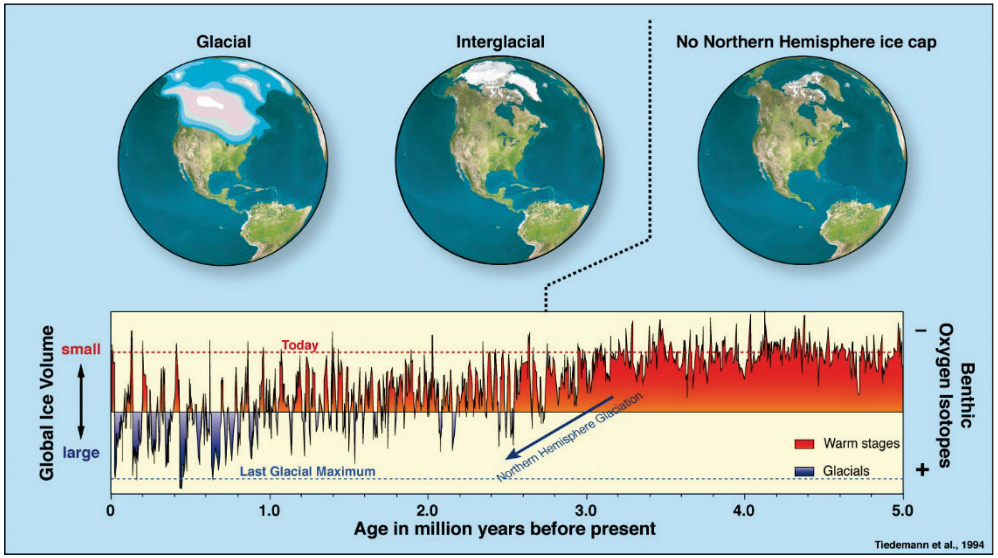
Climates of the Past

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:

http://www2.atmos.umd.edu/~rjs/class/fall2020
https://myelms.umd.edu/courses/1291919



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

15 September 2020

Announcements: Class

1) Problem Set 1 posted:
   - please email me with questions, concerns, difficulties getting started, etc
   - students in 433 have one assignment; students in 633 have a different assignment

2) Lecture material available on-line will reflect what is actually shown in class

09/15	Climates of the Past	Chemistry in Context, Sec 2.2, 3.0, 3.1, 3.2 (14 pages) Houghton, Ch 4 (pgs 77-84) Paris Beacon of Hope Sec 1.1 (7 pages; please review)	AT 4	Lecture 4 2020 Zoom Video		Chylek & Lohmann, GRL, 2008 * IPCC 2007 FAQ (questions 6.1, 6.2) Parrenin et al., Science, 2013 Press release for Sept 2020 paper	Quiz 4
09/17	Global Carbon Cycle	Chemistry in Context, Sec 3.5, 4.0, 4.1, 6.5 (8 pages) Houghton, Pg 33-46 Paris Beacon of Hope Sec 1.2.3.2 (8 pages)	AT 5	Lecture 5 2020 Zoom Video		IPCC 2007, Section 7.3.4.1 & Box 7.3 * Doney, Ocean Acidification, *Scientific American*, March 2006 Global Carbon Project	Quiz 5
09/22	Biogeochemical Cycles of CH_4 and N_2O	Chemistry in Context, Sec 3.8 & Sec 6.9 (8 pages) Houghton, Pg 46-50 Paris Beacon of Hope Sec 1.2.3.3 & 1.2.3.4 (5 pages)	AT 6	Lecture 6 2020 Zoom Video	**Problem Set 1 due today:** 433 Students 633 Students	Kirschke et al., 2013 * Kort et al., 2014 Saunois et al., 2019	Quiz 6

Different URLs

https://www2.atmos.umd.edu/~rjs/class/fall2020

Announcements: Outside of Class

1) Thurs, 17 Sept : AOSC Weekly Seminar (every Thursday at 3:30 pm)

Professor Don Milton, University of Maryland

Infectious Drops and Aerosols

We will review modes of respiratory virus transmission, the history of thinking about modes of transmission and the role of aerosols in the medical community, and the problem with vague terminology and ensuing confusion and miscommunication. We will then review evidence from observational and experimental studies of influenza and SARS-CoV-2 and talk about future plans to resolve the key questions.

https://aosc.umd.edu/seminars/department-seminar

Email Joseph Knisely at jknisely@umd.edu for Zoom connection info

Climates of the Past

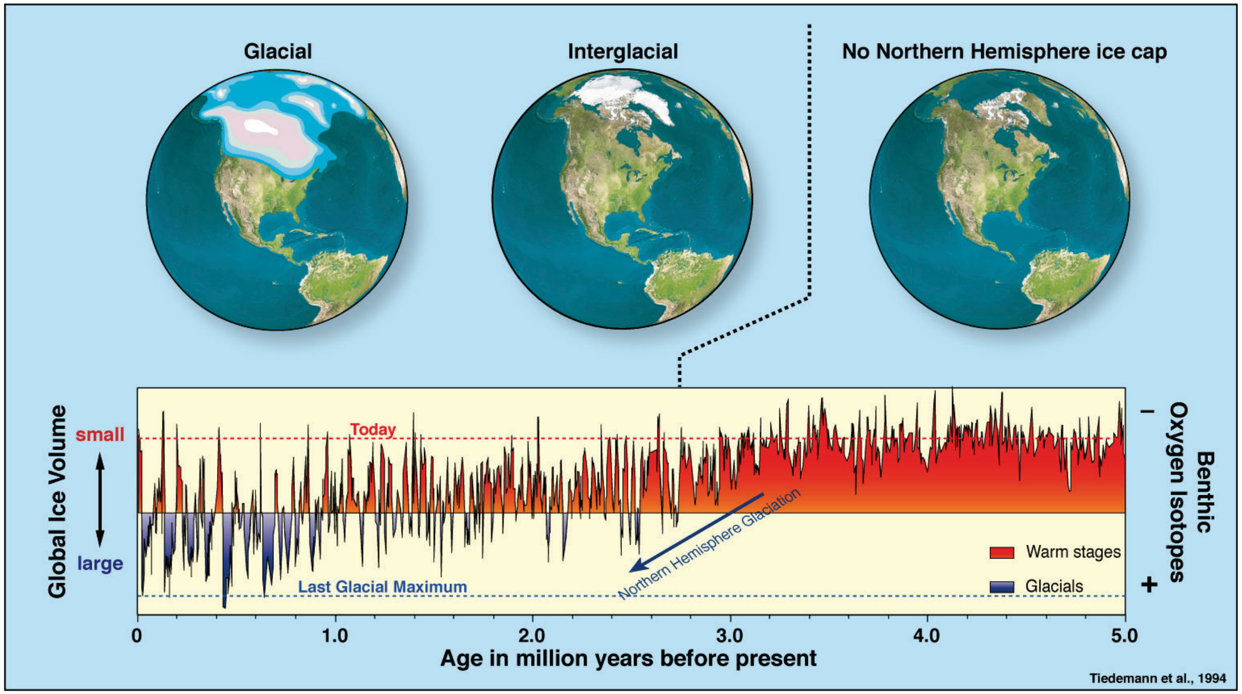
Overview:

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.



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

Climates of the Past

Overview:

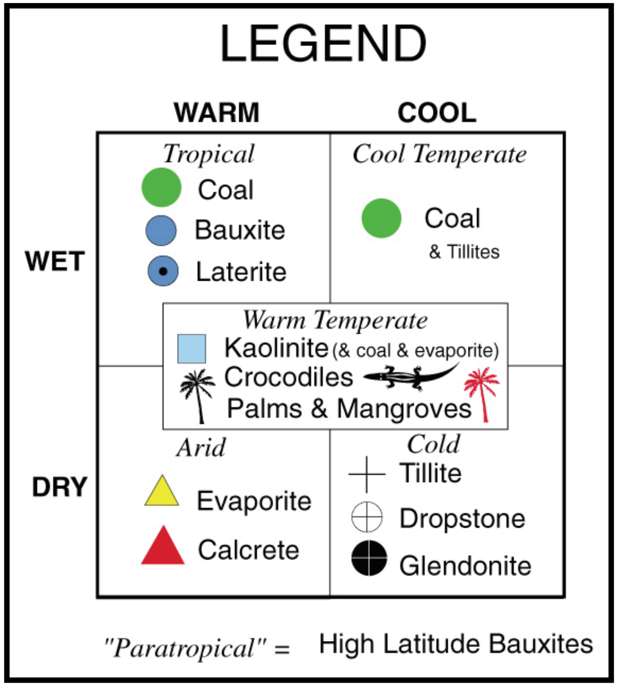
1) Techniques for quantifying past climate

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 →



Climates of the Past

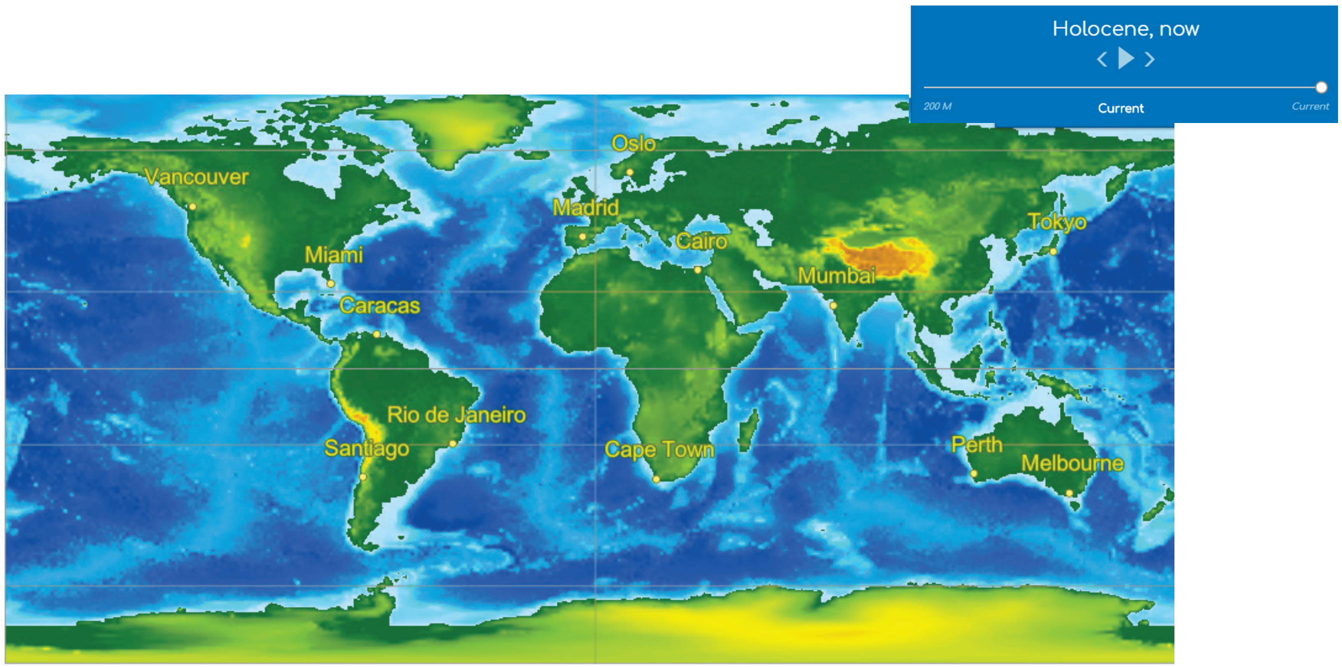
Overview:

1) Techniques for quantifying past climate

2) Remarkable changes in past climate

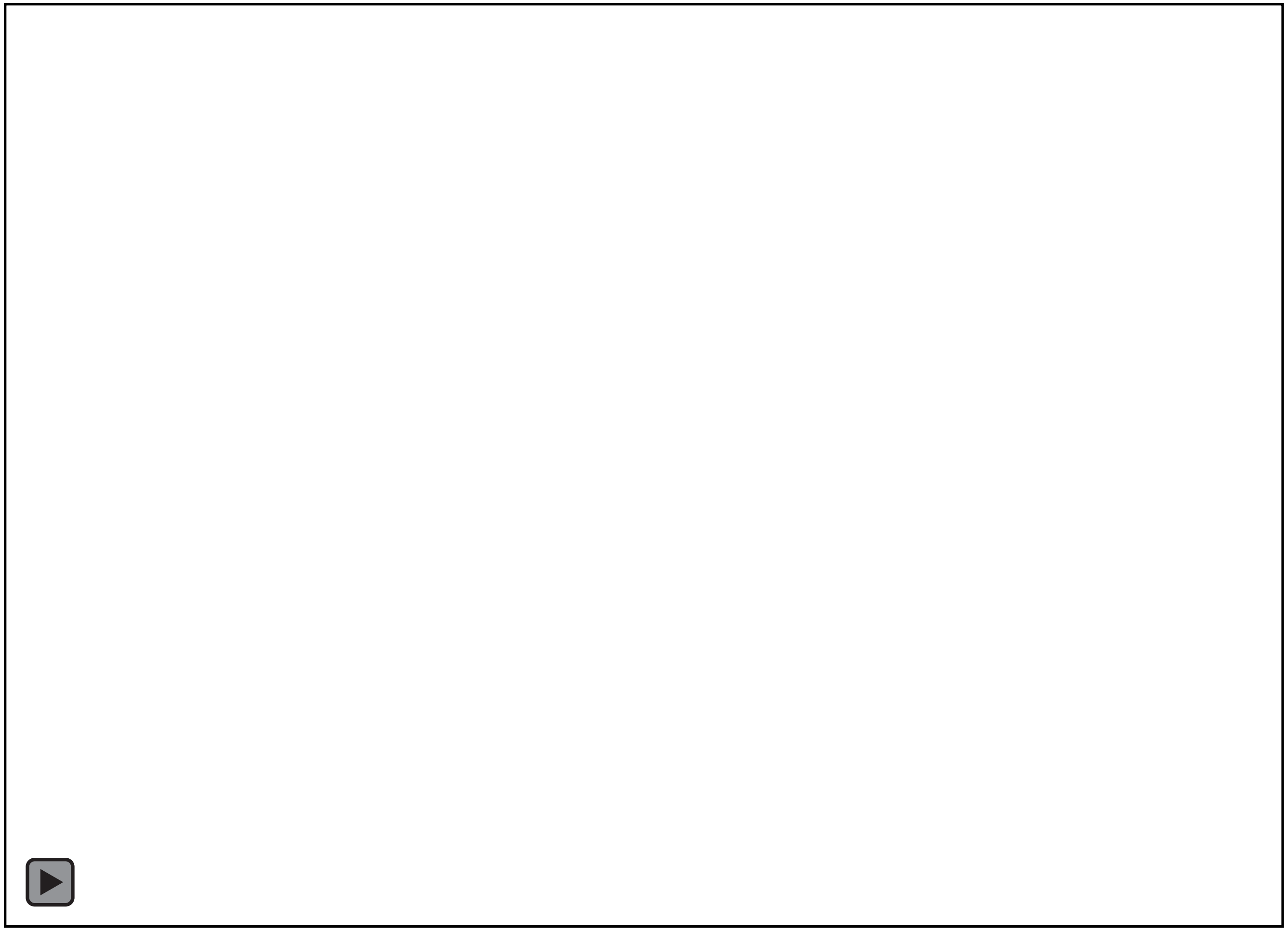
3) Challenge in applying past climate sensitivity to future climate

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.



https://apl.esri.com/jg/PaleoMap/index.html

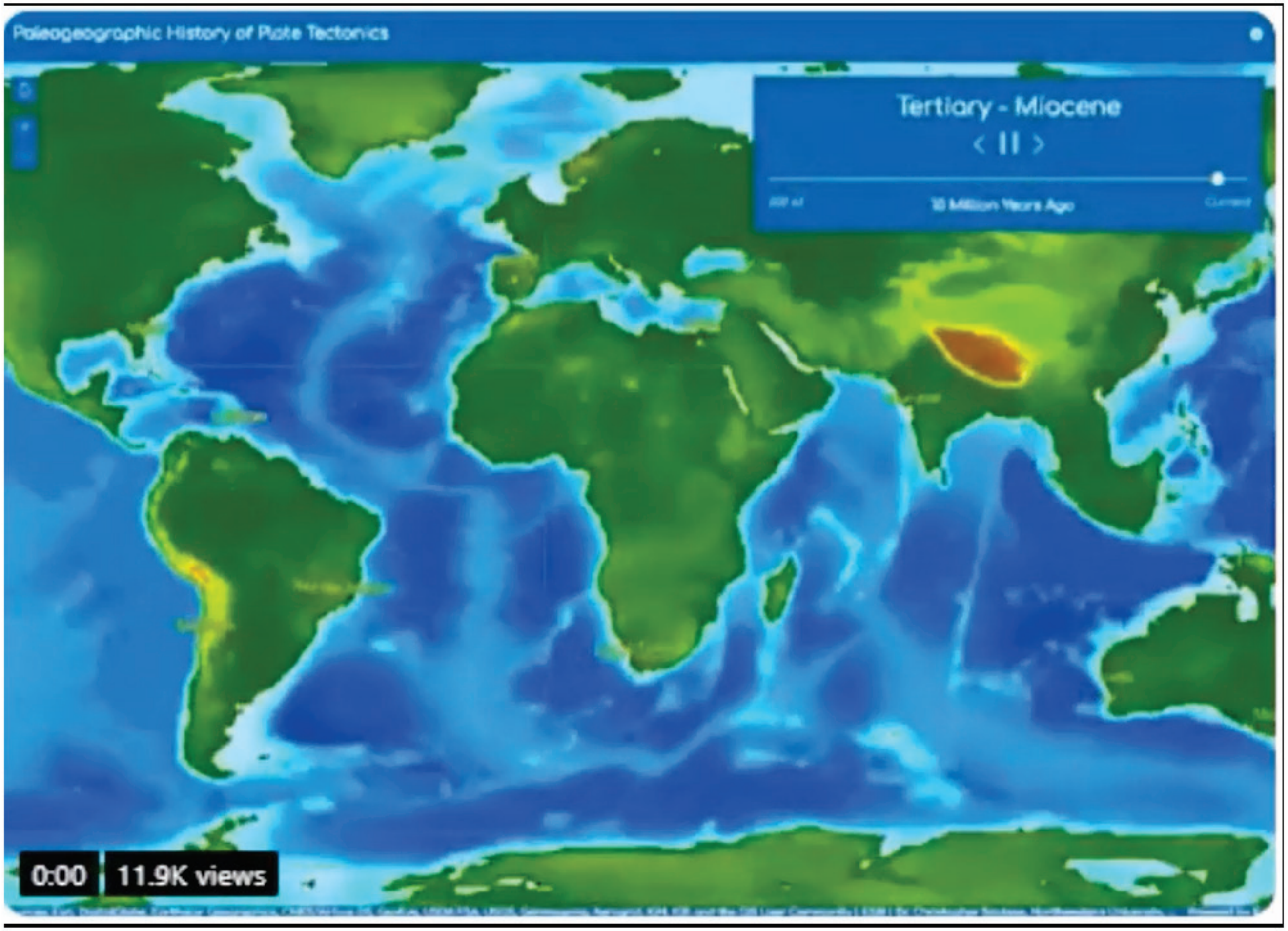
Continental Drift



https://apl.esri.com/jg/PaleoMap/index.html

https://www.youtube.com/watch?v=UXuDb3PWhbE

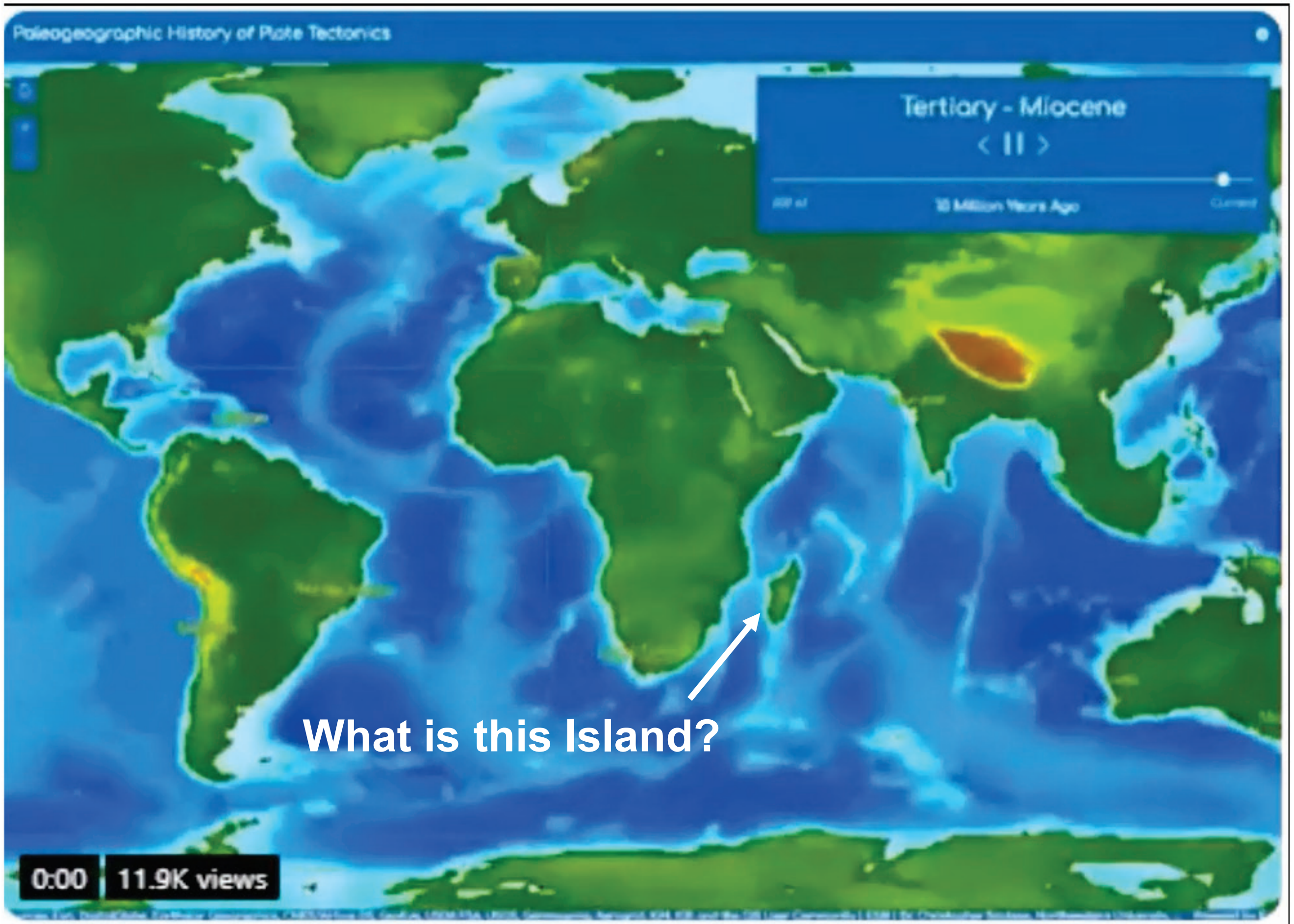
Continental Drift



https://apl.esri.com/jg/PaleoMap/index.html

https://www.youtube.com/watch?v=UXuDb3PWhbE

Continental Drift



https://apl.esri.com/jg/PaleoMap/index.html

https://www.youtube.com/watch?v=UXuDb3PWhbE

Bonus Video

Professor Lewis D. Ashwal, Wits University, South Africa

https://www.youtube.com/watch?time_continue=4&v=o61P6ysKkIM
https://www.wits.ac.za/news/latest-news/research-news/2017/2017-01/lost-continent-found-under-mauritius.html
https://phys.org/news/2017-01-lost-continent-mauritius.html

Mauritius

http://www.traveller.com.au/things-to-do-in-mauritius-a-threeminute-guide-govvn8

Mauritius In The News

Mauritius oil spill: Thousands march in Port Louis

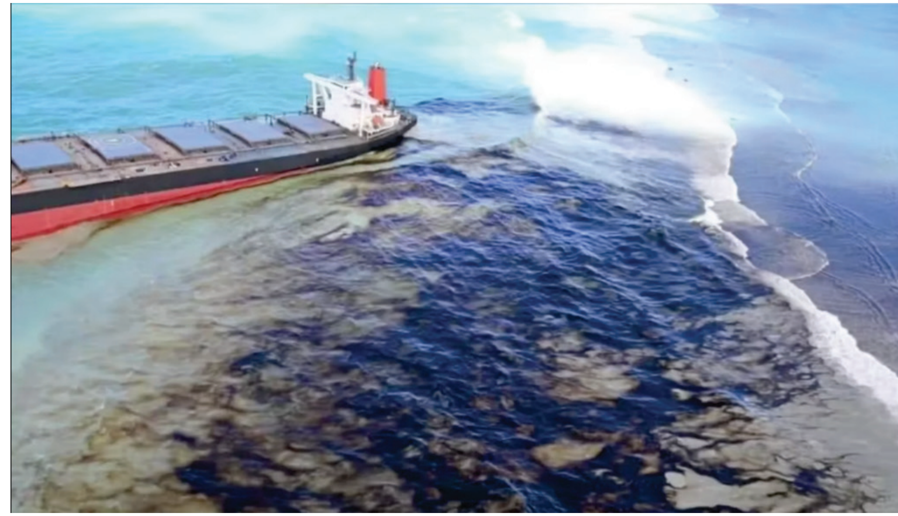
29 August 2020

The protesters called for the government to resign

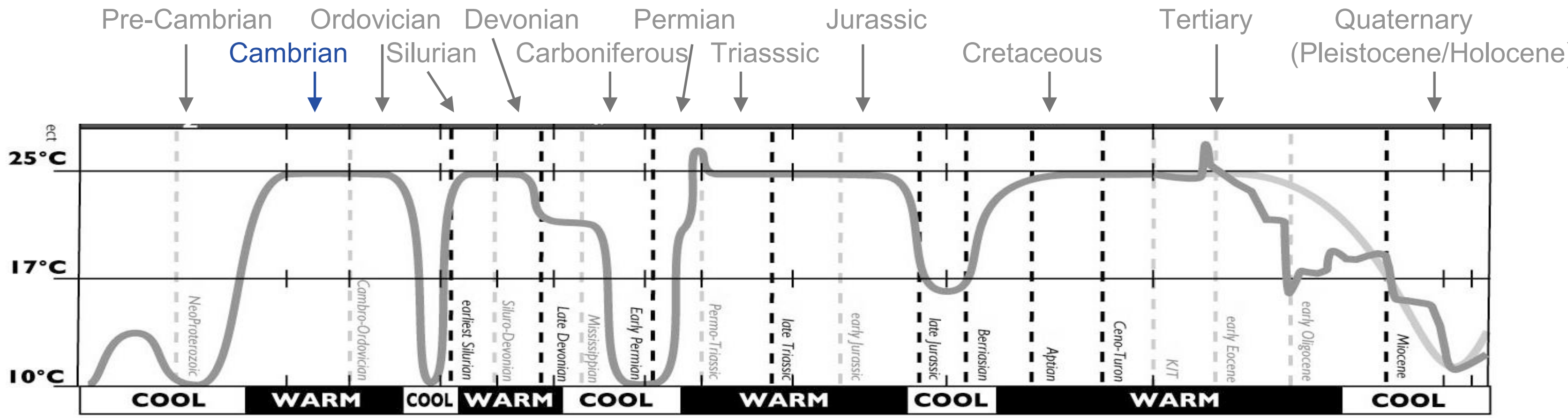
Thousands of people have marched through the Mauritian capital, Port Louis, in protest at the authorities' handling of a massive oil spill, and the discovery of 39 dead dolphins.

Many wore black and waved the national flag, while honking horns and drumming.

Many called for the government to resign and had T-shirts with the inscription: "I love my country. I'm ashamed of my government."

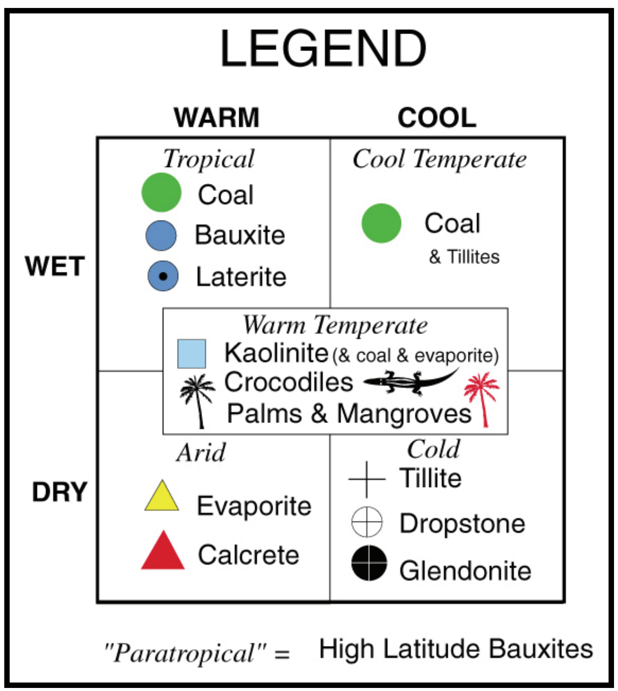


https://www.bbc.com/news/world-africa-53959889
https://www.fleetmon.com/maritime-news/2020/30533/major-oil-spill-mauritius-island

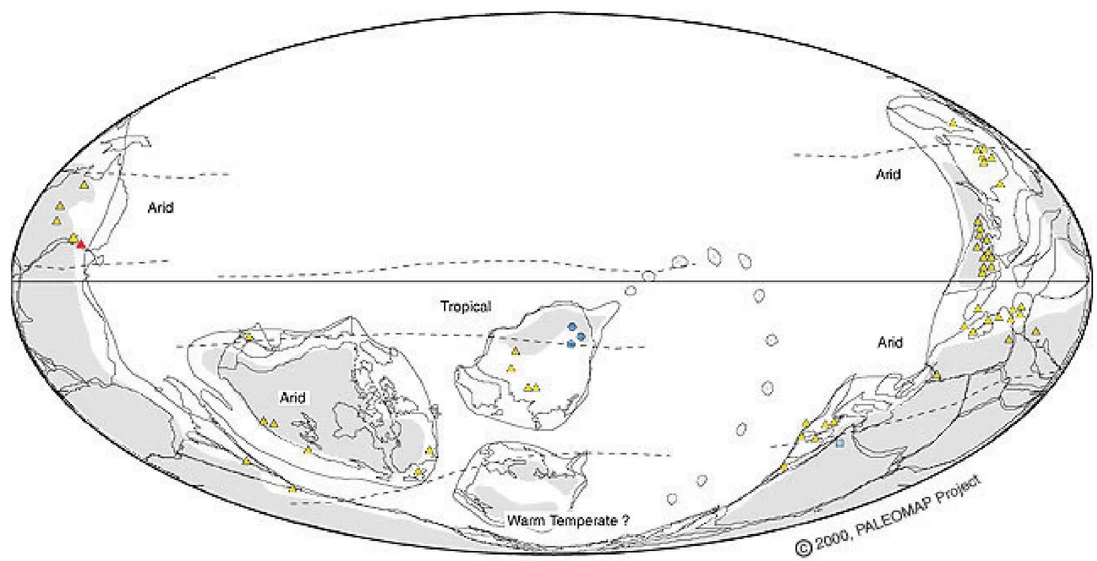


http://www.scotese.com

http://pubs.usgs.gov/gip/fossils/fig15.gif

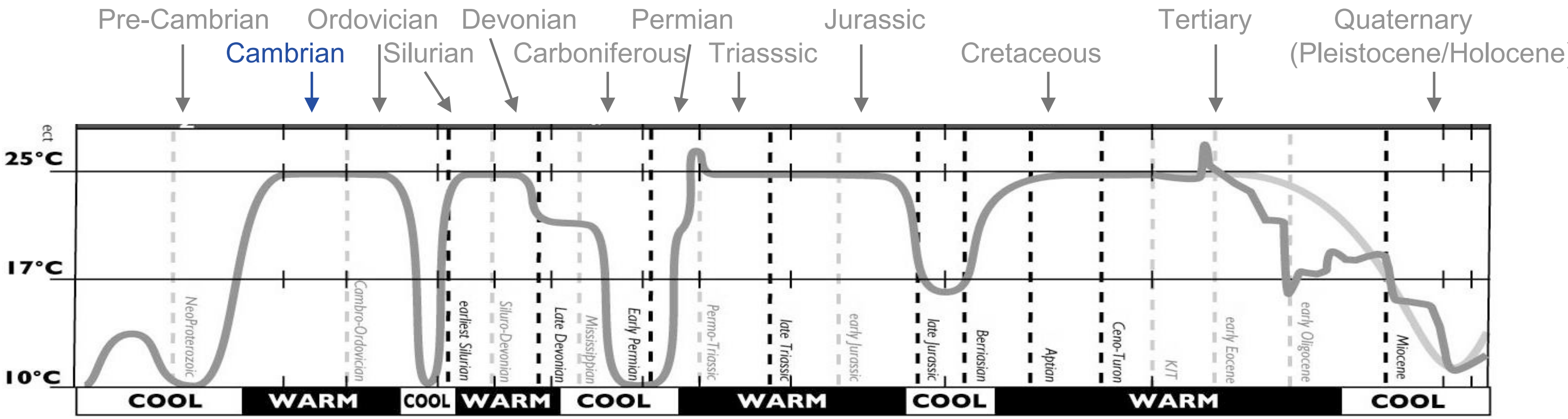


Early Cambrian Climate (540 million years ago)



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.

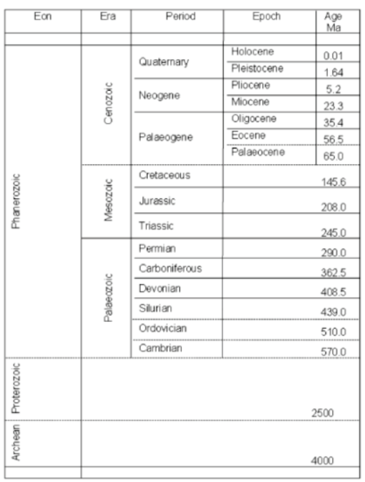
Source: http://www.scotese.com/ecambcli.htm



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

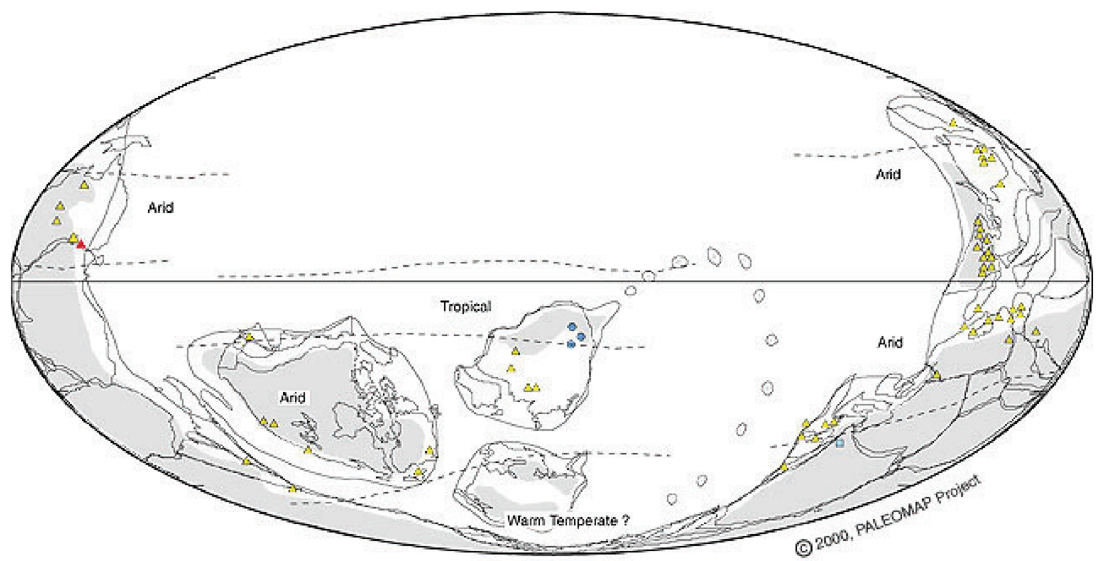
http://www.scotese.com

Early Cambrian Climate (540 million years ago)

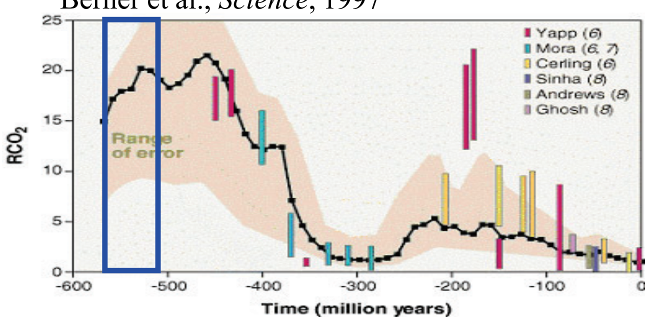


Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

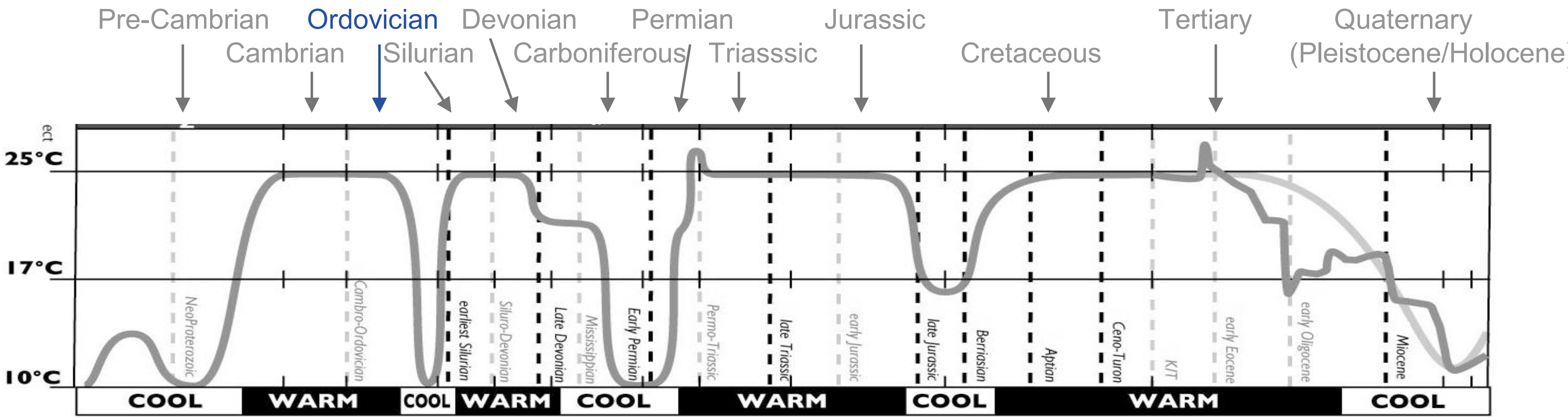


Berner et al., *Science*, 1997



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



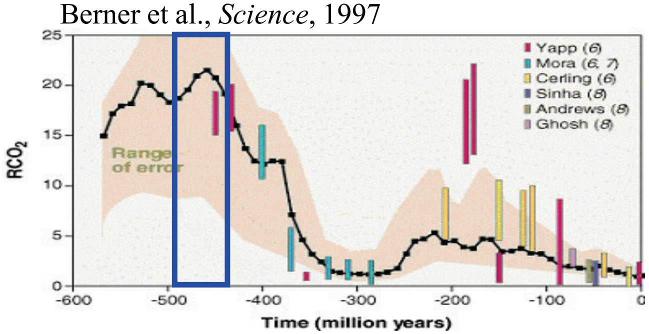
https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

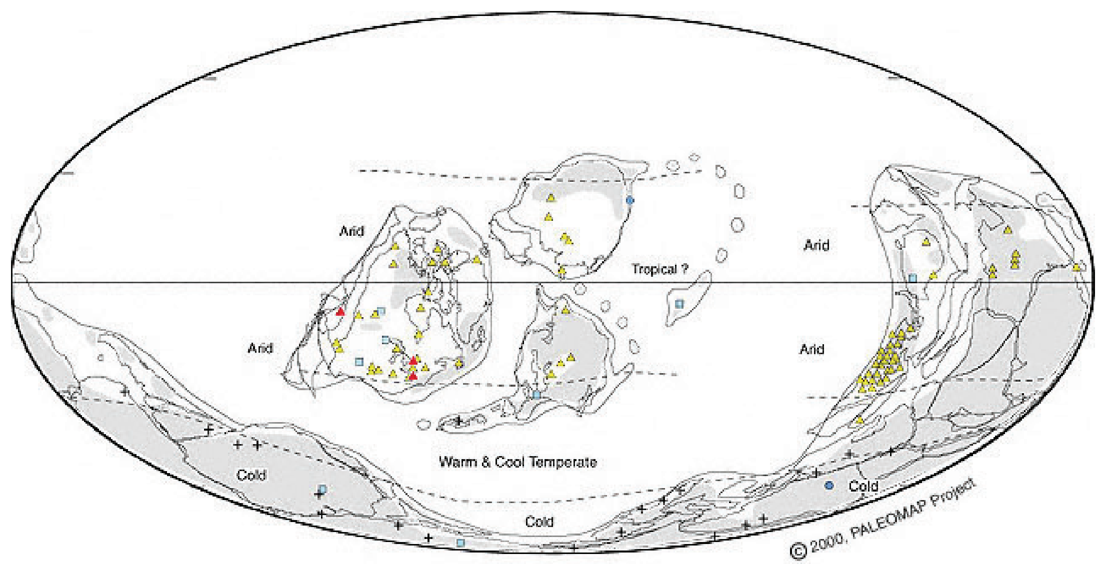
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

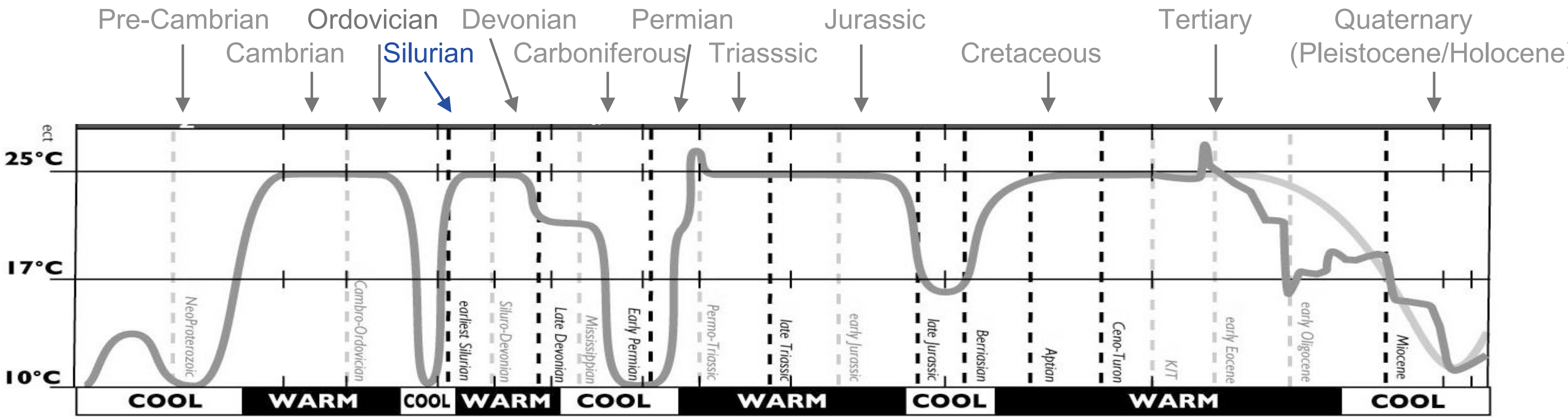


Early Ordovician Climate (480 million years ago)



Mild climates probably covered most of the globe.
The continents were flooded by the oceans creating warm, broad tropical seaways.

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



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

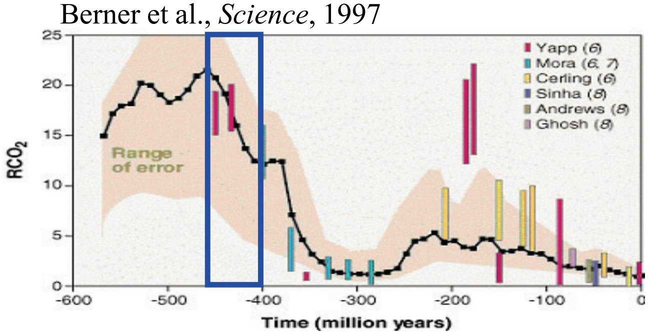
http://www.scotese.com

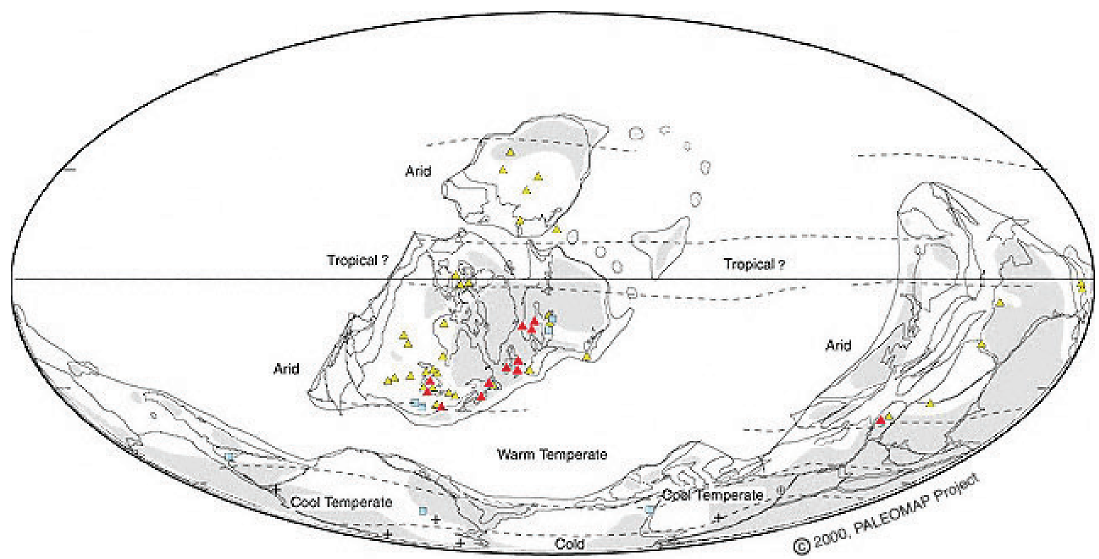
Silurian Climate
(420 million years ago)

Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

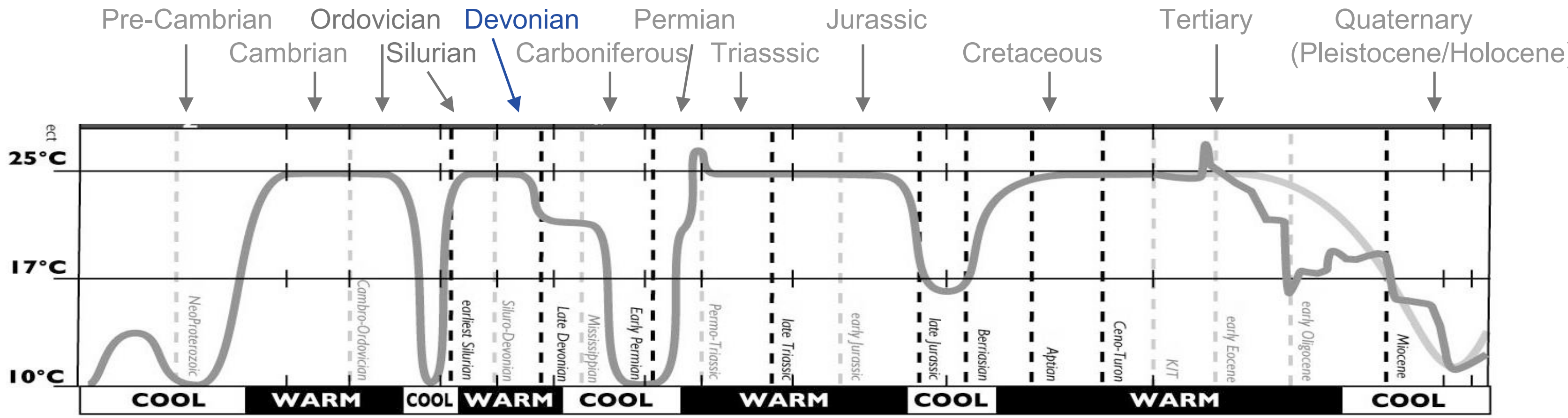
Berner et al., *Science*, 1997





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



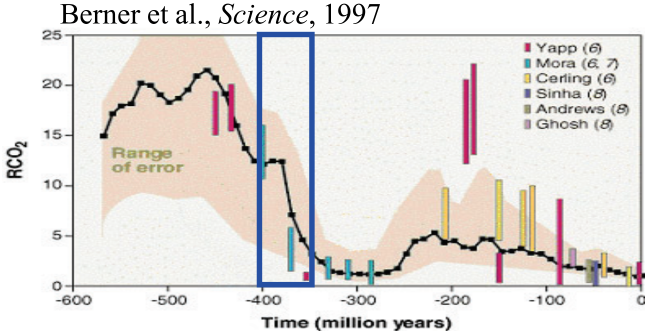
https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

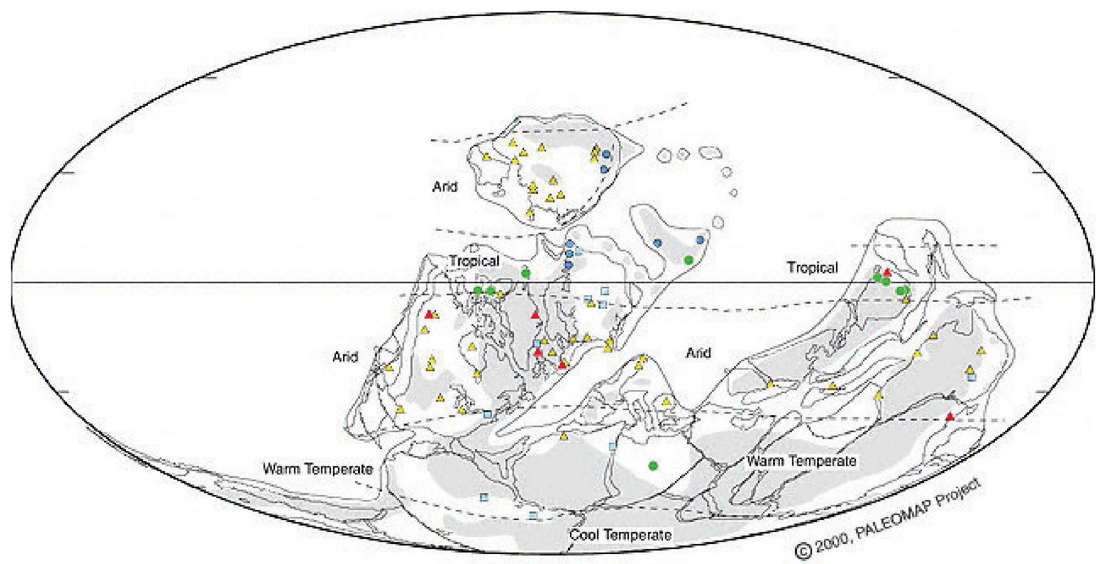
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

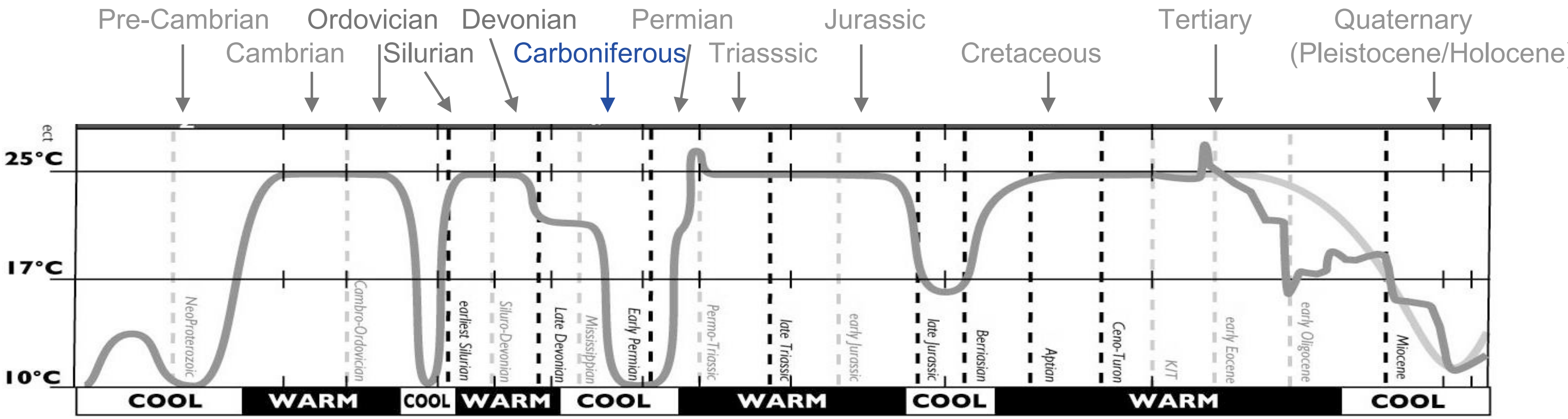


Middle Devonian Climate (380 million years ago)



The Equator ran through today's Arctic Canada. Coal began to accumulate as land plants flourished in the equatorial rainy belt. Warm shallow seas covered much of today's North America & Siberia.

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



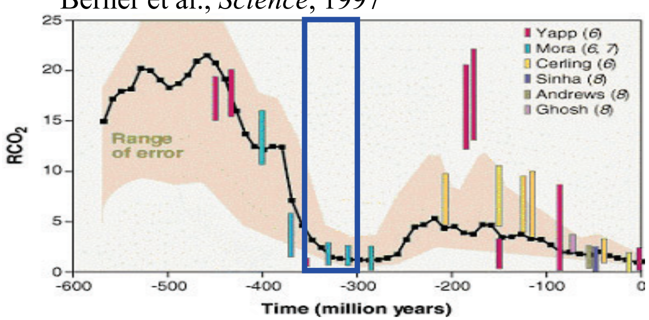
https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

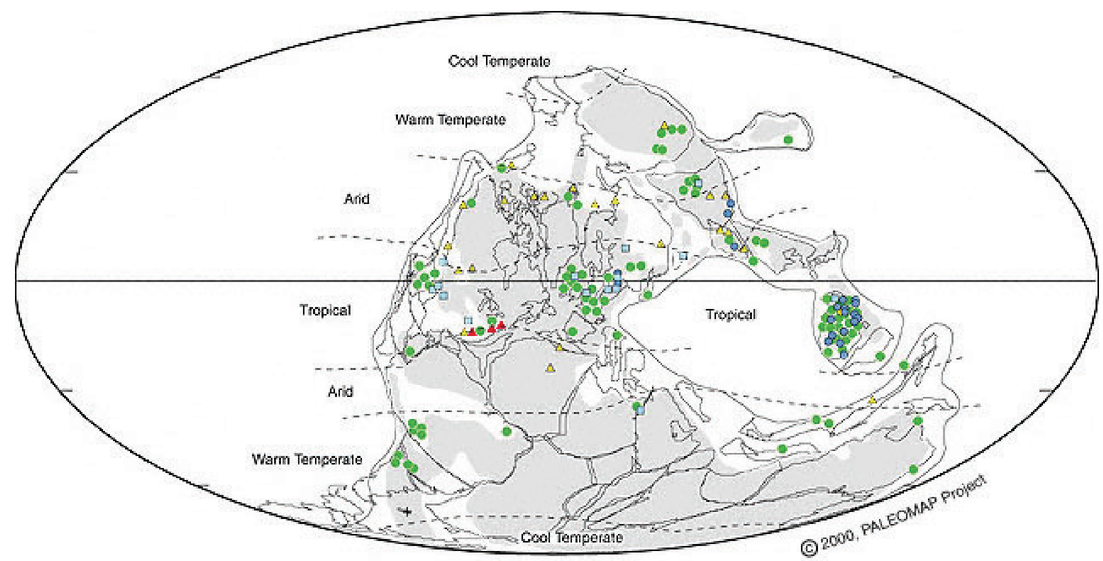
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

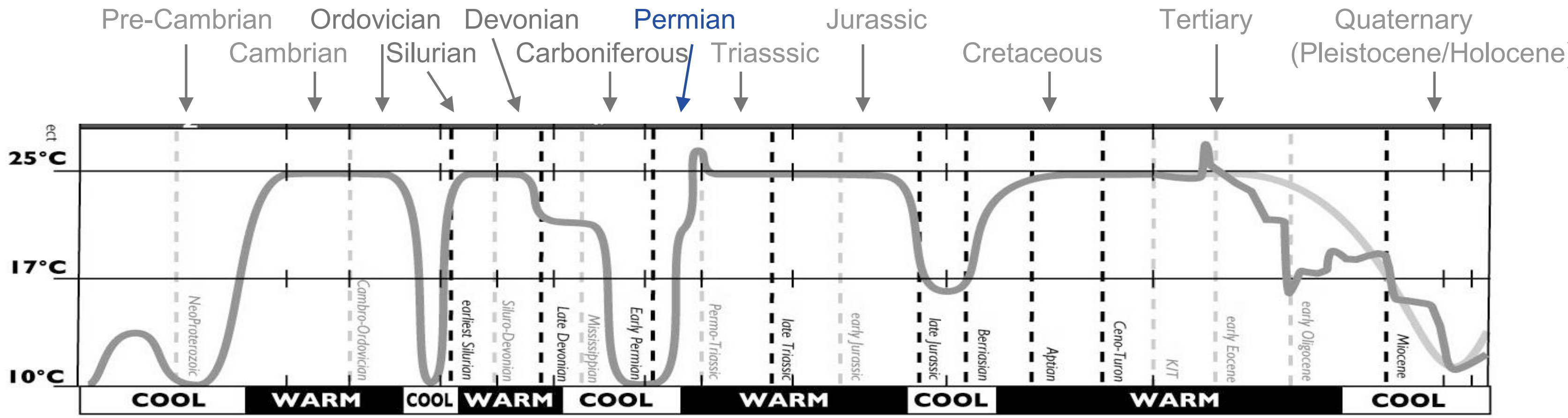


Carboniferous Climate (350 million years ago)



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



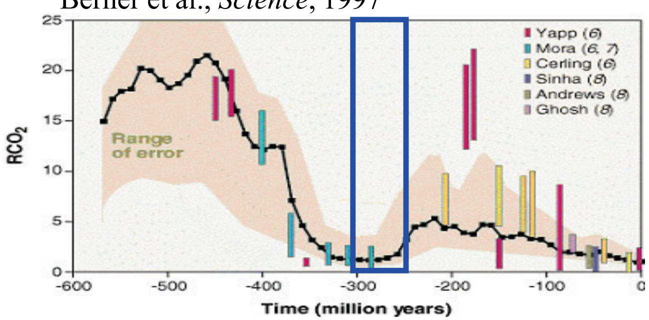
http://www.scotese.com

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

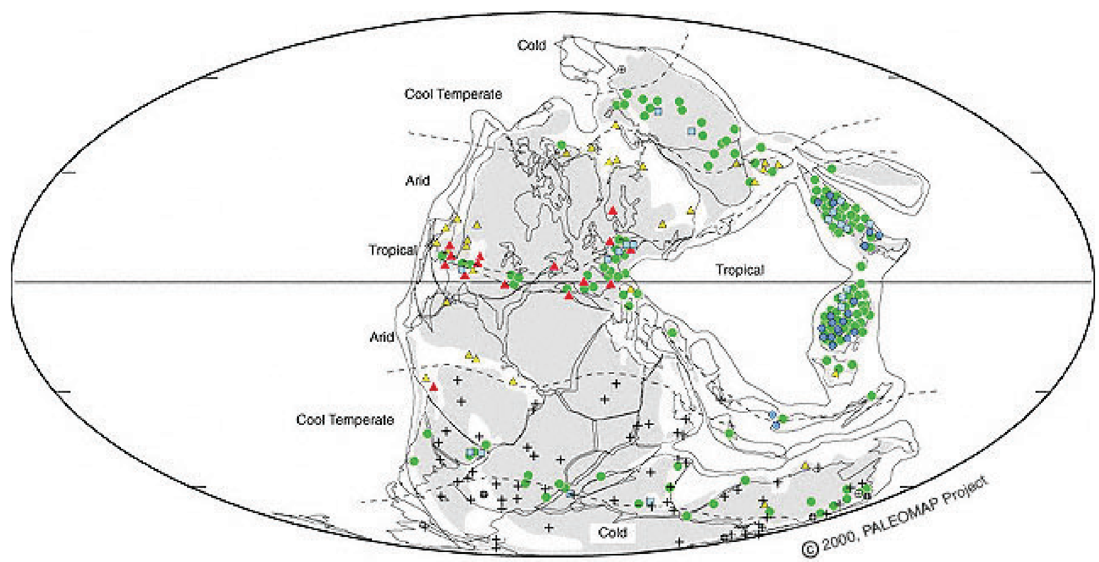
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

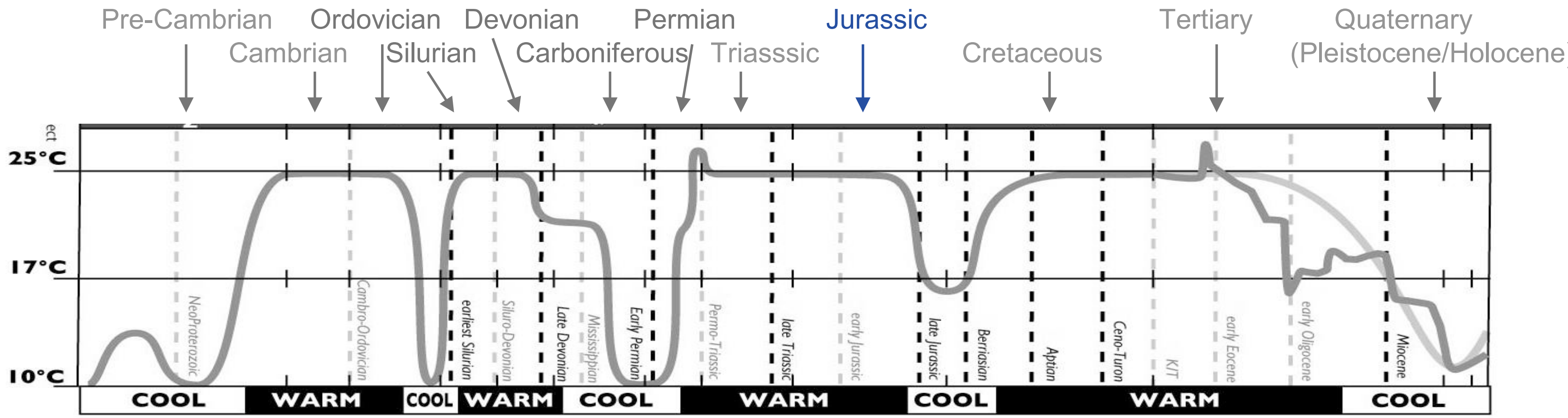


Early Permian Climate (280 million years ago)



Much of the SH was covered by ice as glaciers pushed equator ward.
Coal was produced in Equatorial & Temperate rainforests
during warmer "Interglacial" periods.

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



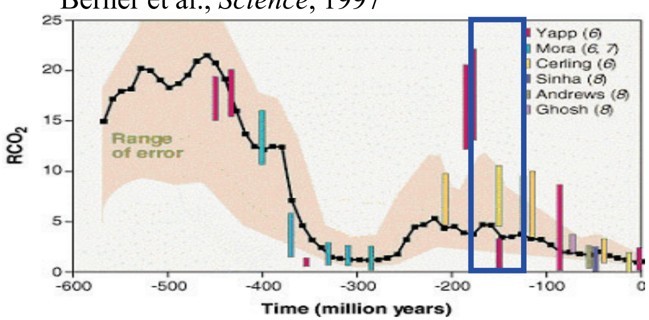
https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

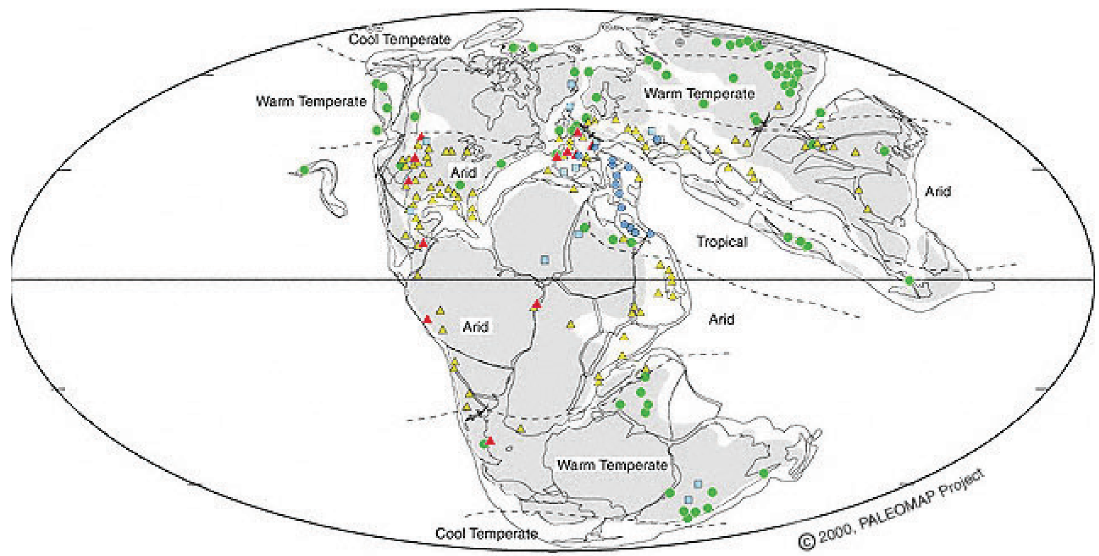
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

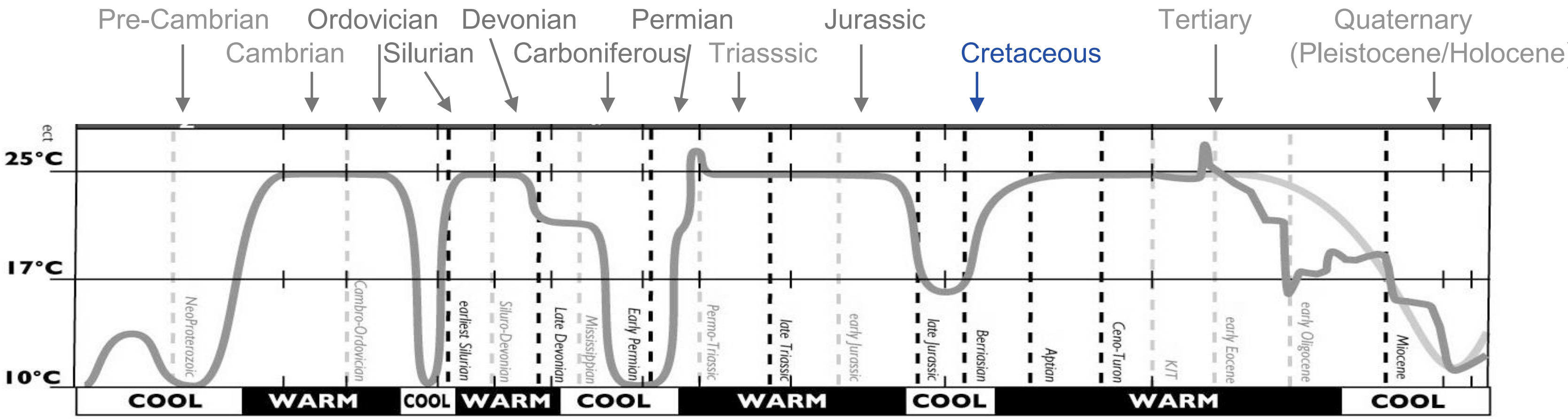


Late Jurassic Climate (150 million years ago)



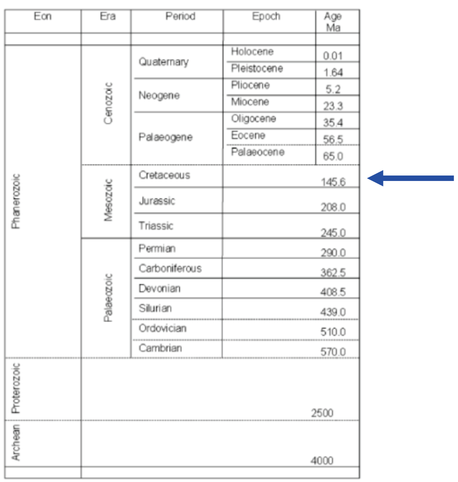
Global climate began to change due to breakup of Pangea. The interior of Pangea became moister and seasonal snow & ice frosted the polar regions

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



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

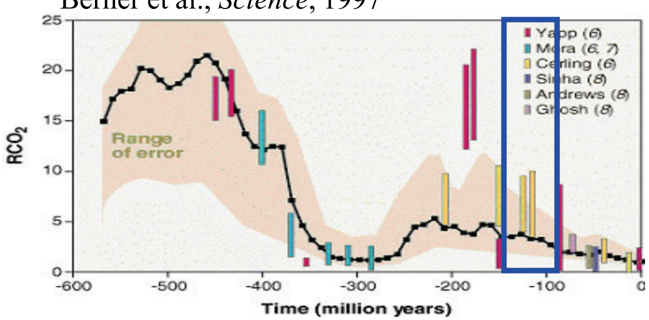
http://www.scotese.com



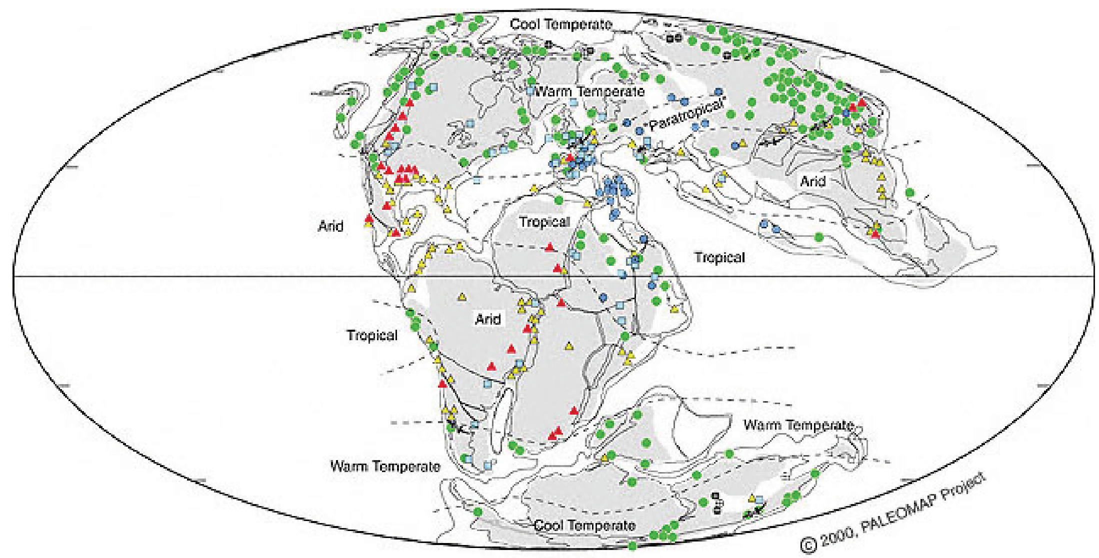
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

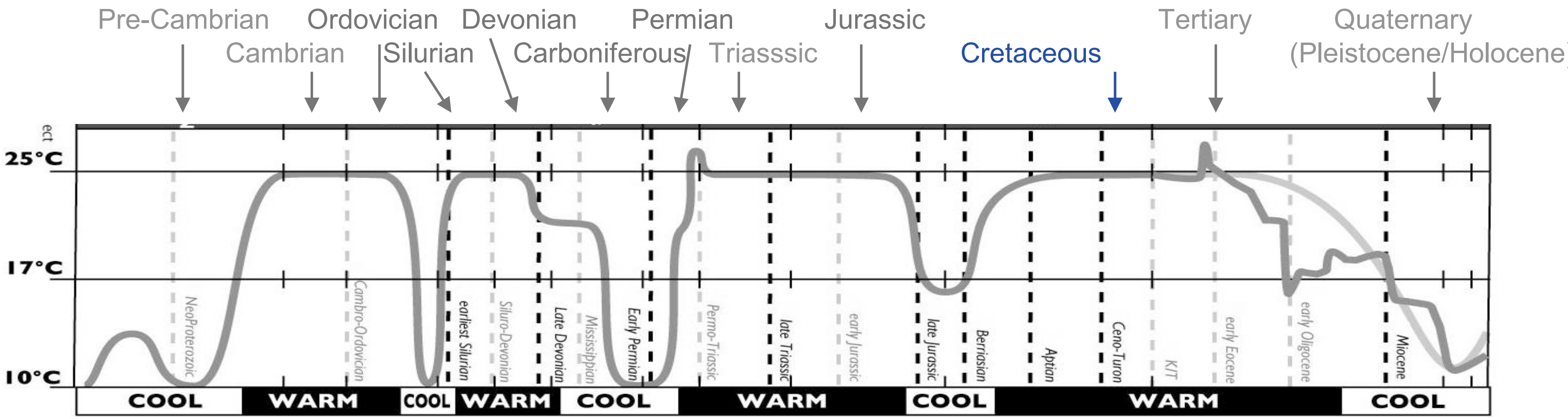


Early Cretaceous Climate (120 million years ago)



Climate was a mild "Ice House" world. Snow and ice were present during winter and cool temperate forests covered polar regions.

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



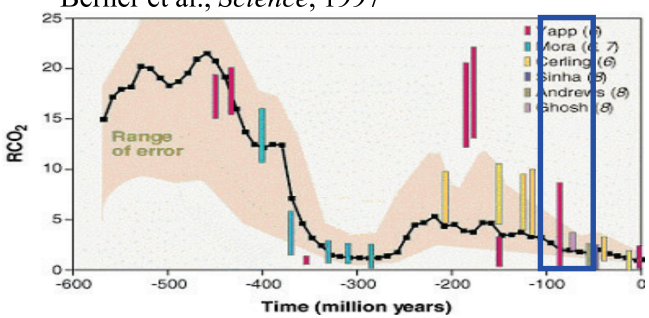
https://www.ucl.ac.uk/GeolSci/micropal/foram.html

http://www.scotese.com

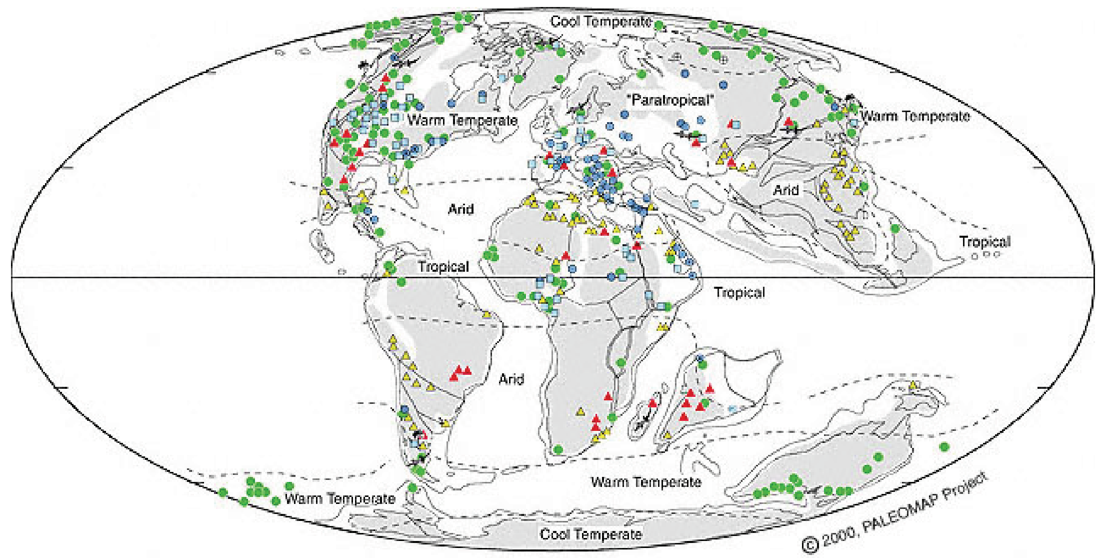
Eon	Era	Period	Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.64
		Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65.0
	Mesozoic	Cretaceous		145.6
		Jurassic		208.0
		Triassic		245.0
	Palaeozoic	Permian		290.0
		Carboniferous		362.5
		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

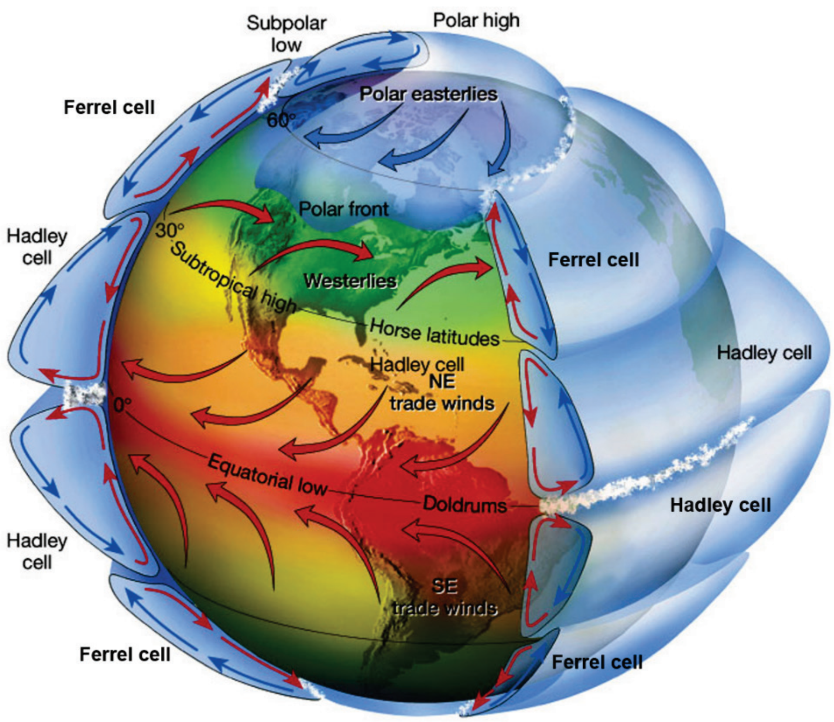


Late Cretaceous Climate (70 million years ago)



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

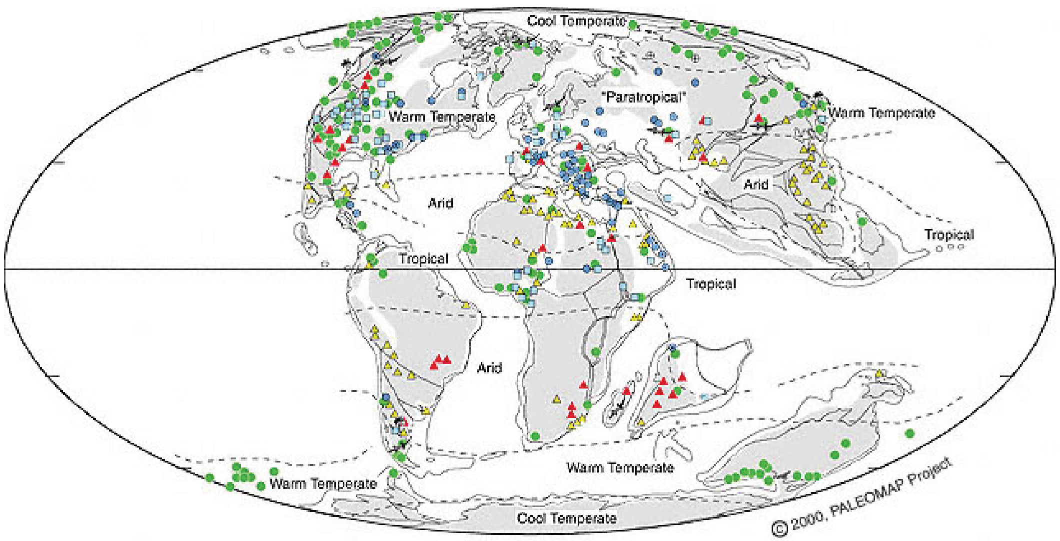
Source: http://www.scotese.com/lcretcli.htm



Lecture #3

Please review "catch-up" video!

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/ecretcli.htm

Earth's Climate History

Accordion-like unraveling of Earth's climate and CO_2

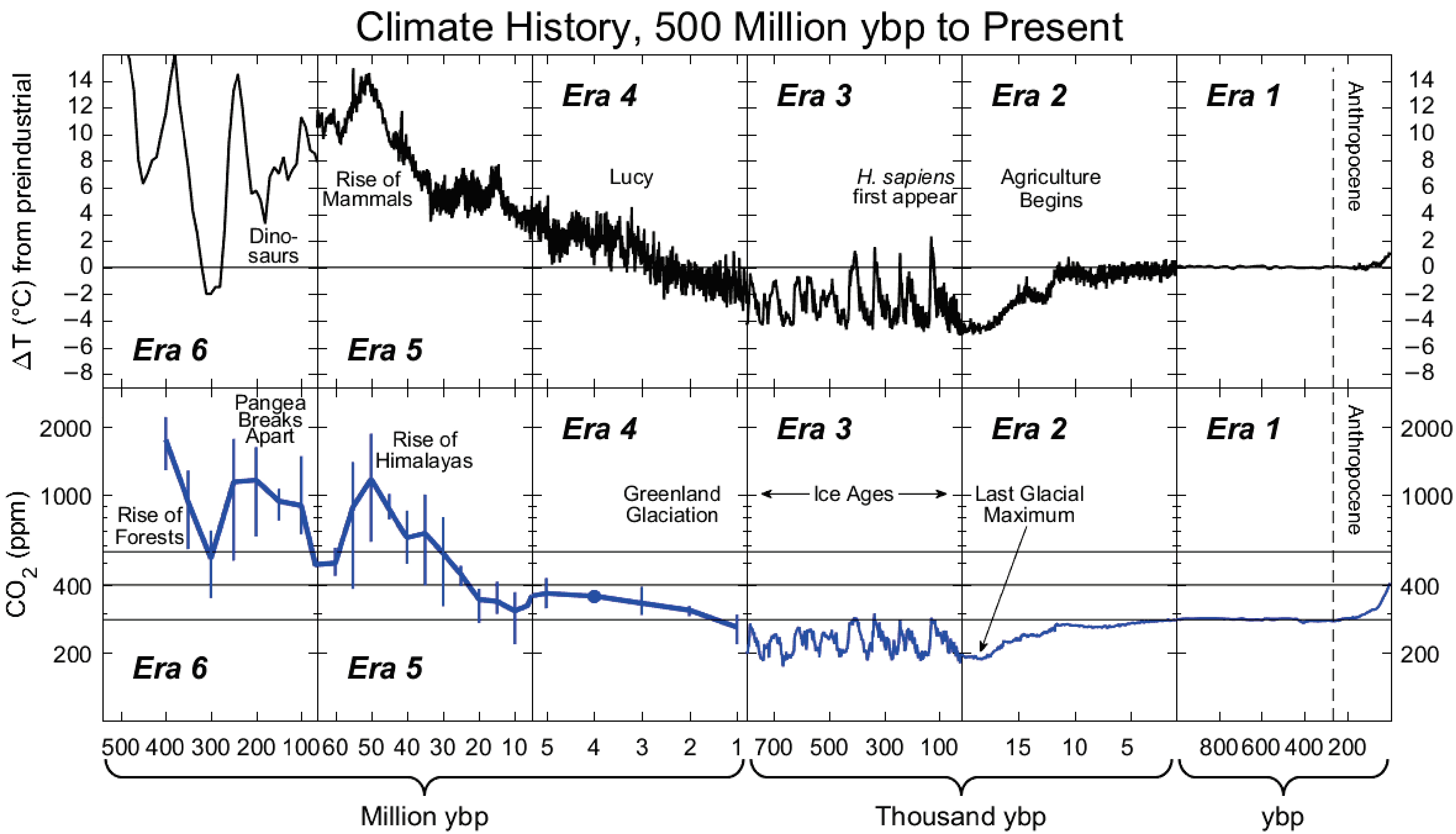


Fig 1.1, *Paris Beacon of Hope*

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"

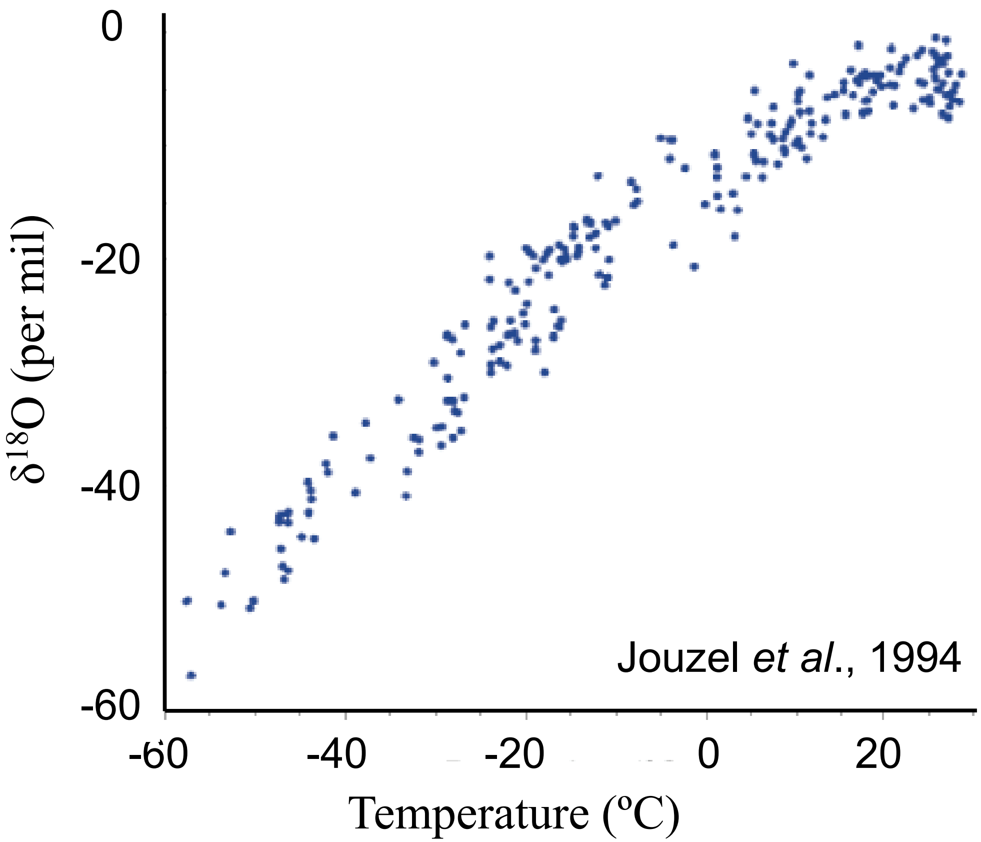
$$\delta^{18}\text{O (per mil)} = \left(\frac{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Sample} - \left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Standard}}{\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{Standard}} \right) \times 10^{3}$$

Standard often referred to as SMOW: Standard Mean Ocean Water

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?

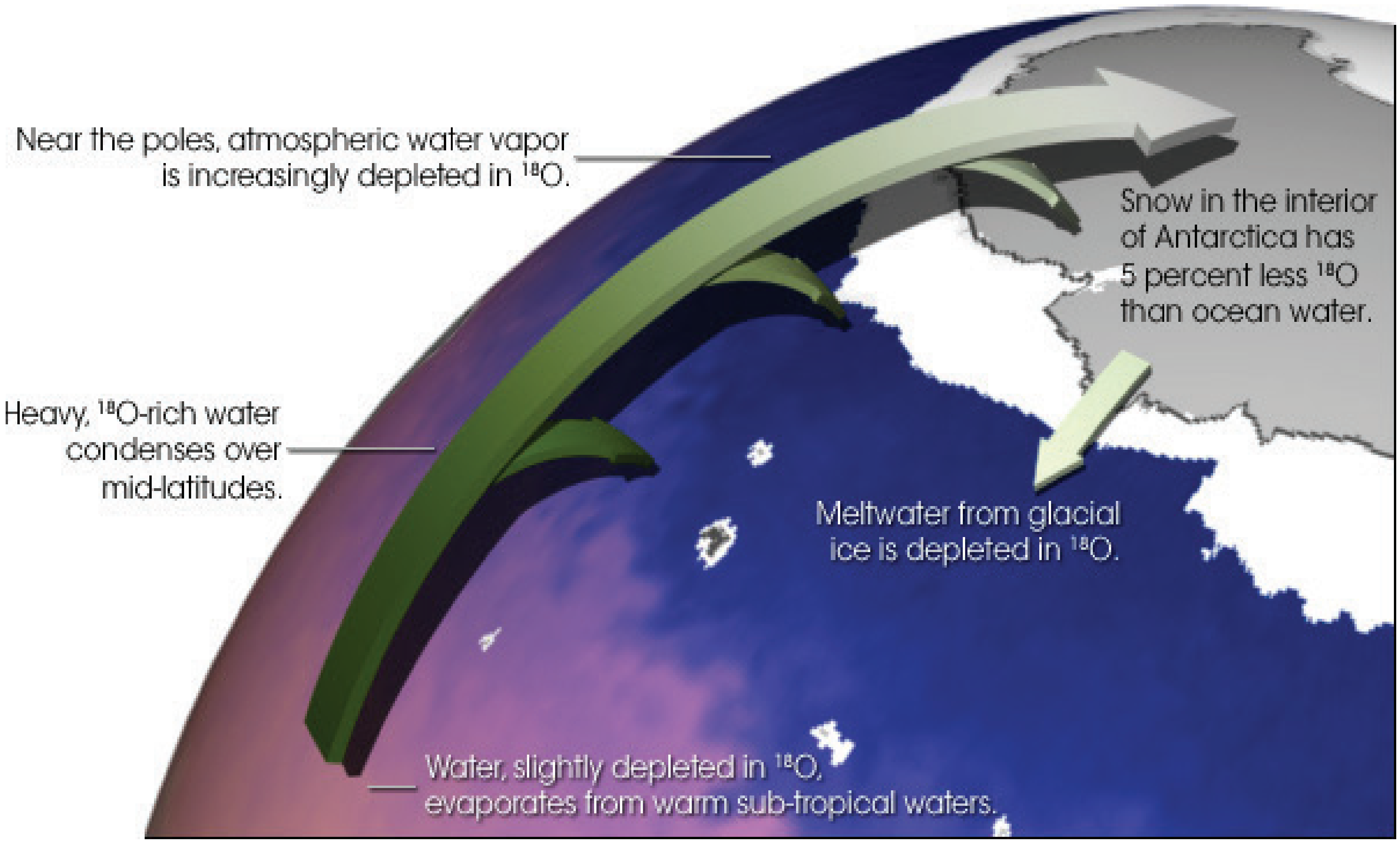


As temperatures drops, the $\delta^{18}O$ of precipitation decreases.

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.

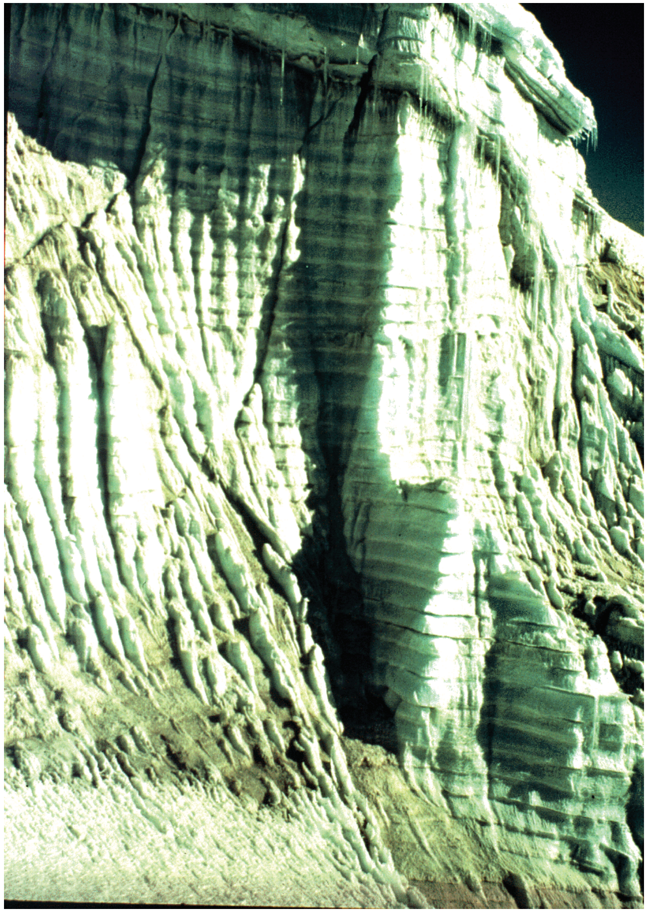


http://earthobservatory.nasa.gov/Study/Paleoclimatology_OxygenBalance/oxygen_balance.html

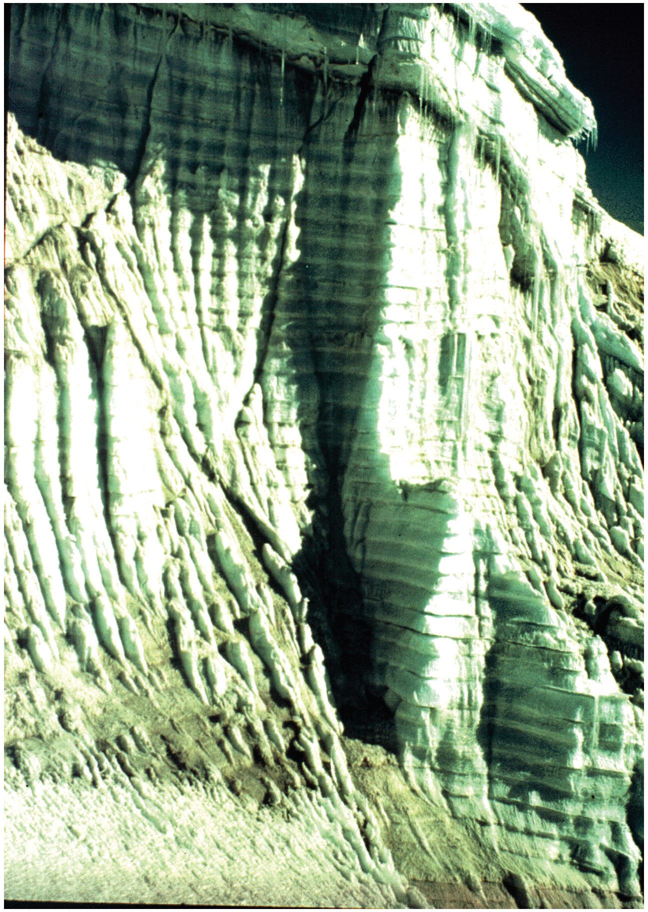
Deuterium (heavy hydrogen) behaves in a way quite similar to ^{18}O (heavy oxygen) !

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



Isotopes in Ice Cores: Late Quaternary

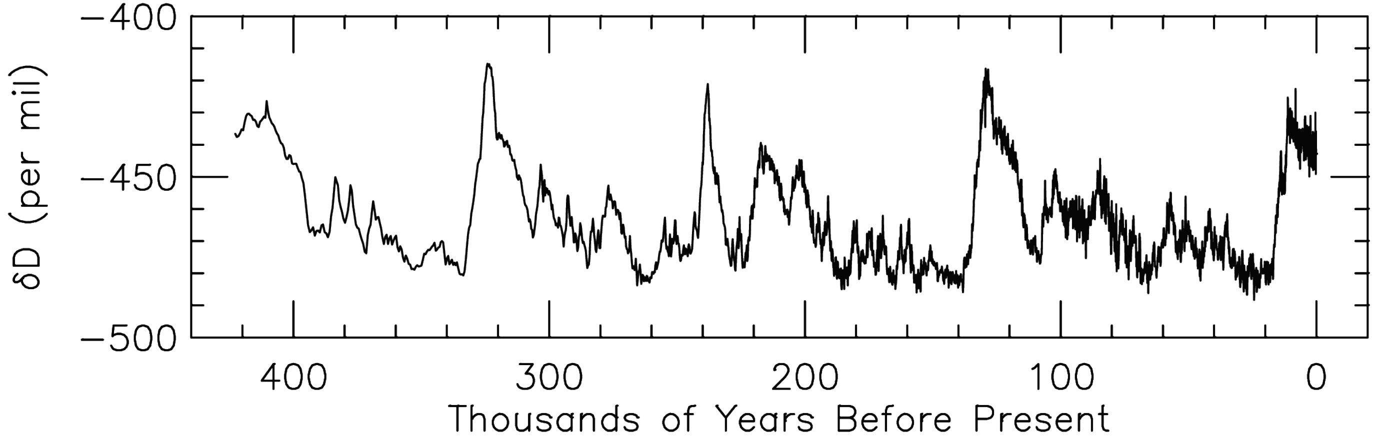


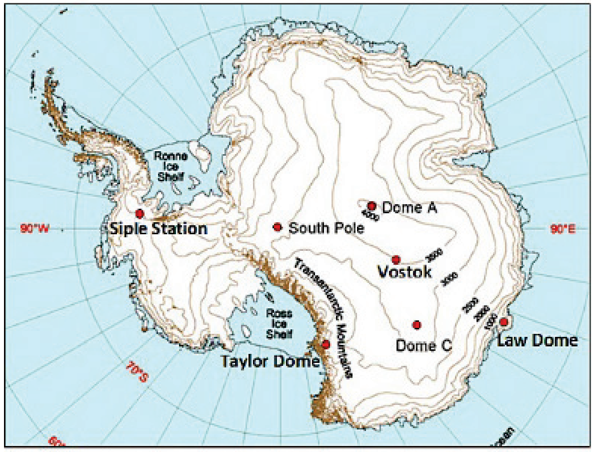
- As the air reaches the pole, ambient water precipitate (*i.e.*, it snows!)
- Over many years, layers of snow accumulate, forming an ice sheet. The water in this ice sheet contains a record of climate ***at the time the snow was deposited***
- By drilling, extracting, and measuring the $\delta^{18}O$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

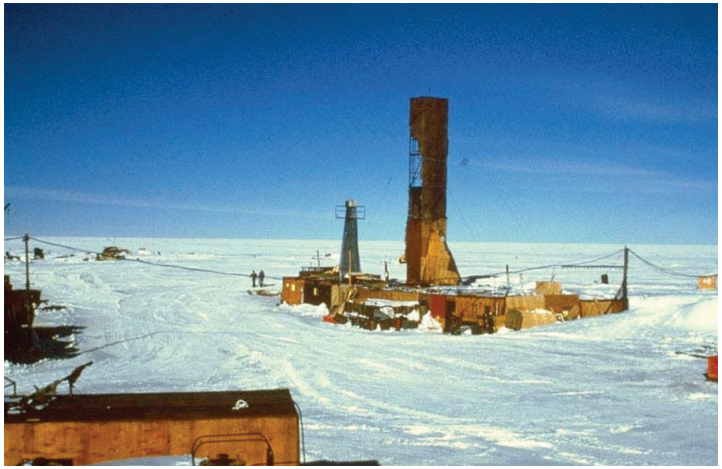
- January 1998: ice core with depth of 3.6 km extracted at Russian Vostok Station, Antarctica
- Vostok ice-core record extends back 400,000 years in time *(*Petit *et al*., *Nature*, 1999)
- Reconstructed temperature based on measurement of the deuterium content of ice
- δ^{18}O shows tremendous variations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





https://cdiac.ess-dive.lbl.gov/trends/co2/ice_core_co2.html

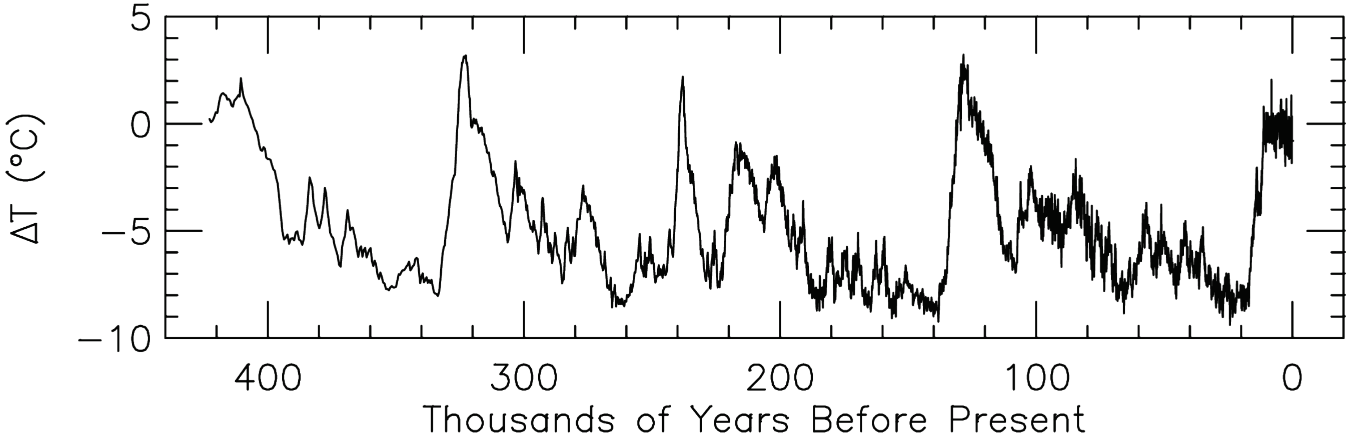
Vostok Drill

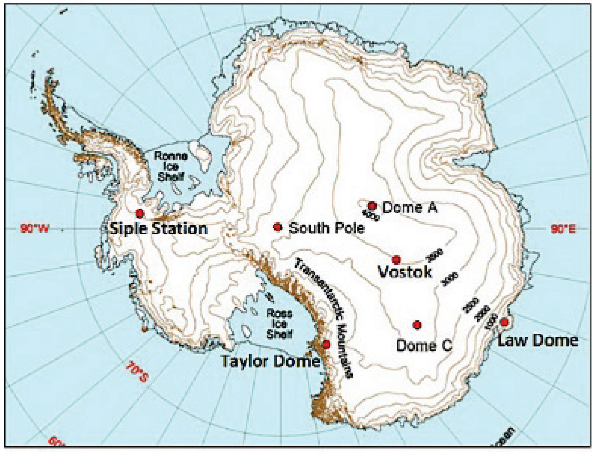


http://www.astrosurf.com/luxorion/Sciences/vostok-drill.jpg

Vostok Ice Core

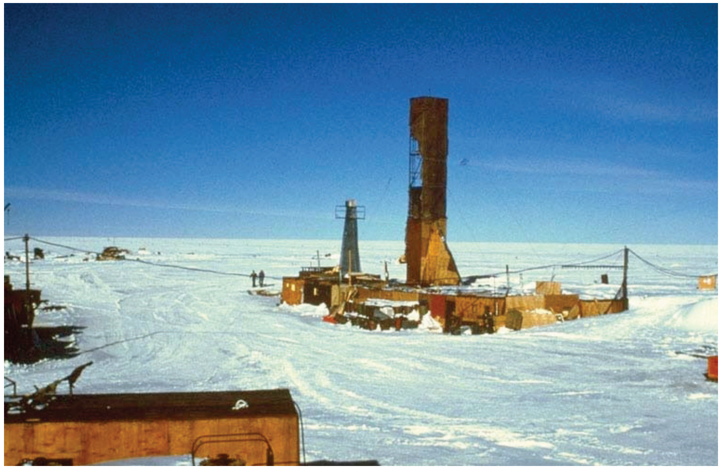
- January 1998: ice core with depth of 3.6 km extracted at Russian Vostok Station, Antarctica
- Vostok ice-core record extends back 400,000 years in time *(*Petit *et al*., *Nature*, 1999)
- **Reconstructed temperature based on measurement of the deuterium content of ice**
- $\delta^{18}O$ shows tremendous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





https://cdiac.ess-dive.lbl.gov/trends/co2/ice_core_co2.html

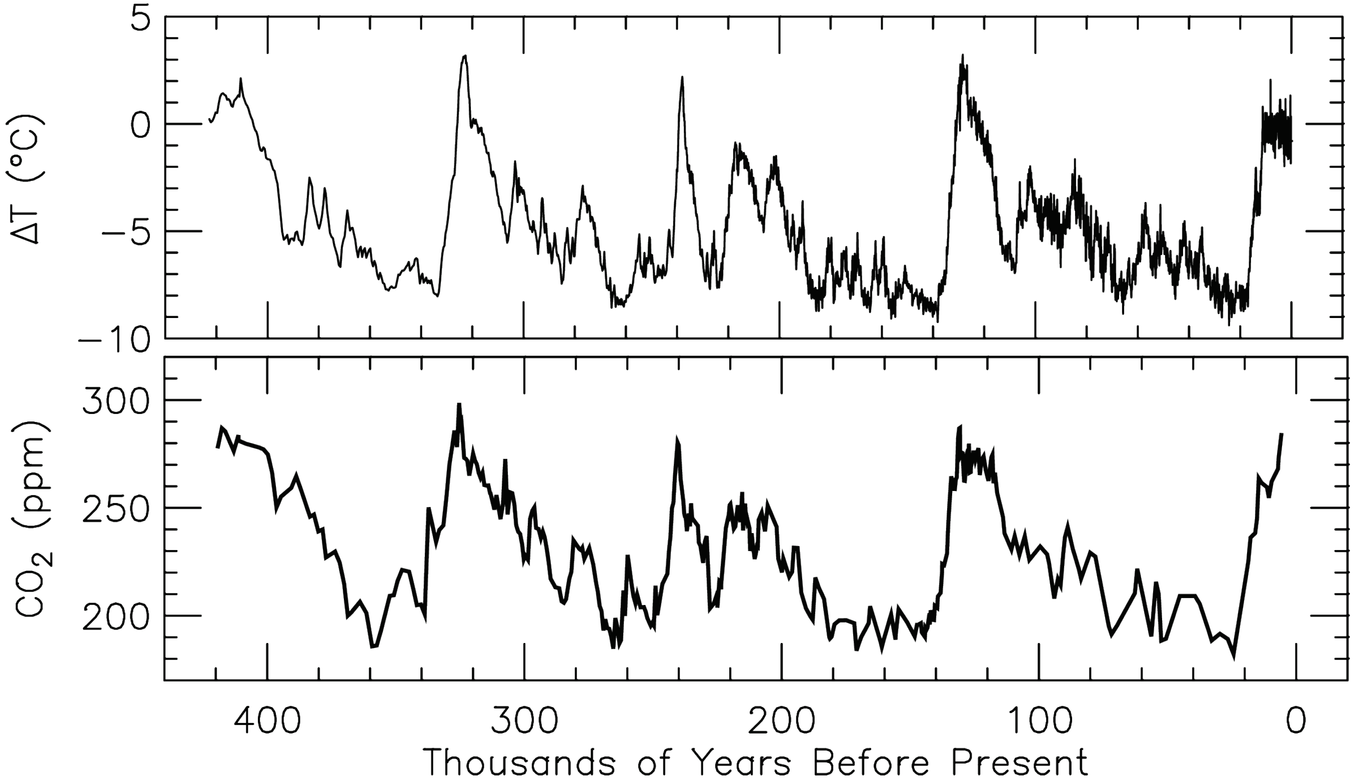
Vostok Drill



http://www.astrosurf.com/luxorion/Sciences/vostok-drill.jpg

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

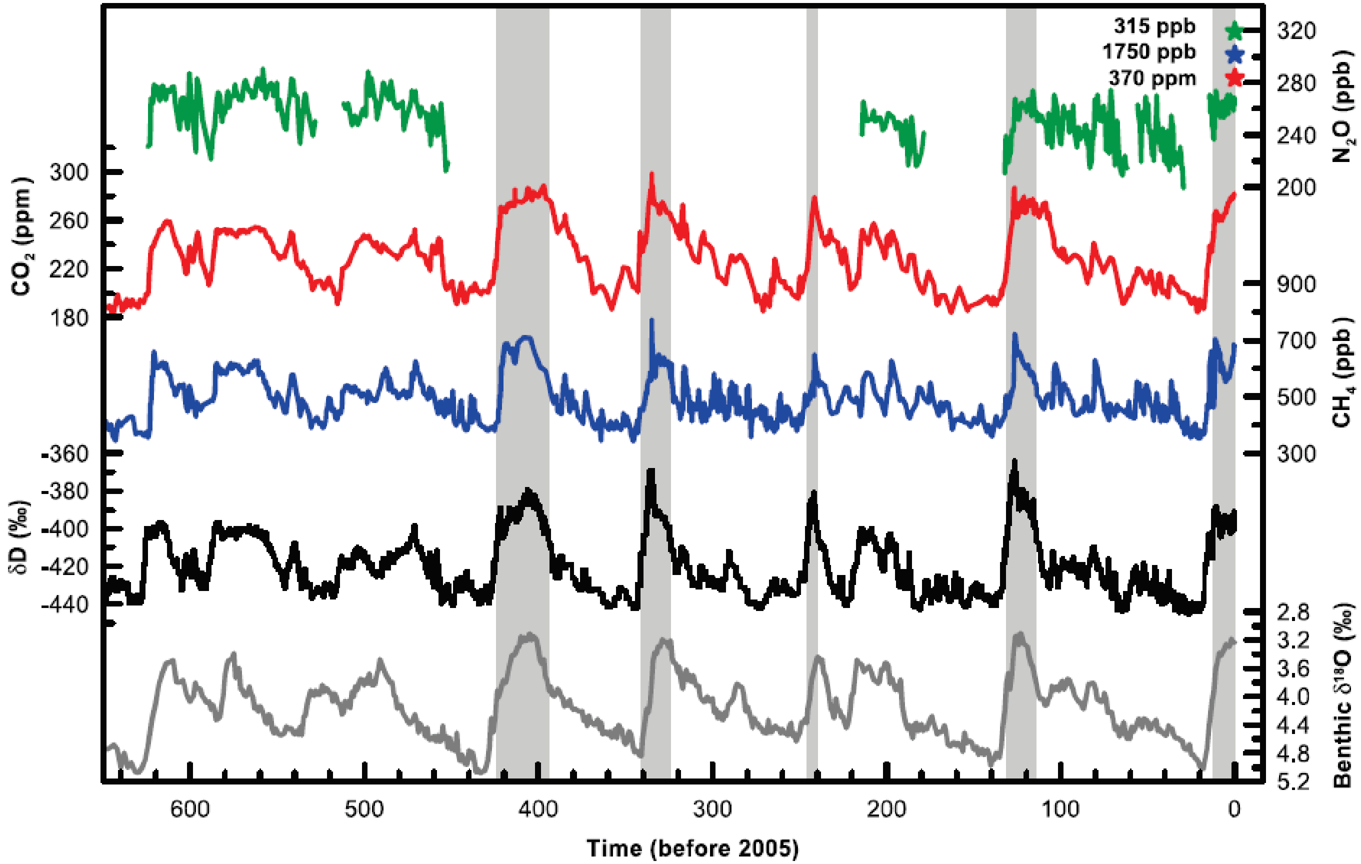


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit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

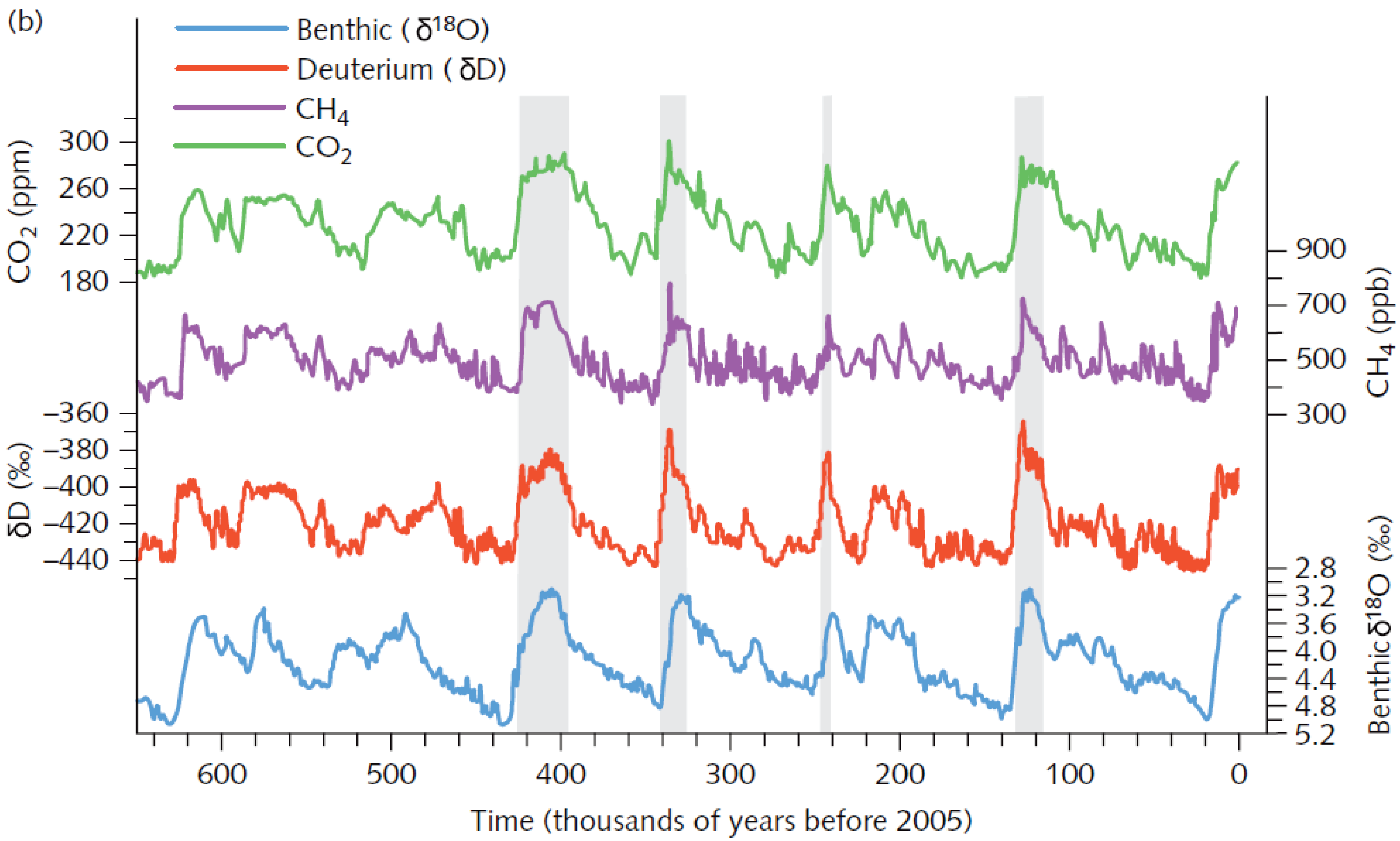


Figure 4.9 (b) Variations of deuterium (δD), a proxy for local temperature; $\delta^{18}O$, a proxy for global ice volume fluctuations; and the atmospheric concentrations of CO_2 and CH_4 derived from air trapped within ice cores from Antarctica. Shading indicates interglacial periods.

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

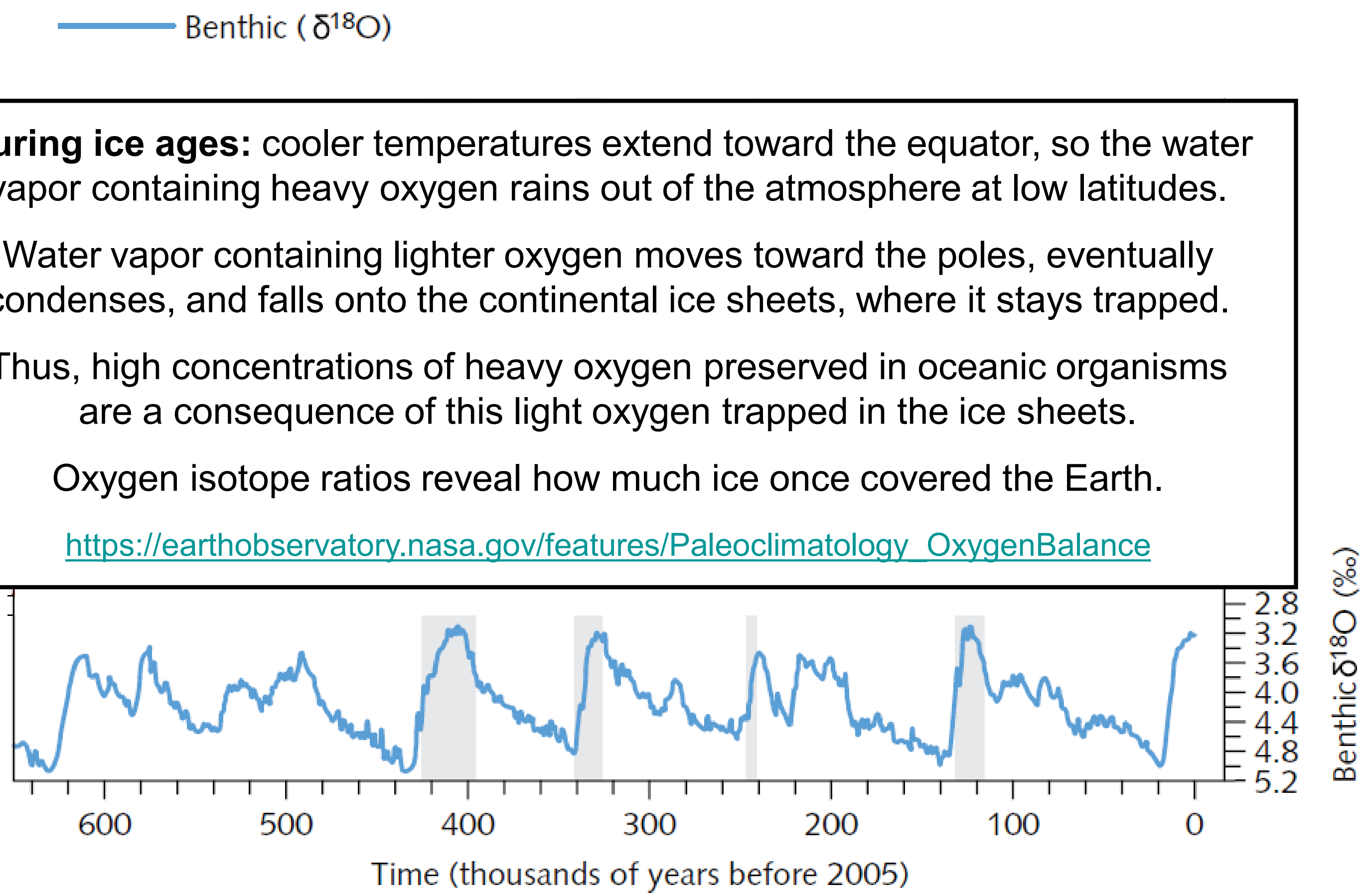
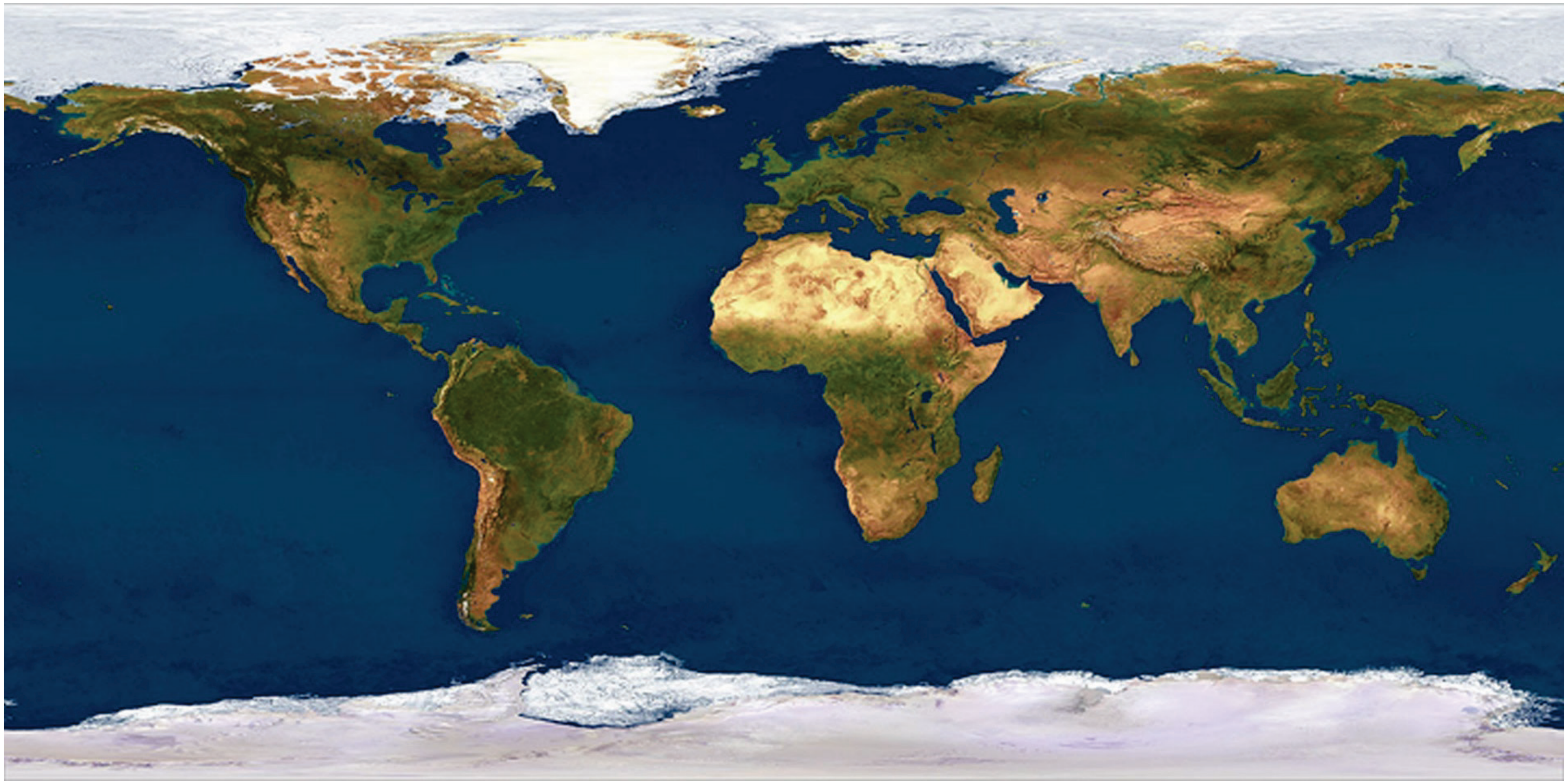


Figure 4.9 (b) Variations of deuterium (δD), a proxy for local temperature; $\delta^{18}O$, a proxy for global ice volume fluctuations; and the atmospheric concentrations of CO_2 and CH_4 derived from air trapped within ice cores from Antarctica. Shading indicates interglacial periods.

Houghton, 2015

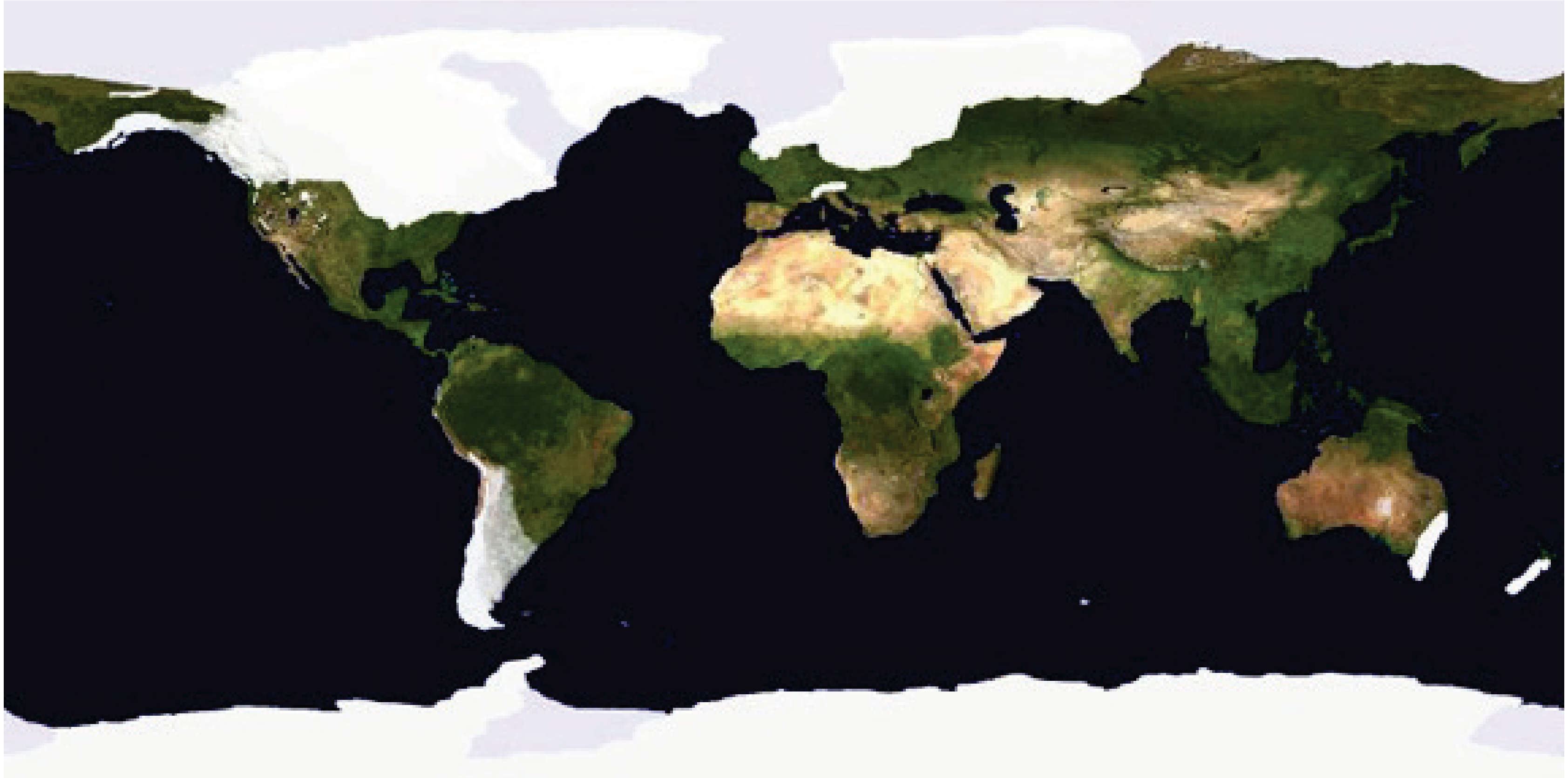
See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica

Present Day



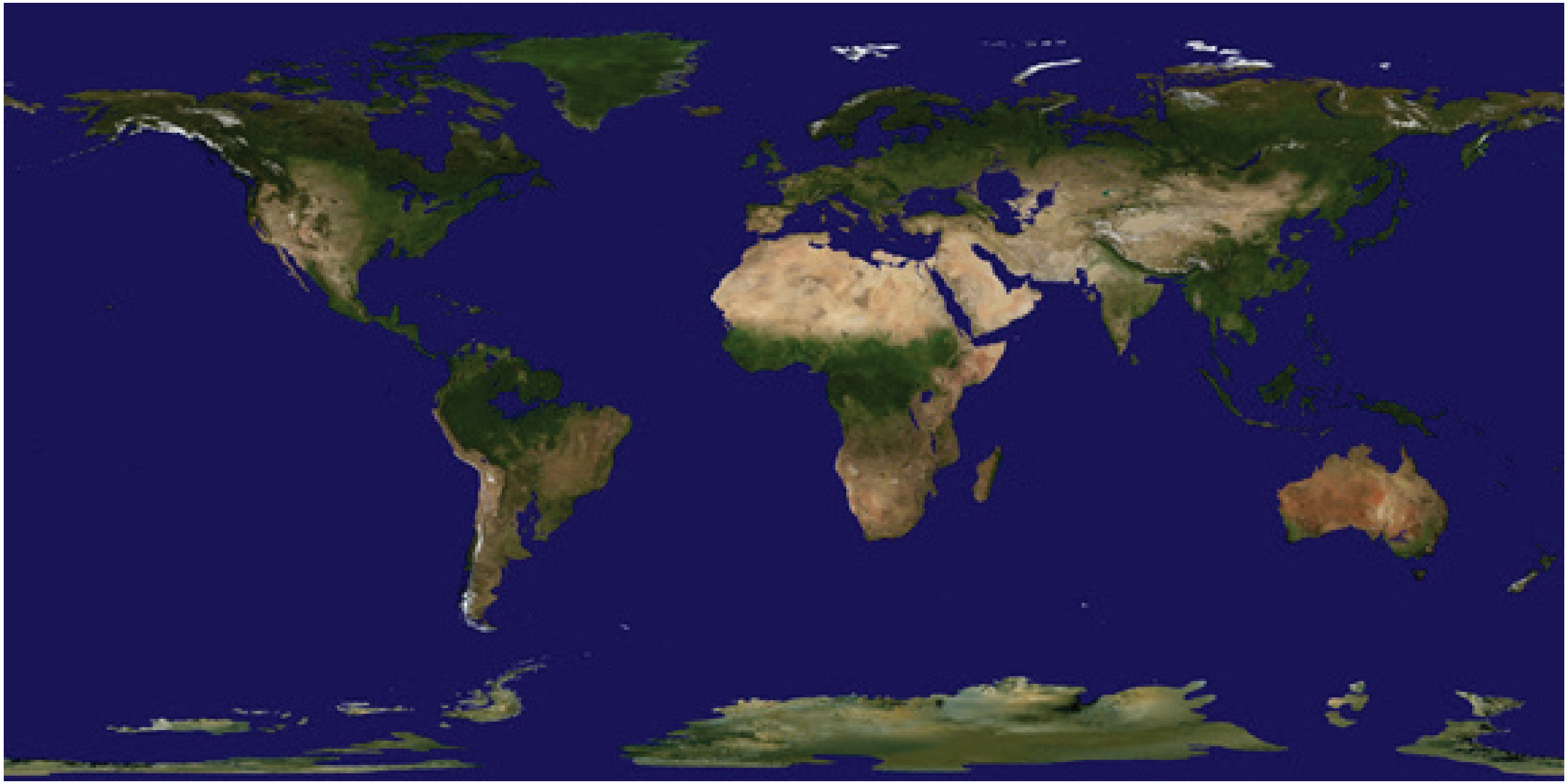
http://www.planetaryvisions.com/release2007-1/satmap.jpg

Glacial Maximum



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

No Polar Ice



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.

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

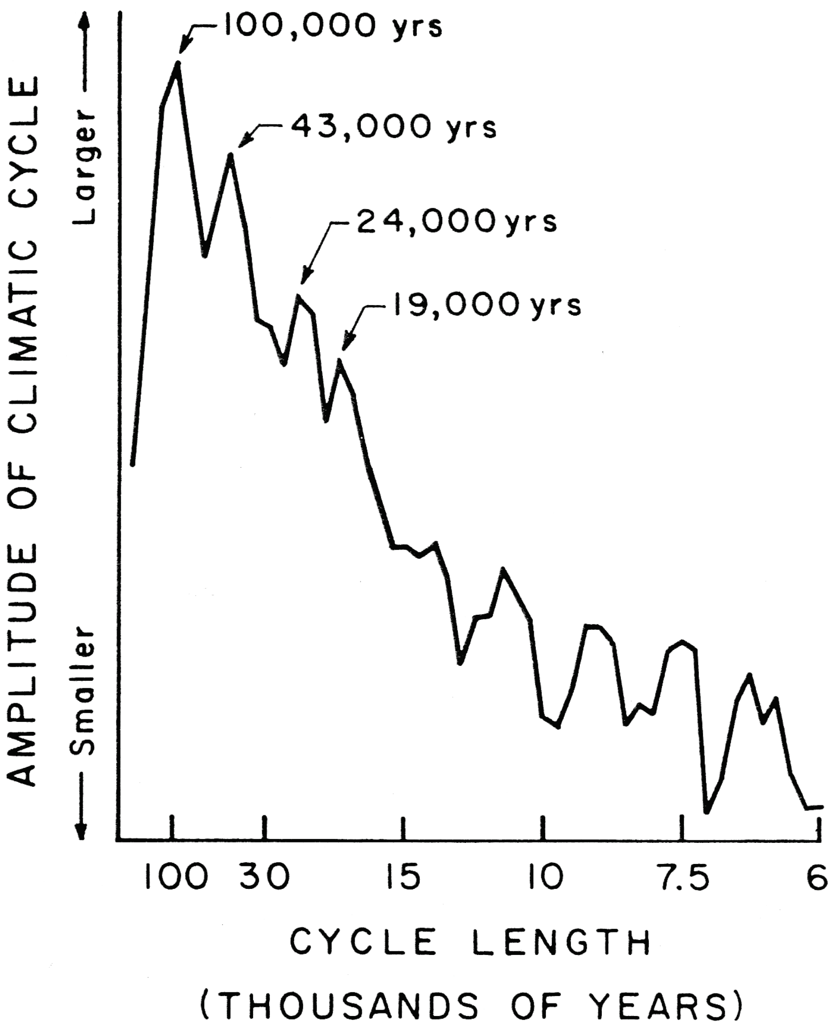


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

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

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

Pacemaker of the Ice Ages 171

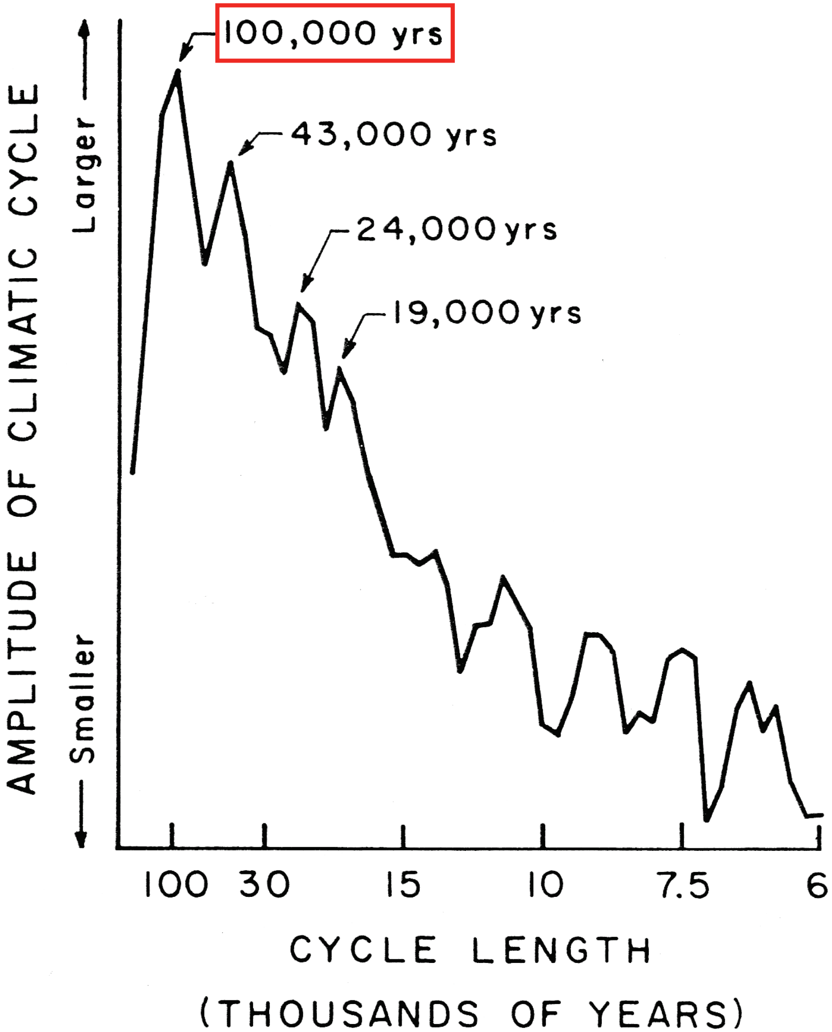
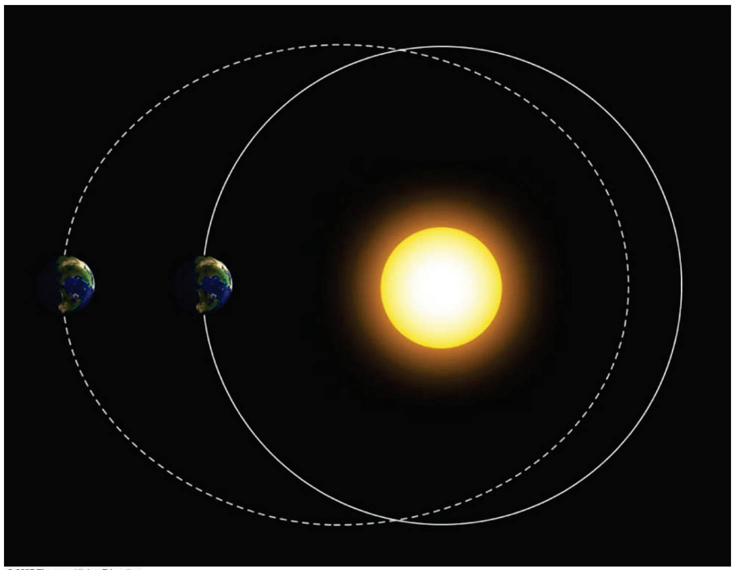


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

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.



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

Pacemaker of the Ice Ages 171

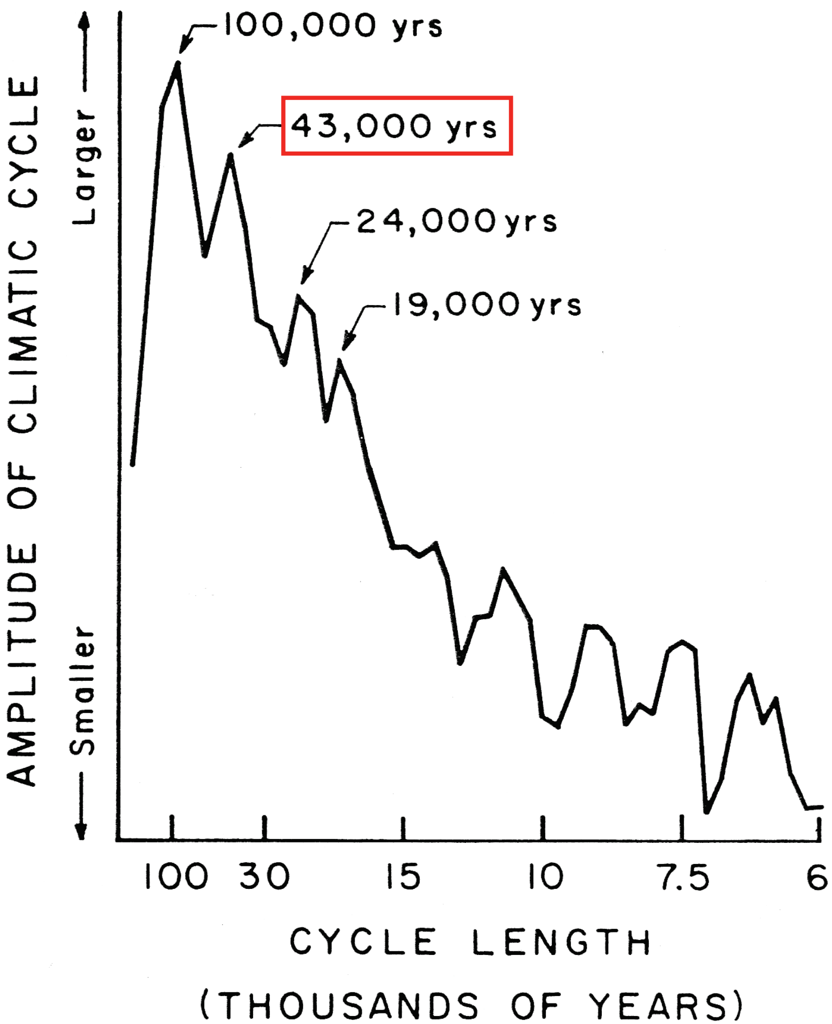
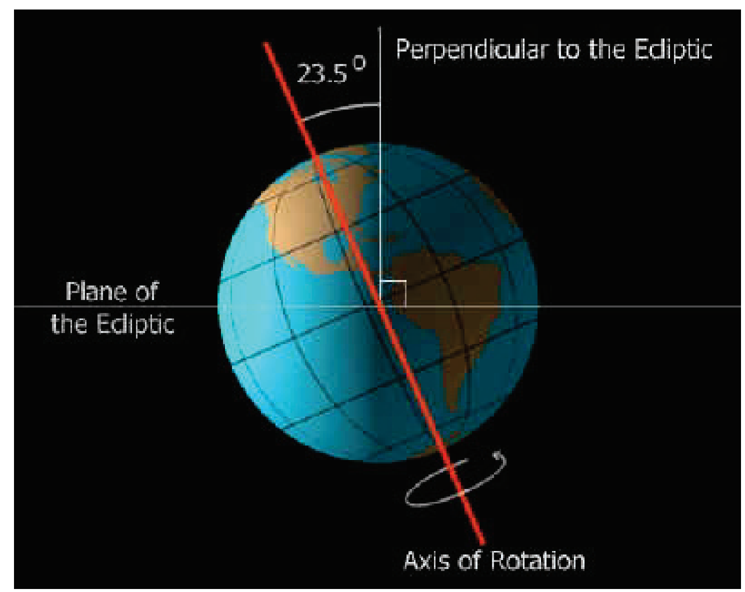


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

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

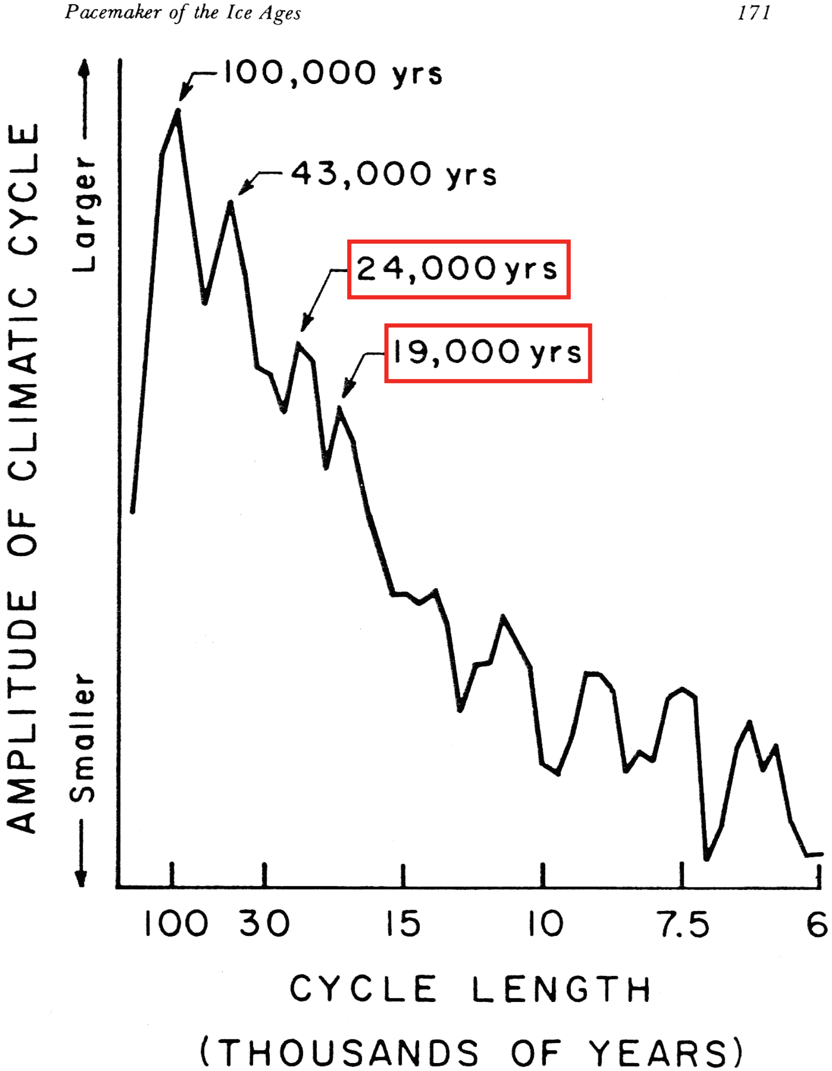
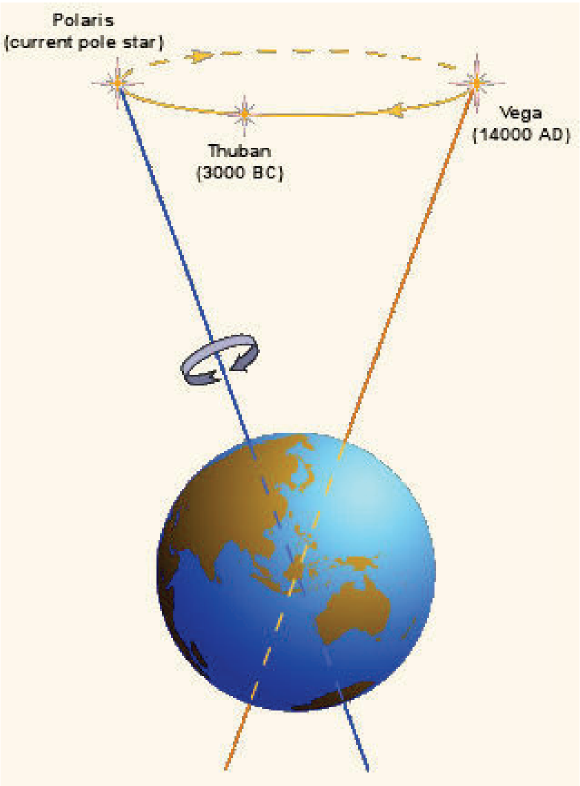


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

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

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



Glacial Periods MUCH Dustier than Interglacials

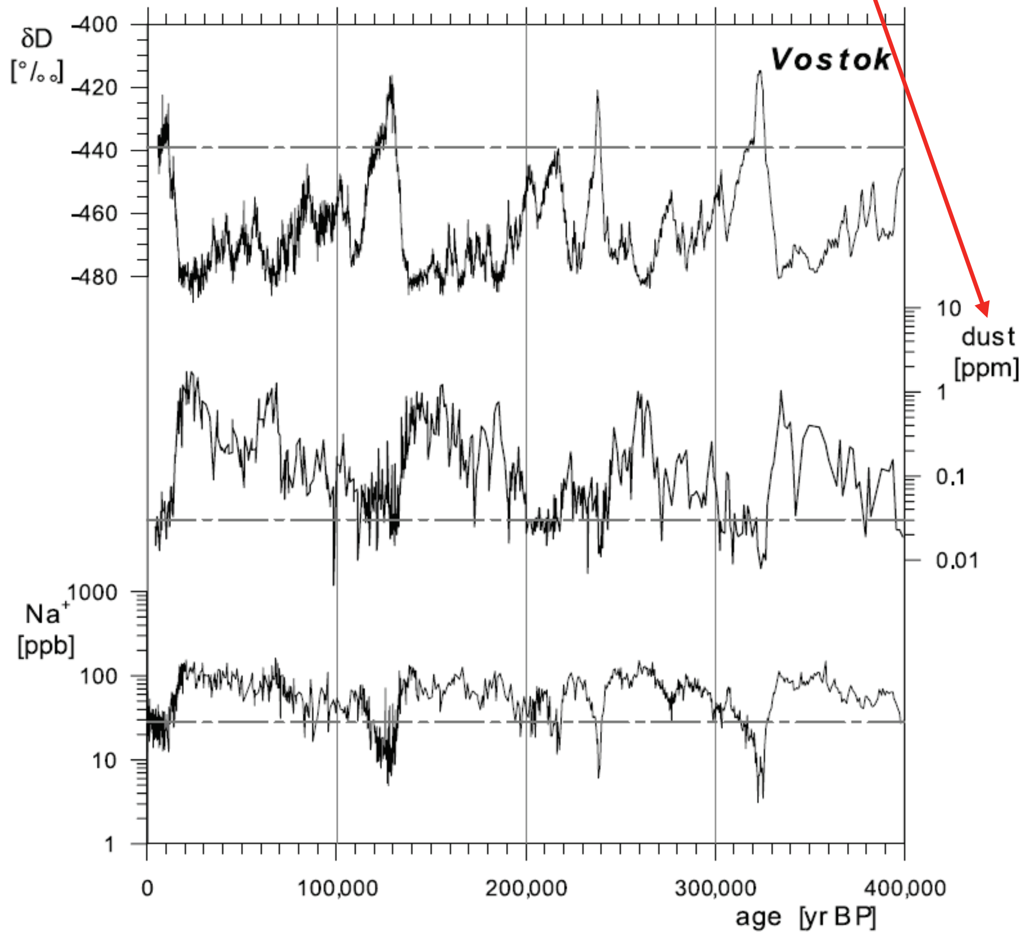


Figure 3. Temporal evolution of δD representing changes in the average local condensation temperature during snow formation, the particulate dust, and the sea-salt component Na^+ over the last four glacial cycles as recorded in the East Antarctic Vostok ice core [*Petit et al.*, 1999]. Dashed-dotted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

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

Glacial Periods MUCH Dustier than Interglacials

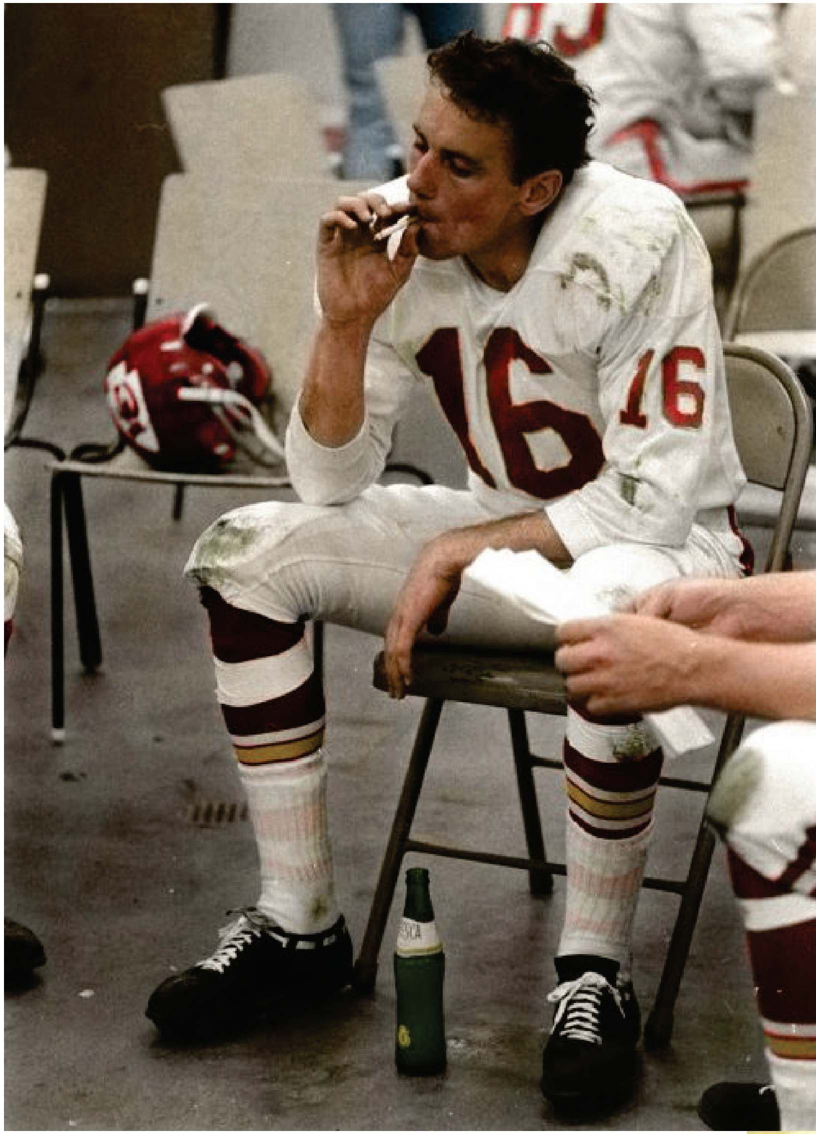
Prélèvements de carottes de glace en Antarctique et au Groenland par des équipes de scientifiques américains (projet GISP2 du NICL notamment) et européens (projet GRIP de l'ESF). Au-dessus à gauche le puits de forage de la station Vostok (78°S et 107°E), considérée comme le "pôle du froid". Il fait en moyenne -55°C ! Les autres images représentent différentes opérations effectuées sur les échantillons : extraction du tube de forage, découpe par une température comprise entre -20 et -35°C, stockage temporaire par -15°C, calibration et analyse préliminaire sur site, analyse détaillée aux Etats-Unis. Documents NCDC/NOAA et Niels Bohr Institute.

http://www.astrosurf.com/luxorion/bioastro-vie-glaces2.htm

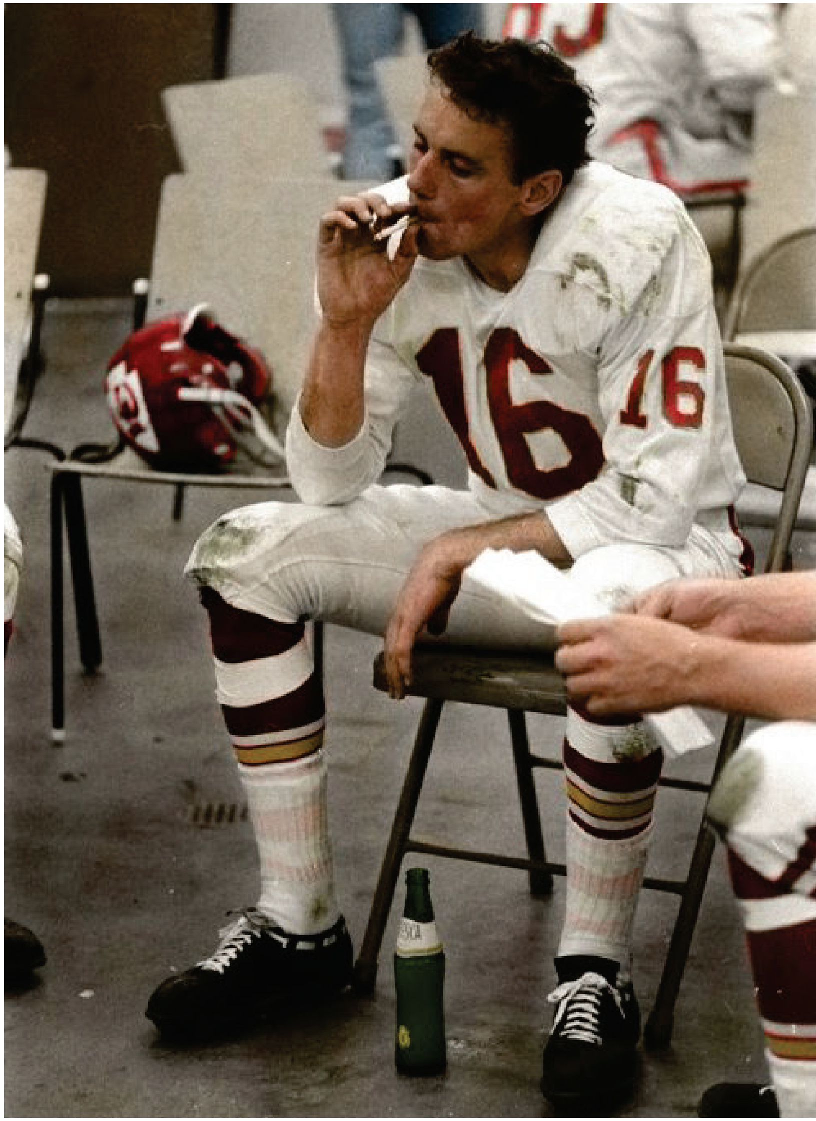
Glacial Periods MUCH Dustier than Interglacials

http://www.astrosurf.com/luxorion/bioastro-vie-glaces2.htm

Glacial Periods MUCH Dustier than Interglacials



Len Dawson, Halftime, Super Bowl I; photo by Bill Ray of Life Magazine



https://www.washingtonpost.com/sports/2020/01/23/len-dawson-cigarette-chiefs-super-bowl/
https://twitter.com/wingoz/status/1217606018508693505

Biology in Today's Ocean

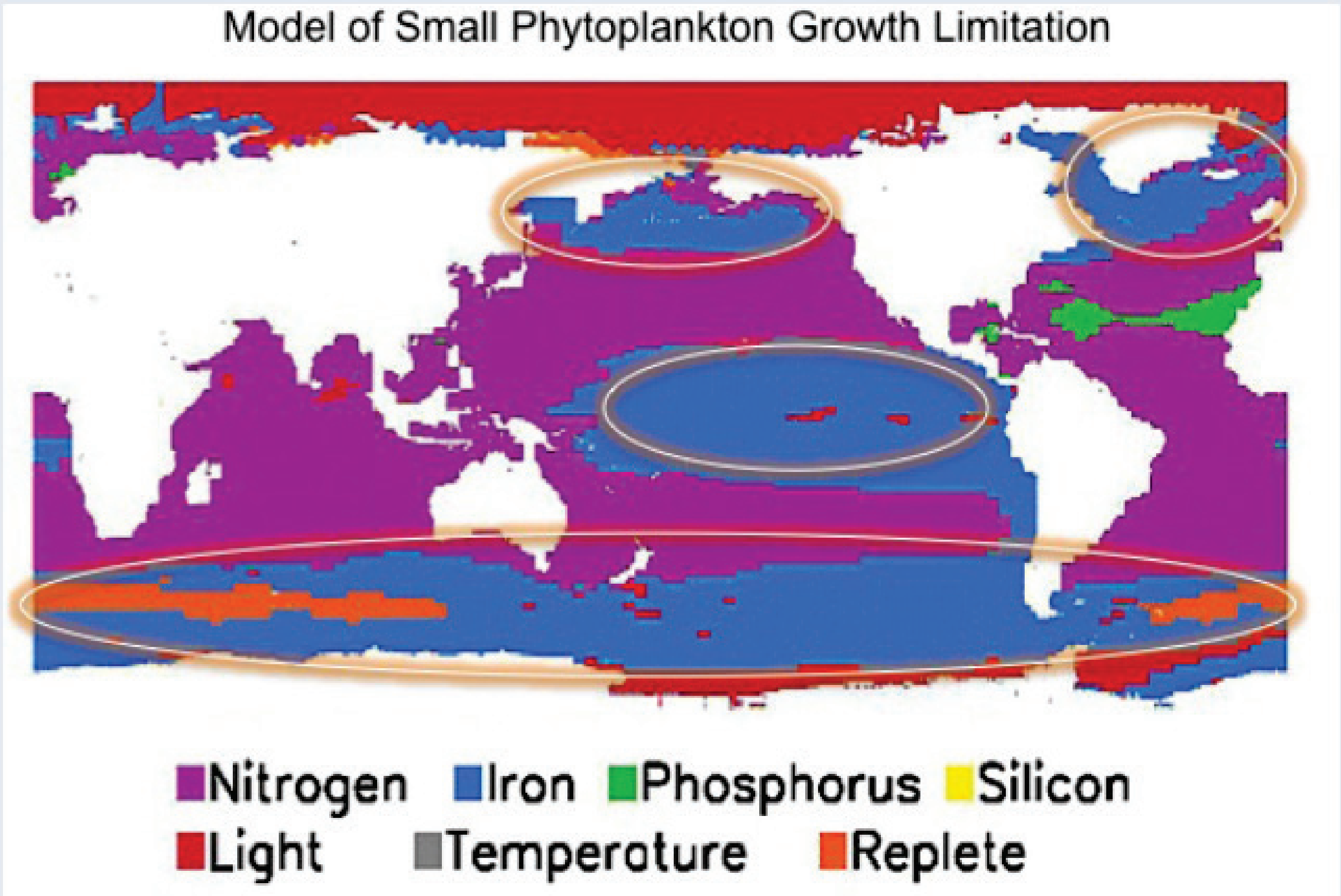


Figure 1. Results of a global model of small phytoplankton growth limitation by Moore et al. 2004 (*Global Biogeochemical Cycles*). Blue shaded areas denote regions that are potentially limited by iron availability. Iron is supplied by dust from continents and by upwelling of deep water. However, high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

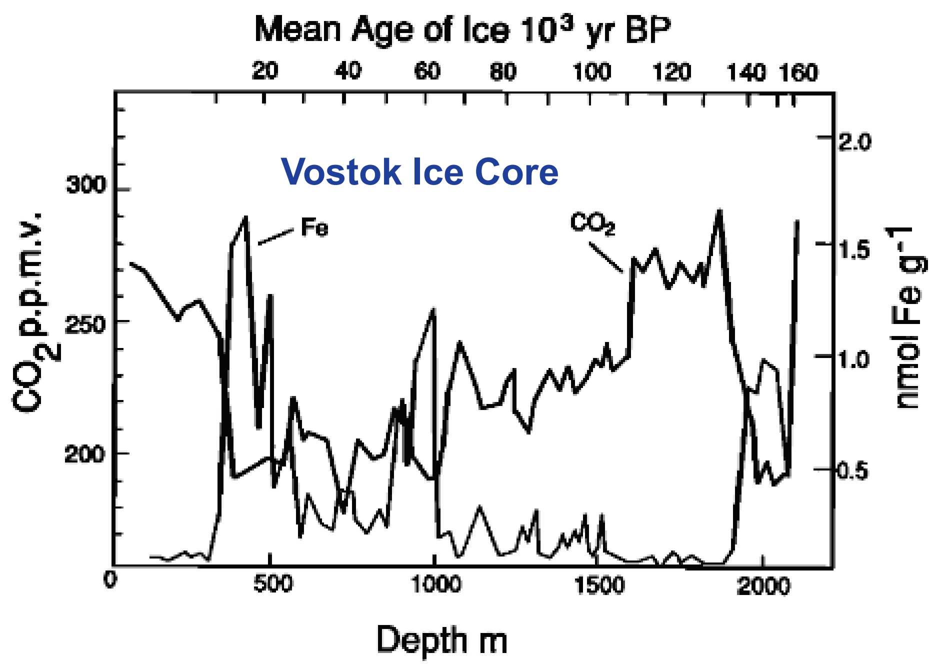
Connection to Glacial CO_2

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

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 $\dfrac{K}{W/m^2}$

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: $F = \sigma \, T^4$

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

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 $\frac{K}{W/m^2}$

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

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

Above equation can be re-arranged to yield:

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

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

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

Do units work?

Units of σ : W m^{-2} K^{-4}

Units of T : K

Units of λ ?

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

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 $\frac{K}{W/m^2}$

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

Earth's atmosphere is slightly more complicated, than a pure black body, as explained for example at http://zebu.uoregon.edu/ph311/lec06.html

$\lambda_P \approx 0.3$ **K / (W m^{-2})**

Here: P refers to Planck Response Function

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 $\frac{K}{W/m^2}$

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

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?

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

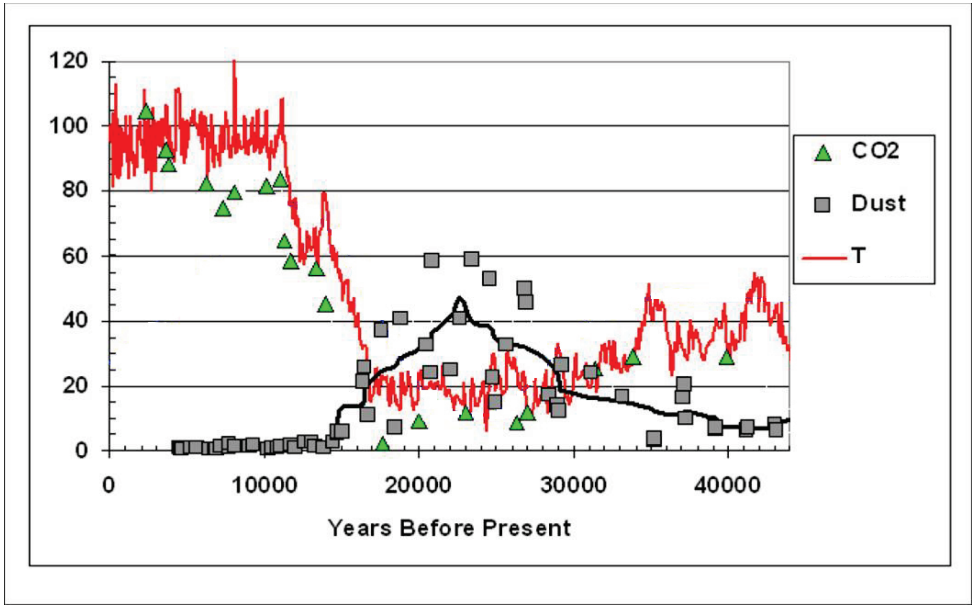
How much does ΔF change when CO_2 changes?

As we will explore in more detail later in class (24 Sept 2020):

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

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) 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

Here we must use $\lambda_{\text{Considering Aerosols}}$ to find ΔT :

$$\Delta T_{\text{Scenario \#1}} = 0.49 \; \frac{\text{K}}{\text{W m}^{-2}} \times 5.2 \;\; \text{W m}^{-2} = 2.5 \text{ K}$$

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

Here we must use $\lambda_{\text{No Aerosols}}$ to find ΔT :

$$\Delta T_{\text{Scenario \#2}} = 0.75 \; \frac{\text{K}}{\text{W m}^{-2}} \times 8.6 \;\; \text{W m}^{-2} = \; 6.5 \text{ K}$$

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
ΔT ⇒	**2.5 K**	**or**	**6.5 K ???**

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)

Take away messages:

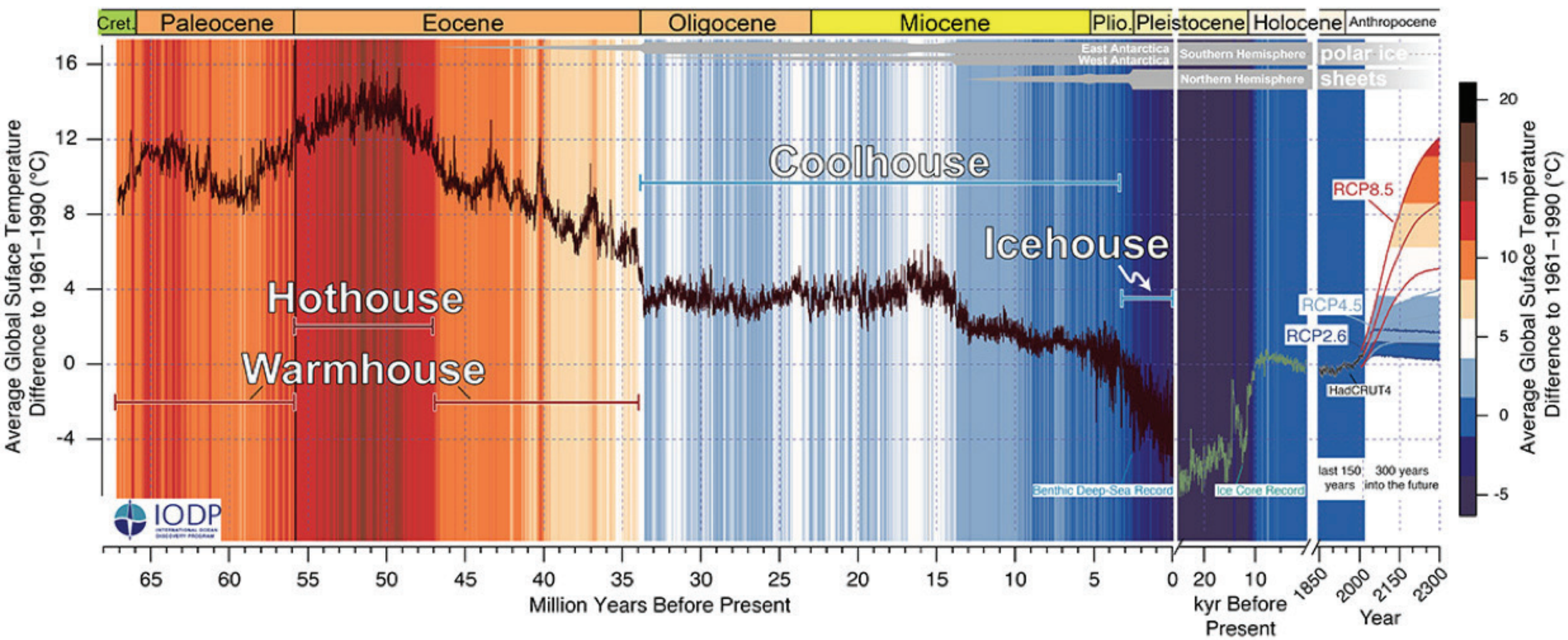
1. ***Climate sensitivity* inferred from ice core record depends on how aerosols are handled**
2. ***Future climate* will be quite sensitive to:**
   - **the efficacy of atmospheric feedbacks (H_2O, clouds)**
   - **the radiative forcing of aerosols (not considered in our simple future scenario)**
   - **how surface albedo changes**

	ΔF (W m^{-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

ΔT ⇒ 2.5 K or 6.5 K ???

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)

Problem Set #1 is due at start of class on September 22 (one week from today) and covers material presented in Lectures 1 to 4.

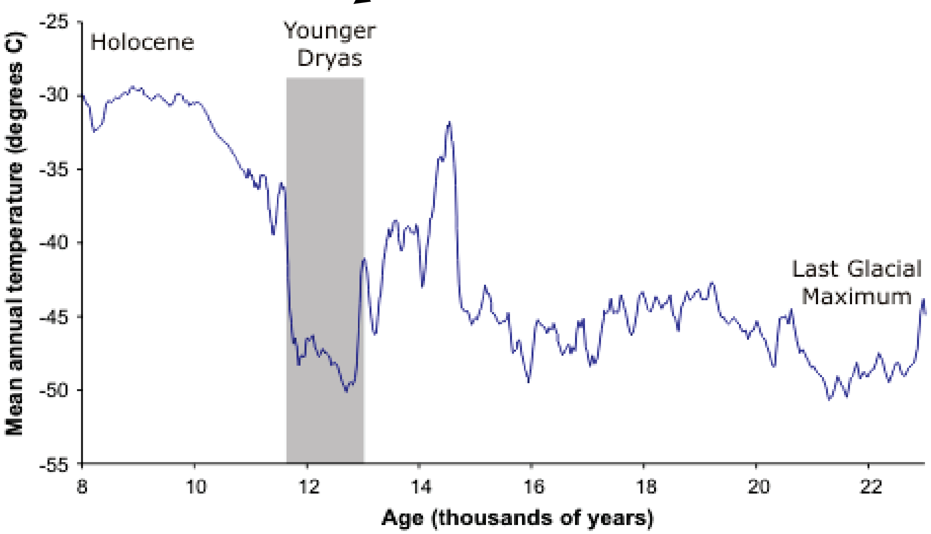
There are separate assignments for those enrolled in 433 and 633, as explained at the start of class.

Please get started early!

If you have questions, please contact me to arrange a Zoom meeting.

Younger Dryas (about 12,000 years ago)

Around 12,000 years ago, mean annual temperatures abruptly dropped to levels similar to those during the last glacial maximum



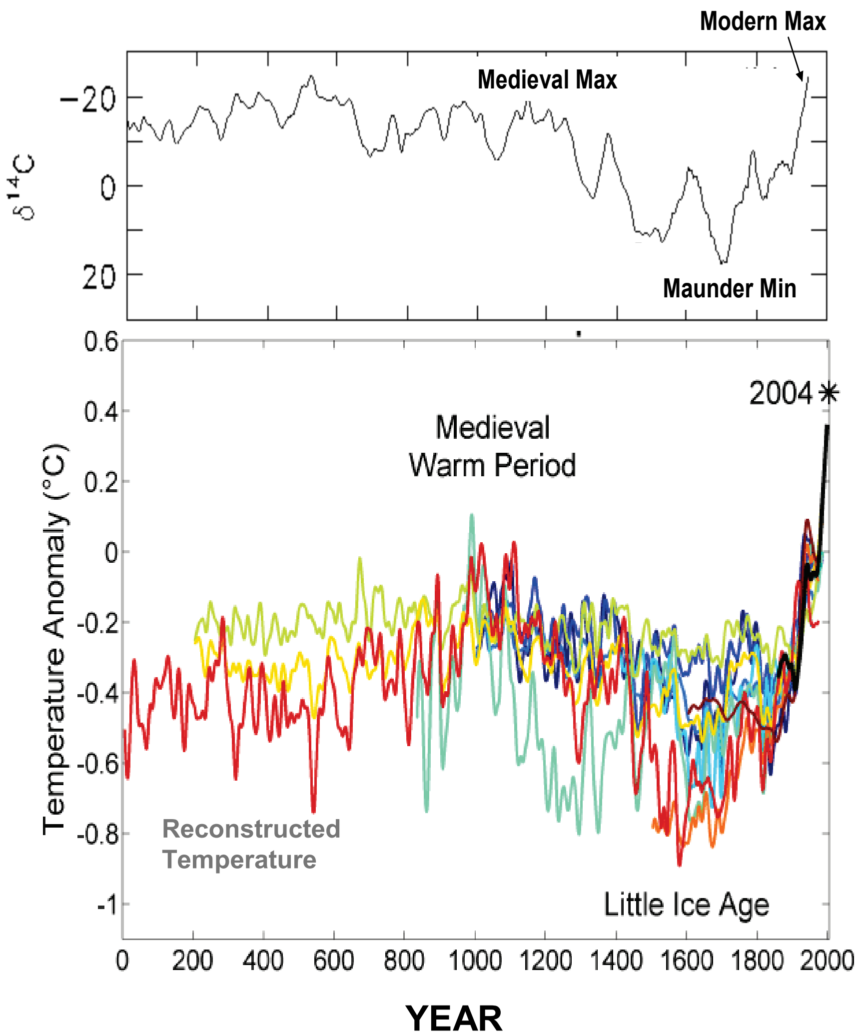
Most scientists believe the cool conditions of the Youger Dryas resulted from a flood of fresh water into the North Atlantic that shut down ocean's thermohaline circulation.

The flood of fresh water was due to discharge from glacial lakes, formed by the melt water of retreating glaciers.

Some geologists (Firestone *et al., PNAS*, 2007) believe that the Younger Dryas was compounded by a terrestrial impact.

http://www.ncdc.noaa.gov/paleo/abrupt/data4.html

Medieval Warm Period (MWP) ~800 to 1300 AD



$\delta^{14}C$ (radiocarbon) is a proxy that can be used to estimate past solar activity.

Carbon-14 is produced when cosmic rays hit nitrogen (^{14}N), inducing a decay that transforms this molecule to Carbon-14 (half life of ~5,730 yrs).

Increased solar activity results in a reduction of cosmic rays reaching Earth's atmosphere, reducing production of carbon-14, because cosmic rays are blocked by the outward sweep of magnetic fields of the solar wind.

Measurements of ^{14}C suggest primary cause of warm conditions during MWP was rise in solar activity

http://en.wikipedia.org/wiki/Solar_variation

http://en.wikipedia.org/wiki/Medieval_Warm_Period

Little Ice Age (~1350 to 1900)

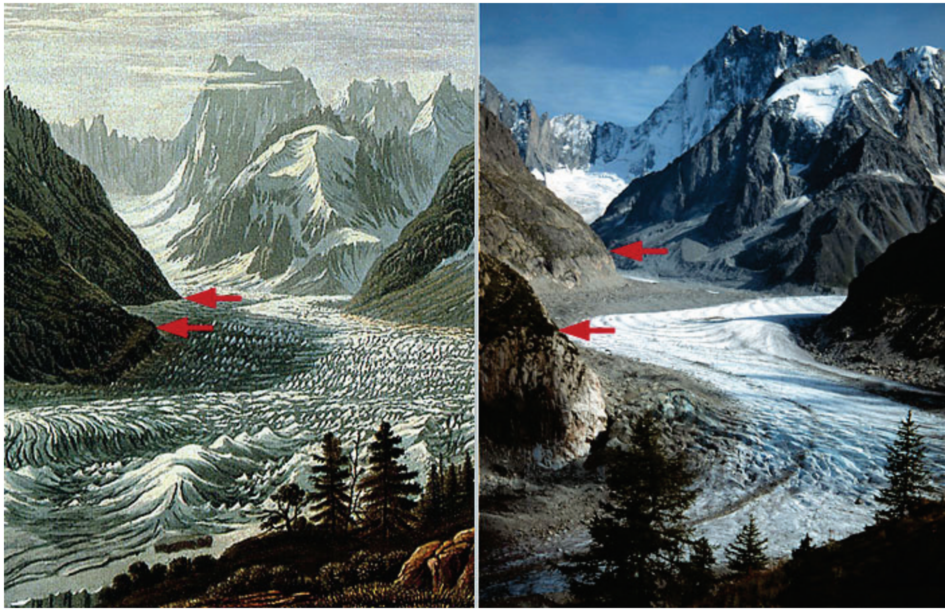
Major rivers (Thames) & waterways (NY harbor) frequently froze.

Crops and livestock failed.

Cities flooded.

Glaciers expanded.

Why did this happen?



http://www.swisseduc.ch/glaciers/glossary/little-ice-age-two-en.html

1. Little ice age was an extended period of quiet solar activity:
   coldest time period is associated with the Maunder Minimum
   (time of very low sunspot activity ⇒ reduced solar irradiance).
2. Several large volcanic eruptions during this period; resulting aerosol loading led to a reduction in amount solar radiation reaching the surface.
3. Increase in albedo associated with the colder temperatures (colder T results in more ice) led to even more cooling.