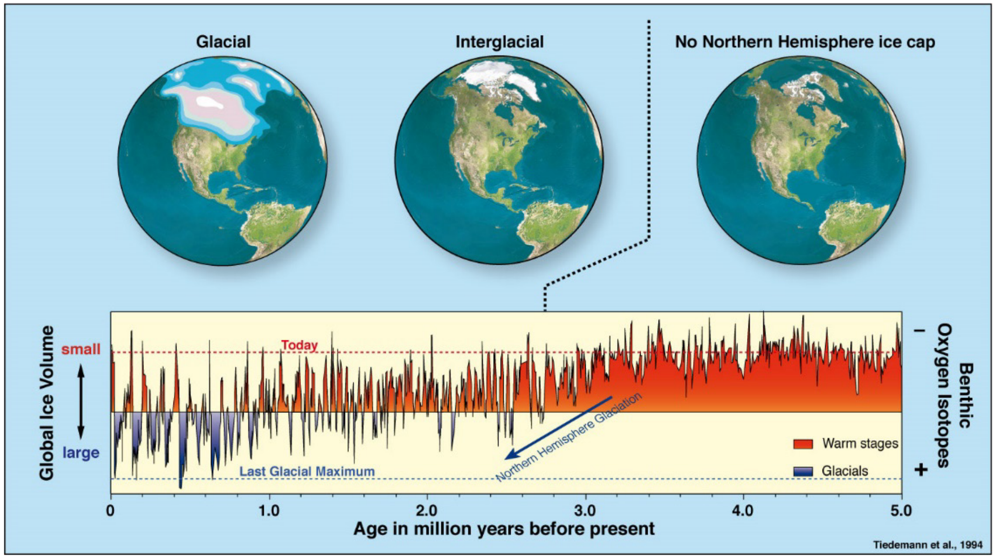
Climates of the Past

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2024
https://umd.instructure.com/courses/1367293



Originally from http://www.awi.de/en/research/research_divisions/geosciences/marine_geology_and_paleontology
Now at https://silentwitnesss.files.wordpress.com/2012/08/klimakurve_webpage.jpg

Lecture 4

10 September 2024

Announcements

1) Problem Set #1, due 2 pm 17 Sept 2024 (a week from now) is posted:
https://umd.instructure.com/courses/1367293/quizzes/1725752

2) An ungraded quiz asking about your research interest, due 11:59 am on 12 Sept 2024, is also posted

Question 1 0.5 pts

Of the potential topic areas for this class, listed in alphabetical order, which best matches your research interest. If you select the last entry, "Other", please describe the topic

1) Atmosphere, Clouds, and Climate

2) Atmospheric Chemistry

3) Cryosphere

4) Ecosystems

5) Hydrology

6) Paleoclimate

7) Other

Question 2 0.5 pts

Of the potential topic areas for this class ***other than the one selected above***, please let me know the top three, in order, you would like to delve into during the student led areas. If you select "Other", again, please of course describe the topic

1) Atmosphere, Clouds, and Climate

2) Atmospheric Chemistry

3) Cryosphere

4) Ecosystems

5) Hydrology

6) Paleoclimate

7) Other

Zircon

Zircon

https://en.wikipedia.org/wiki/Zircon

Article Talk

From Wikipedia, the free encyclopedia

This article is about the mineral and gemstone. For other uses, see Zircon (disambiguation).

Zircon (/ˈzɜːrkɒn, -kən/)[7][8][9] is a mineral belonging to the group of nesosilicates and is a source of the metal zirconium. Its chemical name is zirconium(IV) silicate, and its corresponding chemical formula is $ZrSiO_4$. An empirical formula showing some of the range of substitution in zircon is $(Zr_{1-y}, REE_y)(SiO_4)_{1-x}(OH)_{4x-y}$. Zircon precipitates from silicate melts and has relatively high concentrations of high field strength incompatible elements. For example, hafnium is almost always present in quantities ranging from 1 to 4%. The crystal structure of zircon is tetragonal crystal system. The natural color of zircon varies between colorless, yellow-golden, red, brown, blue, and green.

Zircon

A lustrous crystal of zircon perched on a tan matrix of calcite from the Gilgit District of Pakistan

General	
Category	Nesosilicates
Formula	zirconium silicate ($ZrSiO_4$)

Zircon U-Pb Dating

In subject area: Earth and Planetary Sciences

Zircon U-Pb dating is a method used in Earth and Planetary Sciences to determine the age of rocks by analyzing the radioactive decay of uranium to lead in zircon crystals.

AI generated definition based on: Earth-Science Reviews, 2020

About this page   Add to Mendeley   Set alert

Chapters and Articles

You might find these chapters and articles relevant to this topic.

Volume 2

Yuanbao Wu, in Encyclopedia of Geology (Second Edition), 2021

U—Pb isotope age

Zircon U—Pb dating is by far the most widely used method to determine the age of metamorphic rock. The technique methods are broadly categorized into the whole (part) grain and in situ analyses. Whole grain analysis by thermal ionization mass spectrometer (TIMS) yields U—Pb ages with the greatest precision but potentially poorest accuracy, because of the mixing of different age components and Pb loss domains. In situ analysis by LA-ICPMS and/or SIMS has relatively low precision, but has the advantage of superior spatial resolution such that age components within individual grains can be resolved, which are particularly important for metamorphic zircon.

Contents

https://www.sciencedirect.com/topics/earth-and-planetary-sciences/zircon-u-pb-dating

Why Is India Not A Desert?

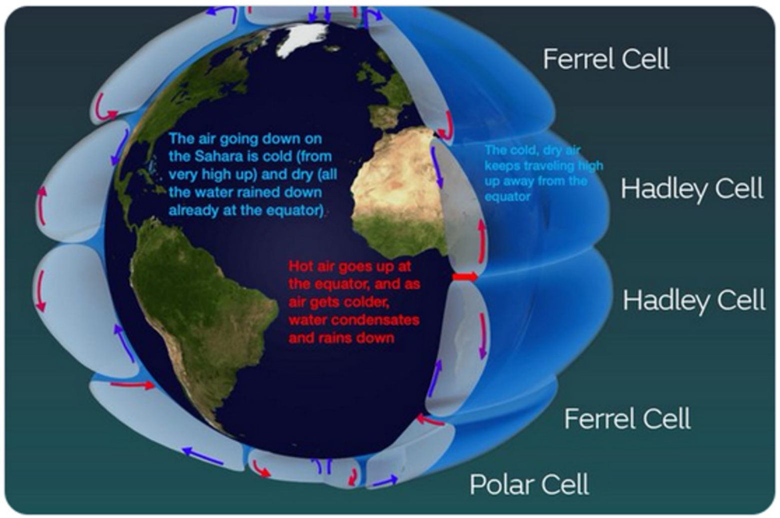
Tomas Pueyo @tomaspueyo · Feb 6

The equator is the warmest part of the world, hit directly by the Sun

Hot air, full of humidity, goes up, hits colder air, water condensates, and rains down.

But air keeps going, and falls down farther north, completely dry. Hence the Sahara.

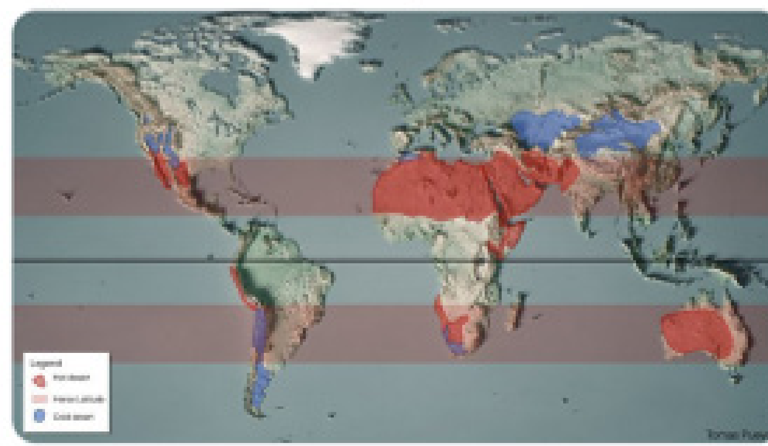
So why not India?



8 156 2,897 943.8K

But hold on, why are there humid winds to begin with?
They're not supposed to be there! Every other part of the world at the same latitude is a desert!

Why is the Sahara a desert but India a garden?



14 308 4,028 1M

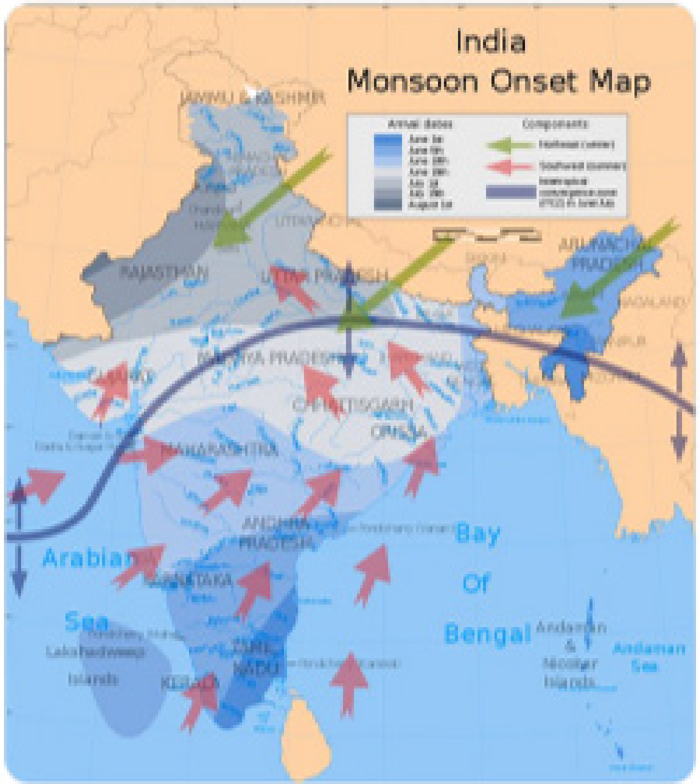
https://twitter.com/tomaspueyo/status/1622753371663867905

Why Is India Not A Desert?

Tomas Pueyo @tomaspueyo · Feb 6

In Indian summers, winds come from the sea, full of water.

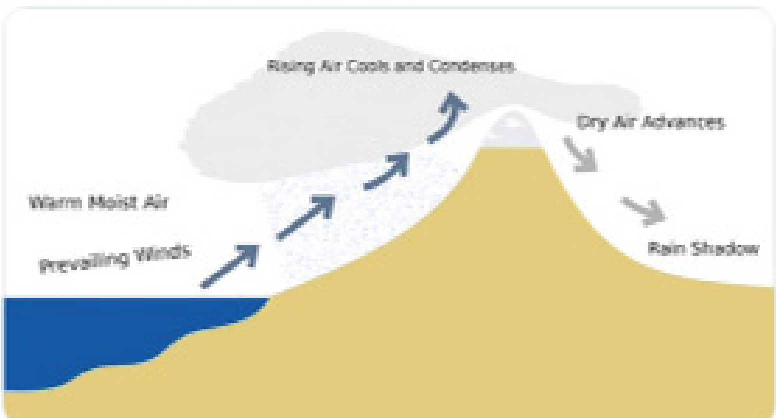
What force pushing the monsoon is so huge that it predominates over the normal circulation of wind on Earth?



11 179 2,896 871.3K

The mountains.

Wind comes from the ocean full of water
It hits the Himalayas
Climbs up
Gets colder
The water condensates and rains down



10 245 4,941 1.3M

https://twitter.com/tomaspueyo/status/1622753371663867905

Why Is India Not A Desert?


Tomas Pueyo @tomaspueyo · Feb 6

1. In summer, the Eurasian plate heats up north of the Indo-Australian plate (Indian ocean)➡️monsoon
2. These plates hit and create the Himalayas➡️stop the waters and rain it down to the Ganges valley
3. The weight of the Himalayas flattens the Ganges basin➡️best for crops

29 137 2,608 660.3K

Tomas Pueyo @tomaspueyo · Feb 6

In summary, in India:
Fertile soil ➡️ Population
Why?
• Hot (tropical)
• Lots of rain
➡️Rivers➡️irrigation & fertilizer

But ALL these conditions exist thanks to an ancient accident: The Indo-Australian Plate hitting the Eurasian one!

15 201 3,236 689.1K

https://twitter.com/tomaspueyo/status/1622753371663867905

Climates of the Past

Overview:

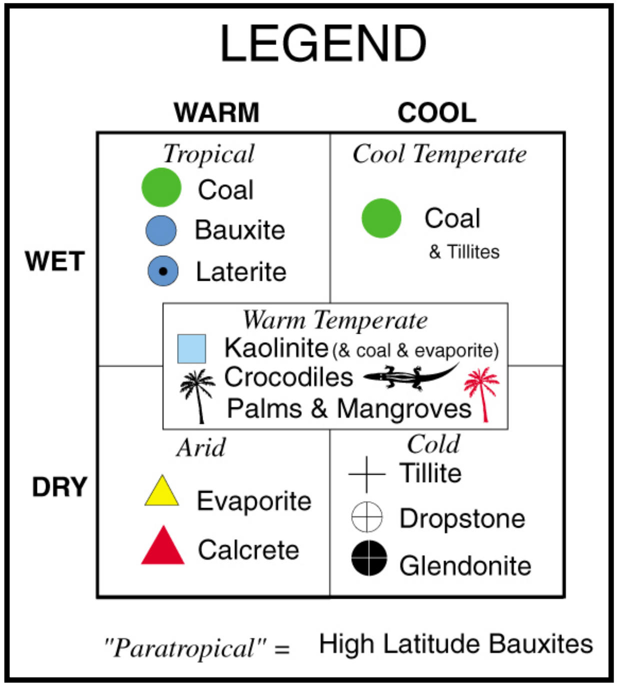
1) Techniques for quantifying past climate

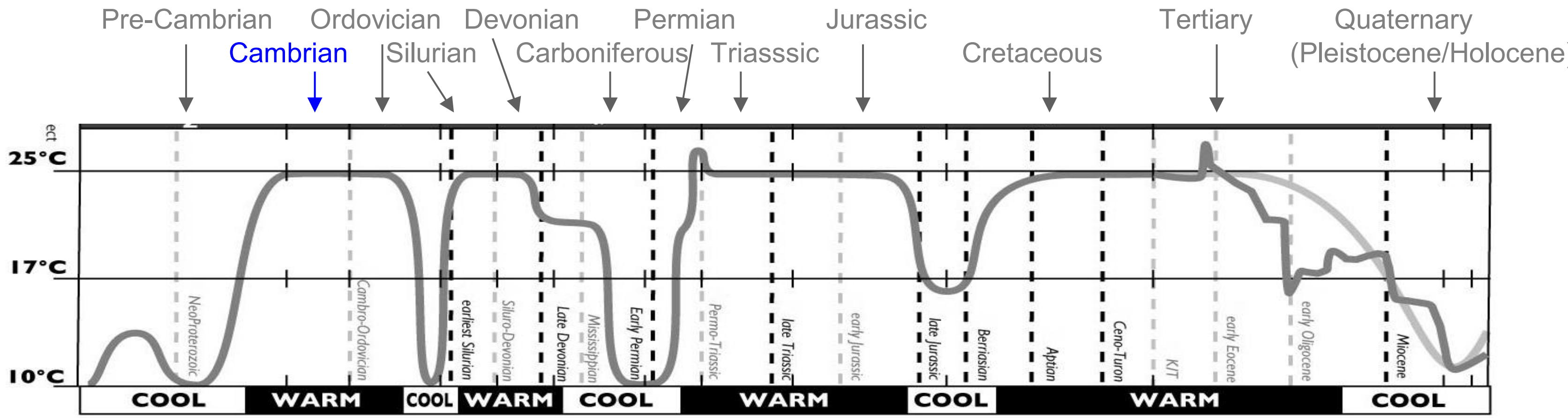
2) Remarkable changes in past climate

3) Challenge in applying past climate sensitivity to future climate

The details of this “challenge” are quantitative and come at end of lecture.
I generally do not like to place quantitative material at the end of lecture;
please bear with me today as this arrangement seems best way to organize material.

Legend for slides to follow →





https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
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	Mesozoic	Cretaceous		145.6
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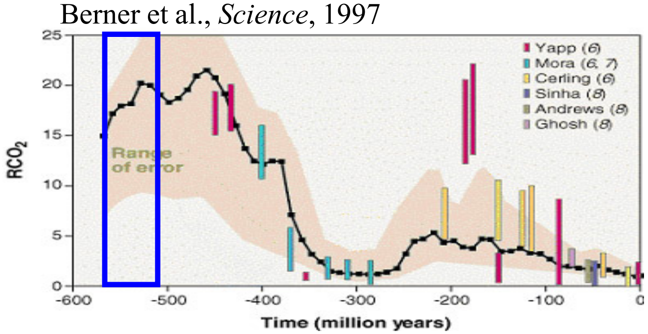
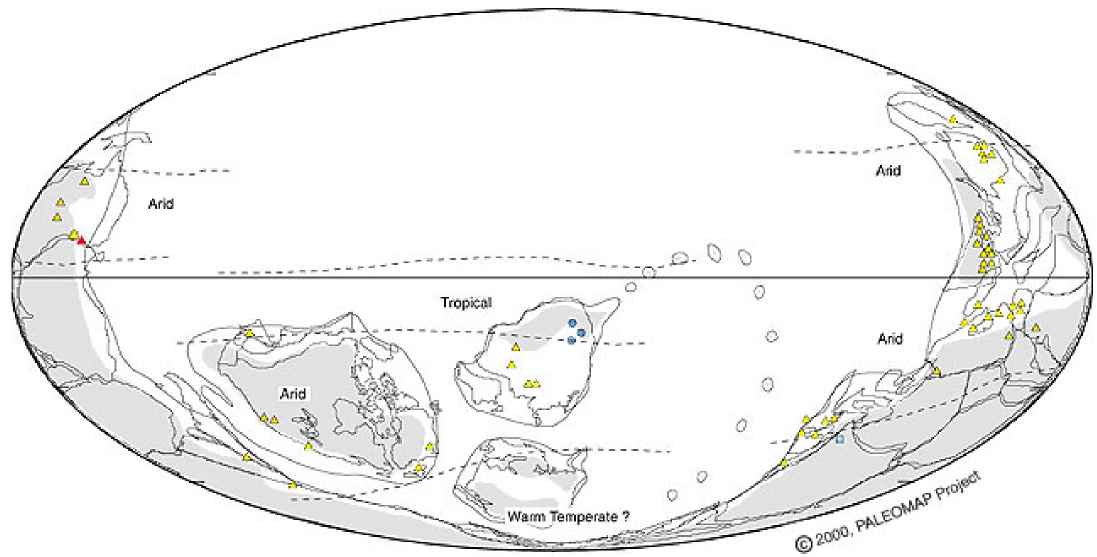
		Devonian		408.5
		Silurian		439.0
		Ordovician		510.0
		Cambrian		570.0
Proterozoic				2500
Archean				4000

Geologic Time Scale based on Harland et al 1989

Berner et al., *Science*, 1997

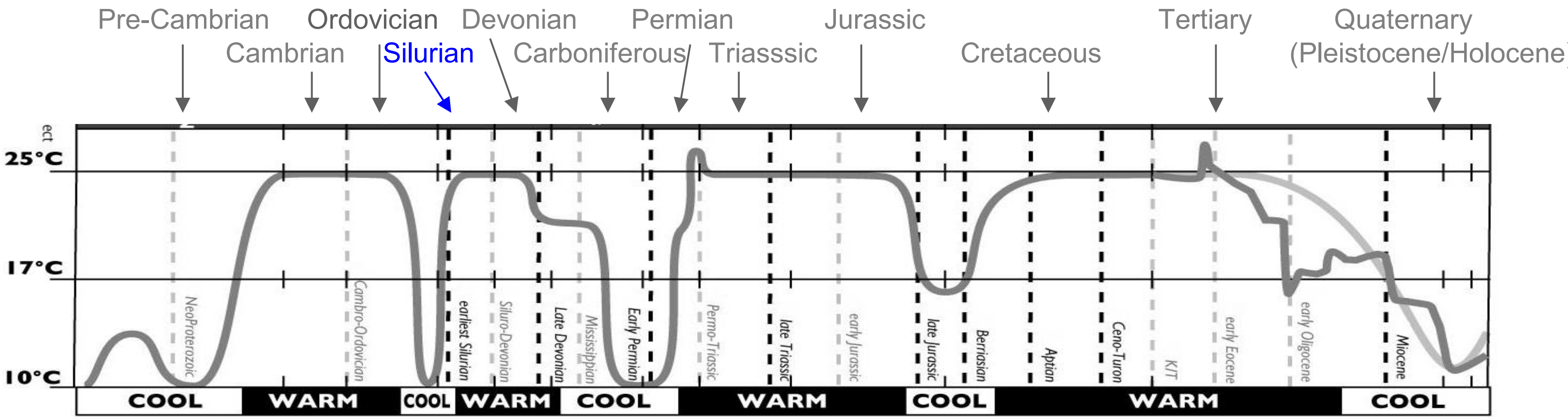


Early Cambrian Climate (540 million years ago)



The climate of the Cambrian is not well known.
It was probably not very hot, nor very cold.
There is no evidence of ice at the poles.

Source: http://www.scotese.com/ecambcli.htm



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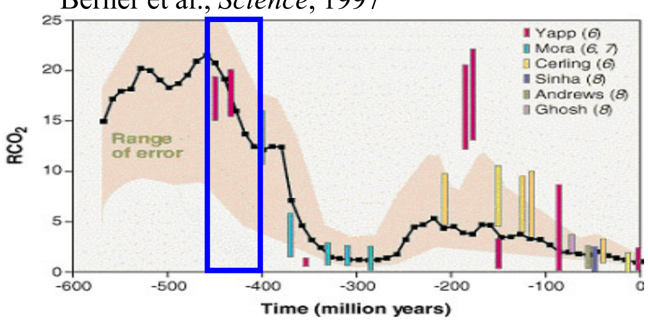
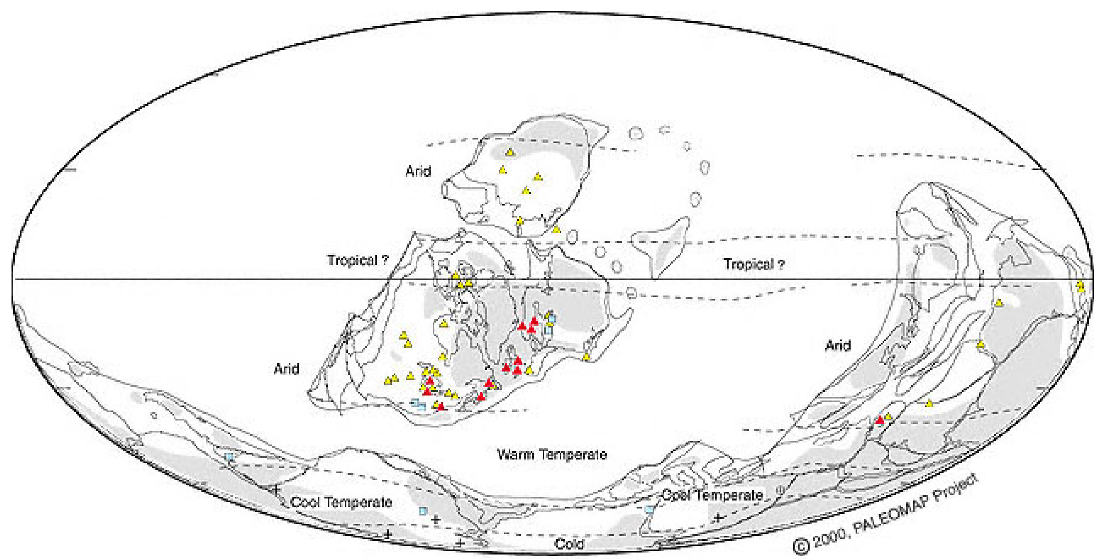
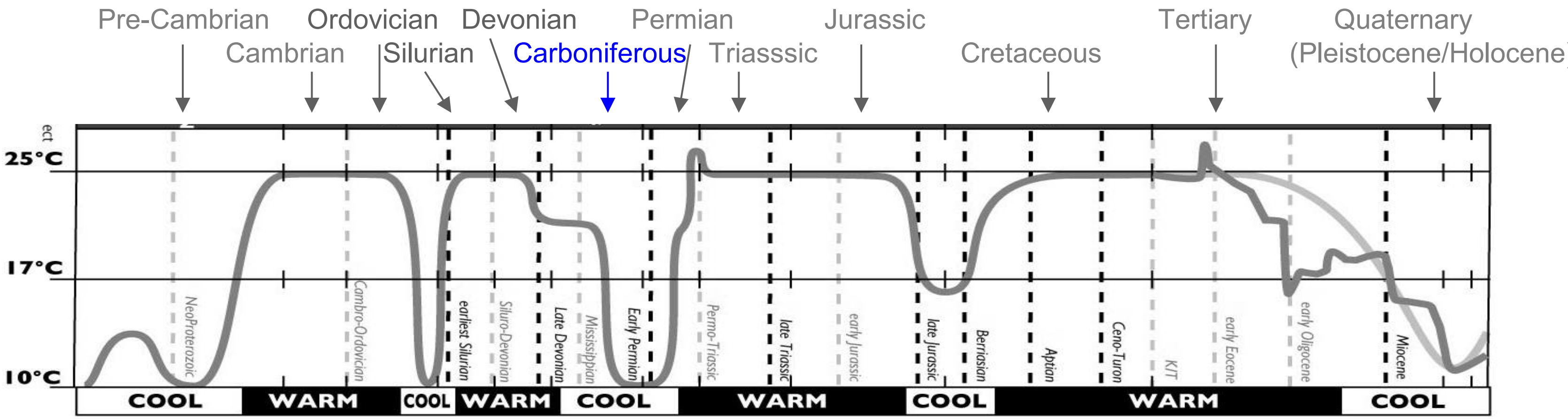


Silurian Climate
(420 million years ago)



Coral reefs thrived in the clear sunny skies of the southern Arid Belt.
Lingering glacial conditions prevailed near the South Pole.

Source: http://www.scotese.com/silclim.htm



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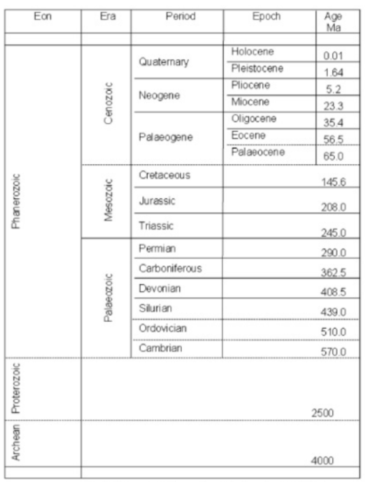

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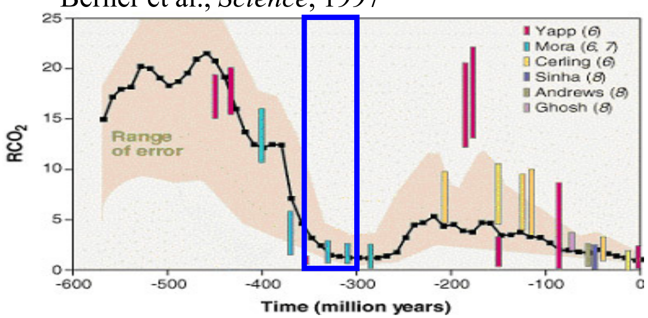
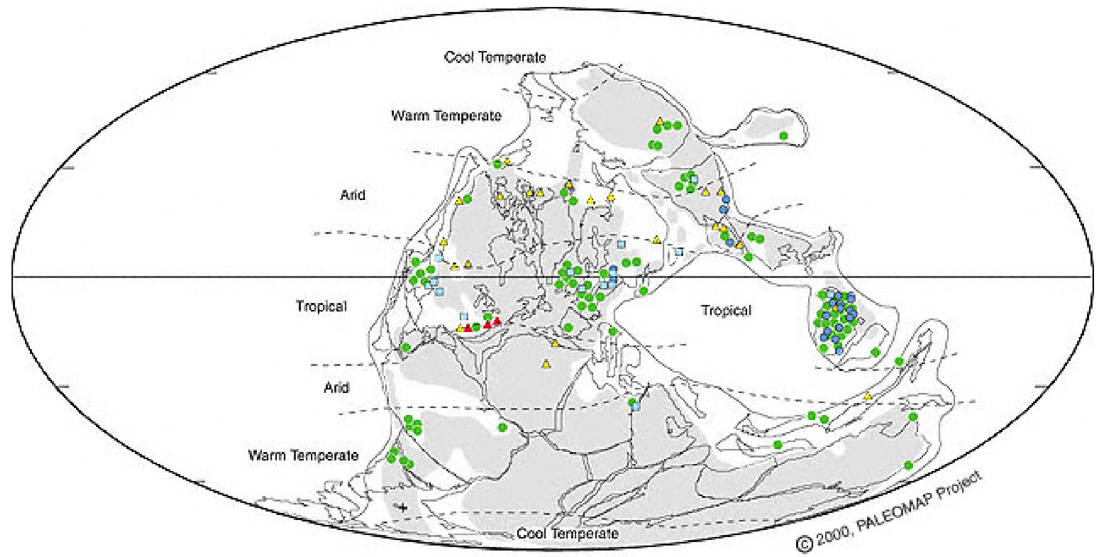
Geologic Time Scale based on Harland et al 1989

Carboniferous Climate (350 million years ago)

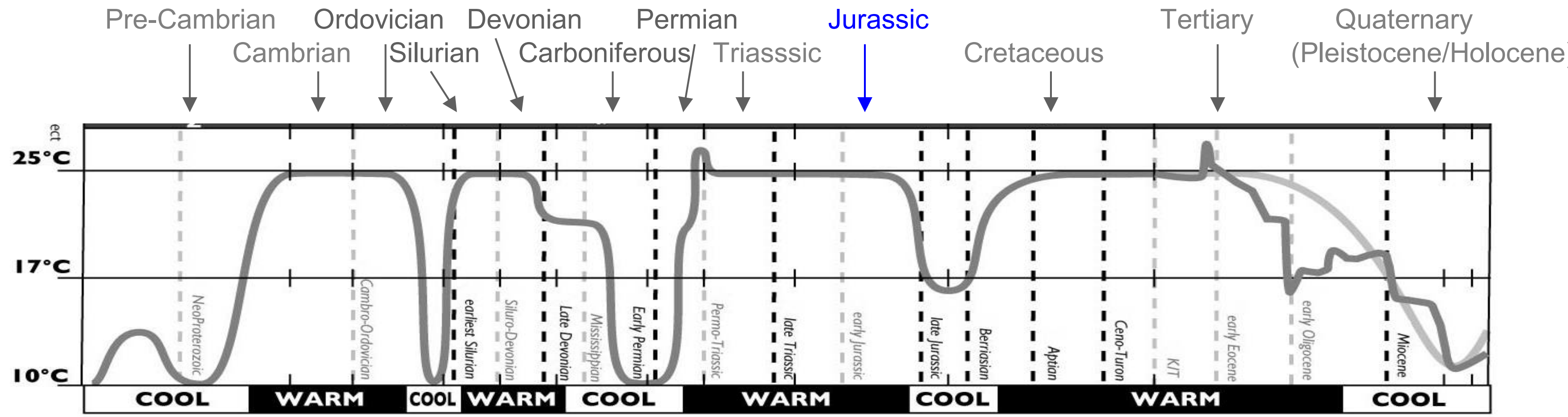
Berner et al., *Science*, 1997





Rainforests covered the tropical regions of Pangea, which was bounded to the north and south by deserts.
An ***ice cap*** began to form on the South Pole.

Source: http://www.scotese.com/serpukcl.htm



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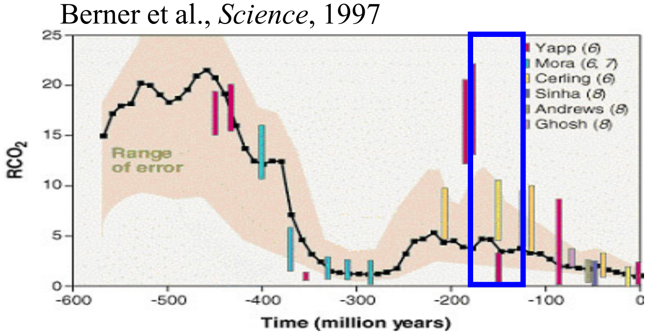
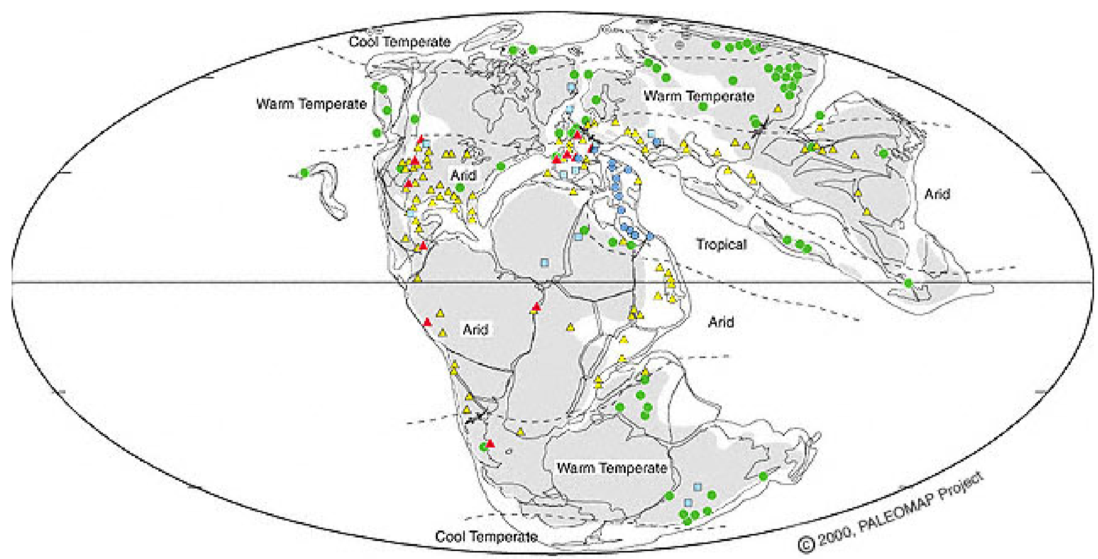
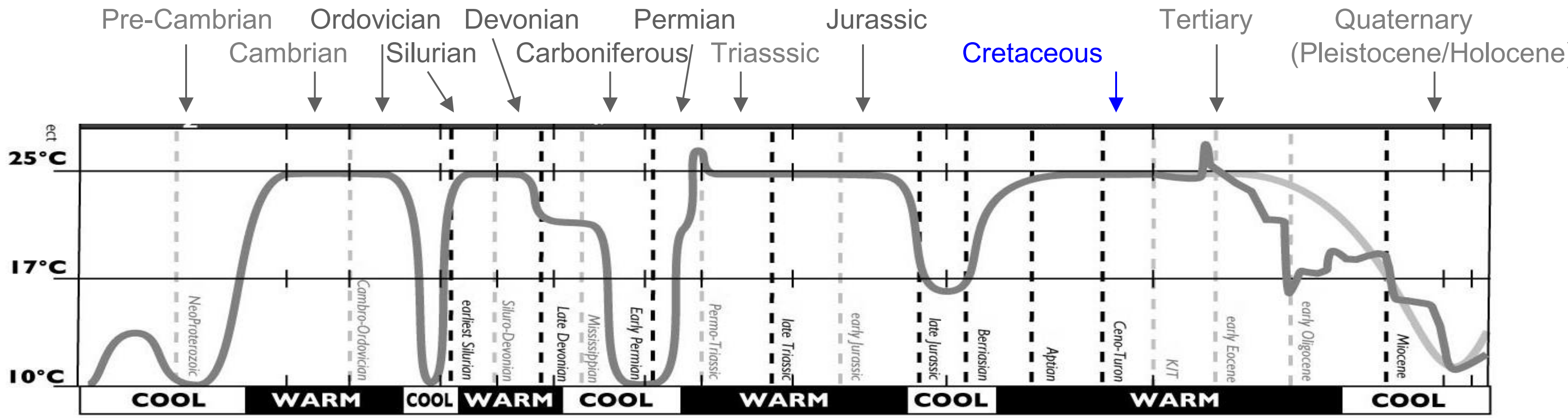


Late Jurassic Climate
(150 million years ago)



Global climate began to change due to breakup of Pangea. The interior of Pangea became moister and seasonal snow & ice frosted the polar regions

Source: http://www.scotese.com/ljurclim.htm



https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

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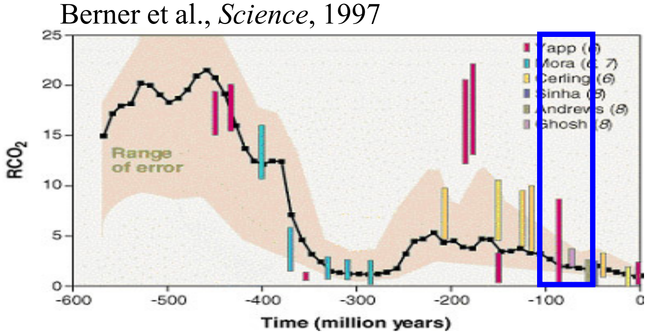
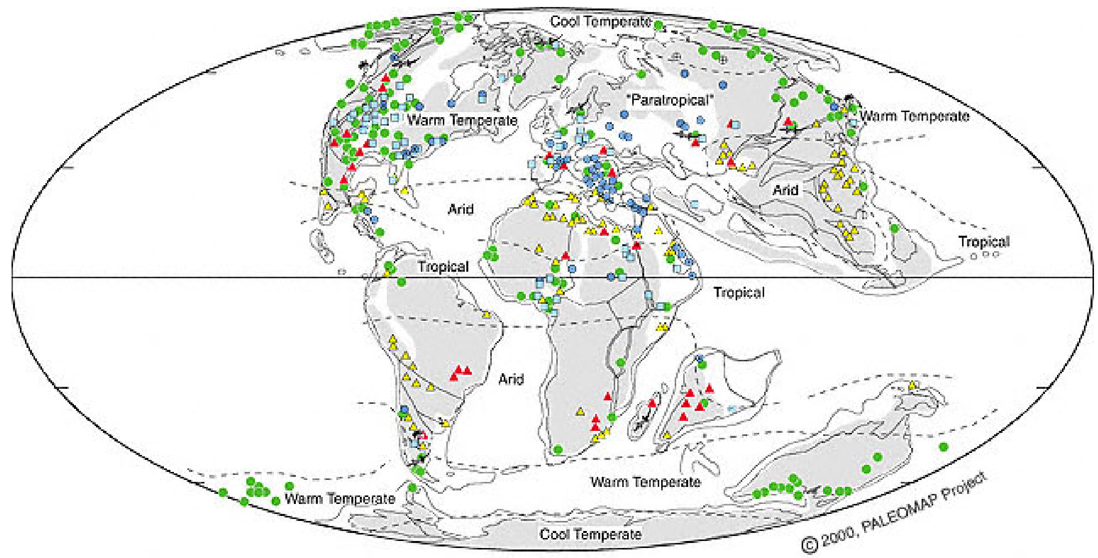
Berner et al., *Science*, 1997



Late Cretaceous Climate (70 million years ago)



Global climate was much warmer than today. No ice existed at the Poles. Dinosaurs migrated between Temperate Zones as the seasons changed.

Source: http://www.scotese.com/lcretcli.htm

Earth's Climate History

Accordion-like unraveling of Earth's climate and CO_2

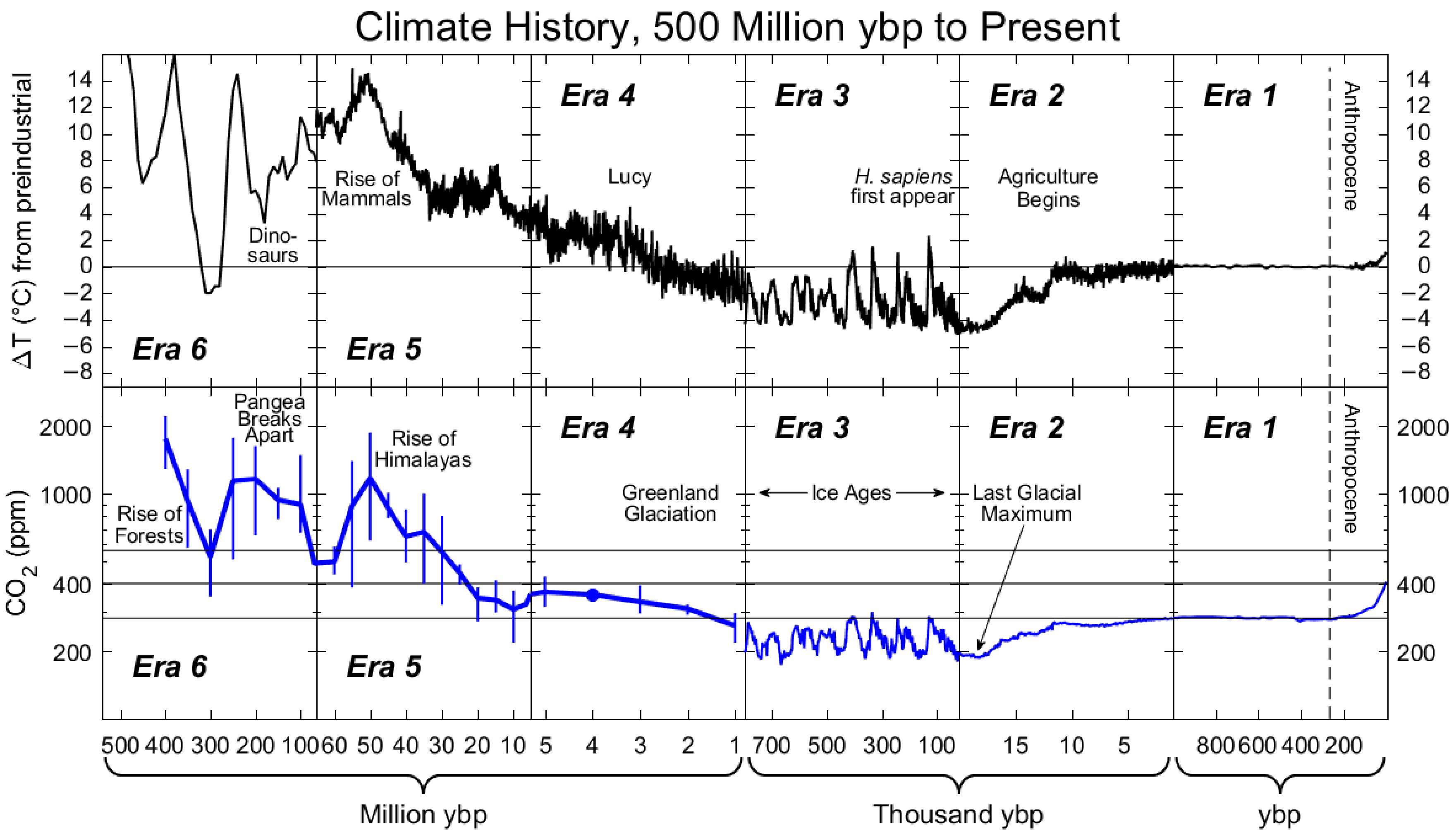


Fig 1.1, *Paris Beacon of Hope*

Oxygen Isotopes and the Quaternary Climate Record

Oxygen has three stable isotopes ^{16}O, ^{17}O, and ^{18}O

	Electrons	Protons	Neutrons	Abundance
^{16}O	8	8	8	99.76 %
^{17}O	8	8	9	00.04 %
^{18}O	8	8	10	00.20 %

^{17}O has such a low abundance that we shall focus on ^{16}O and ^{18}O

Chemical and biological reactions involving ^{18}O require more energy than reactions involving ^{16}O due to increased atomic mass

This "isotope effect" can be used as a proxy to infer past temperature!

Oxygen Isotopes and the Quaternary Climate Record

Scientists measured the ratio of ^{18}O to ^{16}O in a sample (sea water, shells, etc.) and compare to a "standard value"

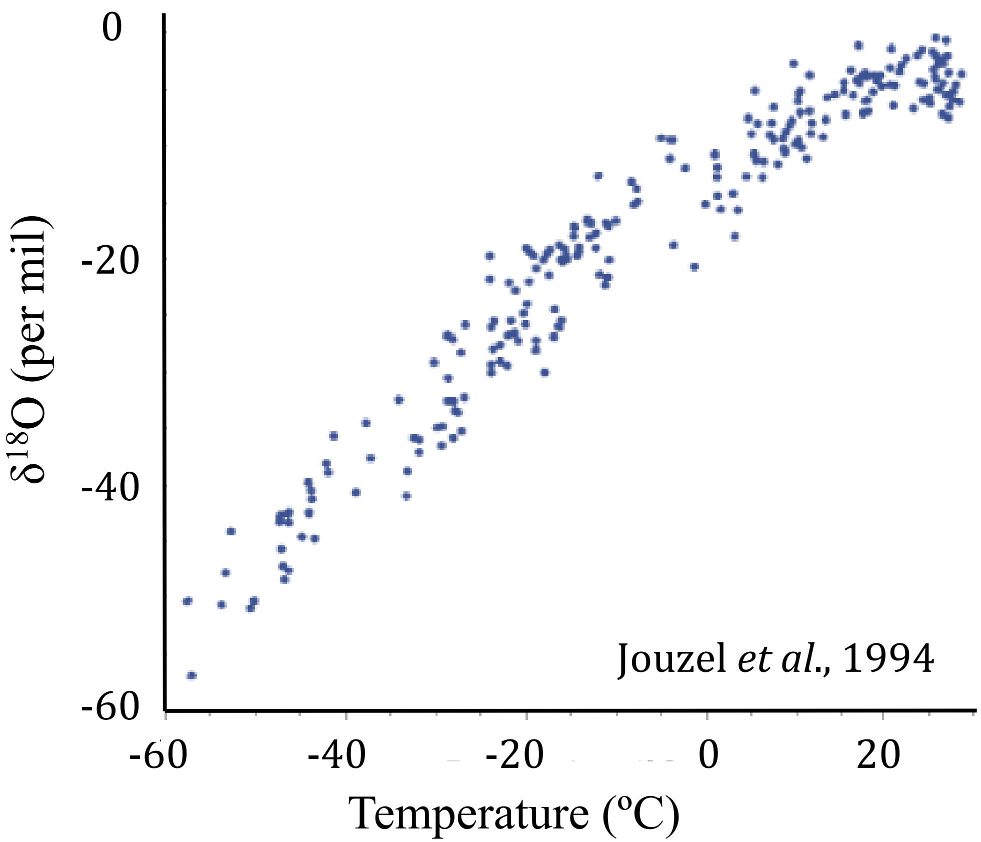
$$\delta^{18}\text{O (per mil)} = \left(\frac{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Sample} - \left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Standard}}{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Standard}} \right) \times 10^3$$

Standard often referred to as SMOW: <u>S</u>tandard <u>M</u>ean <u>O</u>cean <u>W</u>ater

If $\delta^{18}O$ is negative, the sample is "depleted" with respect to current conditions.

If positive, the sample is "enriched".

How might $\delta^{18}O$ become enriched or depleted?



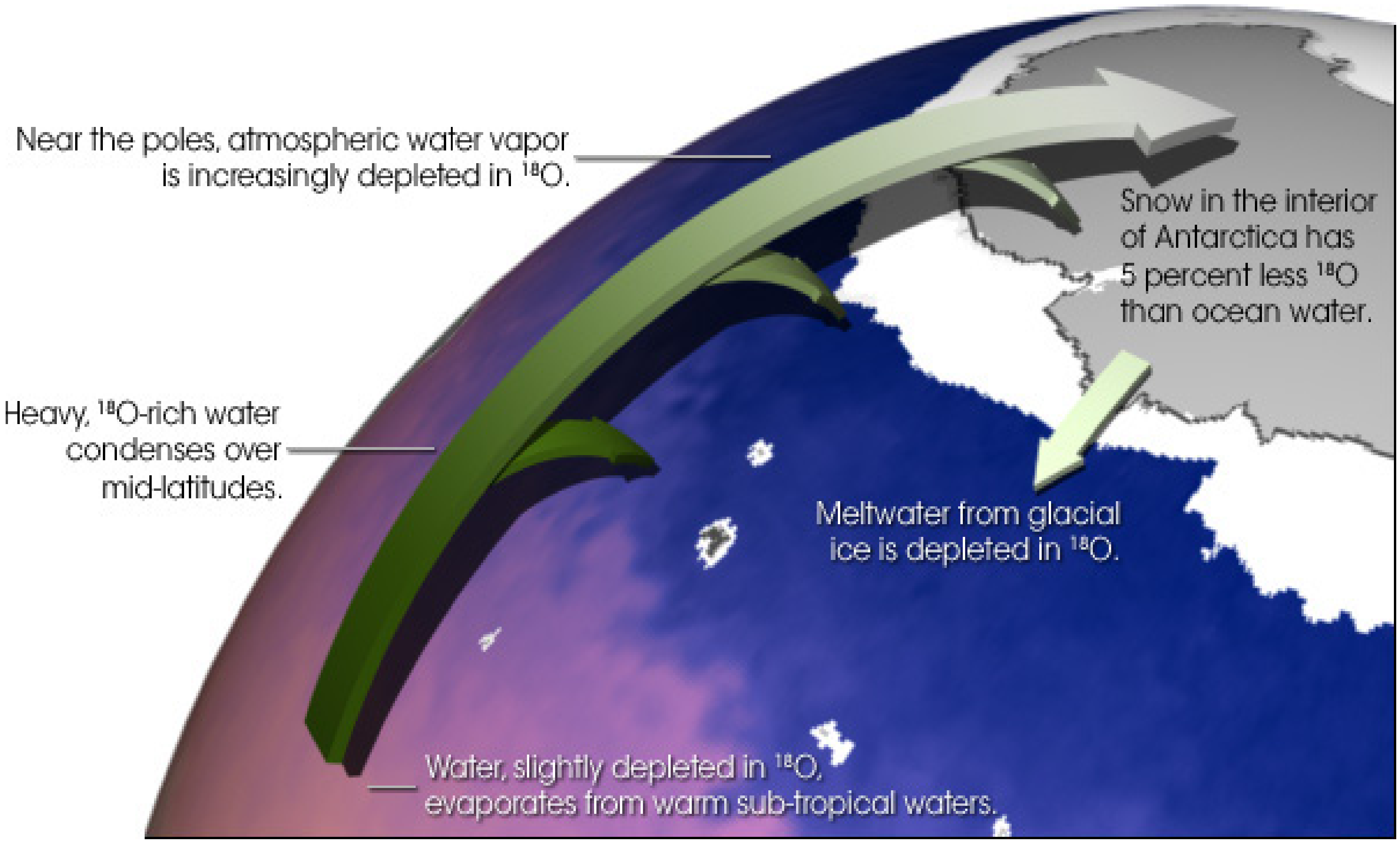
As temperatures drops, the $\delta^{18}O$ of precipitation decreases.

Why does this occur?

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

As an air mass travels poleward, $H_2{}^{18}O$ rains out more readily than $H_2{}^{16}O$

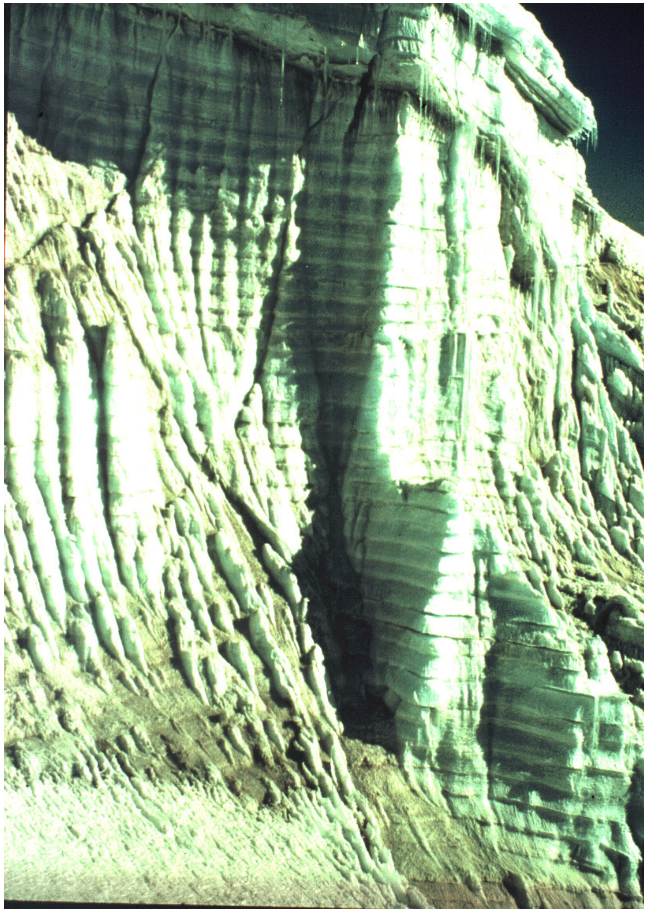
When the air mass reaches the pole, its water can have up to ~5% less ^{18}O than SMOW.



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

Deuterium (heavy hydrogen) behaves in a way quite similar to ^{18}O (heavy oxygen) !

Isotopes in Ice Cores: Late Quaternary

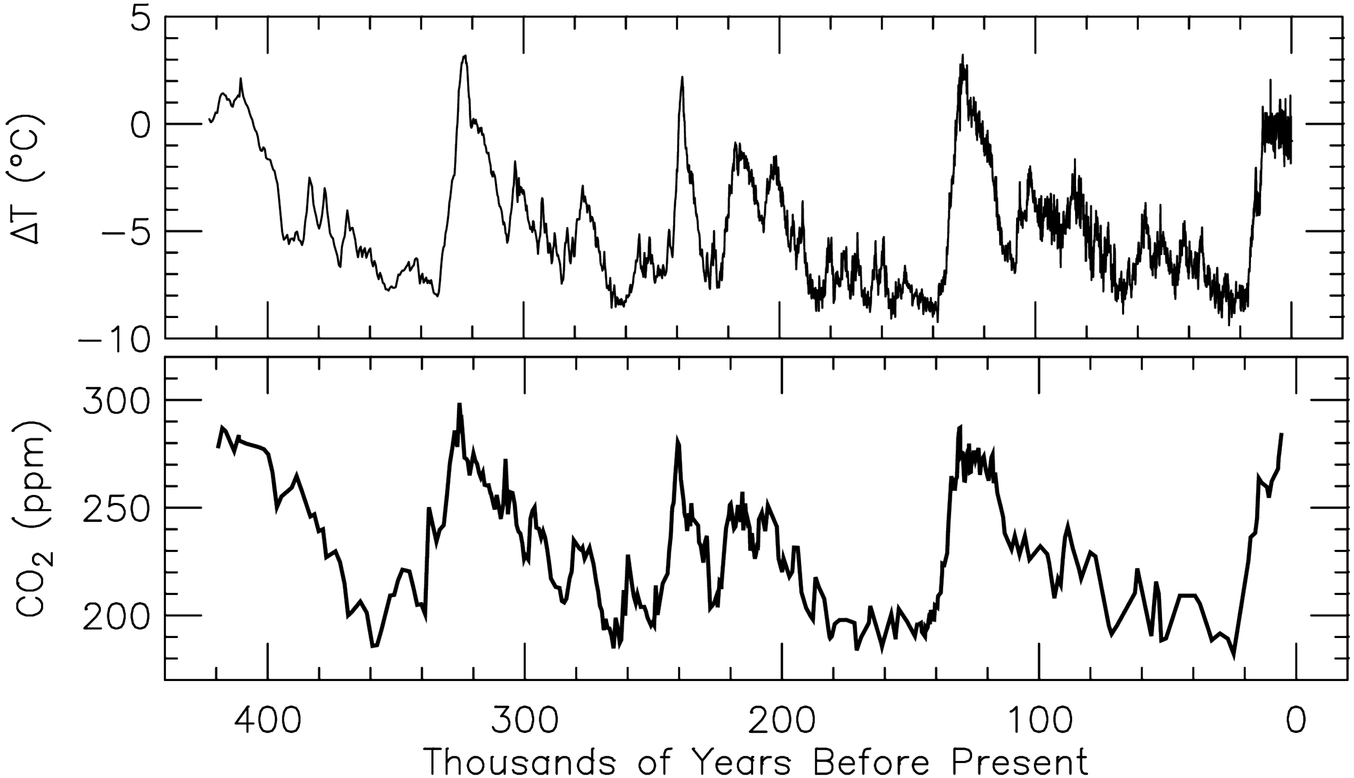


- As the air reaches the pole, ambient water precipitate (*i.e.*, it snows!)
- Over many years, layers of snow accumulate, forming an ice sheet. The water in this ice sheet contains a record of climate ***at the time the snow was deposited***
- By drilling, extracting, and measuring the $\delta^{18}O$ & δD (deuterium/hydrogen ratio) of ice, scientists are able to estimate past ***global temperature & ice volume***
- In reconstructing climate during the quaternary (last 1.6 million years), scientists also look at:
  - CO_2, CH_4, and N_2O of trapped air
  - $\delta^{18}O$ of trapped O_2 in trapped air
  - $\delta^{13}C$ of CO_2 in trapped air
  - Particulate matter and a wide range of ions

atmospheric aerosol loading; oceanic circulation & biology

Vostok Ice Core

- January 1998: ice core with depth of 3.6 km extracted at Russian Vostok Station, Antarctica
- Vostok ice-core record extends back 400,000 years in time *(*Petit *et al*., *Nature*, 1999)
- Reconstructed temperature based on measurement of the deuterium content of ice
- $\delta^{18}O$ shows tremendous variations in global ice volume (not shown)
- Ice core data show last four ice ages, punctuated by relatively brief interglacials



- CO_2 (air trapped in ice bubbles) and inferred temperature very highly correlated
- Variations in ΔT & CO_2 synchronous upon correction of movement of air bubbles (CO_2) relative to ice (ΔT) (Parrenin *et al*., *Science*, 2013: http://science.sciencemag.org/content/339/6123/1060

Going Back 600,000 years

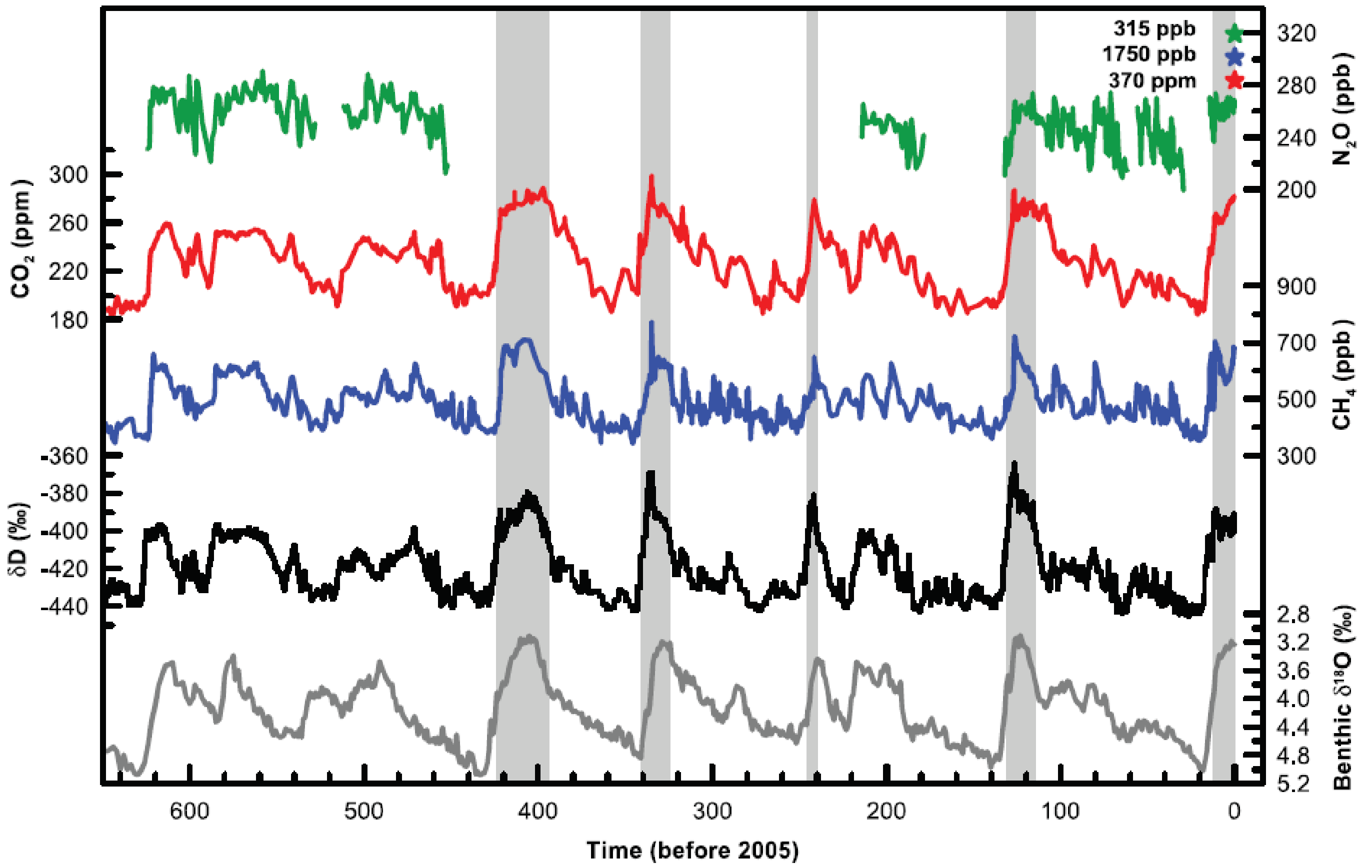


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic $\delta^{18}O$ marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic $\delta^{18}O$ curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.*

Figure 6.3, IPCC 2007

See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica

Going Back 600,000 years

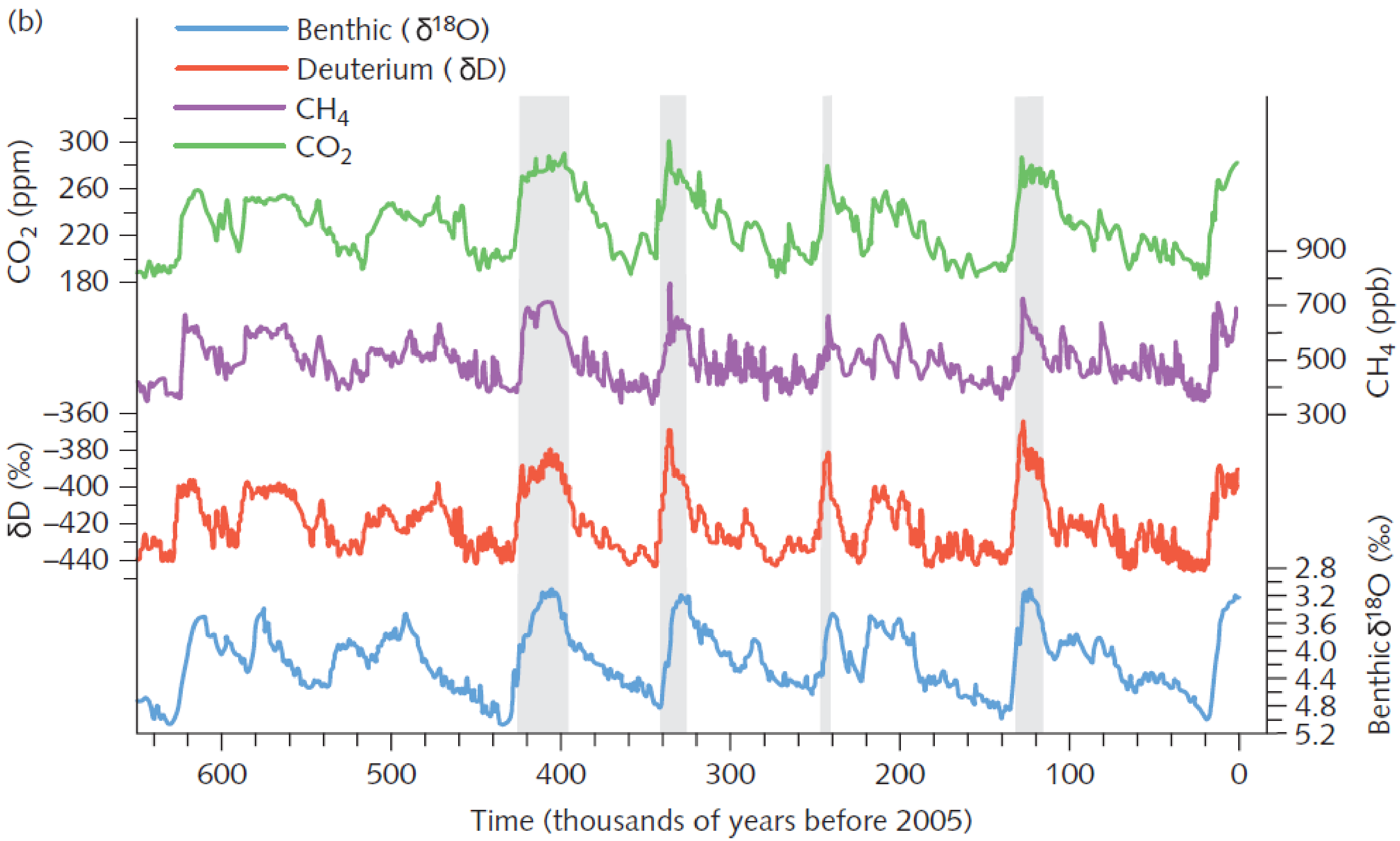


Figure 4.9 (b) Variations of deuterium (δD), a proxy for local temperature; $\delta^{18}O$, a proxy for global ice volume fluctuations; and the atmospheric concentrations of CO_2 and CH_4 derived from air trapped within ice cores from Antarctica. Shading indicates interglacial periods.

Houghton, 2015

See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica

Going Back 600,000 years

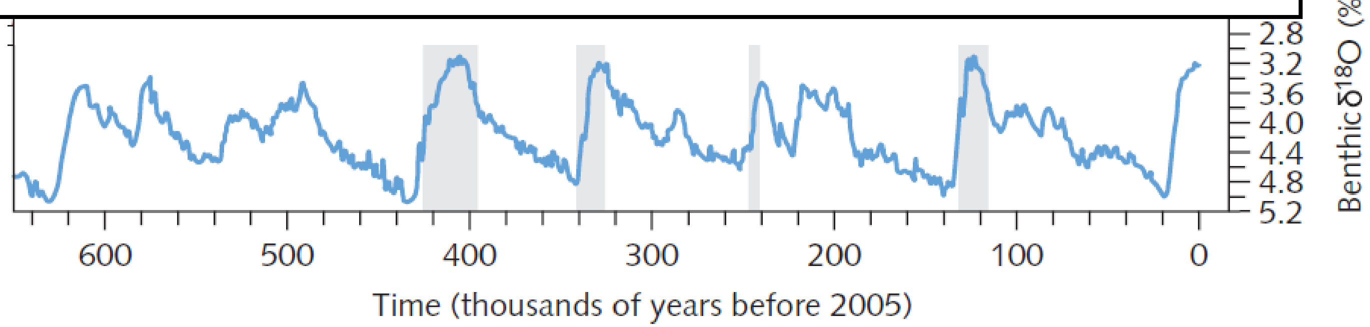
During ice ages: cooler temperatures extend toward the equator, so the water vapor containing heavy oxygen rains out of the atmosphere at low latitudes.

Water vapor containing lighter oxygen moves toward the poles, eventually condenses, and falls onto the continental ice sheets, where it stays trapped.

Thus, high concentrations of heavy oxygen preserved in oceanic organisms are a consequence of this light oxygen trapped in the ice sheets.

Oxygen isotope ratios reveal how much ice once covered the Earth.

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



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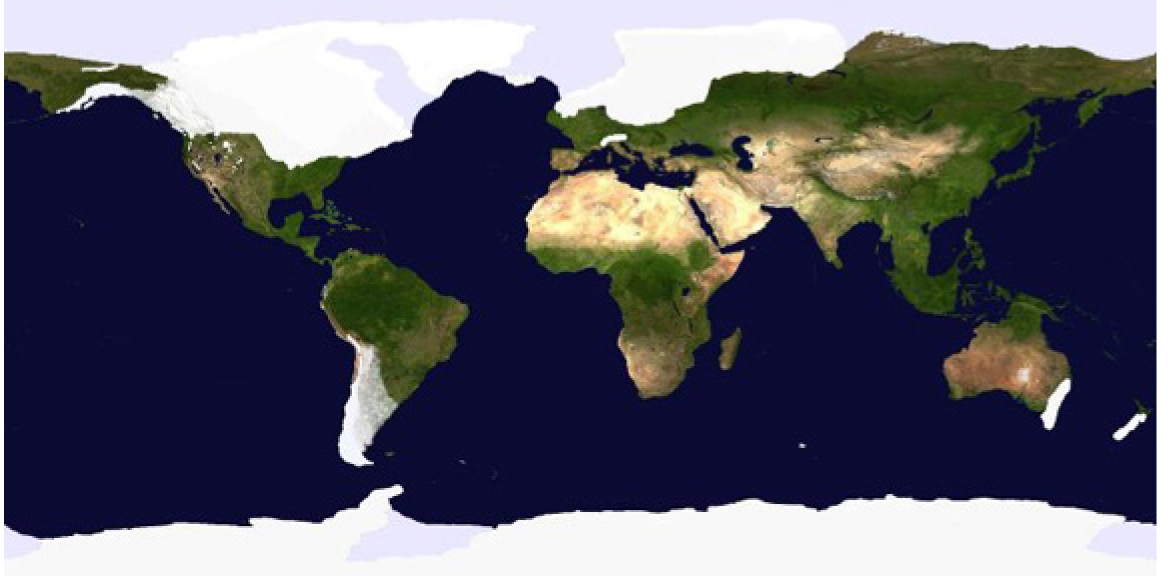
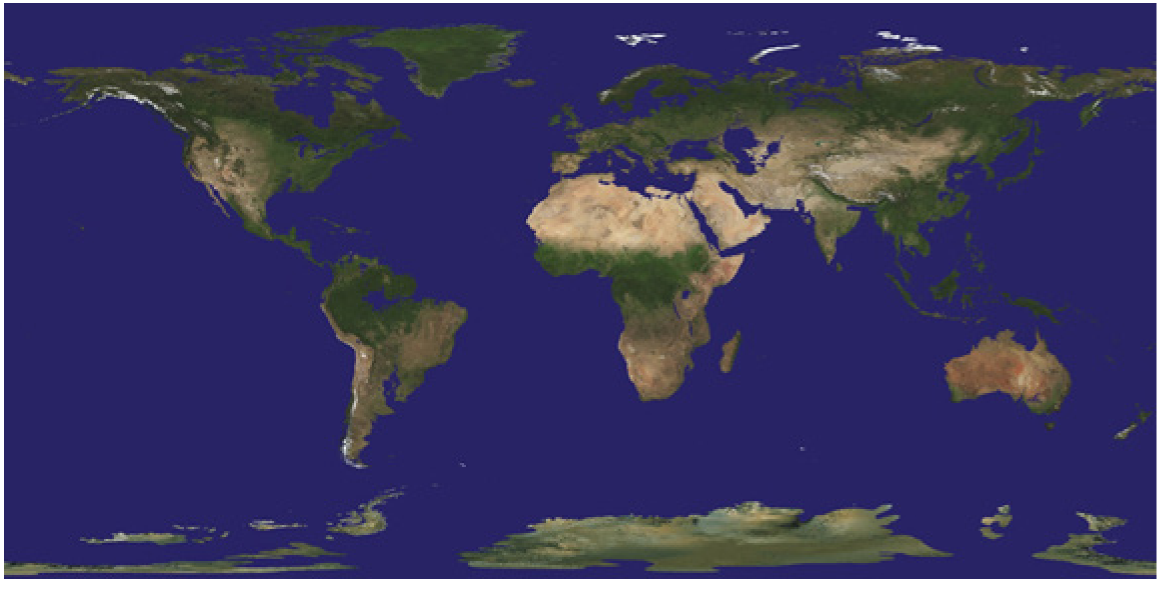
Houghton, 2015

See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica and https://www.ces.fau.edu/nasa/module-3/how-is-temperature-measured/isotopes.php for more info on the use of D and ^{18}O to infer past climate.

Glacial Maximum & Ice-Free Earth





http://www.johnstonsarchive.net/spaceart/cylmaps.html

Fairly Late Appreciation that Earth Undergoes Ice Ages

On 24 July 1837, at the annual meeting of the Swiss Society of Natural Sciences, **Louis Agassiz** (1807–1873) startled his learned associates by presenting a paper dealing not, as expected, with the fossil fishes found in far-off Brazil, but with the scratched and faceted boulders that dotted the Jura mountains around Neuchâtel itself. Agassiz argues that these erratic boulders … chunks of rock appearing in locations far removed from their areas of origin … could only be interpreted as evidence of past glaciation.

This began a dispute – one of the most violent in the history of geology – that was to rage for more than a quarter century and would end with the universal acceptance of the ice-age theory.

Although this concept did not begin with Agassiz, he served to bring the glacial theory out of scientific obscurity and into the public eye.

Ice Ages, Imbrie and Imbrie, Harvard Univ Press, 1979.

Harvard is working to revise its portrayal of **Agassiz's legacy** to accurately acknowledge his contribution to **racist thought**. The Museum of Comparative Zoology (MCZ) Faculty Curators voted to remove the "Agassiz Museum" from MCZ letterhead, the Agassiz name from the MCZ conference room, and the busts and portraits of Louis Agassiz from public view in the Ernst Mayr Library in fall 2020.

Attempts to address Agassiz's legacy continue beyond the Harvard community. The **Cambridge Maria L. Baldwin School**, originally named after Agassiz, was **renamed in 2002**. The Cambridge City Council voted to rename a neighborhood named after Agassiz in February. The European Geophysical Union renamed the **Louis Agassiz Medal**, established in 2005 to recognize outstanding scientific contribution to the study of the cryosphere, to the Julia and Johannes Weertman Medal.

https://eps.harvard.edu/history-of-racism

https://www.egu.eu/news/468/egu-louis-agassiz-medal-renamed-to-honour-julia-and-johannes-weertman/

Fourier analysis reveals Earth's climate is changing in a periodic fashion

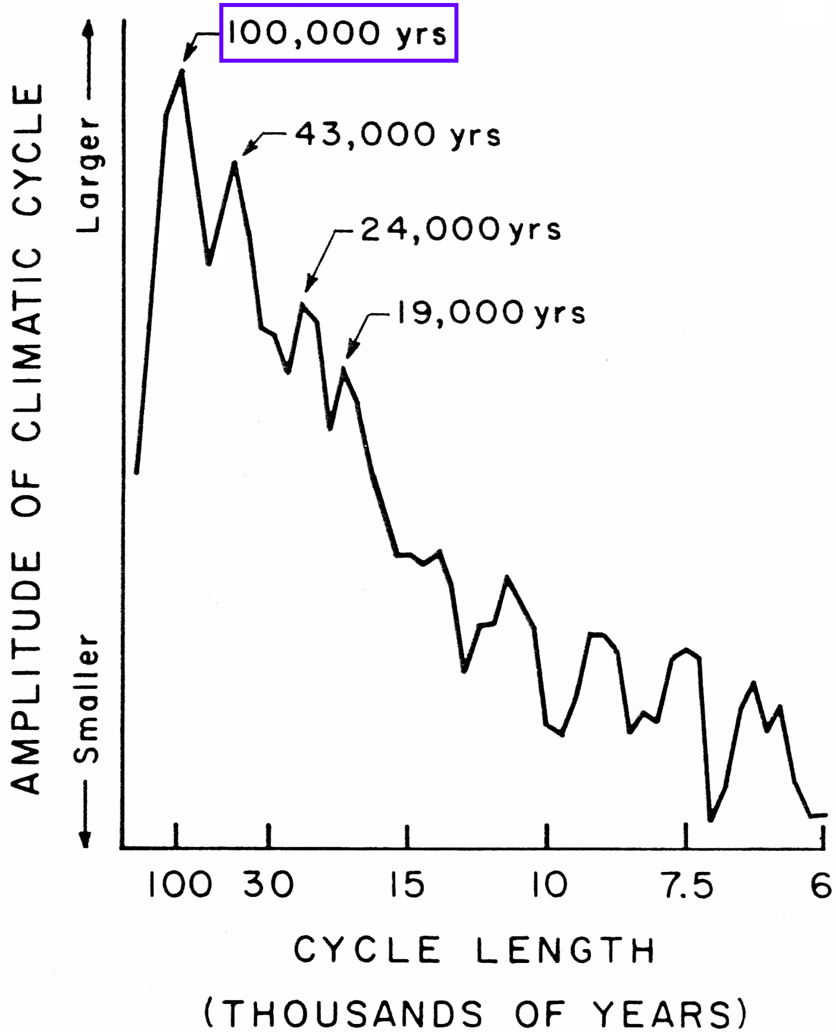
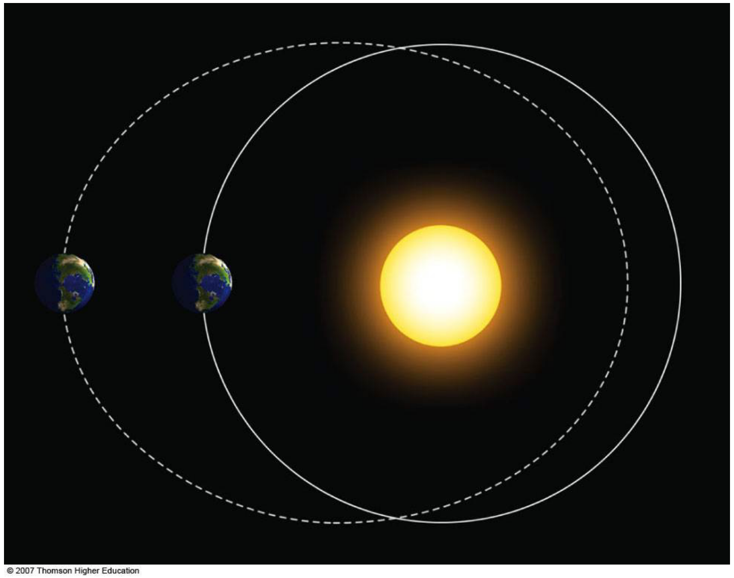


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

100,000 year cycle due to changes in the eccentricity of Earth's orbit, mainly due to gravitational pull of Jupiter and Saturn.



Fourier analysis reveals Earth's climate is changing in a periodic fashion

Pacemaker of the Ice Ages 171

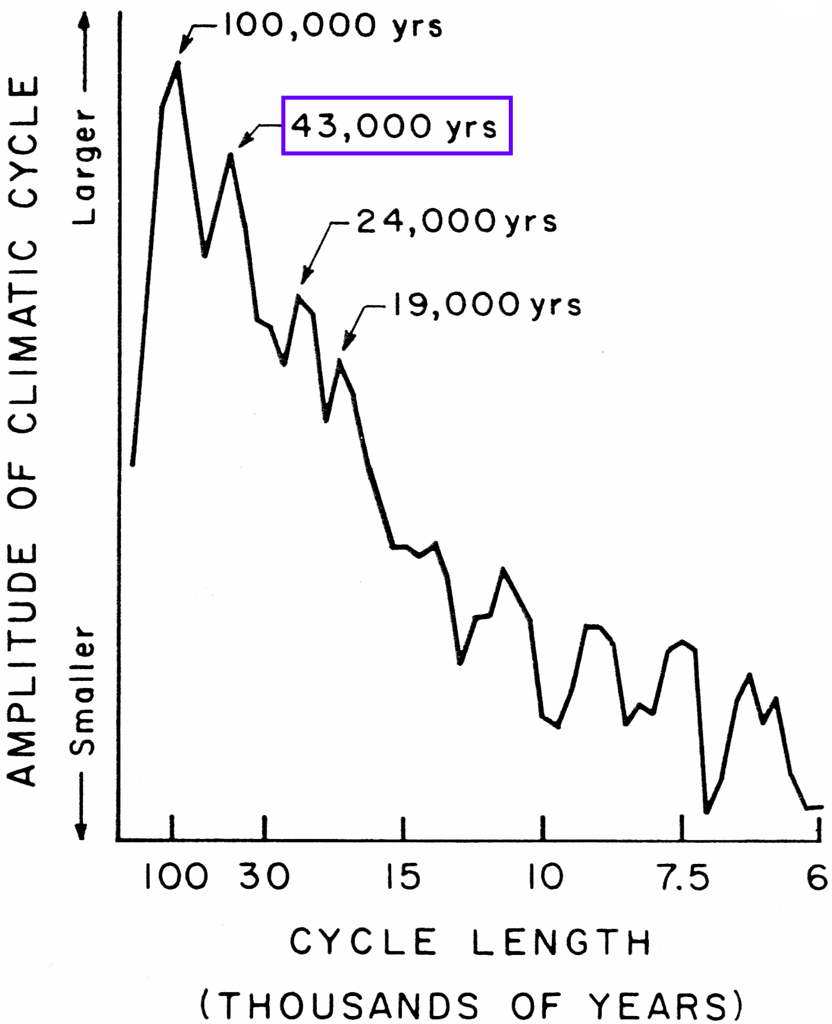
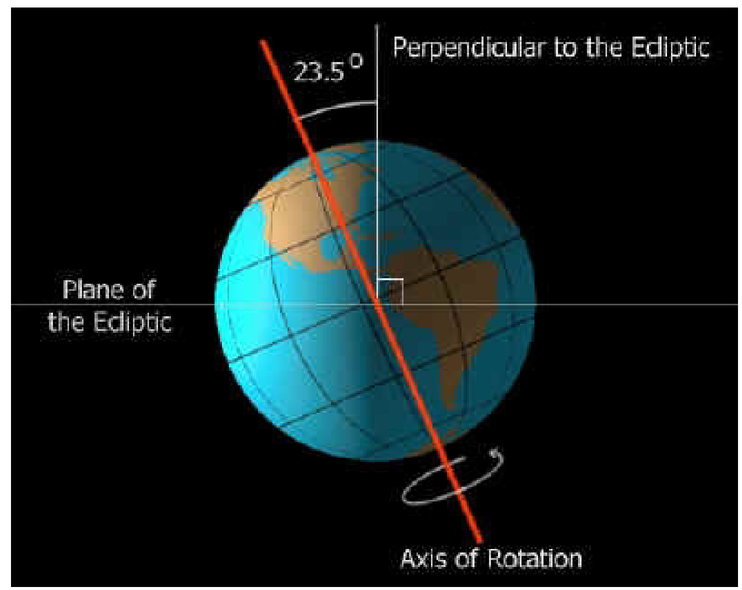


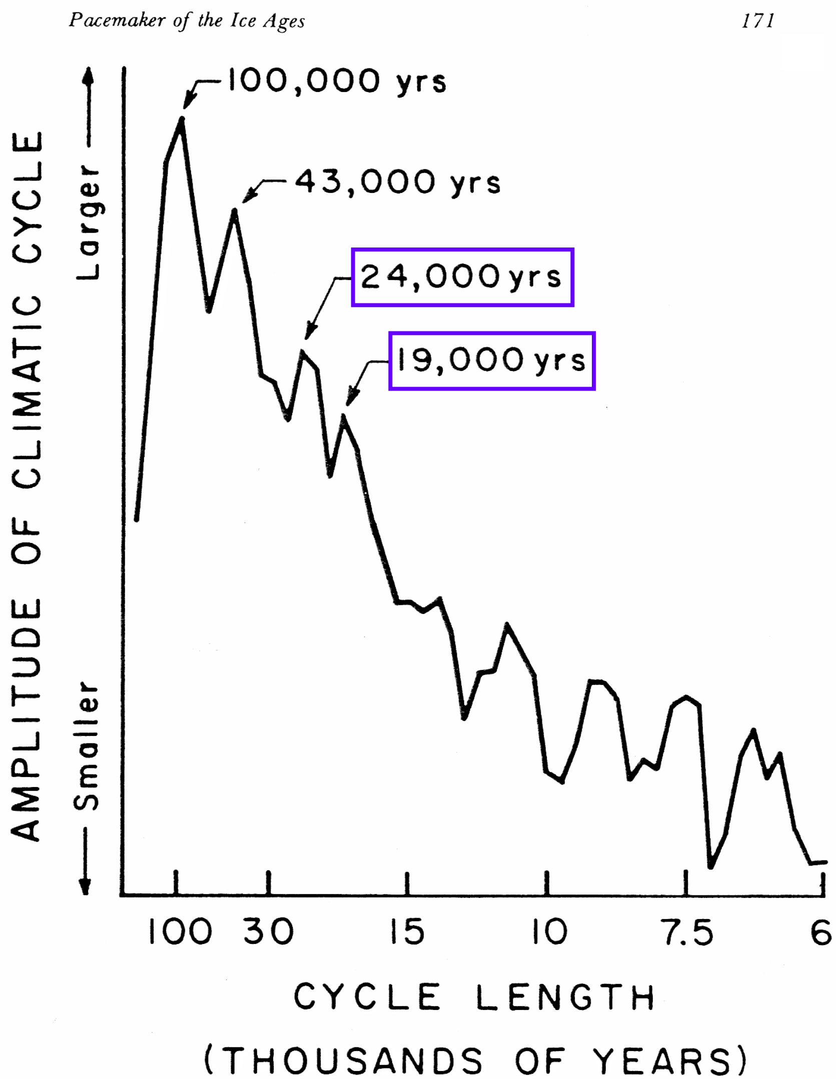
Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

43,000 year cycle due to changes in tilt of Earth's axis (obliquity).



Fourier analysis reveals Earth's climate is changing in a periodic fashion



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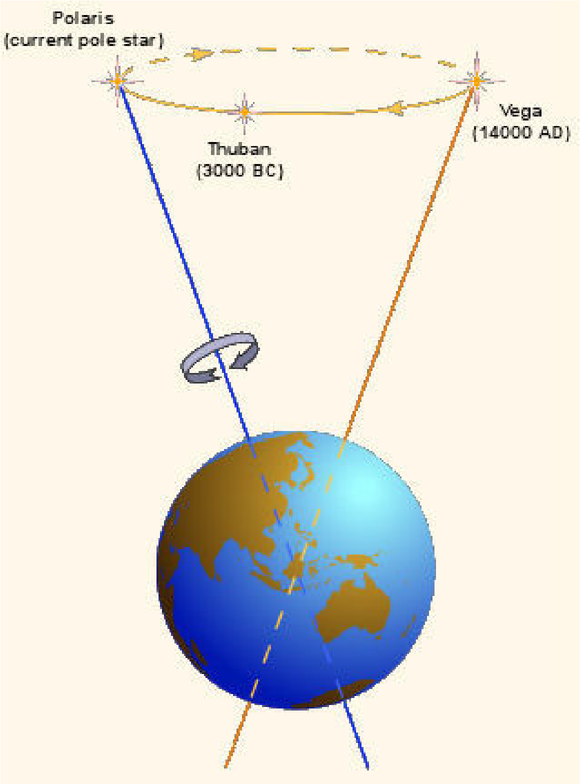
Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

24,000 and **19,000 year cycles** due to Earth "wobbling" on its axis.



Glacial Periods MUCH Dustier than Interglacials

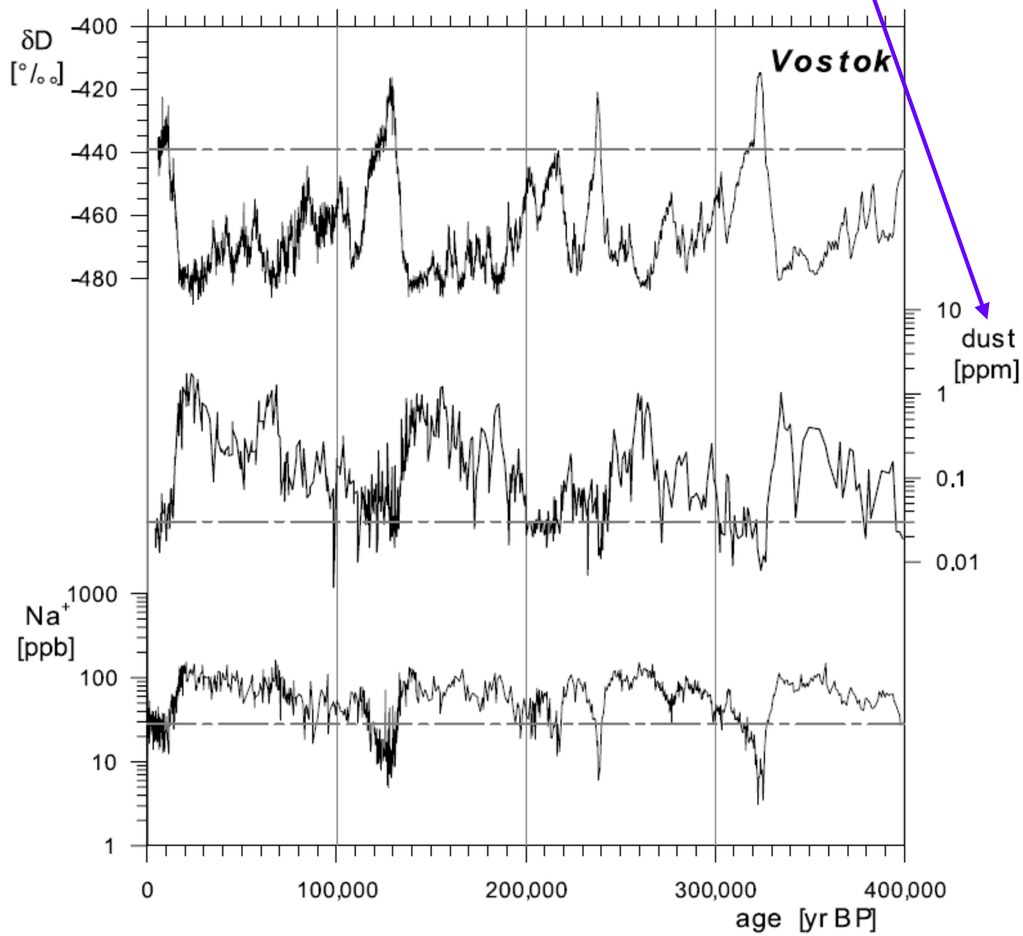


Figure 3. Temporal evolution of δD representing changes in the average local condensation temperature during snow formation, the particulate dust, and the sea-salt component Na^+ over the last four glacial cycles as recorded in the East Antarctic Vostok ice core [*Petit et al.*, 1999]. Dashed-dotted lines indicate the mean Holocene level from 0 to 10,000 years B.P.

Fischer *et al.*, Reviews of Geophysics, 2007

Biology in Today's Ocean

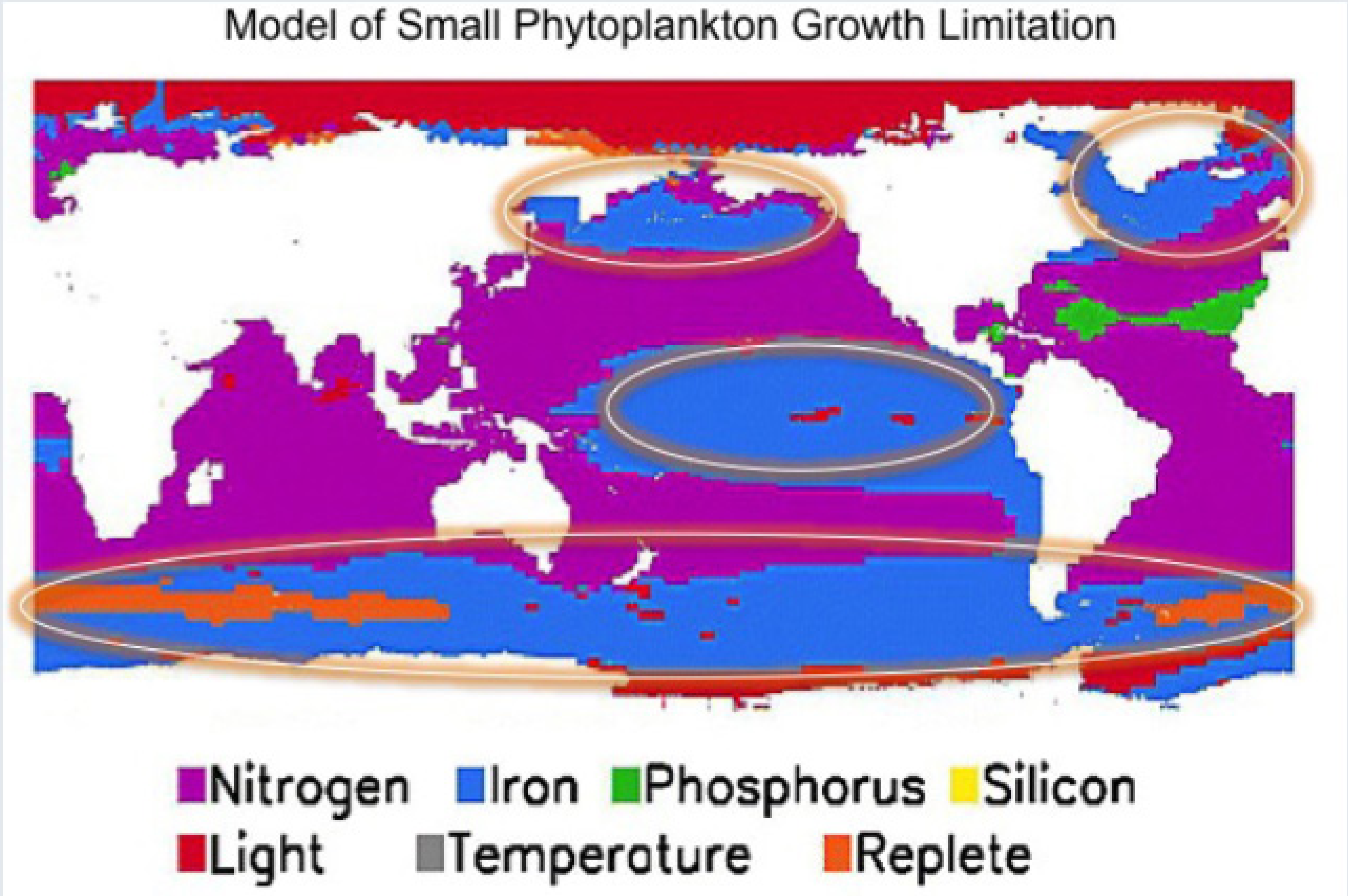


Figure 1. Results of a global model of small phytoplankton growth limitation by Moore et al. 2004 (*Global Biogeochemical Cycles*). Blue shaded areas denote regions that are potentially limited by iron availability. Iron is supplied by dust from continents and by upwelling of deep water. However, high iron demand in the euphotic zone quickly drives iron concentrations to nano- and picomolar levels that can be limiting to many phyto- and bacterioplankton.

http://www.whoi.edu/page.do?pid=130796

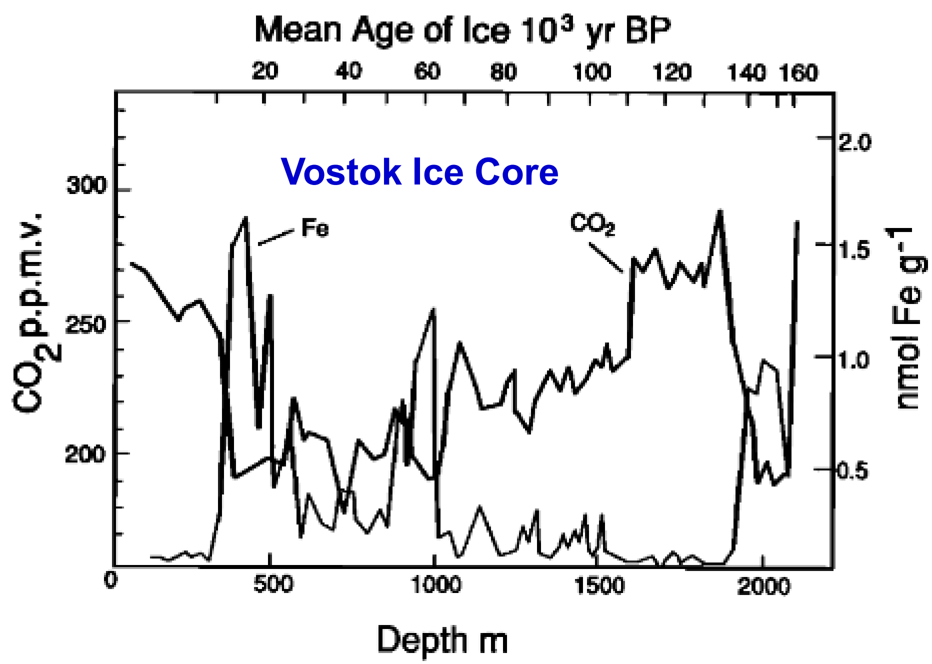
Connection to Glacial CO_2

GLACIAL-INTERGLACIAL CO_2 CHANGE: THE IRON HYPOTHESIS

PALEOCEANOGRAPHY, VOL.5, NO.1, PAGES 1-13 1990

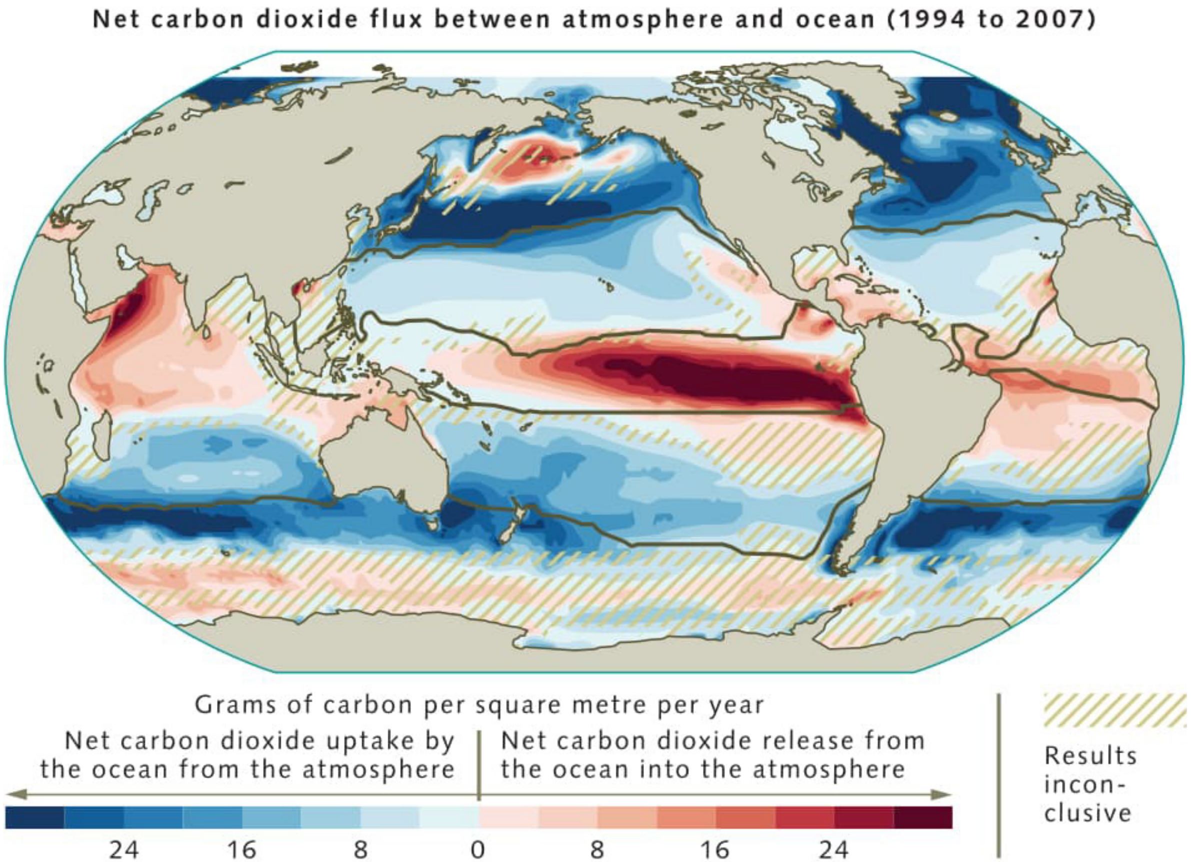
John H. Martin

In contrast, atmospheric dust Fe supplies were 50 times higher during the last glacial maximum (LGM). Because of this Fe enrichment, phytoplankton growth may have been greatly enhanced, larger amounts of upwelled nutrients may have been used, and the resulting stimulation of new productivity may have contributed to the LGM drawdown of atmospheric CO_2 to levels of less than 200 ppm. Background information and arguments in support of this hypothesis are presented.



http://onlinelibrary.wiley.com/doi/10.1029/PA005i001p00001/abstract

To Understand The Drawdown of Atmospheric CO_2 During Glacial Times, let's first have a look at Today's Flux Of CO_2 From Atmosphere to Ocean



The ocean does not absorb the same amounts of CO_2 from the atmosphere everywhere. As this map illustrates, CO_2 uptake occurs primarily in the cold Southern Ocean and in the North Atlantic and North Pacific Oceans (blue shading). In the warm tropical regions, on the other hand, the ocean releases considerably more CO_2 into the atmosphere than it absorbs (red shading).

https://worldoceanreview.com/en/wor-8/the-role-of-the-ocean-in-the-global-carbon-cyclee/how-the-ocean-absorbs-carbon-dioxide

Drawdown of Atmospheric CO_2 During Glacial Times

4.1. Initial decrease in atmospheric CO_2 during glacial inception (115–100 ka) **35 ppm drawdown**

We argue based on existing proxy data that the initial drawdown of atmospheric CO_2 was driven primarily by barrier mechanisms, mostly through expanded sea ice cover. We rule out deep ocean ventilation as a mechanism for early CO_2 drawdown because proxies show no evidence for widespread changes in deep ocean circulation until the MIS 5/4 transition ~30 ka after the initial CO_2 drop.

4.2. Second decrease in atmospheric CO_2, 80–65 ka **40 ppm drawdown**

Between MIS 5a and 4, atmospheric CO_2 dropped a second time by 40 ppmv, just as polar temperatures cooled to near-Ice Age levels, North Atlantic SSTs plunged to 8 °C below interglacial levels, and benthic $\delta^{13}C$ and εNd proxies show their largest deep ocean changes (Fig. 5, Fig. 6d).

We argue that this second decrease in atmospheric CO_2 was driven largely by a more sluggish overturning circulation, which trapped respired CO_2 in the deep ocean and increased whole ocean alkalinity via the carbonate compensation mechanism (Watson and Naveiro Garabato, 2006, Lund et al., 2011, Adkins, 2013). As described above,

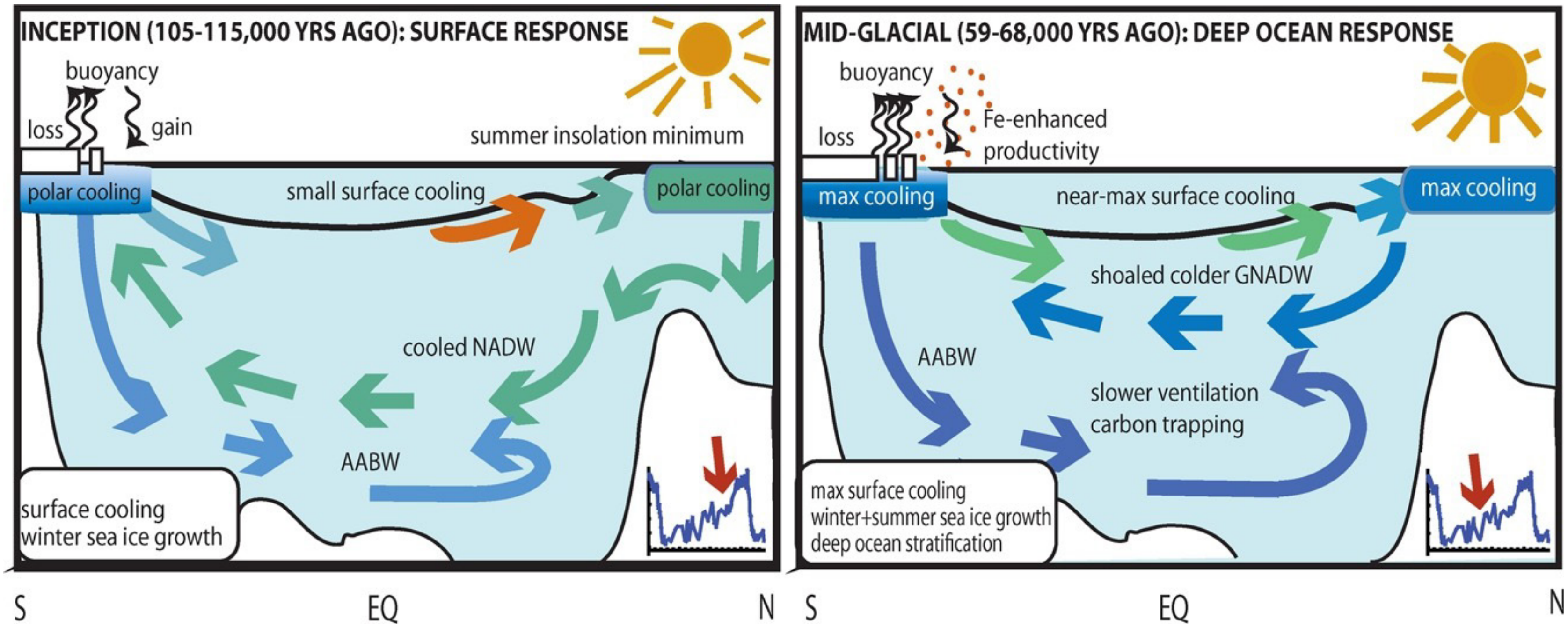
4.3. Final decrease in atmospheric CO_2, 40–18 ka **5 to 20 ppm drawdown**

The final 5–10 ppmv decrease in atmospheric CO_2 occurred between 40 to 18 ka. The first, strong candidate for enhanced CO_2 uptake by the ocean during this time is an increase in the strength of the biological pump, as dust deposition increased to the highest levels observed during the glacial cycle (Fig. 5). Therefore, the maximum 15–20 ppmv effect of this CO_2 uptake mechanism is likely to have occurred during this time. A second, complementary possibility is that enhanced deep-ocean stratification allowed for additional trapping of carbon in the deepest layers of the ocean. Continued reductions

Kohfeld and Chase, *Earth and Planetary Science Letters*, 2017
https://www.sciencedirect.com/science/article/pii/S0012821X17302753

See also Marino, McElroy, Salawitch, and Spaulding, *Nature*, 1992
https://www.nature.com/articles/357461a0
for early work on this topic.

Drawdown of Atmospheric CO_2 During Glacial Times



Kohfeld and Chase, *Earth and Planetary Science Letters*, 2017
https://www.sciencedirect.com/science/article/pii/S0012821X17302753

Time to get quantitative:

how do changes in radiative forcing affect temperature?

Let's relate a change in temperature to a change in radiative forcing:

$$\Delta T = \lambda \, \Delta F$$

λ is the ***climate sensitivity factor*** in units of $\dfrac{K}{W/m^2}$

For an ideal blackbody: $F = \sigma \, T^4$

$$\frac{dF}{dT} = 4 \, \sigma \, T^3$$

Above equation can be re-arranged to yield:

$$\Delta T \approx \frac{1}{4 \, \sigma \, T^3} \Delta F$$

So: $\lambda = \dfrac{1}{4 \, \sigma \, T^3}$

If we plug in value of Boltzmann's constant and Earth's effective temperature of 255 K, we find $\lambda_{BB} \approx 0.266$ K / (W m^{-2})

Here: BB refers to Black Body

Time to get quantitative:
how do changes in radiative forcing affect temperature?

Let's relate a change in temperature to a change in radiative forcing:

$$\Delta T = \lambda \, \Delta F$$

λ is the *climate sensitivity factor* in units of $\dfrac{K}{W/m^2}$

For an ideal blackbody: $F = \sigma \, T^4$

$$\frac{dF}{dT} = 4 \, \sigma \, T^3$$

We write:

$\lambda_{ACTUAL} = \lambda_P \, (1 + f_{H2O})$

where f_{H2O} is the H_2O feedback

Here, $f_{H2O} \approx 1.08$

Above equation can be re-arranged to yield:

$$\Delta T \approx \frac{1}{4 \, \sigma \, T^3} \, \Delta F$$

So: $$\lambda = \frac{1}{4 \, \sigma \, T^3}$$

Another estimate of the response of ΔT to ΔF can be found using a climate model representing that as the atmosphere warms, it can hold more H_2O:

$\lambda_{ACTUAL} \approx 0.63 \pm 0.13$ K / (W m^{-2})

Table 9.5, IPCC (2013)

Time to get quantitative:

how do changes in radiative forcing affect temperature?

Hence: $$\Delta T \approx 0.63 \frac{\mathrm{K}}{\mathrm{W/m^2}} \Delta F$$

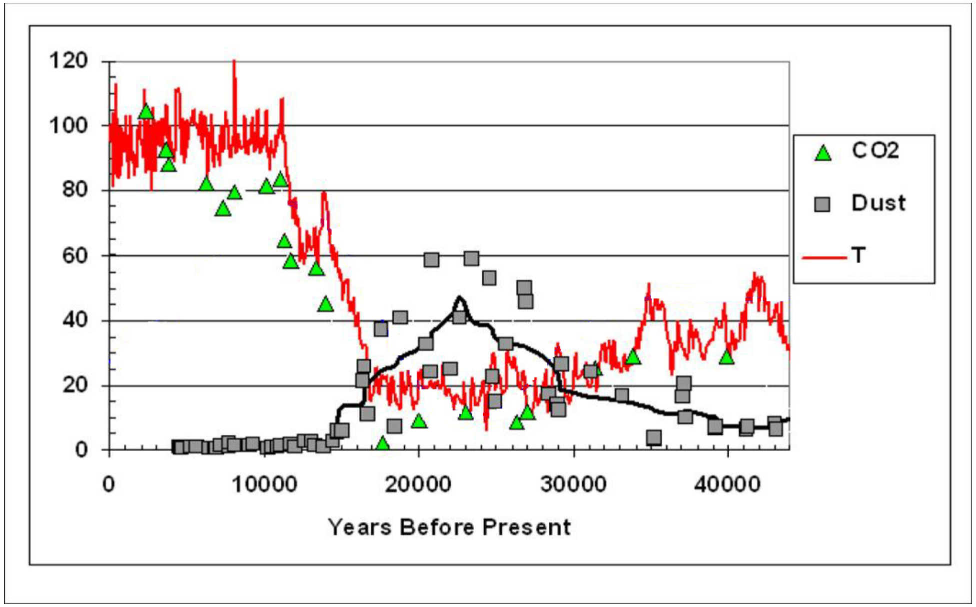
How much does ΔF change when CO_2 changes?

As we will explore in more detail later in class (19 Sep 2024):

$$\Delta F \approx 5.35\ \mathrm{W/m^2}\ \ln\left(\frac{CO_2^{\,Final}}{CO_2^{\,Initial}}\right)$$

Changes in ΔF can be caused by changes in chemical composition (GHGs), albedo, aerosol loading, as well as solar output

Glacial to interglacial changes in T, CO_2 and dust



Vostok ice core data for ***changes*** in temperature (units of 0.1 K), CO_2 (ppmv), and dust aerosols (linear scale normalized to unity for Holocene)
Black line shows 5 point running mean of dust.

Chylek and Lohmann, *GRL*, 2008

Chylek and Lohmann (2008) assume:

a) ***global*** avg ΔT, glacial to interglacial, was 4.65 K *

b) ΔF_{CO2} = 2.4 W m^{-2} , $\Delta F_{CH4+N2o}$ = 0.27 W m^{-2} , ΔF_{ALBEDO} = 3.5 W m^{-2} , & $\Delta F_{AEROSOLS}$ = 3.3 W m^{-2}

From this they deduce **λ_{ACTUAL} = 0.49 K / W m^{-2}**

Since 0.49 K / W m^{-2} < 0.63 K / W m^{-2} , one would conclude that either the H_2O feedback is smaller than found in IPCC climate models ***or*** changes in clouds serve as a negative feedback

*** Global ΔT is about half that recorded at Vostok, as stated in the caption of Fig 4.9a of Houghton**

Glacial to interglacial changes in T, CO_2 and dust

Chylek and Lohmann (2008) are trying to calculate the sensitivity of climate to various forcings, ***with and without the consideration of aerosols***

	ΔF with aerosols(W/m^2)
CO_2	2.40
CH_4+N_2O	0.27
Albedo	3.50
Aerosols	3.30

$$\Delta T = \lambda_{\text{Considering Aerosols}} (\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{ALBEDO} + \Delta F_{AEROSOLS})$$

$$\lambda_{\text{Considering Aerosols}} = \frac{\Delta T}{\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{ALBEDO} + \Delta F_{AEROSOLS}} = \frac{4.65\ \text{K}}{9.47\ \text{W m}^{-2}} = $$

$$= 0.49\ \text{K} \ / \ \text{W m}^{-2}$$

$$\textit{If} \quad \lambda_{\text{Considering Aerosols}} = \lambda_P (1 + f) \ \text{ and } \ \lambda_P = 0.3\ \text{K} \ / \ \text{W m}^{-2},$$

$$\text{then} \quad f = 0.63$$

Glacial to interglacial changes in T, CO_2 and dust

Chylek and Lohmann (2008) are trying to calculate the sensitivity of climate to various forcings, ***with and without the consideration of aerosols***

	ΔF with aerosols(W/m^2)	ΔF without aerosols (W/m^2)
CO_2	2.40	2.40
CH_4+N_2O	0.27	0.27
Albedo	3.50	3.50
Aerosols	3.30	0.

$$\Delta T = \lambda_{\text{No Aerosols}} (\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{ALBEDO})$$

$$\lambda_{\text{No Aerosols}} = \frac{\Delta T}{\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{ALBEDO}} = \frac{4.65\ \text{K}}{6.17\ \text{W m}^{-2}} =$$

$$= 0.75\ \text{K} \ / \ \text{W m}^{-2}$$

If $\lambda_{\text{No Aerosols}} = \lambda_P (1 + f)$ and $\lambda_P = 0.3\ \text{K} \ / \ \text{W m}^{-2}$,

then $f = 1.5$

Let's apply these two climate sensitivities to *future* temperature

Both future scenarios assume:

a) CO_2 doubles: i.e., ΔF_{CO2} = 5.35 ln(2) W/m^2 or = 3.7 W/m^2
b) surface radiative forcing of CH_4 + N_2O will be 40% of CO_2 (future mimics past)

Scenario #1: Weak Feedback found considering aerosol radiative forcing in paleo data & no future change in Earth's albedo

Scenario #2: Strong Feedback found assuming no aerosol radiative forcing in paleo data & additional surface radiative forcing of 3.4 W/m^2 due to decline in Earth's albedo (i.e., the positive ice-albedo feedback will occur)

	Scenario #1 ΔF (W m^{-2})	Scenario #2 ΔF (W m^{-2})
CO_2	3.7	3.7
CH_4+ N_2O	1.5	1.5
Albedo	0.0	3.4
Total ΔF	5.2	8.6

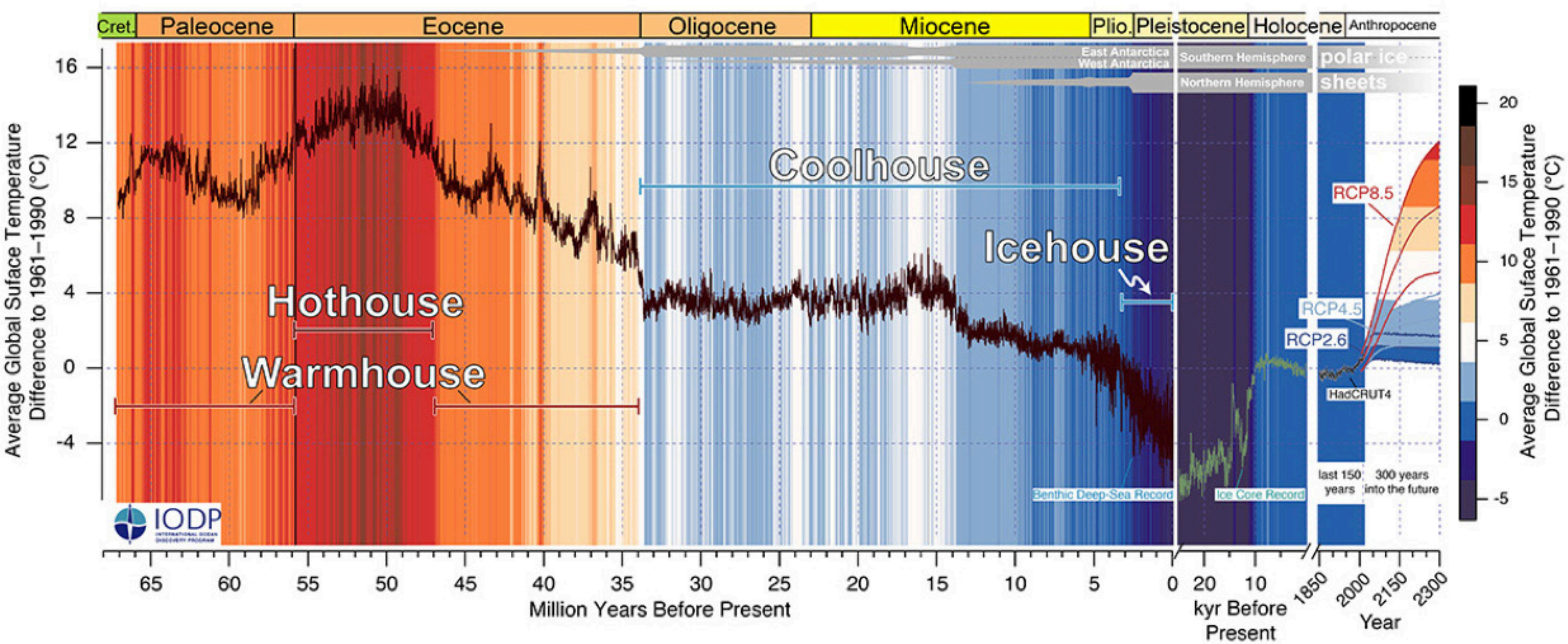
$\Delta T \Rightarrow$ K or

Take away messages:

1. ***Climate sensitivity*** **inferred from ice core record depends on how aerosols are handled**
2. ***Future climate*** **will be quite sensitive to:**
   - **the efficacy of atmospheric feedbacks (H_2O, clouds)**
   - **the radiative forcing of aerosols**
   - **how surface albedo changes**

Earth's Climate History

What message are they trying to convey?



Past and future trends in global mean temperature spanning the last 67 million years. Oxygen isotope values in deep-sea benthic foraminifera from sediment cores are a measure of global temperature and ice volume. Temperature is relative to the 1961–1990 global mean. Data from ice core records of the last 25,000 years illustrate the transition from the last glacial to the current warmer period, the Holocene. Historic data from 1850 to today show the distinct increase after 1950 marking the onset of the Anthropocene. Future projections for global temperature for three Representative Concentration Pathways (RCP) scenarios in relation to the benthic deep-sea record suggest that by 2100 the climate state will be comparable to the Miocene Climate Optimum (~16 million years ago), well beyond the threshold for nucleating continental ice sheets. If emissions are constant after 2100 and are not stabilized before 2250, global climate by 2300 might enter the hothouse world of the early Eocene (~50 million years ago) with its multiple global warming events and no large ice sheets at the poles. (Credit: Westerhold et al., CENOGRID)

https://news.ucsc.edu/2020/09/climate-variability.html
https://news.ucsc.edu/2020/09/images/climate-states-lg-cap.jpg

Final Thought

There is much more “recent climate history”, such as:

a) Younger Dryas cooling event at end of last ice age

b) Medieval climate maximum

c) the Little Ice Age (1650 to 1850)

that is deserving of our attention. A few slides on these topics are included in the Extra Material that follows (you will not be tested on the material in these 3 slides)