Global Climate History from Data

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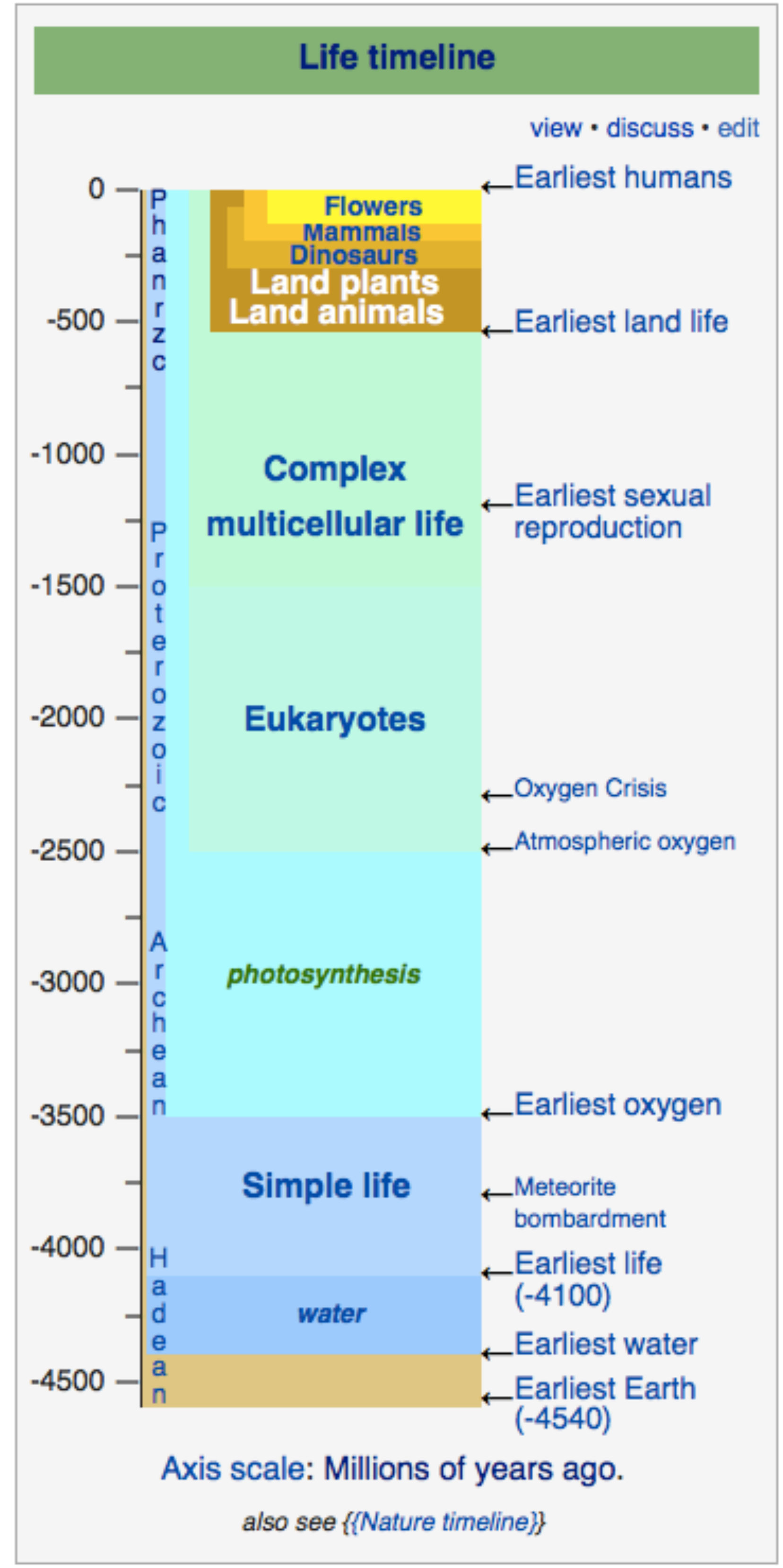
Seminar, April 15, 2016

Introduction

- The first oxygen generating bacteria developed about 3,500 Ma (million years ago).
- Photosynthesis began about 2,700 Ma.
- Free oxygen began to accumulate by about 2,000 Ma.
- By 600 Ma, CO_2 levels had dropped to < 1% and O_2 levels had risen to 15%.
- The era of oxygen breathing life, the **phanerozoic eon**, began about 600 Ma with the beginning of the Cambrian period.

Along with complex life forms came fossils

With fossils came the ability to infer the temperature at which they lived



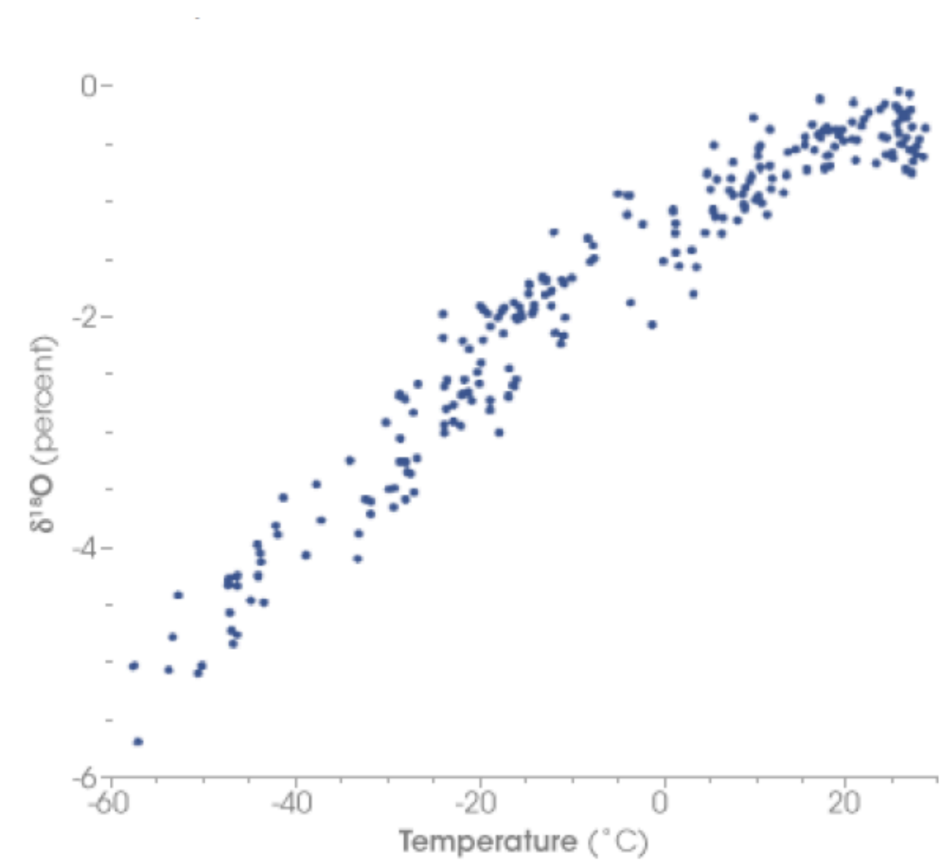
https://en.wikipedia.org/wiki/Timeline_of_the_evolutionary_history_of_life

Introduction (cont.)

Temperature record from ^{18}O / ^{16}O isotope ratios:
The calcite ($CaCO_3$) in limestone is formed from CO_2 dissolved in water and the H_2O that the organism lived in when it formed its shell.

- Water molecules with ^{18}O are more difficult to vaporize, and easier to condense, in a temperature dependent way.
- **Cooler water** thus contains **more ^{18}O** than warmer water, and this can be used to determine the temperature of the water in which a **marine fossil** lived.
- There are large systematic errors for very long periods (> 200 million years), so very long term trends are not so easy to pin down.

Glacial ice forms from precipitation that contains **less ^{18}O** (**or** less ^{2}H) during **colder periods** because the water vapor is preferentially (in a temperature dependent way) depleted of ^{18}O on the way to the poles. So **ice-core samples** from Antarctica, for example, provide a temperature record that goes back several hundred thousand years, as well as information from trapped gases, such as CO_2.



The concentration of ^{18}O in precipitation decreases with temperature. This graph shows the difference in ^{18}O concentration in annual precipitation compared to the average annual temperature at each site.

Introduction (cont.)

Ice volume:

Because polar ice is depleted in ^{18}O relative to ocean water by precipitation as the water vapor travels to the poles, when the polar ice melts it raises the level of 16O in the ocean.

There is a sum-rule: Global ratios of 18O/16O can be used to tell how much water is locked up in ice at the poles.

Dating is important.

For sea floor fossil sediments:

- Radiocarbon dating works for studies of sea bottom sediment
- Radiometric (absolute) or relative dating for ancient fossils in limestone

For ice cores:

- Counting annual layers for newer ice
  - either using visible features or using $^{18}O/^{16}O$ or $^{2}H/^{1}H$ isotope annual variations
- For older ice, the layers thin out and become indistinguishable
  - Look for features (volcanic ash)
  - for deep layers, model accumulation rate variations and ice flow

Outline

Climate change has occurred on all time scales since the earliest times that can be studied using fossil data (about 600 Ma).

I will show data covering:

- The very long perspective (100’s of millions of years)
- The long perspective (millions of years)
- The medium term (100’s of thousands of years)
- The short term (thousands of years, including historical times)

Then I will discuss a proposed explanation for (at least some of the) climate variability

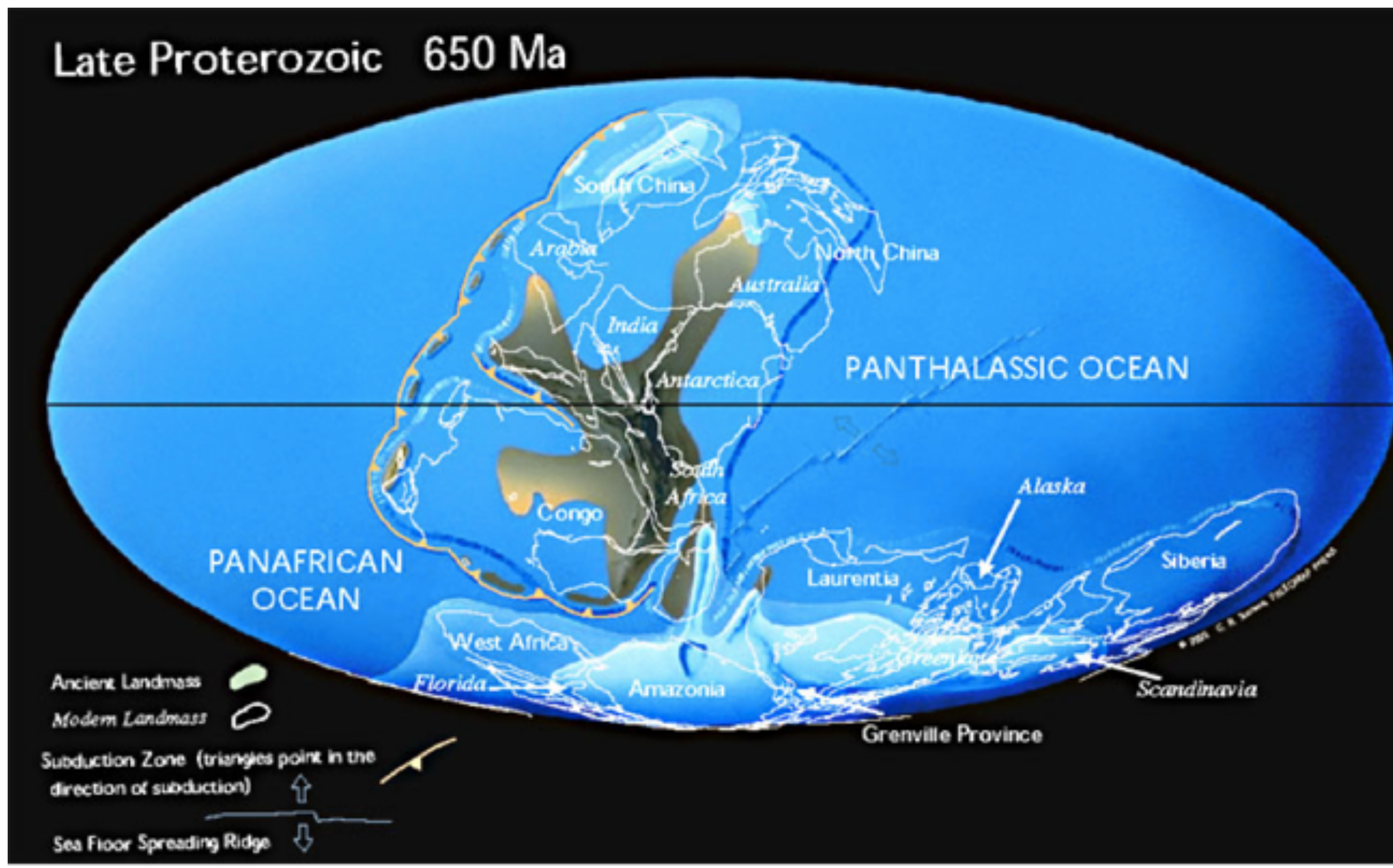
The Phanerozoic era

In the late pre-Cambrian the earth was cold, with large glaciers.

But by the beginning of the Cambrian (600 Ma), the earth had warmed up, and life exploded in the warm oceans.

This began the eon of abundant oxygen breathing life - the Phanerozoic

It resulted in marine fossils that could be used to extract a temperature record of the entire Phanerozoic



The very long perspective (600 M years)

The very long perspective

Veizer, J., Y. Godderis, and L.M. Francois (2000). "Evidence for decoupling of atmospheric CO2 and global climate during the Phanerozoic eon". Nature 408: 698-701.
Data from Veizer, et. al,. (1999) $^{87}Sr/^{86}Sr$, $d^{13}C$ and $d^{18}O$ evolution of Phanerozoic seawater. Chemical Geology 161, 59-88

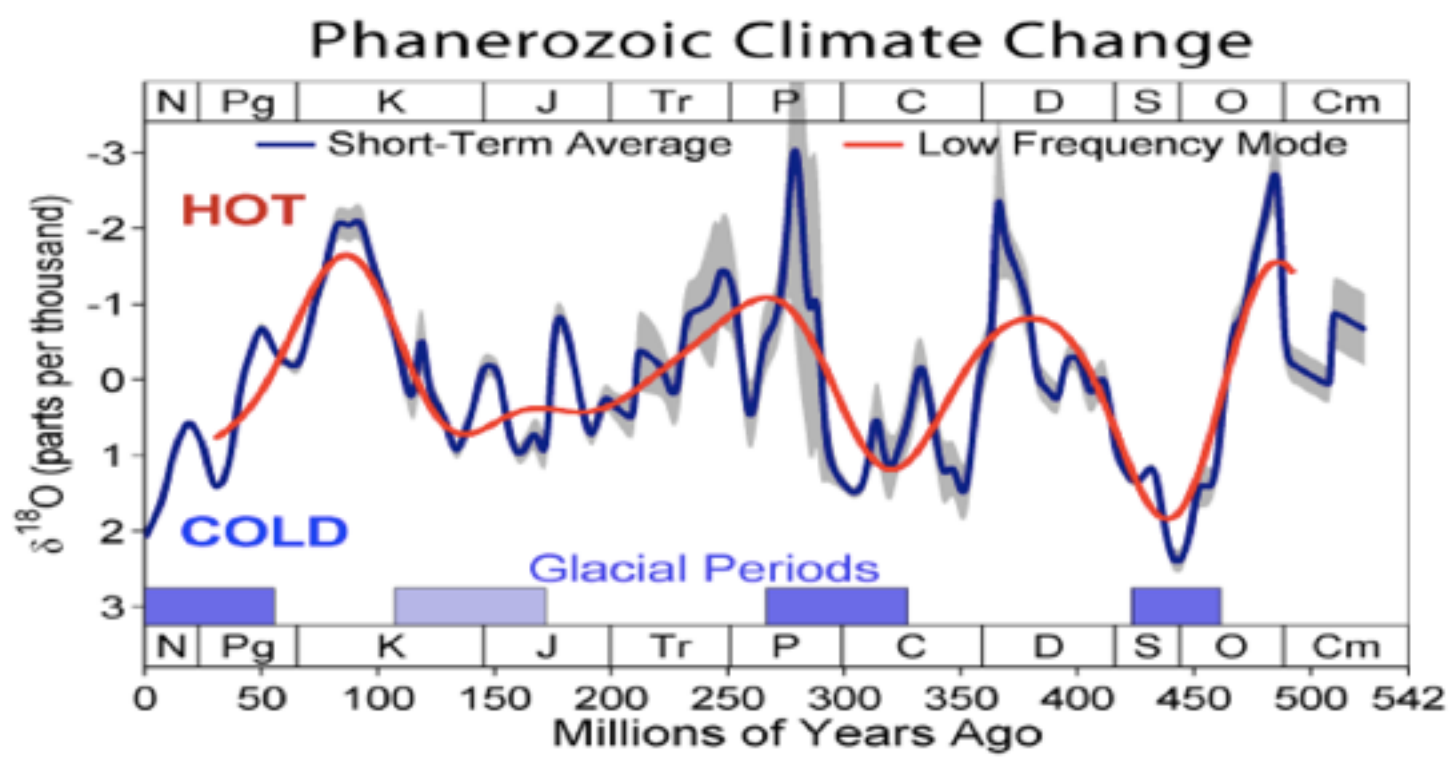
Parts per thousand change in $^{18}O/^{16}O$ ratio versus time.

- Quantitative conversion to a temperature variation is complicated.
  - Each 1 part/thousand change corresponds to ~ 1.5 - 2^0 C change in **tropical** sea surface temperature
- Short term average smoothed with 3M year gaussian

Systematic uncertainties relating data/te

- long term trend is suppressed by subtracting quadratic fit to short term averages

The three ice ages (including our present one) are reported from geological evidence of glaciation



The very long perspective (cont.)

The conditions needed for a full blown ice age seem to be:

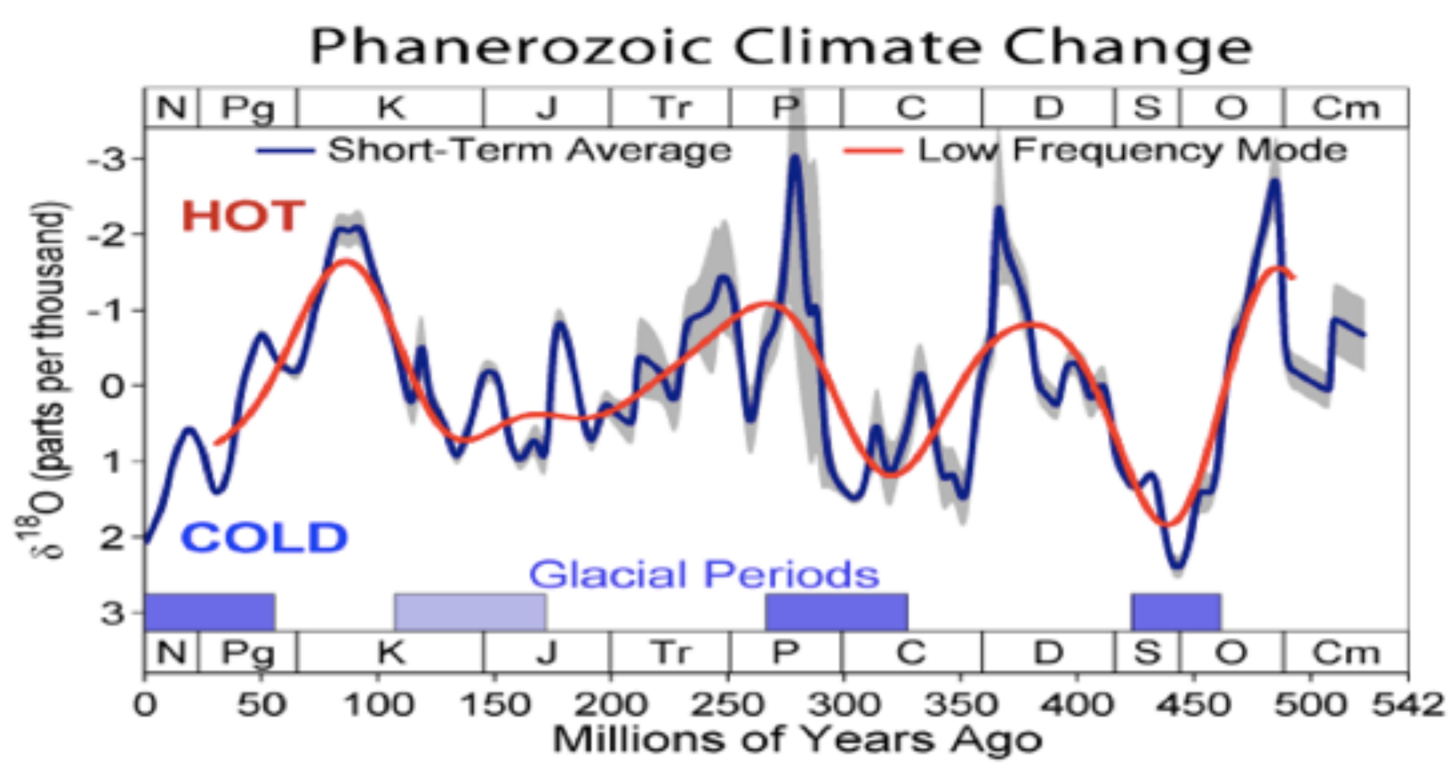
- A large land mass at the south pole
- A continuous land mass stretching from arctic to antarctic

Note the cool, not quite ice age at about 150 Ma.

- No large continents at either pole

The 140 M year periodicity has been noted. Proposed causes include plate tectonics and the galactic orbit of the sun!

- More on the latter later

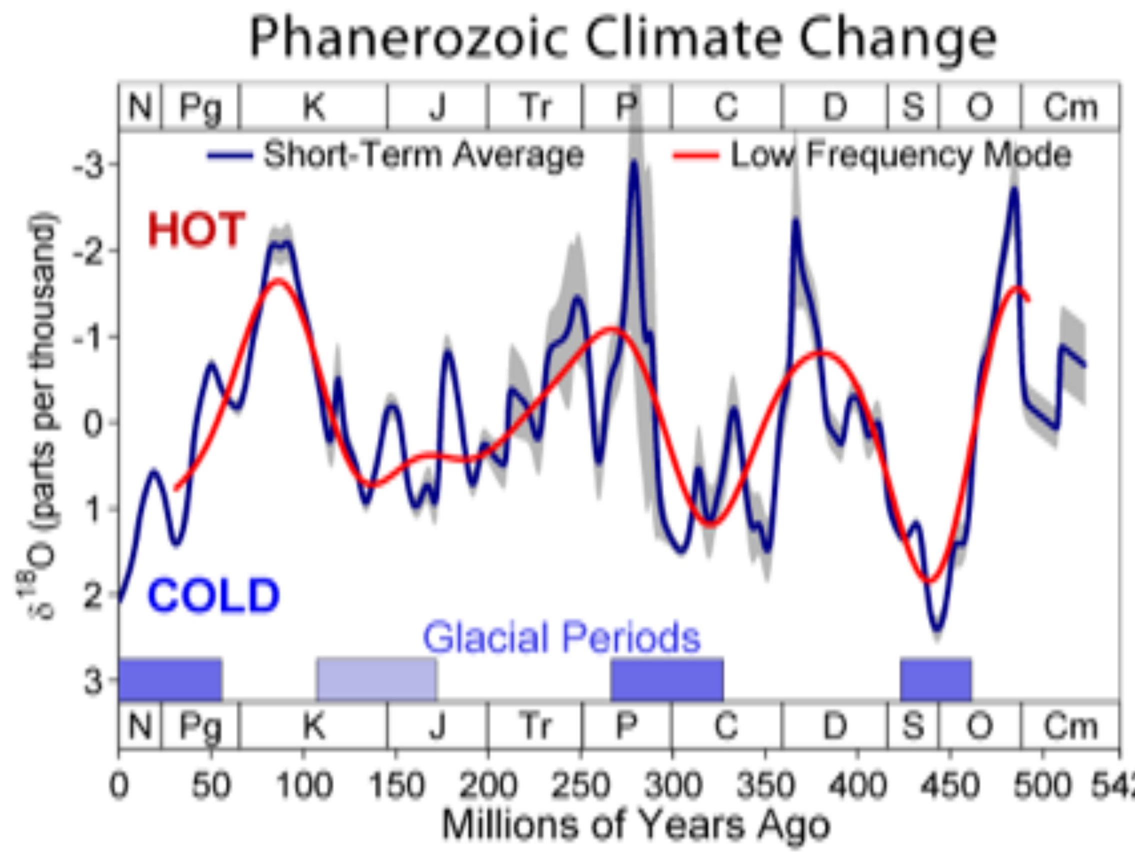


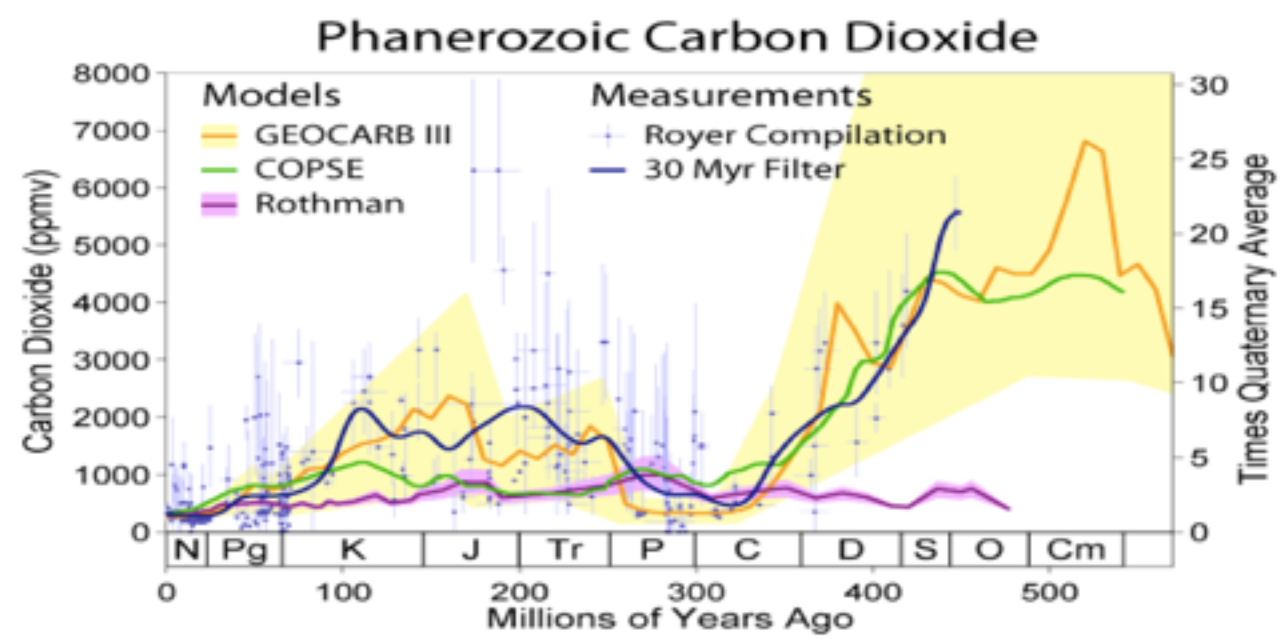
Temperature and CO_2

Interestingly, CO_2 levels, which more recently seem to follow temperature, were very high 450 Ma, during a deep glaciation period.

The lower plot shows a comparison of model predictions with data for CO_2 levels during the Phanerozoic.

This suggested that the factors that control climate are complex!





Temperature and CO_2

From http://en.wikipedia.org/wiki/Geologic_temperature_record

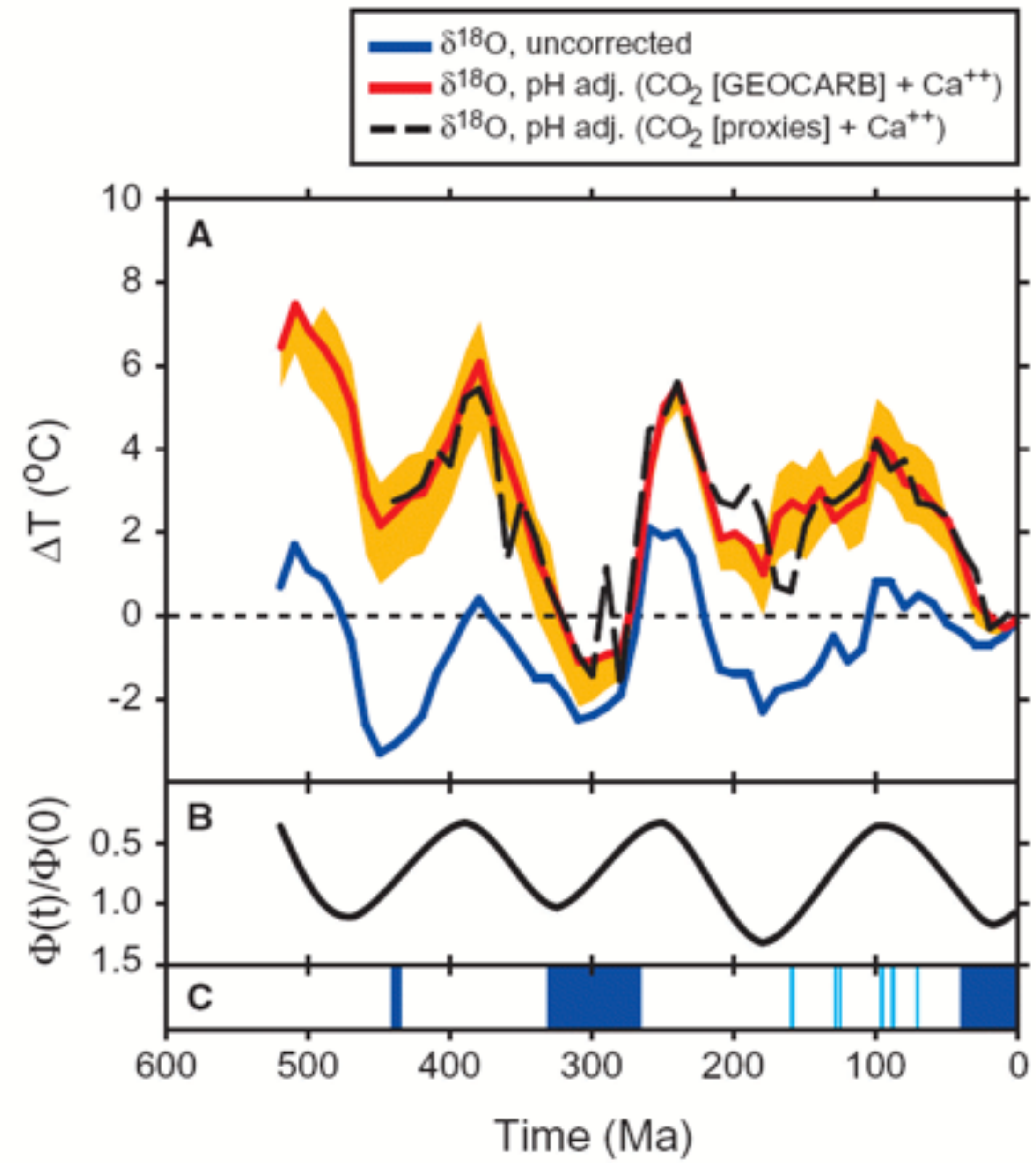
”On geologically short time scales, greenhouse gases are the most important process influencing temperature. By trapping solar radiation, carbon dioxide, water vapor, methane, and some other gases, contribute to a greenhouse effect essential to maintaining the Earth's temperature.

However, modern reconstructions of greenhouse gas concentrations do not show fluctuations over geologically long periods that match to the observed changes in temperatures and ice volumes. **This has led most observers to believe that changes in continent configurations are much more important in determining long-term temperature.** In particular, the lack of land masses at the poles inhibits the formation of large ice sheets. Similarly, the presence of expansive sea ways, especially near the equator, aids in distributing heat across the globe and leads to higher temperature on average.”

BUT: be careful of systematic effects

Royer et al., Geological Society of America, GSA Today, volume 14, issue 3, March 2004. Argues that just suppressing the long term trend is incorrect, pH matters:

A: **Blue curve**: temperature deviations relative to today calculated by Shaviv and Veizer (2003) from the "10/50" $\delta^{18}O$ compilation presented in Veizer et al. (2000), where the original data (Veizer et al., 1999) were detrended and then averaged in 10 m.y. time-steps using a 50 m.y. moving window.
The two remaining curves: data from the blue curve adjusted for pH effects due to changes in seawater Ca++ concentration and CO_2 based either on GEOCARB III or proxies. A sensitivity analysis was performed on the GEOCARB + Ca ++ curve by holding Ca++ levels constant (lower bound of orange band), or by allowing the saturation state of CaCO3 in the ocean to vary through time (upper bound).
B: **Cosmic ray flux** (relative to the present day) as reconstructed by Shaviv (2002). C: Intervals of glacial and cool climates, as in Fig. 2B.



I will return to this later

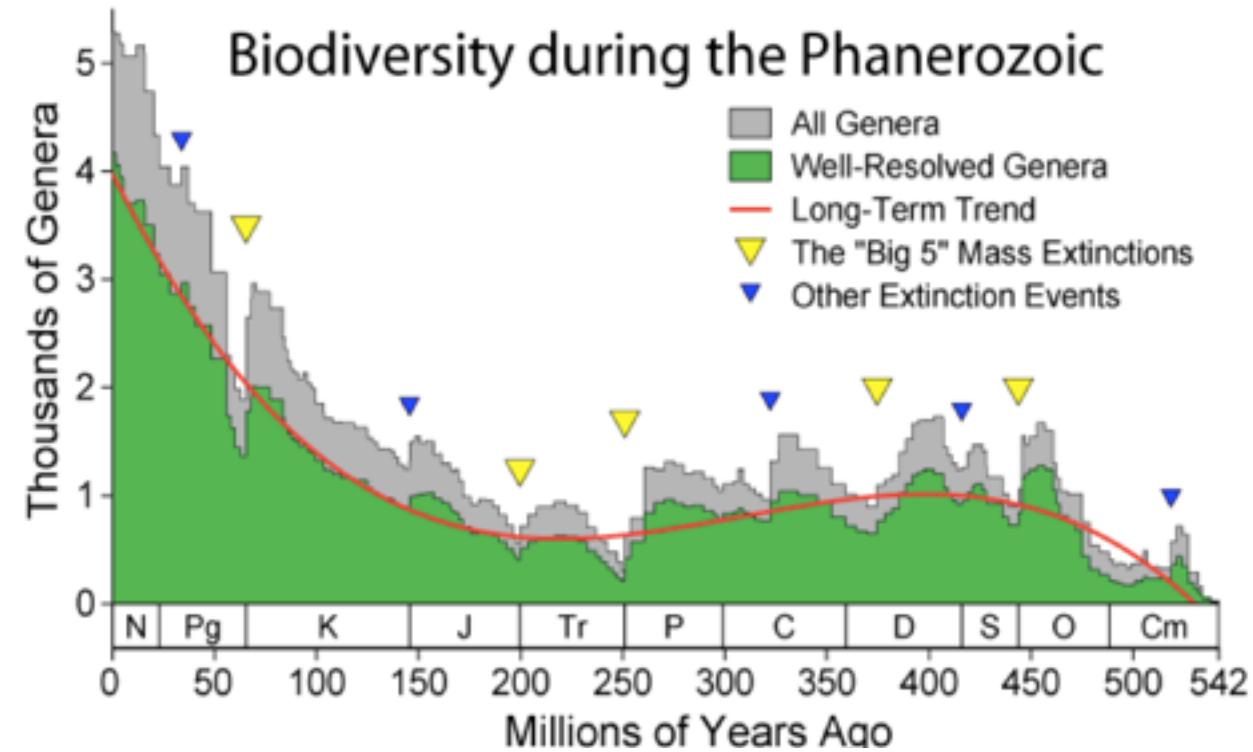
Biodiversity in the Phanerozoic

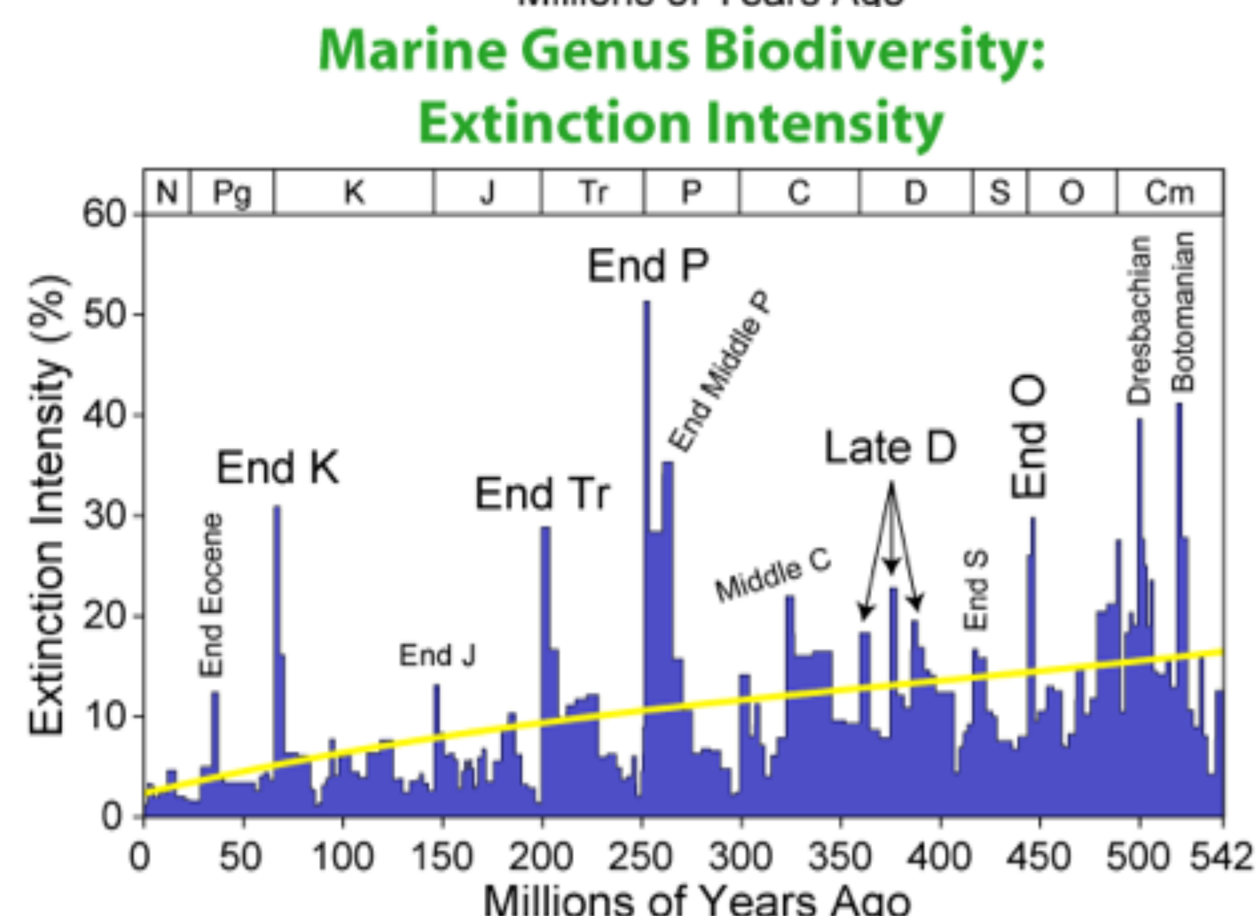
Biodiversity results from changes in rate of extinctions and rate of new originations.
Grey: total known genera from Sepkowski's catalogue (cited by Rohde & Muller)
Green: ”well-defined genera” = known genera excluding those represented by "single occurrences" and those whose dates are uncertain.
Red: trend for "well-defined genera".
Yellow: the "Big Five" mass extinctions.
Blue: other extinction events.

Very striking to me is that there seems to be little evidence of an effect from the large temperature swings.

The mass extinction events are very evident though!

Rohde, R.A., and Muller, R.A. (2005-03). "Cycles in fossil diversity". Nature 434: 208-210.

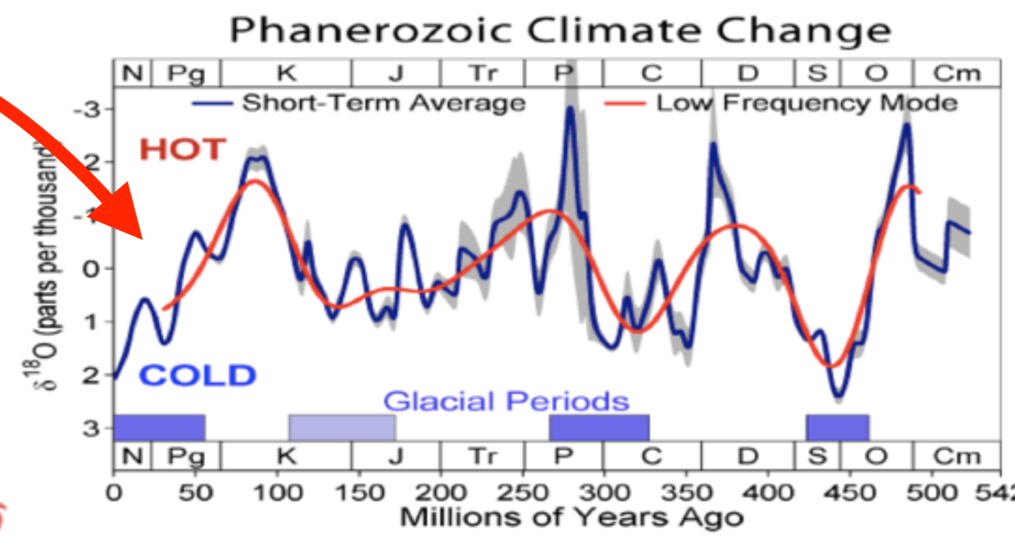


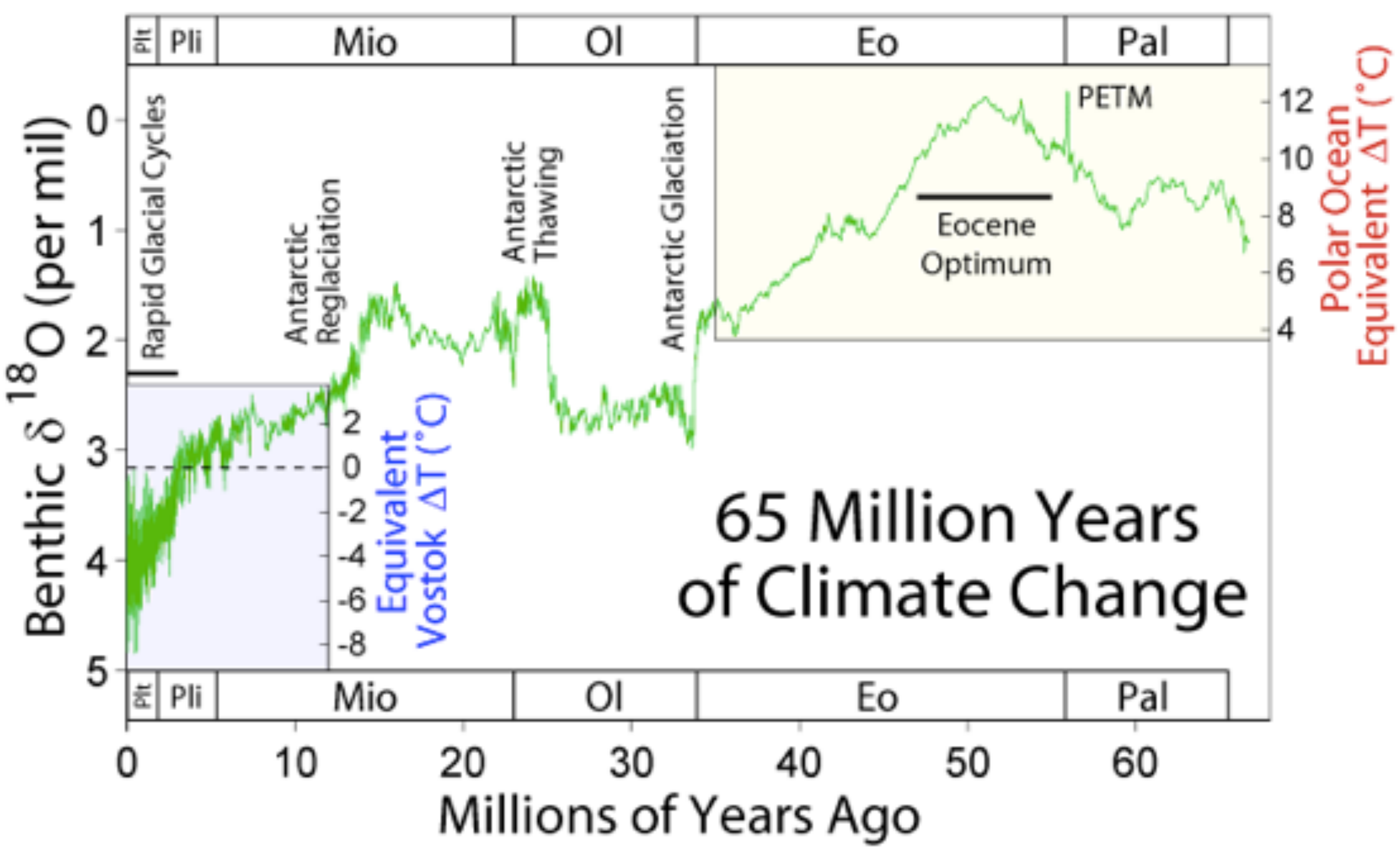


The Long Perspective
(Age of mammals)

The Age of Mammals

Based on Veizer, et. al,. (1999) $^{87}Sr/^{86}Sr$, $d^{13}C$ and $d^{18}O$ evolution of Phanerozoic seawater. Chemical Geology 161, 59-88
and http://www.science.uottawa.ca/~veizer/isotope_data/





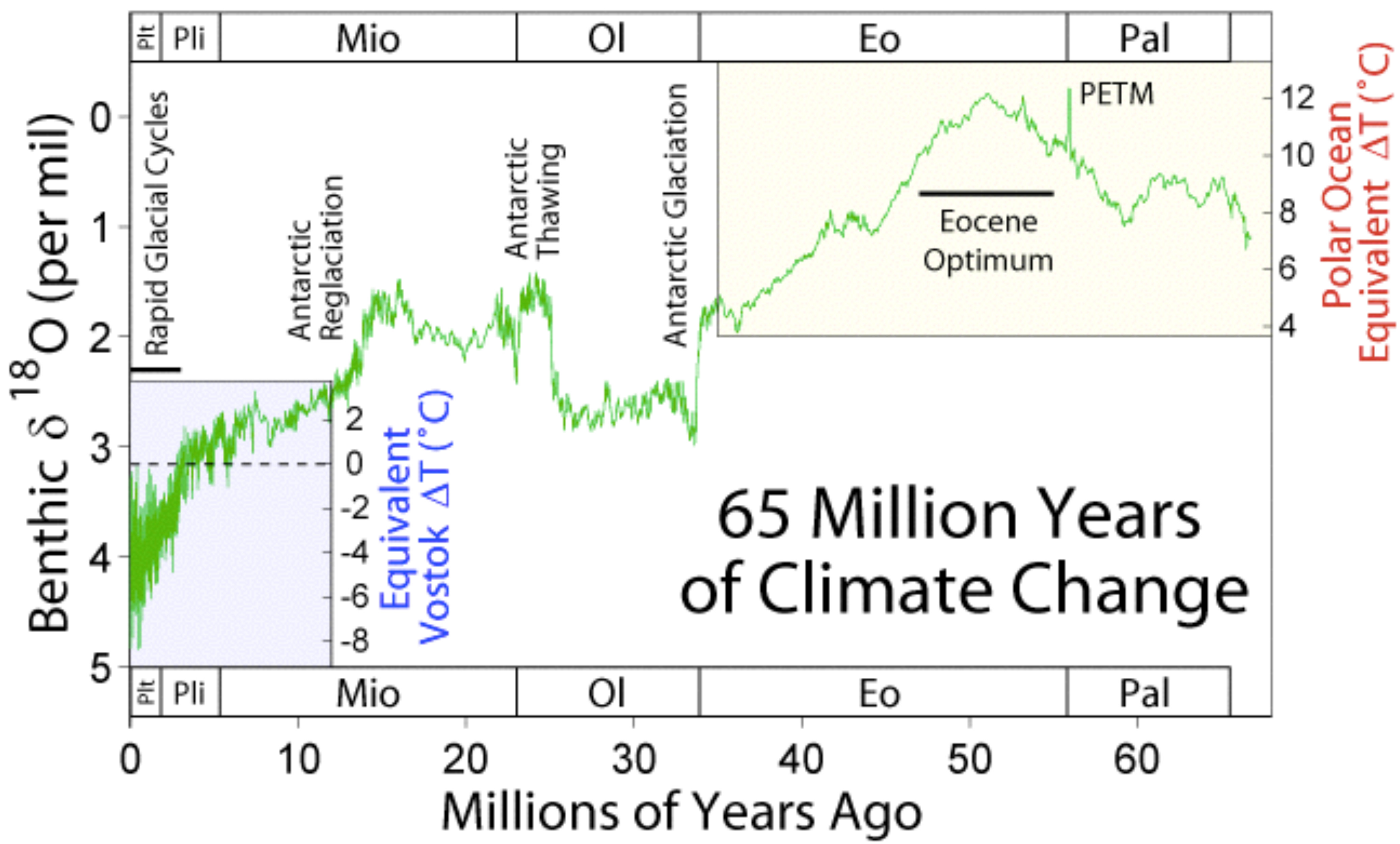
Note the maximum temperature swing in the last 50 M years - 20^0 C

The Age of Mammals

The age of mammals started out hot

- and ended up colder by ~ 12 - 20^0 C in the polar oceans

Many interesting features in this temperature record ….

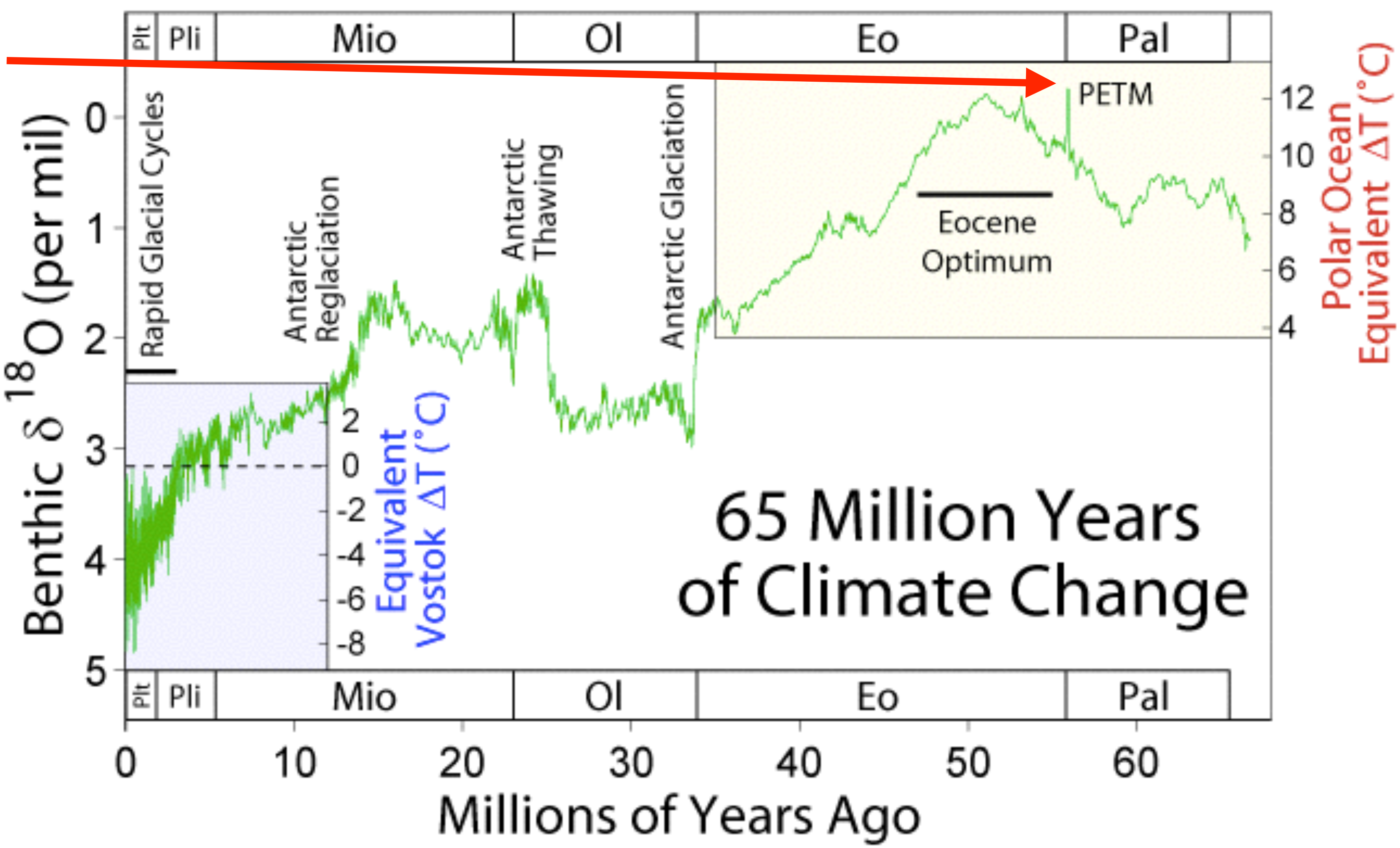


The PETM

The size of the spike is thought to be underestimated in the data because it was short (80-200K years). Postulated to be due to eruptions of methane from frozen methane ices (clathrates) at the bottom of the ocean, or to CO_2 from massive volcanic eruptions.

it is believed that arctic ocean sea surface temperature rose to ~ 23 C., and even the deep waters warmed dramatically. About 40% of sea floor organisms became extinct, and there was also a massive turnover of mammal species, resulting in the ancestors of the modern forms.

A climate catastrophe - the Paleocene-Eocene thermal maximum (PETM)



So it is possible to do **something** to the atmosphere that produces sudden, massive climate changes

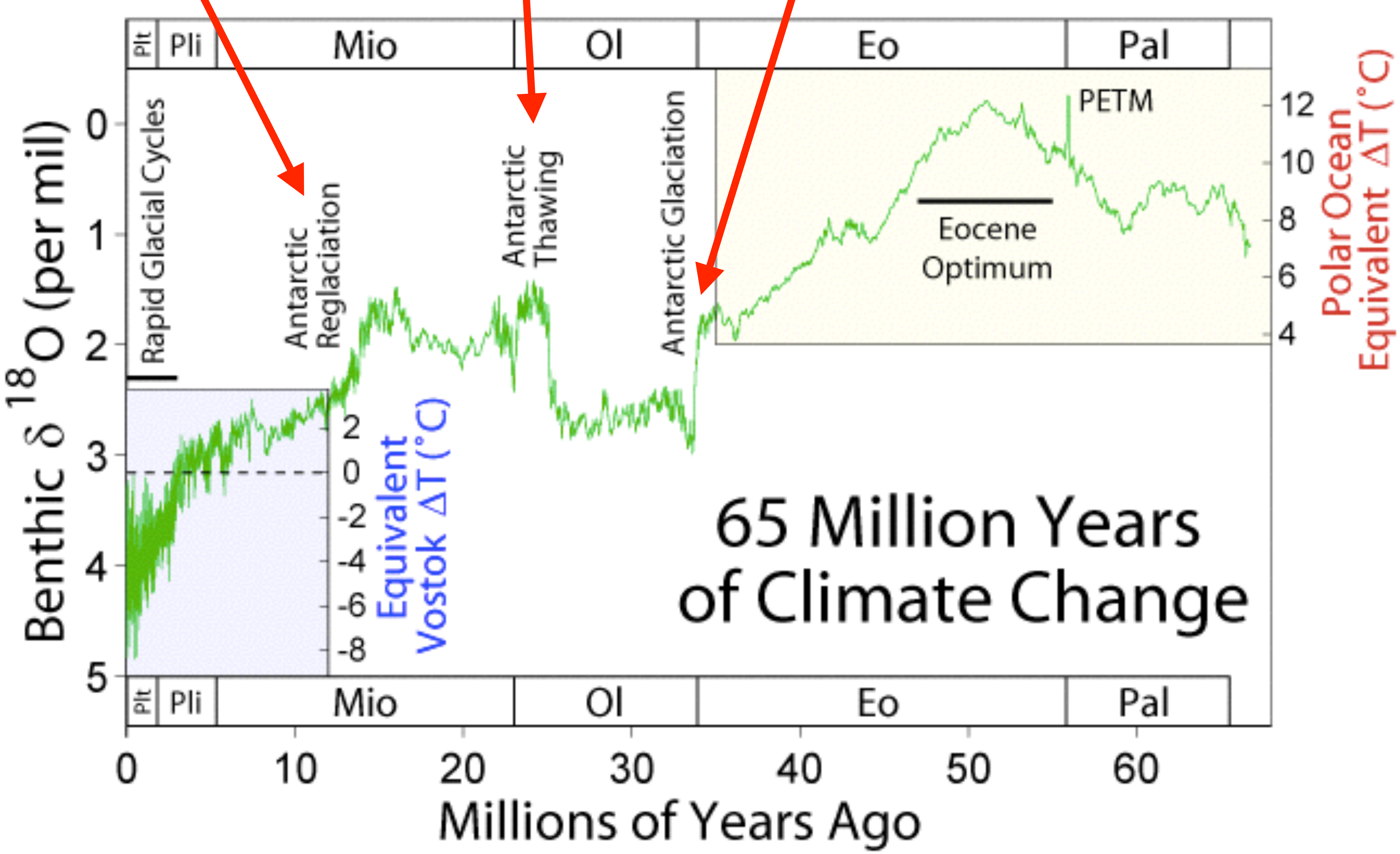
Antarctic glaciation

The Antarctic glacier forms

Melts

And forms again

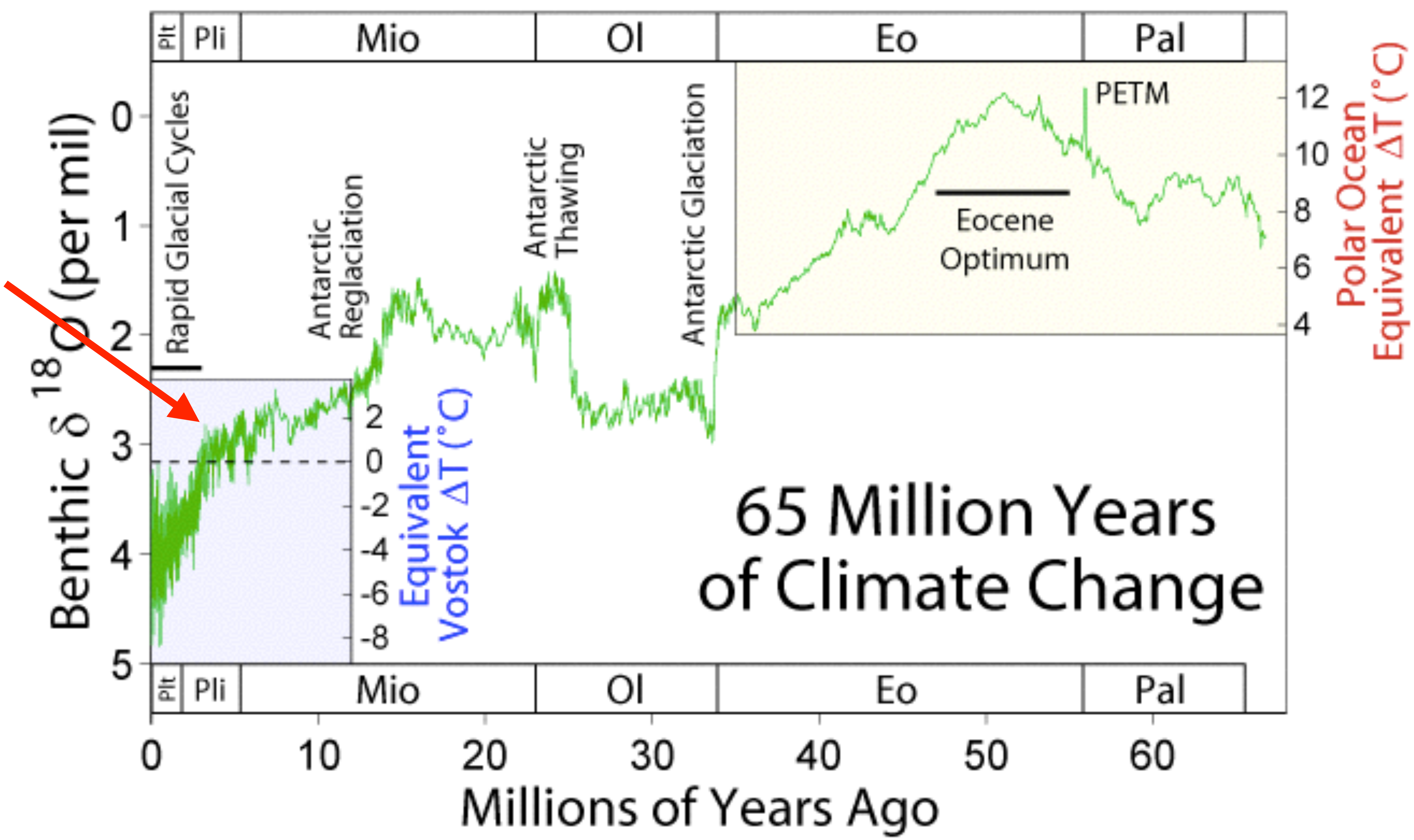
In case you were wondering if the Antarctic ice has much effect on the global temperature



The last straw …

Cutting off the polar circulation makes a difference too …

The isthmus of Panama closes ~ 3 Ma



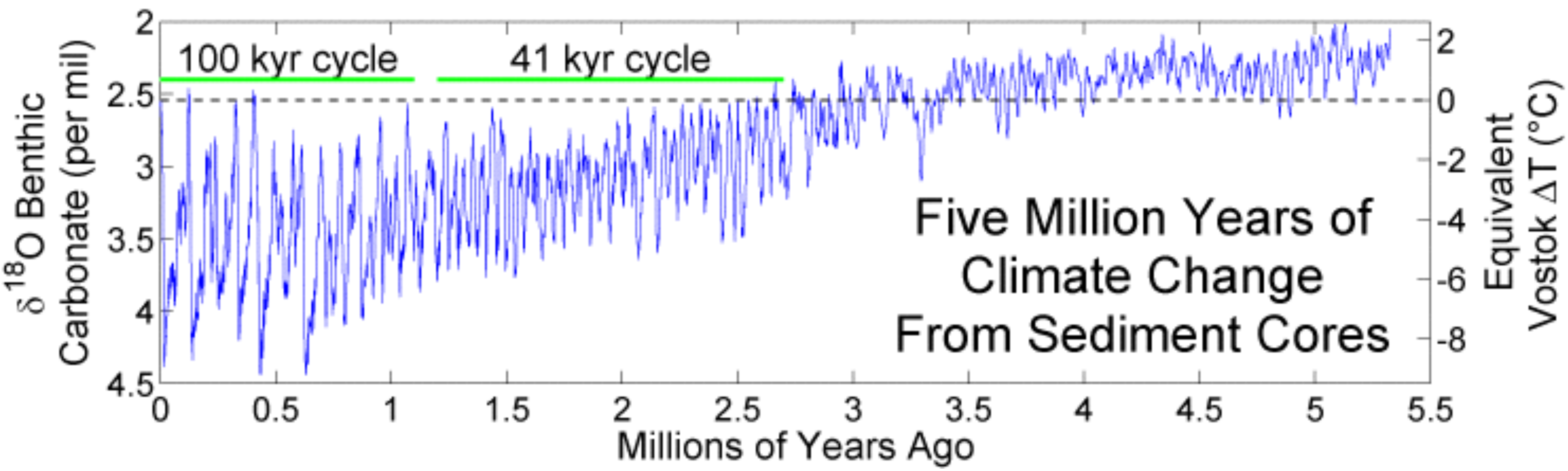
The medium term

Glacial cycles

What appears to be noise in the last few million years of this record is real. These are large temperature swings.

- From1 Ma they are up to ~ 8 degrees C on a roughly 100 kyr cycle.
- From ~2.5-1 Ma, they were smaller and on a roughly 41 kyr cycle.

These are supposedly driven by orbital mechanics (Milankovitch cycles). And they are correlated - but a detailed understanding is lacking.



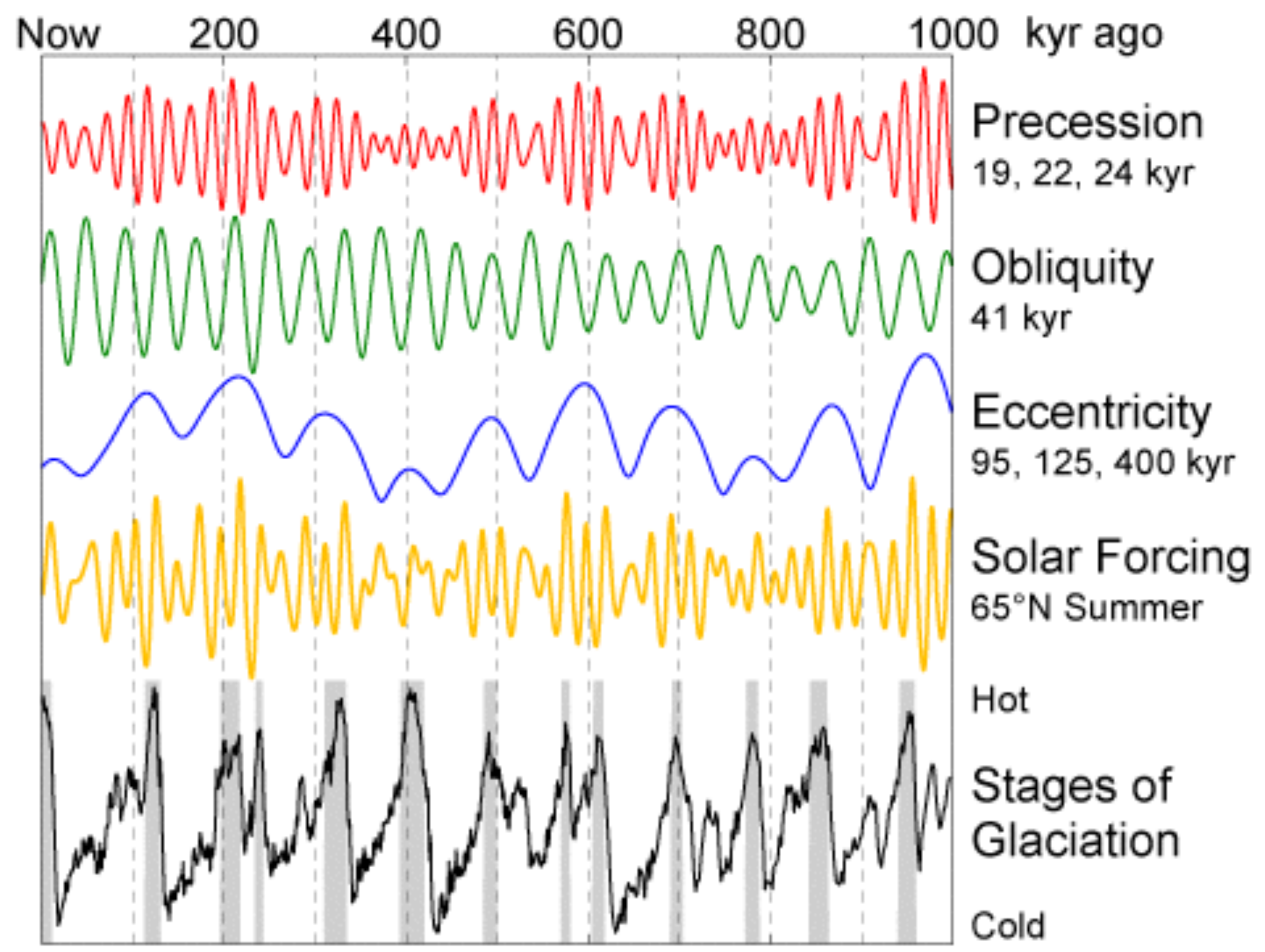
Milankovitch cycles

See for example https://en.wikipedia.org/wiki/Milankovitch_cycles

The warm periods in the last million years align (fairly) nicely with the peaks in the eccentricity cycle. This is actually a problem:

- The eccentricity is expected to produce weaker effects than precession or obliquity on the overall solar forcing.
- There are a number of other problems, including the transition from a 41K year cycle (1-3M years ago) to a 100K year cycle (1M years ago to now), which has no known cause.

These all suggest that the details are not well understood.



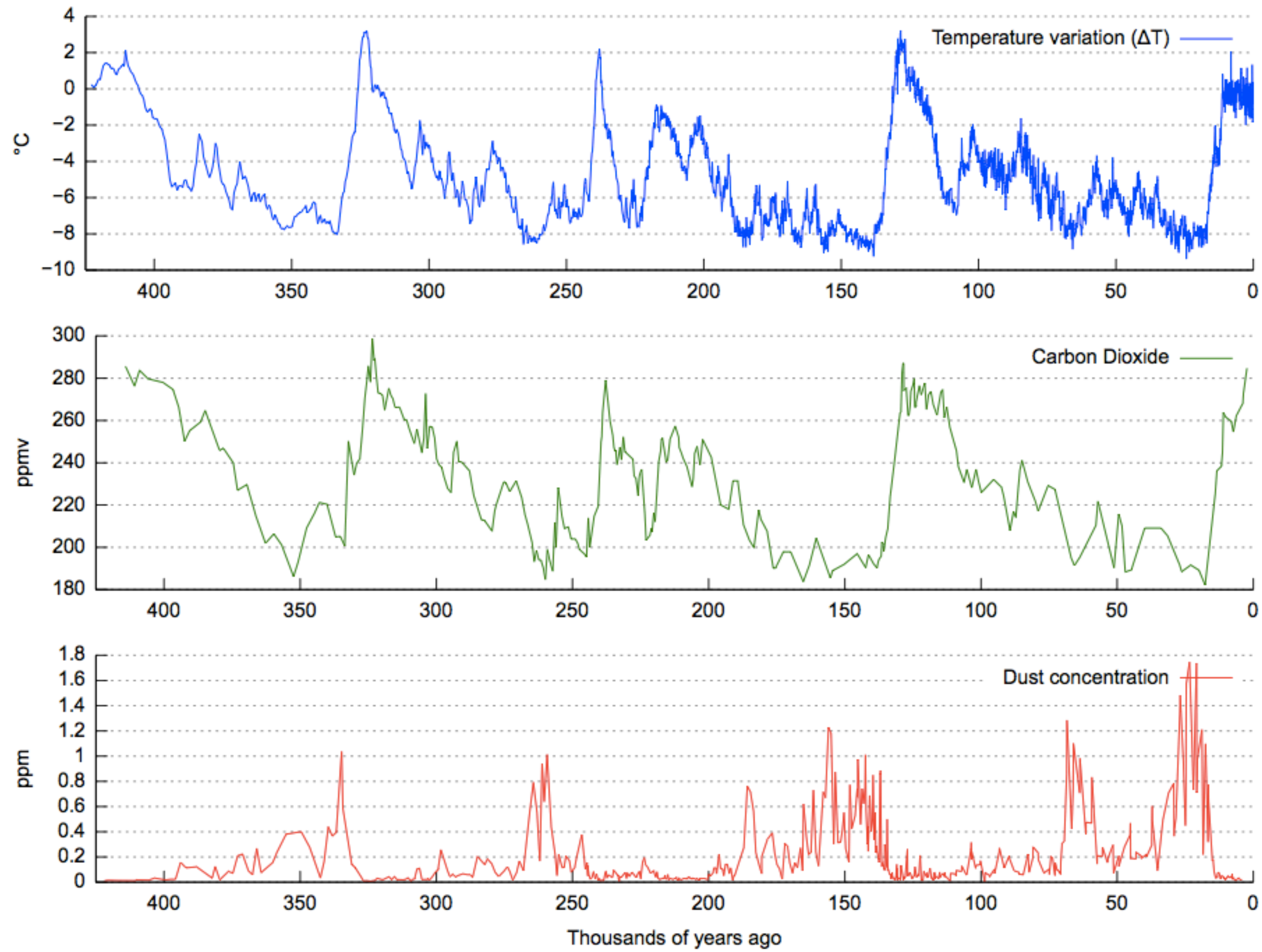
The last 450 K years

CO2, temperature and dust concentration measured from the Vostok, Antarctica ice core as reported by Petit et al., 1999.

CO_2 levels follow temperature change "with a lag of some hundreds of years" (visible on a graph more zoomed in than this);

- Among other factors, CO_2 is more soluble in colder than in warmer waters.

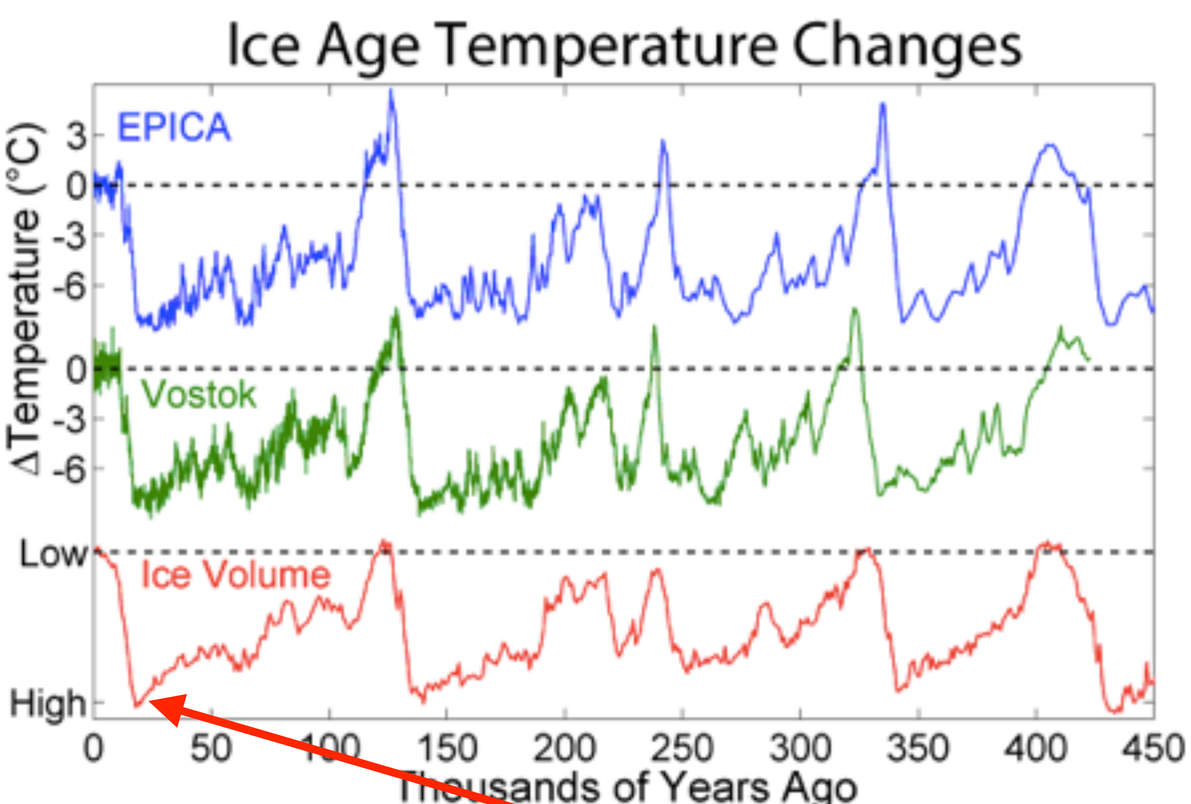
Higher dust levels are believed to be caused by cold, dry periods.

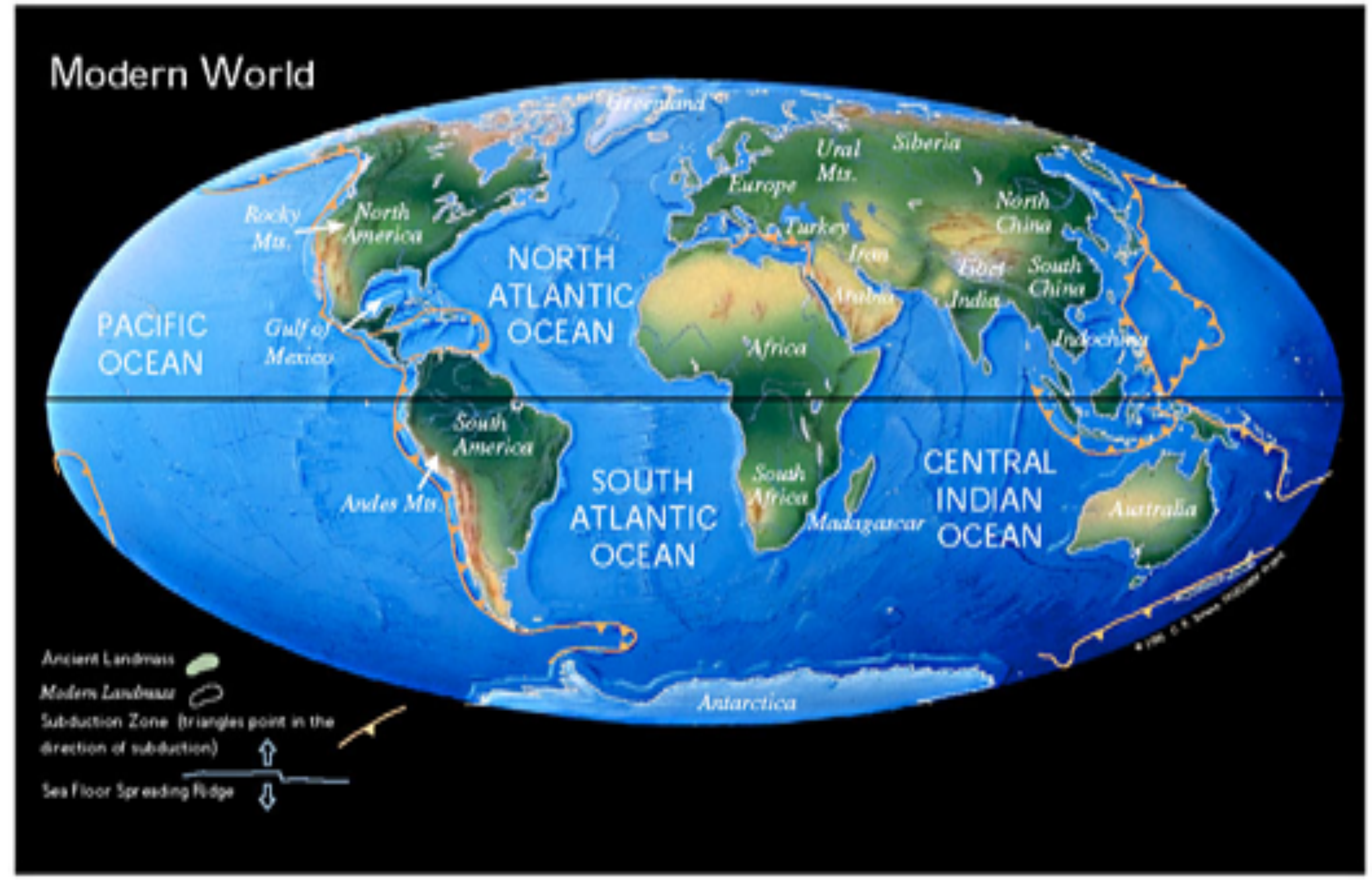


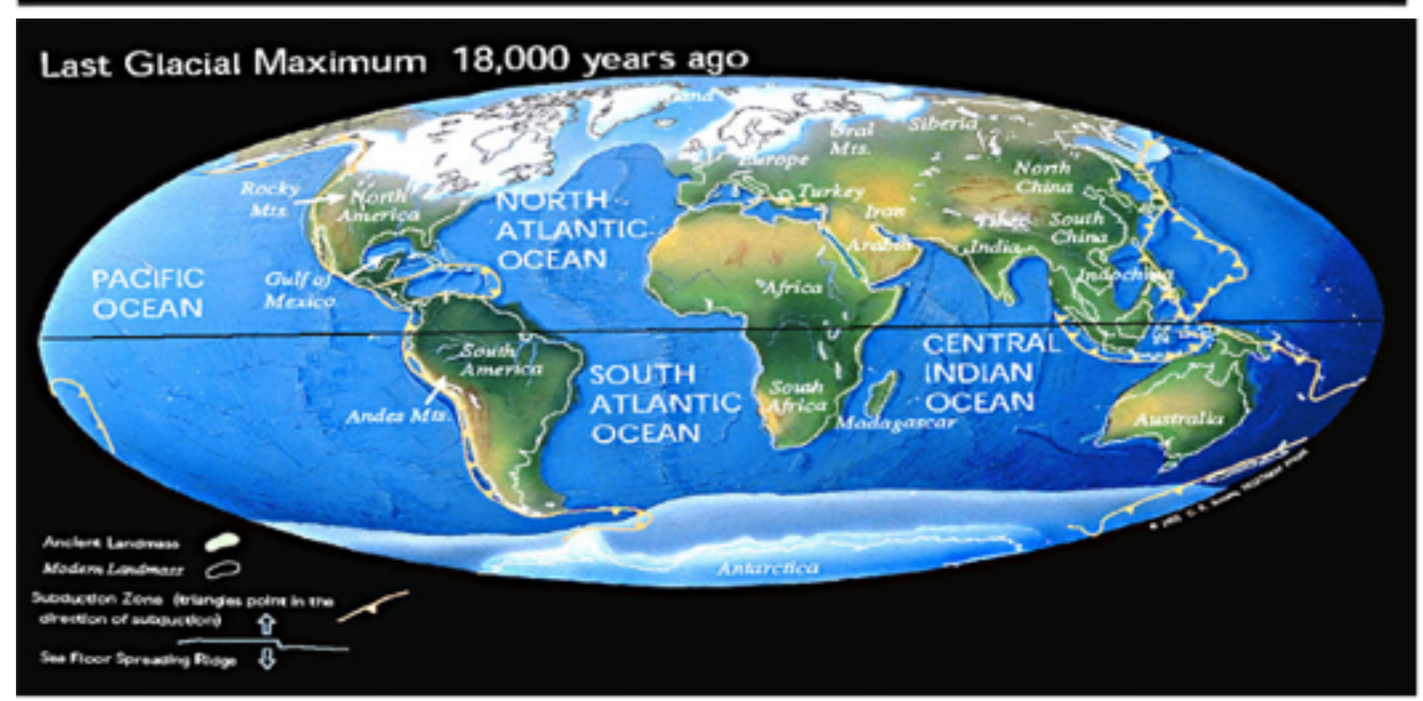
The last 450 K years

Deuterium isotopic measurements from Antarctic ice core samples.

Ice volume estimates from $^{18}O/^{16}O$ isotope ratios from a global composite of sea floor sediments.



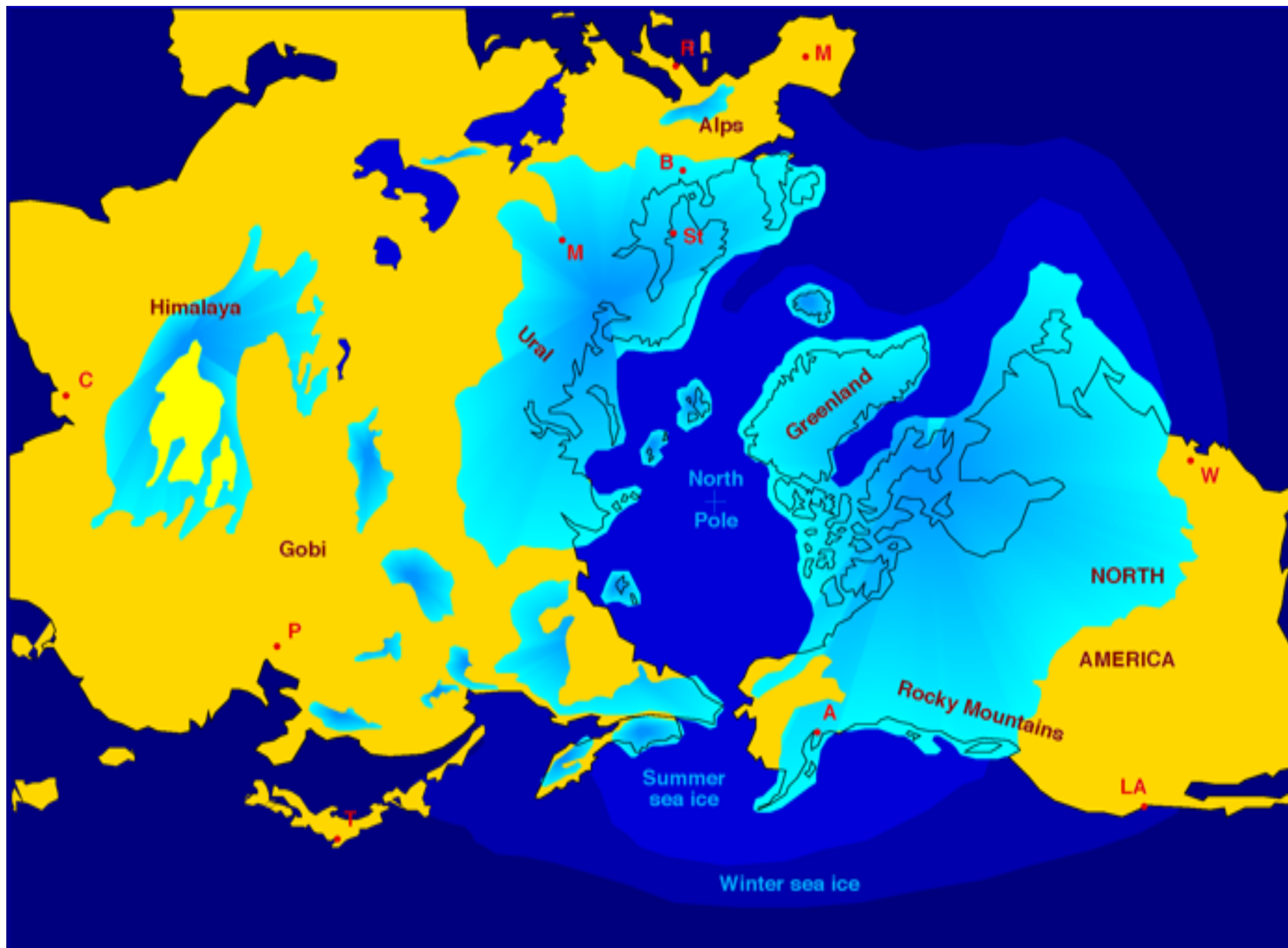


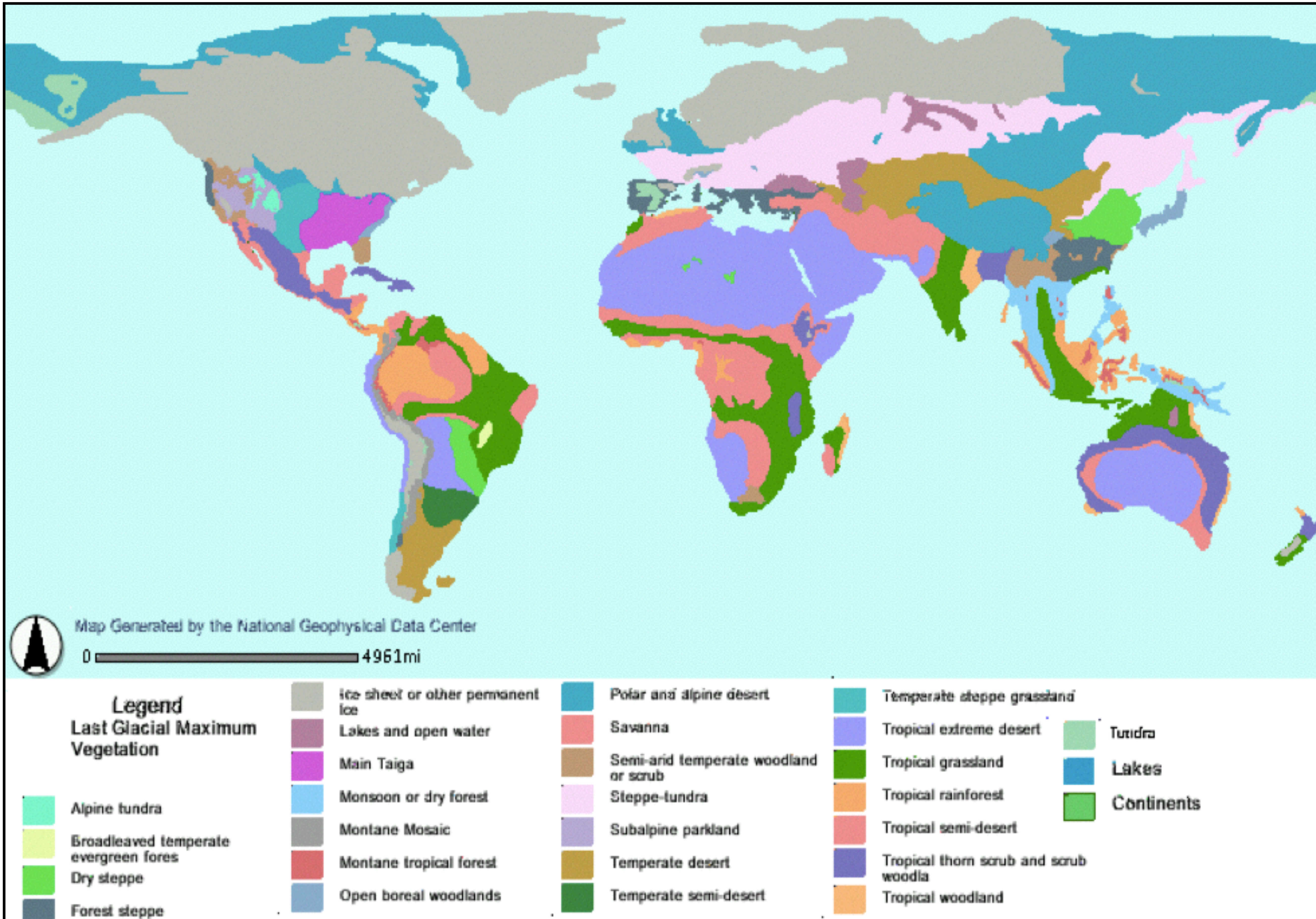


The height of the last glacial period

By Hannes Grobe, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany. See: **http://commons.wikimedia.org/wiki/Image:Northern_icesheet_hg.png**

Polar bears in Seattle. Winter sea ice off LA. Oh my!




Map Generated by the National Geophysical Data Center
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Legend
Last Glacial Maximum Vegetation
Alpine tundra
Broadleaved temperate evergreen fores
Dry steppe
Forest steppe
Ice sheet or other permanent ice
Lakes and open water
Main Taiga
Monsoon or dry forest
Montane Mosaic
Montane tropical forest
Open boreal woodlands
Polar and alpine desert
Savanna
Semi-arid temperate woodland or scrub
Steppe-tundra
Subalpine parkland
Temperate desert
Temperate semi-desert
Temperate steppe grassland
Tropical extreme desert
Tropical grassland
Tropical rainforest
Tropical semi-desert
Tropical thorn scrub and scrub woodla
Tropical woodland
Tundra
Lakes
Continents

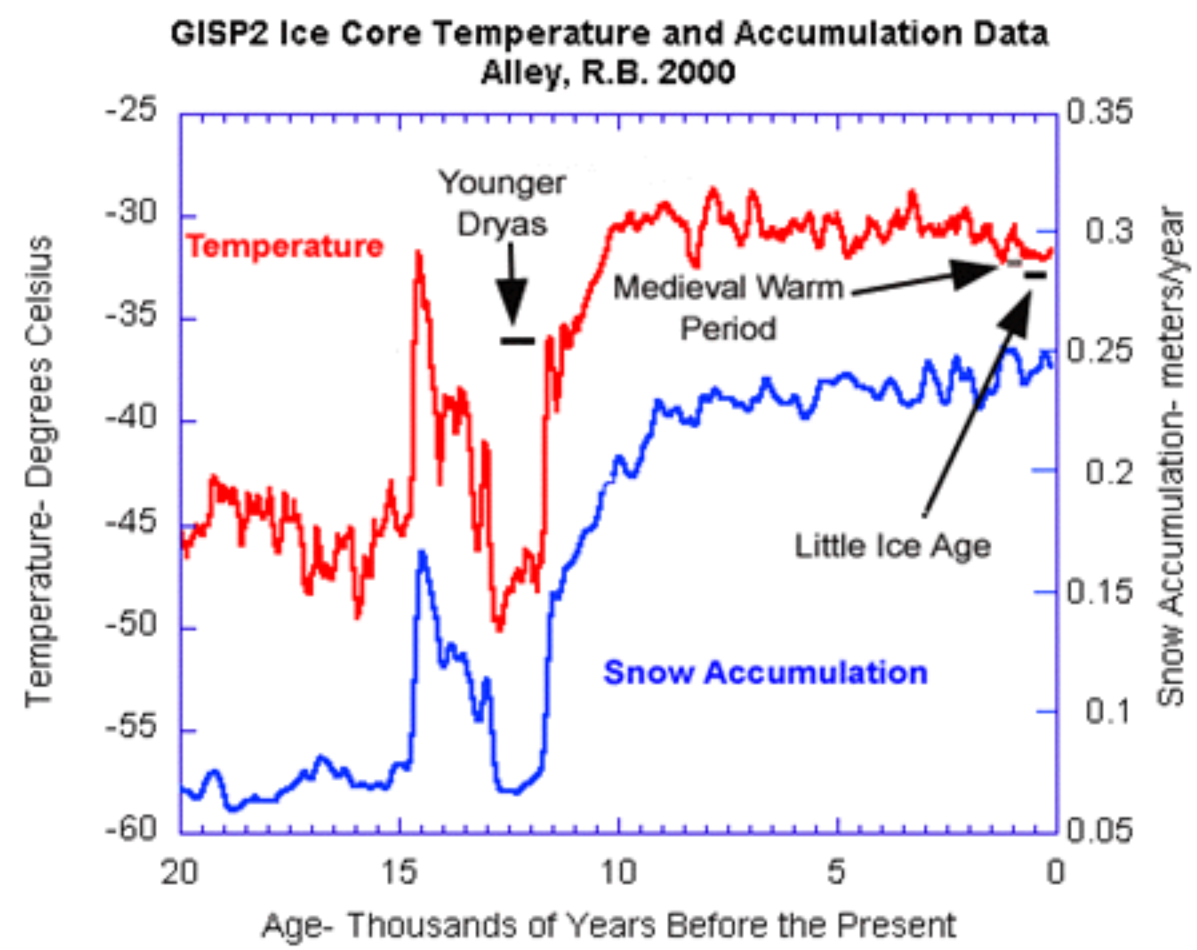
Aside: The Younger-Dryas stadial – abrupt climate change

Visible in the ice core temperature record is a **sudden interruption** of the warming leading to the present interglacial. It took place from ~12,700 to 11,500 years ago. It occurred over a decade or so. This is clear in Greenland and Northern Europe, less so in the southern hemisphere, where the timeline also seems to be different. So it may not have been global.

The prevailing theory is that the Atlantic thermohaline circulation was shut down by a sudden influx of fresh water from melting glaciers. This does not explain why South America cooled first, or why it did not happen at the start of previous interglacials.

However it does show that abrupt climate change is possible.

The Younger Dryas cold interval as viewed from Central Greenland, Richard B. Alley
Quaternary Science Reviews
Volume 19, Issues 1-5, 1 January 2000, Pages 213-226.



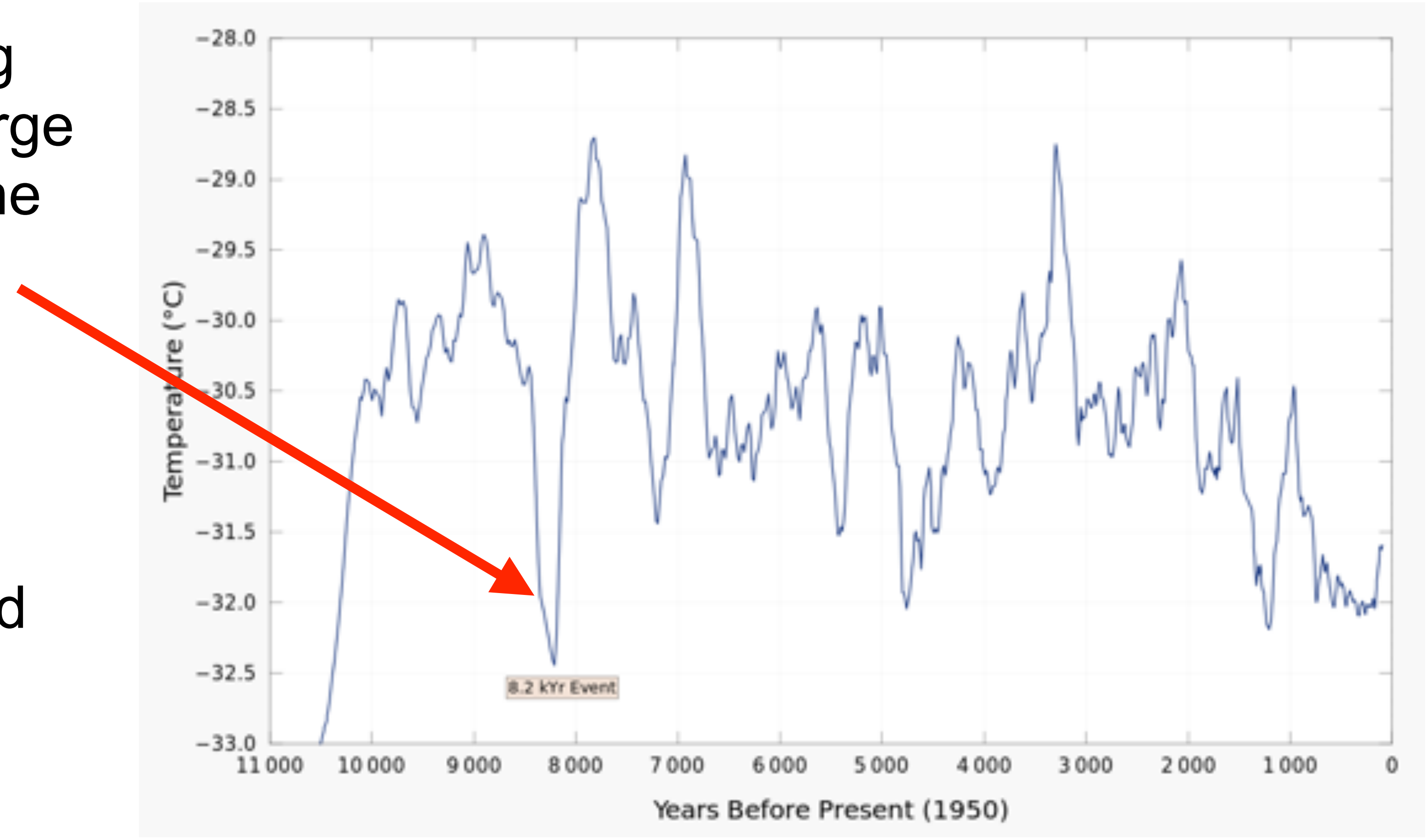
The short term - a few thousand years

The present interglacial period

Data source:http://www.ncdc.noaa.gov/paleo/pubs/alley2000/alley2000.html
From: https://en.wikipedia.org/wiki/8.2_kiloyear_event

Central Greenland temperatures during the present interglacial period show significant variation in temperature. (Note: The Antarctic temperature records indicate that the present interglacial is **relatively cool** compared to previous interglacials, at least at the sites studied.)

The 8.2 kiloyear event was a sudden decrease in global temperature, lasting 2-4 centuries. Possibly caused by a large meltwater pulse from the collapse of the Laurentide ice sheet of NE North America, most likely when the glacial lakes Ojibway and Agassiz suddenly drained into the North Atlantic Ocean.



The meltwater pulse may have affected the North Atlantic thermohaline circulation, reducing northward heat transport in the Atlantic.

It was associated with up to 4 m of (permanent) sea level rise

Historical temperature events

Two periods of unusual temperatures that were known to historians:

The **Medieval Climate Optimum** or Medieval Warm Period (MWP) was a warm period that spanned the years from ~950-1250 AD

- Increased agricultural productivity and crop diversity in northern Europe
    - Wheat cultivation and vineyards at latitudes and elevations that were far higher than today
- Viking colonization of Greenland ~ 985 - 1412
    - Started out raising cattle sheep and goats
    - Shifted to marine sources and seal hunting as temperature declined, finally left

The **Little Ice Age** (LIA) was a period of extreme cold in Europe that spanned the years from ~ 1300 - 1850 AD

- Farms and villages in the Swiss Alps destroyed by encroaching glaciers during the mid-seventeenth century.
- Canals and rivers in Great Britain and the Netherlands frequently frozen deeply enough to support ice skating and winter festivals.
    - The first River Thames frost fair was in 1607 and the last in 1814;
- Sea ice surrounding Iceland extended for miles in every direction, closing harbors to shipping.
- Crop practices throughout Europe had to be altered to adapt to the shortened, less reliable growing season, and there were many years of dearth and famine

Do these events appear in the temperature record? **Yes**.

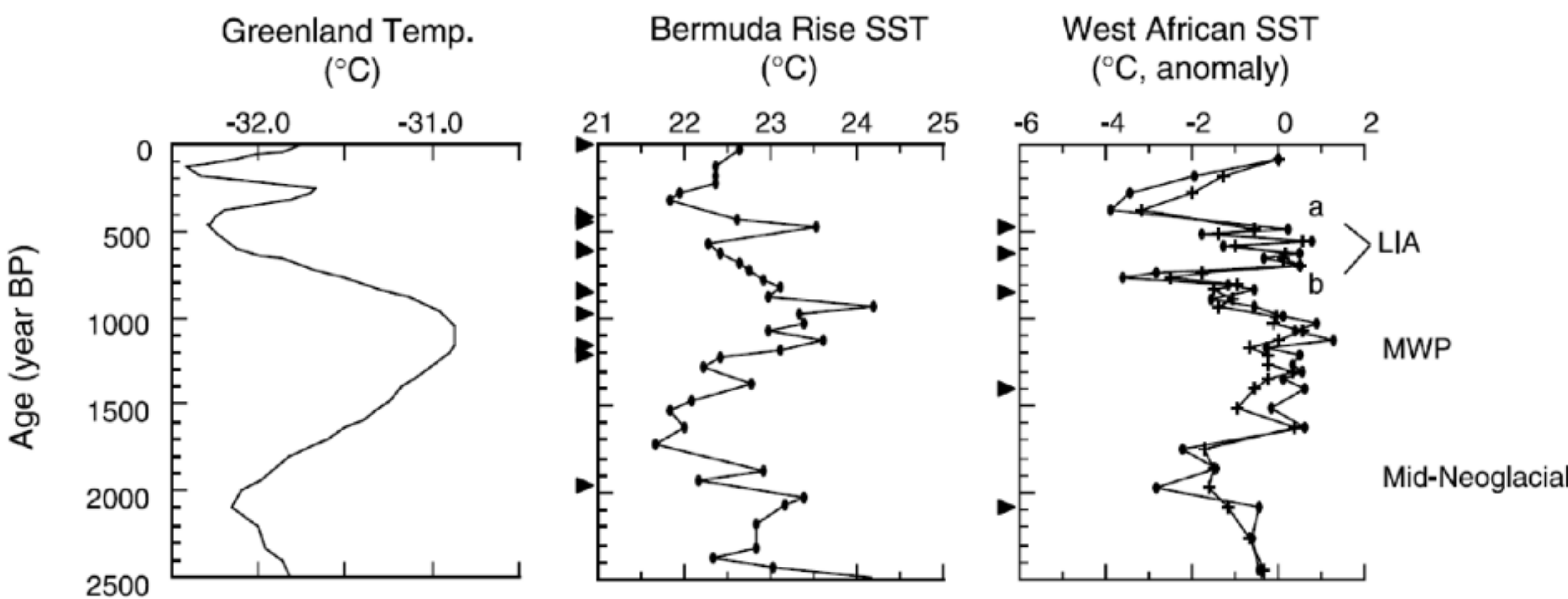
Surface temperature data

Peter deMenocal, Joseph Ortiz, Tom Guilderson and Michael Sarnthein, Science 288, 2198 (2000).

Comparison of surface temperature records from three data sets

- Greenland surface temperature data from glacier ice cores
- Oxygen isotope analyses of ^{14}C dated planktonic foraminifera in sediment cores from:
  - The Bermuda Rise in the western North Atlantic (Sargasso Sea)
  - Off Cap Blanc, Mauritania, West Africa

Indicates that the MWP and LIA occurred synchronously (within dating uncertainties) at three widely separated locations



The Sargasso Sea Sediment Core Data

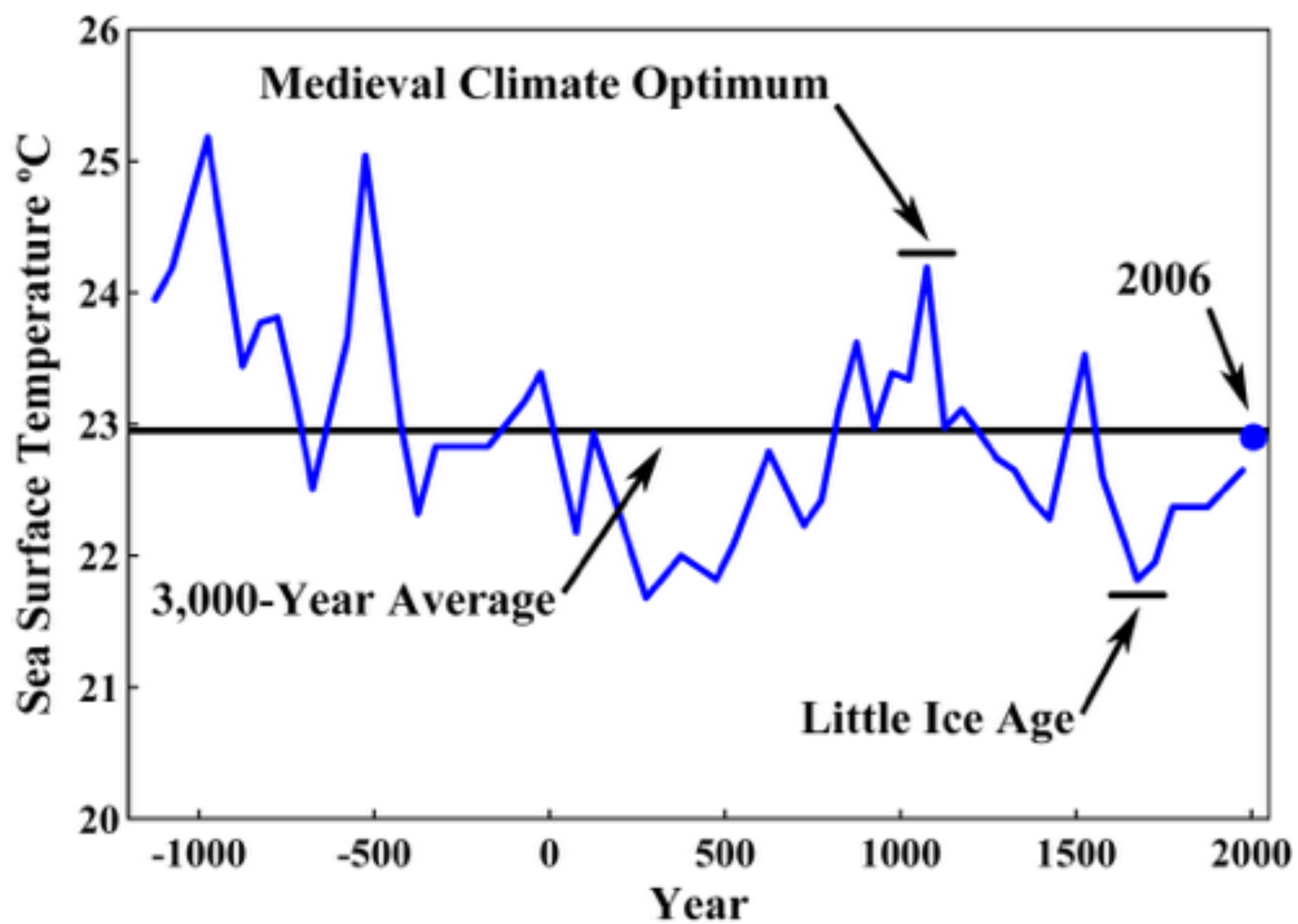
Keigwin L.D., "The Little Ice Age and Medieval Warm Period in the Sargasso Sea", Science, v.274 pp. 1504-1508, 1996

These are the data labeled “Bermuda Rise” in the previous slide.

The temperature is sampled every 67 years.

The site was chosen because the sediment layers are deposited at a high rate, and they are very stable.

The sea surface temperature difference between the MWP and the LIA is about 4^0 C in these data.

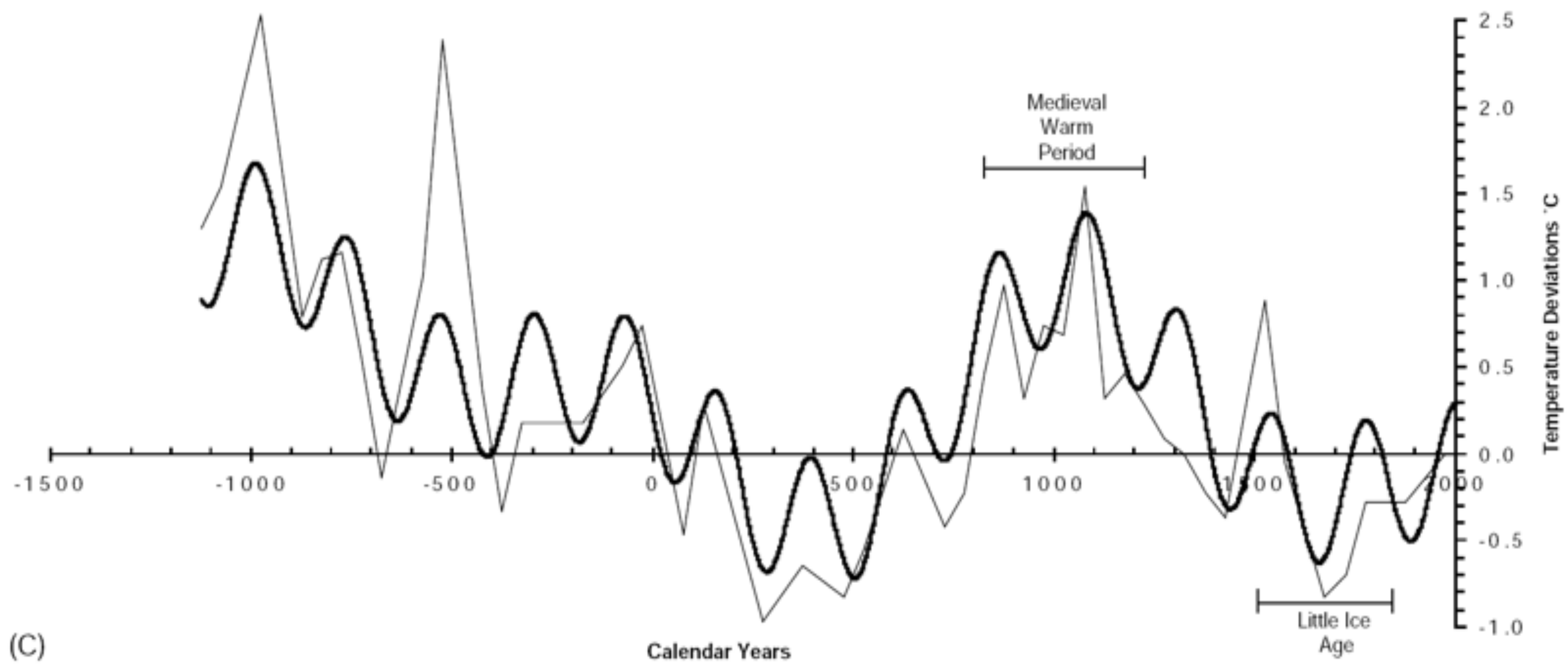


Frequency analysis (pre-1900)

C. Loehle, Ecological Modelling 171, No. 4, pp. 433-450, February 1, 2004
The Keigwin Sargasso Sea data fitted (pre-1900 only) using a model with:

- A linear cooling trend of 0.19 degrees C per thousand years.
- Periodic cycles of 1947, 1044 and 230 years.

No attempt was made to tie the cycles to solar or other cycles.

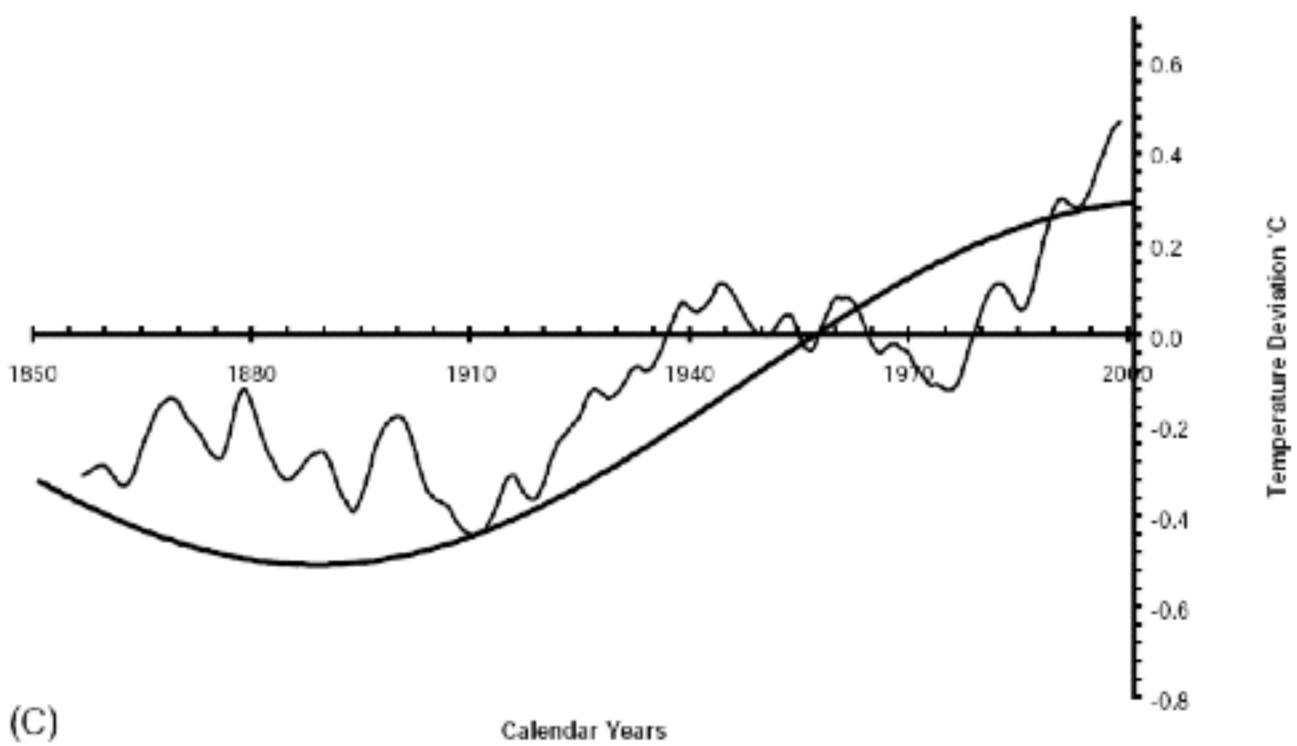


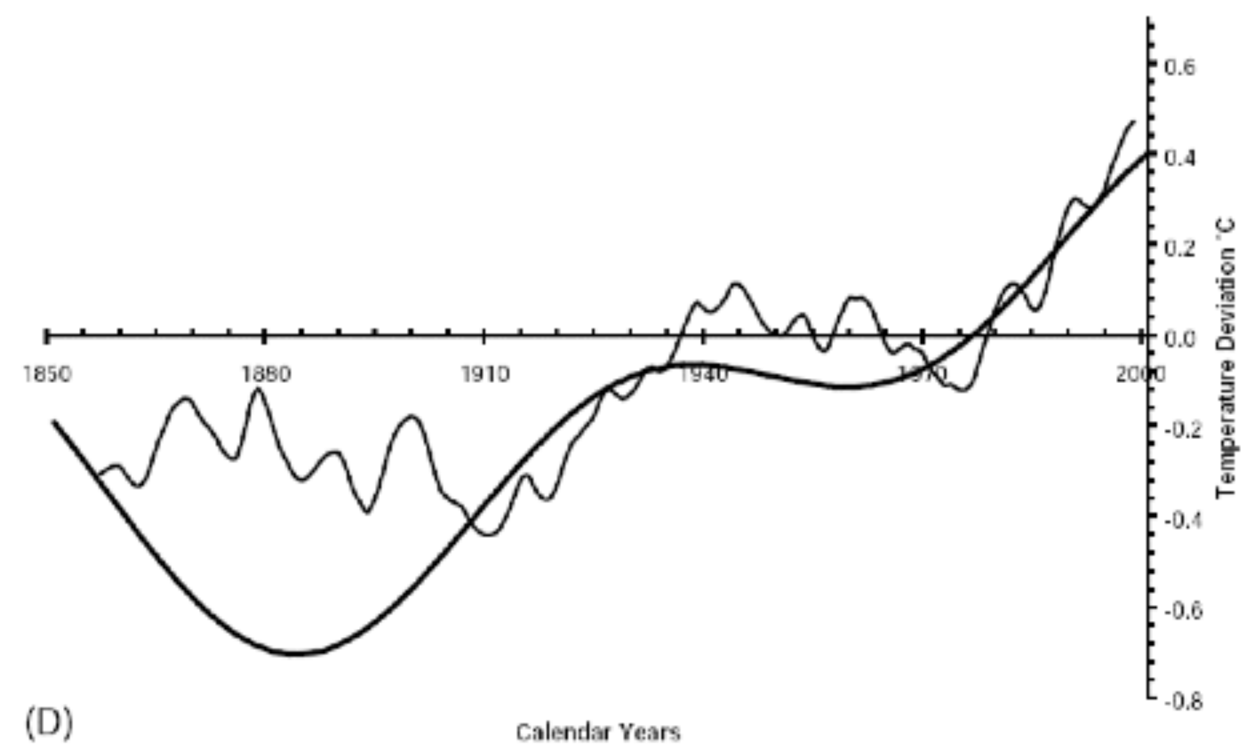
Projection of fit into1900-2000

Data from Jones et. al, (Rev. Geophys. 37, 173–199 (1999)) showing the warming during the 20th century.

Left: Model projection (fitted only to data before 1900) into the 20th century.

Right: The same model fit, plus 88 year period solar Gleissberg cycle. The Gleissberg cycle parameters are taken from other studies. (The fitted data do not have the resolution to see 88 year period effects).





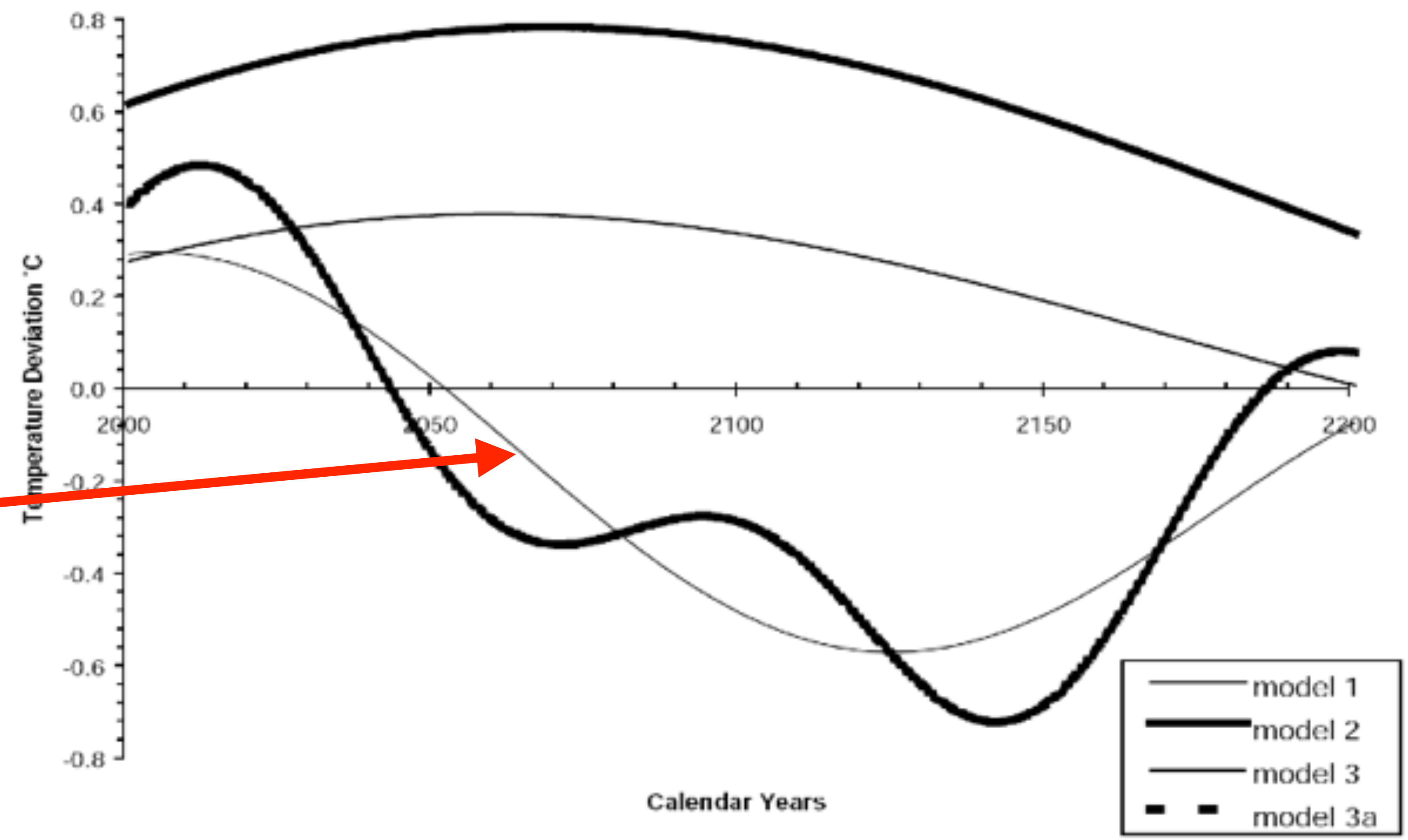
Projection of fit into 2000-2200

Projection of the fit to the Sargasso sea oxygen isotope ratio data (before the year 1900) into the next 200 years. The lowest two lines are the model fit (thin line) and the model fit plus 88 year Gleissberg cycle (thick line) from the previous slides.

The upper two curves are from fits to the data containing only longer period cycles (> 500 years).

The fit projection has the temperature leveling off now, and dropping for the next 100+ years.

We should be able to tell if that is the case within 10 years

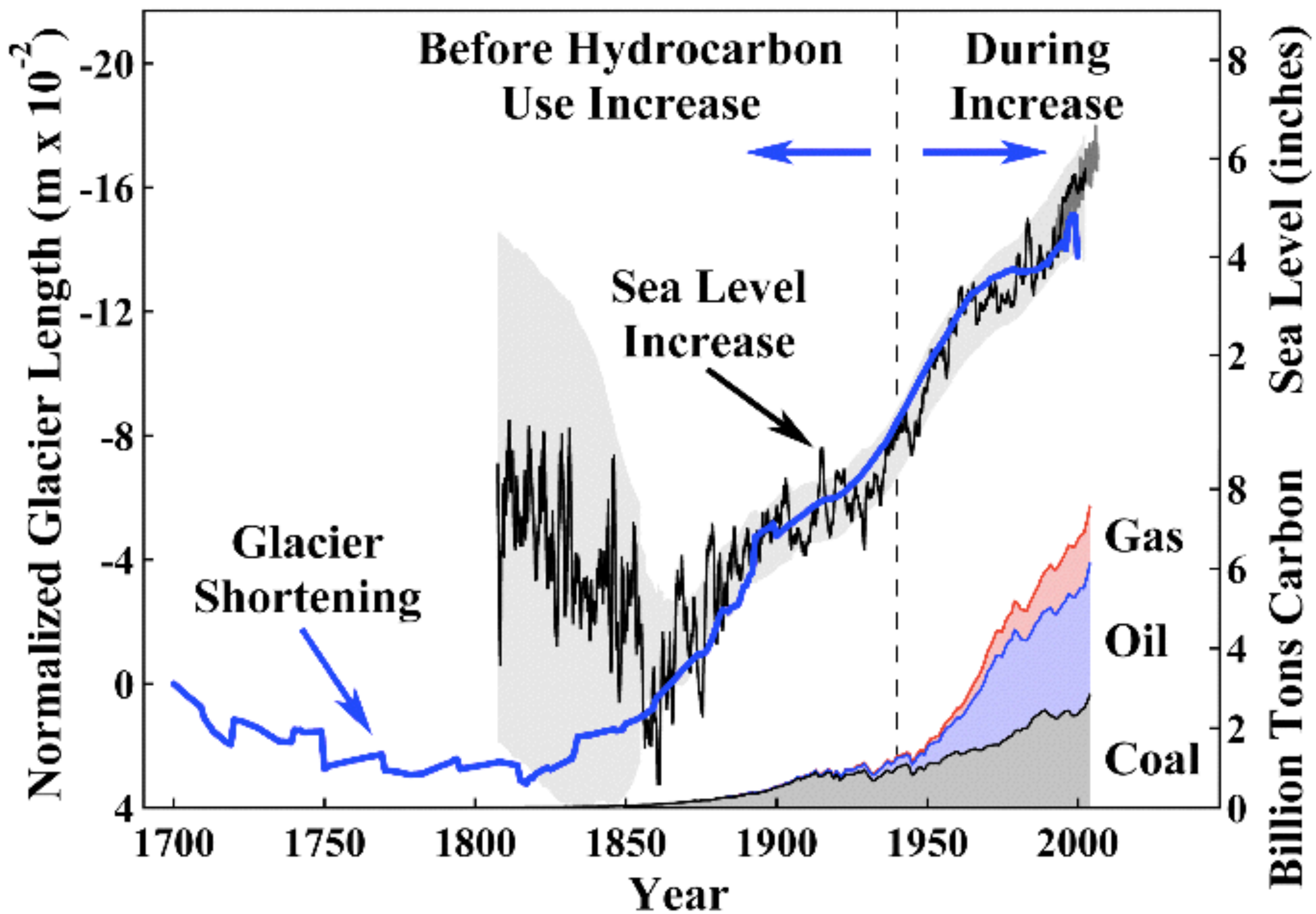


A couple of other comments

Sea level rise and glacier shortening

Compilation of data from records of sea level and glacier length

- This seems to have been going on at a steady pace since before the period of large scale industrial CO_2 production.



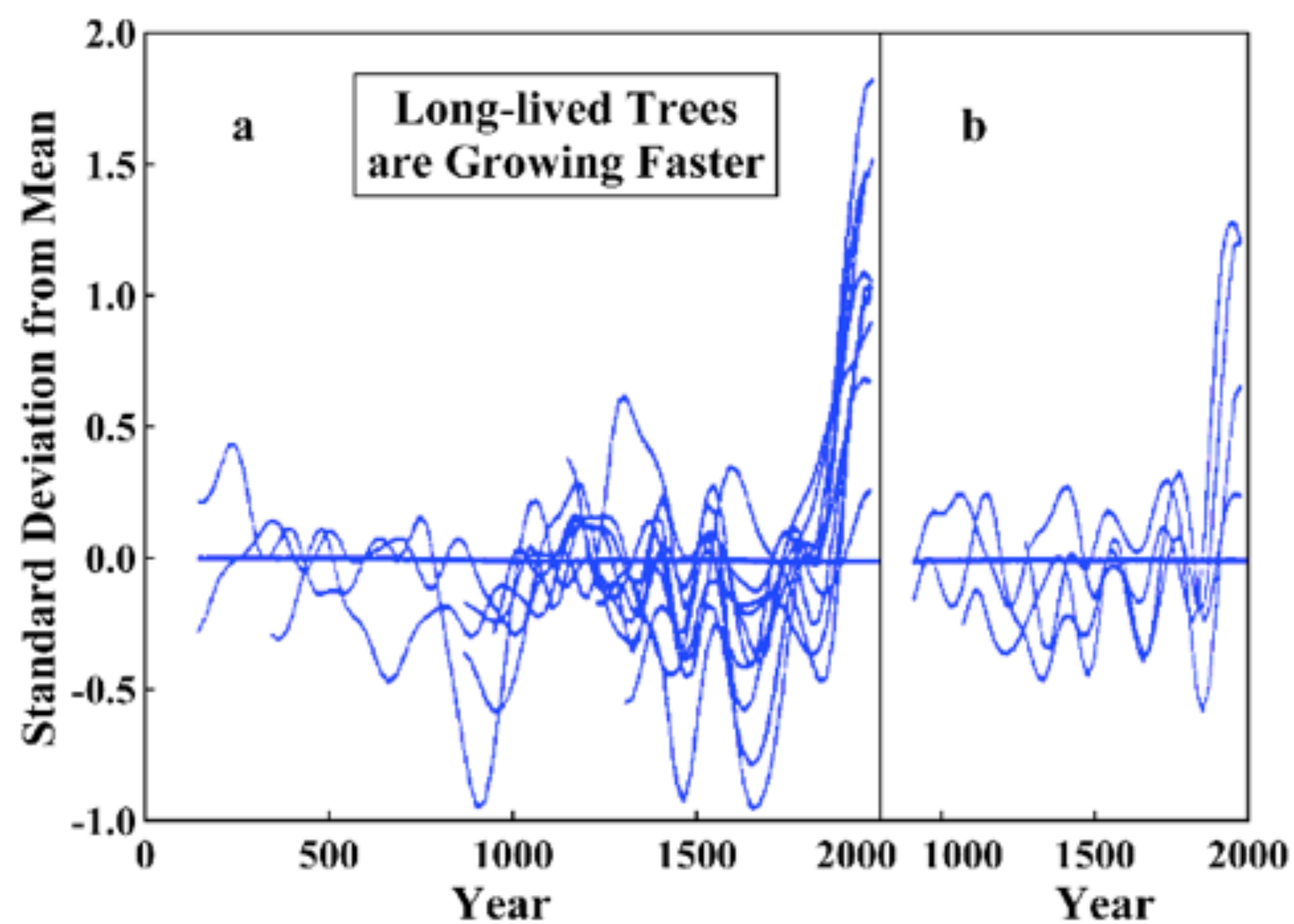
CO_2 is plant food!

Standard deviation from the mean of tree ring widths for
(a) bristlecone pine, limber pine, and fox tail pine in the Great Basin of California, Nevada, and Arizona.
(b) bristlecone pine in Colorado (110).

Tree ring widths were averaged in 20-year segments and then normalized so that the means of prior tree growth were zero. The deviations from the means are shown in units of standard deviations of those means.

CO_2 is not an environmental poison.

It has large positive ecological effects.



What might cause this climate variability?

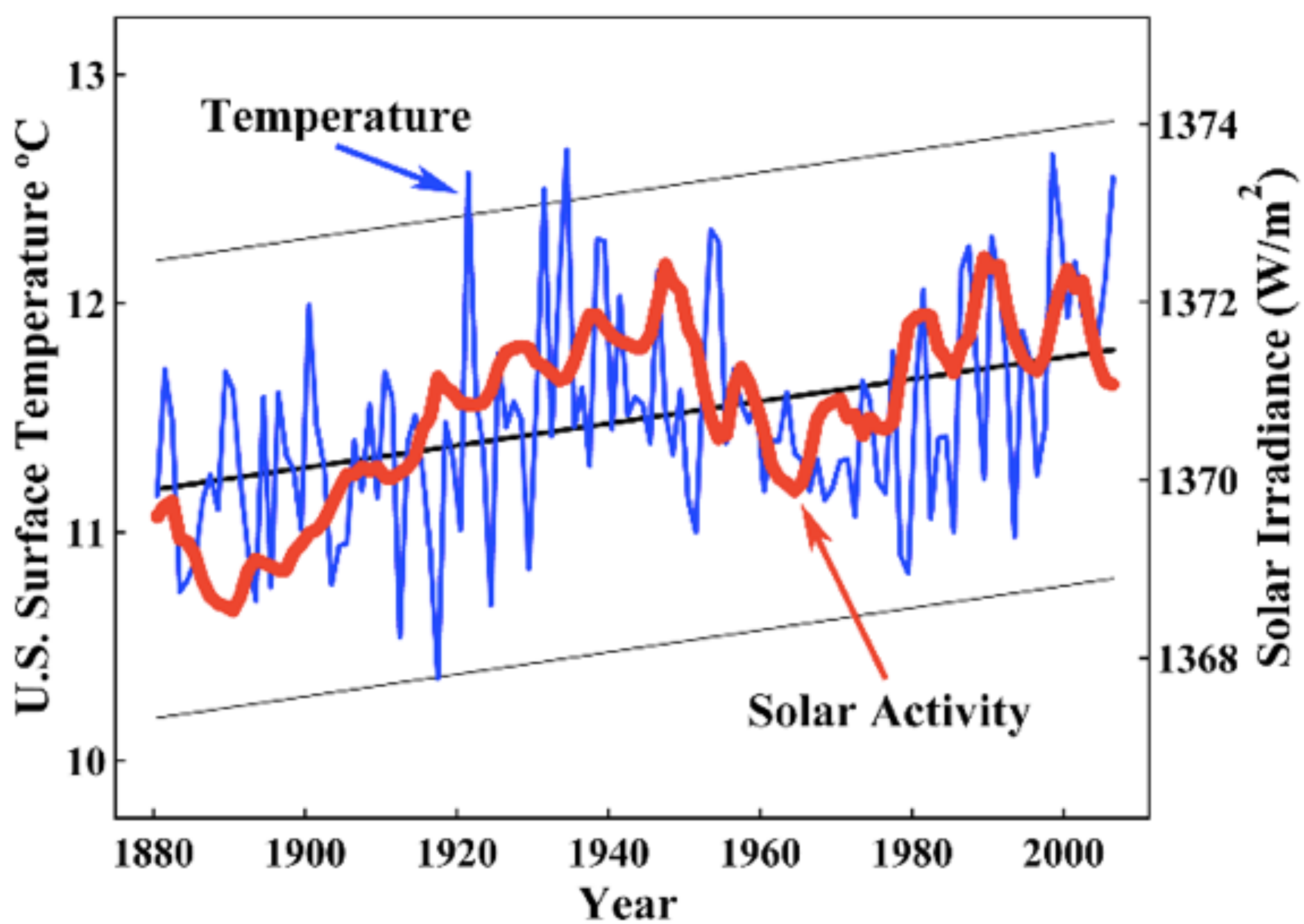
The sun?

The variations of temperature with time over the last 130 years or so seem to correlate well with solar activity.

But there is a problem. The variations in solar irradiance do not seem to be **large enough** to explain the temperature variations.

However the sun does more than just shine.

The **solar wind** also shields us from **galactic cosmic rays**.



The solar wind

The magnetic field of the sun is interwoven with the solar wind, a plasma off mainly protons and electrons that "evaporate" from the solar atmosphere

The solar wind changes from supersonic to sub-sonic at the termination shock (believed to be at about 200 AU). The part of space inside this is called the **Heliosphere**

Because of the magnetic field of the Heliosphere, only some **galactic cosmic rays** (GCR) penetrate to the inner part of the solar system

If Solar activity was constant, the GCR flux on Earth would be constant. But the magnetic activity of the sun varies (for example every 11 years the suns magnetic field reverses), and the GCR flux varies with the solar cycles.

- When the sun is active the magnetic field is stronger and fewer GCR arrive at Earth.
- When the solar activity is low, the field is weaker and more GCR arrive at Earth.

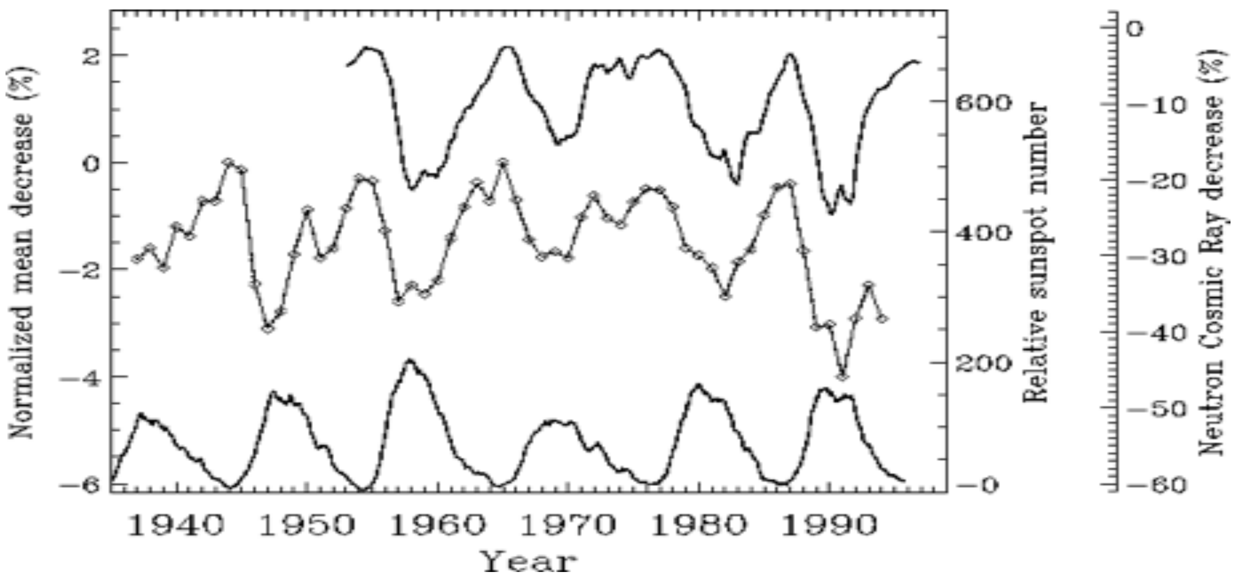
Cosmic rays, the sun and clouds

Top curve: cosmic ray flux from the neutron monitor in Climax, Colorado (1953 -- 1996).

Middle curve: annual mean variation in Cosmic Ray flux as measured by ionization chambers (1937 -- 1994). The neutron data has been normalized to May 1965, and the ionization chamber data has been normalized to 1965.

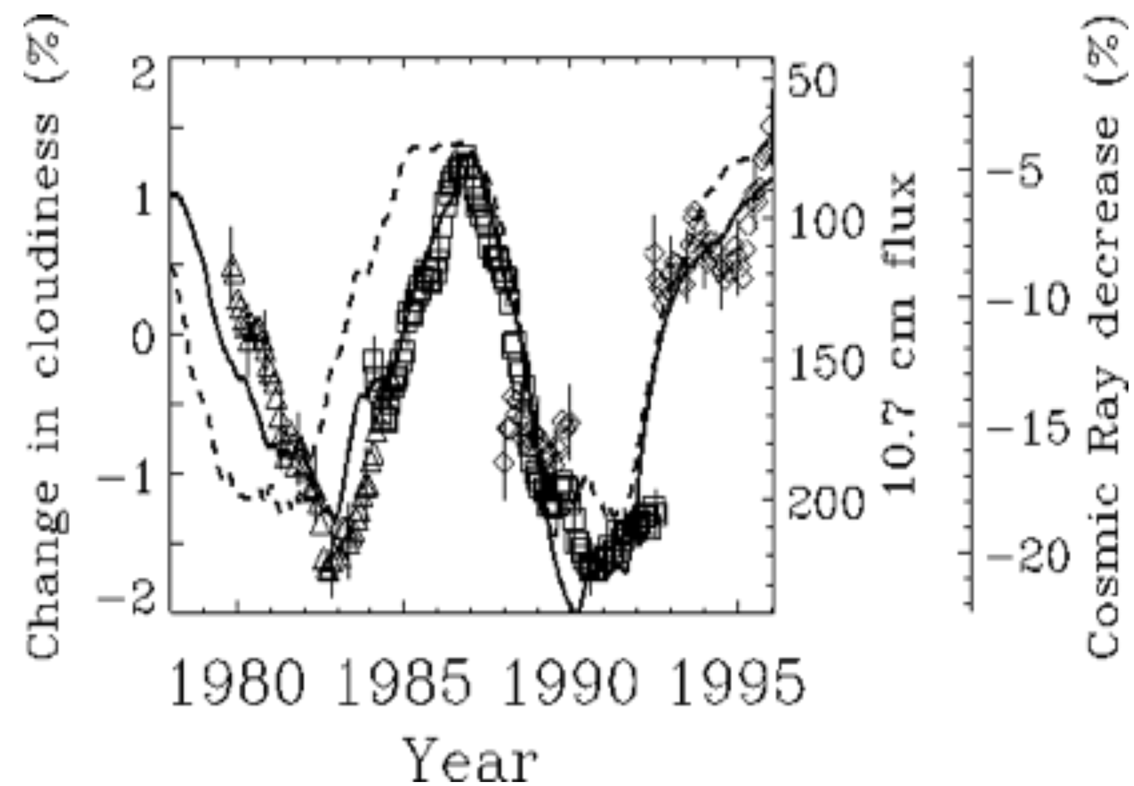
Bottom curve: relative sunspot number.

Note: though there is a clear solar cycle modulation of the Cosmic ray flux, the amplitudes are not well correlated.



Changes in Earth's cloud cover from four satellite cloud data sets together with cosmic ray fluxes from **Climax** (**solid curve**), and **10.7 cm Solar flux** (**broken curve**). Triangles - Nimbus-7 data, squares - ISCCP_C2 and ISCCP_D2 data, diamonds - DMSP data.

Data have been smoothed using a 12 month running mean. The Nimbus-7 and the DMSP data are total cloud cover for the Southern Hemisphere over oceans, and the ISCCP data have been derived from geostationary satellites over oceans, tropics excluded.



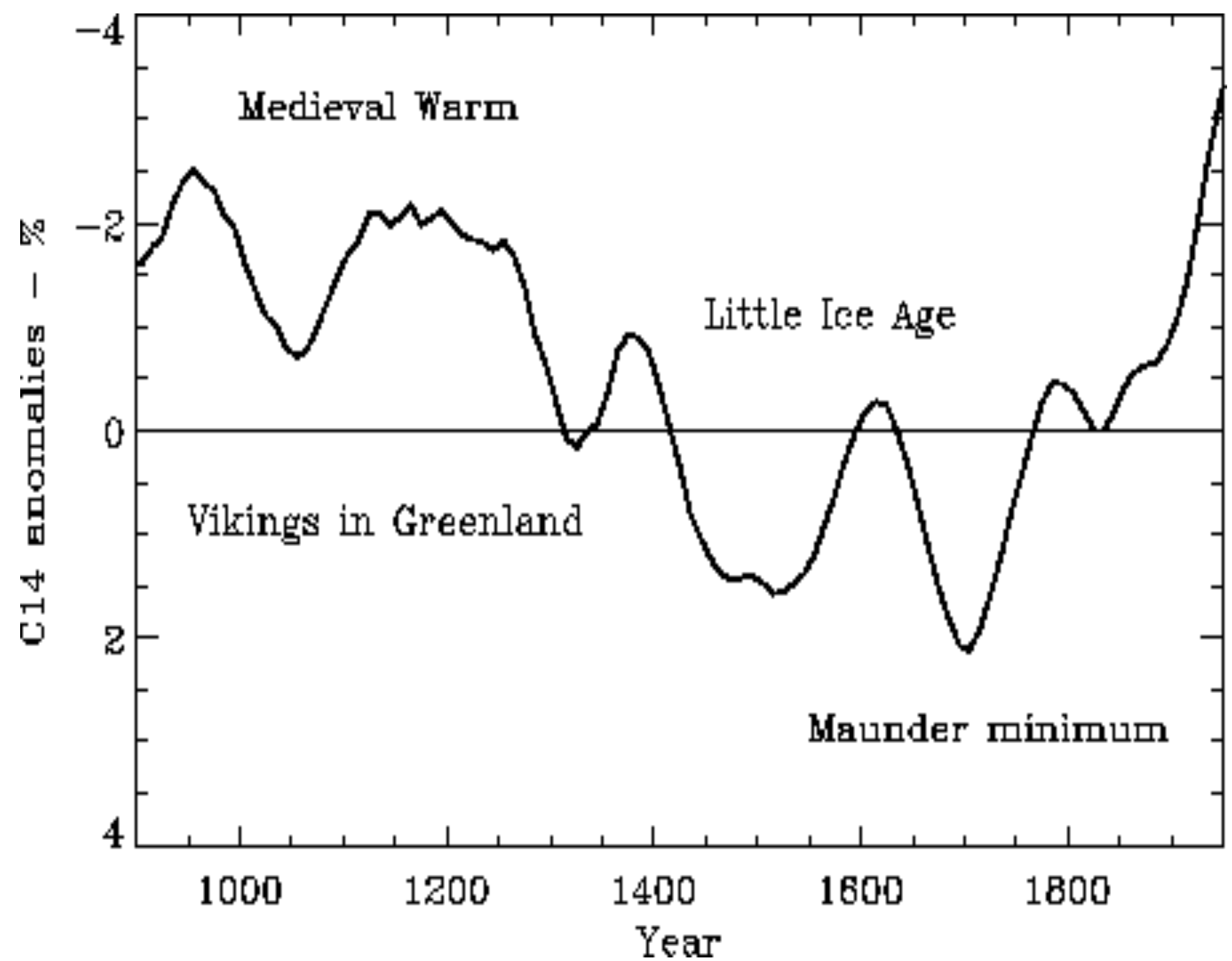
Variation in ^{14}C abundance versus time

From Henrik Svensmark , Danish Space Research Institute, Juliane Maries Vej 30,DK-2100 Copenhagen. http://www.dsri.dk/~hsv/Noter/solsys99.html

Production of ^{14}C during the last 1000 years. The variation in ^{14}C production is caused by changes in solar activity. When solar activity is high the production of ^{14}C is low, due to the shielding effect of the solar wind against cosmic rays.

Note that the axis for the ^{14}C production has been reversed. The **Maunder minimum** refers to the period 1645 -- 1715 when very few sunspots where observed on the sun. In this period the production of ^{14}C was very high, in agreement with a low solar activity and large GCR flux.

14C anomalies and time line are from tree ring data



Cosmic rays and wheat prices

Pustilnik and Din, Solar Phys. 223 (2004) 335. Analysis of medieval wheat prices in England versus ^{10}Be concentrations in Greenland ice core samples

This is just a cute idea!

Wheat is a marginal crop in England, so it has a non-linear response to weather conditions.

Limited supply from the continent in medieval times means extreme sensitivity to wheat production in England.

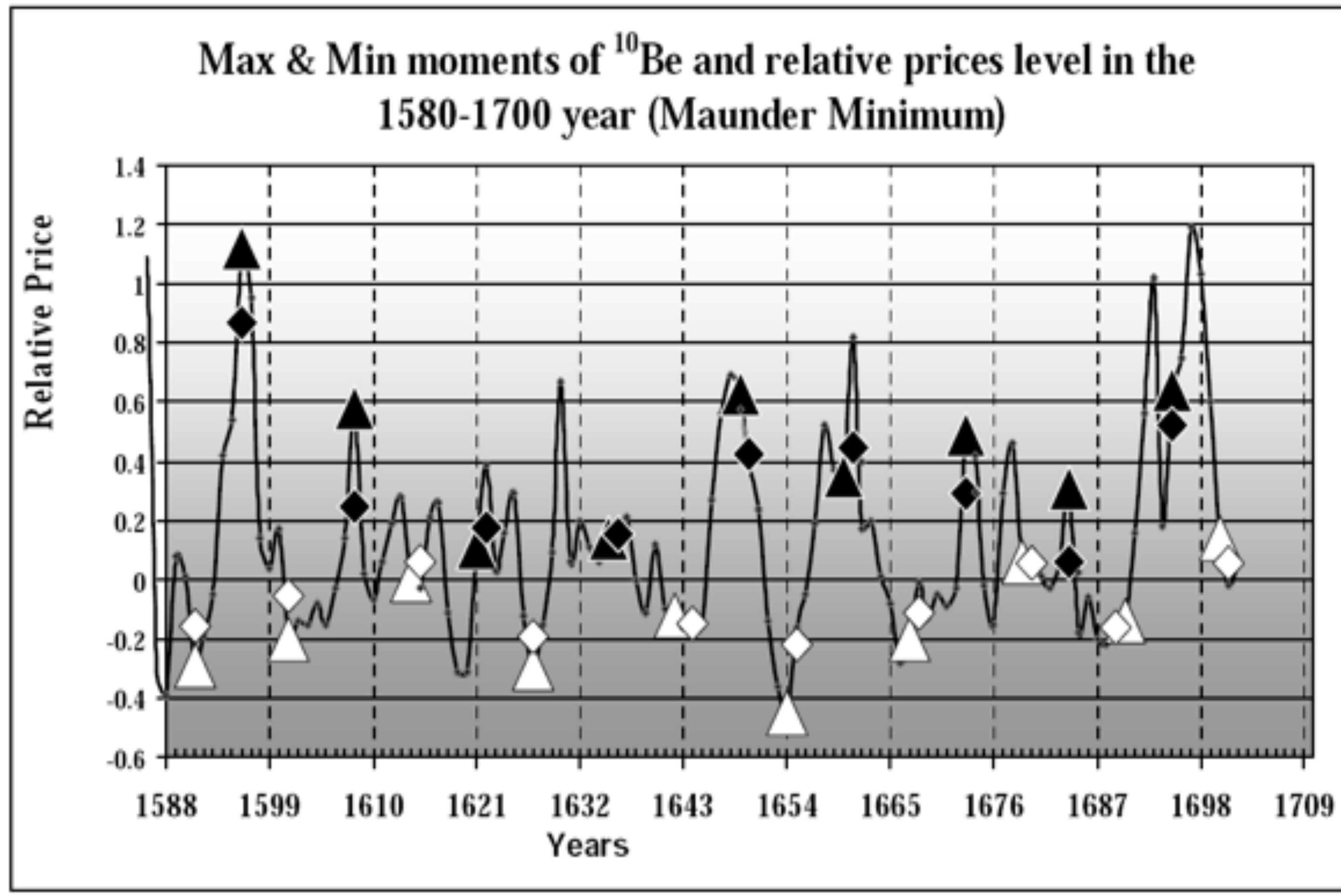


Figure 9. Consistent differences in prices at moments of maximum and minimum states of solar activity (1600-1700). White and black rectangles are prices averaged for 3-years intervals centered on moments of maximum and minimum of solar activity, white and black triangles are prices in the moment of the maximum and minimum.

The CLOUD experiment

The “Cosmics Leaving Outdoor Droplets” (CLOUD) experiment at CERN:
http://home.cern/about/experiments/cloud

It is a sophisticated cloud chamber designed to be able to mimic the temperature conditions anywhere in the atmosphere in a very clean environment.

- Allows the study of the effects of small concentrations of atmospheric aerosols

“Cosmic Rays” are supplied by the CERN Proton Synchrotron.

It is intended to remove much of the uncertainty about the role of clouds in climate - currently the largest uncertainty in climate models.

CLOUD motivation

From the introduction to the CLOUD proposal:

"If a causal connection between GCR intensity and low cloud cover were to be confirmed, it could have profound consequences for our understanding of the solar contributions to the current global warming. During the 20th century the Sun's magnetic activity increased dramatically and the solar wind more than doubled in strength [11]. As a consequence, the mean GCR intensity on Earth diminished by about 15%. The implied reduction in low cloud cover by about 1.3% absolute could have given rise to a radiative forcing of about +0.8 Wm^{-2}, which is comparable to the estimated total anthropogenic forcing of about +1.3 Wm^{-2}."

The proposal introduction has a nice discussion of background material.

- I will show a few of the figures here.

From the CLOUD proposal

Monthly mean values for the global absolute variations of infra red (IR) cloud coverage for **low** (>680 hPa) clouds (solid lines) compared with cosmic ray intensity.

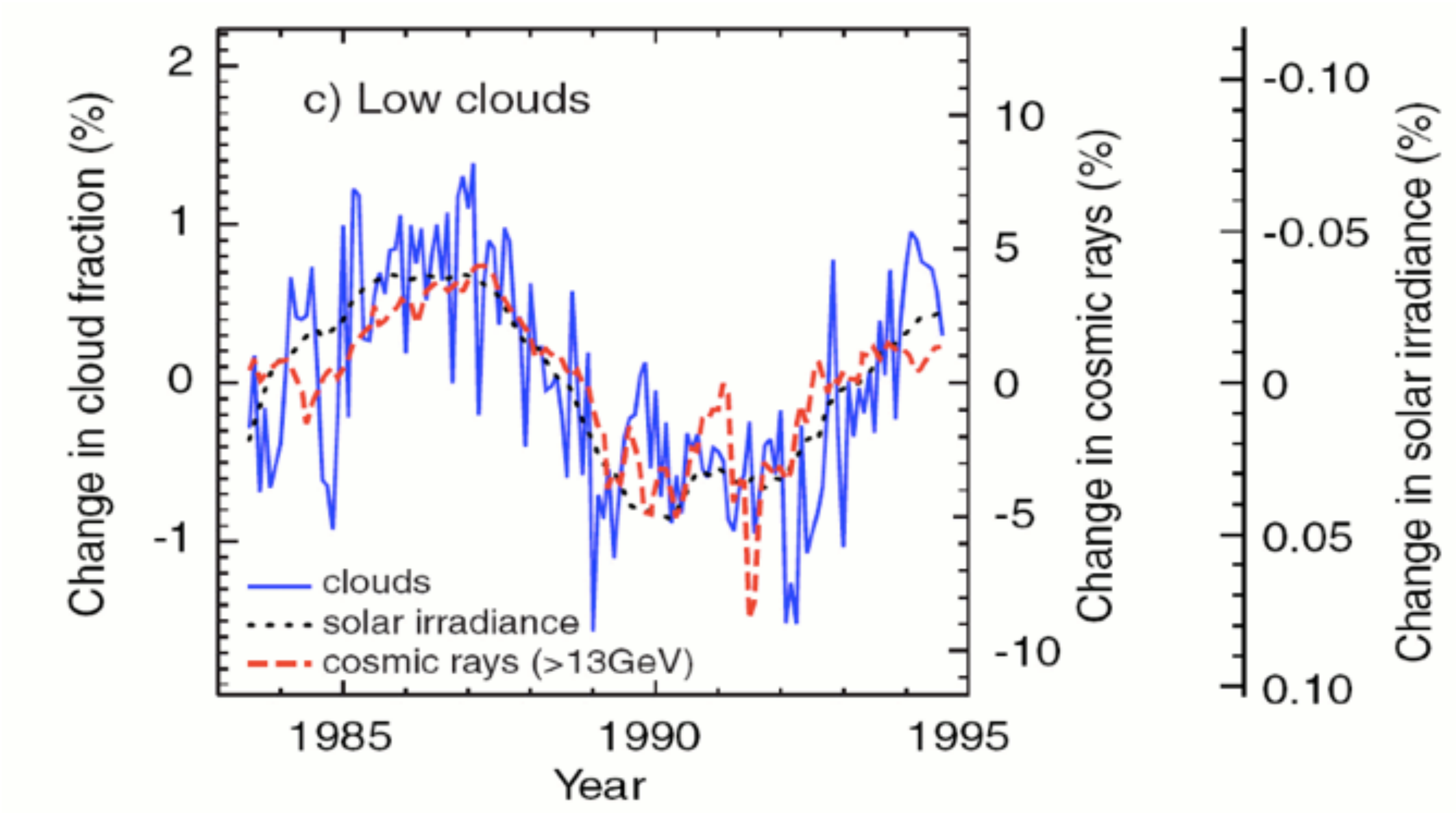
- For middle and high clouds no effect is observed from cosmic rays.

ISCCP-D2 cloud data obtained at infra-red wavelengths (10–12 μm)

- has complete global coverage, day and night.

The variations of cosmic ray intensity are shown as the dashed line (13 GeV/c rigidity cutoff).

The mean global cloud fraction over this period for low IR clouds is 28.0%.



From the CLOUD proposal

Global mean temperature anomaly versus GCR intensity:

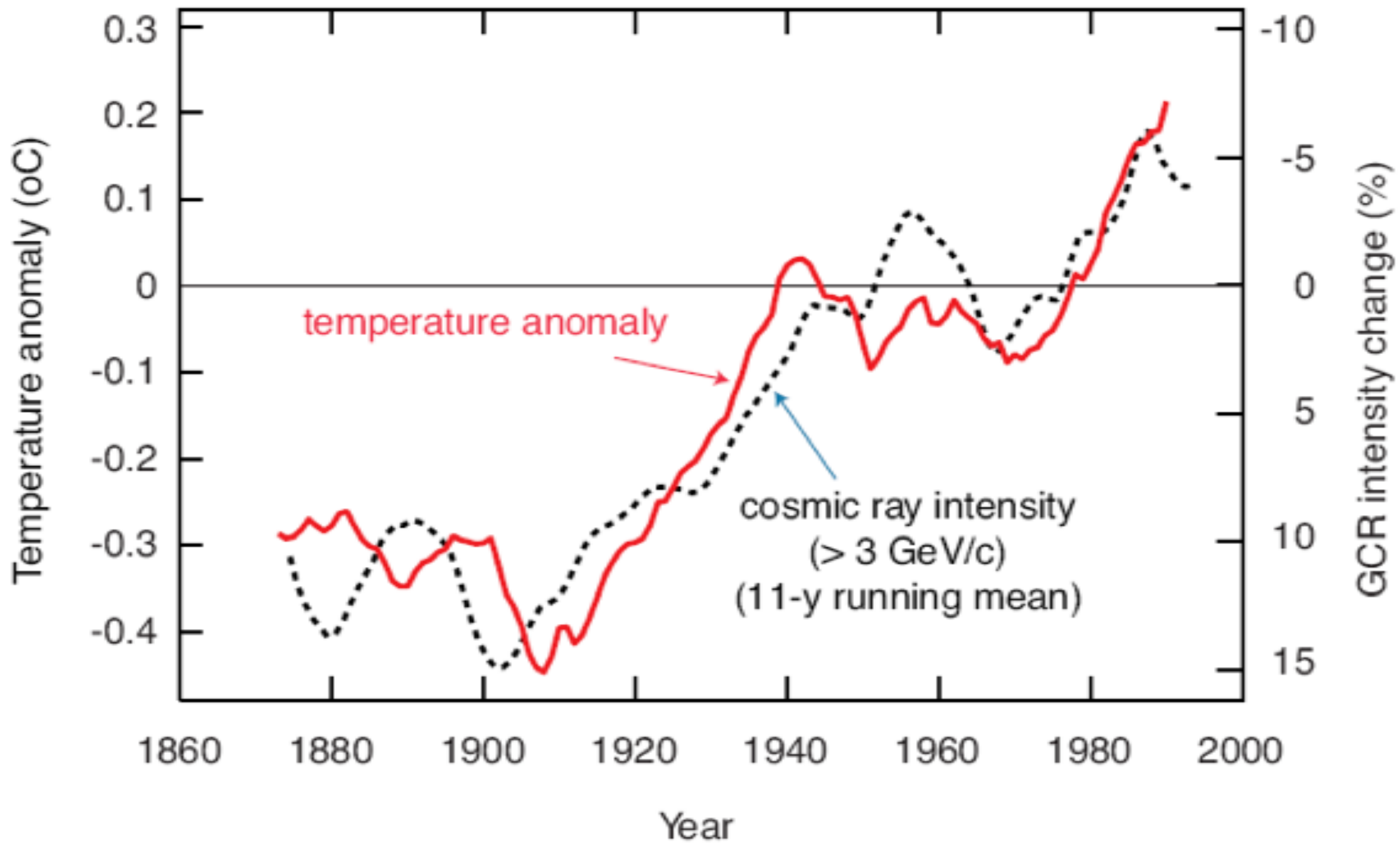


Fig. 17: The mean GCR intensity (3 GeV/c cutoff) over the period 1870–1990, smoothed with an 11-year running mean, together with the global mean temperature anomaly in the same period. The GCR intensity is based on the correlation between directly measured values and the coronal source flux estimates of Lockwood *et al.* (§3.3) [11].

From the CLOUD proposal

^{10}Be concentration in Greenland ice cores versus GCR intensity:

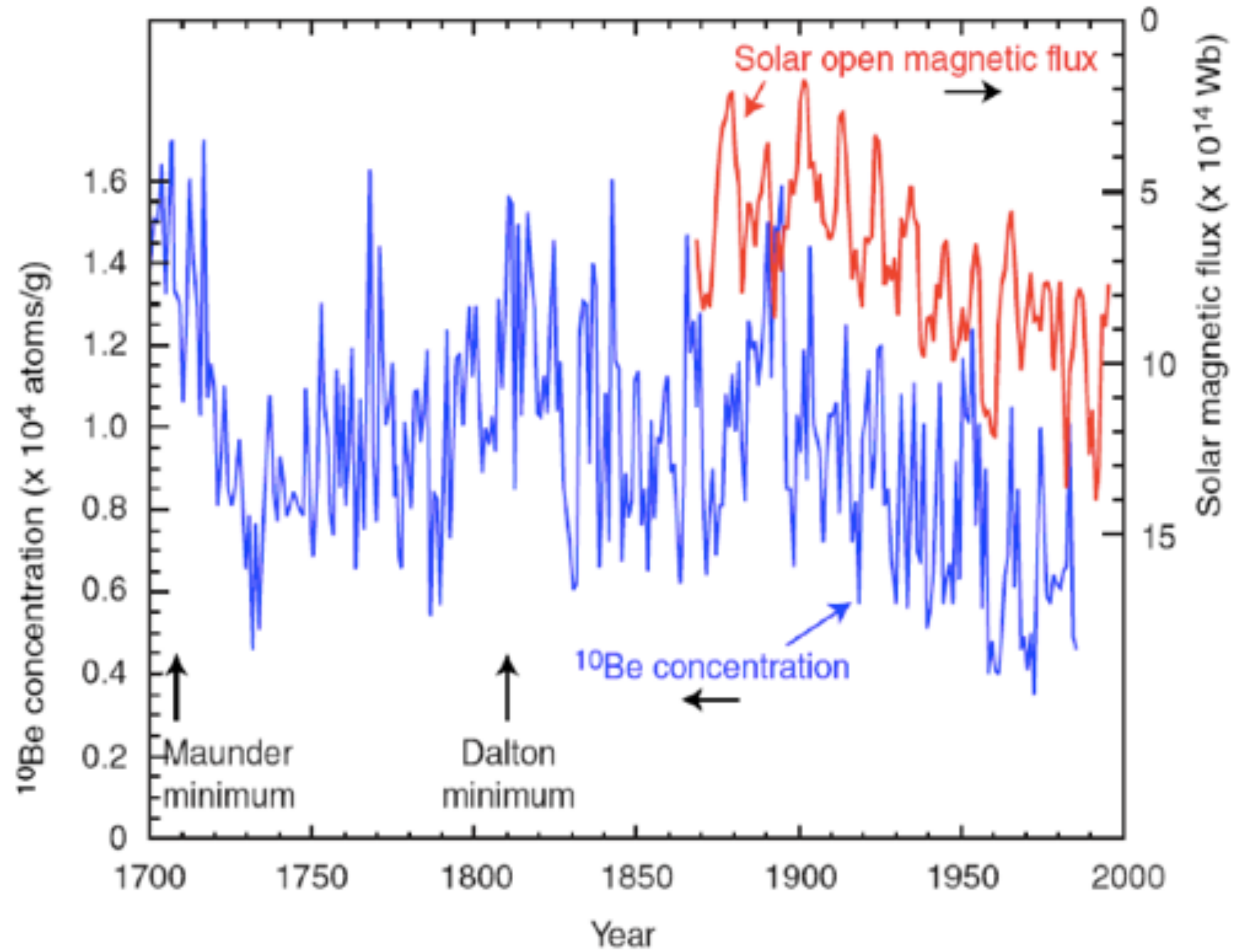


Fig. 13: Variation of ^{10}Be concentration in the Greenland ice core over the last 300 years [46], due to changes of solar magnetic activity (thin line). The variation of the solar coronal source flux, F_S, over the last 140 years is shown by the thick line [11] (note inverted scale and unsupressed zero). In the period since 1901, the increase of the solar open magnetic flux has been a factor 2.3.

But what about the (huge) long term variation?

OK - modulation of the GCR flux by variations in the shielding by the solar magnetic field is correlated with short term variations in temperature.

But what about the very large temperature variations on a time scale of ~ 140 M years?

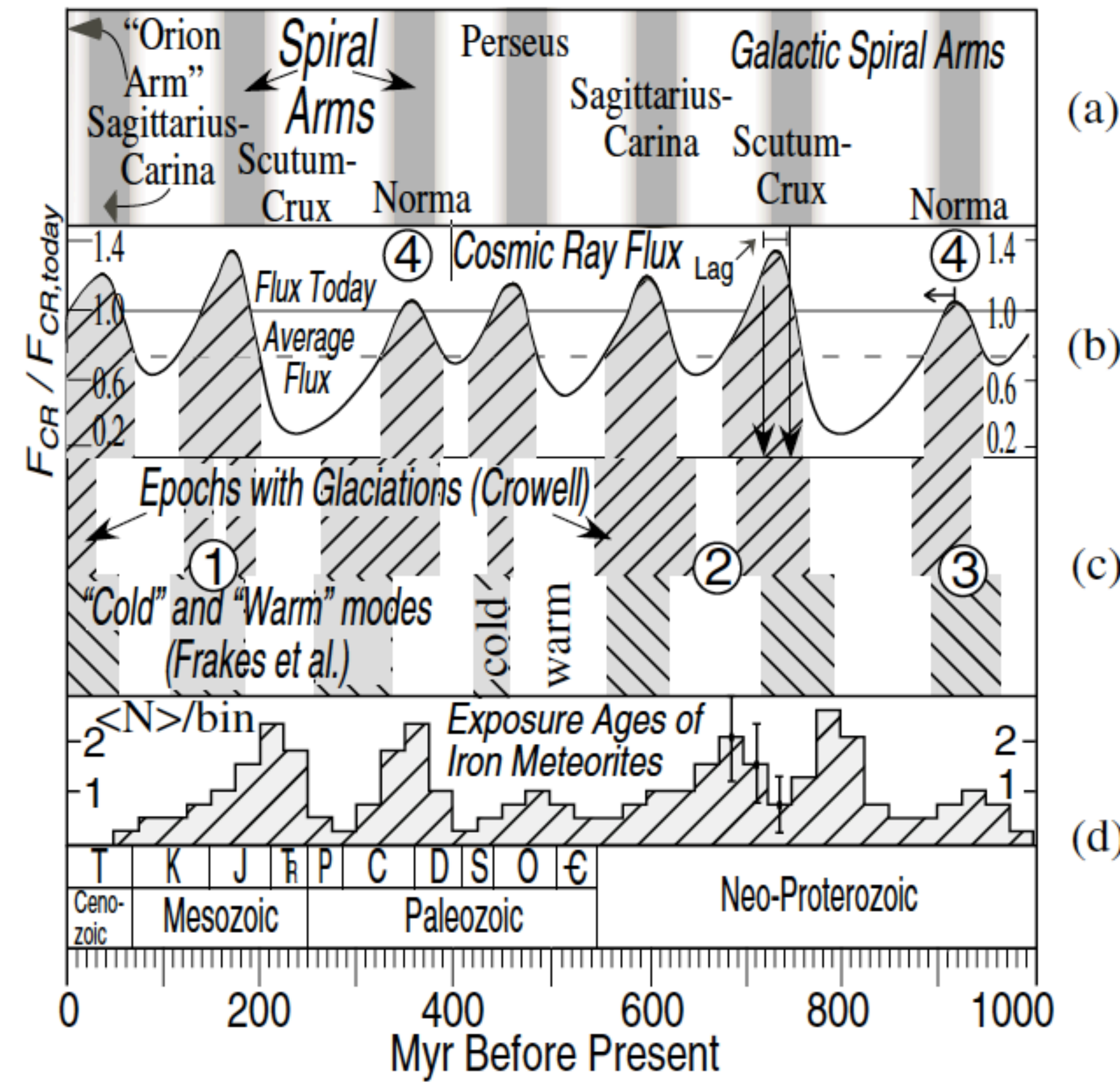
Well, you could also vary the GCR flux itself!

Galactic cosmic rays and long term climate change

Nir J Shaviv, Phys. Rev. Lett. 89, 051102 (2002)

Abstract:

We construct a Galactic cosmic ray (CR) diffusion model. The CR flux reaching the Solar System should **periodically increase with each crossing of a Galactic spiral arm.** We confirm this prediction in the CR exposure age record of iron meteorites. We also find that although the geological evidence for the occurrence of ice-age epochs in the past eon is not unequivocal, it appears to have a nontrivial correlation with the spiral arm crossings and the CR flux variability—agreeing in period and phase.



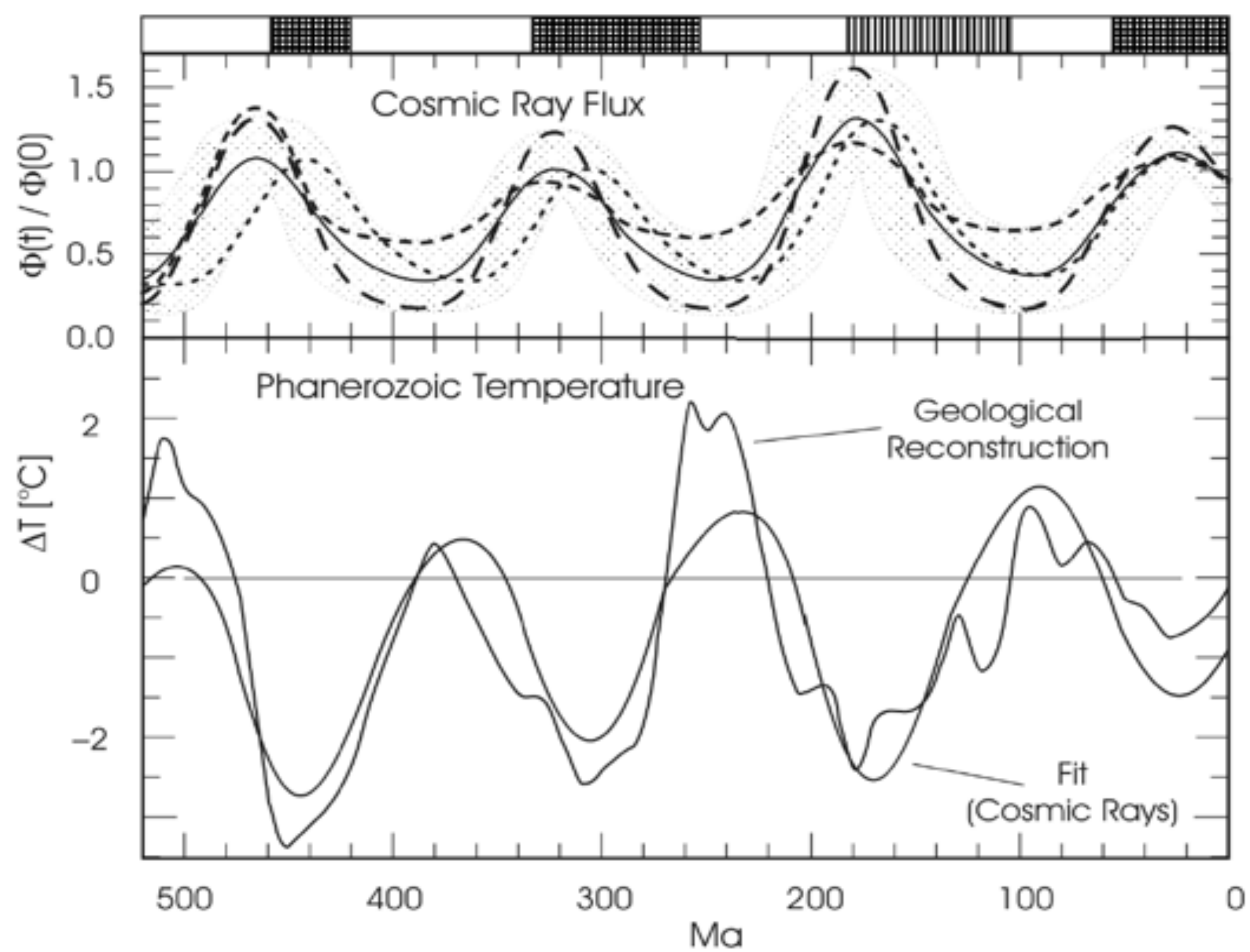
Galactic cosmic rays (cont.)

Jan Veizer, Geoscience Canada vol 32, number 1, p 13, March 2005.

See also Nir J Shaviv, Phys. Rev. Lett. 89, 051102 (2002) and Nir J. Shaviv, New Astronomy Volume 8, Issue 1, January 2003, Pages 39-77

Variations in the cosmic ray flux (Φ) and tropical seawater temperature variations (ΔT) over the Phanerozoic.

Upper curves: the reconstructed trends for cosmic ray flux (CRF) within their uncertainty band (stippled).
Bottom curves: the smoothed temperature anomaly (“Geological Reconstruction”) based on the $\delta^{18}O$ record, and the model cosmic ray flux (“Fit”). The peaks and valleys represent greenhouse and icehouse episodes as in Fig. 5. Note that no polar ice caps were as yet demonstrated for the third (hatched) icehouse. Adapted from Shaviv and Veizer (2003).



Summary

The climate history of the earth is complex:

Large, somewhat regular, temperature fluctuations on time scales of hundreds of millions of years

- The location of the continents seems to be very important
- Modulation of the GCR flux by the earth's motion relative to the galaxy may be important

During our present ice age, a ~ 90 K year cycle of glaciations that has gone on for over a million years, preceded by a smaller amplitude ~ 41 K year cycle that went on for ~ 1.5 M years

- There is a recurring overall pattern, but the details look semi-chaotic (and unpredictable)

During the present interglacial smaller, but still significant, temperature fluctuations occur on time scales of hundreds and thousands of years.

- Variation in cloudiness (and albedo) due to variations in GCR flux caused by solar magnetic field variations looks promising as a contributor

One thing is clear: There is another possible temperature direction besides "up" that one might be concerned about!

Temperature of Planet Earth