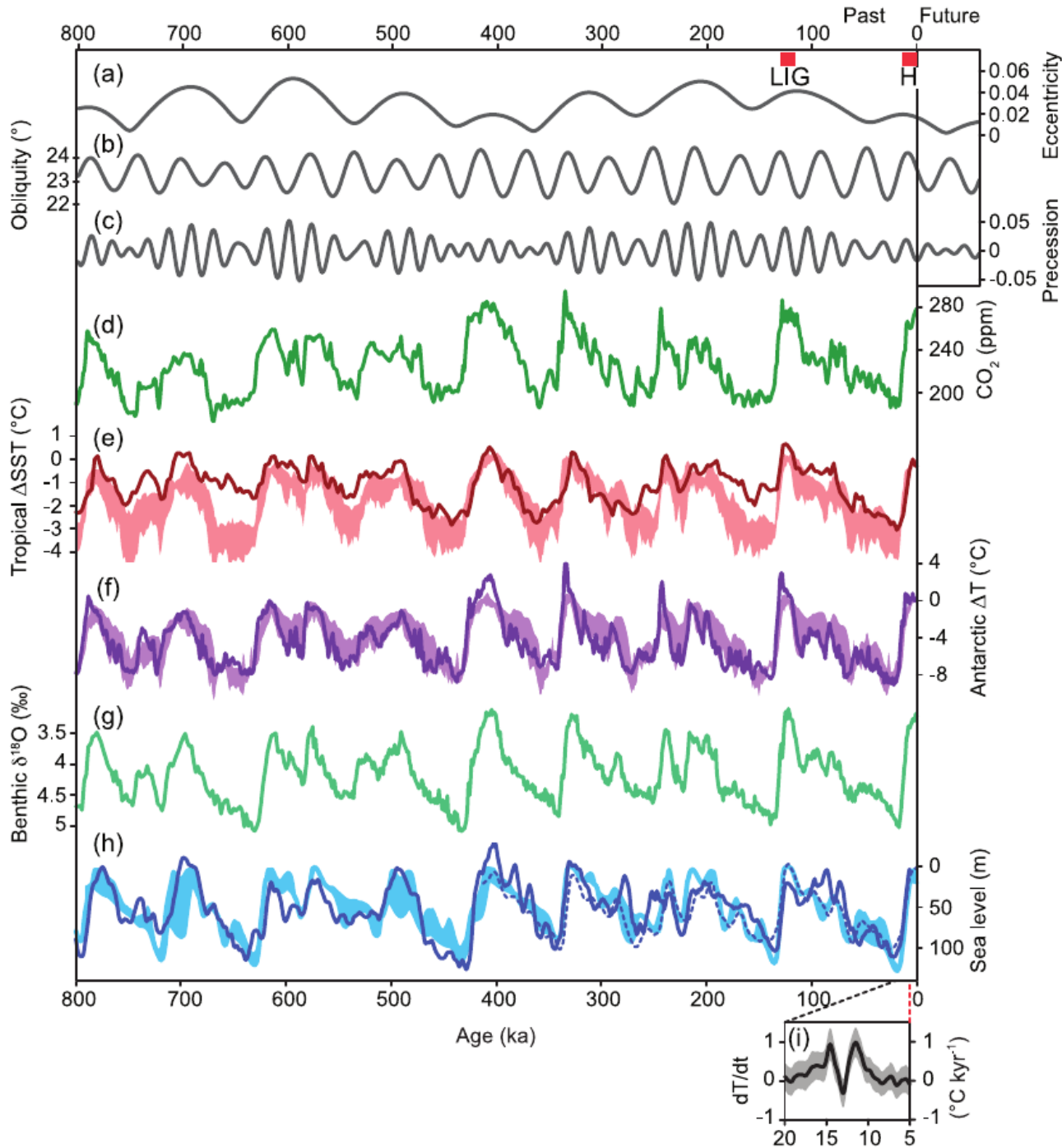
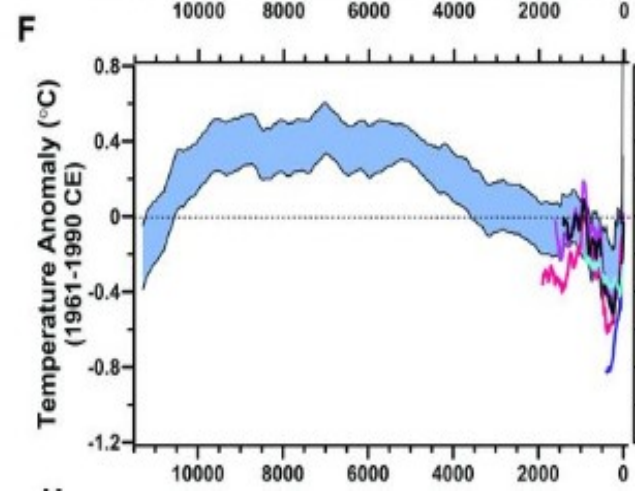
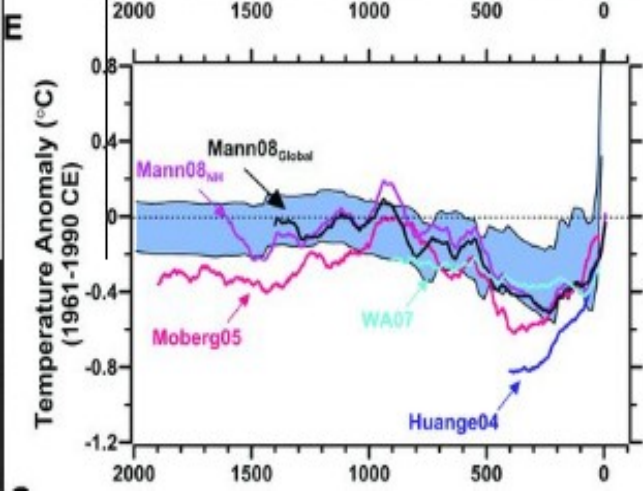
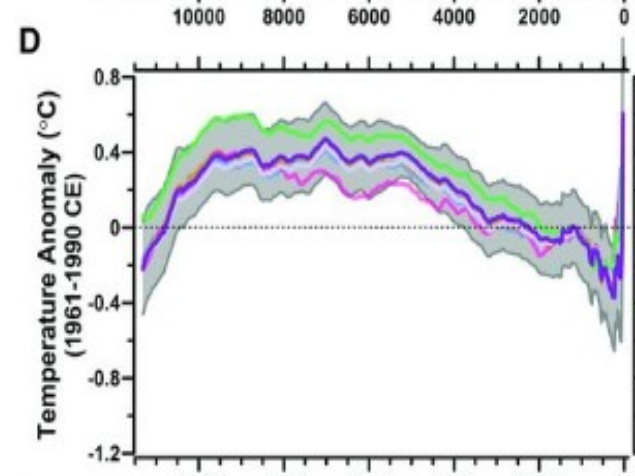
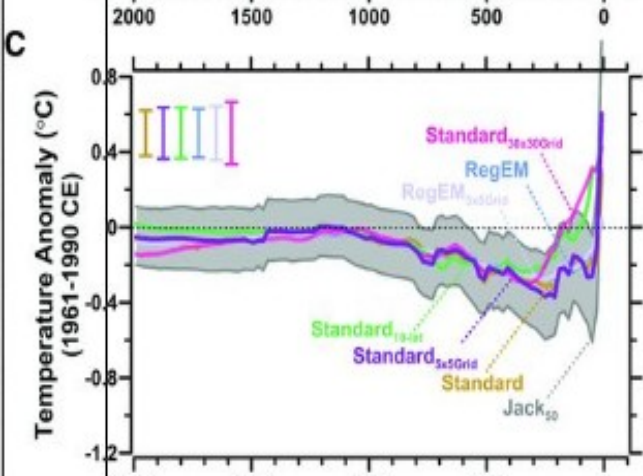
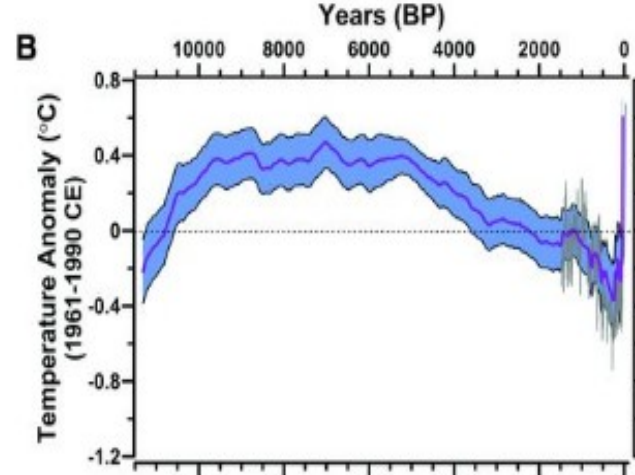
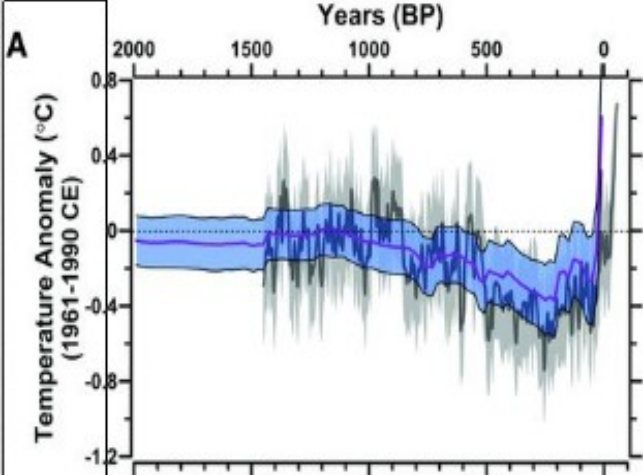


Fig. 7.5: The seasonal and latitudinal distribution of daily-mean flux factor for four different values of the obliquity. In these plots, a circular orbit has been assumed. To obtain the daily mean energy flux incident on each square meter of the planet's surface, one multiplies the flux factor by the solar constant. For example, if the solar constant is 1000W/m^2 , the incident solar flux at the pole during the Summer solstice is about 700W/m^2 if the obliquity is 45° . (Pierrehumbert, „Principles of planetary climate”)



Wymuszenia
 orbitalne
 I ich efekty
 zapisane w
 proxies.
 (IPCC 2013)



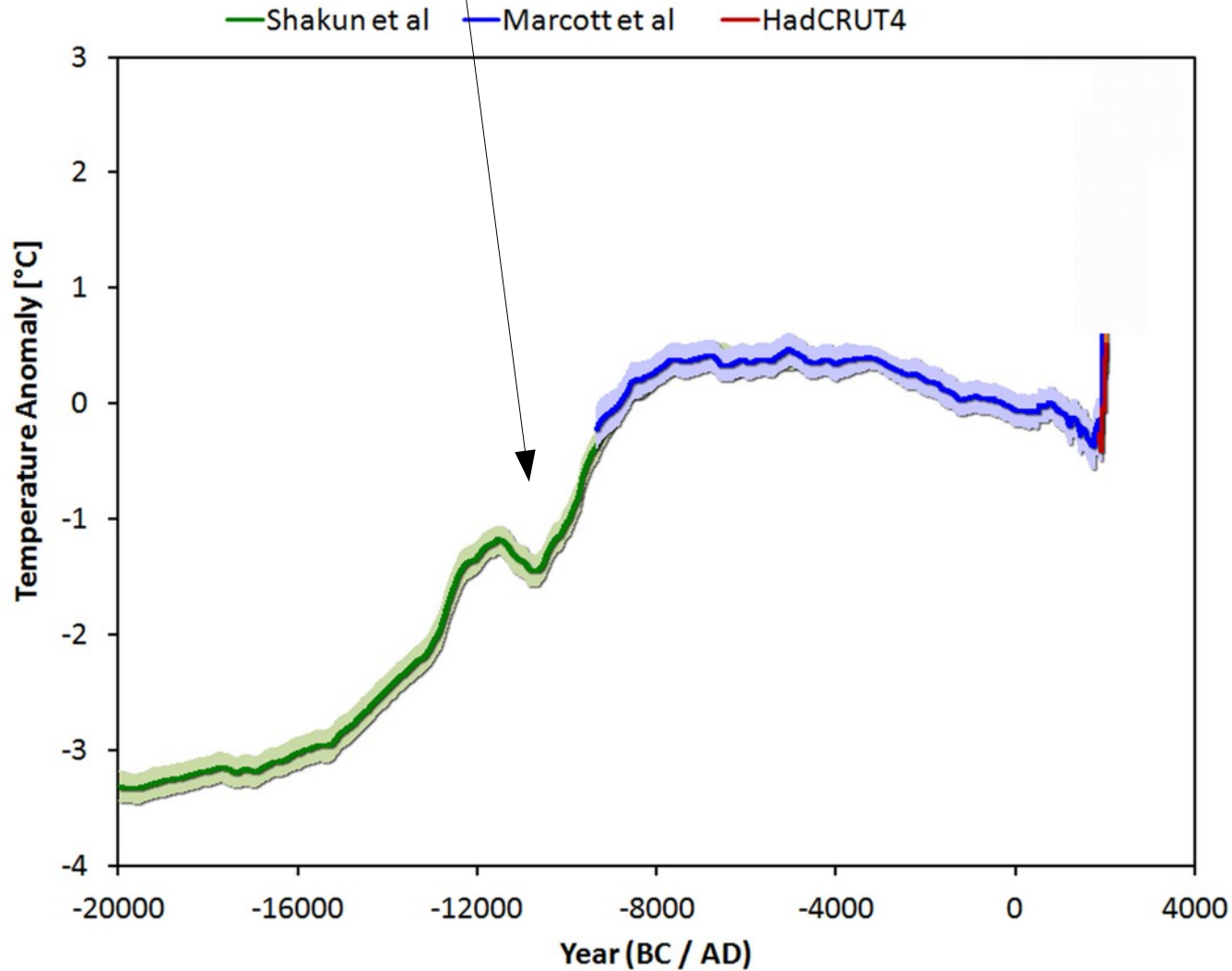
Czy teraz jest podobnie?

Porównanie rekonstrukcji globalnych i hemisferycznych zmian temperatury w holocenie (ostatni interglacja) oraz obserwowanego ostatnio wzrostu temperatury

S A Marcott et al.
Science 2013;339:1198-1201



Abrupt Climate Change – przykład: Drias Młodszy



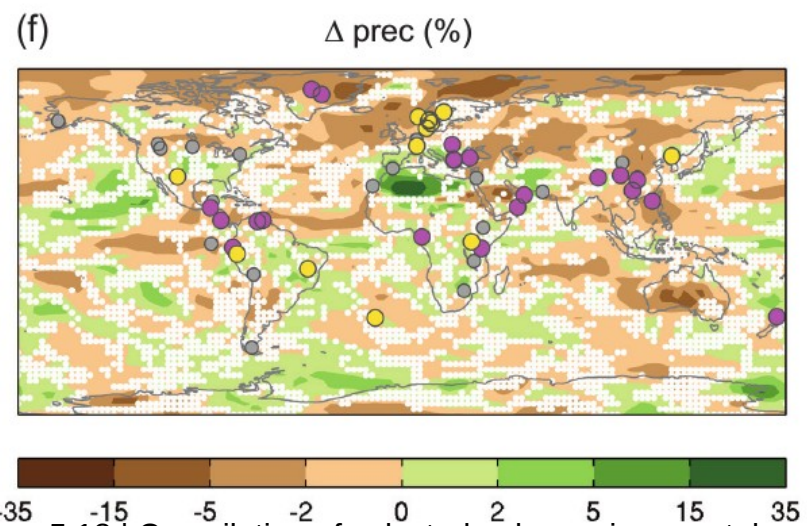
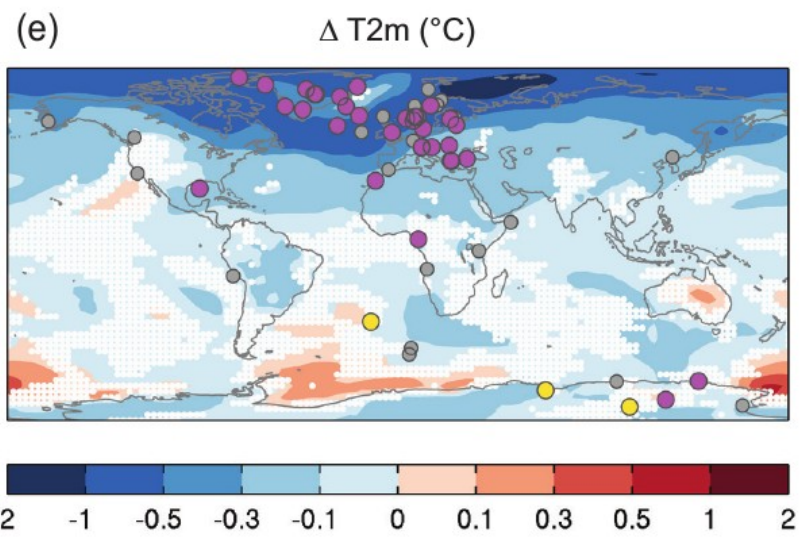
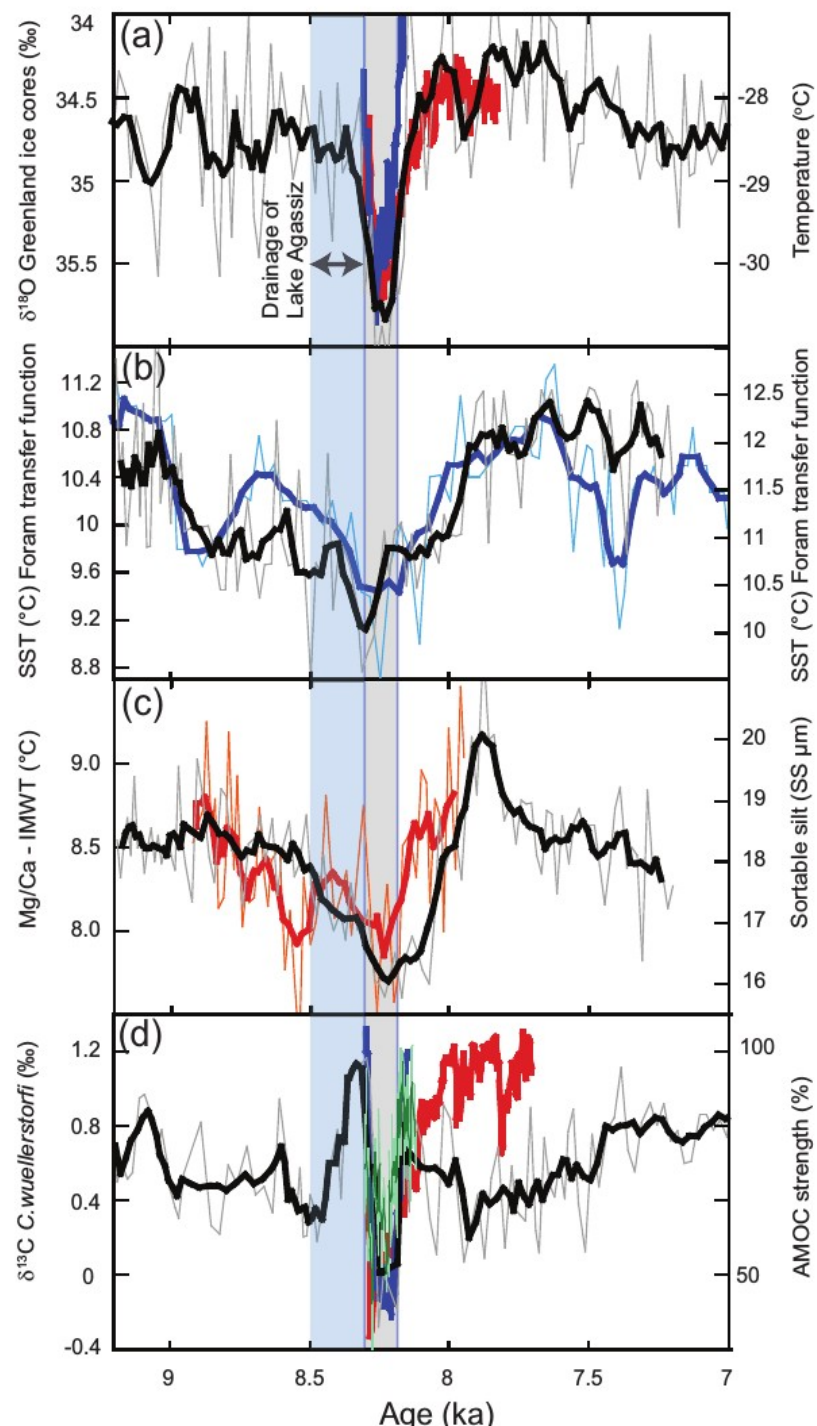
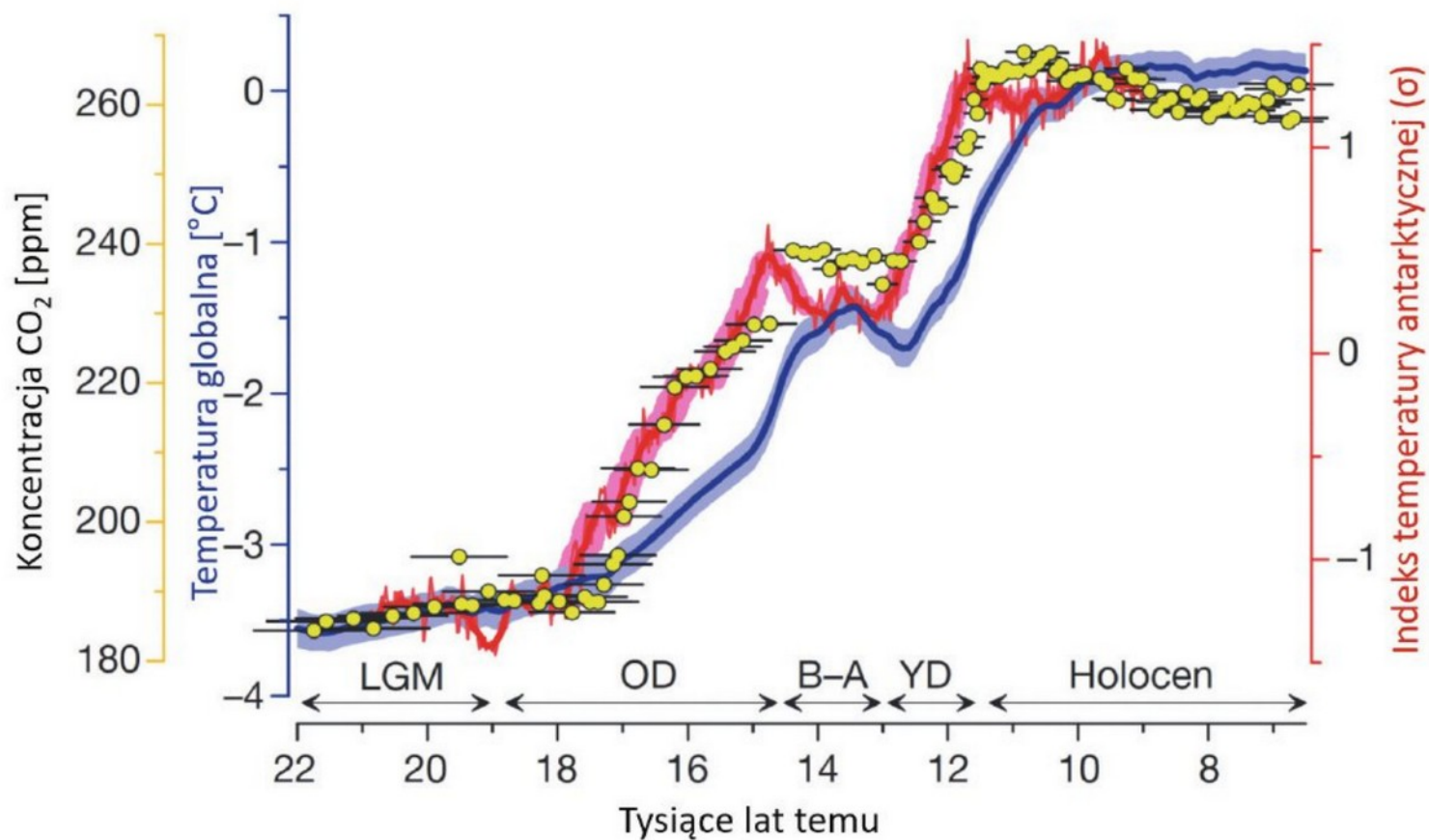
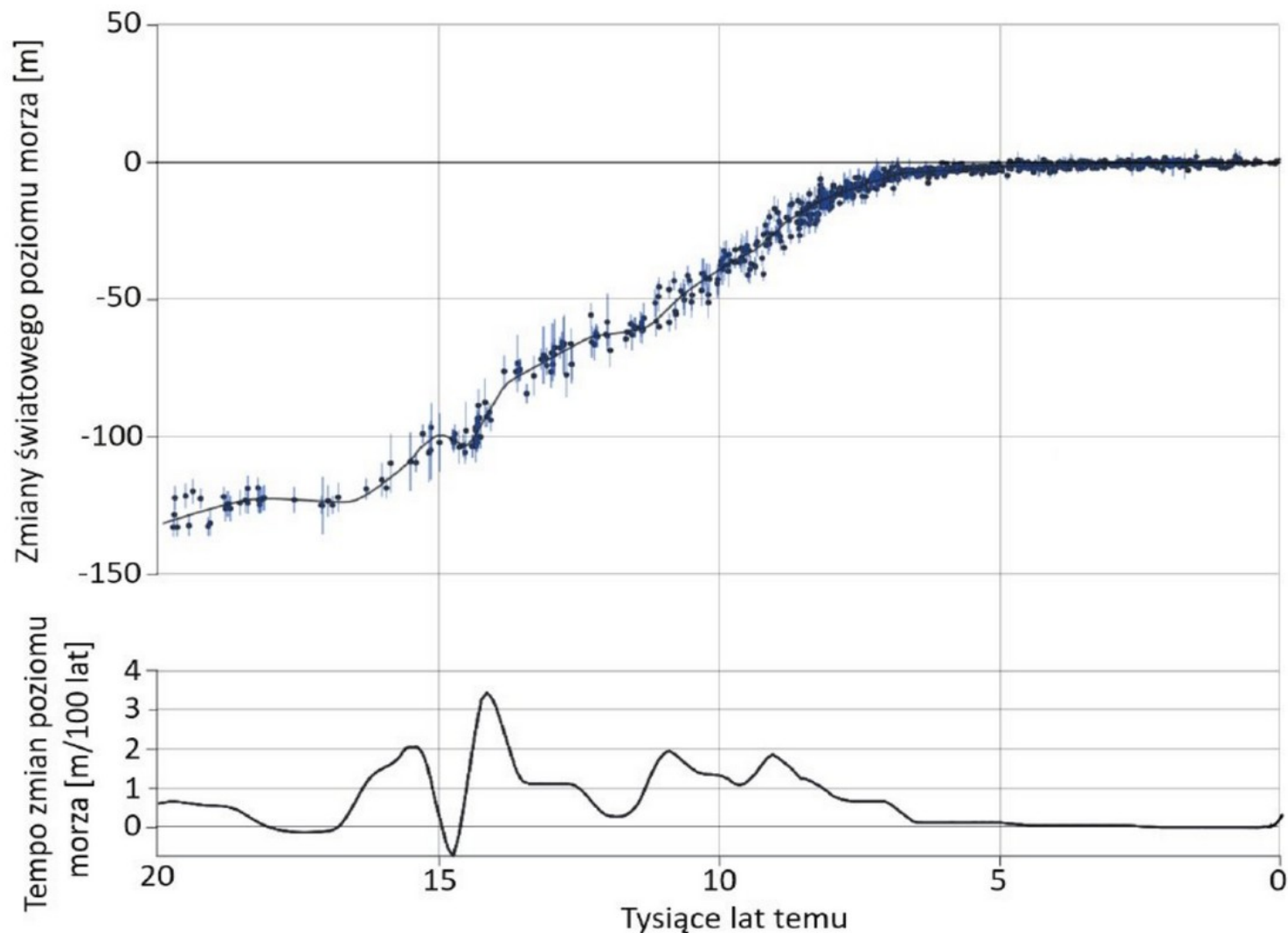


Figure 5.18 | Compilation of selected paleoenvironmental and climate model data for the abrupt Holocene cold event at 8.2 ka, documenting temperature and ocean-circulation changes around the event and the spatial extent of climate anomalies following the event (IPCC 2013)

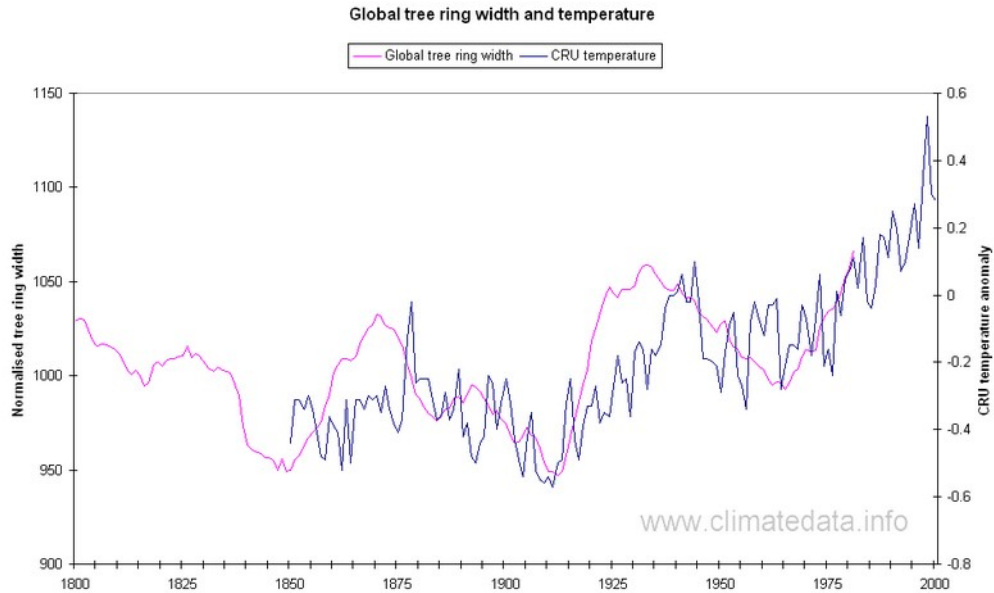


Ilustracja 3.1.6. Średnia globalna temperatura (niebieska linia) określona na podstawie wskaźników klimatycznych, temperatura Antarktydy (czerwona linia) określona na podstawie rdzeni lodowych i atmosferyczna koncentracja CO₂ (żółte kółka). Zaznaczony stopień niepewności 1σ. Zaznaczone są okresy: maksimum ostatniej epoki lodowej (LGM), starszy dryas (OD), Bølling-Allerød (B-A), młodszy dryas (YD) oraz holocen.

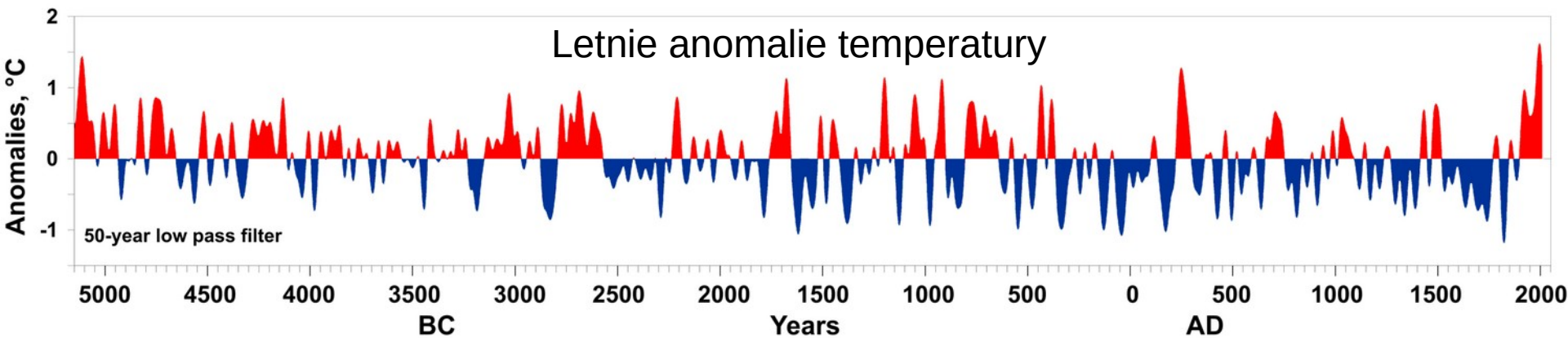


Ilustracja 3.1.11. Górny panel: zmiana światowego poziomu morza w ciągu ostatnich 20 tys. lat (czarna linia), na podstawie pośrednich wskaźników poziomu morza (czarne kropki z pionowymi niebieskimi liniami pokazującymi stopień niepewności). Dolny panel: Tempo zmiany światowego poziomu morza uśrednione w interwałach 500 lat (z wyjątkiem zmian z ostatniego stulecia).

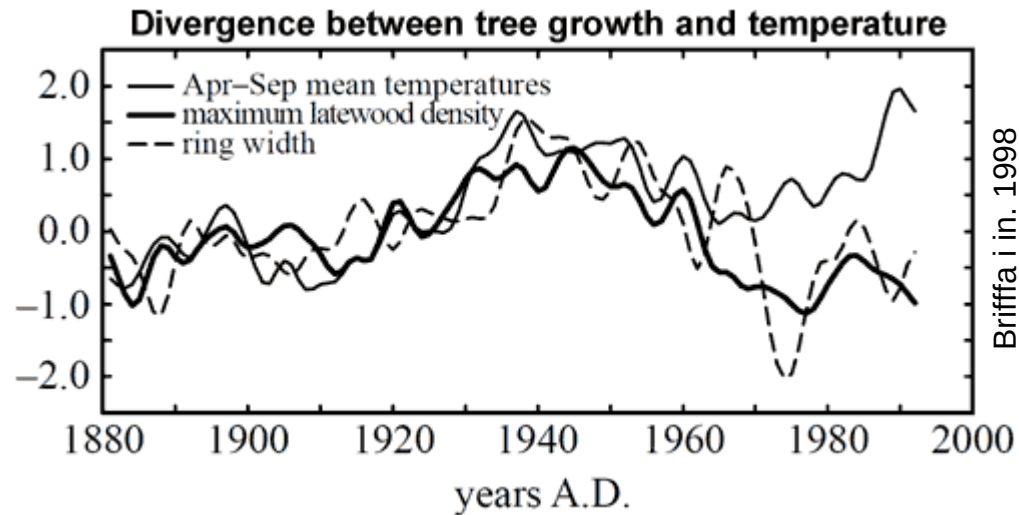
Słoję drzew



Na podstawie szerokości i struktury słojów określa się warunki panujące w poszczególnych latach.



Słoję drzew – „divergence problem”



- od lat sześćdziesiątych,
- tylko na półkuli północnej,
- związane być może z zanieczyszczeniem i podwyższonymi poziomami dwutlenku węgla i azotanów, obniżoną aktywnością słoneczną lub suszami

Wielorakie rekonstrukcje: multiproxy.

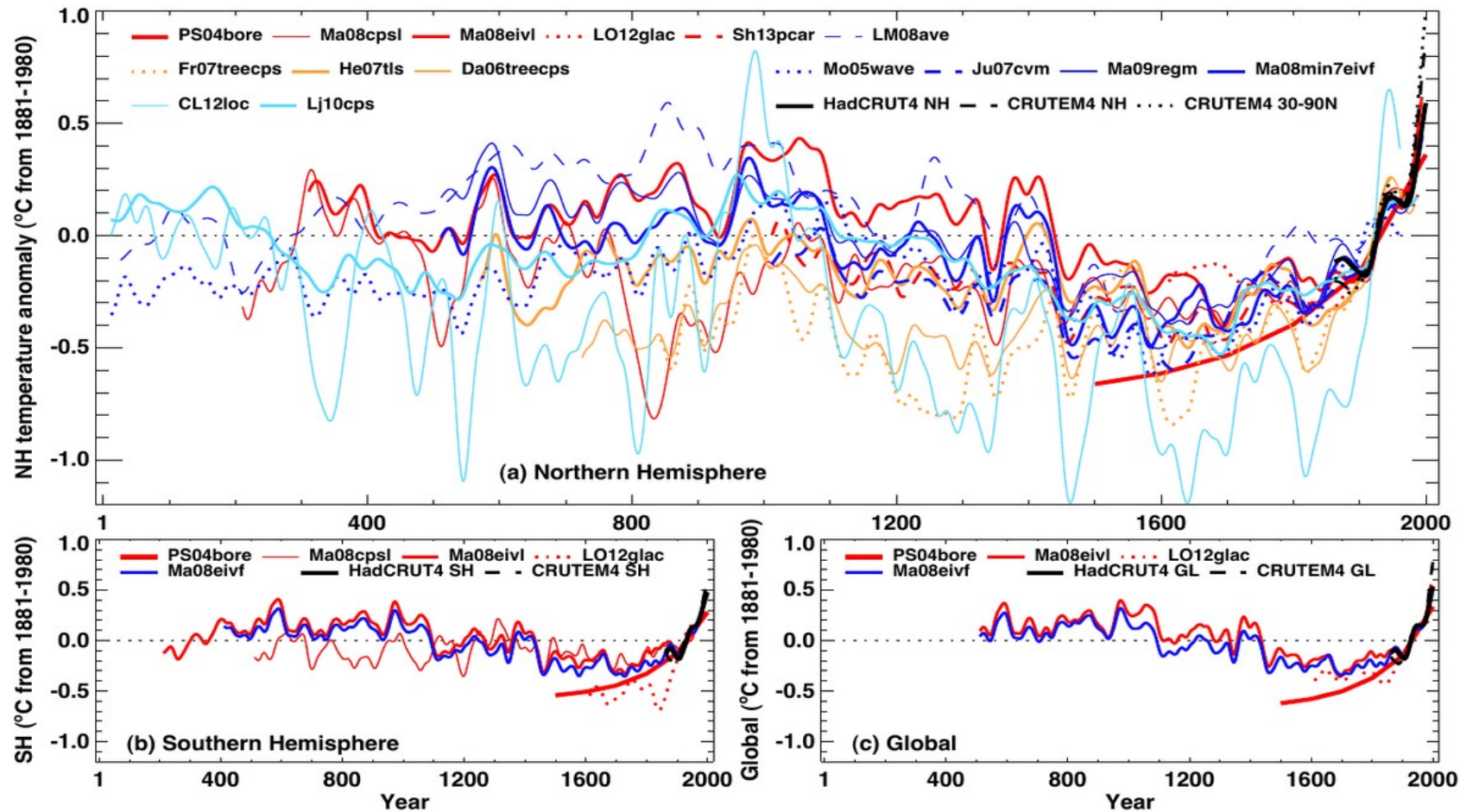
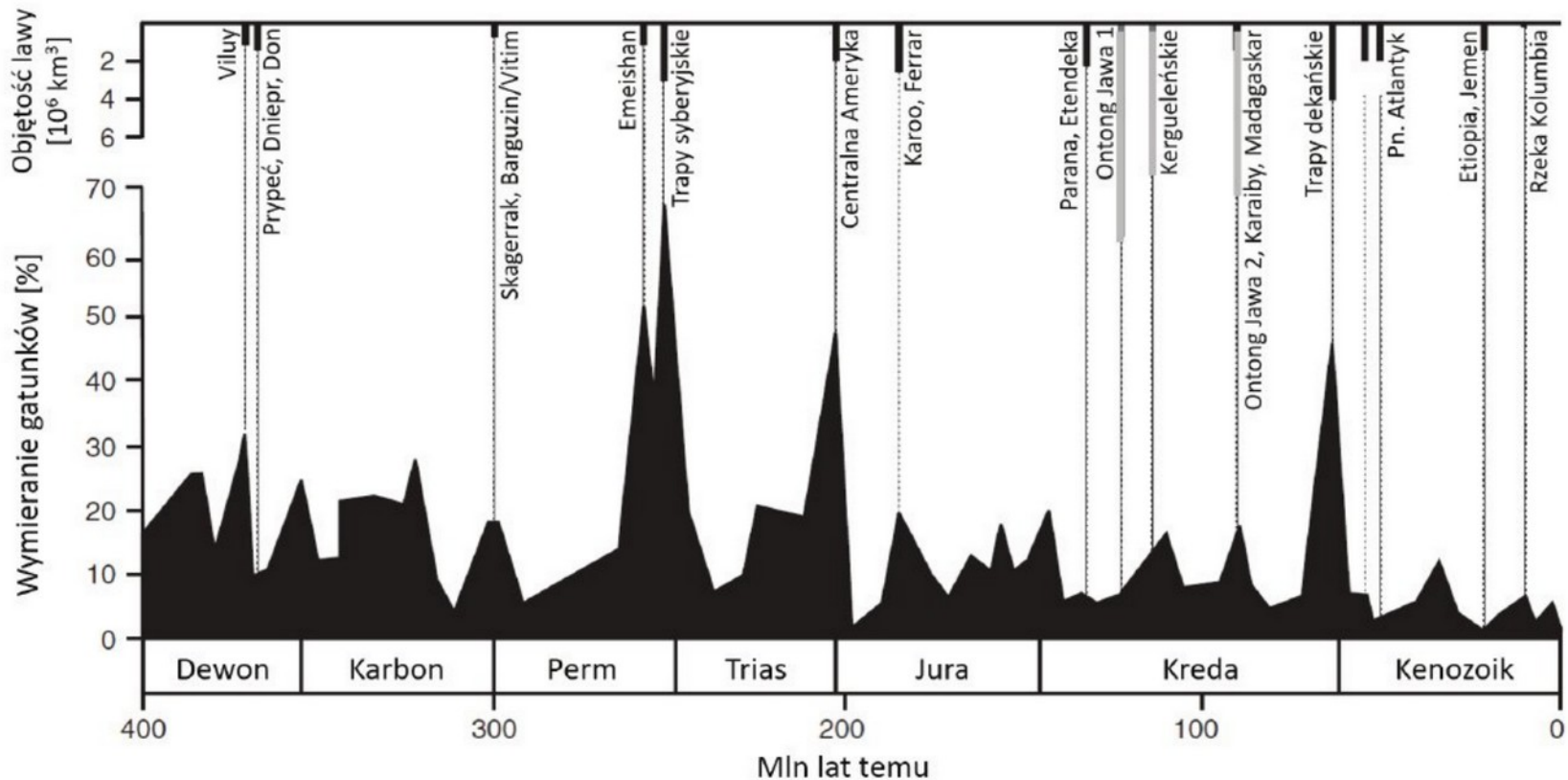
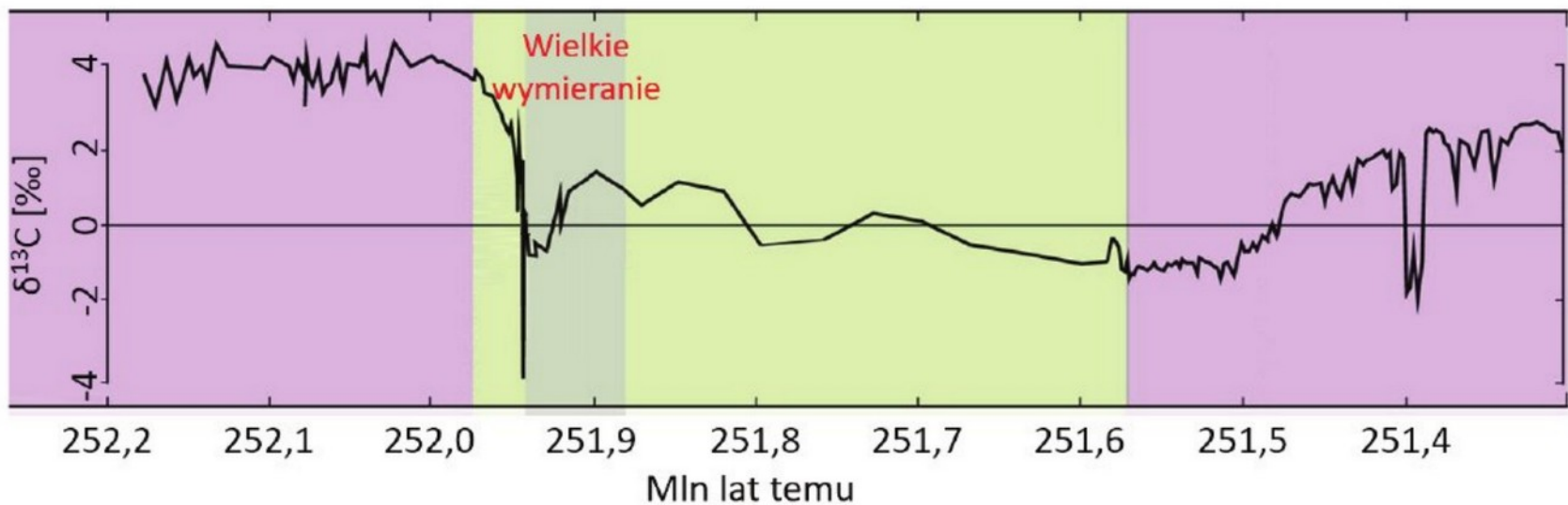


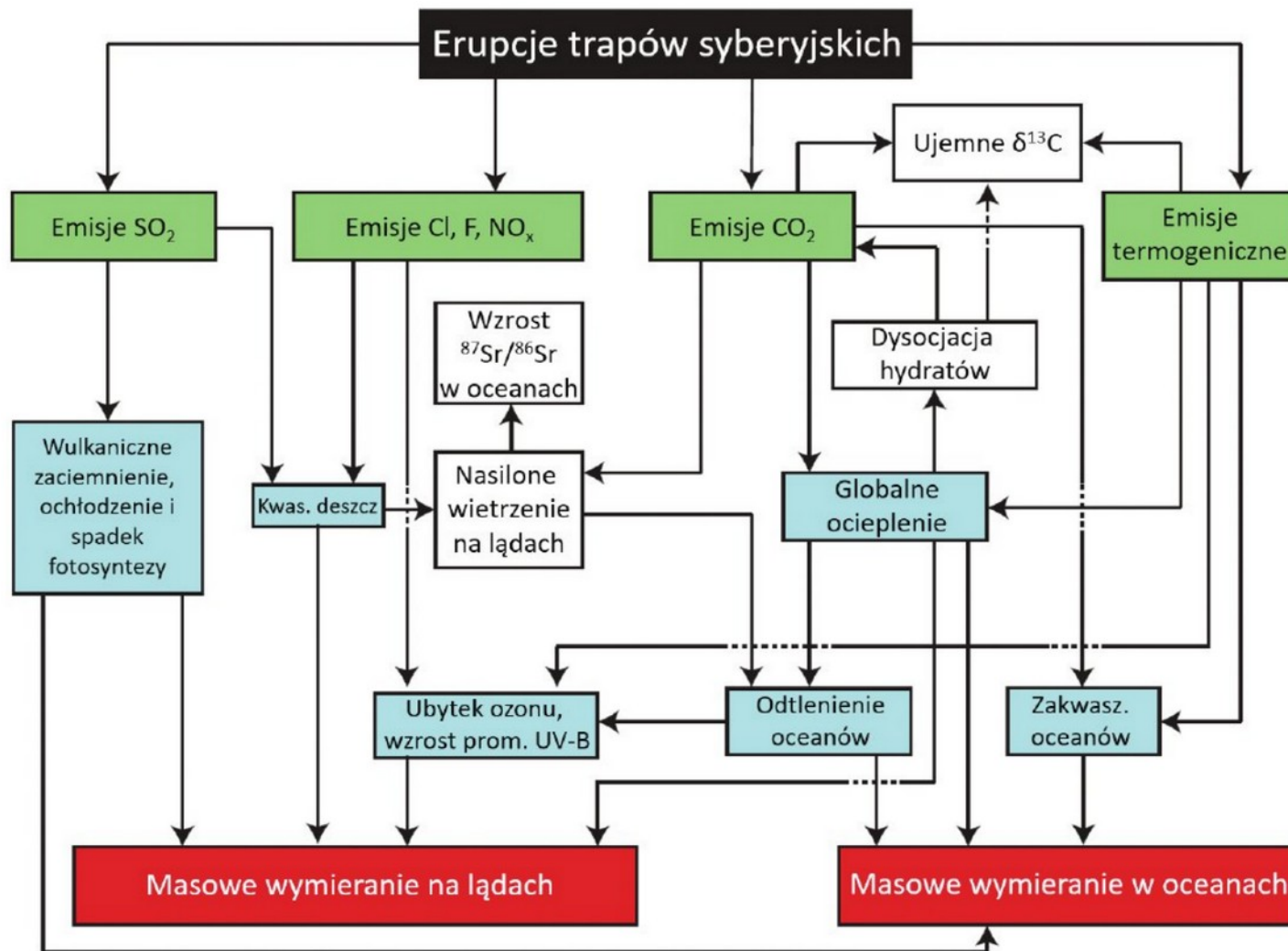
Figure 5.7 | Reconstructed (a) Northern Hemisphere and (b) Southern Hemisphere, and (c) global annual temperatures during the last 2000 years (IPCC 2013)



Ilustracja 3.4.1. Skala wymierań gatunków w ostatnich 400 mln lat (na dole) vs objętość wielkich prowincji magmatycznych (na górze). Kontynentalne wylewy bazaltu pokazane są jako słupki w kolorze czarnym, oceaniczne w kolorze szarym. Wyraźnie widoczna jest korelacja pomiędzy wielkimi wymieraniami a wylewami lawy z wielkich prowincji magmatycznych.



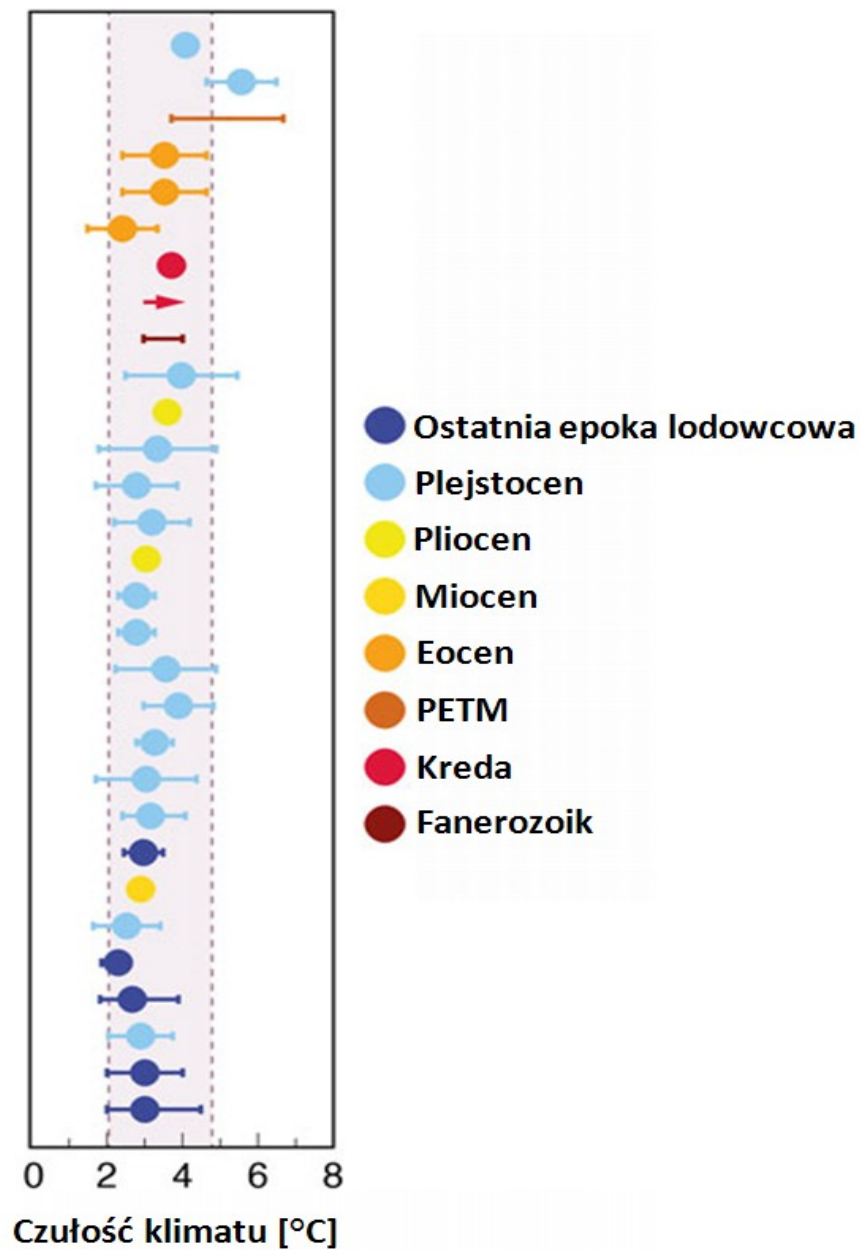
Ilustracja 3.4.2. Zmiany $\delta^{13}\text{C}$, pokazujące bardzo szybkie wprowadzenie do cyklu węglowego bardzo dużych ilości lekkiego izotopu węgla (pochodzenia organicznego) 251,94 mln lat temu. Kolorowe tła prezentują stadia erupcji wulkanów trapów syberyjskich (fioletowe – wylewy powierzchniowe, zielone – wylewy podpowierzchniowe). Okres wielkiego wymierania jest zaznaczony szarym polem.



Ilustracja 3.4.3. Diagram podsumowujący procesy zachodzące podczas wielkiego wymierania na przełomie permu i triasu. Zielone prostokąty: bezpośrednie działania wulkanów. Niebieskie prostokąty: bezpośrednie mechanizmy eksterminacji życia. Stosunek izotopów ⁸⁷Sr/⁸⁶Sr w różnych rodzajach skał jest różny, jeśli przyspieszają procesy wietrzenia skał lądowych, powoduje to zmianę stosunku izotopu strontu w osadach oceanicznych.

**Wielkie wymierania następowały,
gdy dochodziło do silnego
zdestabilizowania
cyklu węglowego przez duże
emisje CO₂ i w konsekwencji dużej
i szybkiej zmiany klimatu.**

Wartości czułości klimatu wraz z zakresem niepewności określone na podstawie badań paleoklimatycznych (PALEOSENS 2012).



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

Caroline H. Lear^{1*}, Pallavi Anand², Tom Blenkinsop¹, Gavin L. Foster³, Mary Gagen⁴, Babette Hoogakker⁵, Robert D. Larter⁶, Daniel J. Lunt⁷, I. Nicholas McCave⁸, Erin McClymont⁹, Richard D. Pancost¹⁰, Rosalind E.M. Rickaby¹¹, David M. Schultz¹², Colin Summerhayes¹³, Charles J.R. Williams⁷ and Jan Zalasiewicz¹⁴

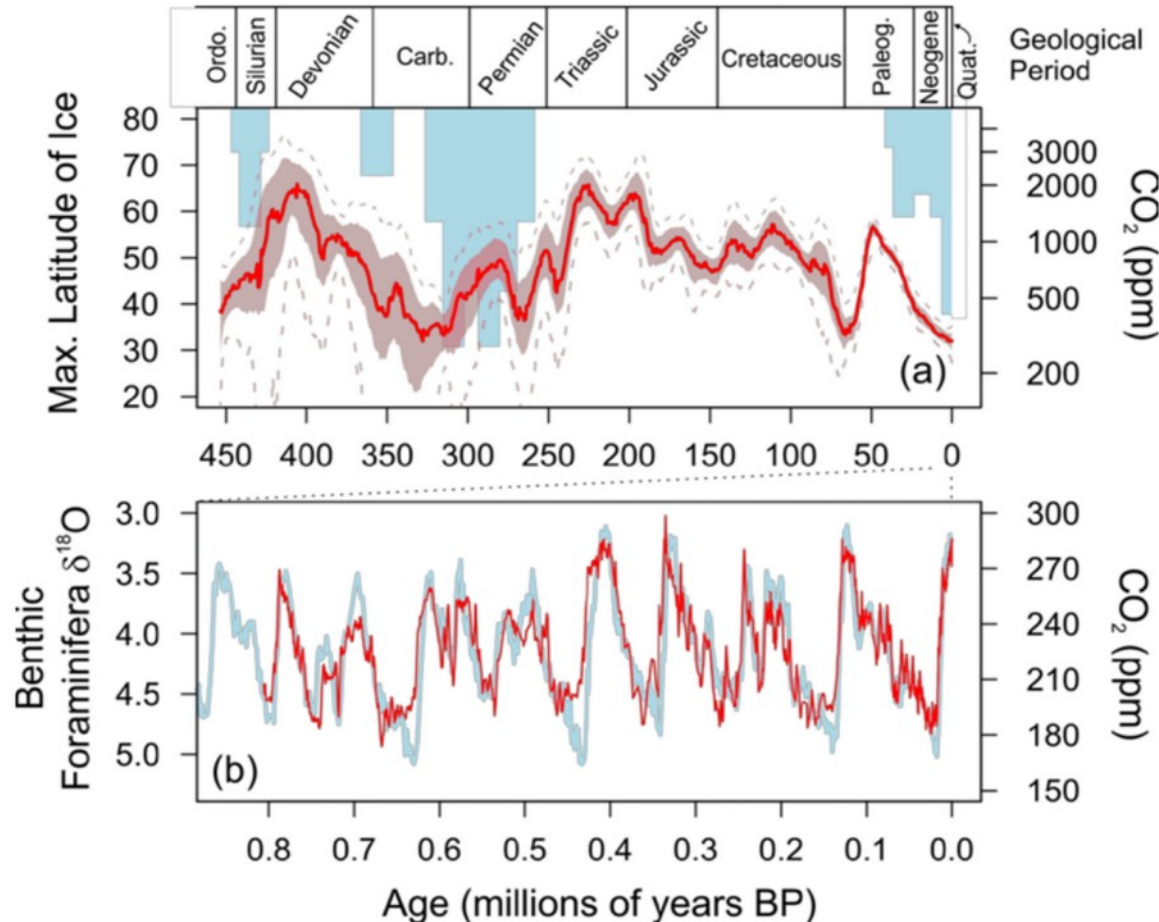
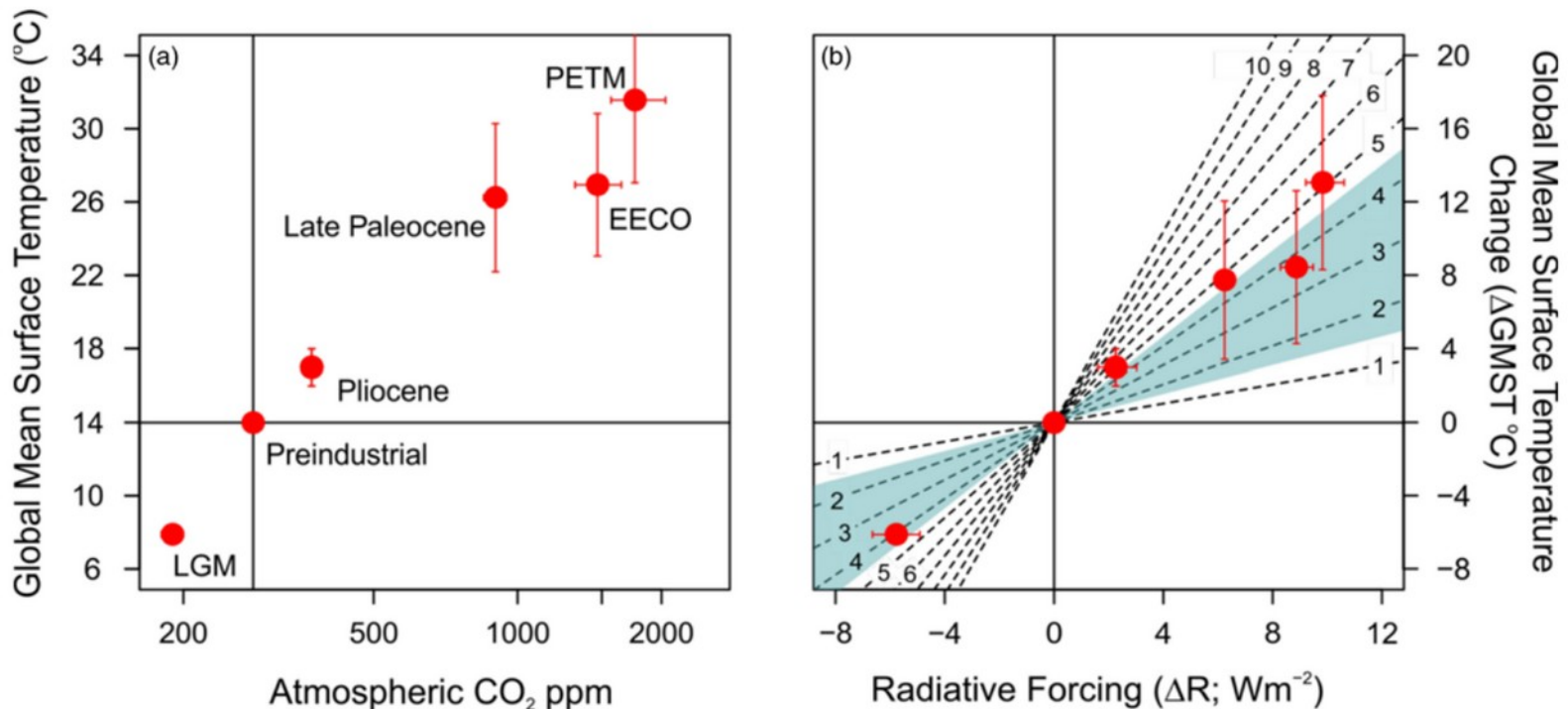


Fig. 1. Carbon dioxide and climate through the Phanerozoic. (a) Latitudinal extent of continental ice deposits shown as blue bars (left axis) and atmospheric CO₂ content (red, right axis). (b) A close-up of the last 0.8 million years comparing CO₂ from ice cores (red, right axis) with benthic foraminiferal oxygen isotope ratios ($\delta^{18}\text{O}$) (blue, left axis).



(a) The relationship between atmospheric CO₂ concentration and global mean surface temperature (GMST) for five time intervals where both variables have been recently well constrained by geological data.

(b) The relationship between radiative forcing (ΔR in $W m^{-2}$) and global mean surface temperature ($\Delta GMST$) relative to pre-industrial values. Contours show equilibrium climate sensitivity from 1 to 10°C per CO₂ doubling, and the blue band shows the canonical IPCC range of Equilibrium Climate Sensitivity of 1.5 to 4.5°C per CO₂ doubling.