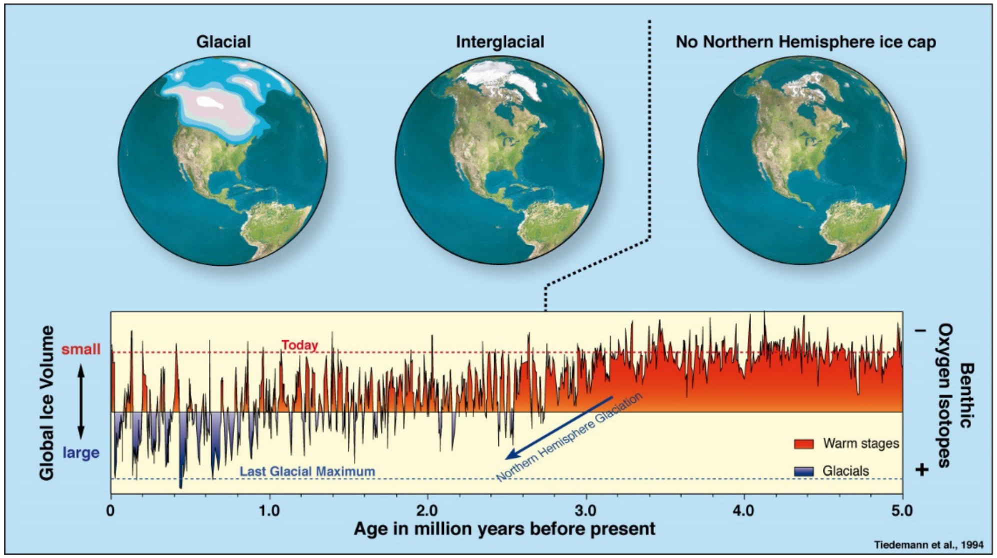
Climates of the Past

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2022
https://umd.instructure.com/courses/1327017



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

13 September 2022

Climates of the Past

Overview:

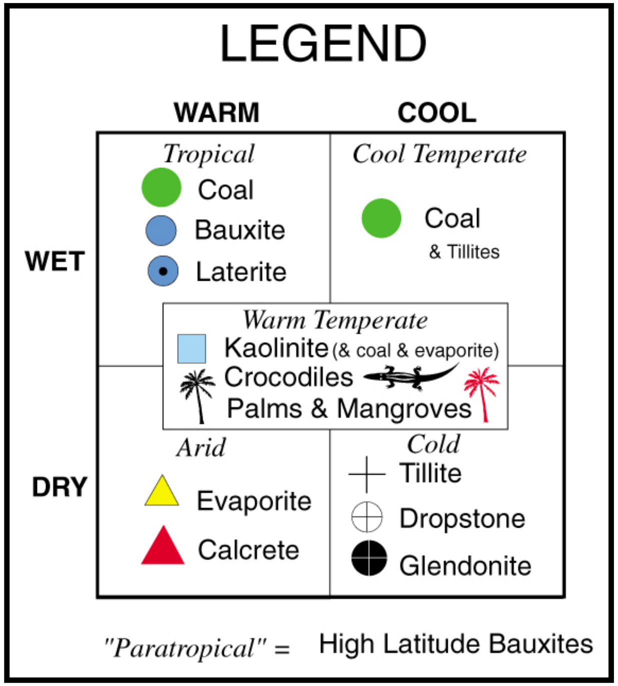
1) Techniques for quantifying past climate

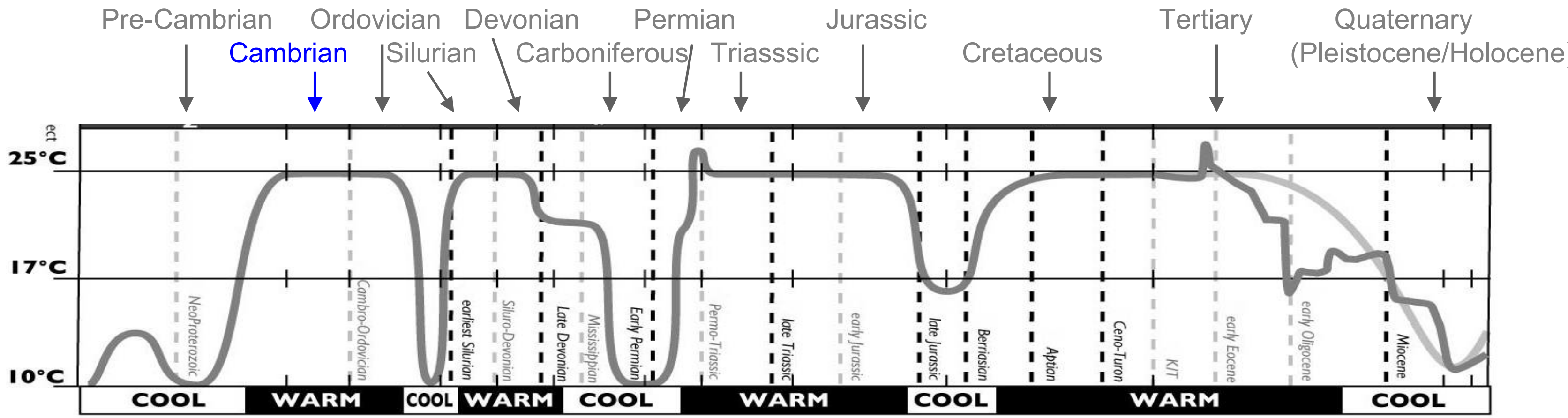
2) Remarkable changes in past climate

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
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			Miocene	23.3
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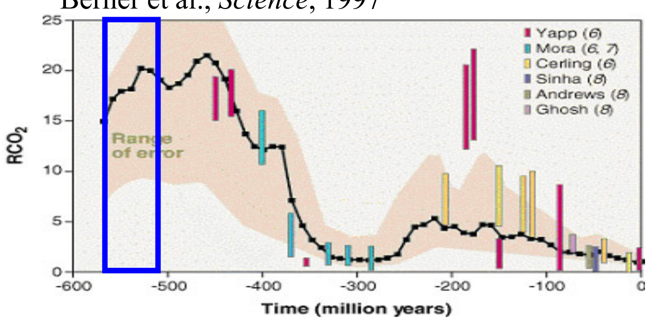
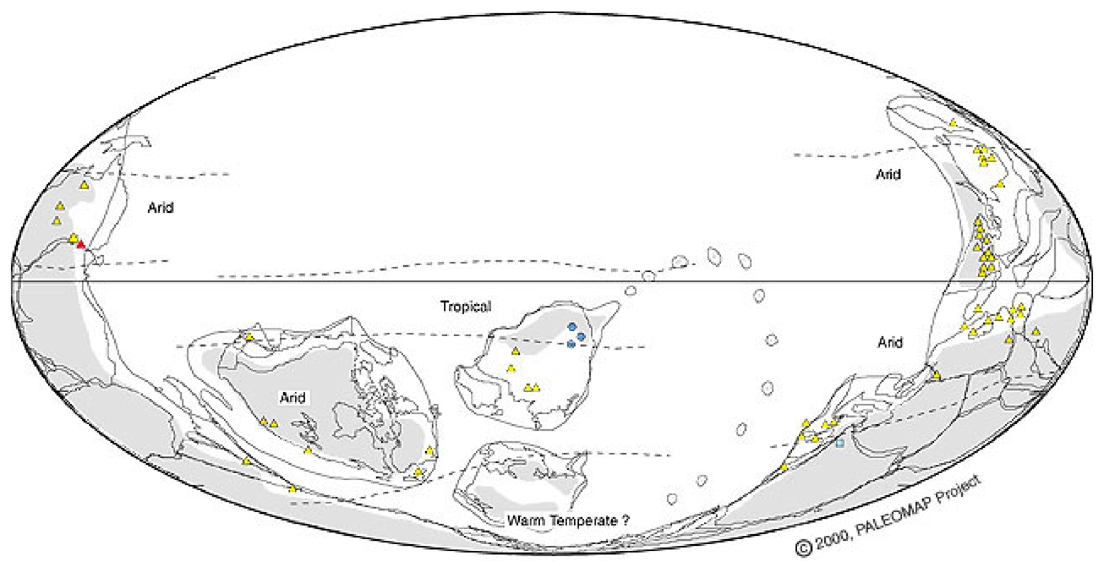
		Cambrian		570.0
Proterozoic				2500
Archean				4000

Geologic Time Scale based on Harland et al 1989

Berner et al., *Science*, 1997

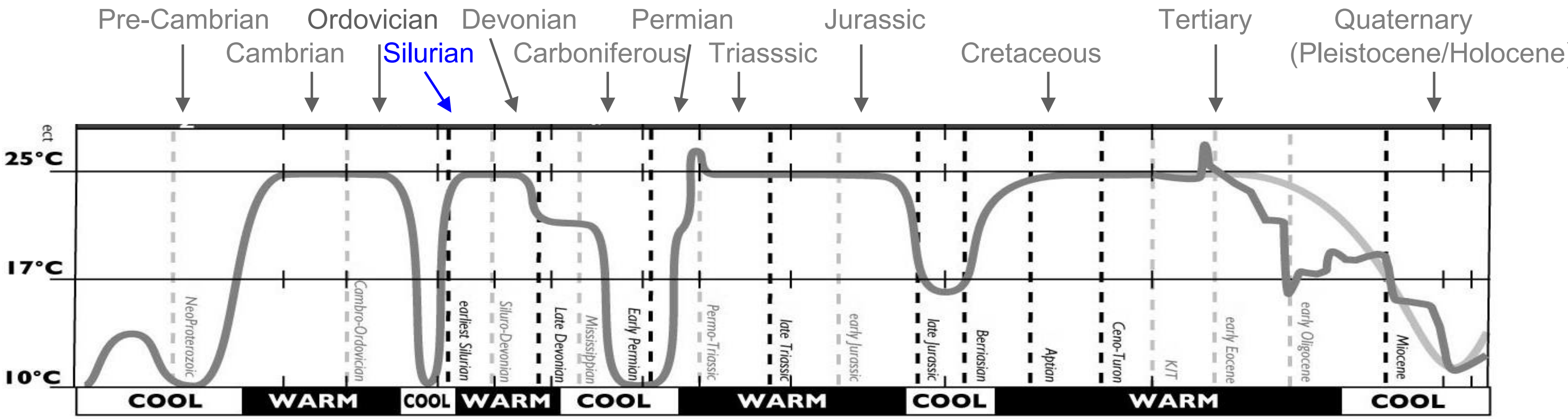


Early Cambrian Climate
(540 million years ago)



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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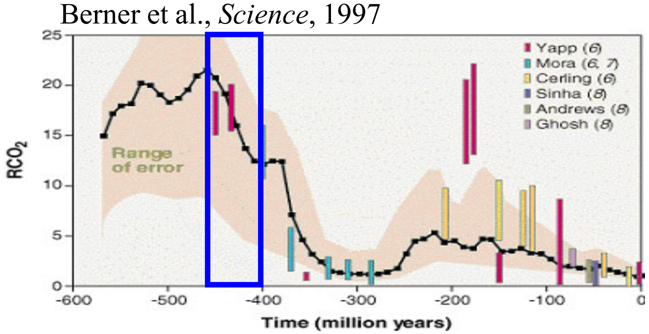
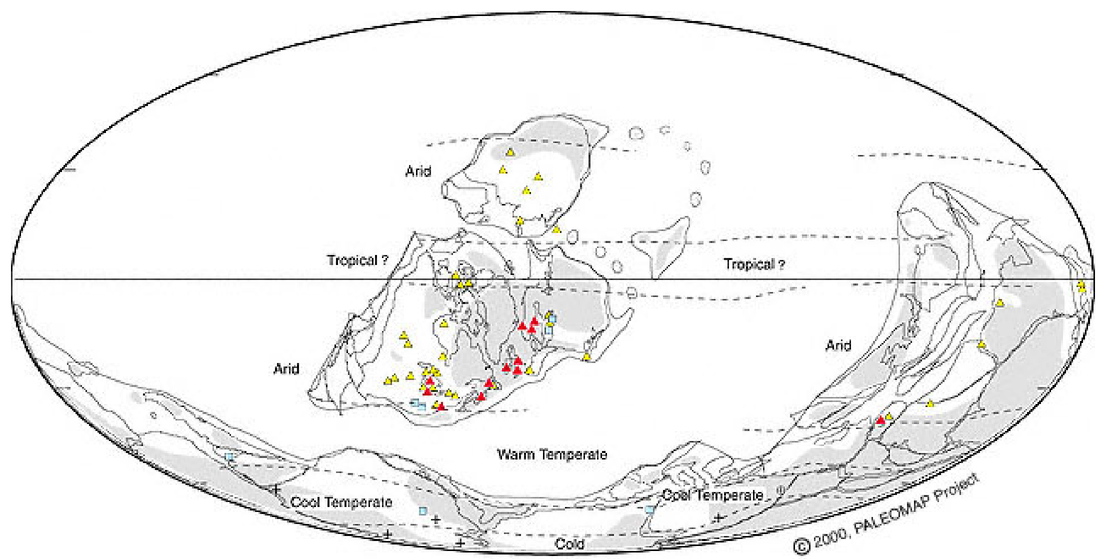
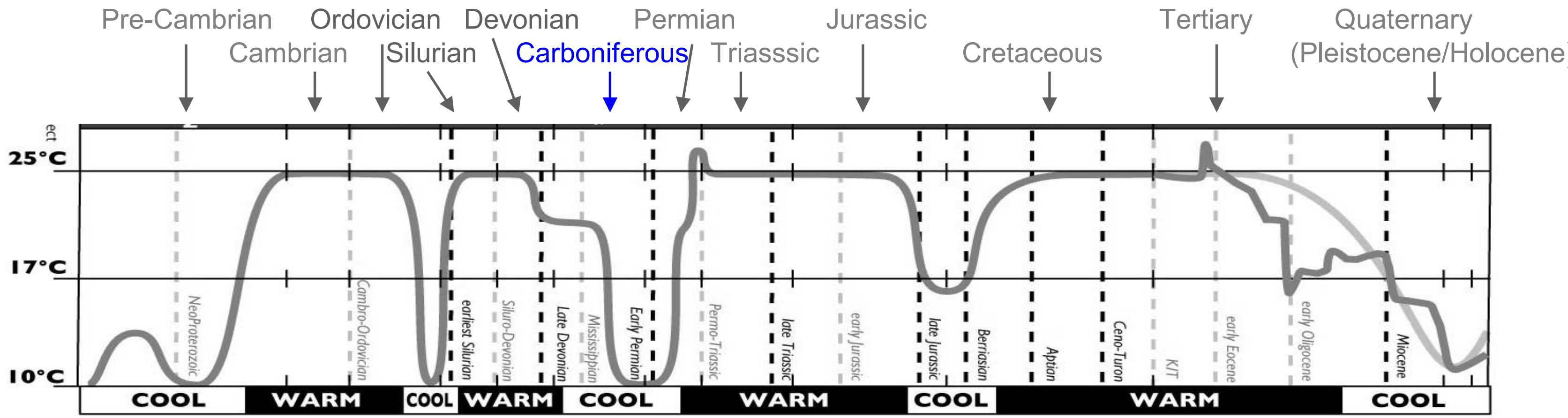


Silurian Climate
(420 million years ago)



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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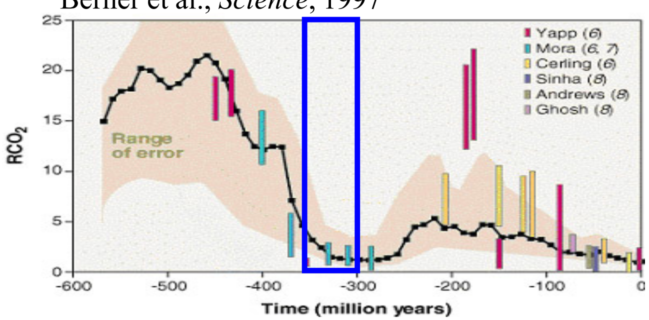
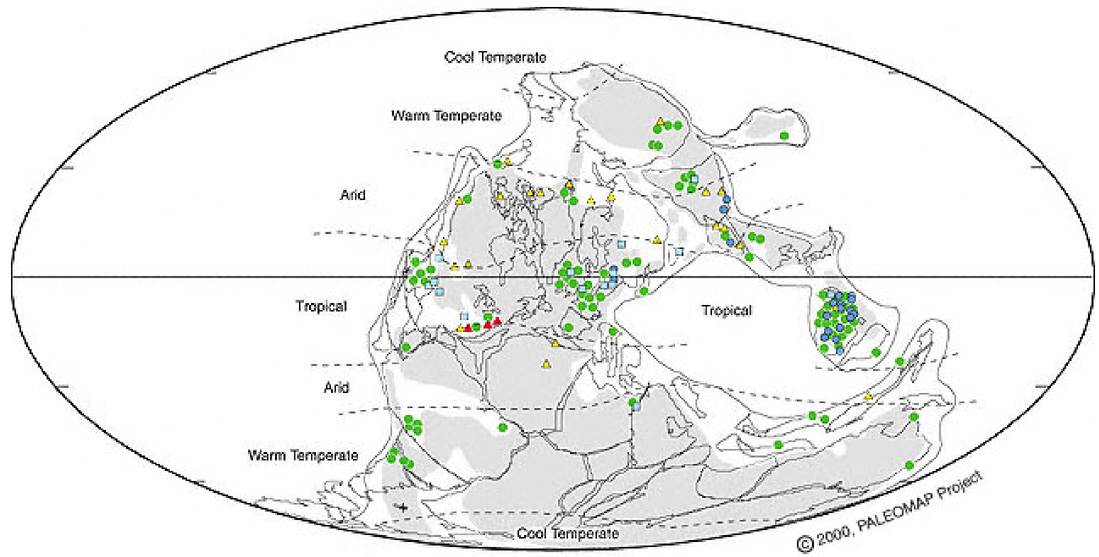
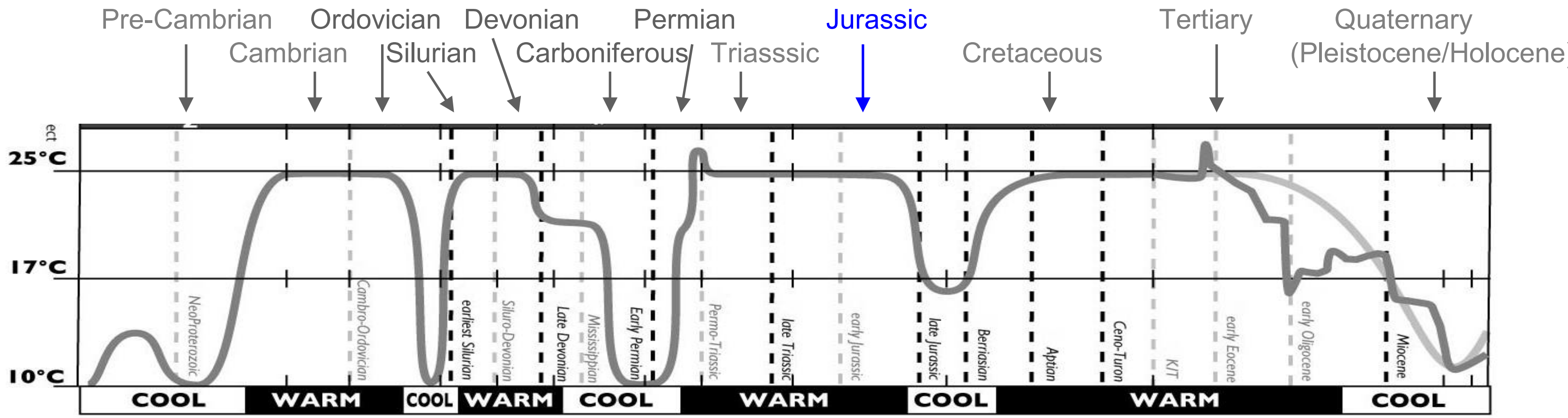


Carboniferous Climate (350 million years ago)



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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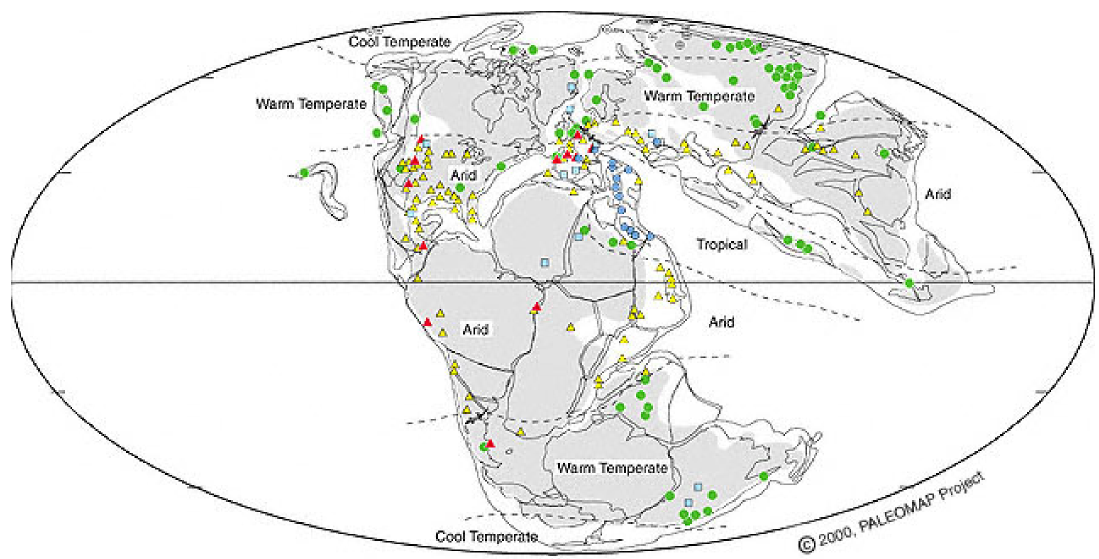
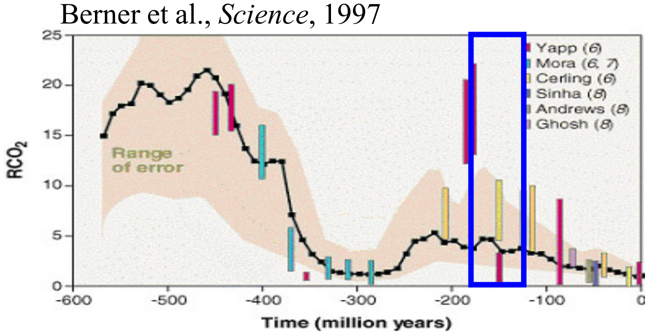
Geologic Time Scale based on Harland et al 1989

Late Jurassic Climate (150 million years ago)

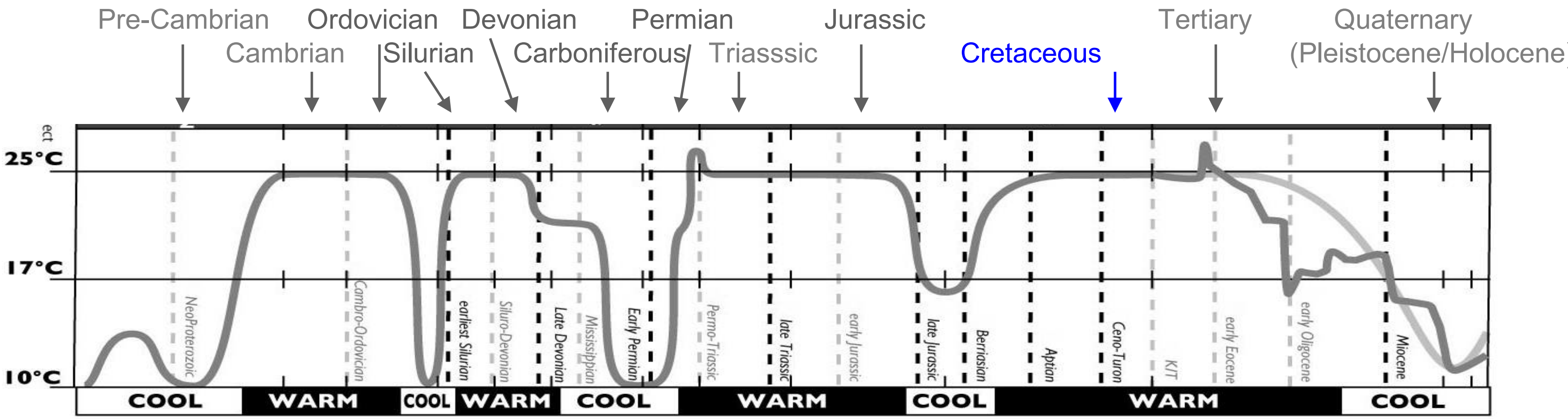


Berner et al., *Science*, 1997



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



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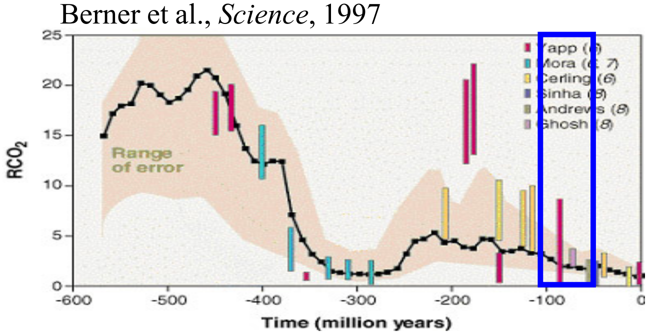
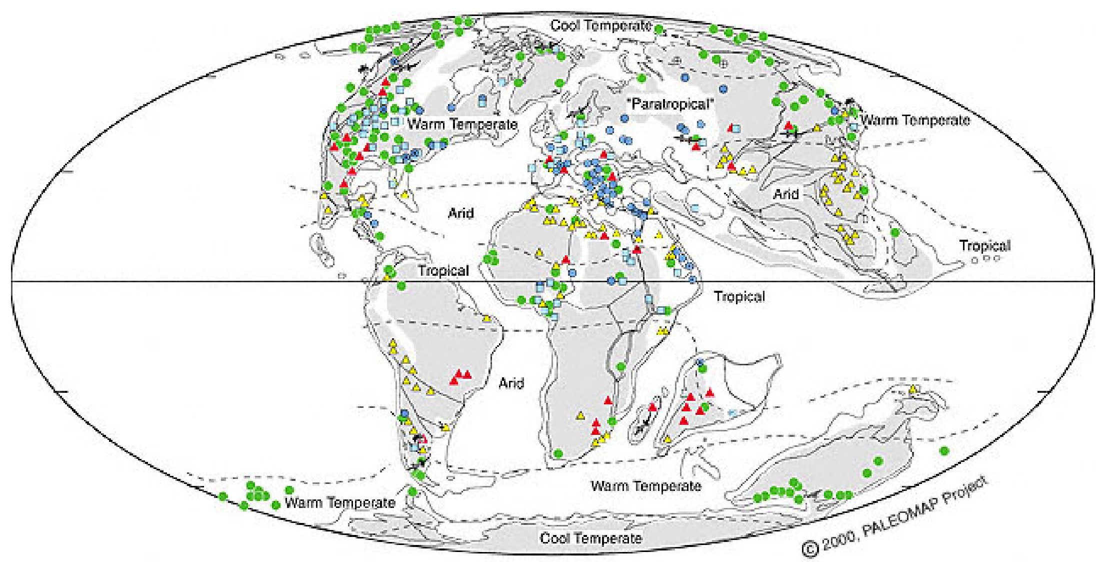


Late Cretaceous Climate (70 million years ago)



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

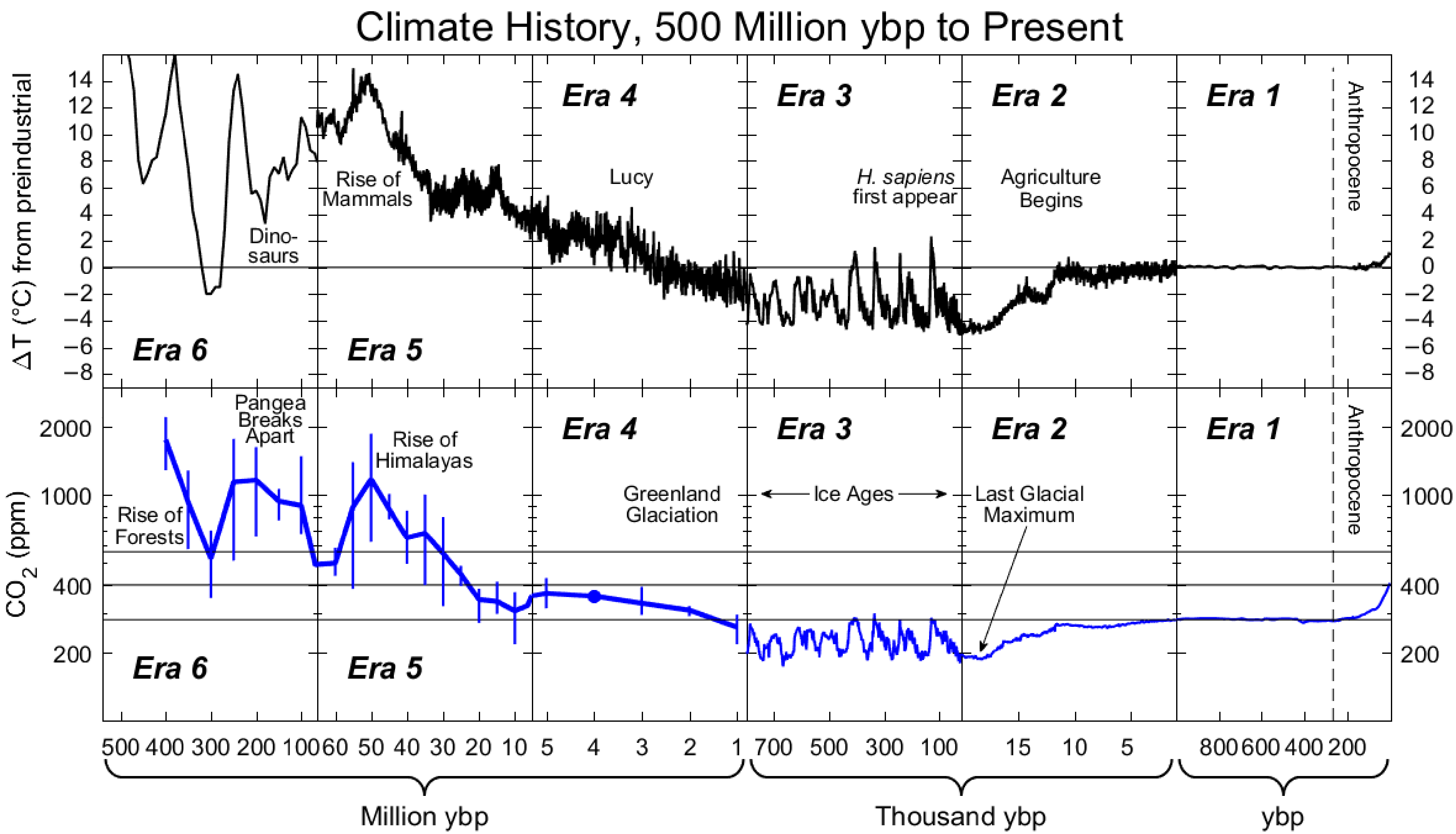


Fig 1.1, *Paris Beacon of Hope*

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"

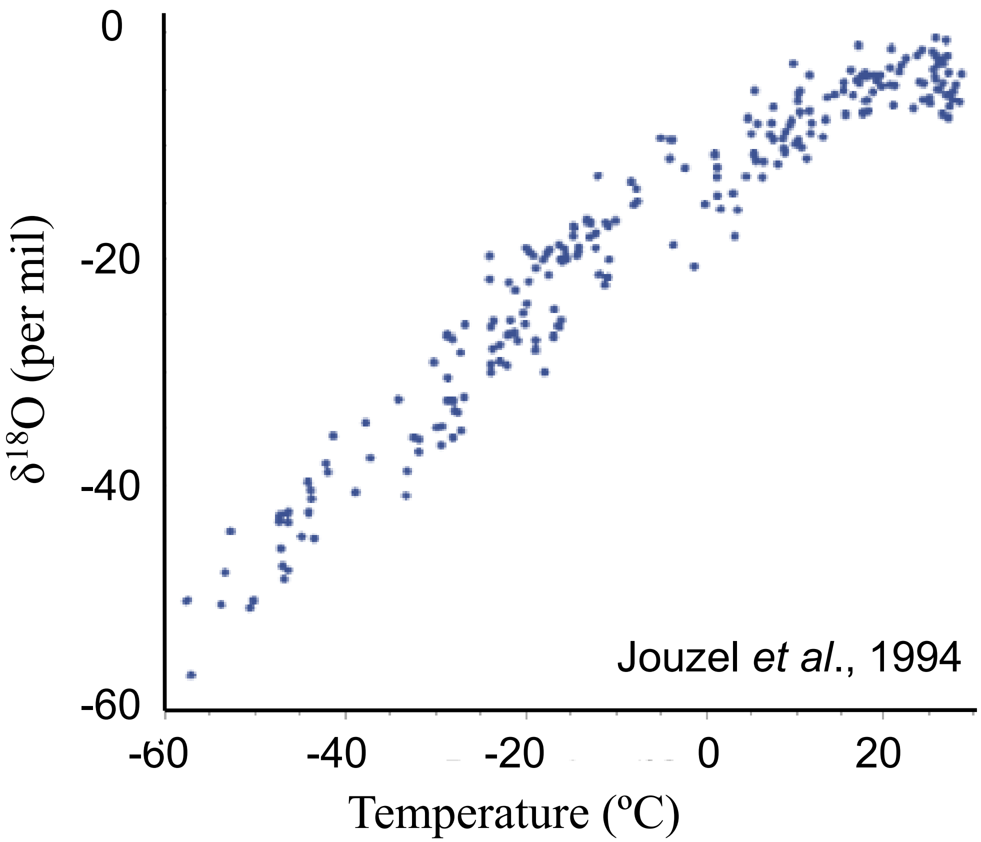
$$\delta^{18}\text{O (per mil)} = \left(\frac{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Sample} - \left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Standard}}{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Standard}} \right) \times 10^{3}$$

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?

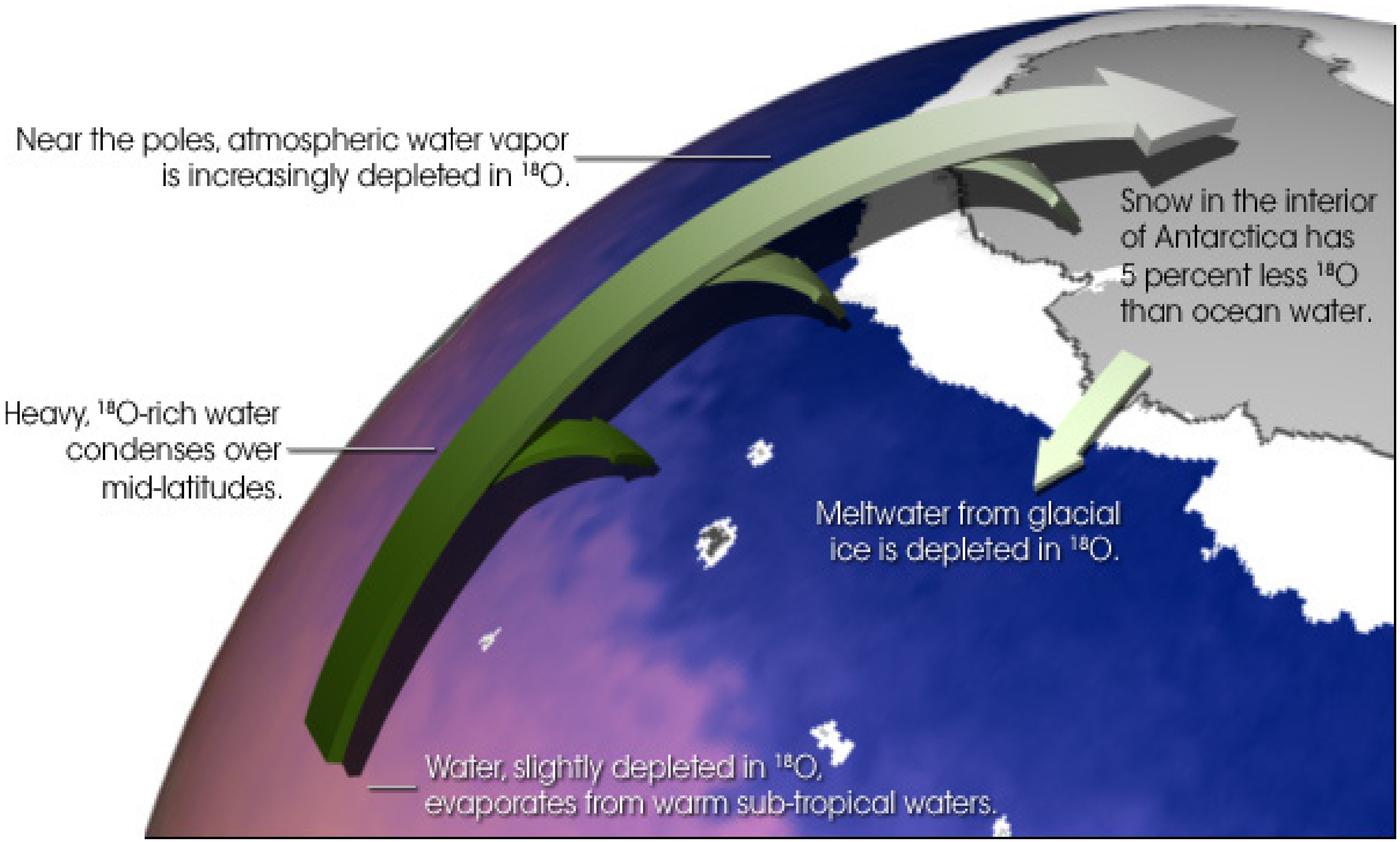


As temperatures drops, the $\delta^{18}O$ of precipitation decreases.

Why does this occur?

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

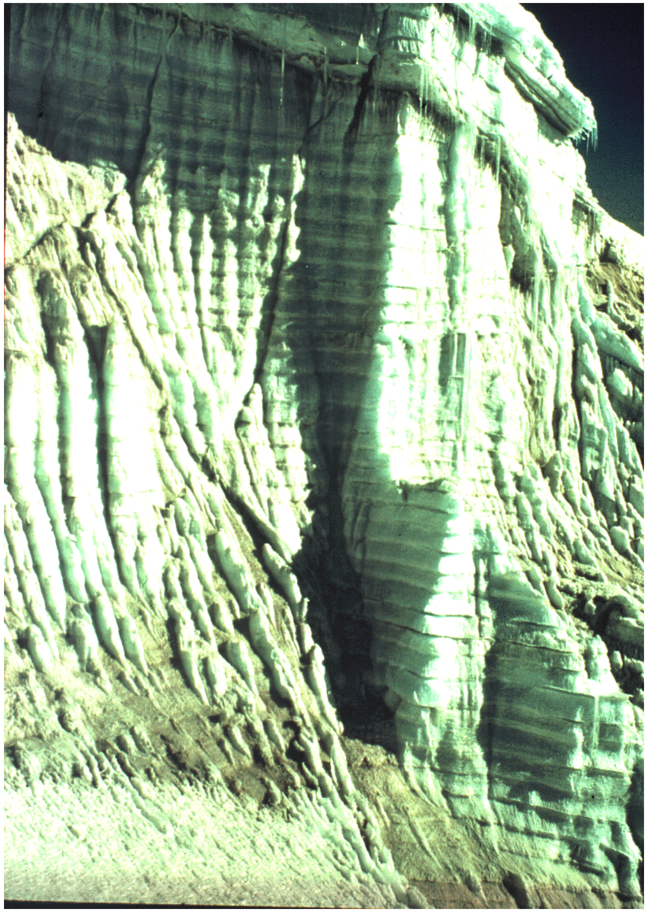
When the air mass reaches the pole, its water can have up to ~5% less ^{18}O than SMOW.



http://earthobservatory.nasa.gov/Study/Paleoclimatology_OxygenBalance/oxygen_balance.html

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

Isotopes in Ice Cores: Late Quaternary

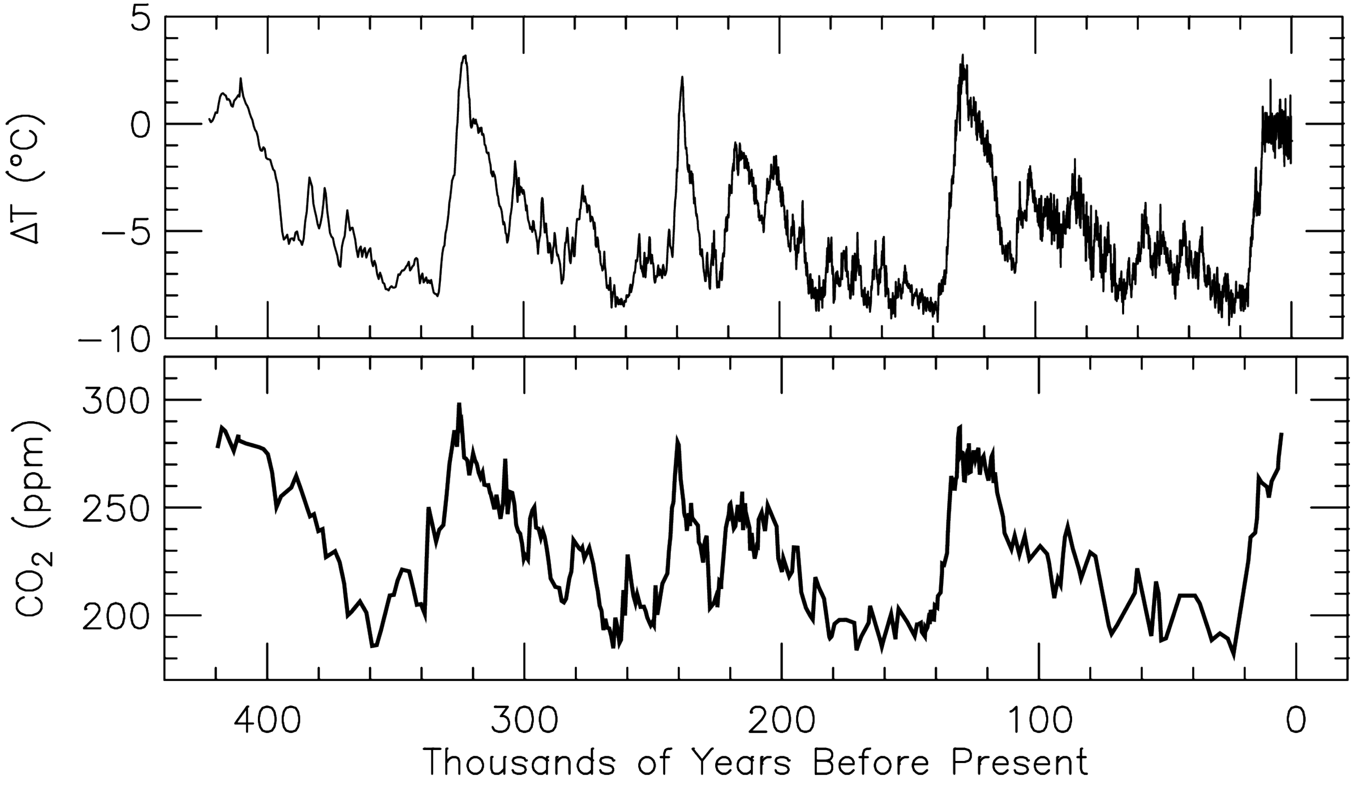


- As the air reaches the pole, ambient water precipitate (*i.e.*, it snows!)
- Over many years, layers of snow accumulate, forming an ice sheet. The water in this ice sheet contains a record of climate ***at the time the snow was deposited***
- By drilling, extracting, and measuring the $\delta^{18}O$ & 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

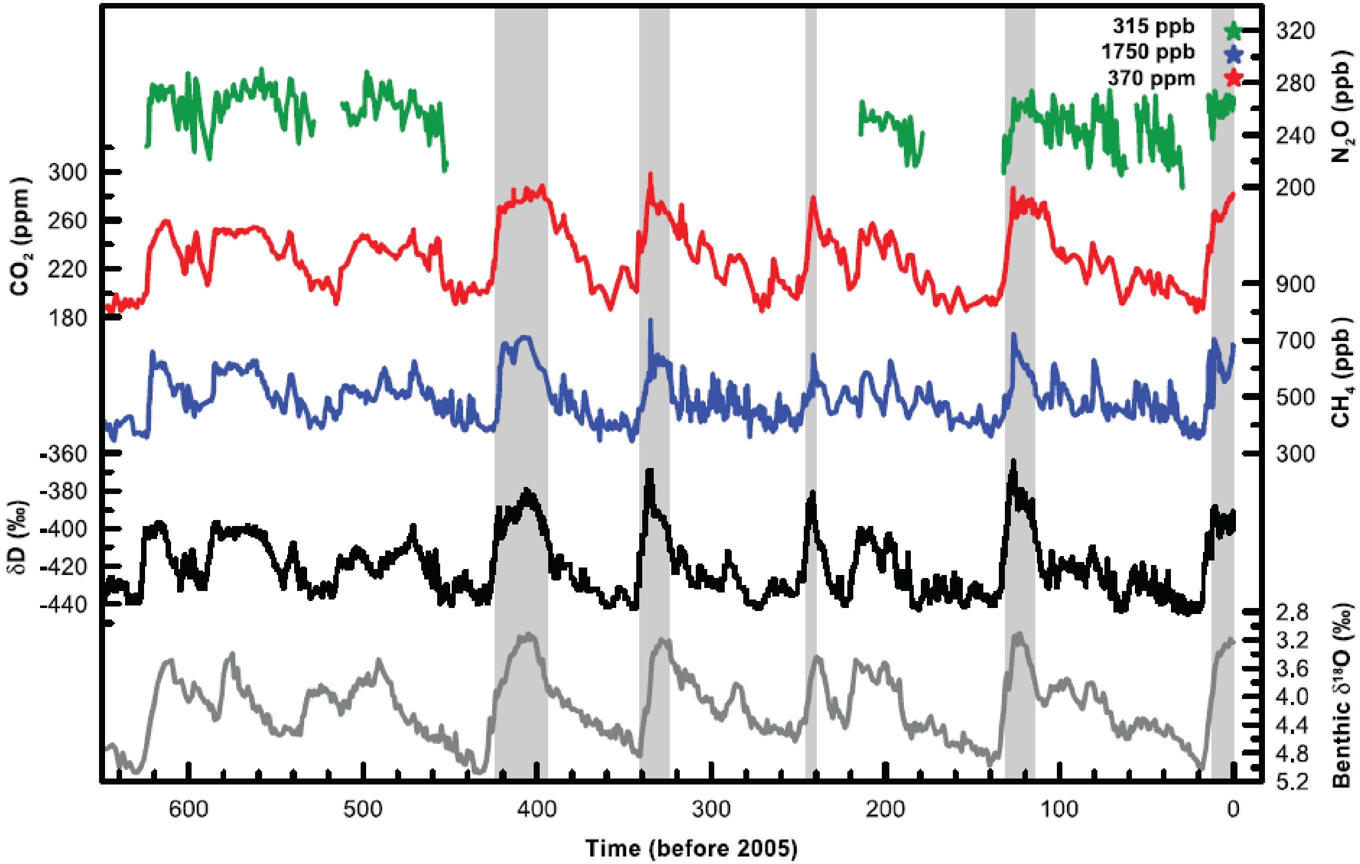
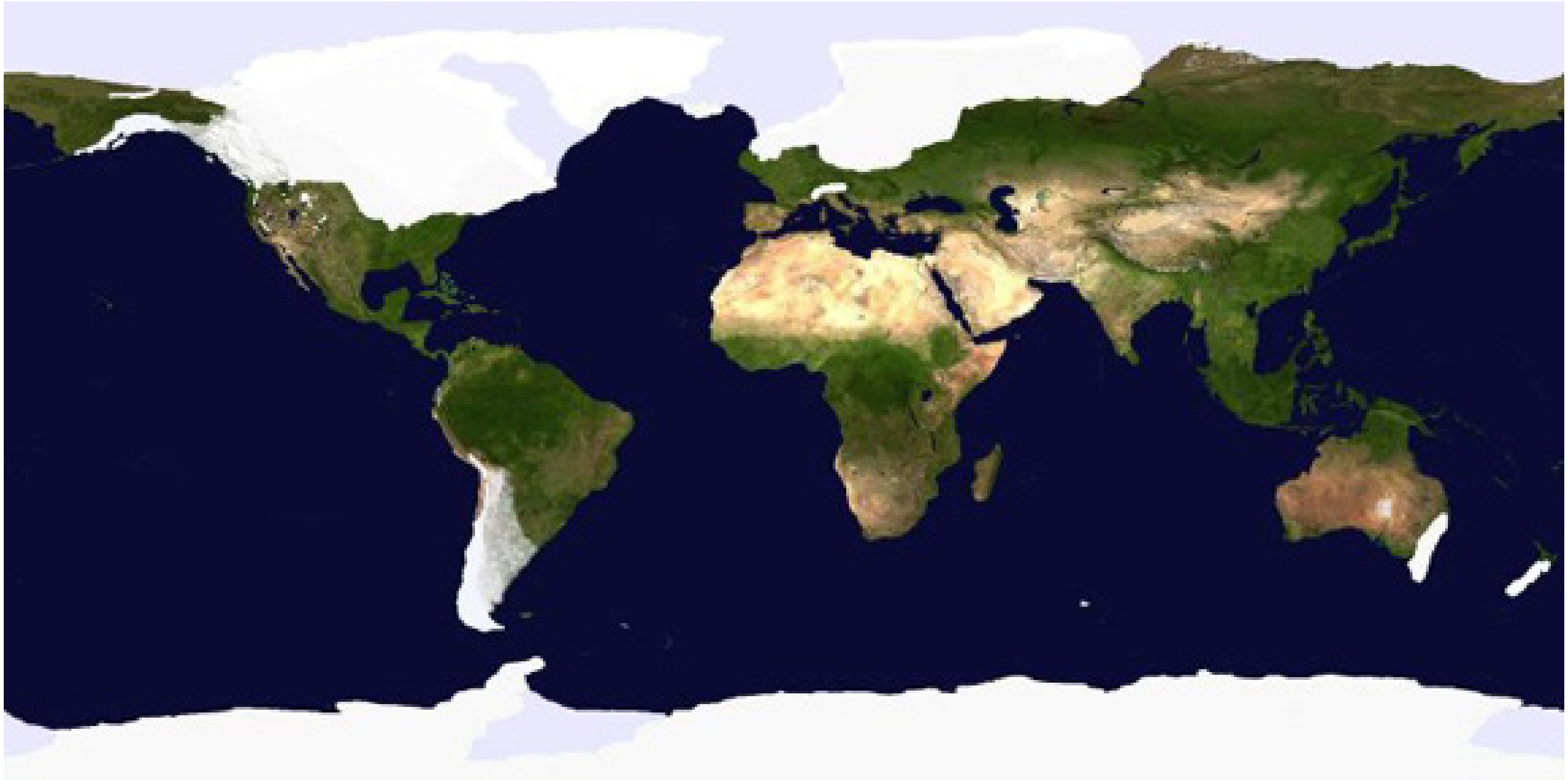


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit 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 δ^{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 δ^{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

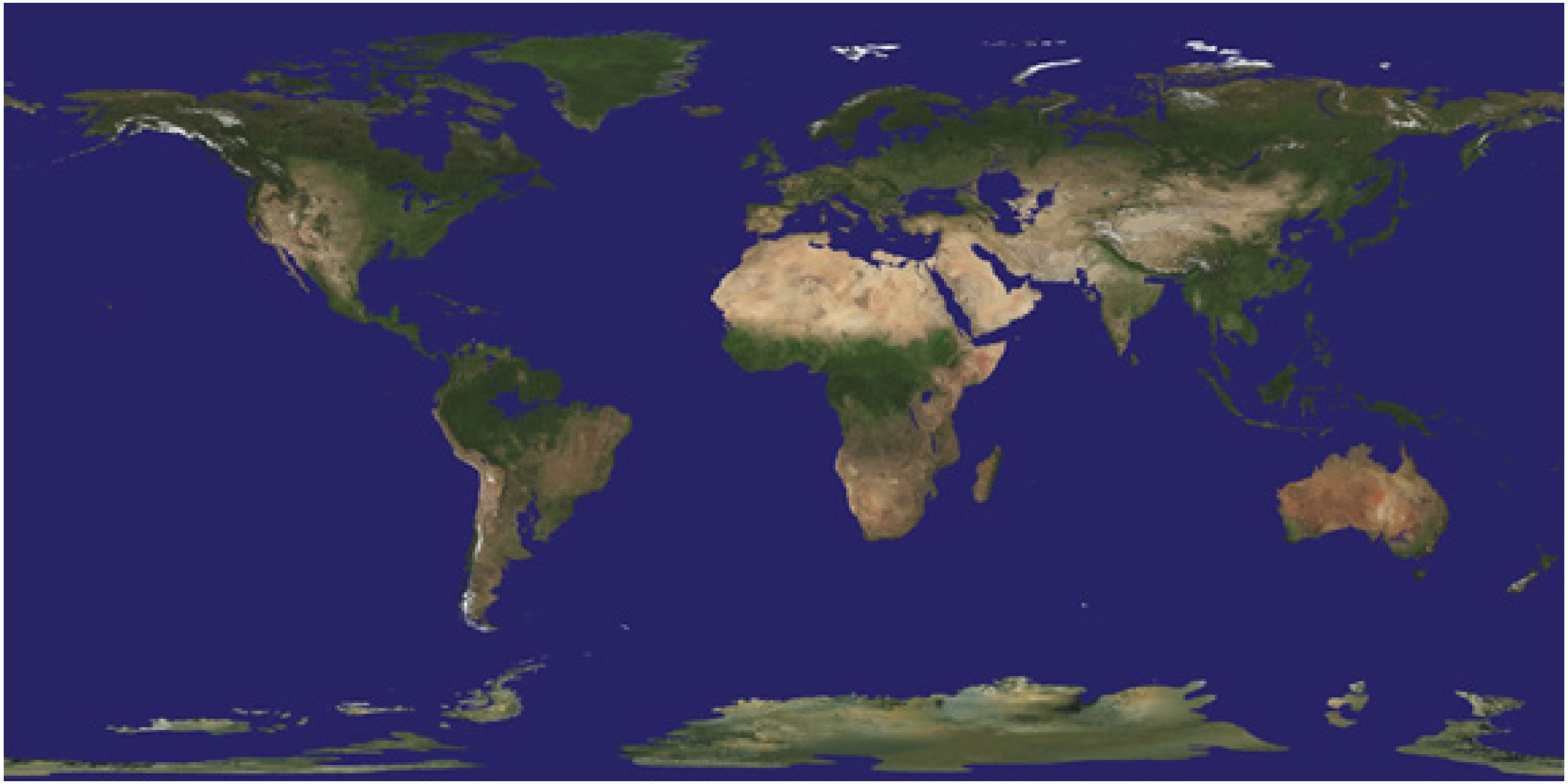
See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica

Glacial Maximum



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

No Polar Ice



http://www.johnstonarchive.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.

Portrait of Louis Agassiz at the Unteraar Glacier

http://www.museum-neuchatel.ch/new/images/dynamic/pages/12/agassiz.jpg

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

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

Pacemaker of the Ice Ages 171

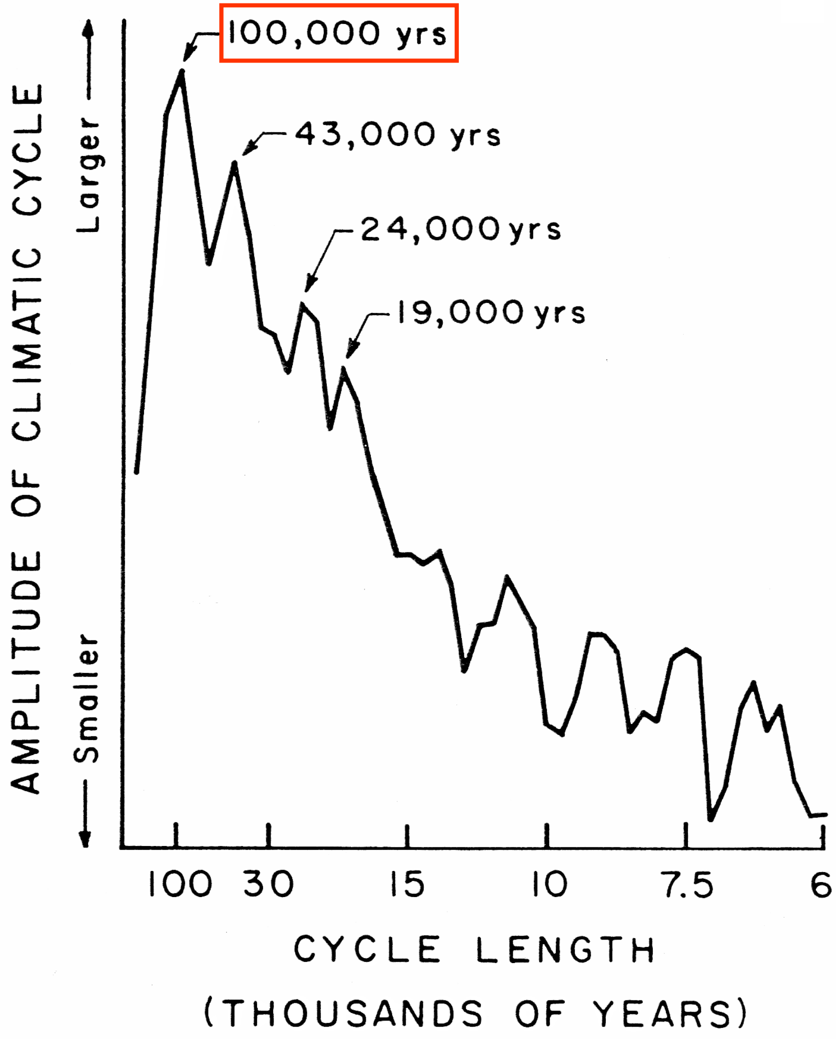
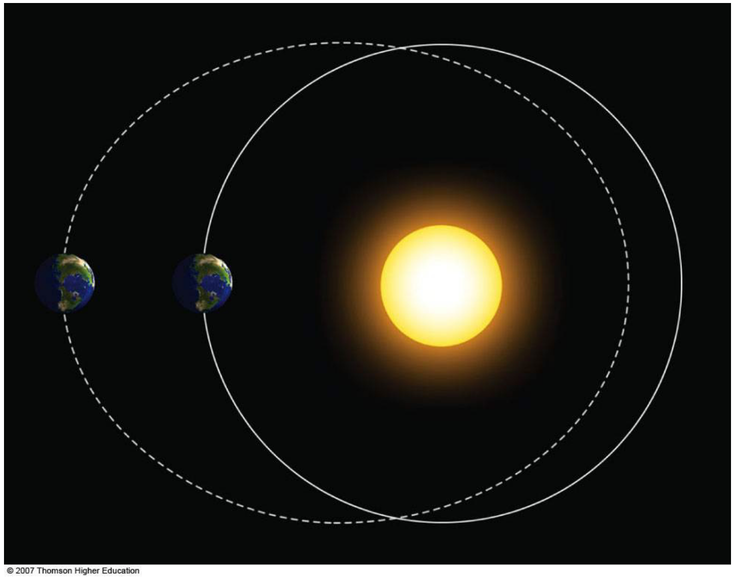


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

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

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



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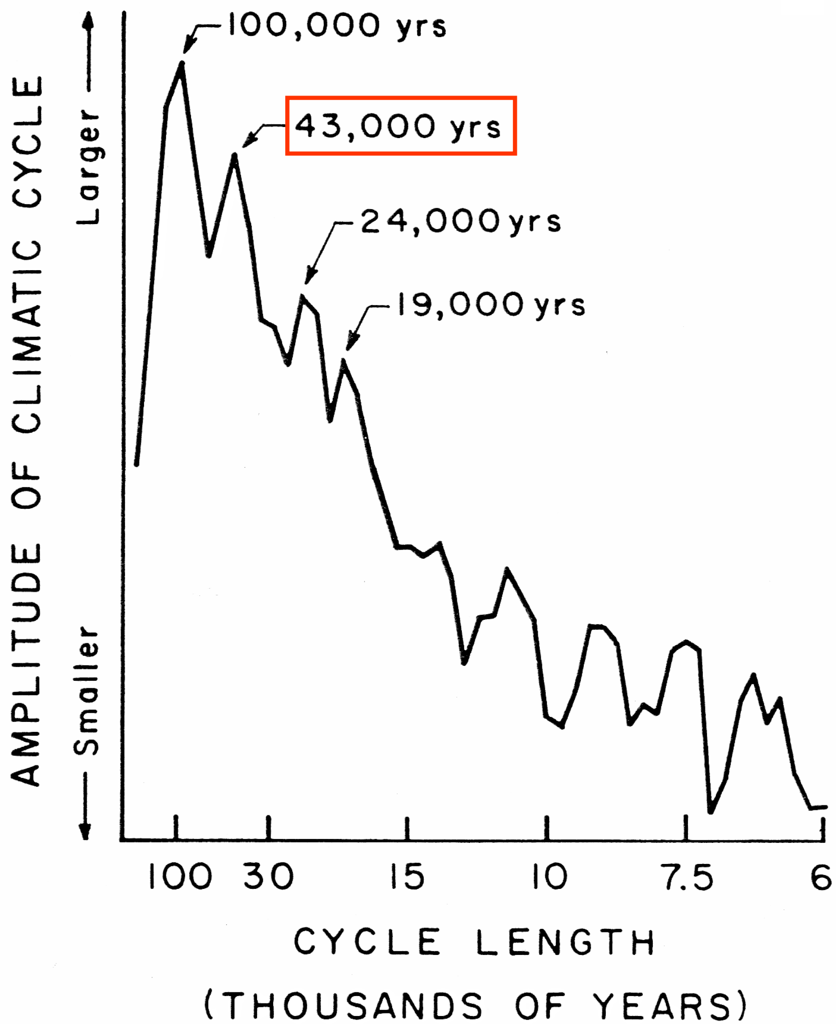

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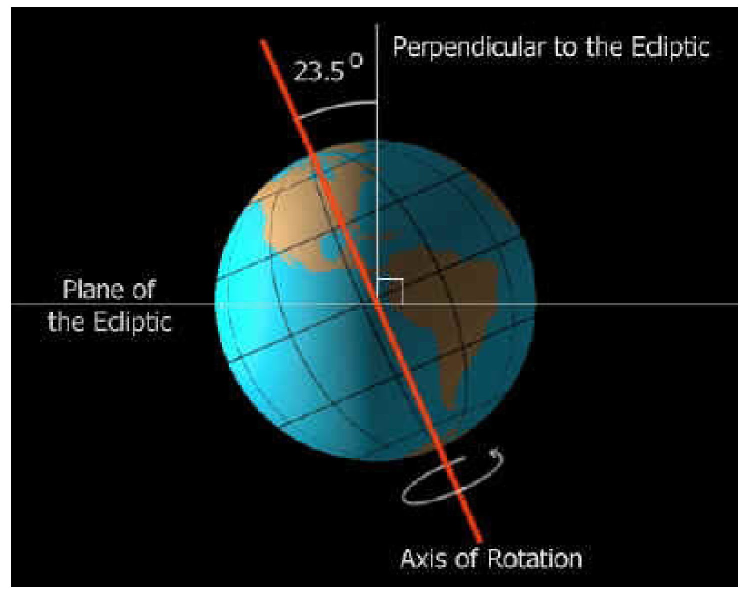
Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

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



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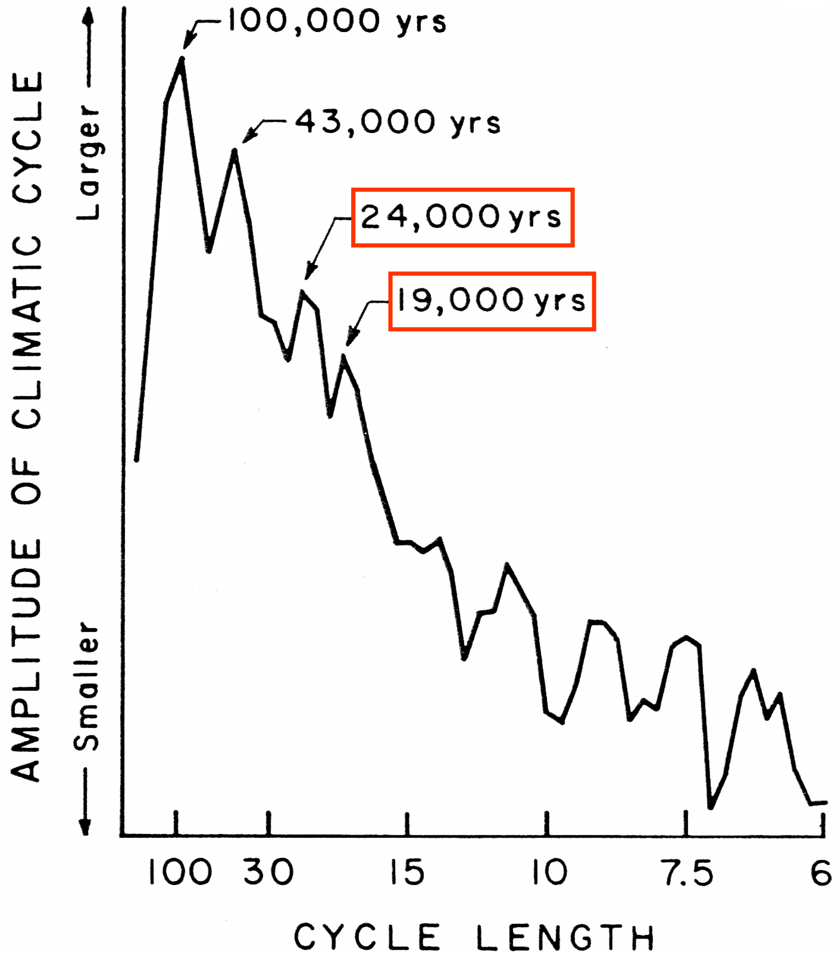

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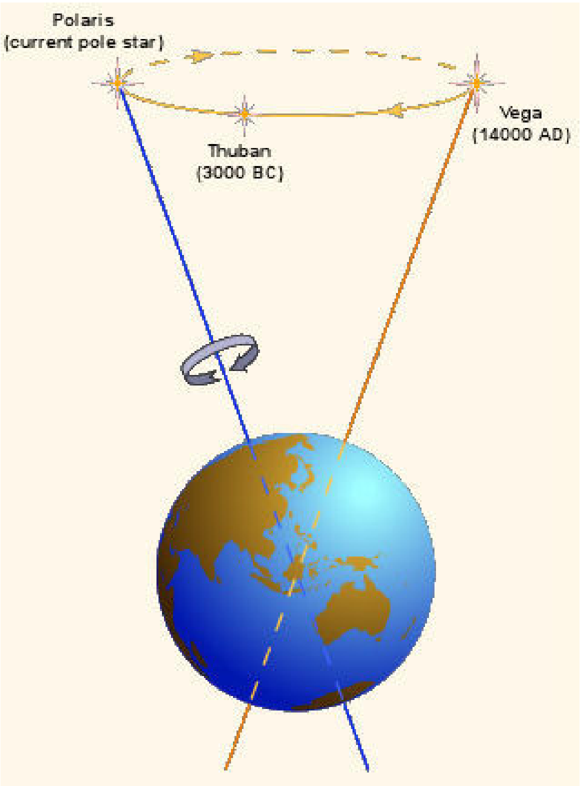
Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

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



Glacial Periods MUCH Dustier than Interglacials

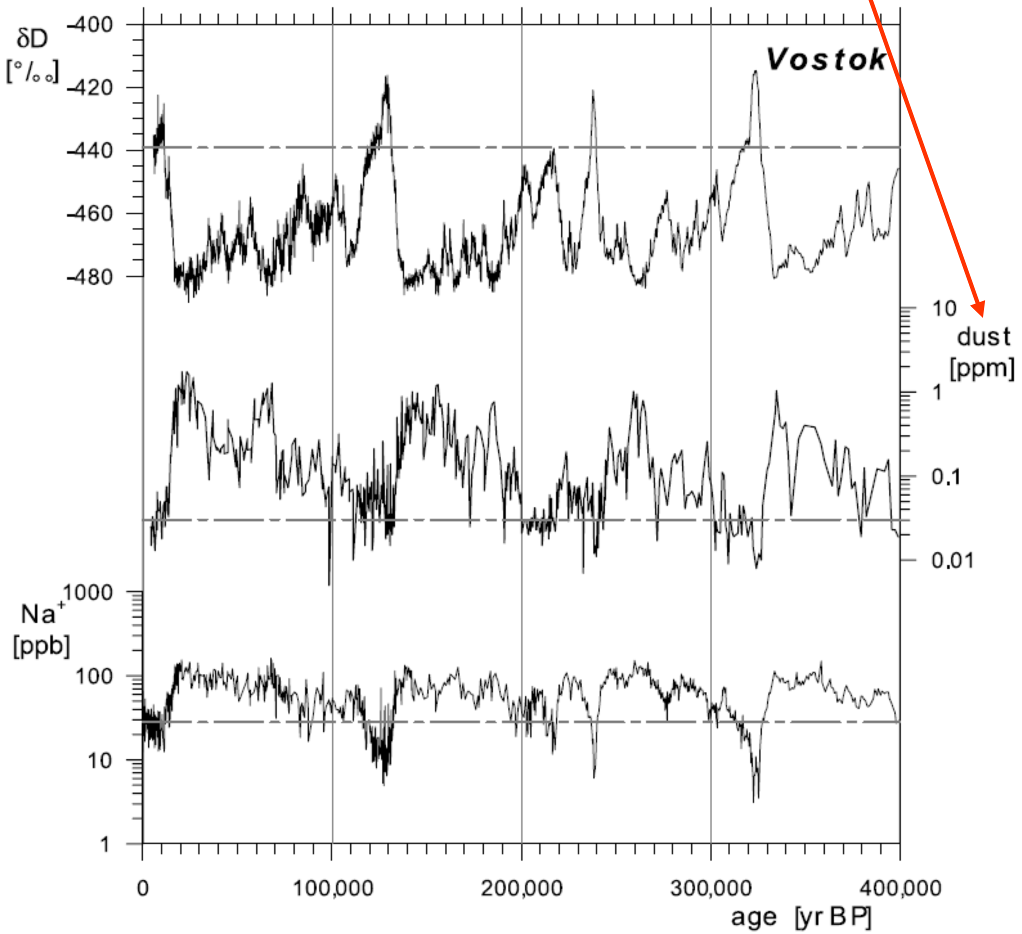


Figure 3. Temporal evolution of δD representing changes in the average local condensation temperature during snow formation, the particulate dust, and the sea-salt component Na^+ over the last four glacial cycles as recorded in the East Antarctic Vostok ice core [*Petit et al.*, 1999]. Dashed-dotted 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

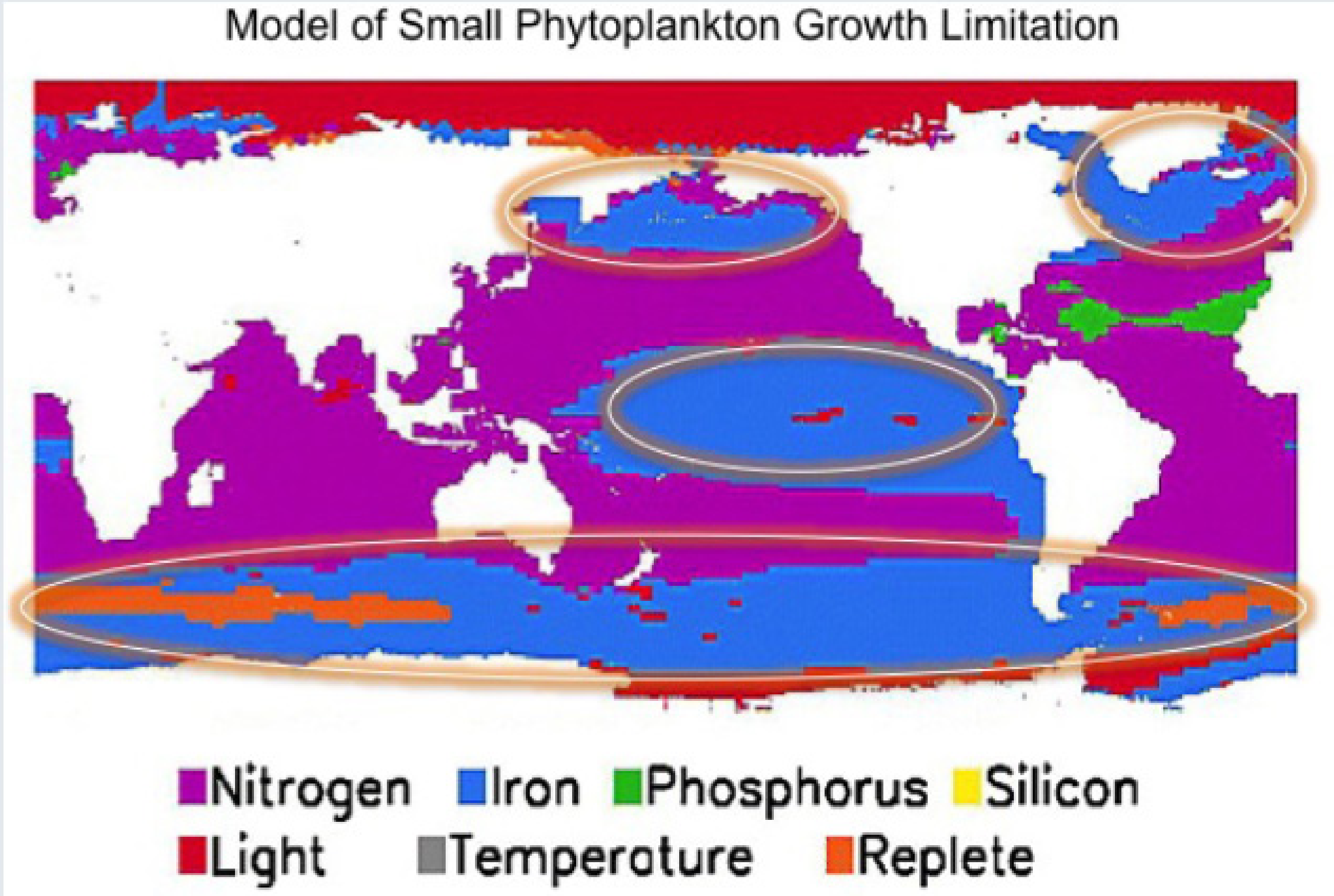


Figure 1. Results of a global model of small phytoplankton growth limitation by Moore et al. 2004 (*Global Biogeochemical Cycles*). Blue shaded areas denote regions that are potentially limited by iron availability. Iron is supplied by dust from continents and by upwelling of deep water. However, high 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

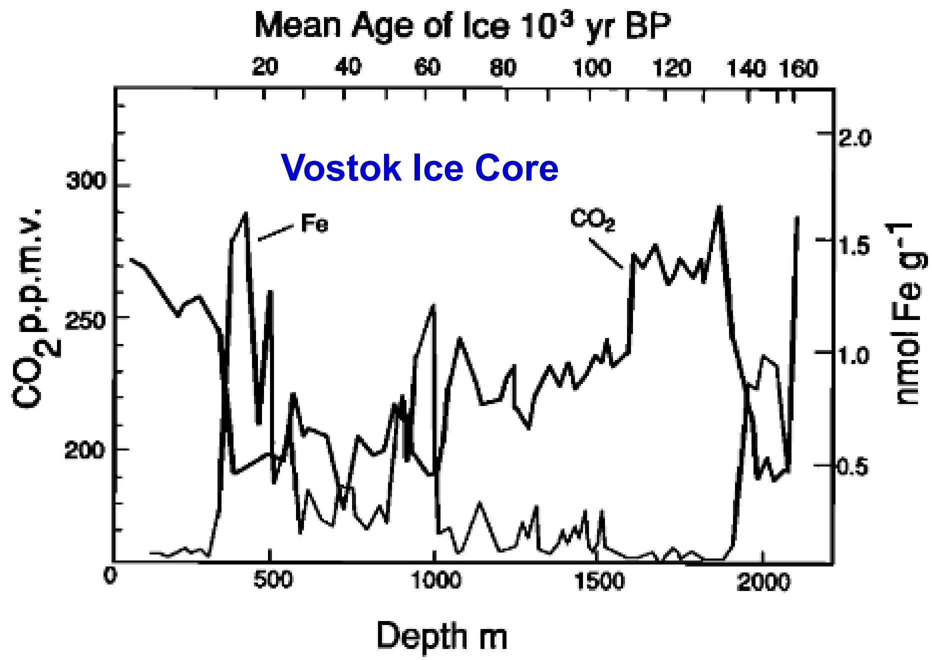
Connection to Glacial CO_2

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

GLACIAL-INTERGLACIAL CO_2 CHANGE: THE IRON HYPOTHESIS

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

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

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

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

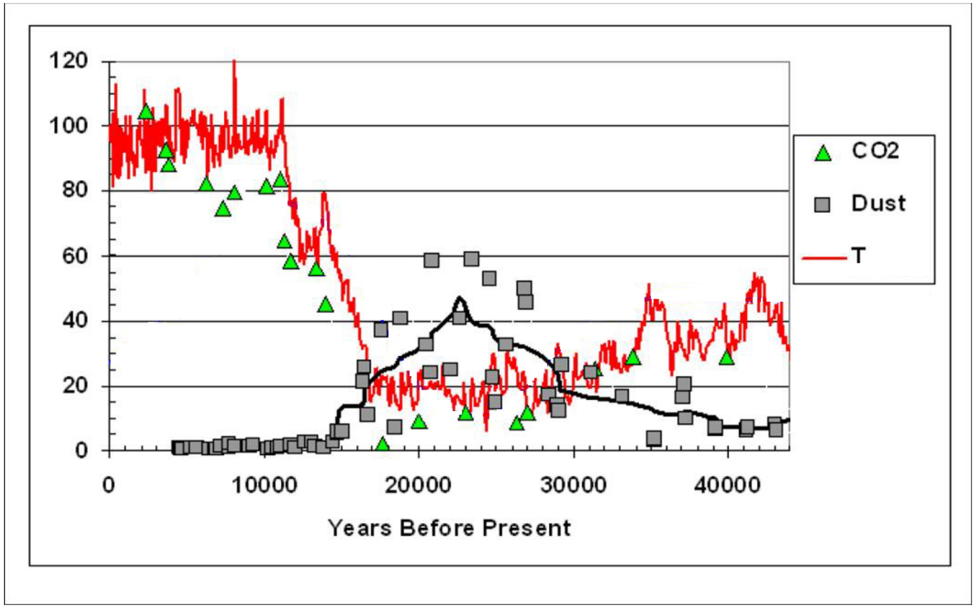
How much does ΔF change when CO_2 changes?

As we will explore in more detail later in class (22 Sep 2022):

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

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

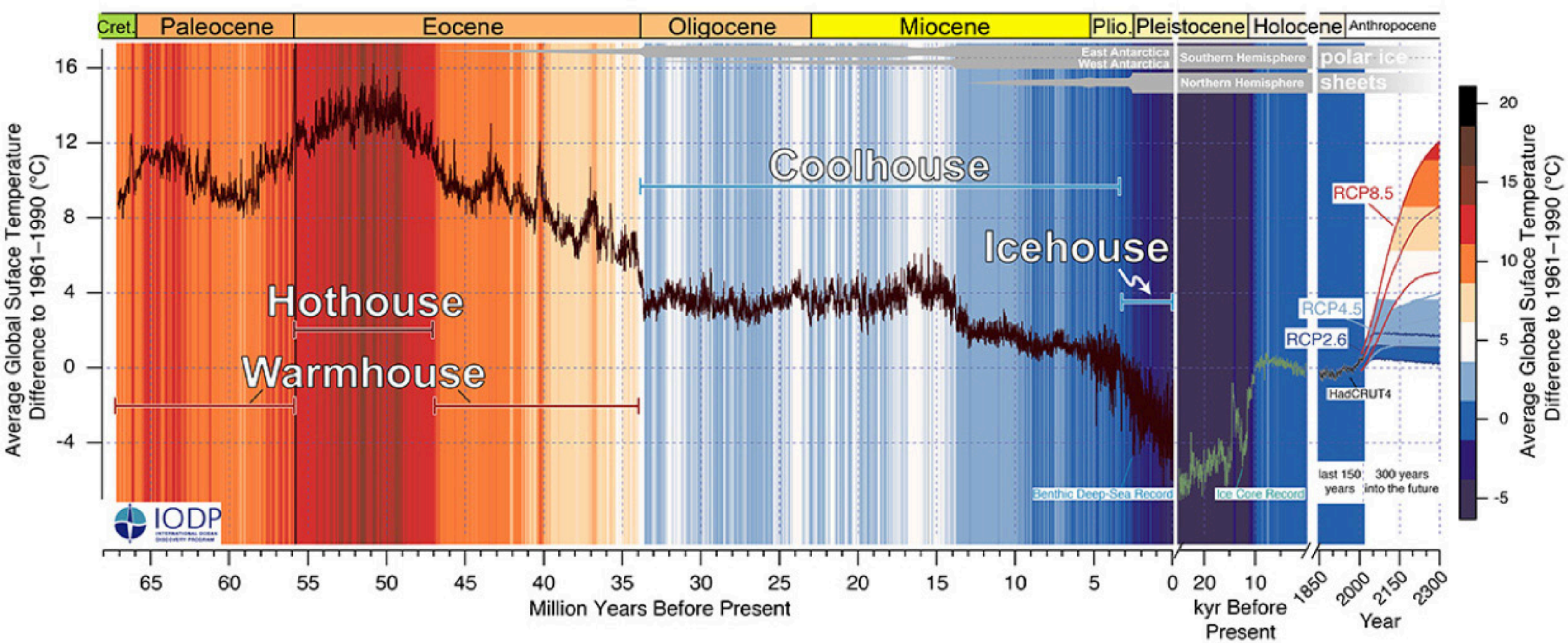
$\Delta T \Rightarrow$ **or**

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