תורת האקלים

יום ה, 9-12, קפלון 205

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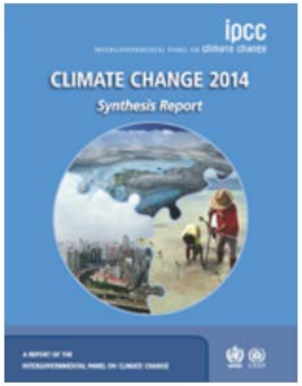
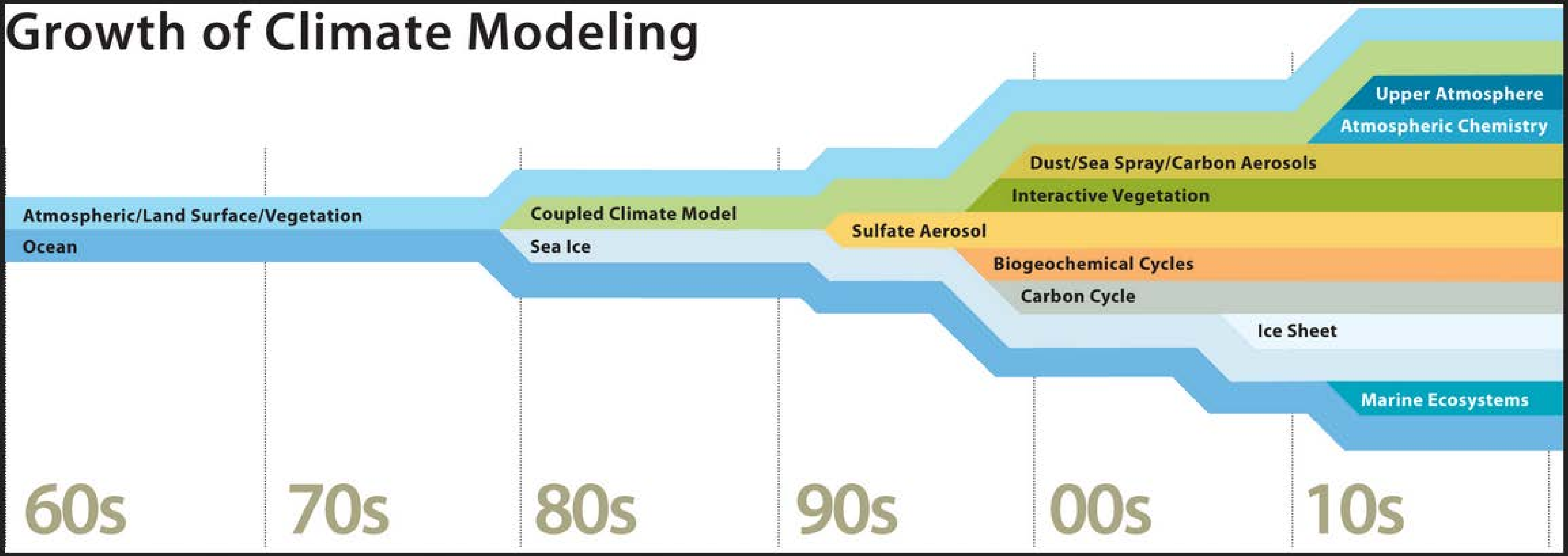
A brief history of Climate Science

Modern climate science is relatively new since it heavily relies on computer models which were only developed in the second half of the 20th century





The earliest thoughts and studies on Climate:

- Climatology- compilation of weather statistics for different geographical locations

"Climate is what you expect, weather is what you get"

- Ice ages – how could the climate have changed so much?
- The Greenhouse Effect (first suggested by Fourier in 1820)

The Greenhouse Effect:

Joseph Fourier

Jean-Baptiste Joseph Fourier

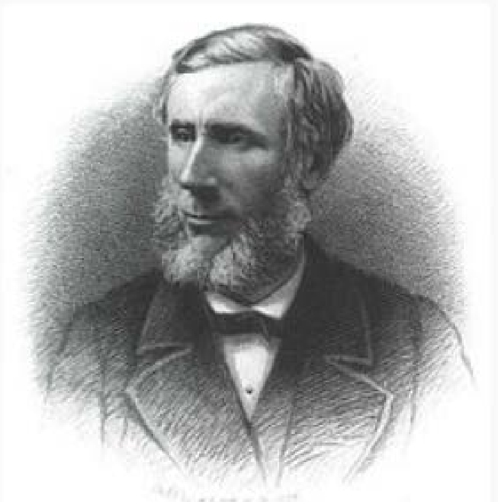
Fourier: 1820s- the effective temperature of the Earth is below freezing. Suggested the atmosphere might trap heat

Claude Pouillet

Claude Servais Mathias Pouillet

Pouillet: 1837- first measurement of the solar constant

John Tyndall



Tyndall: 1859- Experimentally proved the possibility of the Greenhouse Effect by showing that atmospheric gasses absorb IR. Noted the dominance of water vapor

Ice Ages:

18th -19th century: attribution of erratic boulders to the dispersion by glaciers (various scientists, including Geothe)

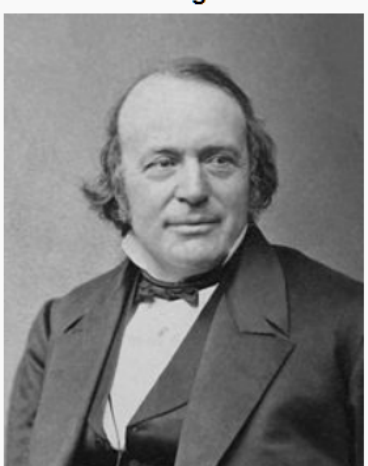
Yeager Rock (Washington state)

Karl Friedrich Schimper

German naturalist and poet

Schimper: 1830s- there existed times when the earth was much colder and most of Europe covered by ice - Called these times “Eiszeit” (Ice Ages)

Louis Agassiz



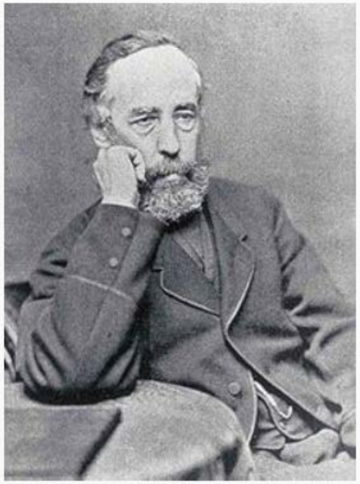
Agassiz: 1837- extended and presented the ice age idea. Community rejected this idea because contradicted established idea that Earth has been gradually cooling since its creation.

Lived on a glacier to study its motion.

1840- published book “Study on Glaciers”

Ice Ages:

James Croll
FRS



Croll: 1875 – "Climate and time in their geological relations" - tied changes in climate and glaciation to orbital variations.
His specific mechanism was wrong but the basic idea of orbital forcing effect was correct.

Ice Ages and the Greenhouse Effect:

Svante Arrhenius

Arrhenius: 1896 – calculated how changes in CO_2 could affect Earth's temperature, to explain ice ages.
His formula relating radiative forcing change to CO_2 change still holds today: $\Delta F = \alpha \ln(C/C_0)$
Predicted that fossil fuel burning would result in global warming, and included a water vapor feedback. Treated CO2 as forcing water vapor changes because it is long lived.
Estimated doubling of CO_2 in 1000 years.

Milutin Milankovich (1879-1958)

Milutin Milanković

Milankovitch as a student with a pocket watch.

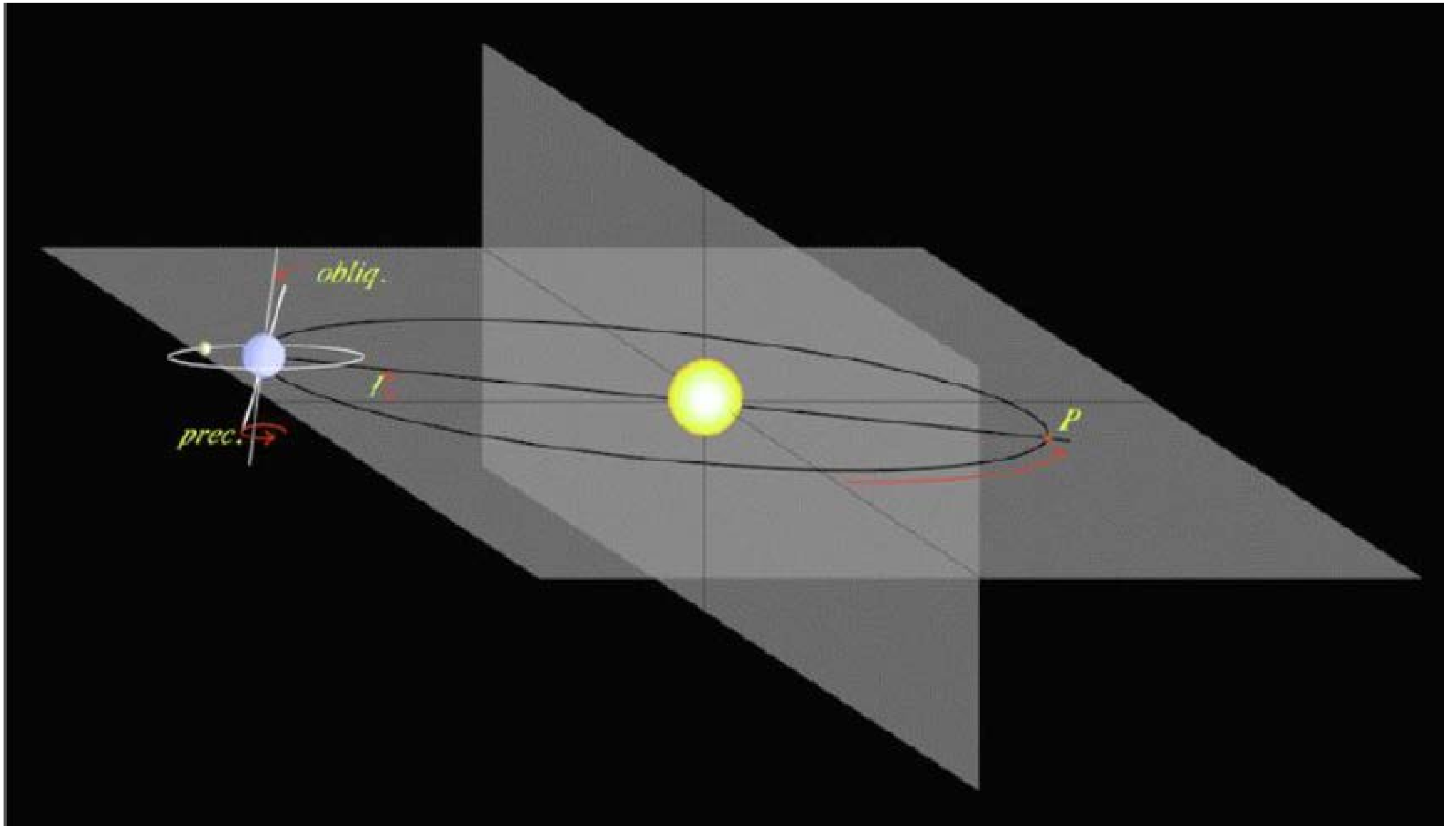
A Serbian mathematician and civil engineer, who became interested in climate when read about ice ages and realized that meteorology was mostly empirical, a few physical theories used, and hardly any math.

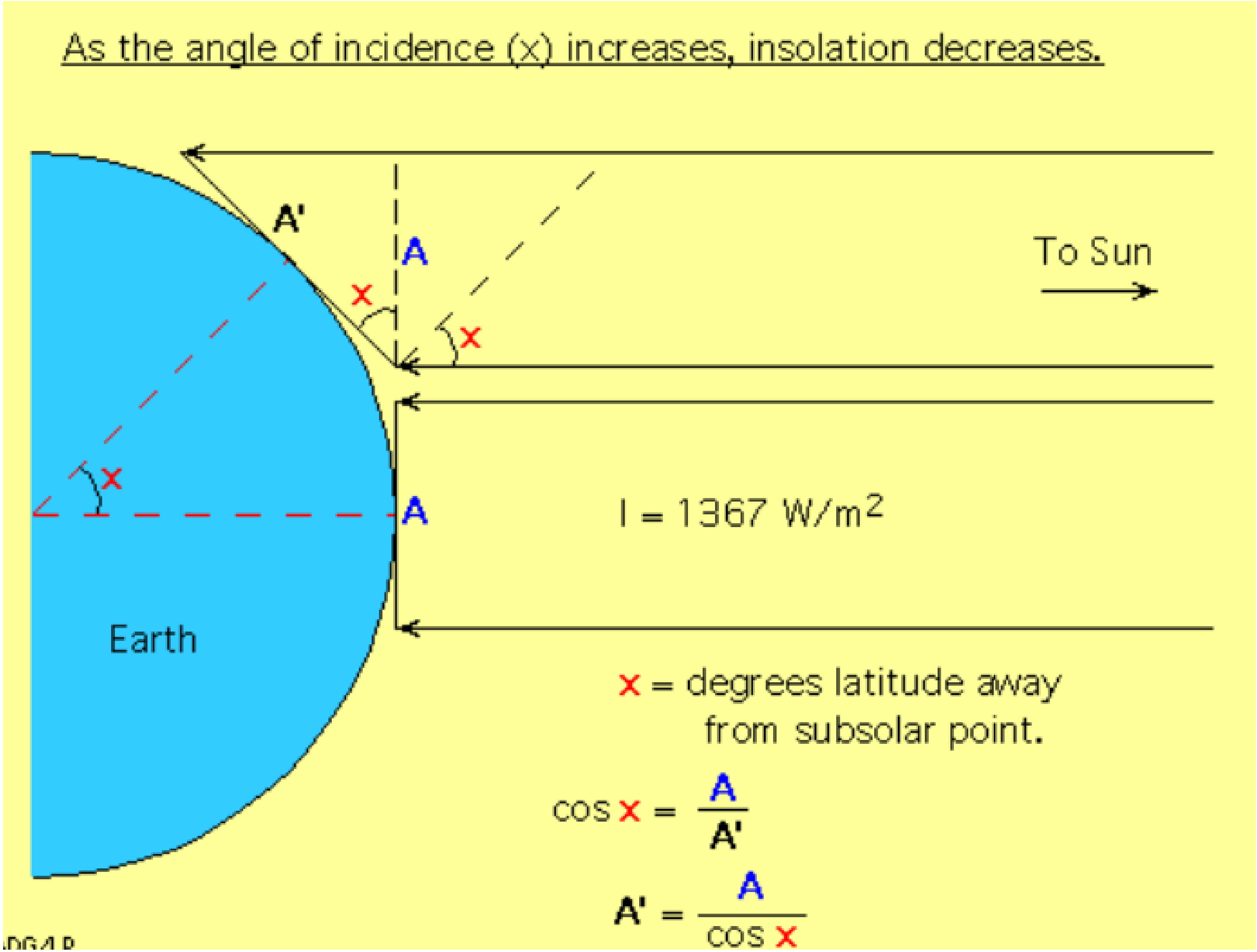
Correctly calculated the intensity, temporal variations and latitudinal distribution of solar insolation

Applied this theory to study climate change and the climates of other planets.

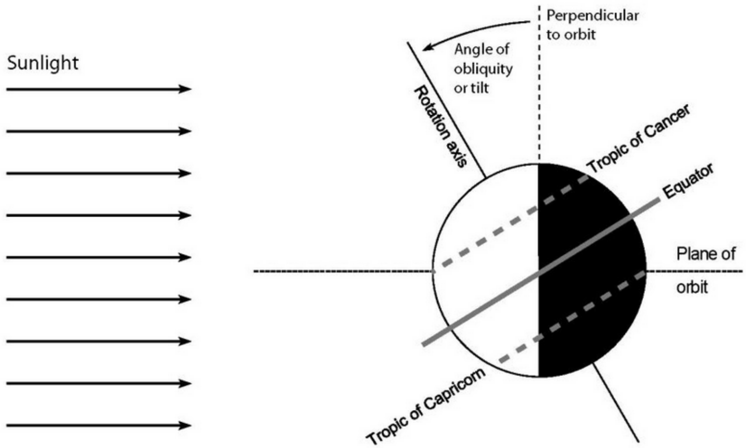
1920- published a comprehensive book: *Mathematical Theory of Heat Phenomena Produced by Solar Radiation*.

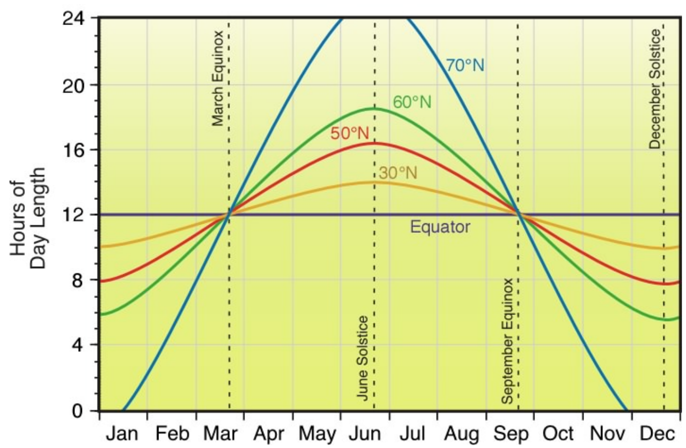
Milankovic’s theory:
The planets and moon cause variations in the Earth’s orbit around the sun, affecting insolation.
Main variations: eccentricity, obliquity and precession



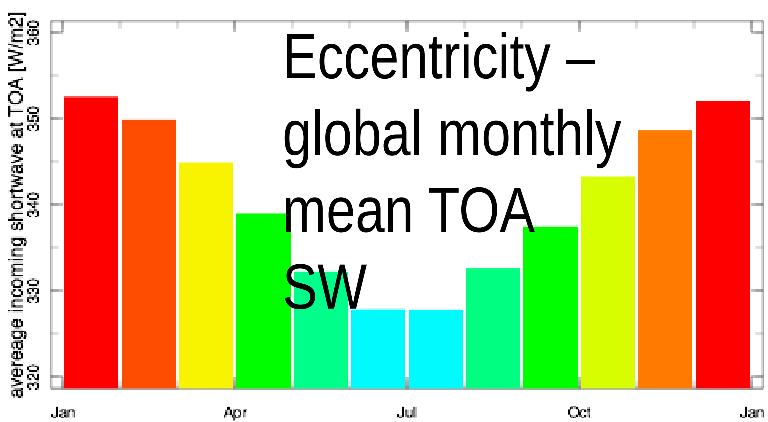

As the angle of incidence (x) increases, insolation decreases.
A'
A
x
x
To Sun
x
A
I = 1367 W/m2
Earth
x = degrees latitude away from subsolar point.
cos x = A / A'
A' = A / cos x

Daily mean incoming solar radiation at top of the atmosphere (W/m^2)



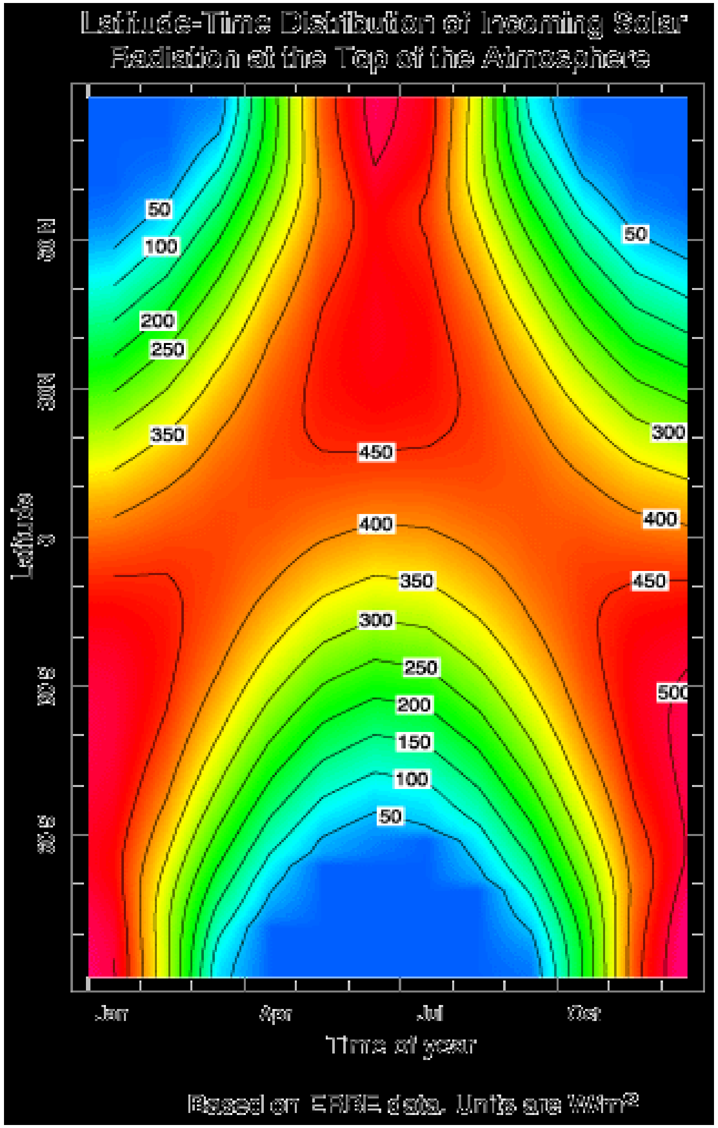


Length of day



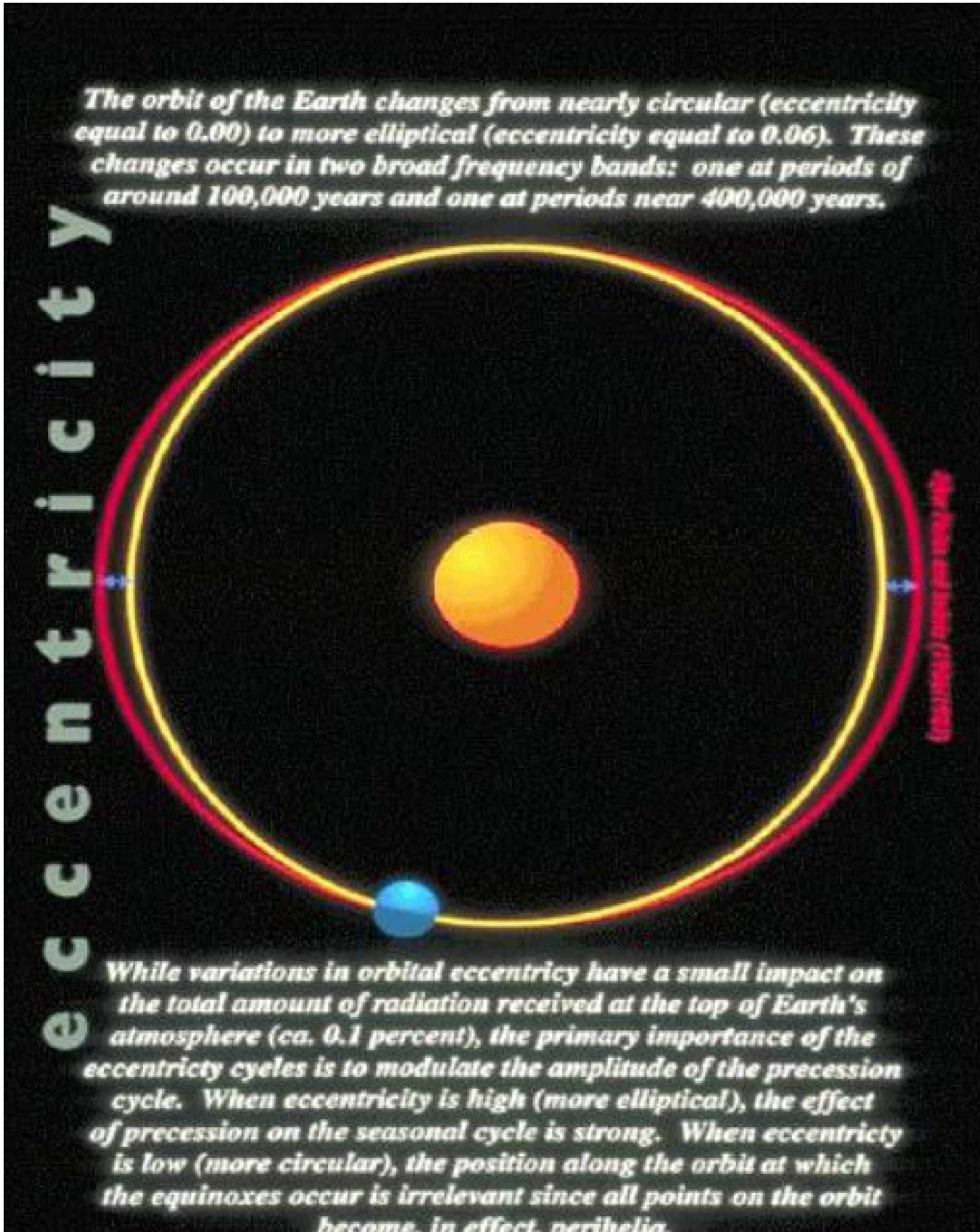
Eccentricity – global monthly mean TOA SW

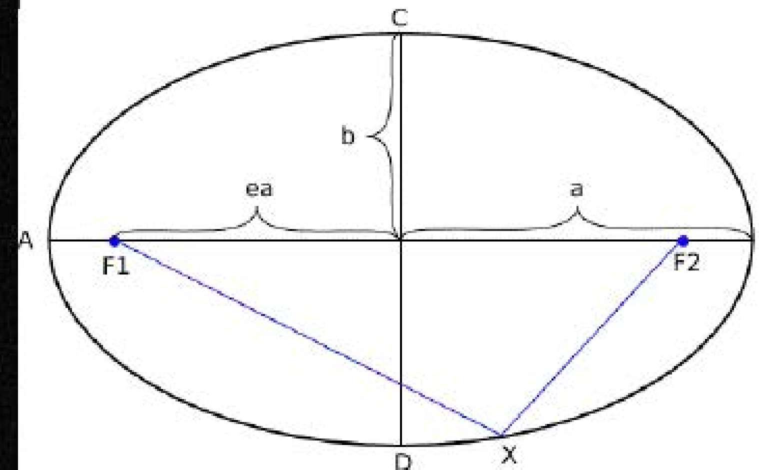
Latitude



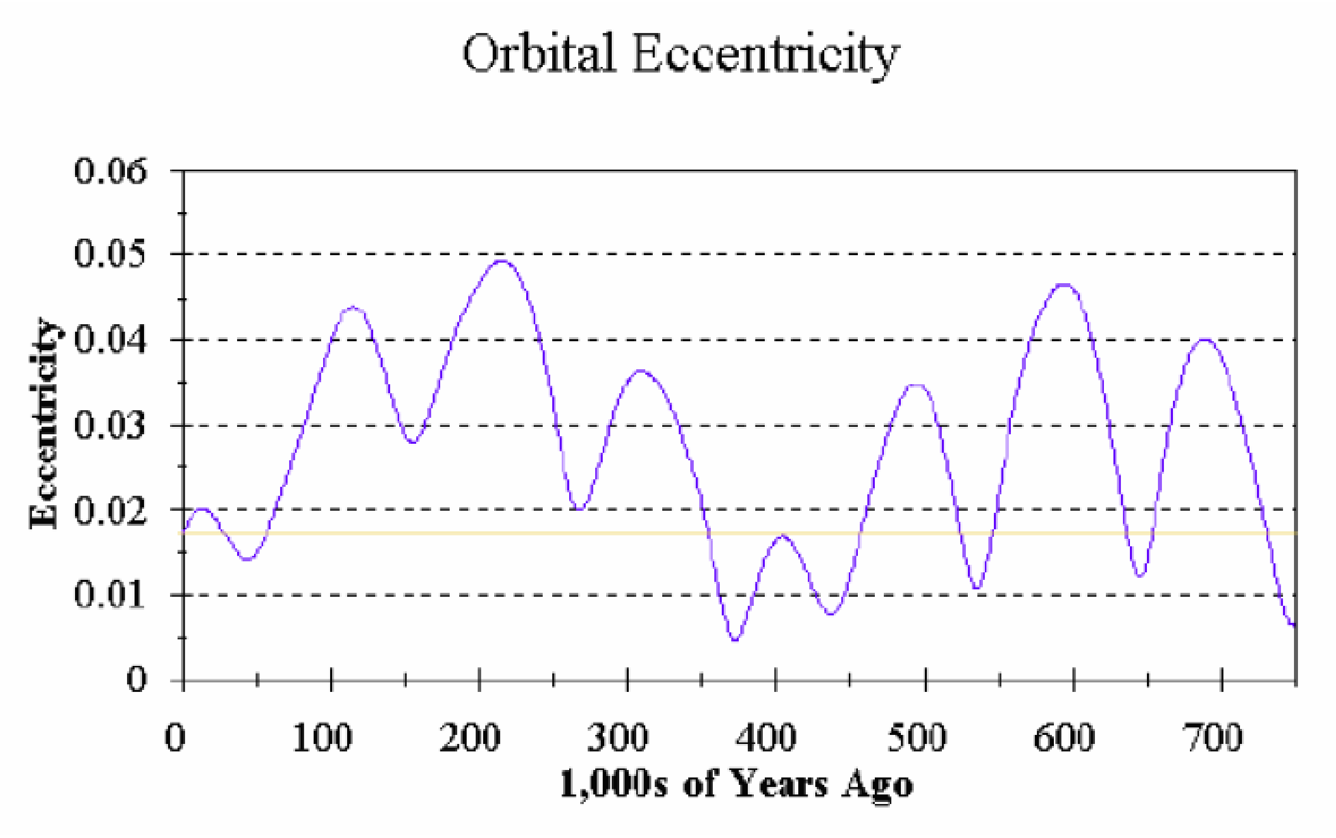
Based on ERBE data Time of year

Eccentricity





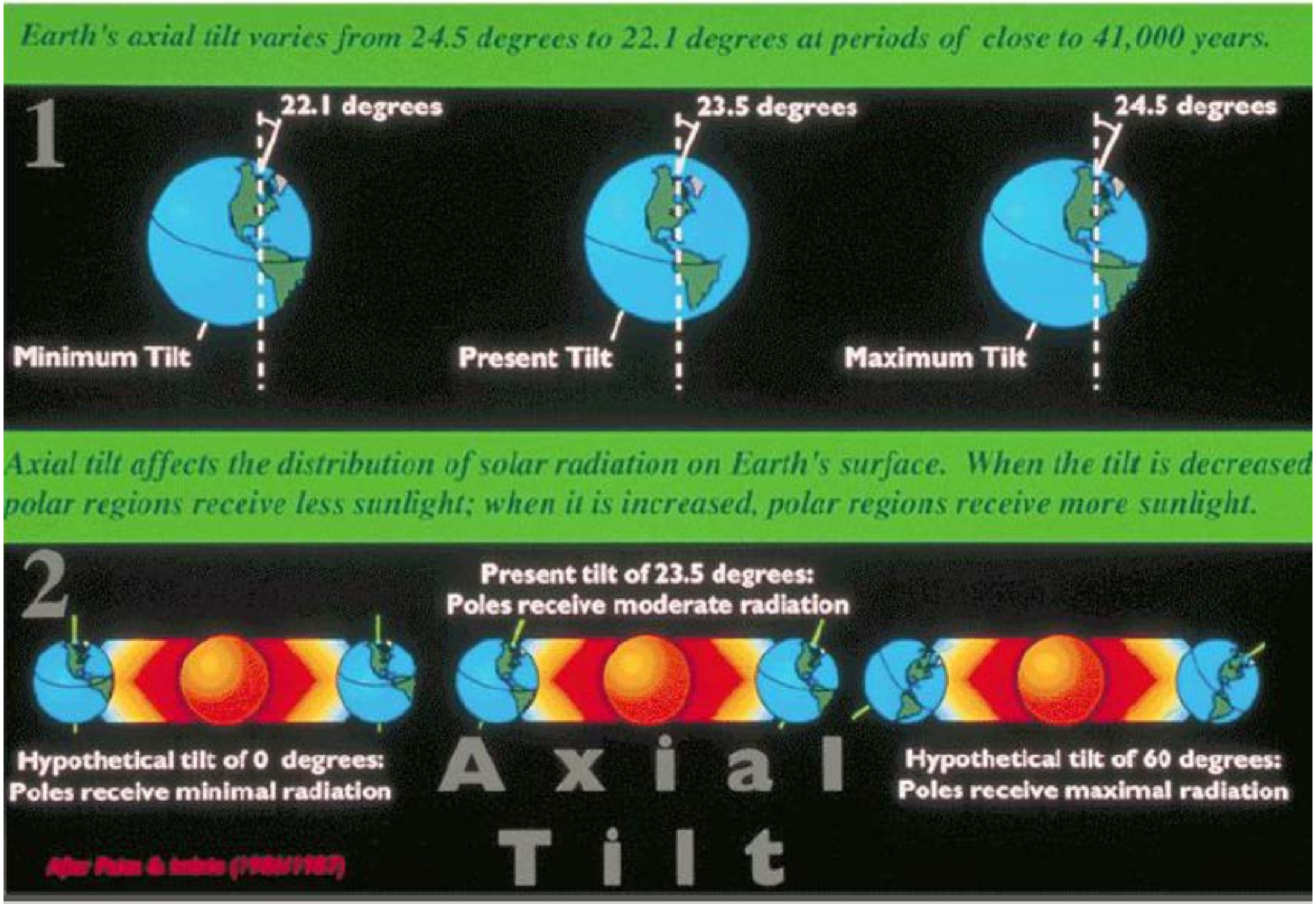
$$e = \sqrt{1 - \frac{b^2}{a^2}}.$$

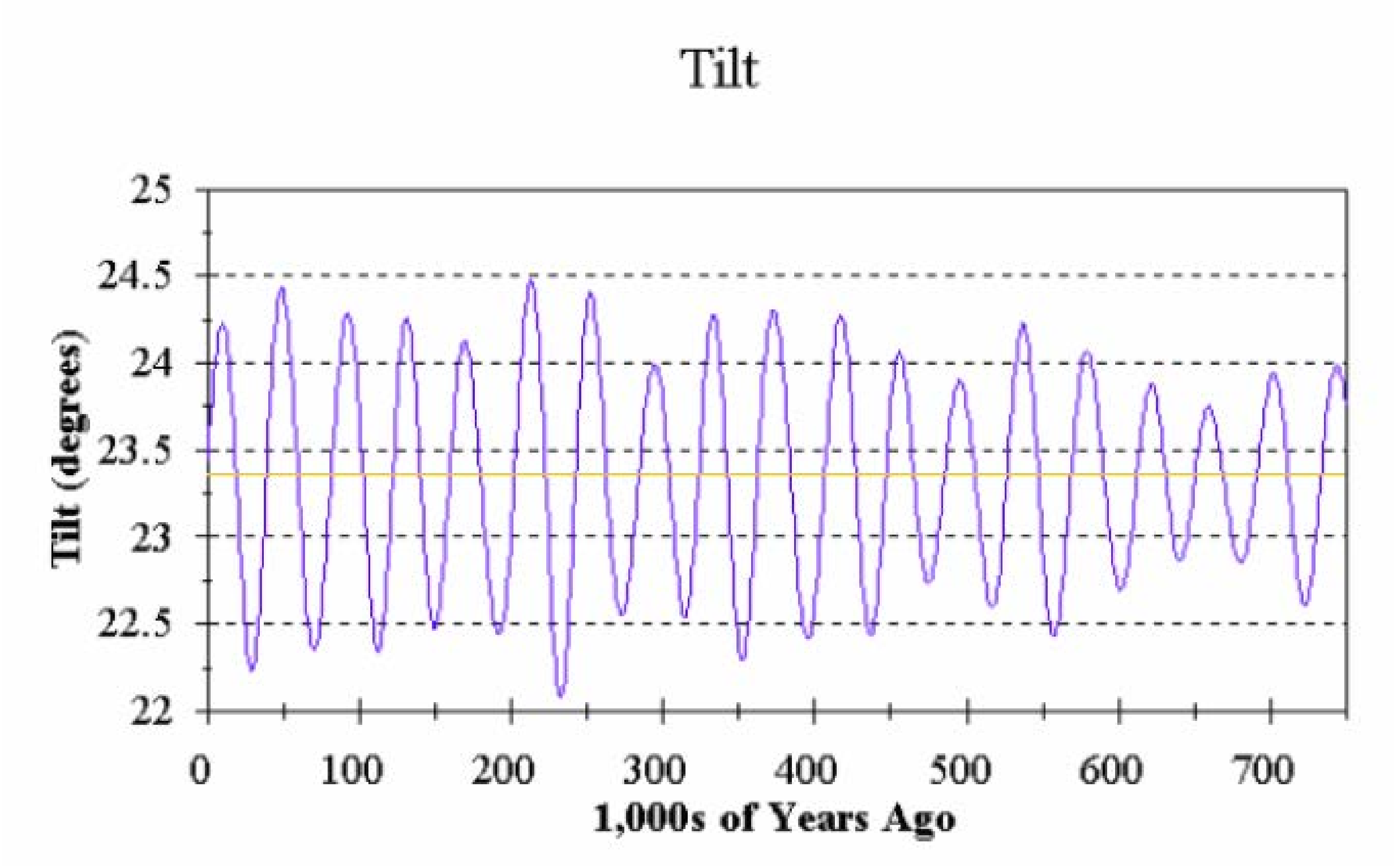


100Kyr and 400Kyr periodicities. Small variations of 0.01% in insolation.

Eccentricty affects the global mean annual mean insolation.

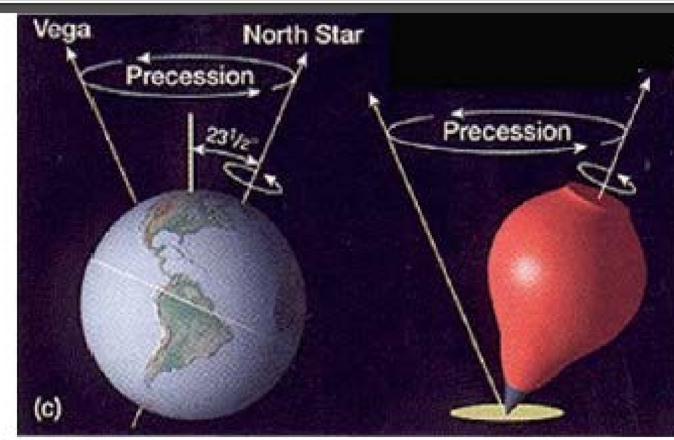
obliquity


Earth's axial tilt varies from 24.5 degrees to 22.1 degrees at periods of close to 41,000 years.
1
22.1 degrees
23.5 degrees
24.5 degrees
Minimum Tilt
Present Tilt
Maximum Tilt
Axial tilt affects the distribution of solar radiation on Earth's surface. When the tilt is decreased polar regions receive less sunlight; when it is increased, polar regions receive more sunlight.
2
Present tilt of 23.5 degrees:
Poles receive moderate radiation
Hypothetical tilt of 0 degrees:
Poles receive minimal radiation
Axial Tilt
Hypothetical tilt of 60 degrees:
Poles receive maximal radiation

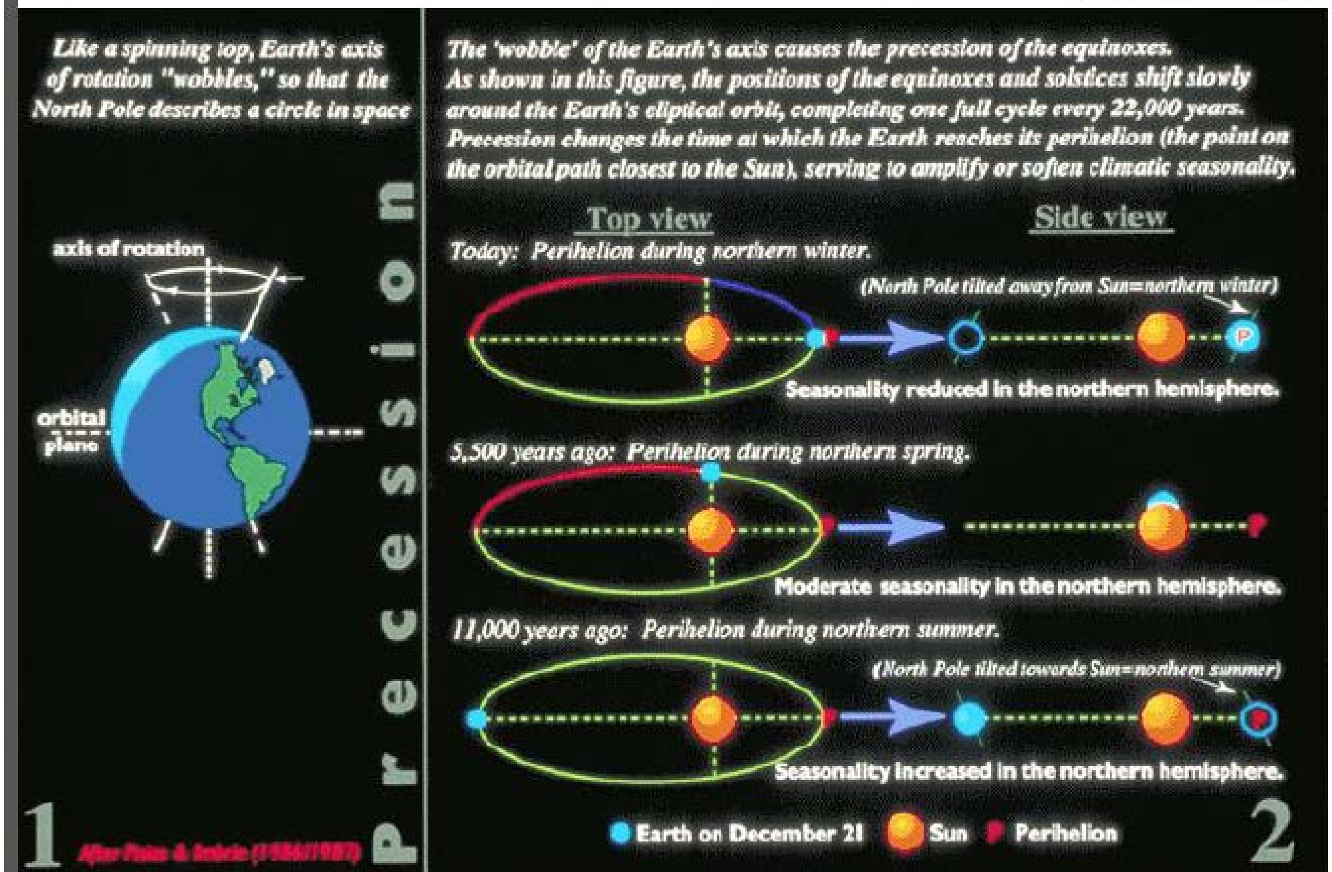


41Kyr periodicity dominant.
Latitude of peak insolation moves about 1km each century.
Global mean annual mean insolation unaffected, but high latitude insolation (important for ice sheet formation) varies strongly

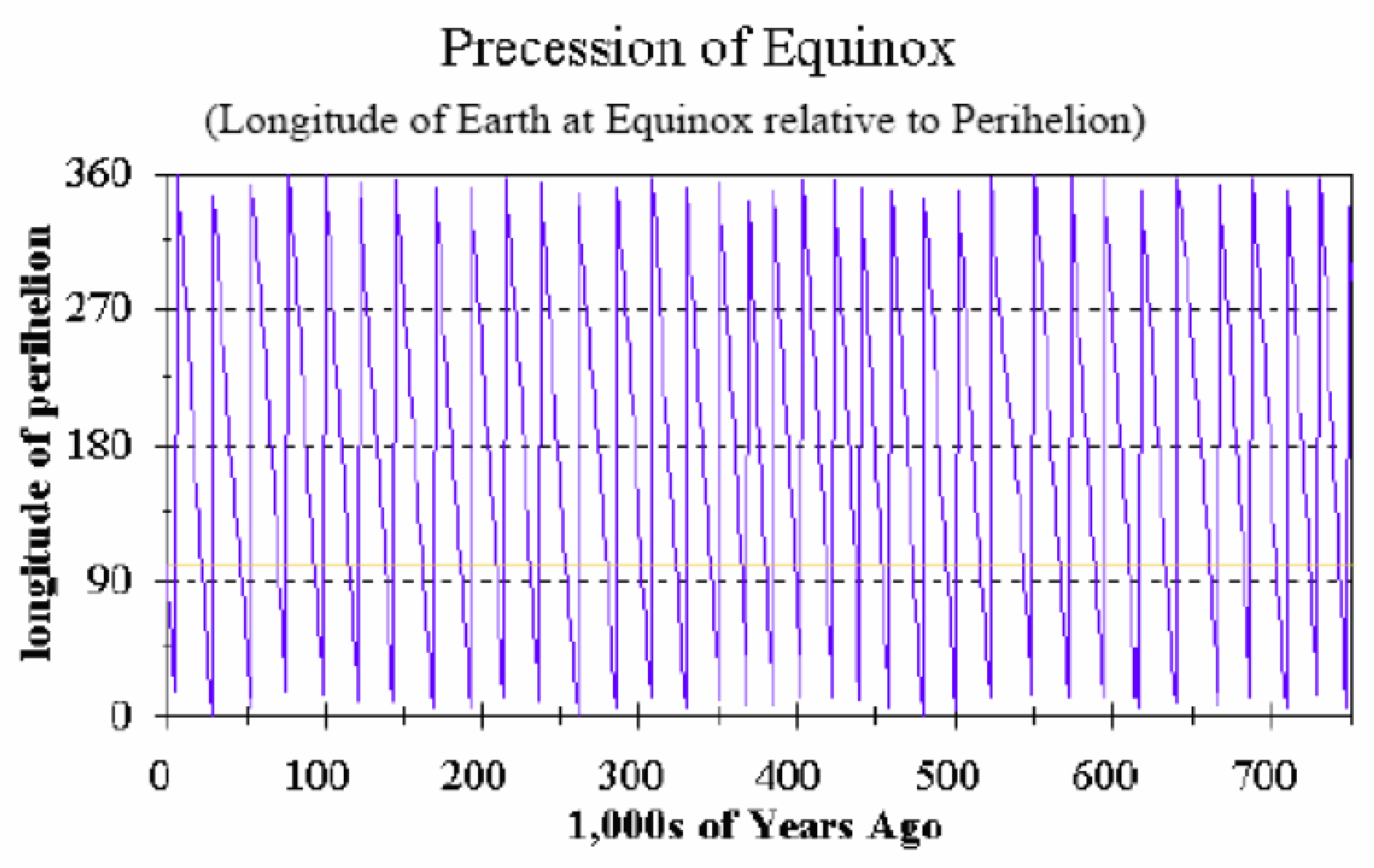
Precession



Vega
North Star
Precession
23½°
Precession
(c)

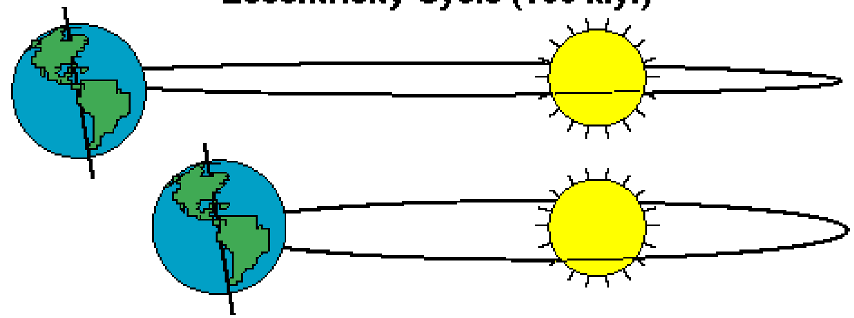


Like a spinning top, Earth's axis of rotation "wobbles," so that the North Pole describes a circle in space
axis of rotation
orbital plane
Precession
1
The 'wobble' of the Earth's axis causes the precession of the equinoxes. As shown in this figure, the positions of the equinoxes and solstices shift slowly around the Earth's eliptical orbit, completing one full cycle every 22,000 years. Precession changes the time at which the Earth reaches its perihelion (the point on the orbital path closest to the Sun), serving to amplify or soften climatic seasonality.
Top view
Side view
Today: Perihelion during northern winter.
(North Pole tilted away from Sun=northern winter)
P
Seasonality reduced in the northern hemisphere.
5,500 years ago: Perihelion during northern spring.
Moderate seasonality in the northern hemisphere.
11,000 years ago: Perihelion during northern summer.
(North Pole tilted towards Sun=northern summer)
Seasonality increased in the northern hemisphere.
Earth on December 21
Sun
Perihelion
2

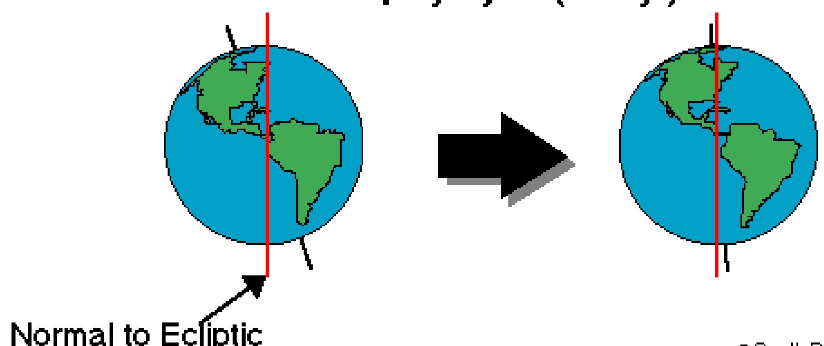


23Kyr and 19Kyr periodicities (low resolution peak of 22Kyr)
Global mean annual mean insolation unaffected.
Insolation depends on combination of eccentricity *e* and precession angle *w* : e *sin(w)*

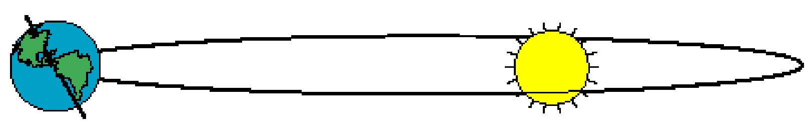
Eccentricity Cycle (100 k.y.)



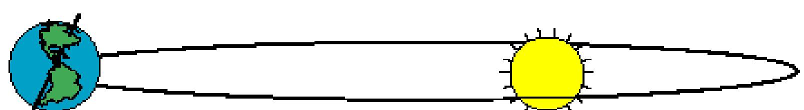
Obliquity Cycle (41 k.y.)



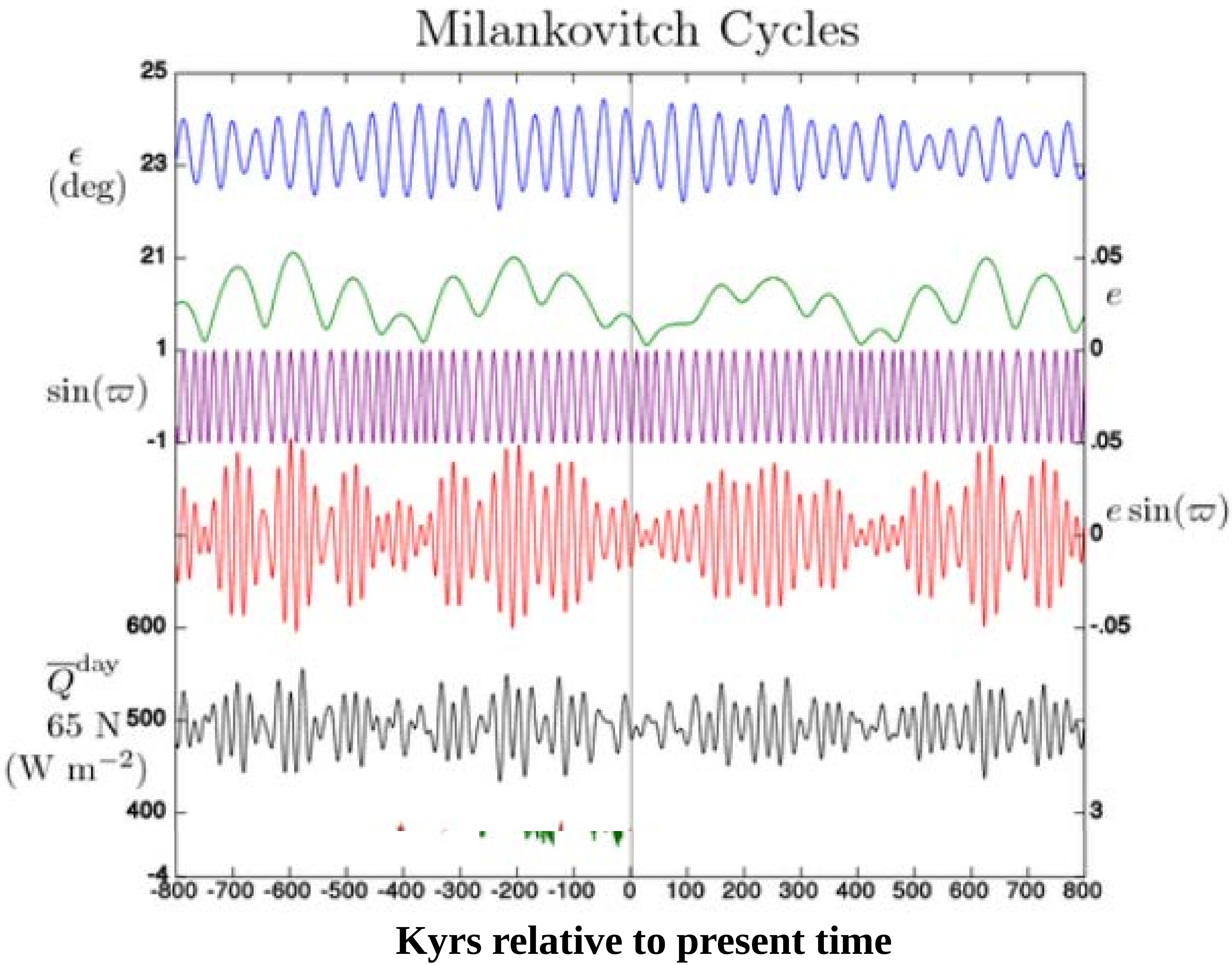
Precession of the Equinoxes (19 and 23 k.y.)



Northern Hemisphere tilted away from the sun at aphelion.

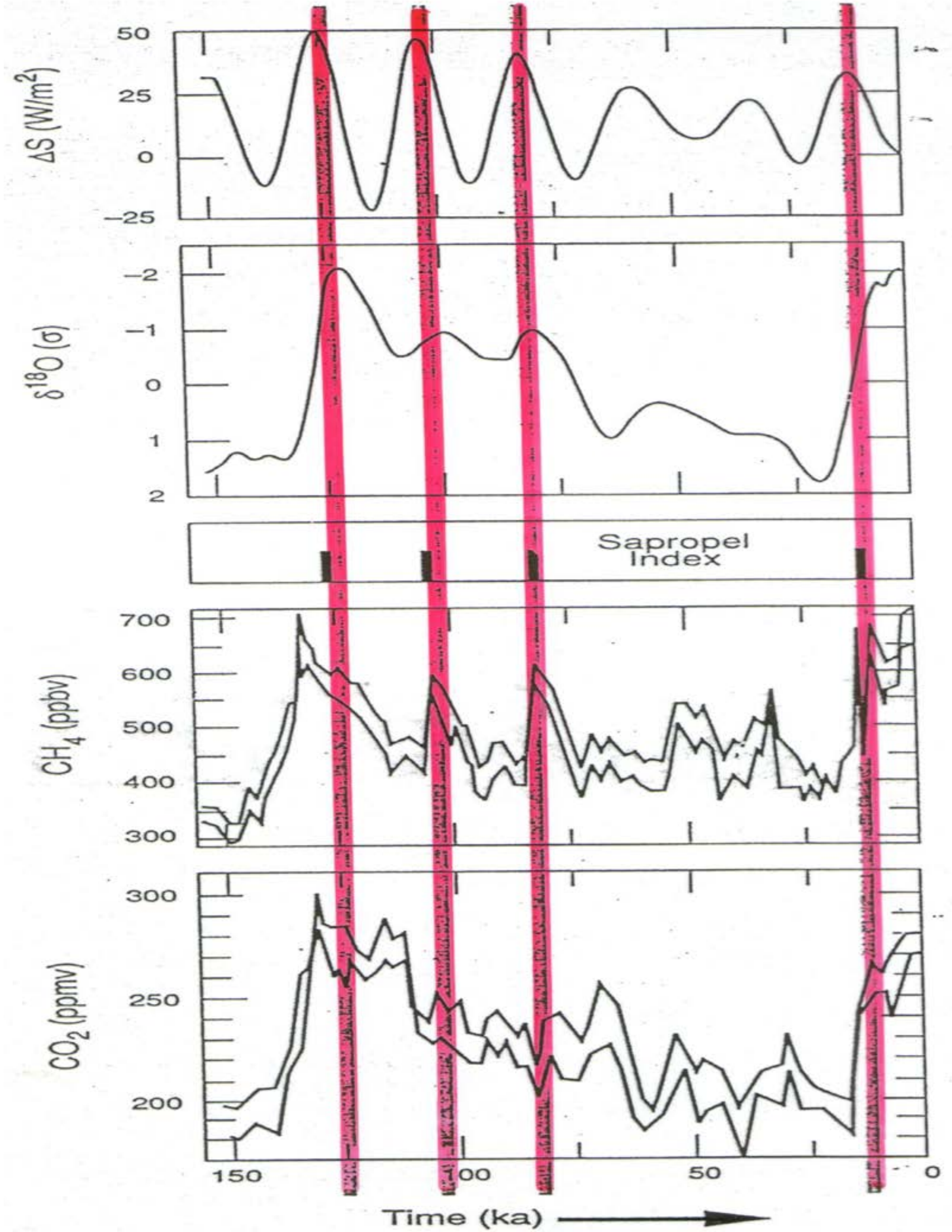


Northern hemisphere tilted toward the sun at aphelion.



We are at a period of minimum eccentricity.

Is Milankovich's theory of influence on climate correct?



NH summer radiation

Volume of continental ice

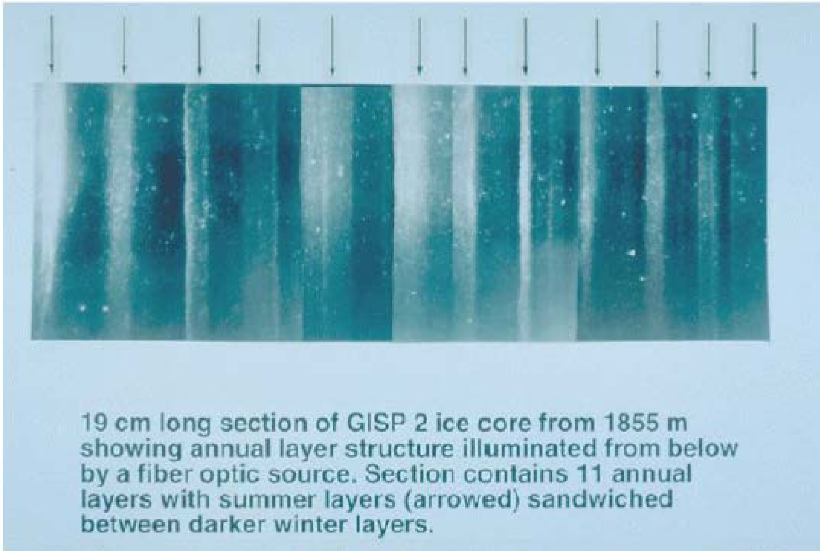
Strength of African Monsoon

Methane concentrations from Vostok

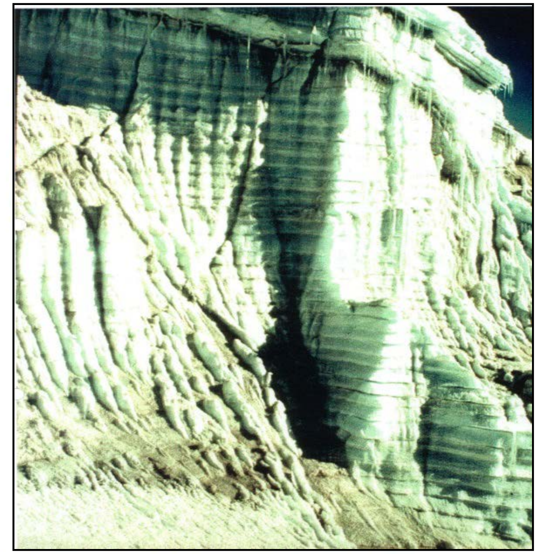
CO_2 concentrations from Vostok

Ice Cores

Example: 19cm representing 11 years



19 cm long section of GISP 2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.



Can analyze both water and air bubbles

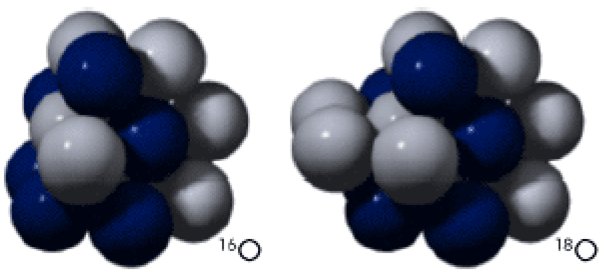
Analyze trace gases (CO_2, CH_4) in bubbles in ice.
Determine temperature from oxygen isotopes (O^{18}/O^{16} ratios).
Useful in Greenland and Antarctica
Length of layered records: 10,000 up to 600,000 years or more for temperature, trace gases and accumulation.

Isotopic Evidence

- Most elements have several stable isotopes, differing only by the number of neutrons and hence the weight of the atom and the molecule of which it is a part.

- For example: water, H_2O, can contain isotopes of hydrogen and oxygen.

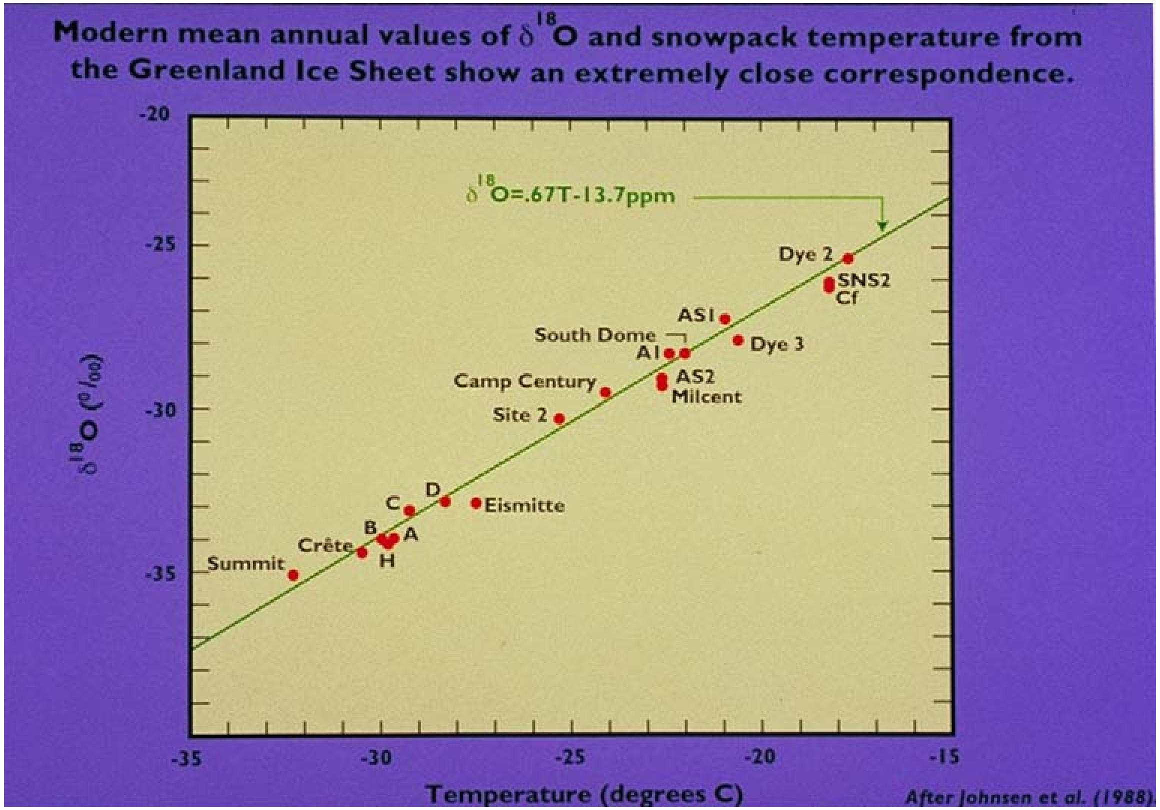
- Hydrogen has H^1 and H^2=D=deuterium
- Oxygen has O^{16} (99.762%), O^{17} and O^{18}.
- Carbon has C^{12} (98.93%), C^{13} and C^{14} (C^{14} is radioactive with a half life of 5,730 years. It's made from Nitrogen.)



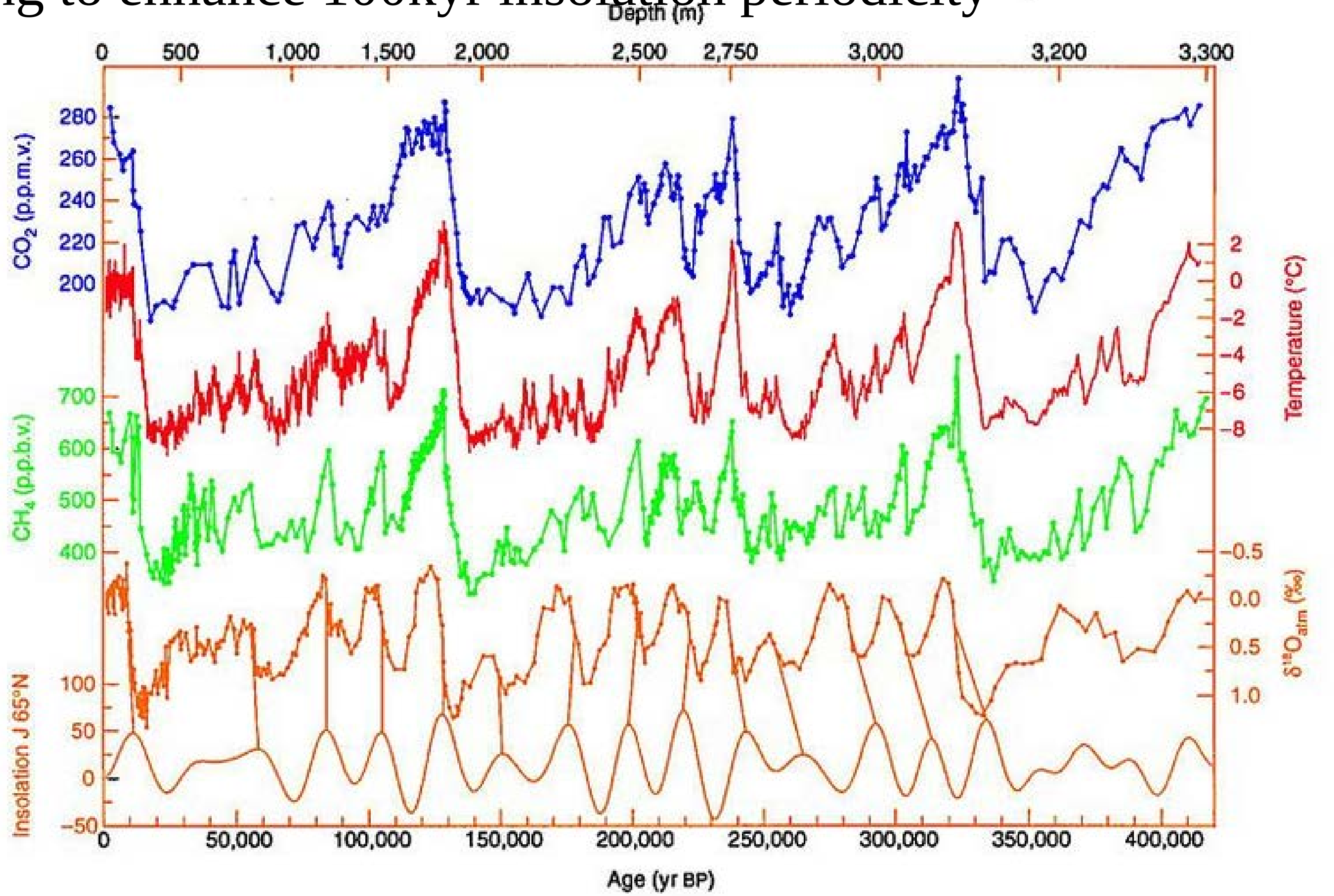
$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) \times 1000\,‰$$

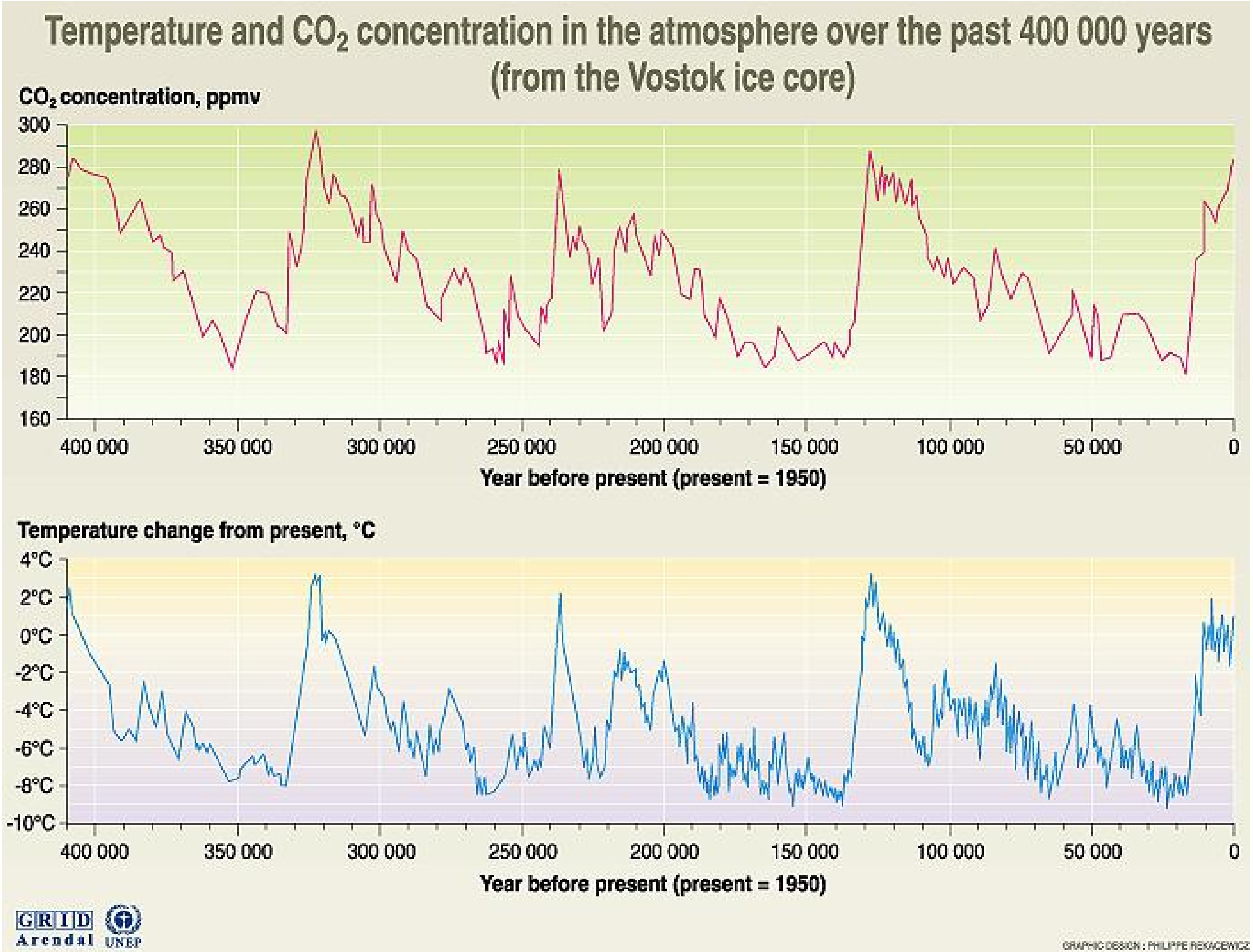
Measure anomaly from Standard Mean Ocean Water (SMOW)

This ratio is sensitive to sea temperature, and to global ice volume. ^{16}O evaporates more easily



Vostok ice core: Temperature, CO2, methane and ice volume vary together, driven by insolation, with feedbacks acting to enhance 100kyr insolation periodicity

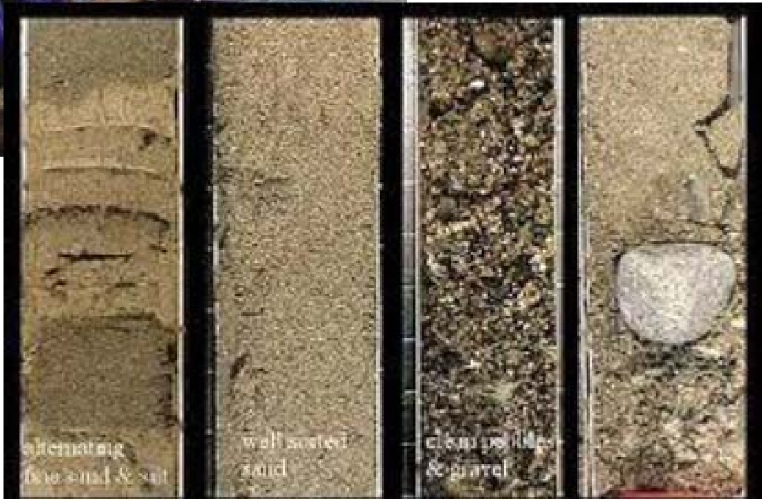




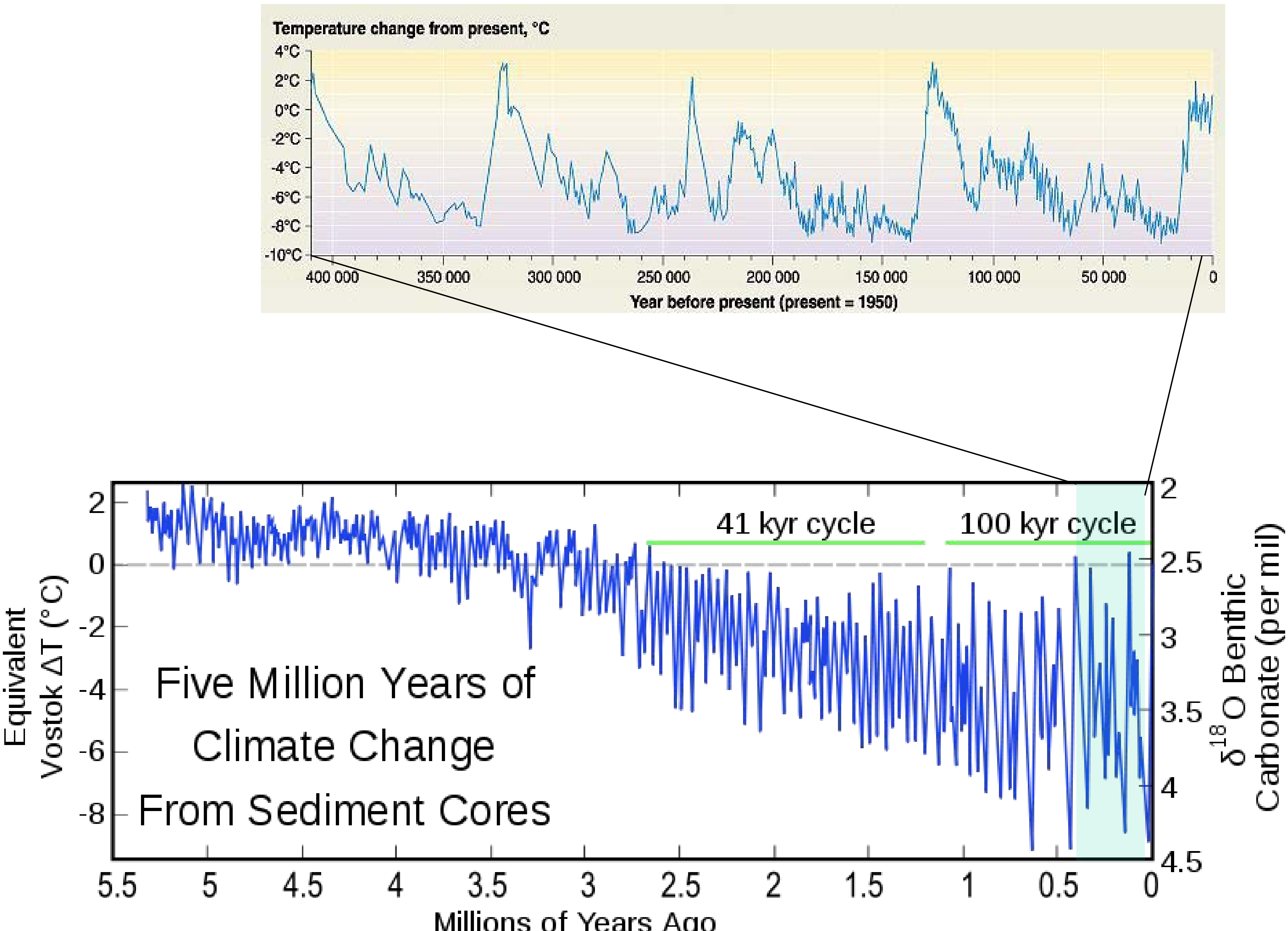
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

Lets put this in longer context – go back further in time.

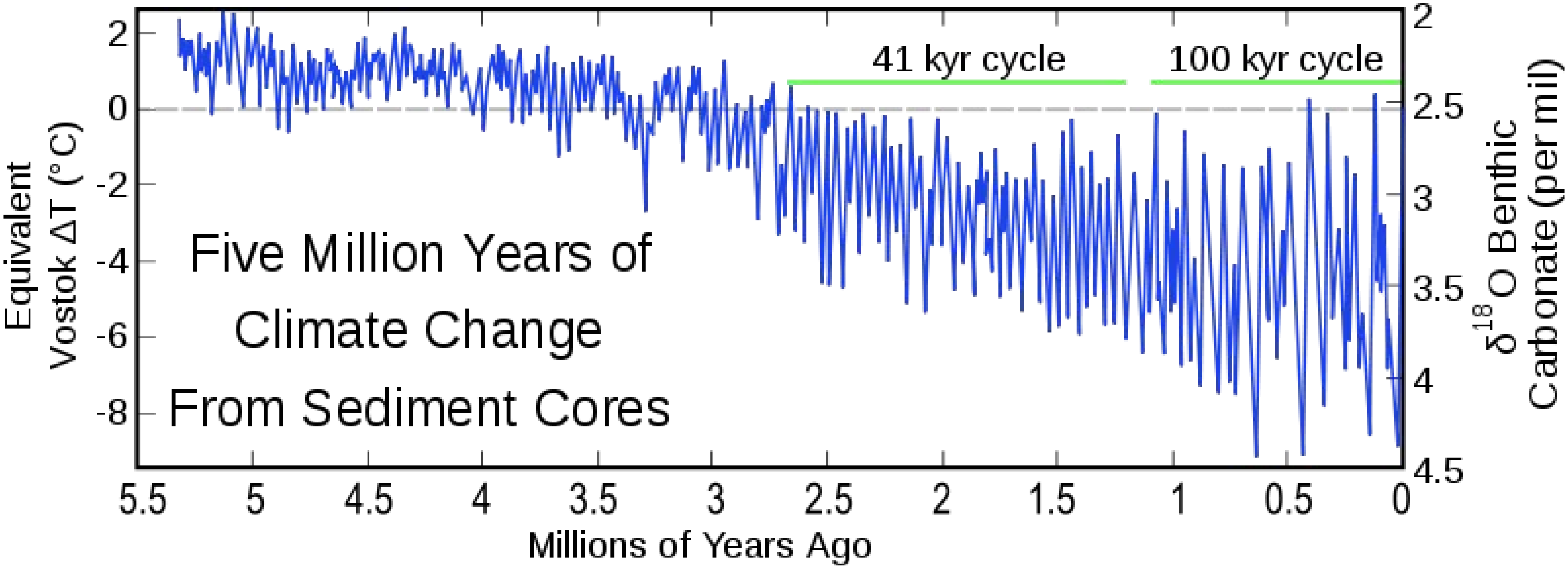
Ocean Sediment Cores

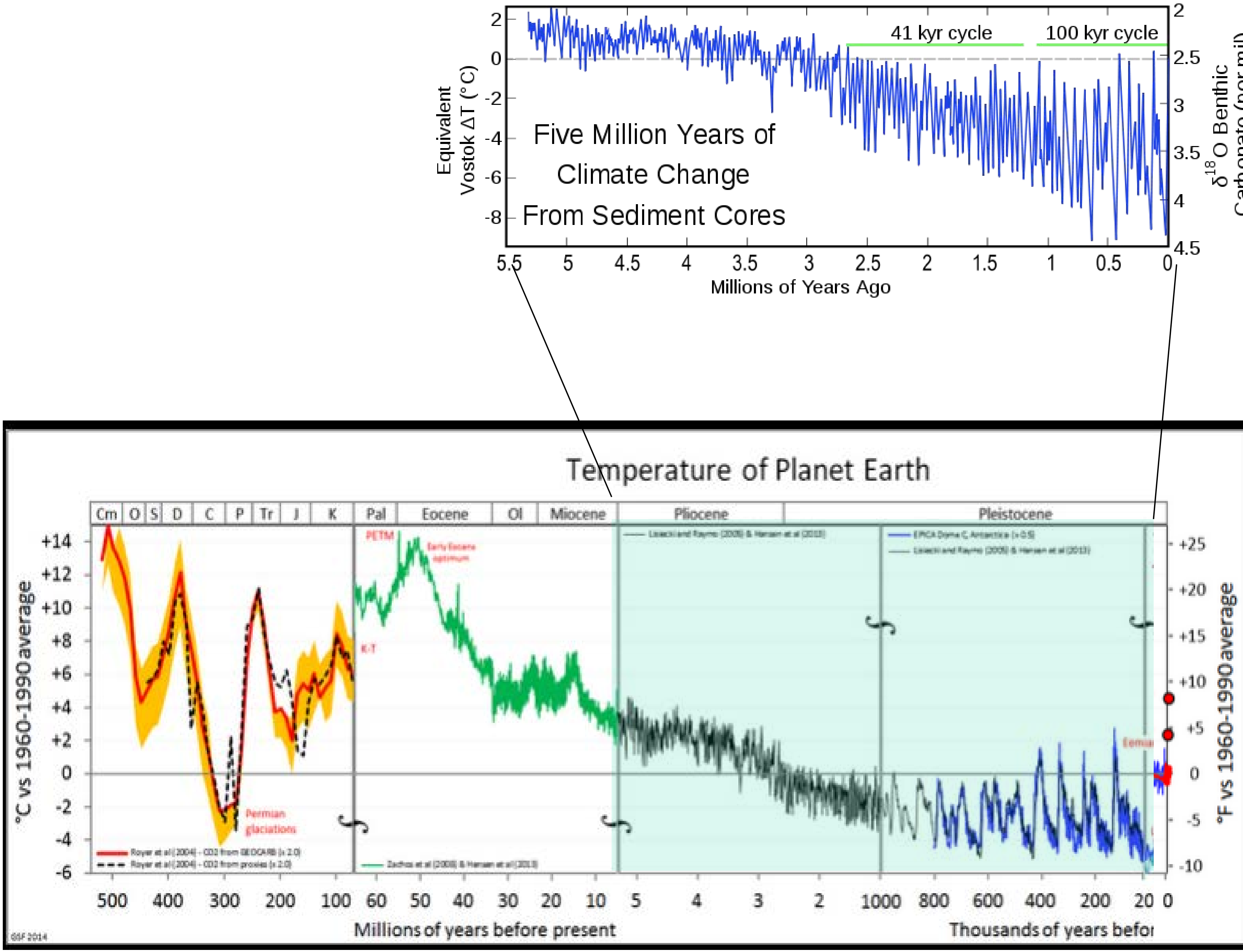


Find little dead creatures, and analyze their composition and deduce things from the relative abundance of different types


Temperature change from present, °C
4°C
2°C
0°C
-2°C
-4°C
-6°C
-8°C
-10°C
400 000
350 000
300 000
250 000
200 000
150 000
100 000
50 000
0
Year before present (present = 1950)
41 kyr cycle
100 kyr cycle
Equivalent Vostok ΔT (°C)
2
0
-2
-4
-6
-8
Five Million Years of Climate Change From Sediment Cores
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Millions of Years Ago
δ^{18}O Benthic Carbonate (per mil)
2
2.5
3
3.5
4
4.5

Earth has been cooling over the past 5.5 million years (My). Ice cycles started around 2.8 My ago, first with a periodicity of 41 Ky (obliquity), then changed to 100Kyrs around 1 My ago.

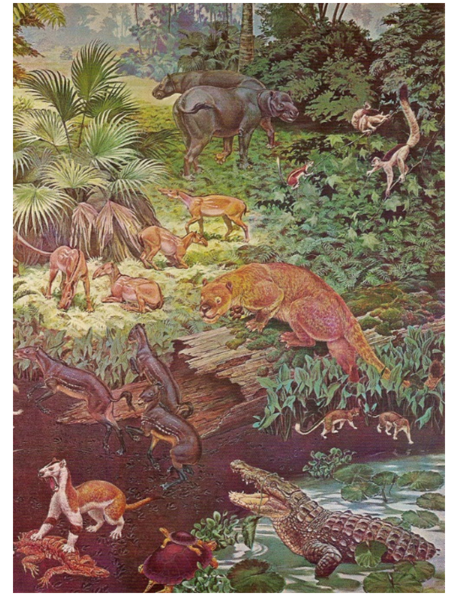


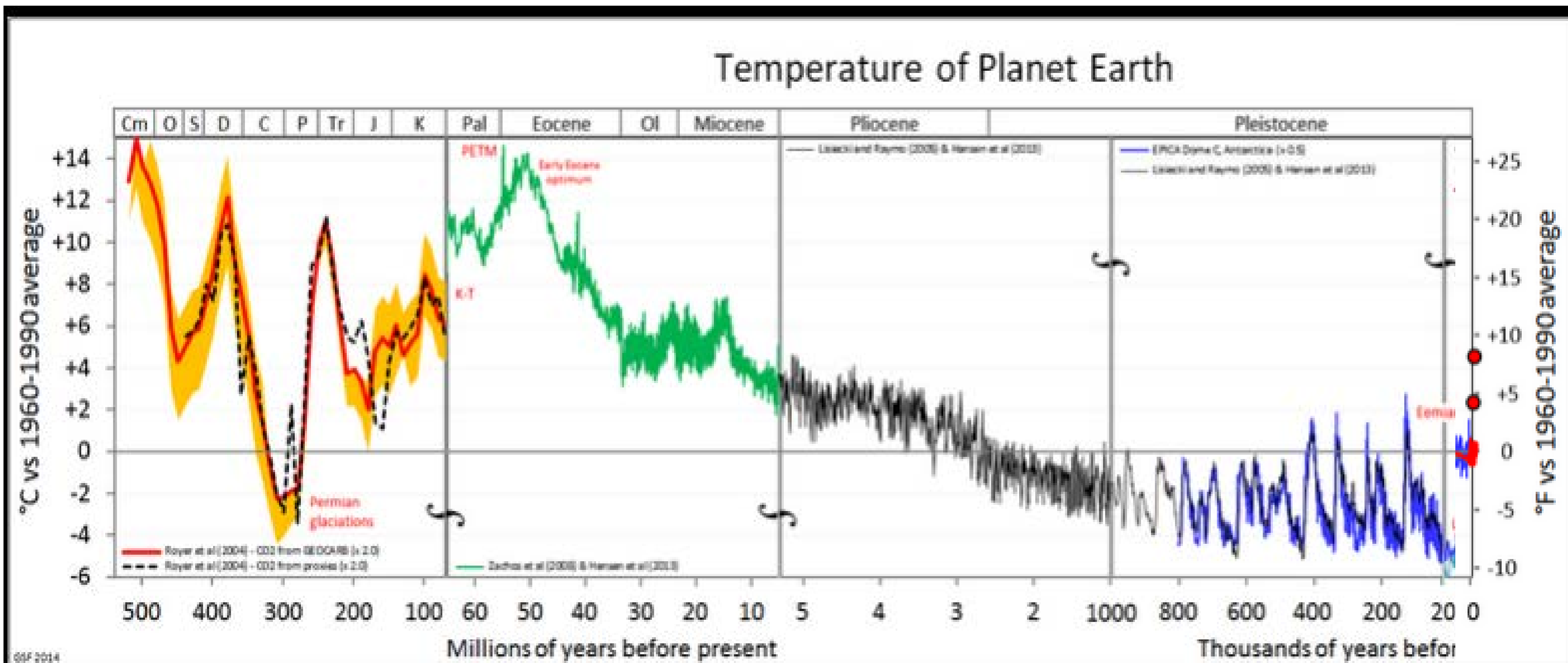


Five Million Years of Climate Change From Sediment Cores
Equivalent Vostok ΔT (°C)
δ18O Benthic Carbonate (per mil)
41 kyr cycle
100 kyr cycle
Millions of Years Ago
Temperature of Planet Earth
Cm O S D C P Tr J K Pal Eocene Ol Miocene Pliocene Pleistocene
PETM
K-T
Permian glaciations
°C vs 1960-1990average
°F vs 1960-1990average
Millions of years before present
Thousands of years befor

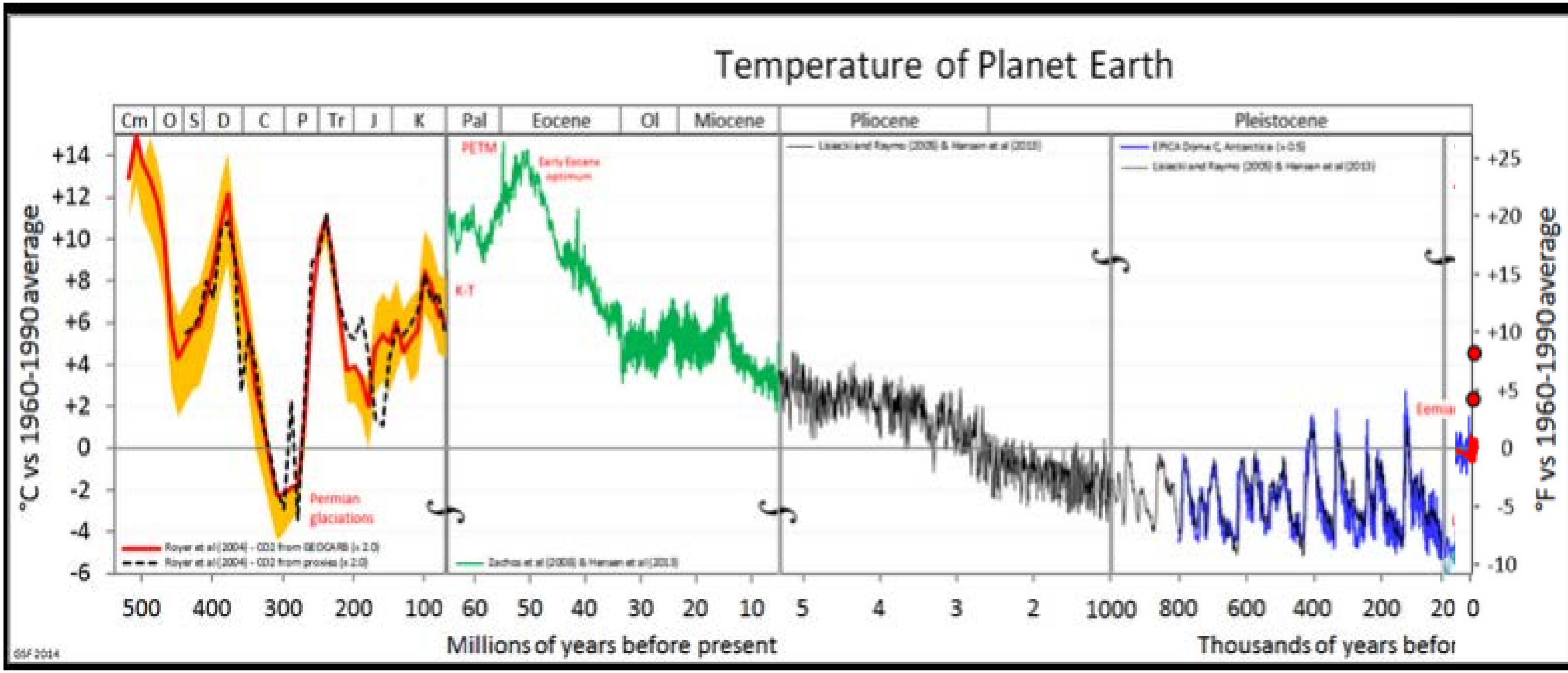
In fact Earth has been cooling over the past 50 My, and was warmest during the Eocene. CO_2 was higher than 500ppm

Tropical plants and animals in North America

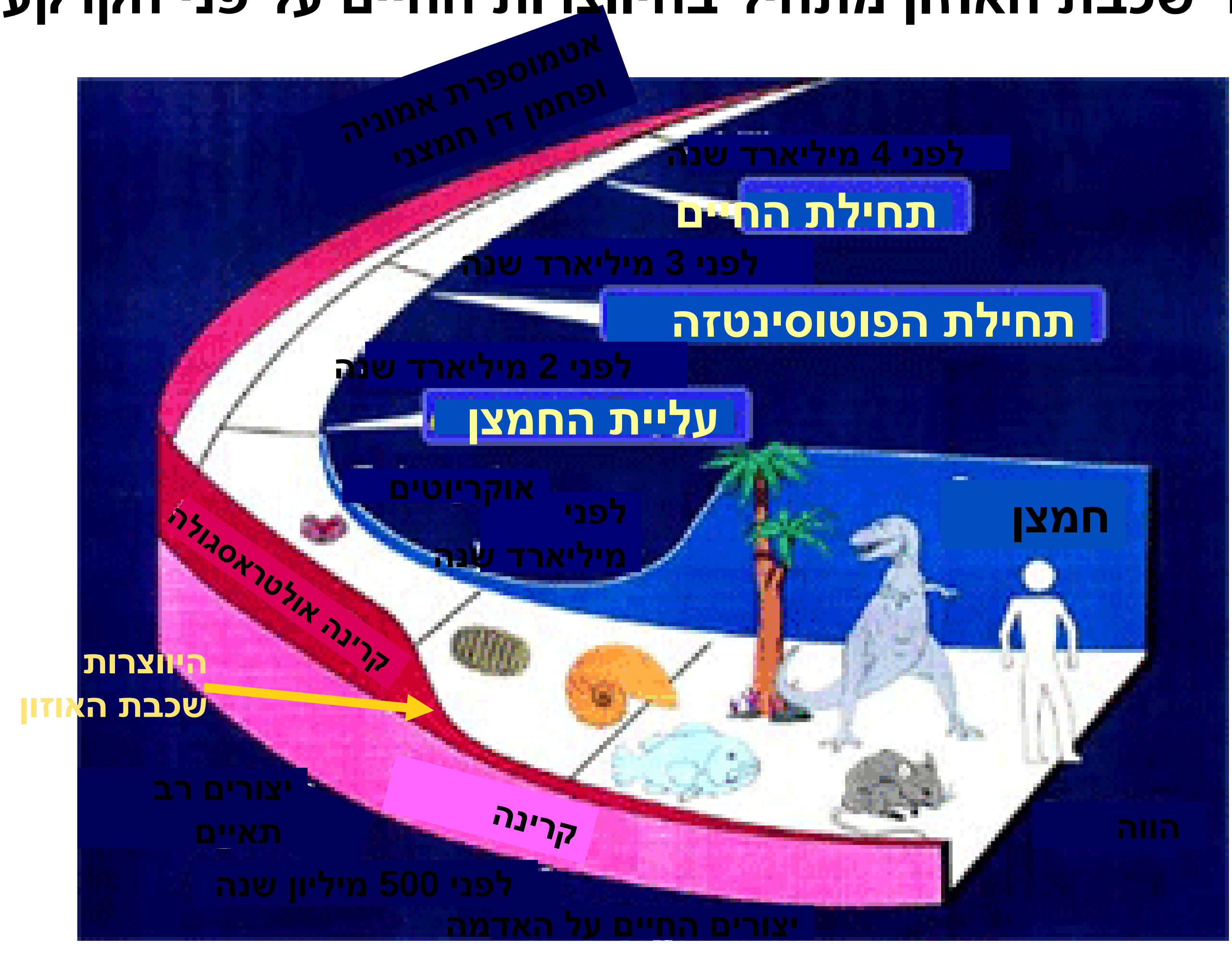




There was a prolonged ice age around 260-360My ago – the Karoo ice age. This is thought to be related to the reduction of CO_2 following the evolution of land plants and increase of oxygen in the atmosphere



סיפור שכבת האוזון מתחיל בהיווצרות החיים על פני הקרקע



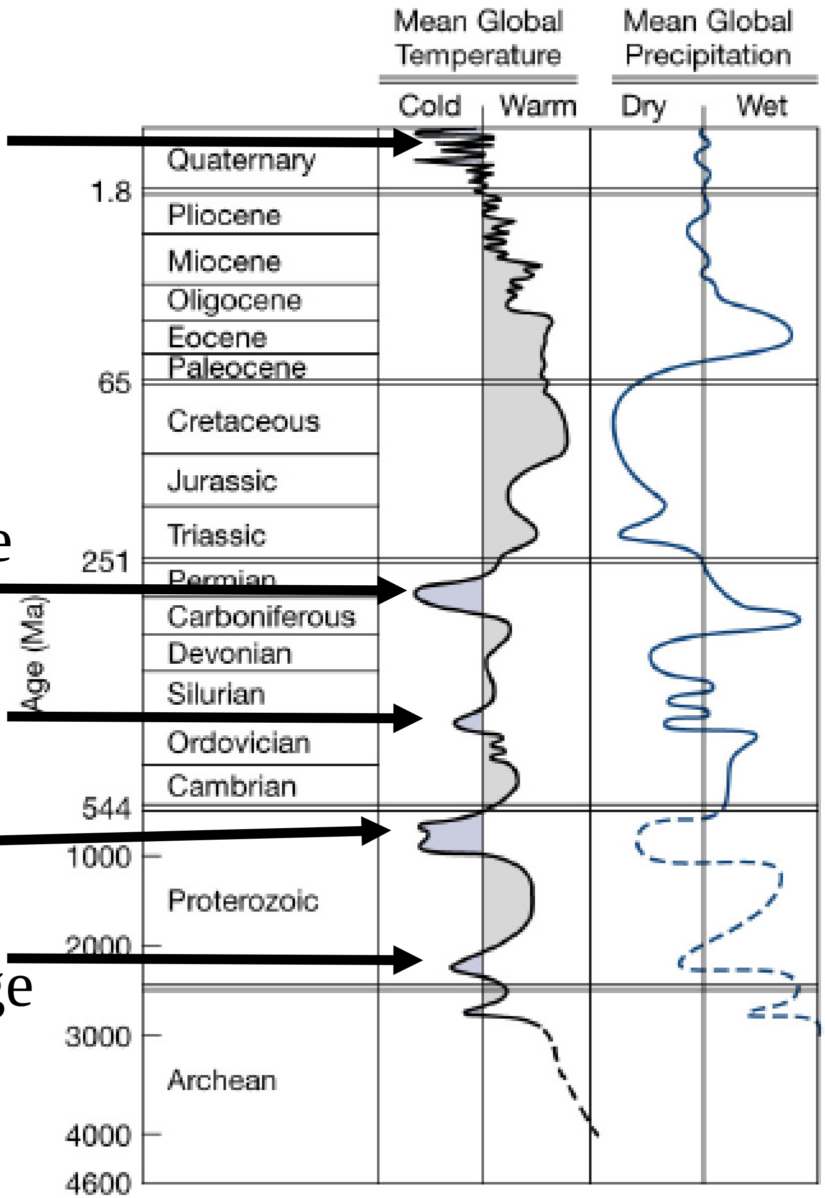
Quaternary ice ages

The Karoo Ice age

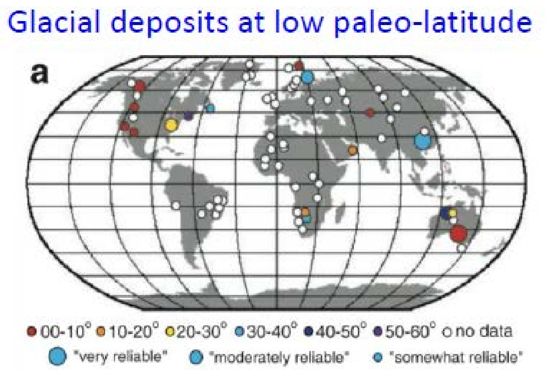
Andean-Saharan ice age

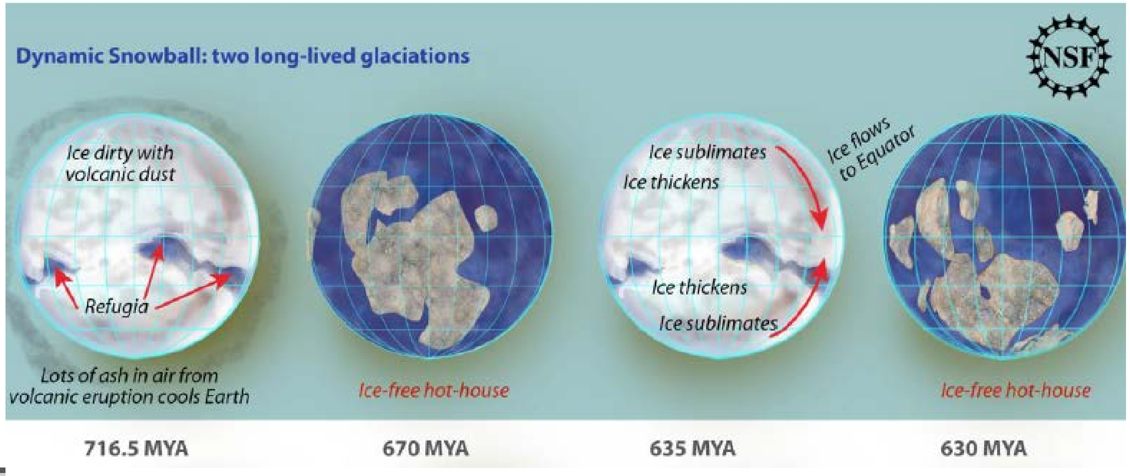
Cryogenian ice age:
Snowball earth

Huronian ice age

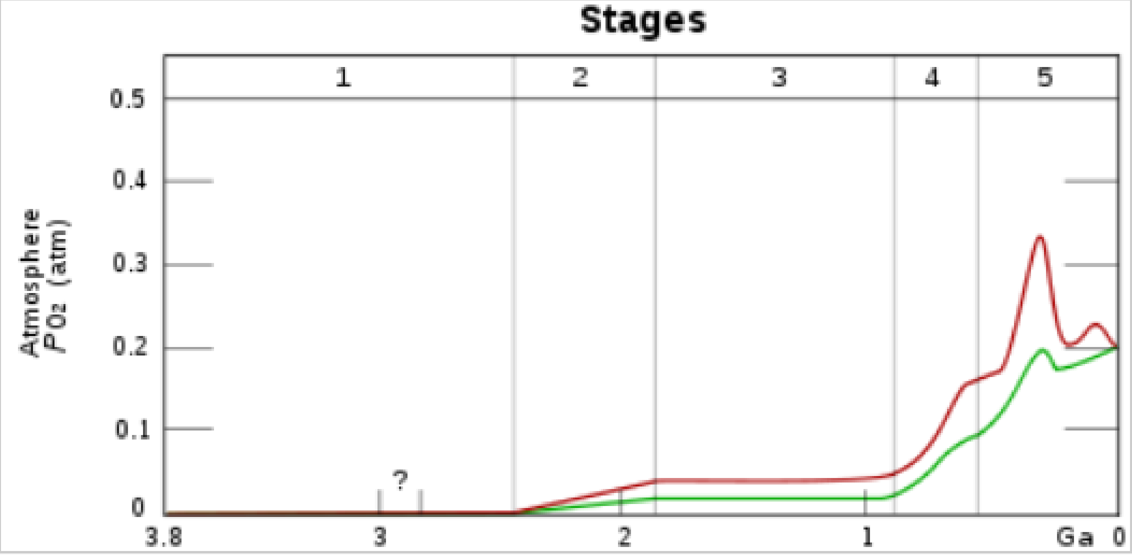


Snowball Earth: during the Cryogenian ice age – 630-850 My ago – there was at least one period, maybe 2-3 during which the Earths surface was covered with ice. Still debated if fully ice covered or not so at equator.





The earliest Huronian ice age- may have been onset by Methane reduction following the Great Oxygenation Event around 2.3 Billion years ago

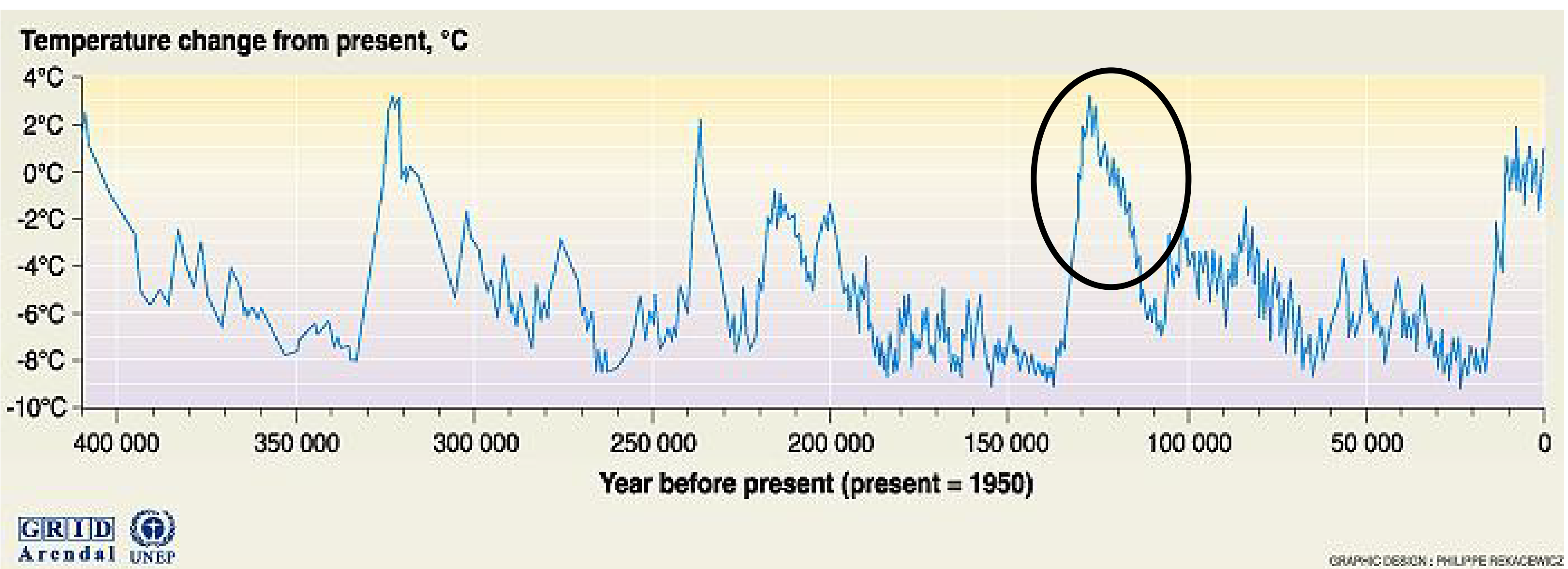


O_2 build-up in the Earth's atmosphere. Red and green lines represent the range of the estimates while time is measured in billions of years ago (Ga).
Stage 1 (3.85–2.45 Ga): Practically no O_2 in the atmosphere.
Stage 2 (2.45–1.85 Ga): O_2 produced, but absorbed in oceans & seabed rock.
Stage 3 (1.85–0.85 Ga): O_2 starts to gas out of the oceans, but is absorbed by land surfaces.
Stages 4 & 5 (0.85–present): O_2 sinks filled and the gas accumulates.[1]

Back to closer times the last interglacial, around 125Ky ago, (the Emian) was slightly warmer than present, and lasted around 10Kyr

Want to connect to present and to expected future natural variations

Emian interglacial



Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

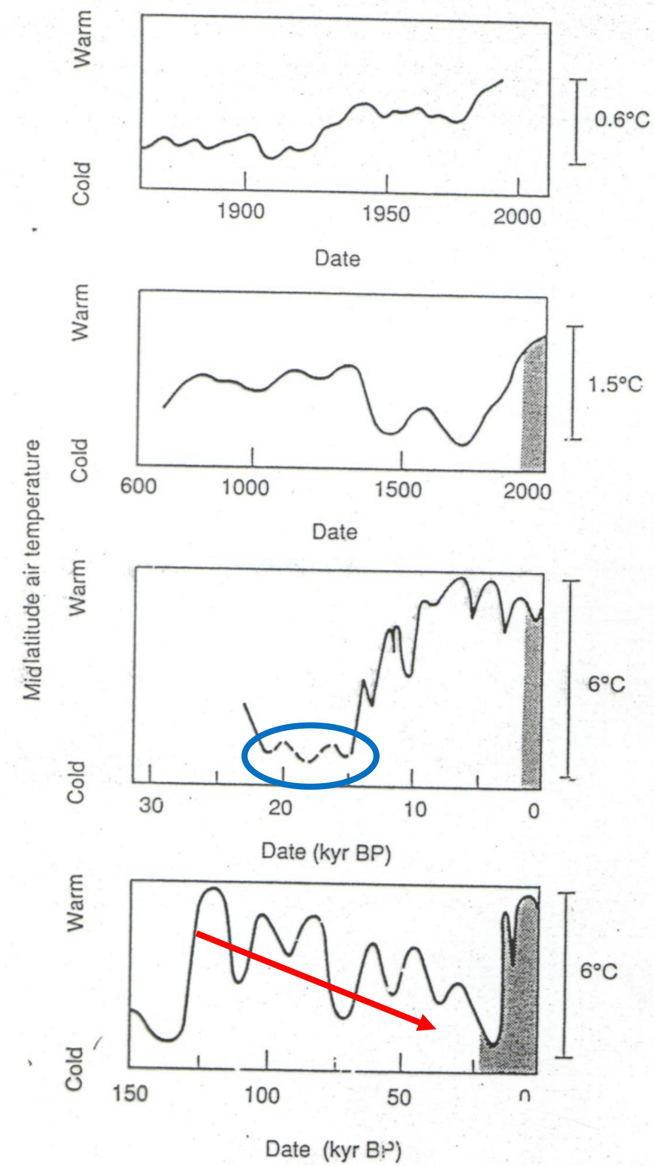
Recent Climate Changes (last 150 kyr)

115 kyr – 18 kyr: Generally declining temperatures superimposed with large fluctuations in the climate.

22-14 kyr: Last Ice Age, maximum ~18kyr ago.

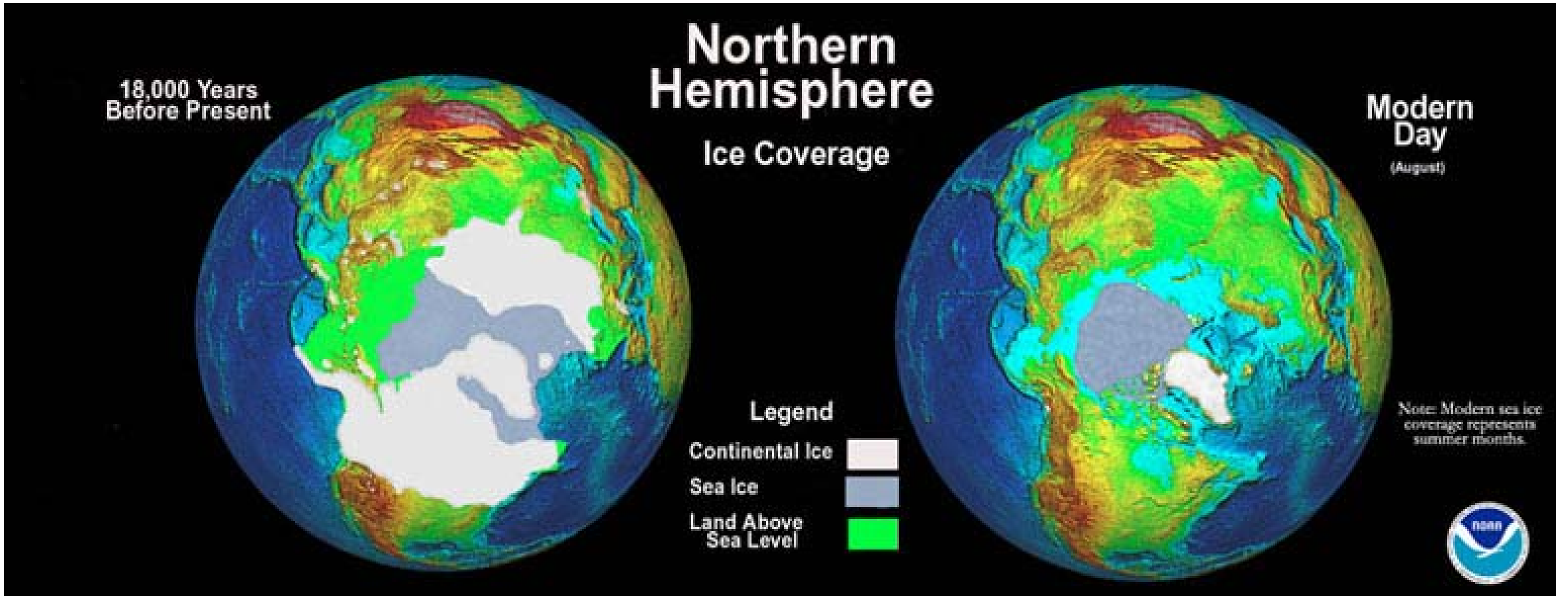
The "Laurentide Ice Sheet" over N. America and the Scandenavian Ice Sheet" over parts of Europe, reached a maximum extent 22-13kyr ago.

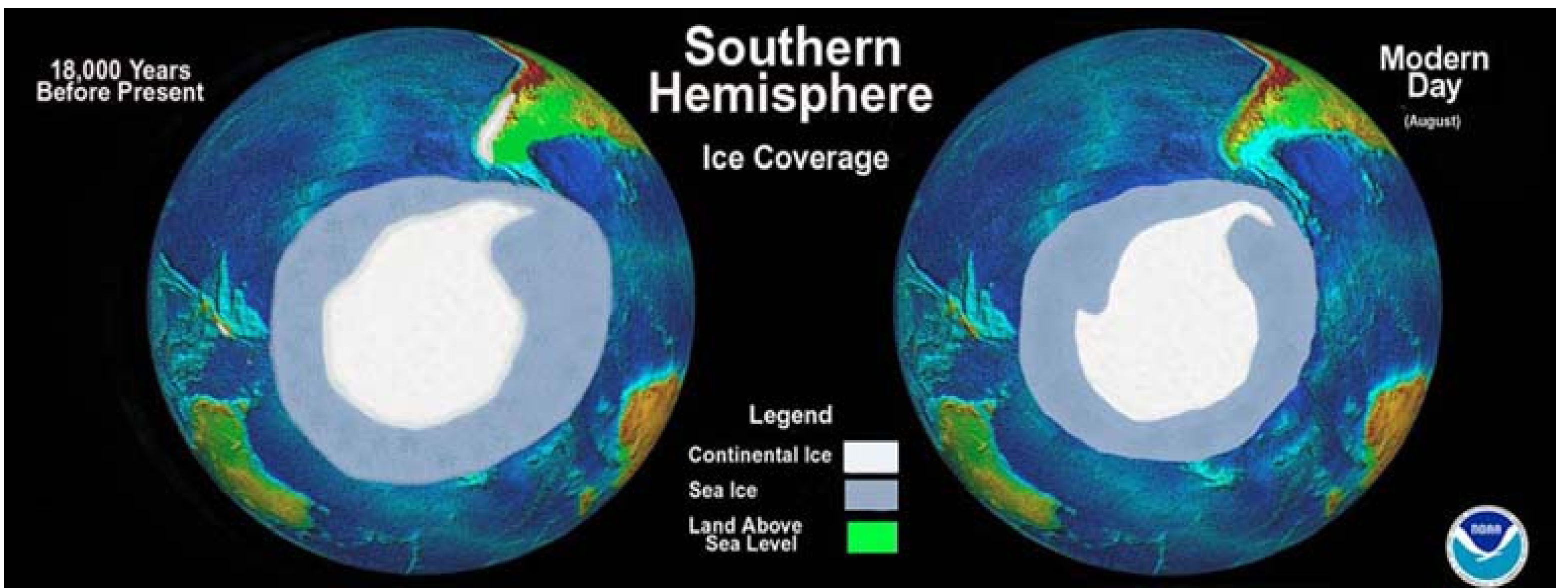
"Cordilleran Ice Sheet" over western N. America reached maximum 14kyr ago.



During the last ice age maximum:

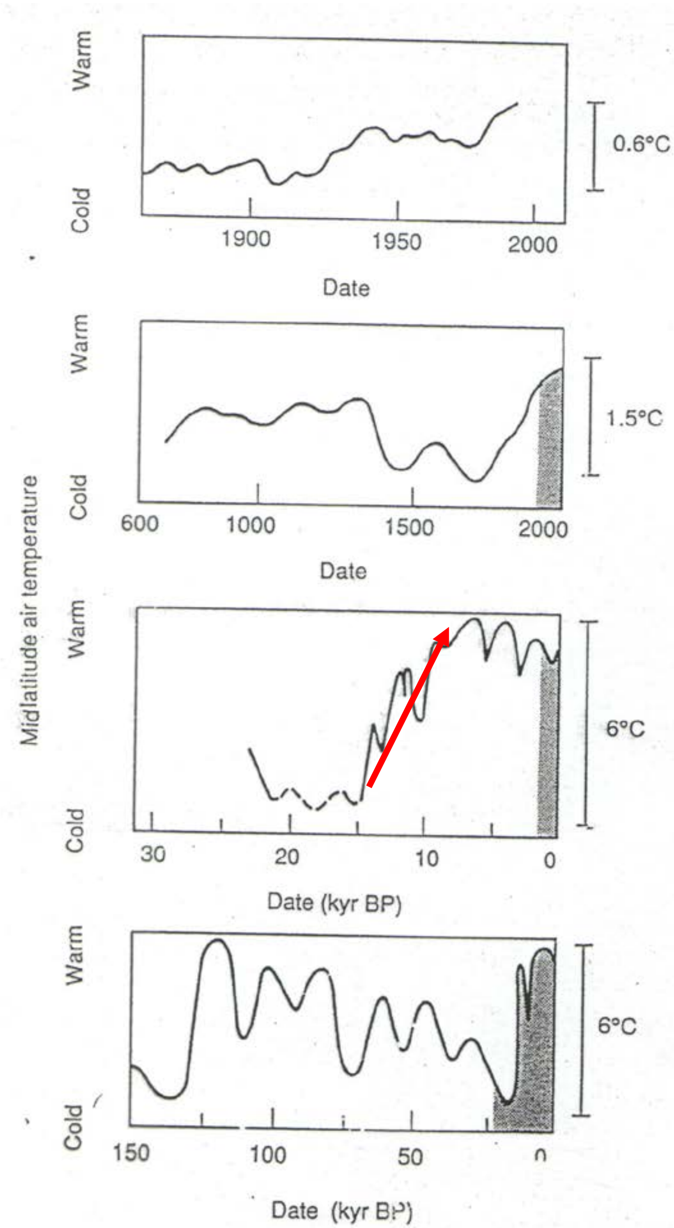
New York buried under 1 km of ice. Maximum area of NH ice sheets was ~90% of maximum ice cover during the last 1 MY. Sea level dropped ~85 m; sea surface temperatures (SST) fell as much as 10C in mid latitudes of the N. Atlantic, 3C in the Caribbean.


Northern Hemisphere
Ice Coverage
18,000 Years Before Present
Modern Day
(August)
Legend
Continental Ice
Sea Ice
Land Above Sea Level
Note: Modern sea ice coverage represents summer months.


Southern Hemisphere
Ice Coverage
18,000 Years Before Present
Modern Day
(August)
Legend
Continental Ice
Sea Ice
Land Above Sea Level

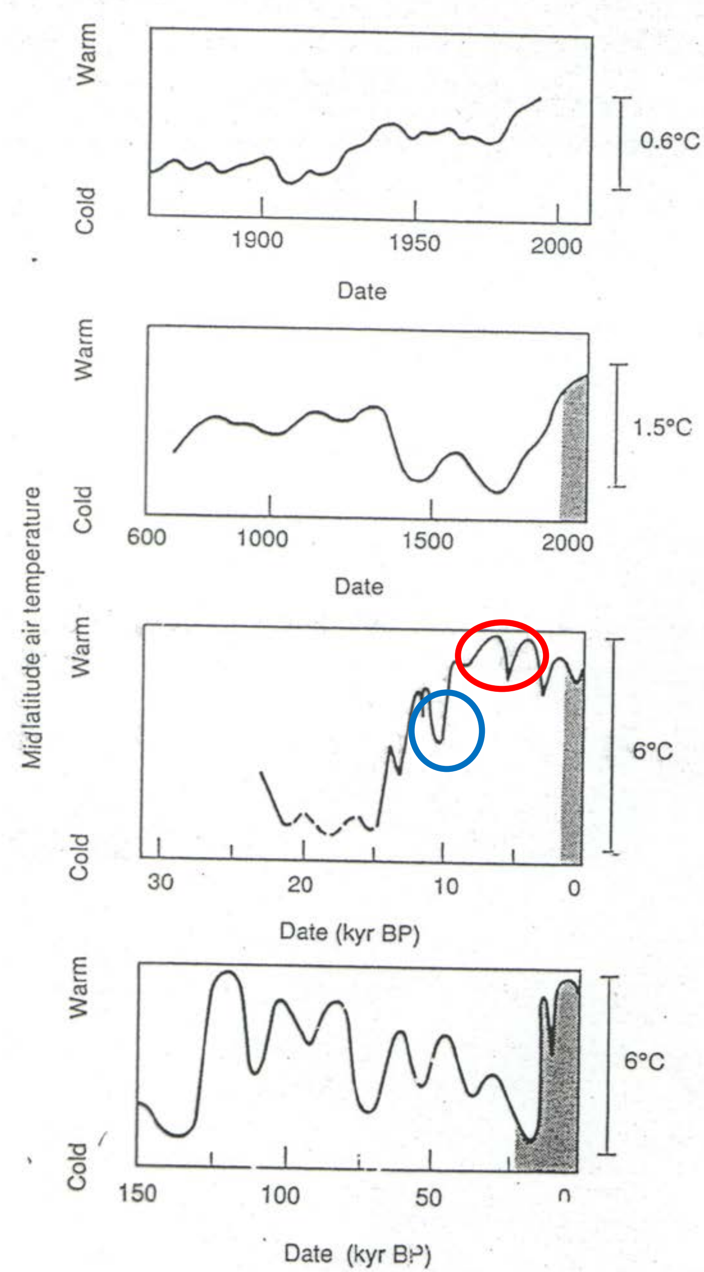
14-7kyr: Deglaciation.

Widespread deglaciation began rather abruptly ~14,000 years ago. Cordilleran Ice Sheet melted rapidly and was gone by ~10,000 years ago. Scandinavian Ice Sheet lasted only slightly longer. By 8,500 years ago the conditions in Europe had reached their present state; in N. America by ~7,000 years ago.



10.8-10.1kyr ago: Younger Dryas cooling Interspersed in the general warming were periods of widespread cooling and glacial advance spaced about 2,500 years apart. The Younger Dryas Event established itself within 100 years and lasted 700 years.

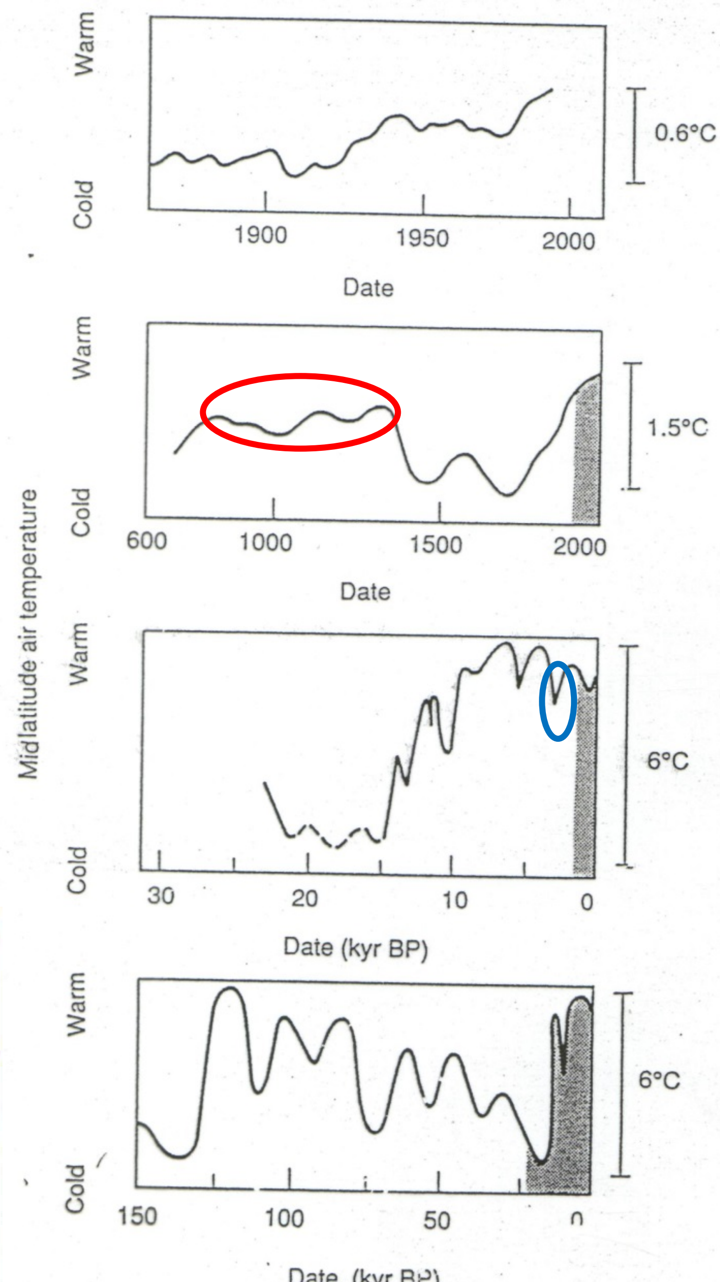
7-4kyr ago: Post Glacial Optimum Warmest period culminated between 7-5kyr ago. Sea level rose rapidly maybe reaching its peak ~4kyr ago– higher than today by ~3 meters. Mainly due to reduction of ice on land, but sea ice in Arctic Ocean also reduced. Both Antarctica and Europe (in summer) 2-3C warmer than they are today.



2.9-2.3kyr ago: Iron Age Cold Epoch (900-300 BC)

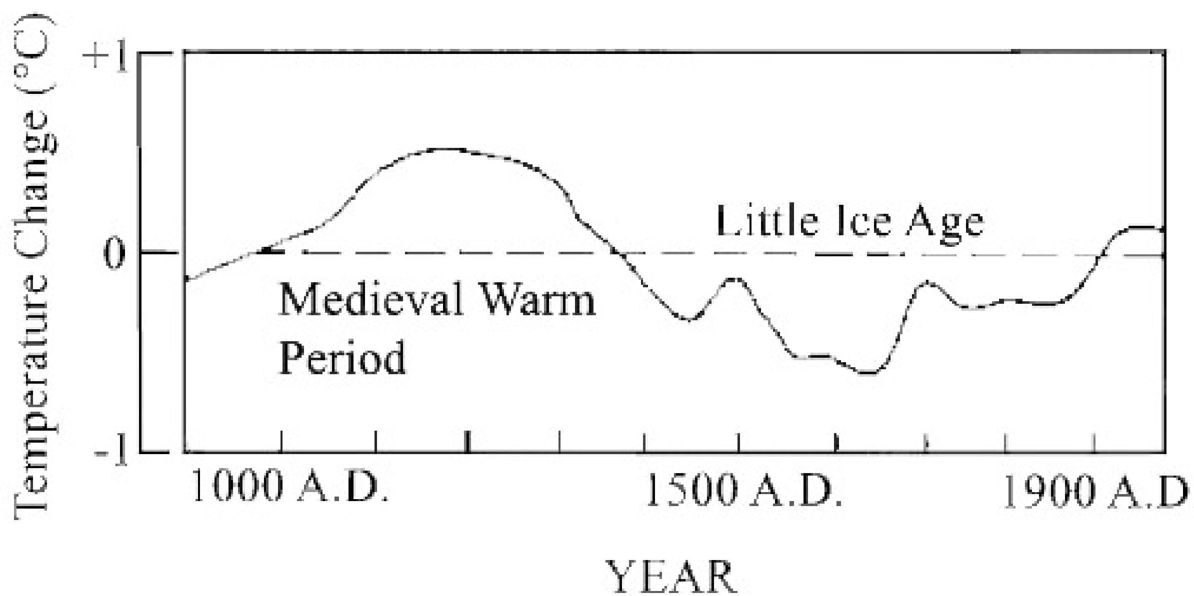
900-1200 AD: The medieval Warm Period (the Medival Optimum)

Weaker and shorter warming than post-glacial optimum. Melting of the Arctic ice – founding of the Norse Colonies across the northern N. Atlantic to America (Iceland and Greenland). Summer temperatures probably 1C higher than today in western and central Europe. Lasted until 1300 AD.



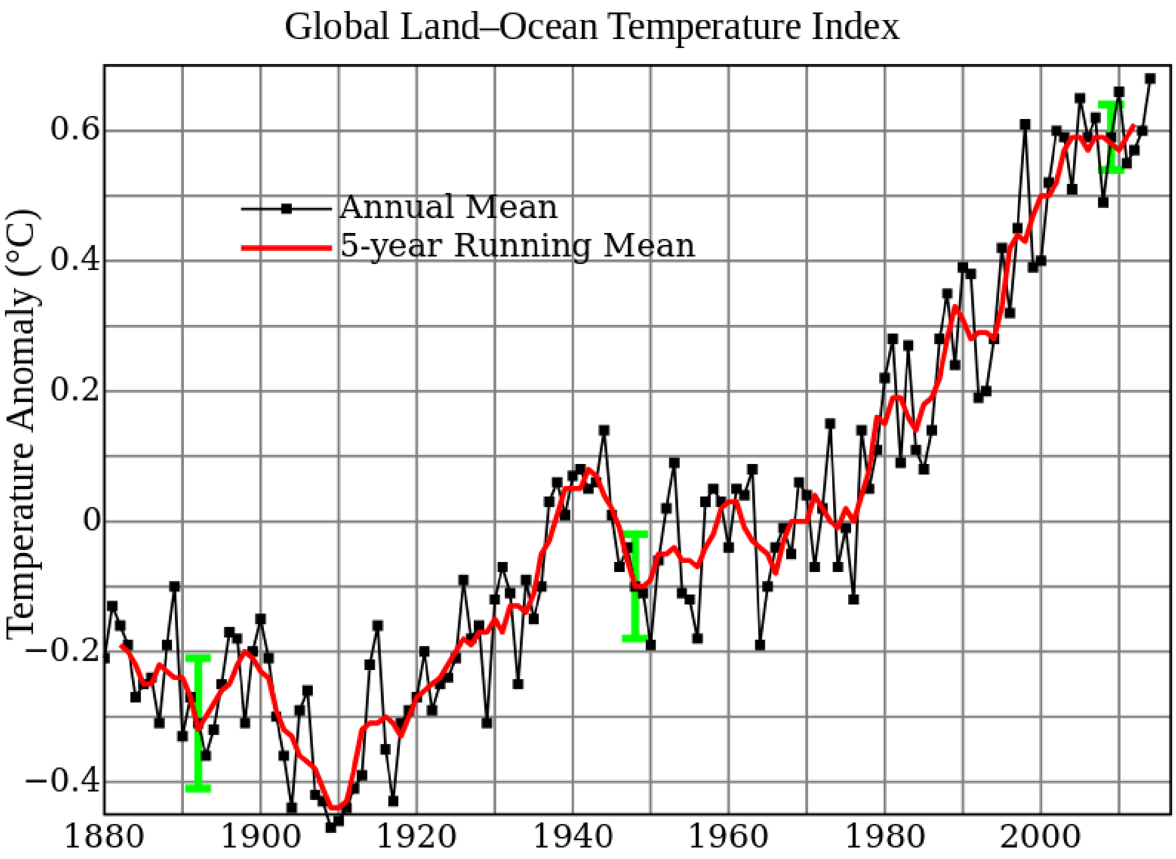
1430-1850: The Little Ice Age

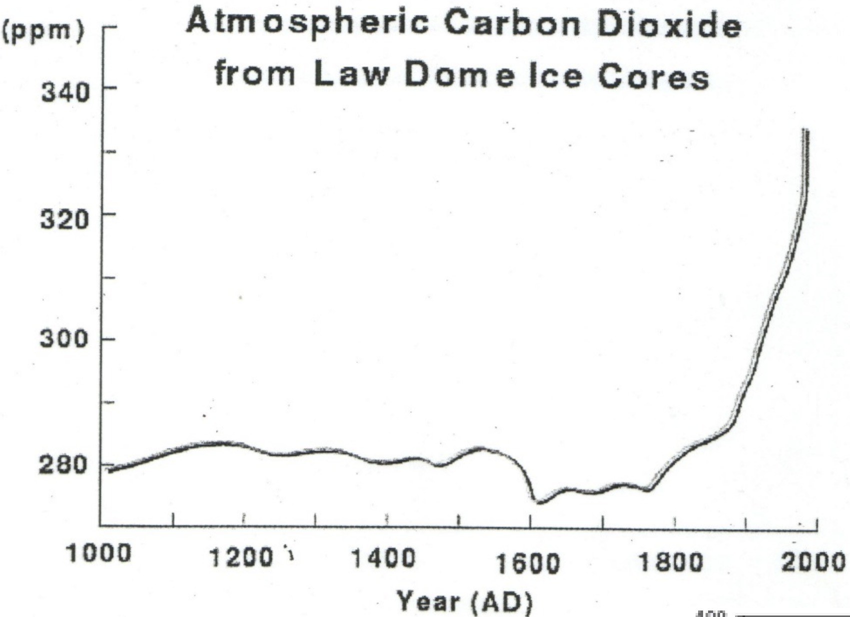
Two peaks (1400 and late 1600s). Most harsh in Britain during the second half of 17th Century. Thames river often covered with ice. Arctic pack ice expanded south with important effects for Greenland and Iceland. By 1780-1820 the temperature across the N. Atlantic north of 50N was 1-3C colder than today. Glaciers advanced in Europe, Asia and N. America. However, the Southern Hemisphere seems to have partly escaped this cold period, i.e., not a global phenomenon. In fact, Antarctic may have been warmer than today during the period 1760-1830.



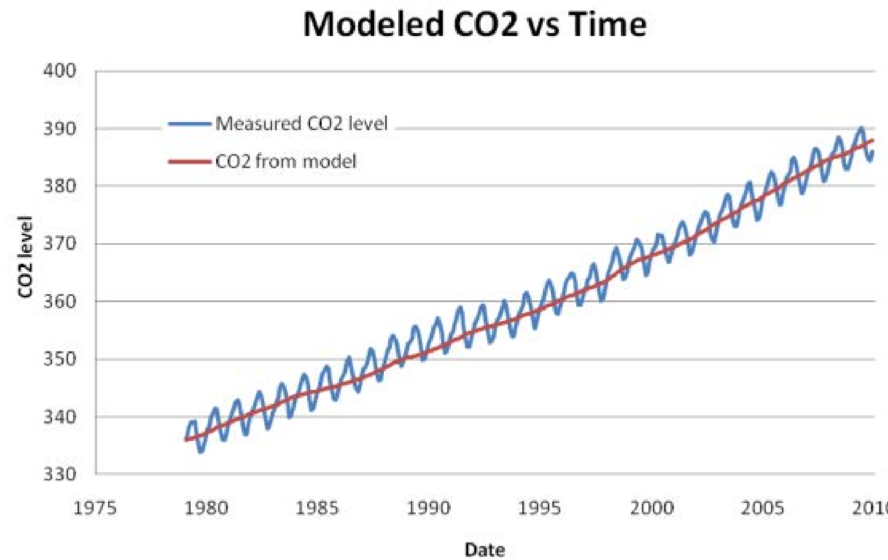
1880-present: Global Warming Trend

- ~0.8C global warming since 1880
- 1940-1960 - a slight cooling in the global temperature record.
- Since 1970 the rate of warming has increased.
- Ten of the hottest years since the beginning of instrumental record (~1860) have occurred since 2000: 2014 in first place. 14 of hottest 15 years in 21st century.

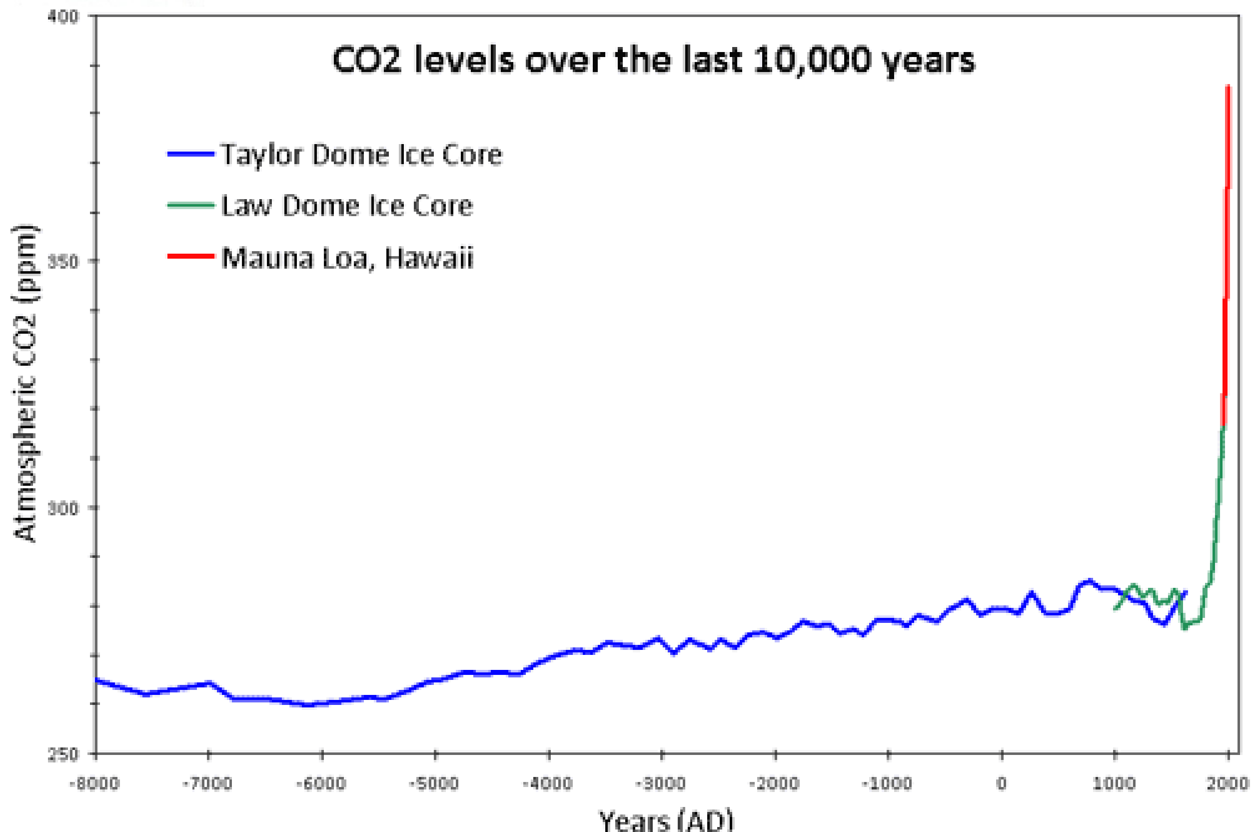




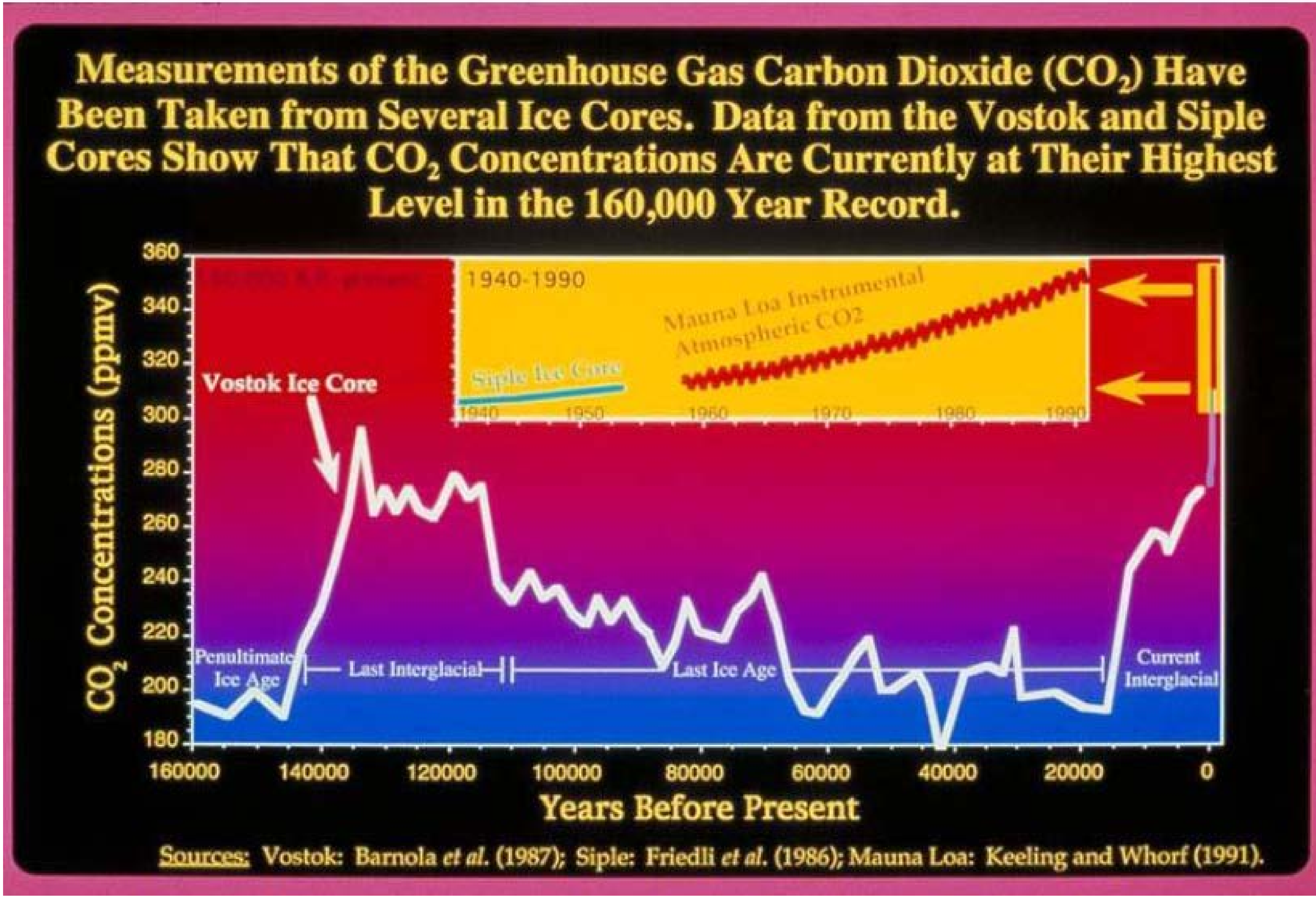
Atmospheric Carbon Dioxide
from Law Dome Ice Cores
(ppm)
340
320
300
280
1000
1200
1400
1600
1800
2000
Year (AD)



Modeled CO2 vs Time
Measured CO2 level
CO2 from model
CO2 level
400
390
380
370
360
350
340
330
1975
1980
1985
1990
1995
2000
2005
2010
Date



CO2 levels over the last 10,000 years
Taylor Dome Ice Core
Law Dome Ice Core
Mauna Loa, Hawaii
Atmospheric CO2 (ppm)
400
350
300
250
-8000
-7000
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
2000
Years (AD)


Measurements of the Greenhouse Gas Carbon Dioxide (CO2) Have Been Taken from Several Ice Cores. Data from the Vostok and Siple Cores Show That CO2 Concentrations Are Currently at Their Highest Level in the 160,000 Year Record.
CO2 Concentrations (ppmv)
360
340
320
300
280
260
240
220
200
180
1940-1990
Mauna Loa Instrumental Atmospheric CO2
Siple Ice Core
1940
1950
1960
1970
1980
1990
Vostok Ice Core
Penultimate Ice Age
Last Interglacial
Last Ice Age
Current Interglacial
160000
140000
120000
100000
80000
60000
40000
20000
0
Years Before Present
Sources: Vostok: Barnola et al. (1987); Siple: Friedli et al. (1986); Mauna Loa: Keeling and Whorf (1991).

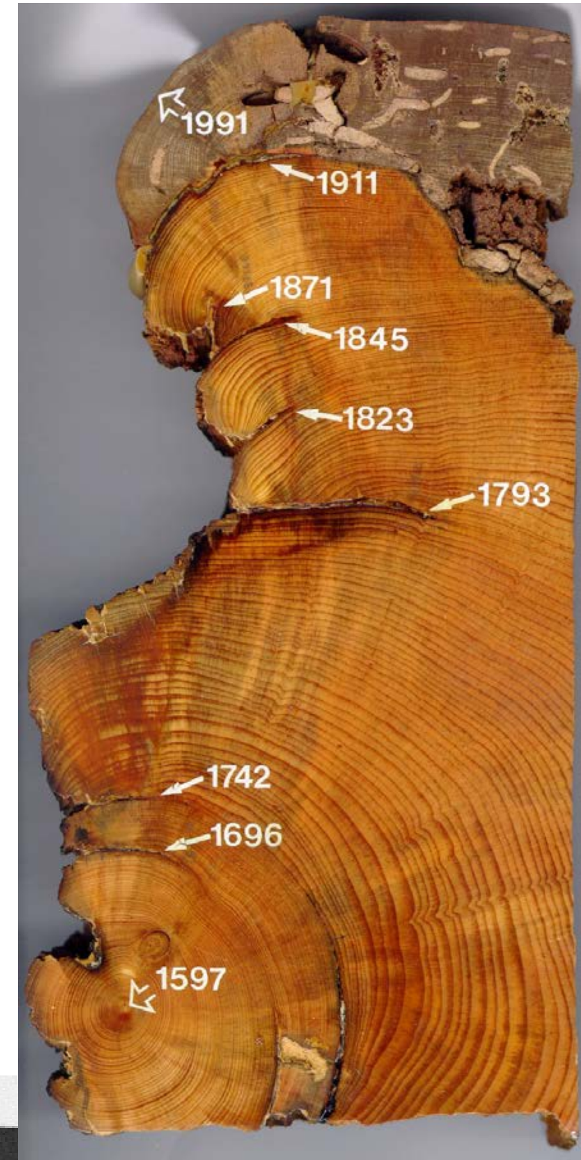
To relate very recent warming to more distant past we need to discuss the observational methods

1. *Instrumental Observations*:
   - -barometer/thermometer (invented in 17th Century)
   - -temporal resolution: hours/days
   - -length of record: ~100-200 years.

2. *Historical Records*:
   - -books, manuscripts, paintings, logs, ….
   - -temporal resolution: years
   - -length of record: up to 1000 years.

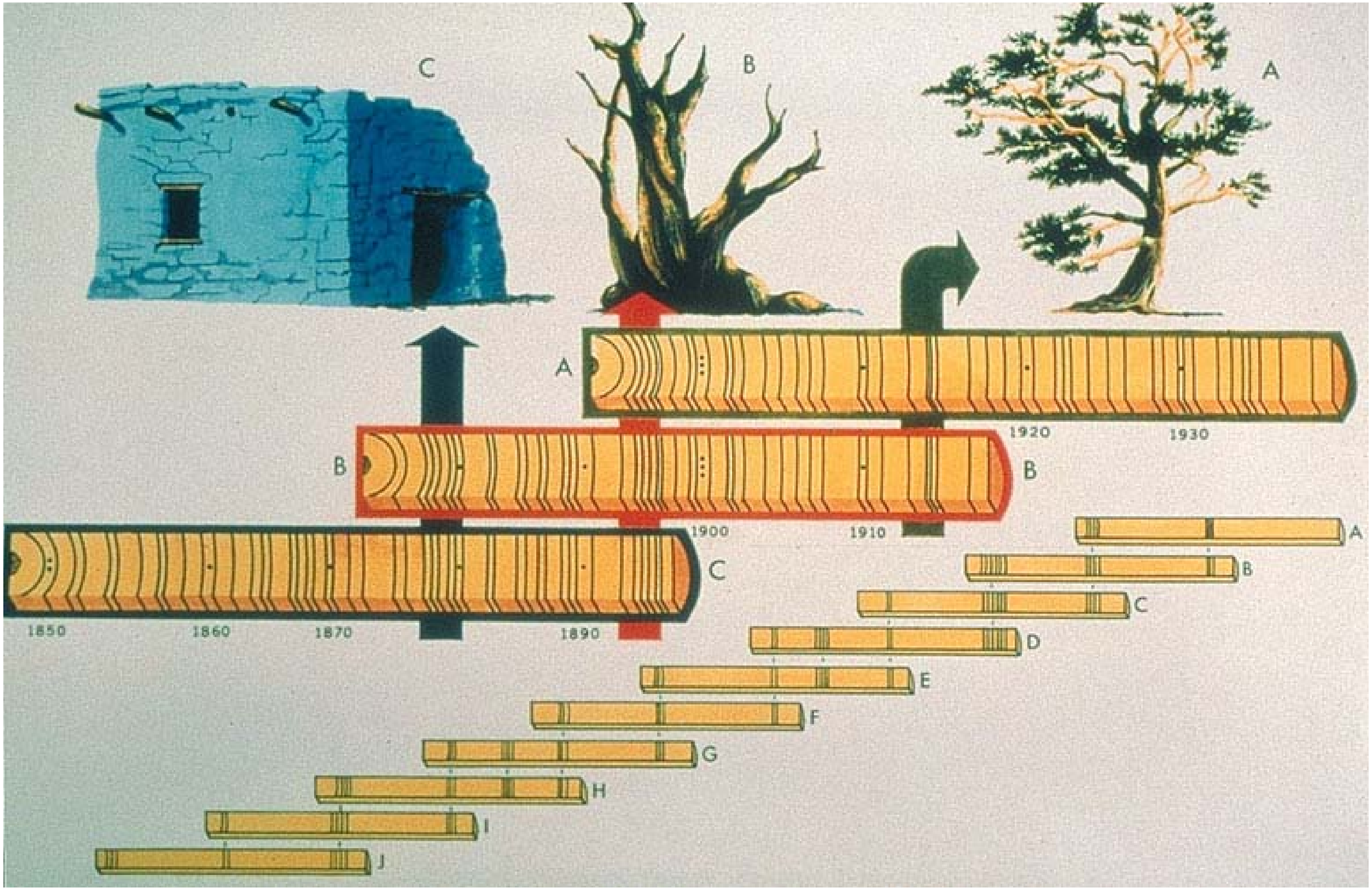
3. *Tree Rings*:
   - -respond to temperature, moisture and sunlight
   - -annual variations: ring widths.
   - -useful in mid and high latitudes
   - -length or record: up to 1000 yrs (rare cases 8000 yr)
   - -at low latitudes not useful due to small annual T and P variability

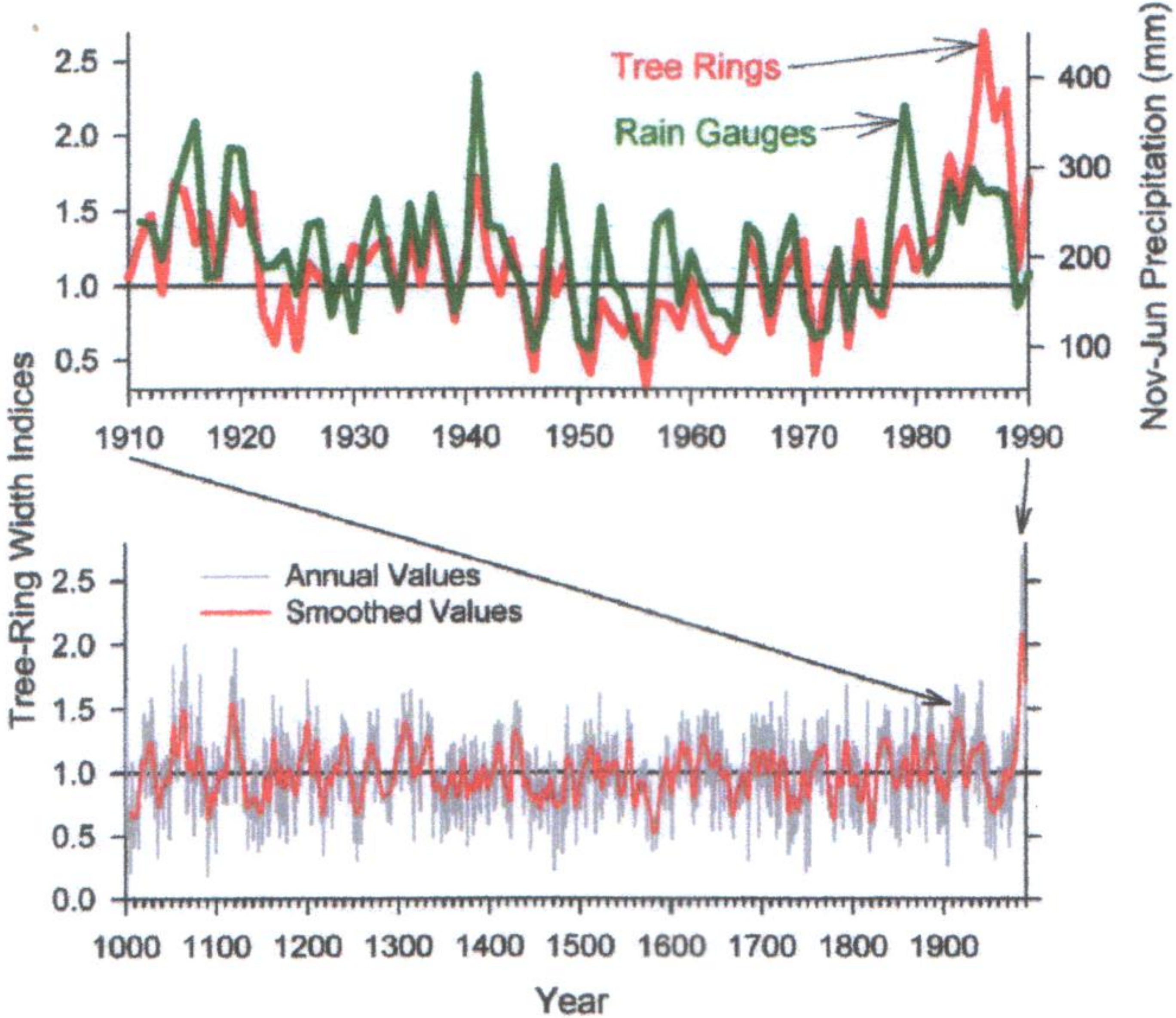
Tree Rings


1991
1911
1871
1845
1823
1793
1742
1696
1597

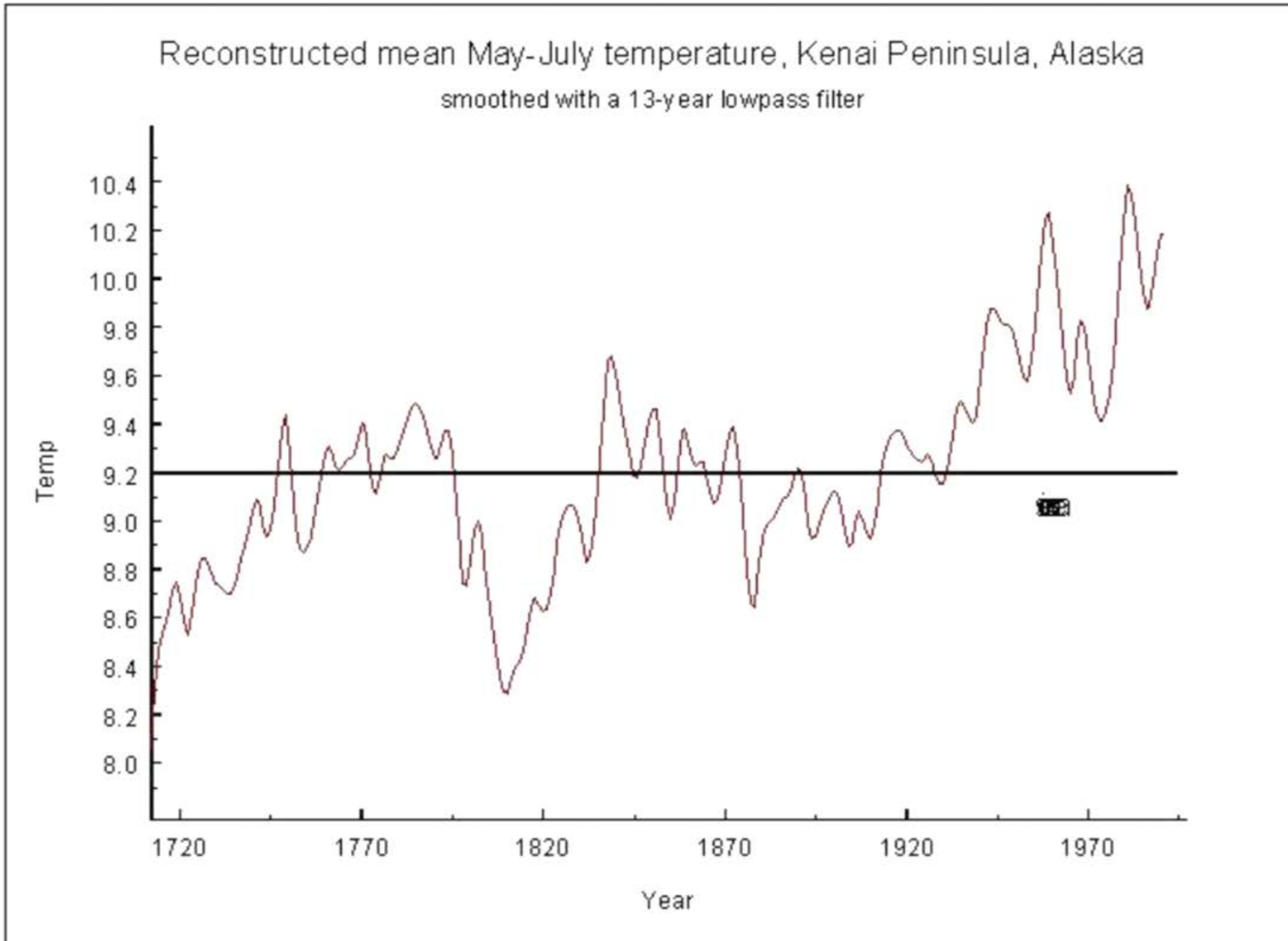

X-ray of White Spruce core
1950
1960

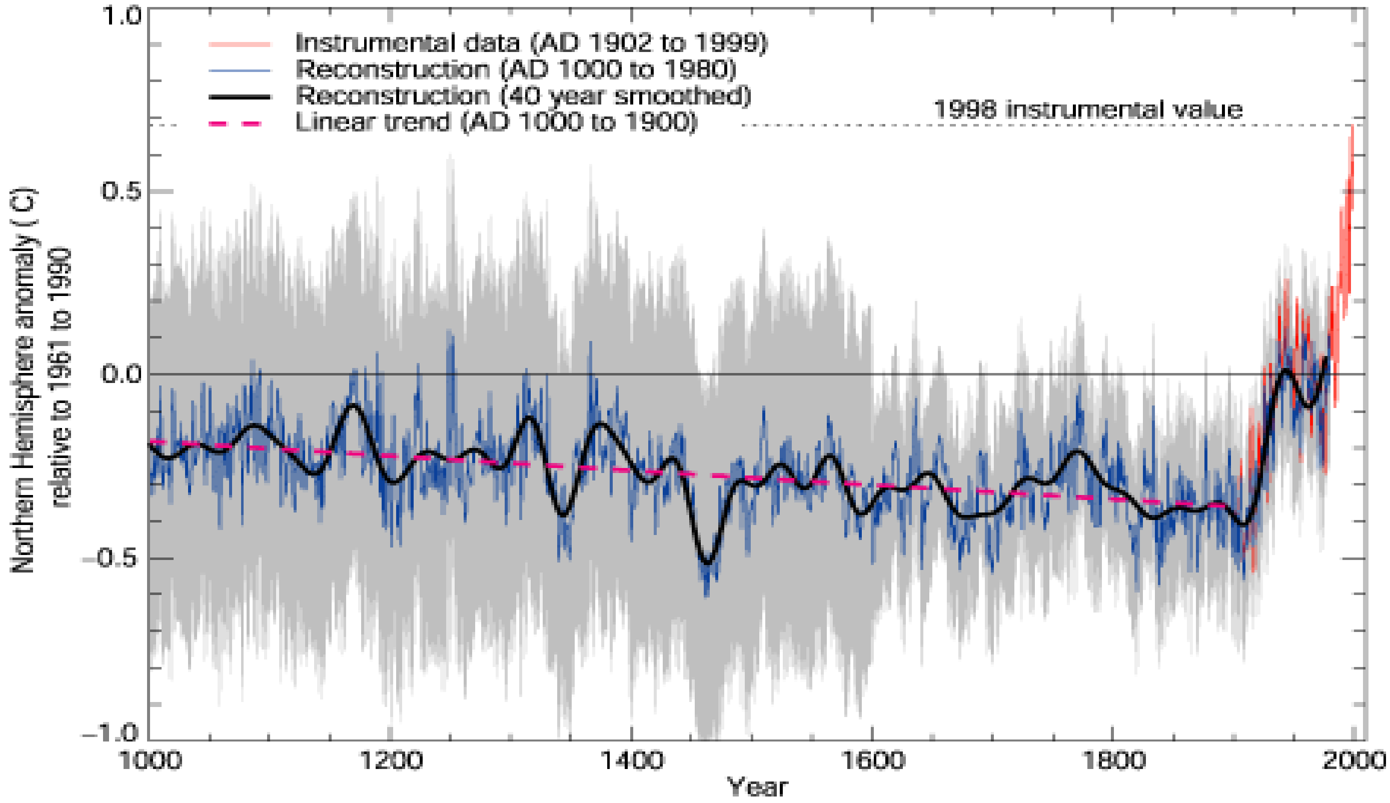
Cross dating: Extending the time series back in time





Tree Rings
Rain Gauges
Nov-Jun Precipitation (mm)
100
200
300
400
2.5
2.0
1.5
1.0
0.5
0.0
1910
1920
1930
1940
1950
1960
1970
1980
1990
Tree-Ring Width Indices
Annual Values
Smoothed Values
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Year


Reconstructed mean May-July temperature, Kenai Peninsula, Alaska
smoothed with a 13-year lowpass filter
Temp
10.4
10.2
10.0
9.8
9.6
9.4
9.2
9.0
8.8
8.6
8.4
8.2
8.0
1720
1770
1820
1870
1920
1970
Year



Millenial Northern Hemisphere temperature reconstruction (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann et al. (1999). Smoother version of Northern Hemisphere series (black), linear trend from AD 1000 to 1850 (purple dashed) and two standard error limits (grey shaded) are shown.

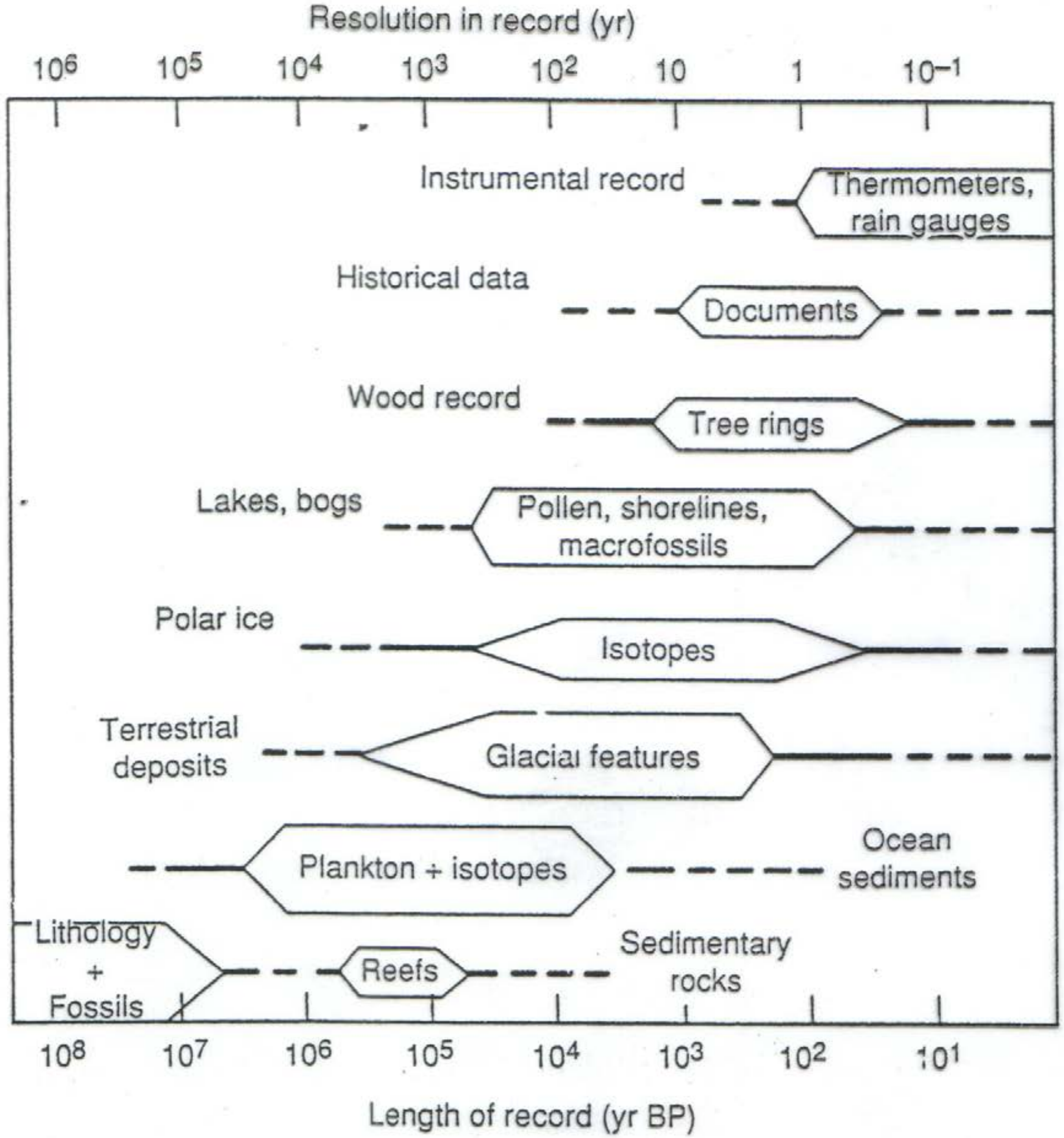
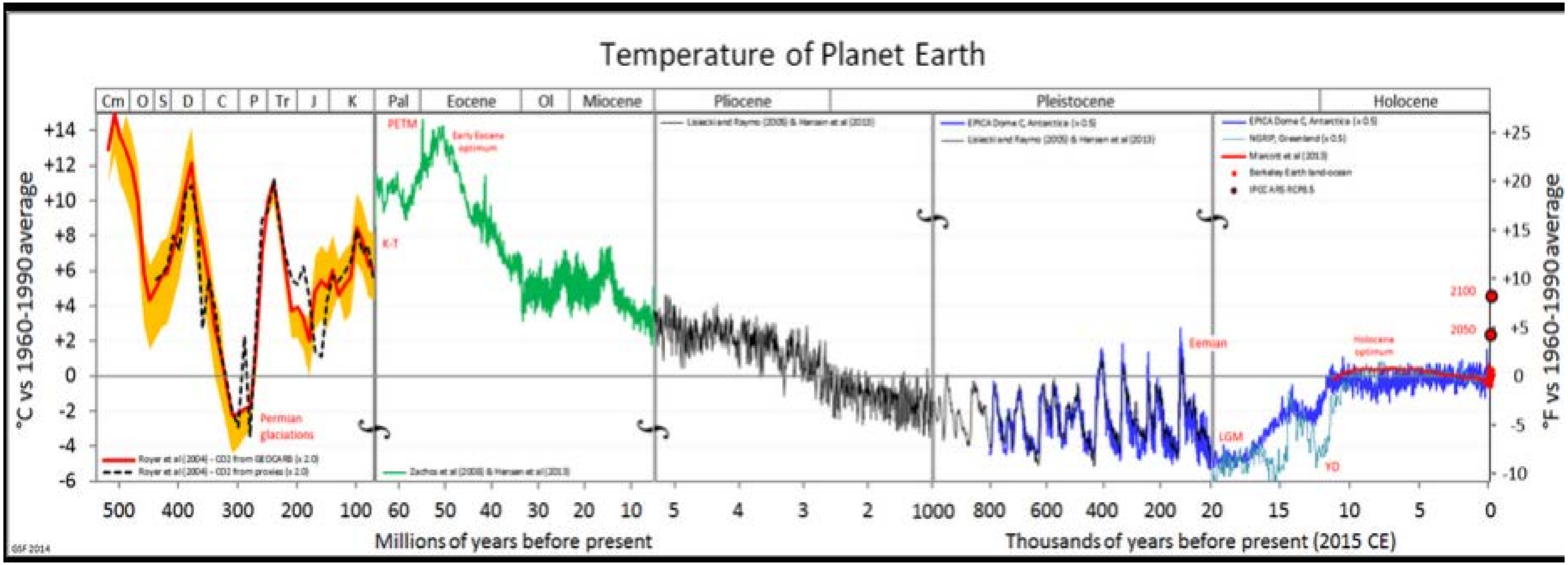


Figure 10.1 The time span of various climatic records from decades to hundreds of millions of years. The resolution in each record is also indicated, given the rule of thumb that it is about 1% of the length of the individual climatic record. The thickness of each polygon is an attempt to reflect the relative contribution for each contributing record at each time in the past. (Adapted with permission from T. Webb III, J. Kutzbach, and F. A. Street-Perrott, in *Global Change*, T. F. Malone and J. D. Roederer, eds., pp. 182-218. Copyright 1985 by Cambridge University Press, UK.)



Temperature of Planet Earth
Cm
O
S
D
C
P
Tr
J
K
Pal
Eocene
Ol
Miocene
Pliocene
Pleistocene
Holocene
°C vs 1960-1990 average
°F vs 1960-1990 average
PETM
Early Eocene optimum
K-T
Permian glaciations
Eemian
LGM
YD
Holocene optimum
2100
2050
Millions of years before present
Thousands of years before present (2015 CE)