ATM 241, Spring 2020
Lecture 12
Paleoclimate

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Marshall & Plumb

Ch. 12.3

In this section…

Definitions

- Temperature proxy
- Dendroclimatology
- $\delta^{18}O$
- Milankovich Cycles

Questions

- How have we developed Earth's historical temperature record?
- What are the major factors affecting Earth's temperatures in the past?
- In the historical record, why does CO_2 tend to lag temperature changes?
- What are the characteristics of Earth's past greenhouse and glacial climates?

Historical Temperatures

Discovering Earth's Temperature Record

The first methodical records of temperature didn't start until **1850**. To figure out the Earth's temperature before this date we rely on **proxies**.

Definition: A **temperature proxy** is a measurement that can be used to calculate the value of temperature (for example when direct measurements are not available).

Proxies for Temperature:

- Tree rings (dendroclimatology)
- Ice cores: Chemistry of trapped air bubbles, and ice layer thickness
- Geological evidence in ancient coal beds, sand dunes and fossils

- Documents concerning droughts, floods, and crop yields
- The chemistry of lake bottom sediment and soil deposits
- Pollen in deep ice caves, soil deposits, and sea sediments

Dendroclimatology

Definition: Dendroclimatology refers to studying the Earth's climate through the study of tree rings.

- Trees grow one ring per year
- Distance between rings can tell you something about temperature and moisture fluctuations related to climate variability

Dendroclimatology

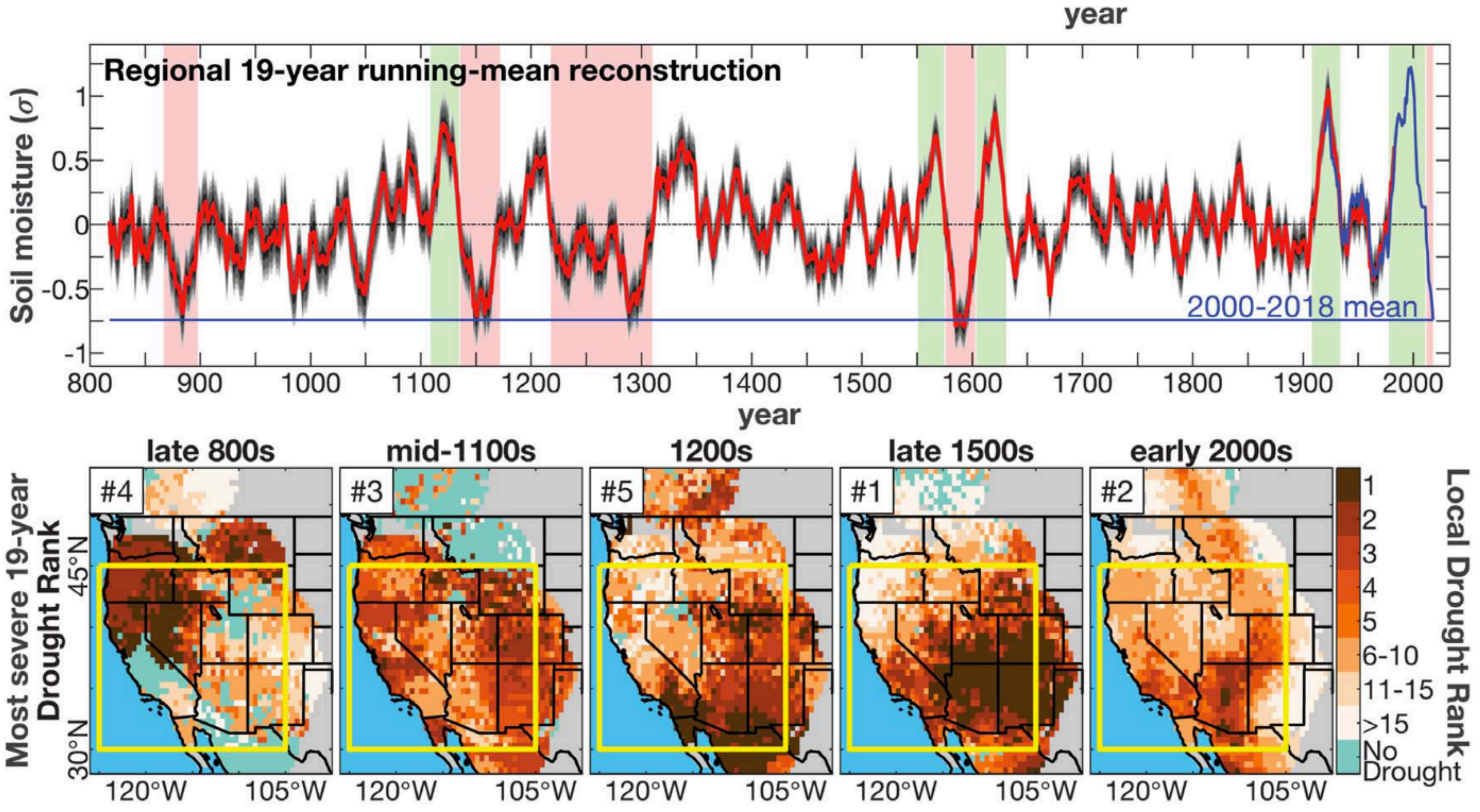
Question: Based on the cross-section of a tree below:

- What were the two warmest years?
- What was the coolest year?

Dendroclimatology

Figure: Williams et al. (2020) used tree ring records to reconstruct temperatures and soil moisture over the past 1200 years in the US West.

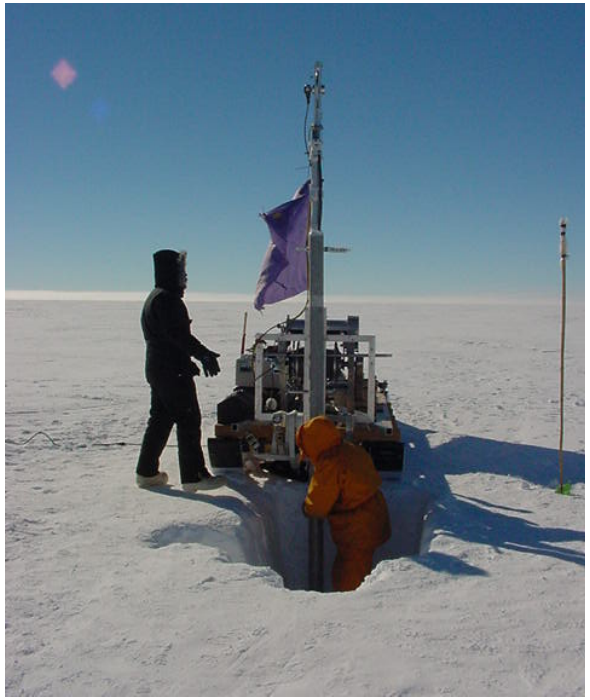
The results suggest the periodic occurrence of "megadroughts" – periods of prolonged dry conditions.



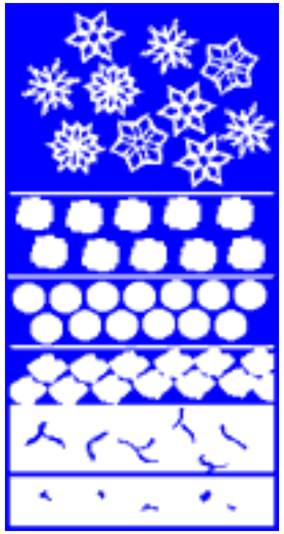
Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K., Baek, S.H., Badger, A.M. and Livneh, B., 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, *368*(6488), pp.314-318.

Temperature from Ice Cores

Our knowledge of past climates comes in large part from investigating ***ice cores***. The **thickness of each layer** can give clues to the amount of precipitation. **Air bubbles** can give clues to the **chemistry** of the atmosphere.



Snow becomes ice



Temperature from Ice Cores

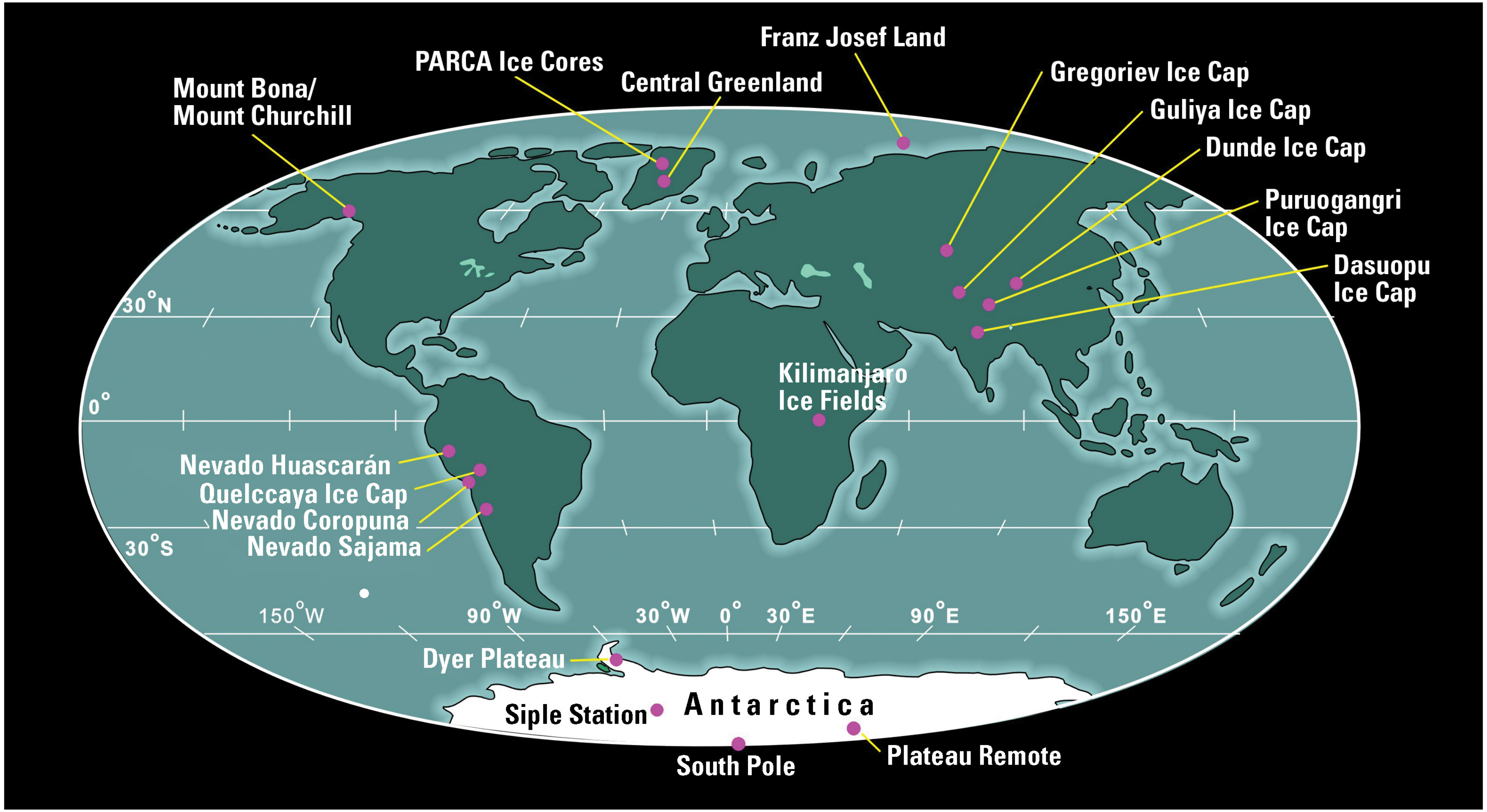


Figure: Some global ice core sites.

Antarctic Ice Core Sites

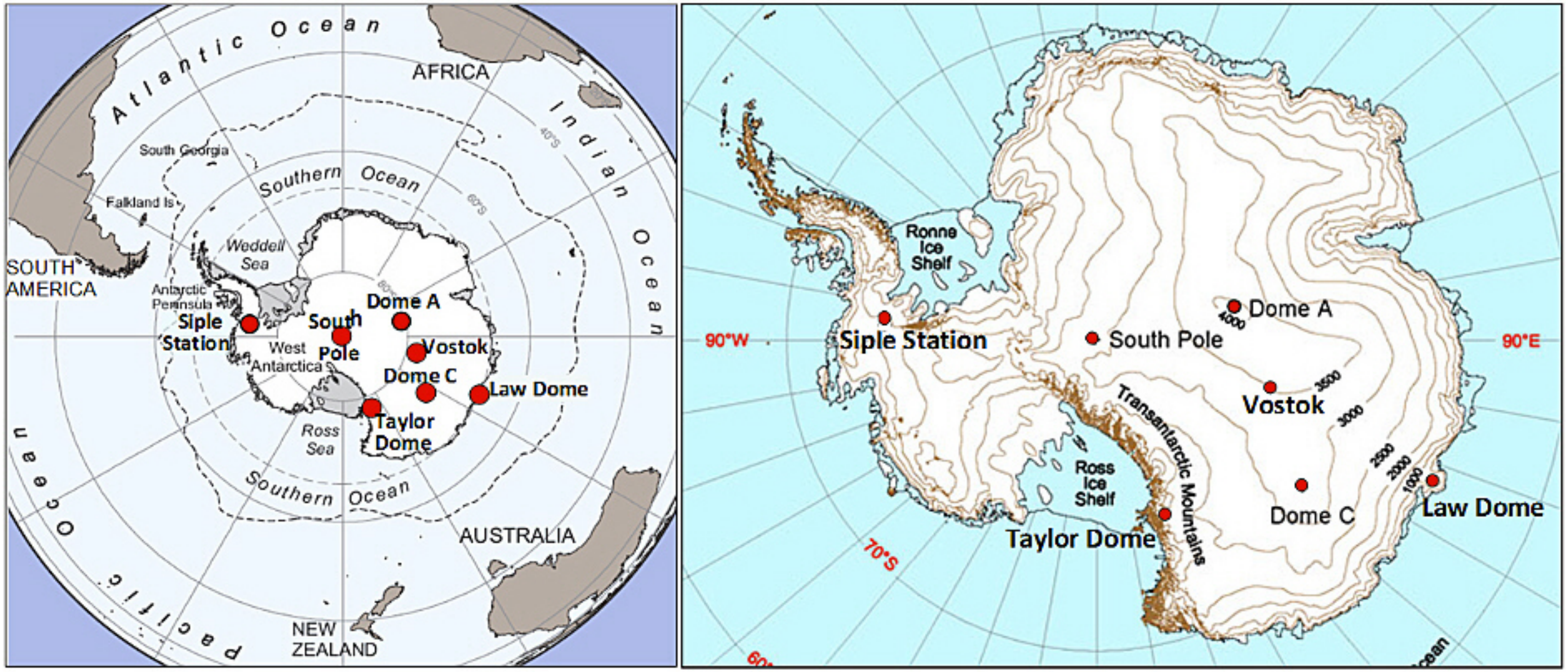
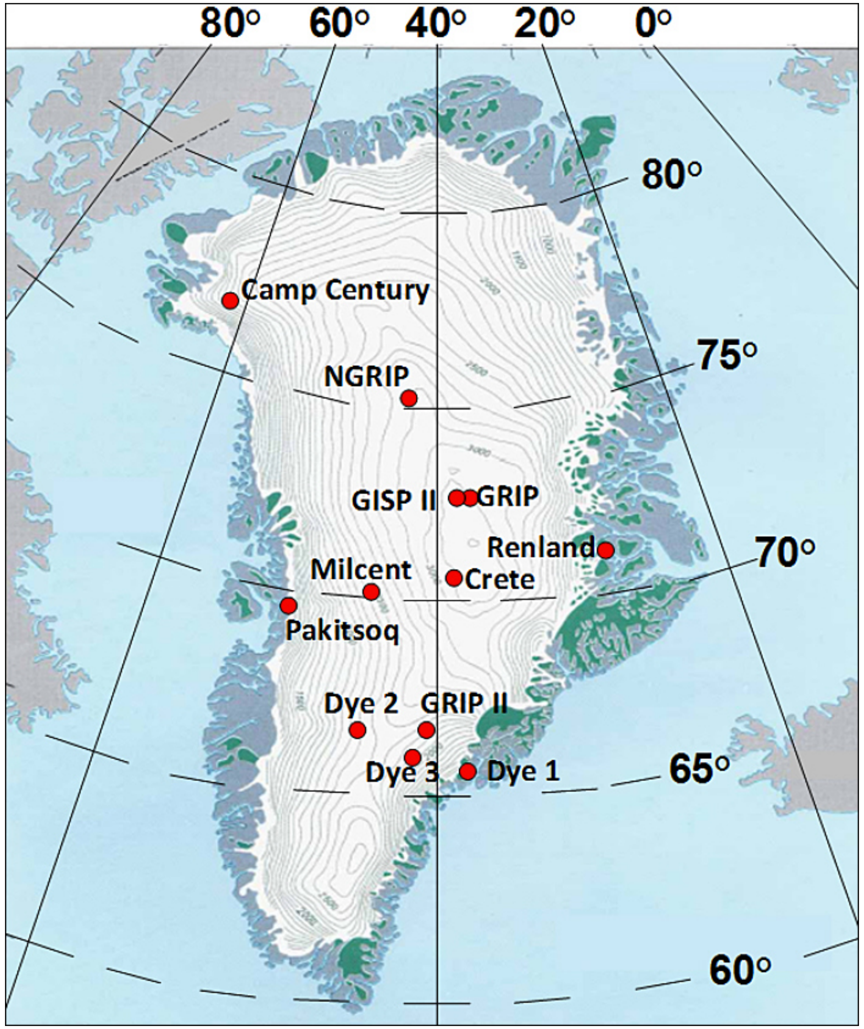


Figure: A map of Antarctic ice core sites. A recent 2.7Myr ice core was recently extracted from the Allan Hills, near Taylor Dome.

Greenland Ice Core Sites

Figure: A map of Greenland ice core sites. The oldest Greenland ice cores date to 130,000 years before present.



Temperatures from Fossils

- Normal oxygen contains 8 protons and 8 neutrons (^{16}O)
- A small fraction (one in a thousand) of oxygen atoms contains 8 protons and 10 neutrons (^{18}O). These are the ***isotopes*** of oxygen – ^{18}O is heavier than ^{16}O.
- ^{16}O will evaporate more readily than ^{18}O because it is lighter.
- **During ice ages ^{16}O rich water is stored in glaciers**, removing it from the ocean; **in these cold times $\delta^{18}O$ is high in the oceans** (here δ means "relative concentration").
- Looking at the ratio of ^{16}O to ^{18}O in **ocean fossils** (which are derived from the oxygen atoms of the ocean) can give clues about global temperatures.

Temperatures from Fossils

Earth's temperature record over geological time scales has typically been measured using the **$\delta^{18}O$ record (pronounced delta "18" oh)**.

Definition: $\delta^{18}O$ is the difference in the $[^{18}O]/[^{16}O]$ ratio between a sample and an associated standard, normalized by the standard.

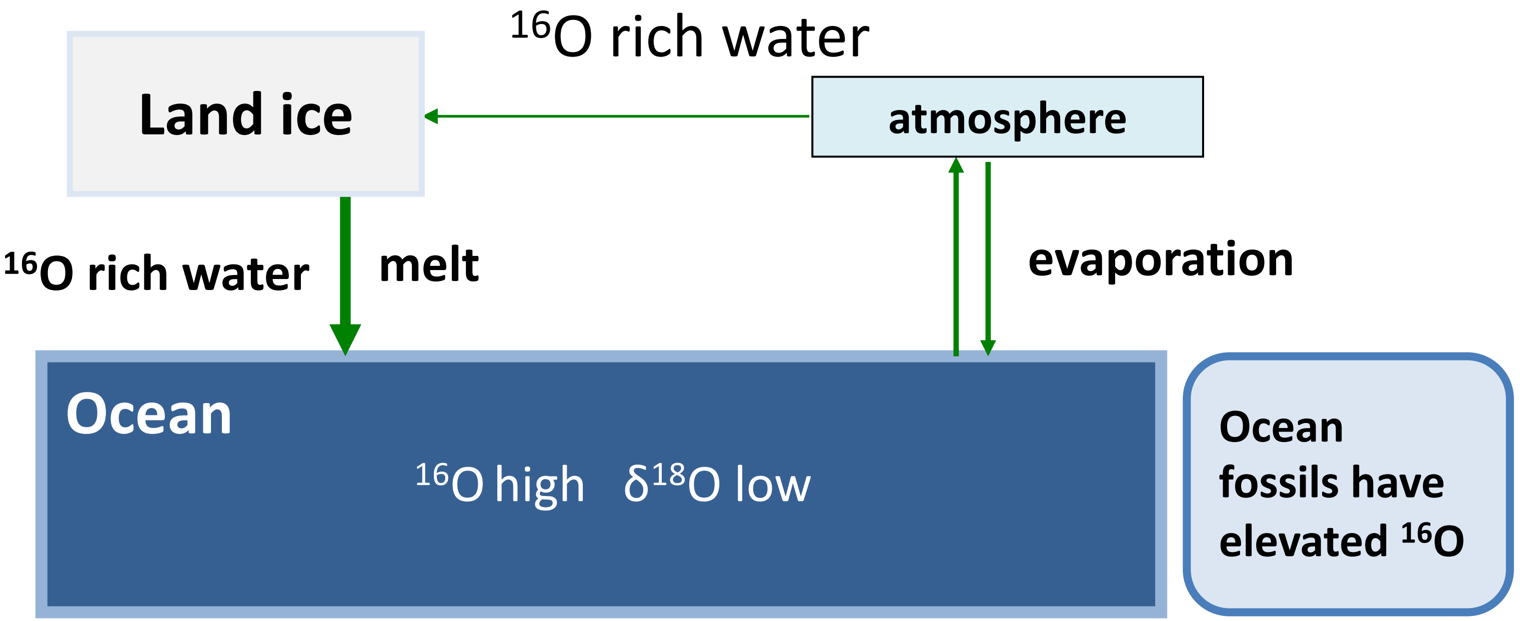
Per mille

$$\delta^{18}O = \left\{ \frac{\left(\frac{[^{18}O]}{[^{16}O]}\right)_{sample}}{\left(\frac{[^{18}O]}{[^{16}O]}\right)_{standard}} - 1 \right\} \times 1000 \ {}^{\circ}/_{\circ\circ}$$

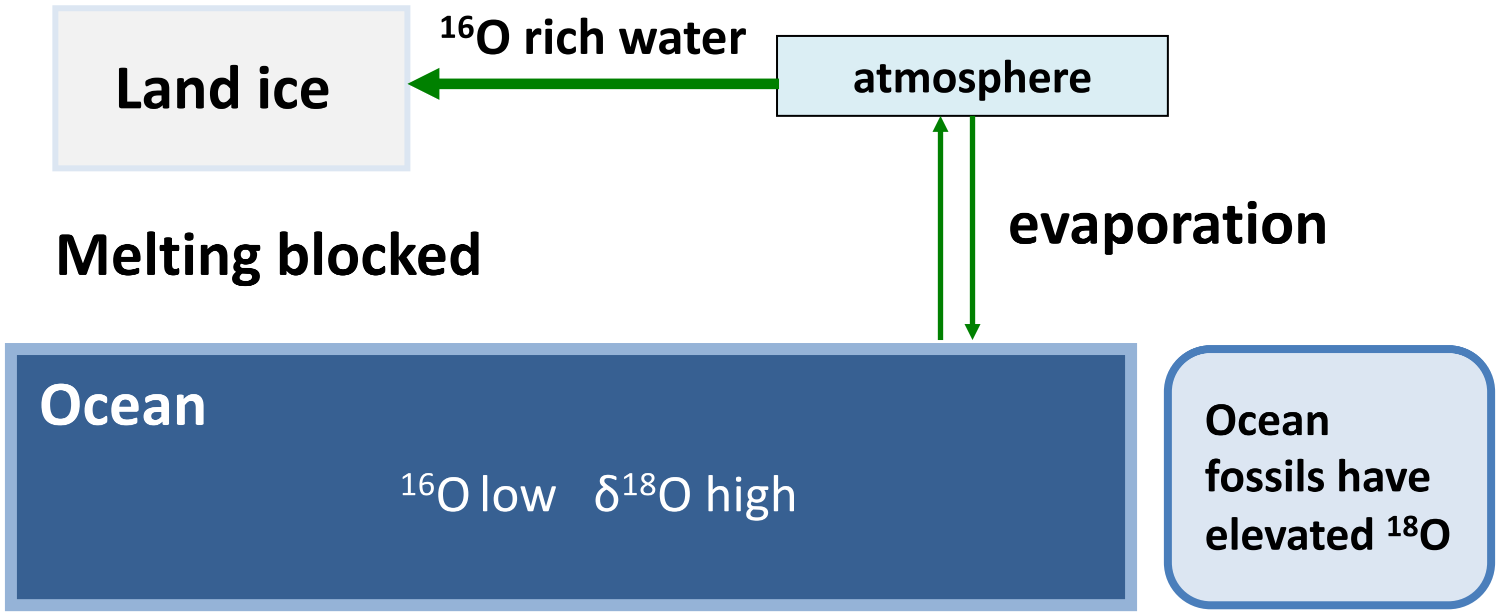
This ratio is closely **correlated with temperature** since ^{16}O is preferentially evaporated from seawater. It can be measured in the calcium carbonate shells from the fossil record.

Ignoring effects of salinity, a 0.22 ${}^{\circ}/_{\circ\circ}$ increase of $\delta^{18}O$ is equivalent to 1 degree of cooling.

Warm
Interglacial
Periods



Cold
Glacial
Periods



The Temperature Record

Earth’s Temperature Record (1000y ago)

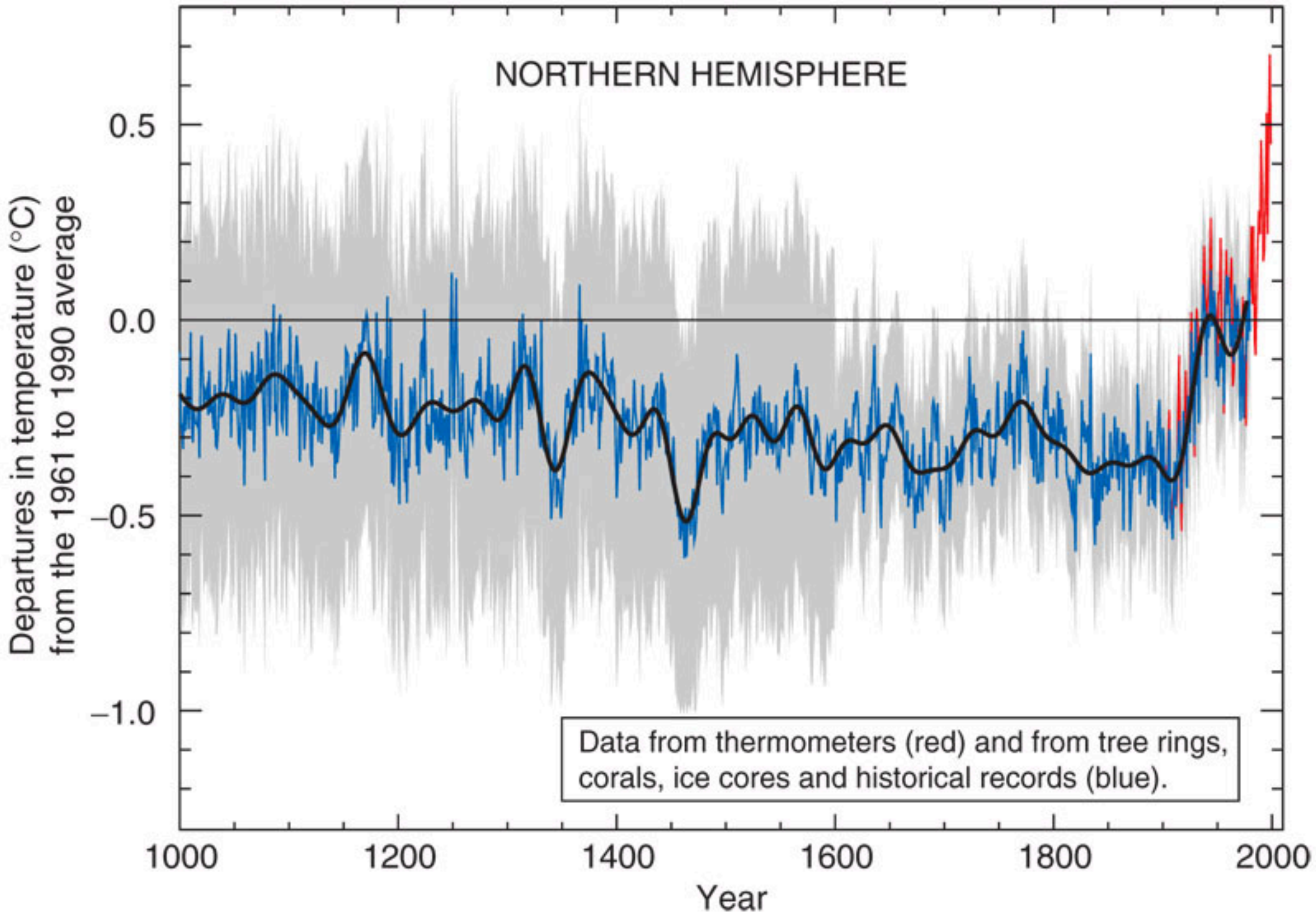


Figure: Global average temperature anomaly over the past 1000 years. The characteristic “**hockey stick**” analogy refers to the recent dramatic increase in temperatures over the past century.

Earth's Temperature Record (20ky ago)

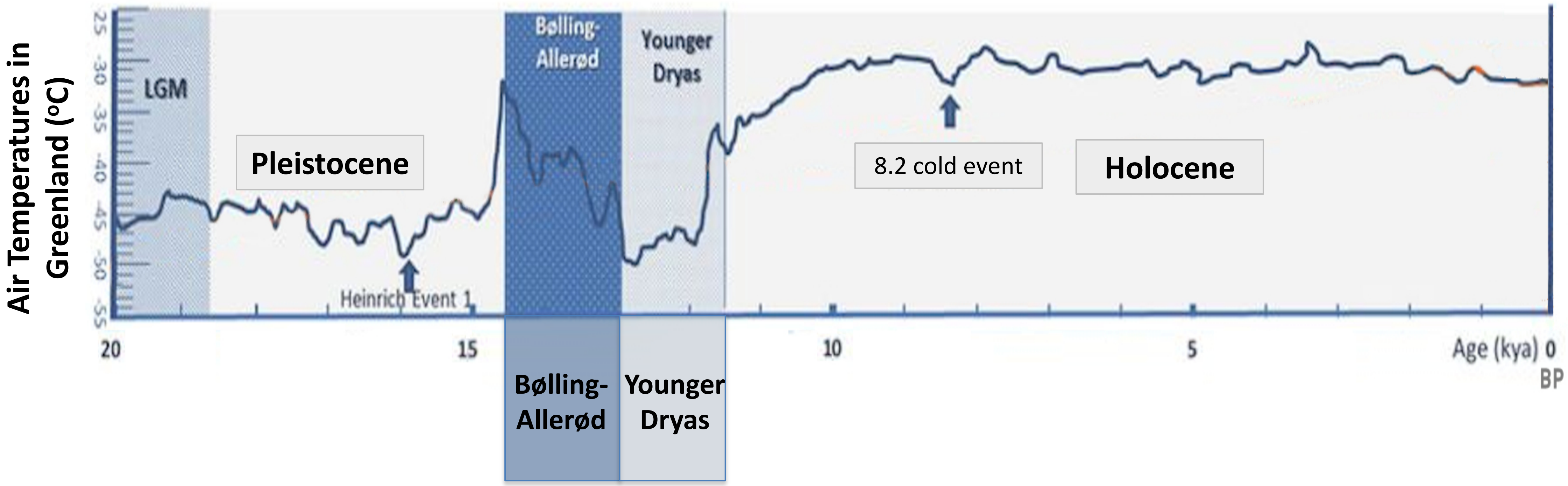


Figure: Geological record of Greenland temperatures over the past 20kya.
Also see https://xkcd.com/1732/

Earth's Temperature Record (800ky ago)

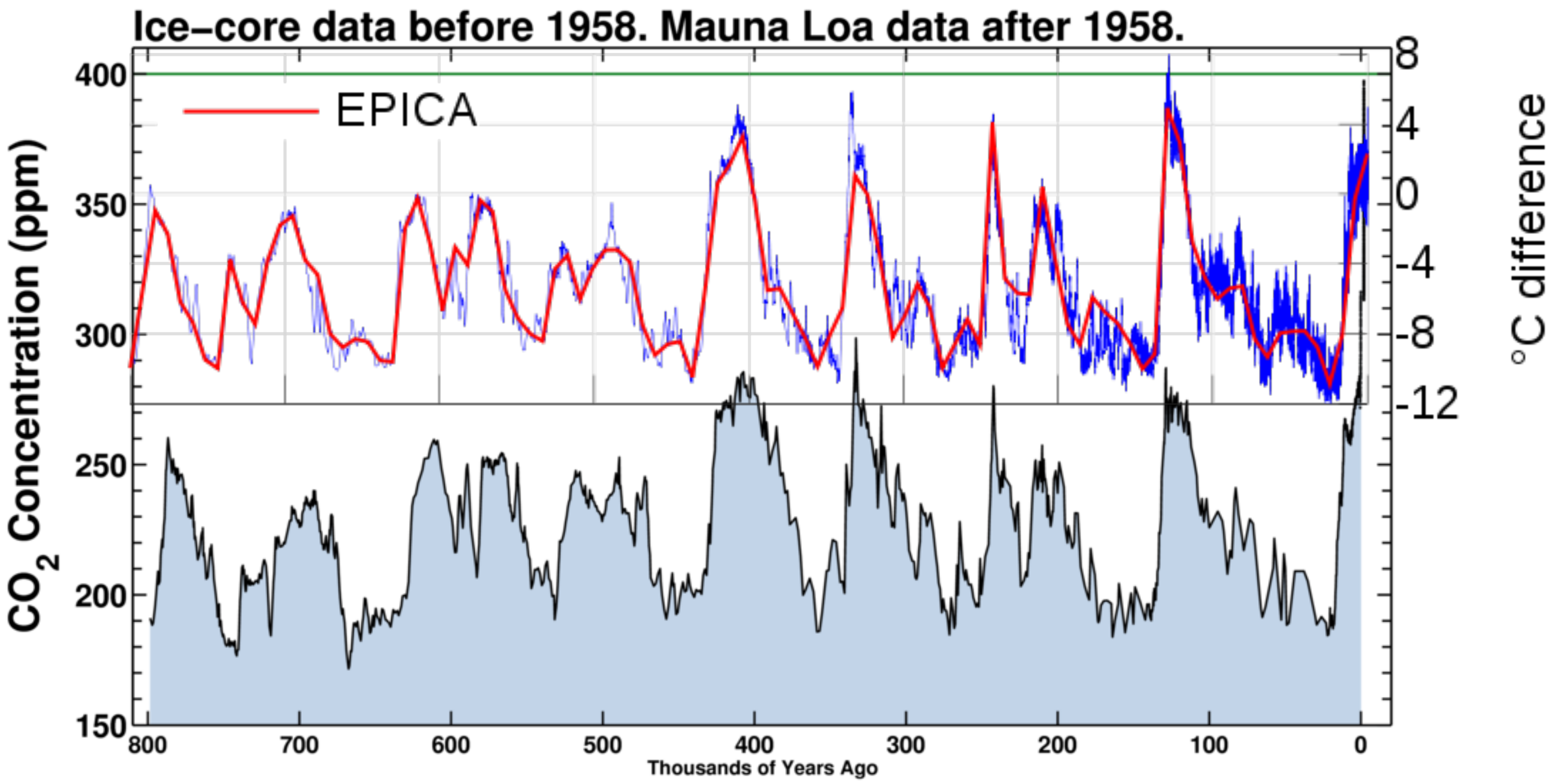


Figure: Geological record of CO_2 concentration from ice cores over the past 800ky and superimposed temperature record. Observe the close correlation between CO_2 and temperatures.

Earth's Temperature Record (800ky ago)

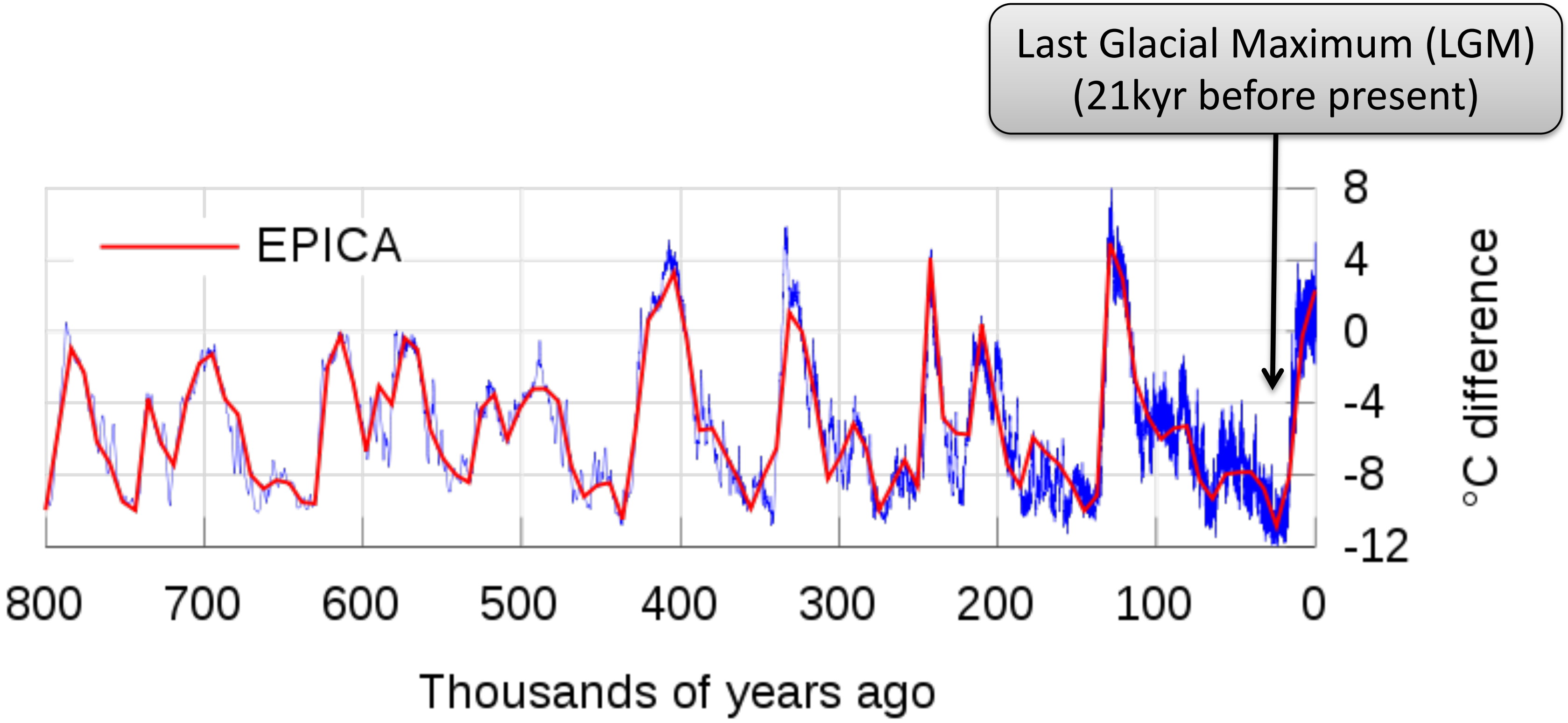


Figure: Geological temperature record over the past 800 thousand years. The 100kyr oscillations becomes more apparent in the record, with short-term warm periods (interglacial periods) interspersed among periods of prolonged cooling (glacial periods).

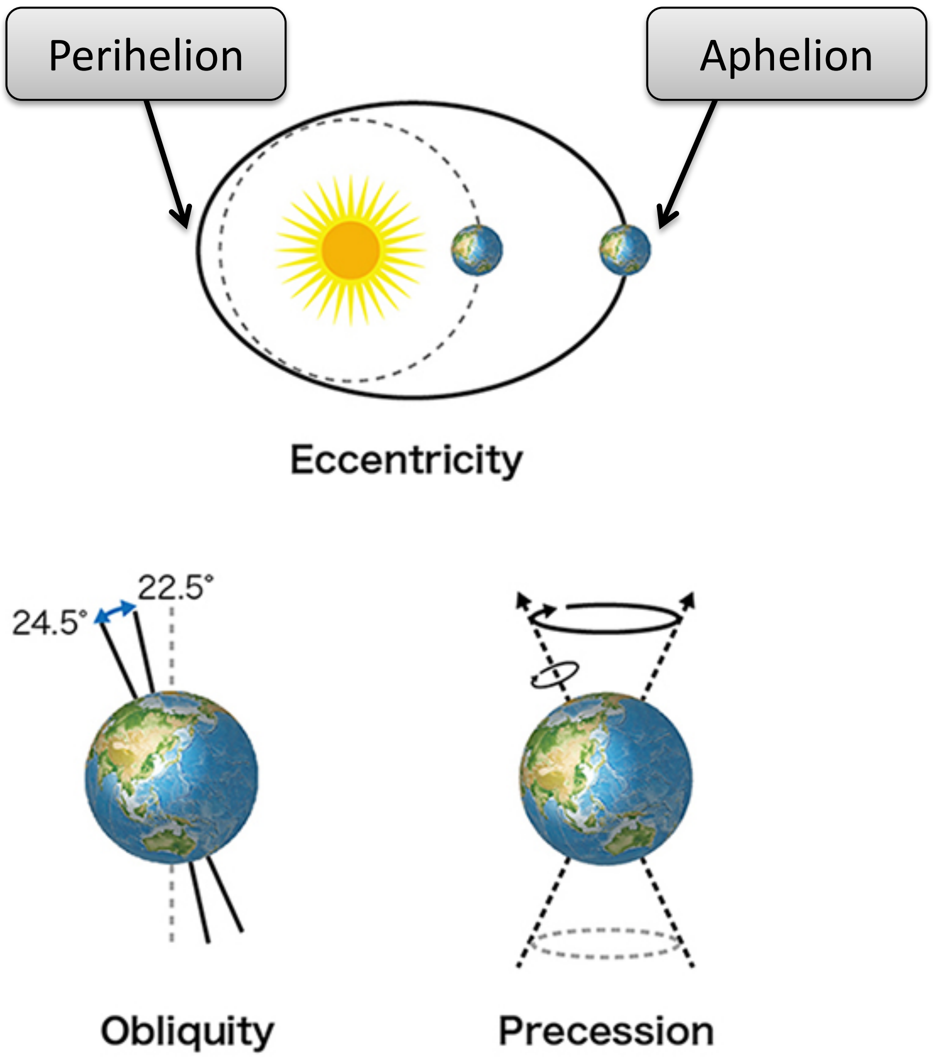
Orbital Impacts on Insolution

Figure: (a) The **eccentricity** of the Earth's orbit varies on 100ky to 400ky timescales from (almost) zero, a circle to 0.07, a very slight ellipse.

Note that at present perihelion falls on January 3rd, so northern hemisphere winter and southern hemisphere summmer are slightly warmer than winter/summer in the opposite hemisphere.

(b) The **change in the tilt** of the Earth's spin axis – the obliquity – varies between 22.1° and 24.5° on a timescale of 41ky.

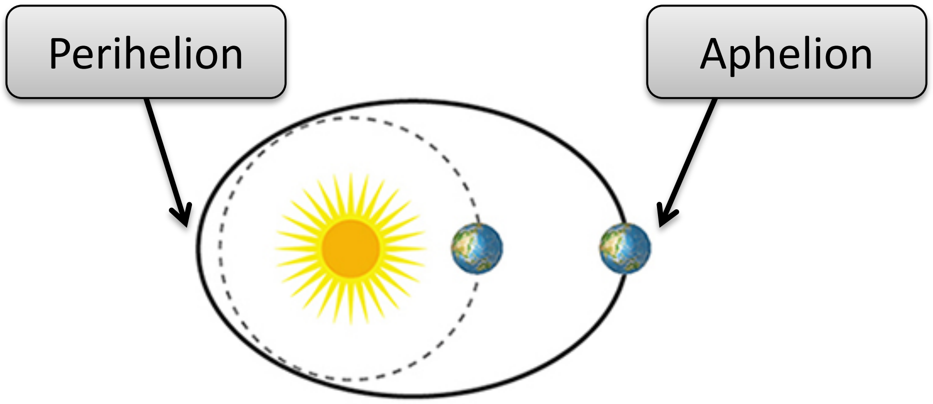
(c) The direction of the Earth's spin vector precesses with a period of 23ky.



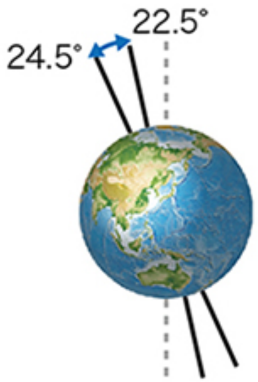
Milankovich Cycles

Definition: The **Milankovich Cycles** of the Earth refer to oscillations in the Earth's orbital parameters that affect its climate over thousands of years.

These include cycles in the Earth's eccentricity, obliquity, precession, and other orbital parameters.



Eccentricity



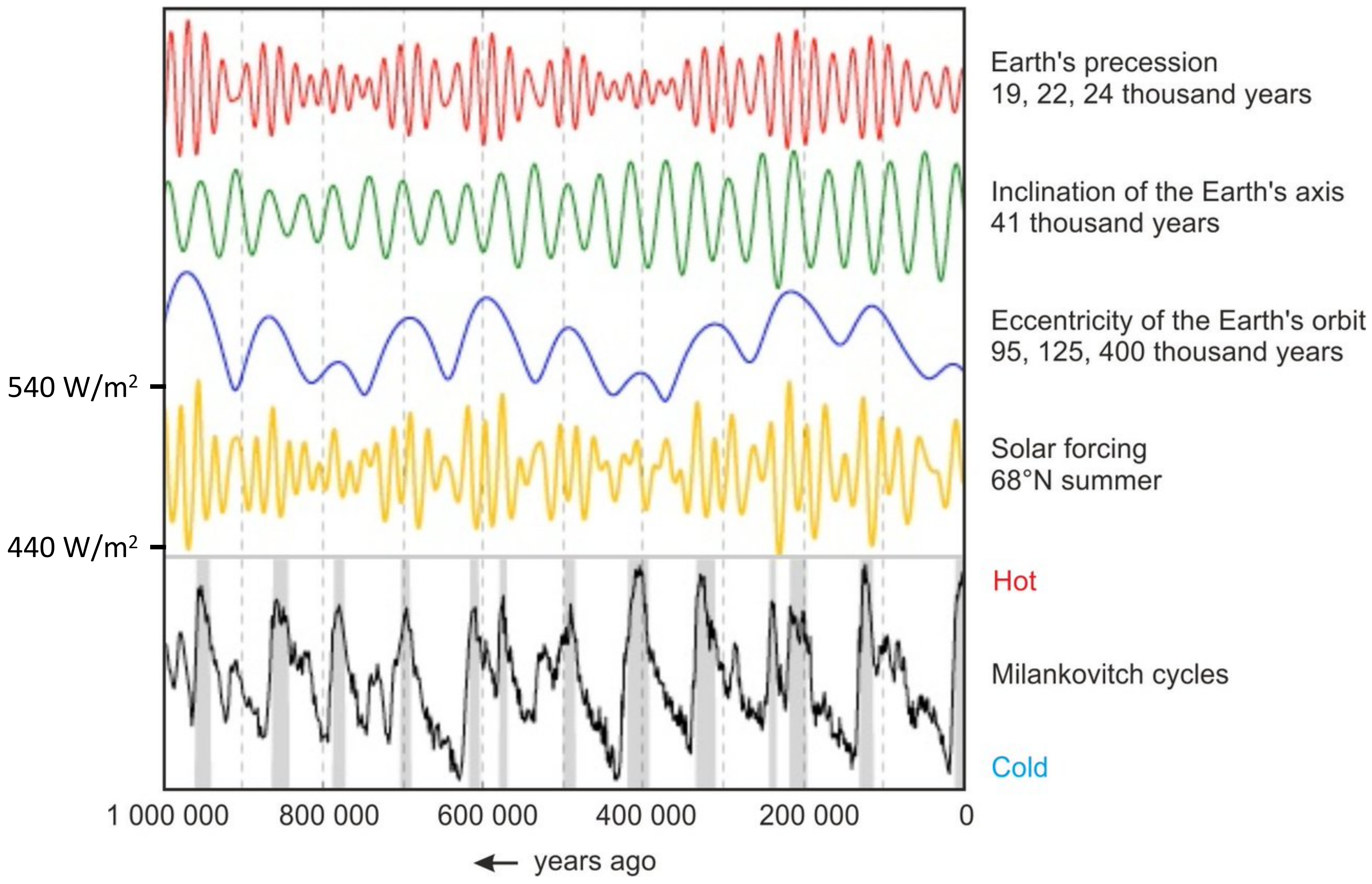
Obliquity

Precession

Milankovich Cycles

Figure: Variations in eccentricity, precession and obliquity over 300ky, starting 200ky in the past, through present day and 100ky into the future.

Due to the strong sensitivity of ice sheets to temperature, certain combinations of eccentricity, precession and obliquity can lead to dramatic differences in ice sheet extent.



Milankovich Cycles

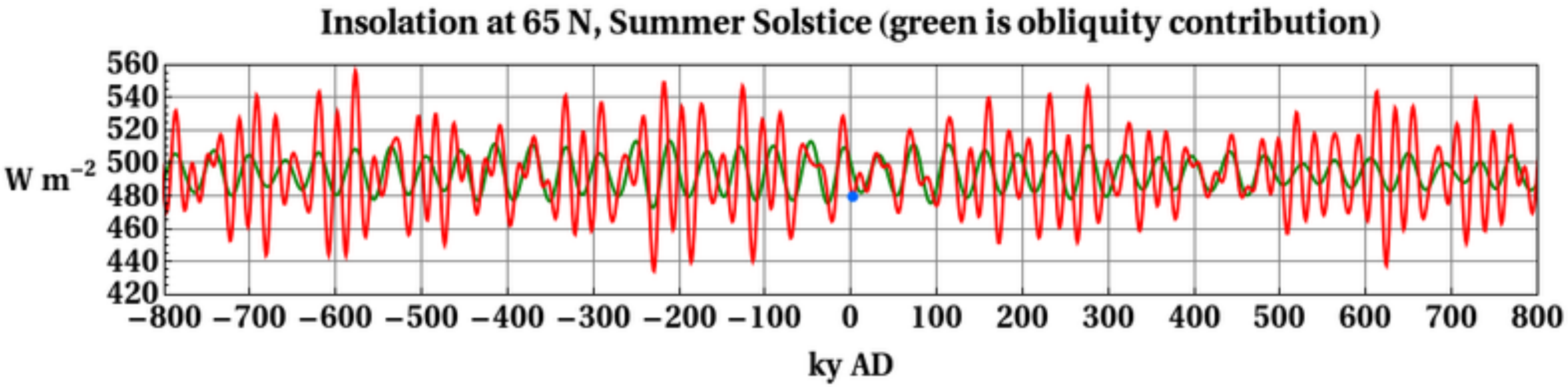
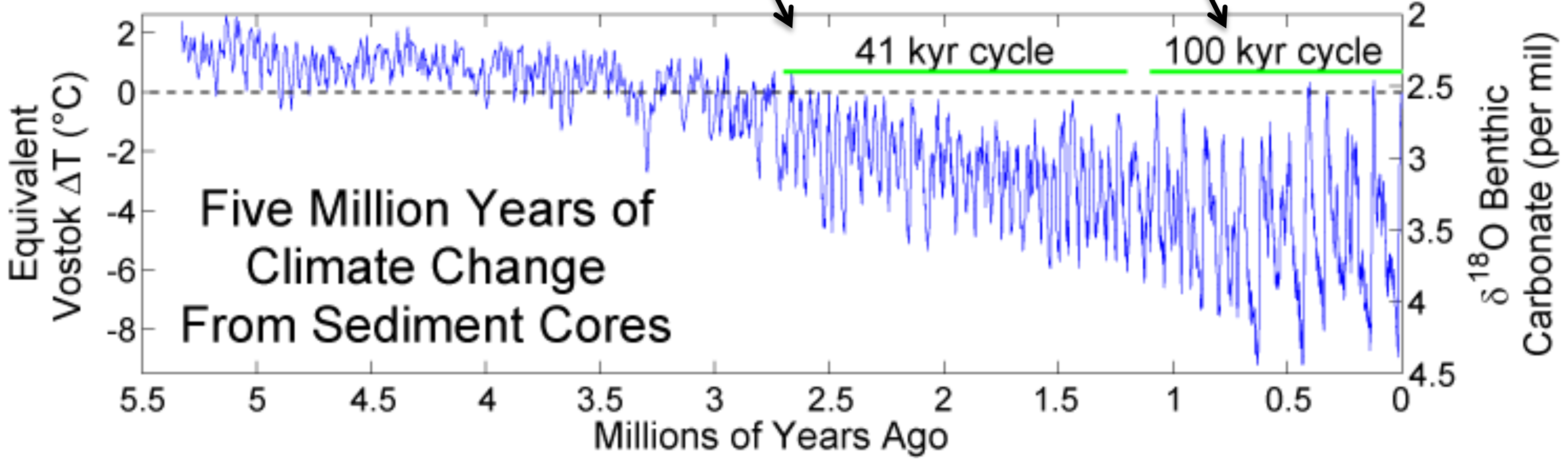


Figure: Variations in summer solstice insolation at 65N due to the components of the Milankovich cycle. Variations in total insolation are as large as 130 W/m^2, or about 25%.

Milankovich Cycles

40ky cycle closely related to change in obliquity of the Earth's orbit, leading to temperature changes of 6-7 degrees.

100ky cycle closely related to change in eccentricity. Reason for switch to longer cycle time is unknown.



CO_2-Temperature Lag

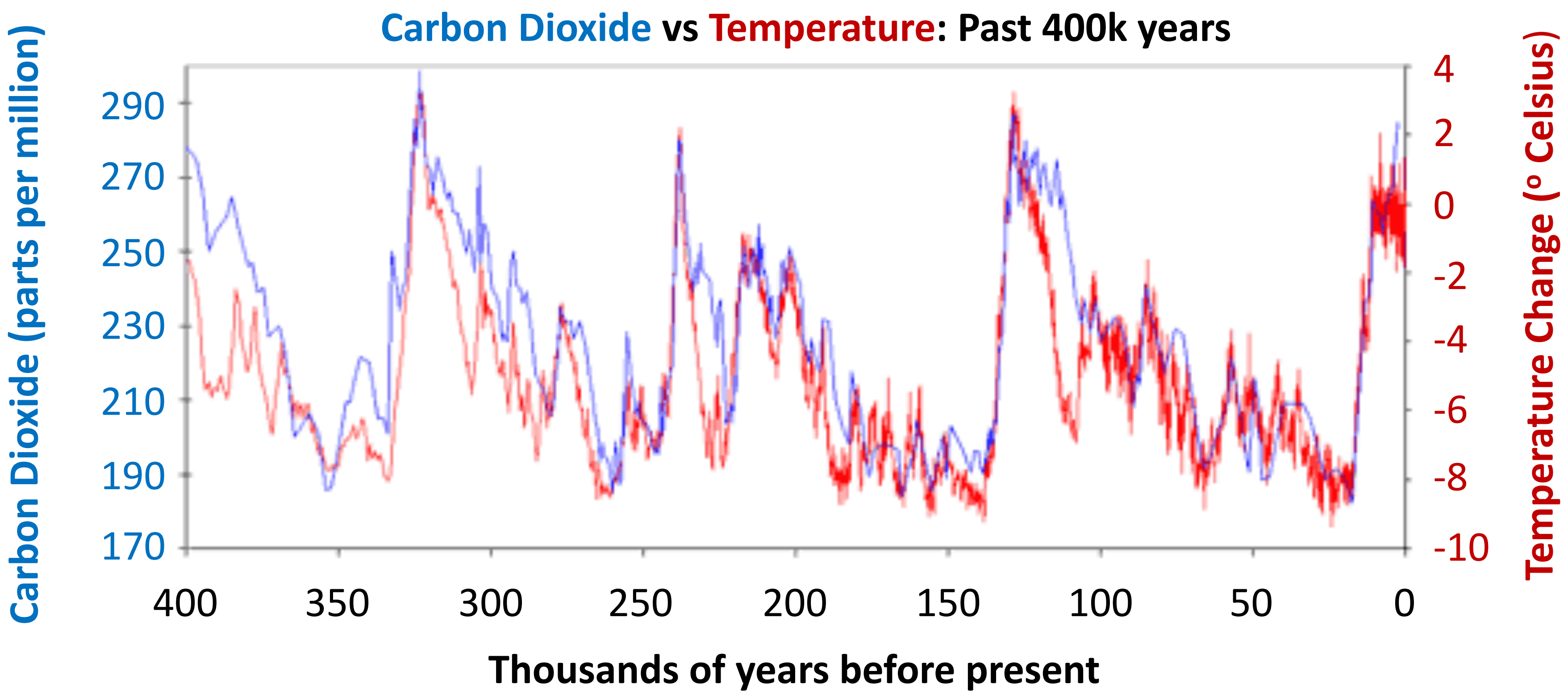


Figure: Vostok ice core records for carbon dioxide concentration and temperature change. Note that over the historical record CO_2 has lagged temperature change by ~800yr.

Temperature-CO_2 Feedback (Warming)

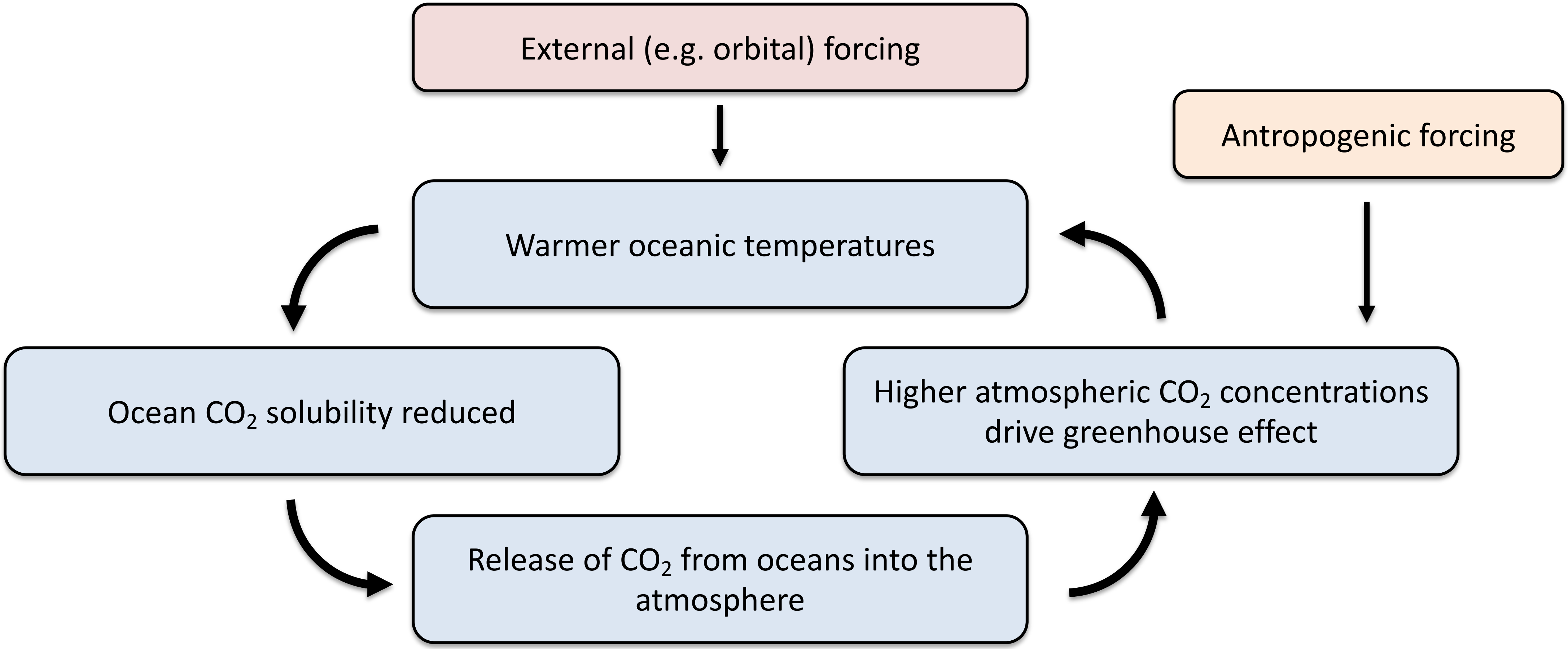


Figure: Temperature-CO2 feedback when Earth emerges from a glacial period. This results in approximately a 800 yr time lag of CO_2 concentration and temperatures.

Temperature-CO_2 Feedback (Cooling)

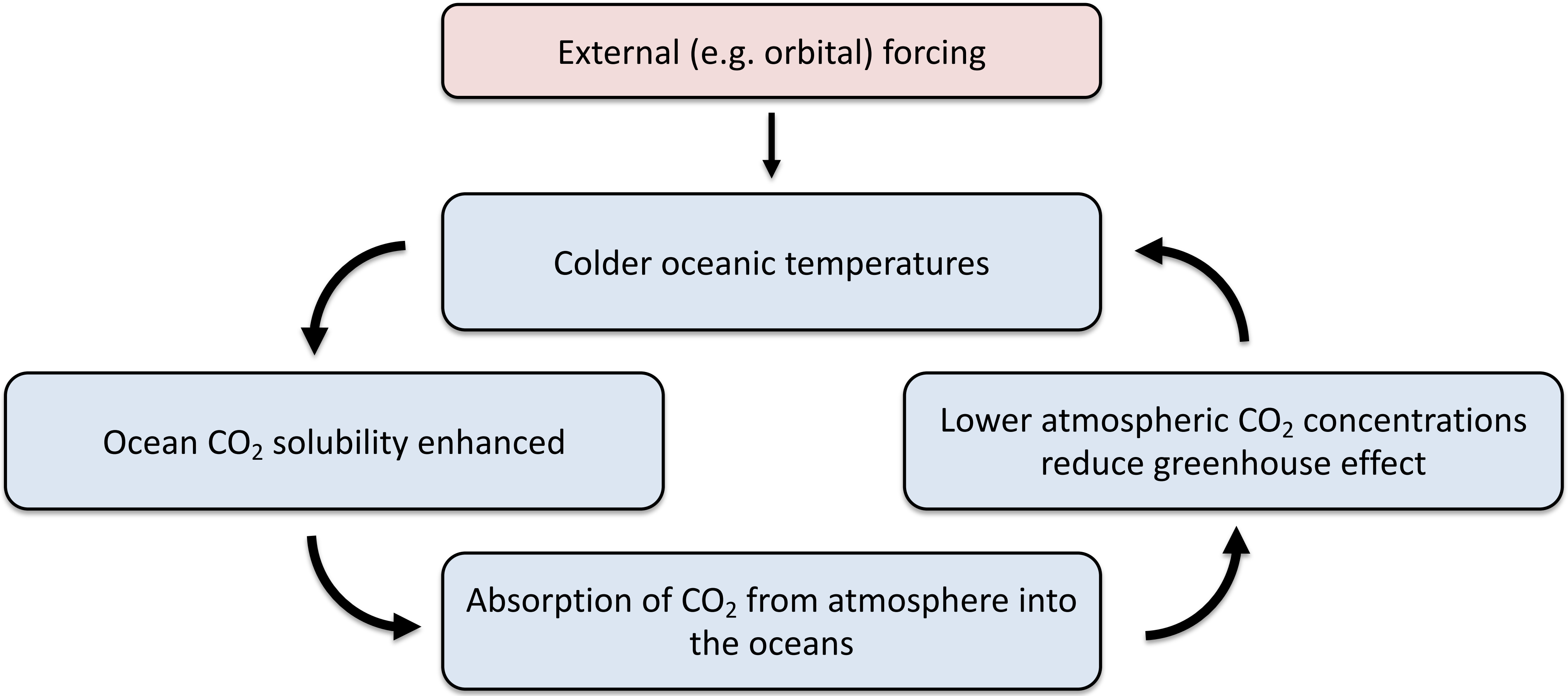
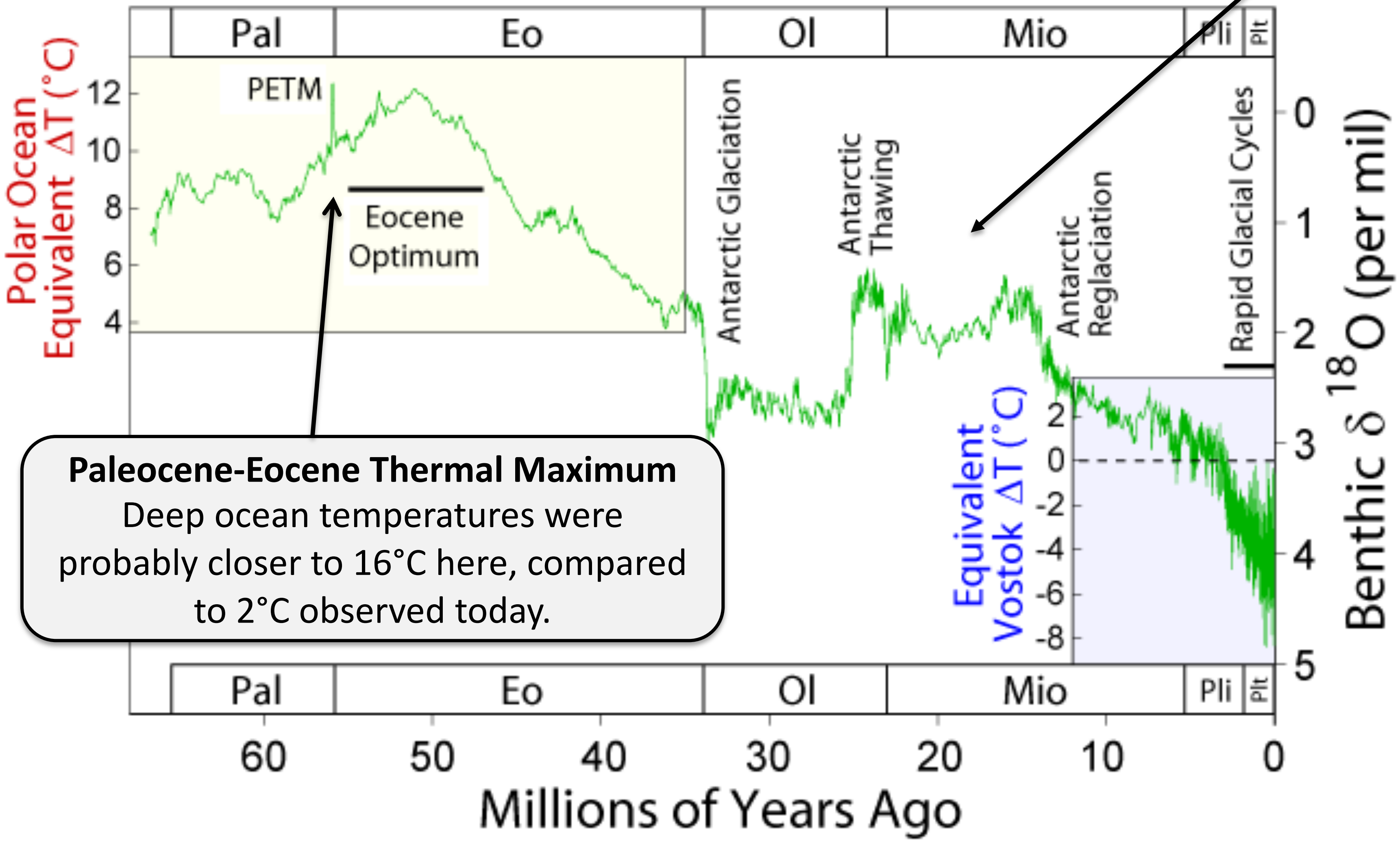


Figure: Temperature-CO2 feedback when Earth enters a glacial period. This results in approximately a 800 yr time lag of CO_2 concentration and temperatures.

Earth's Temperature Record (60Myr ago)

Ice-albedo feedback



Paleocene-Eocene Thermal Maximum
Deep ocean temperatures were probably closer to 16°C here, compared to 2°C observed today.

Ice-Albedo Feedback (Warming)

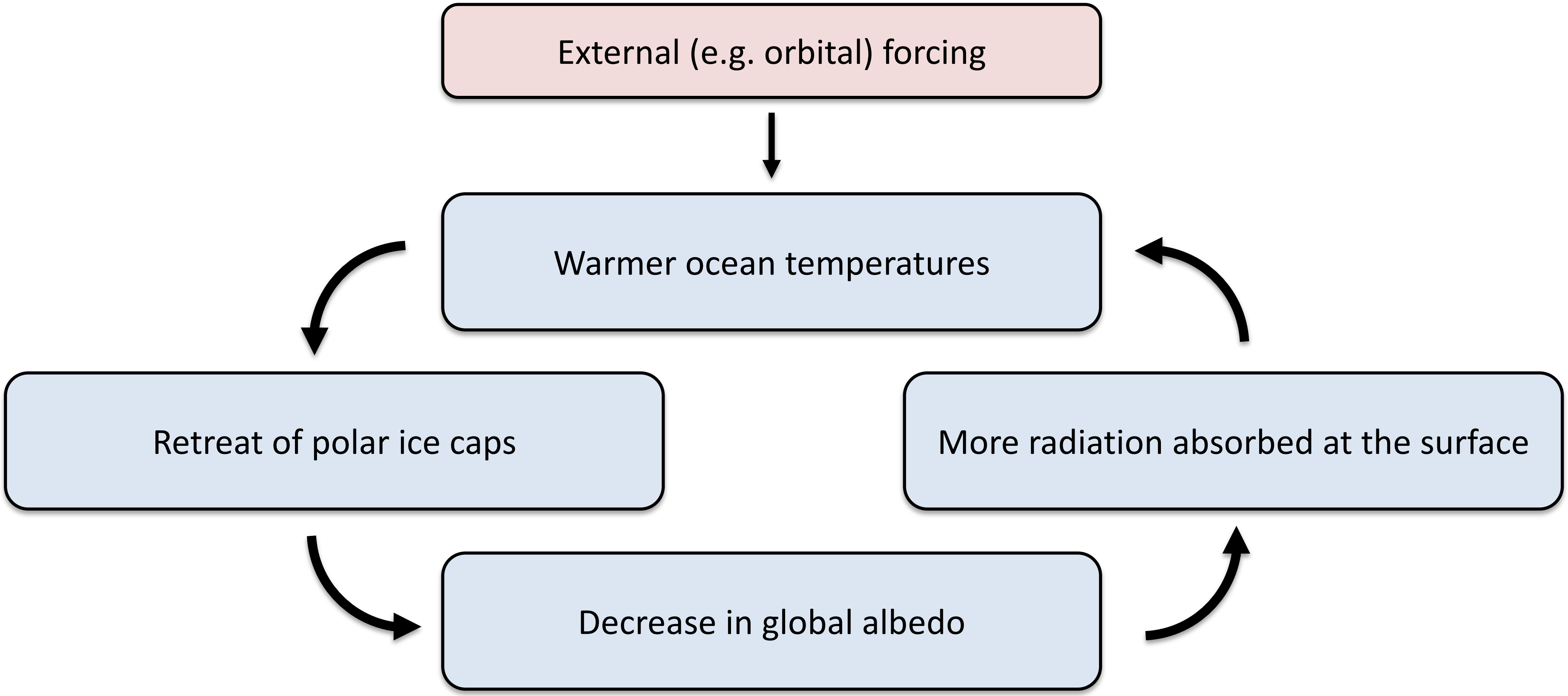


Figure: The warming cycle associated with the Ice-Albedo feedback (for example when Earth emerges from a glacial period).

Earth’s Temperature Record (542Myr ago)

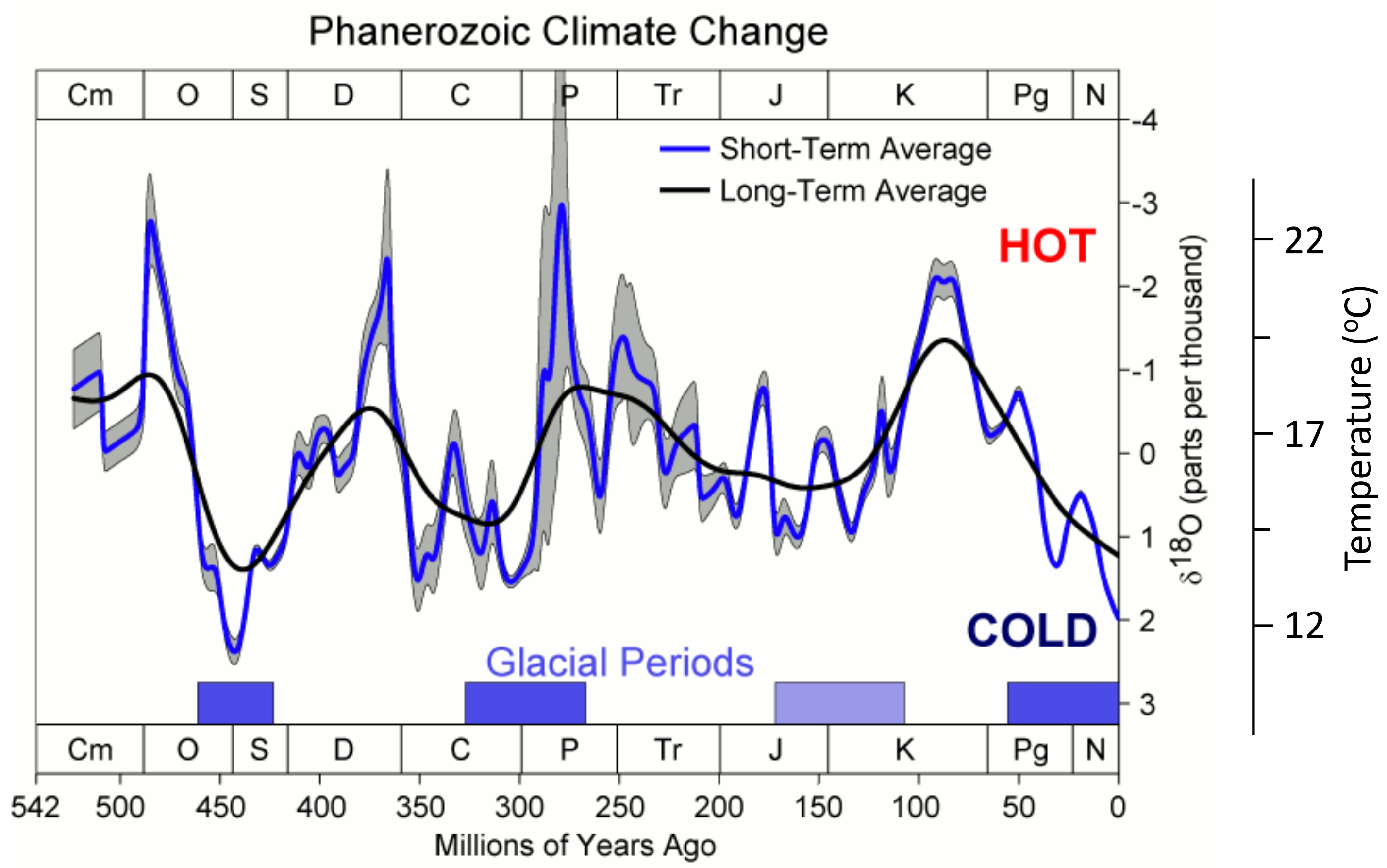
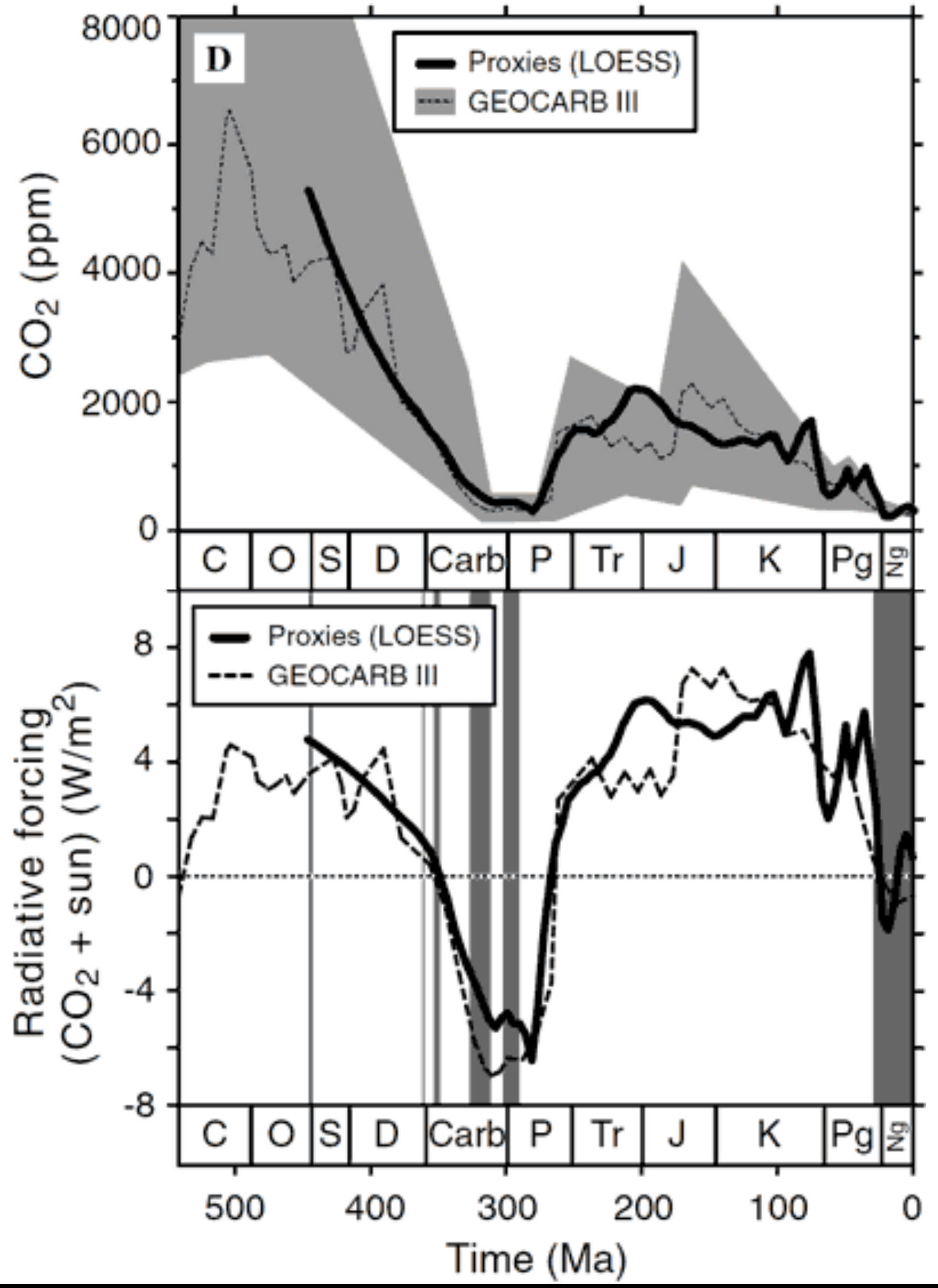


Figure: Reconstructed temperature record to 542 Myr ago using fossil records and δ^{18}O.

Historical CO_2

Figure: (Top) Atmospheric CO_2 concentration in parts per million through the Phanerozoic. (Bottom) Combined radiative forcing from CO_2 and the sun through the Phanerozoic. Grey bands are periods where there is evidence of geographically widespread ice. From Royer (2006).

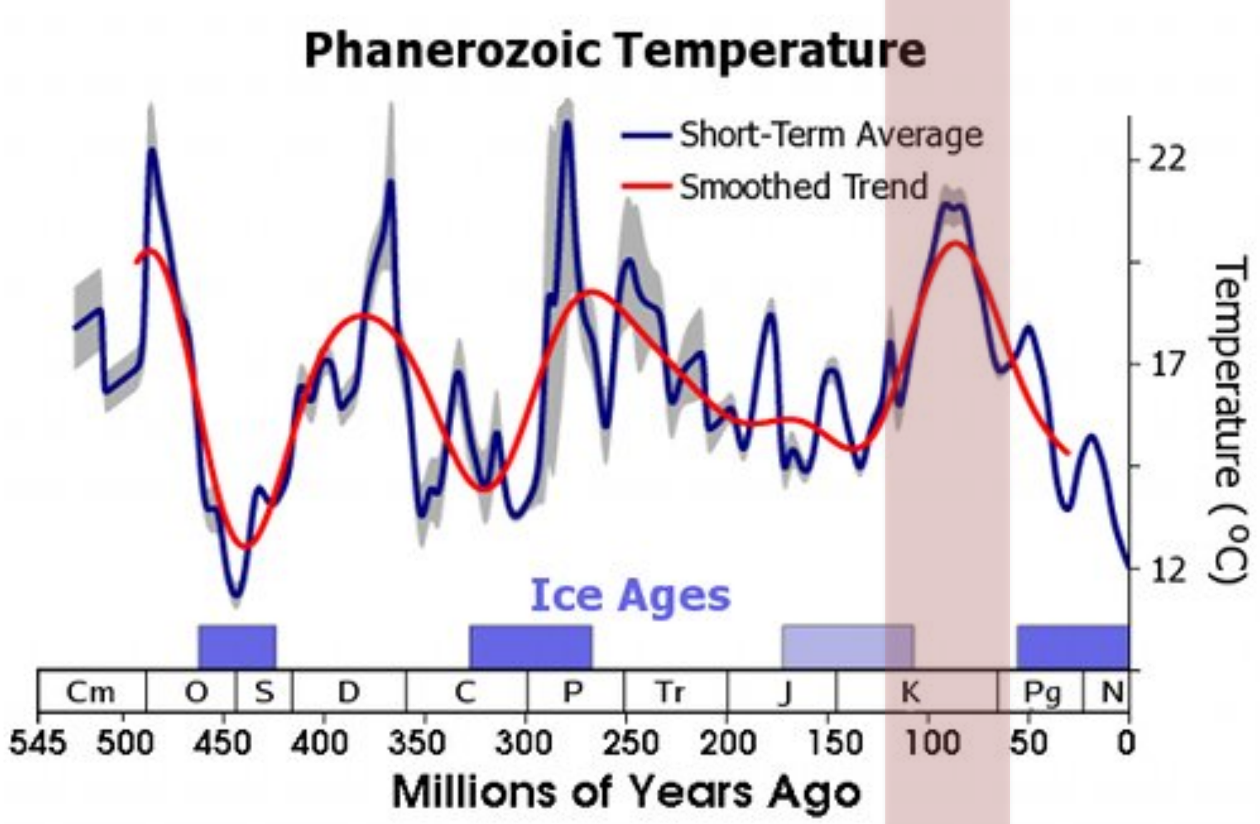
In the deep past, energy emitted by the sun was much weaker than present. Higher CO_2 concentrations in the Earth's atmosphere enabled it to maintain a temperature climate and support liquid water. Temperatures in the were only 5-10 degrees warmer than present.



Greenhouse Climates

During these greenhouse climate periods:

- No ice caps.
- Sea level 100-200m higher (due to melting of ice caps and thermal expansion of the ocean).
- Broad-leaved plants, dinosaurs, turtles lived north of the Arctic circle.
- CO_2 thought to be about five times preindustrial.



Greenhouse Climates

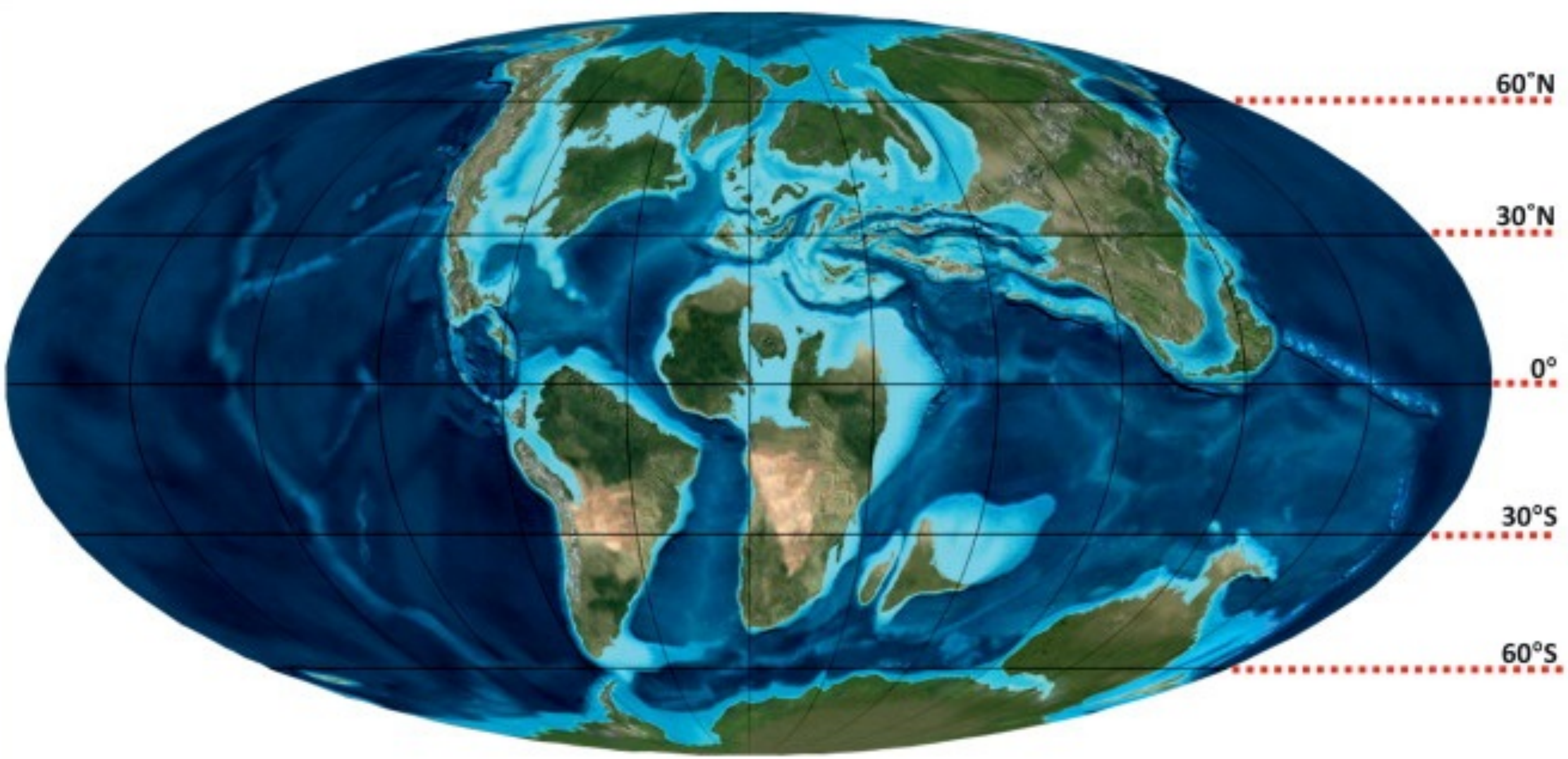
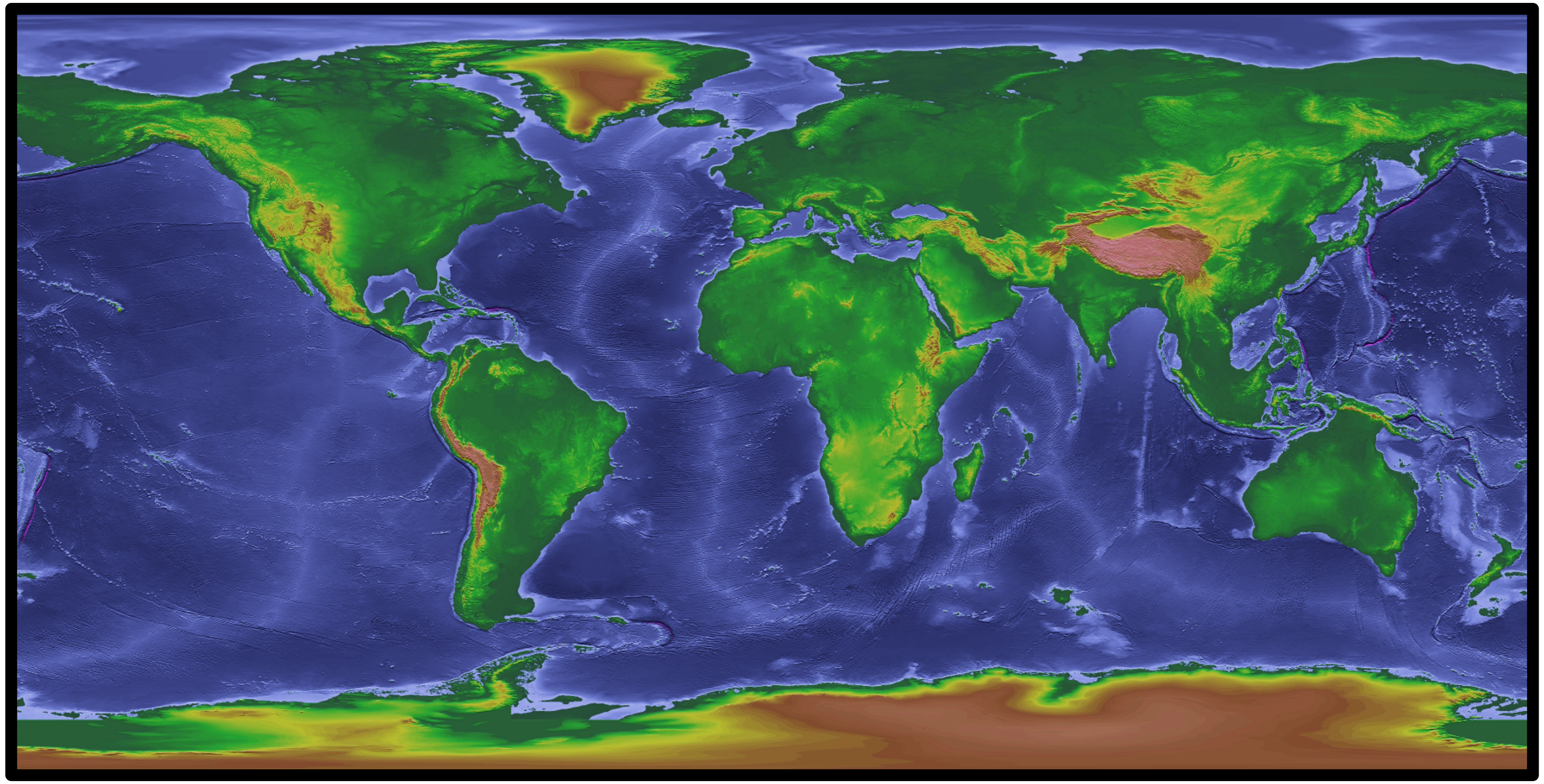


Figure: Paleogrography of the Late Cretaceous (90My ago)

Glacial Climates

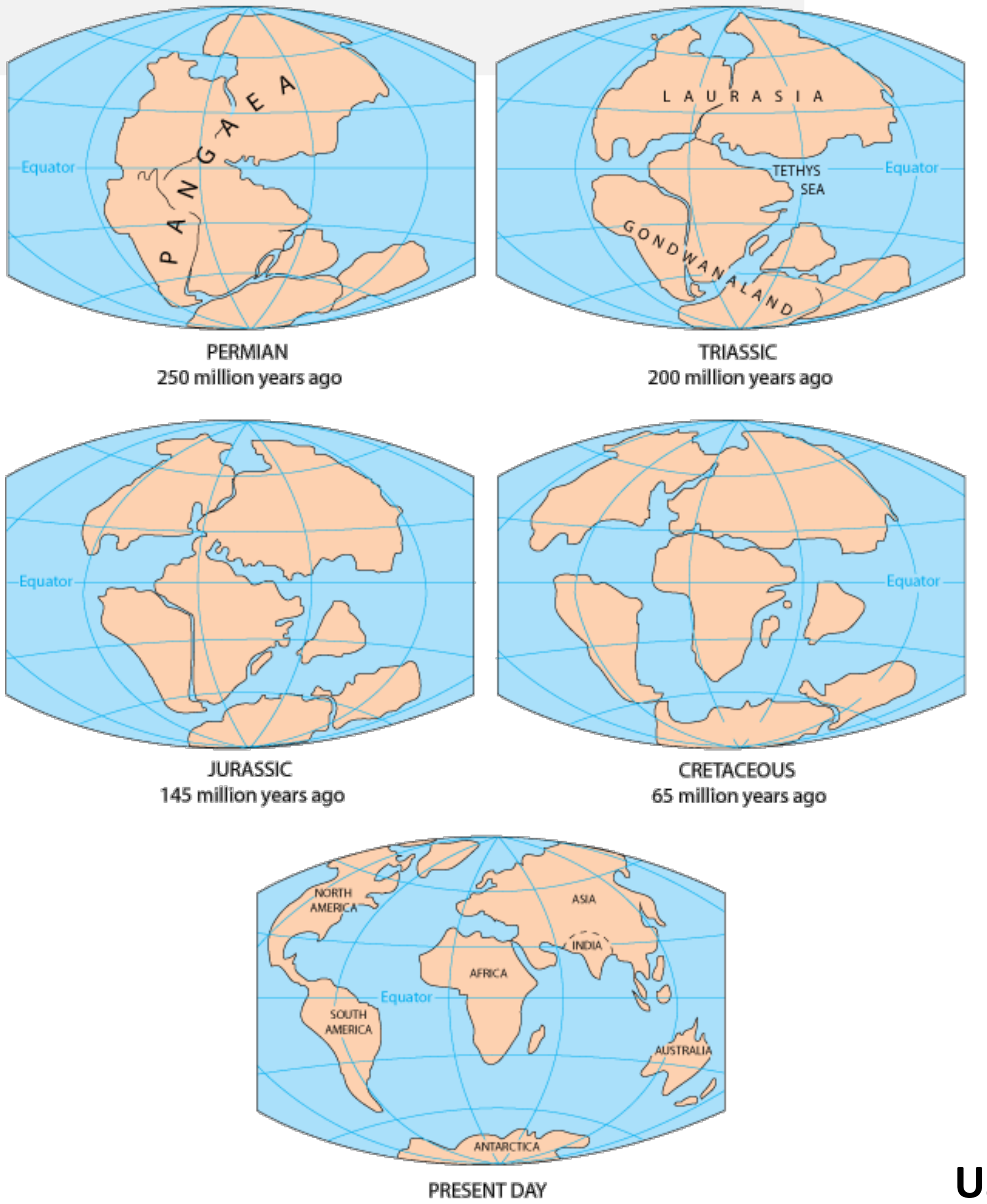
Figure: NOAA National Geophysical Data Center map of the world with sea levels comparable to the Last Glacial Maximum.

- Lower sea-surface heights on the order of 120-130m (closure of Bering sea and and connection of British Isles to Europe)
- Massive ice sheets covering Northern hemisphere.
- Windy, cold, arid conditions worldwide.



Geologic Climate Record

- Major changes in Earth’s climate over the geological record are often associated with movement of the Earth’s tectonic plates.
- The closure of the Isthmus of Panama (Panama Canal) by plate tectonics is thought to be the driver of the modern ice age by preventing oceanic distribution of heat.
- Opening of the Drake passage led to the formation of the Antarctic Circumpolar Current, which led to an isolation of Antarctica and its eventual glaciation.
- When the Bering Straight was wider than present, the Arctic ocean was much more accessible by warm ocean currents.



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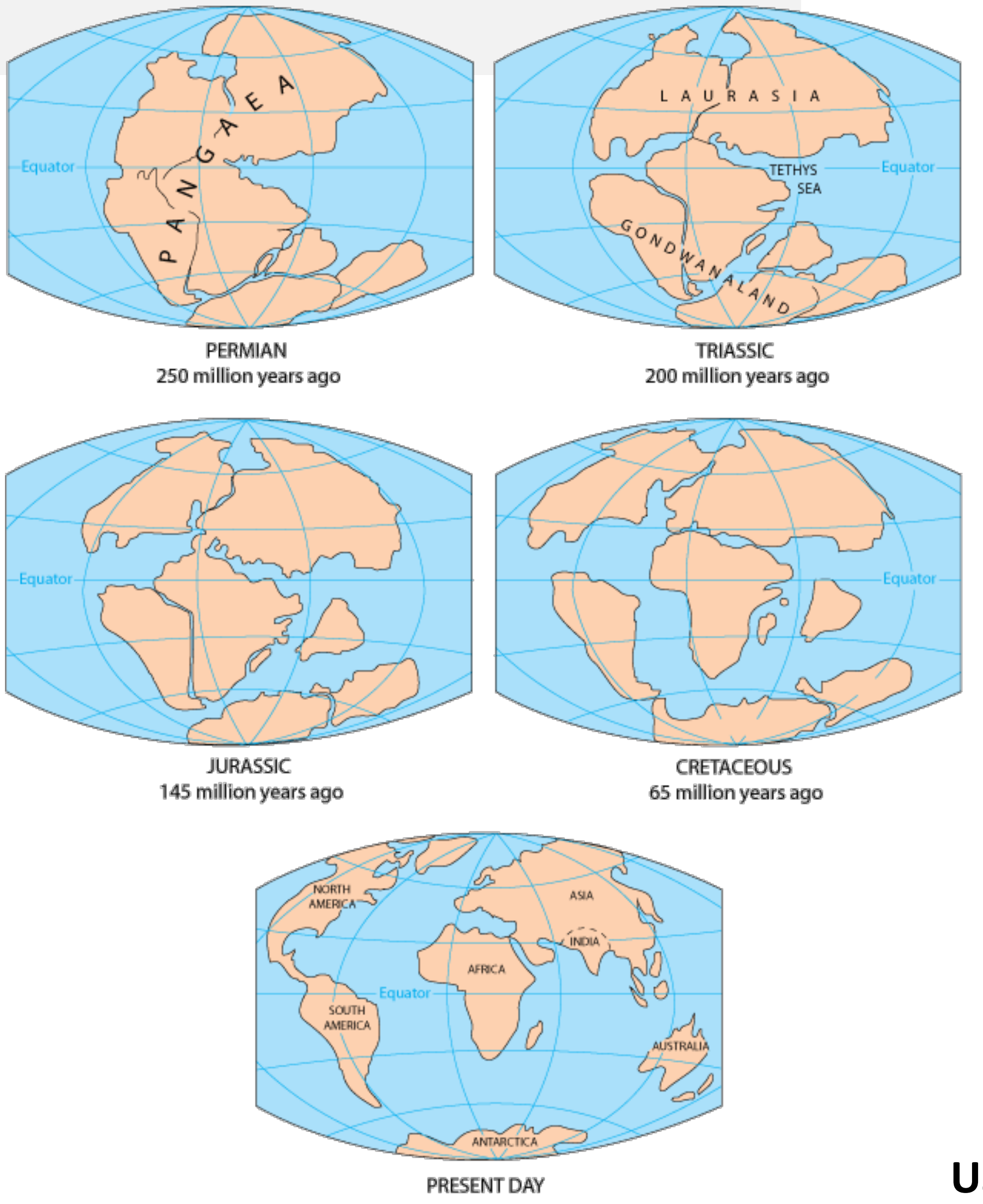
Geologic Climate Record

- However… Although many theories have been put forward to account for the shape and period of long term climate oscillations *none can exactly account for the observed record*.



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ATM 241 Climate Dynamics
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Thank You!