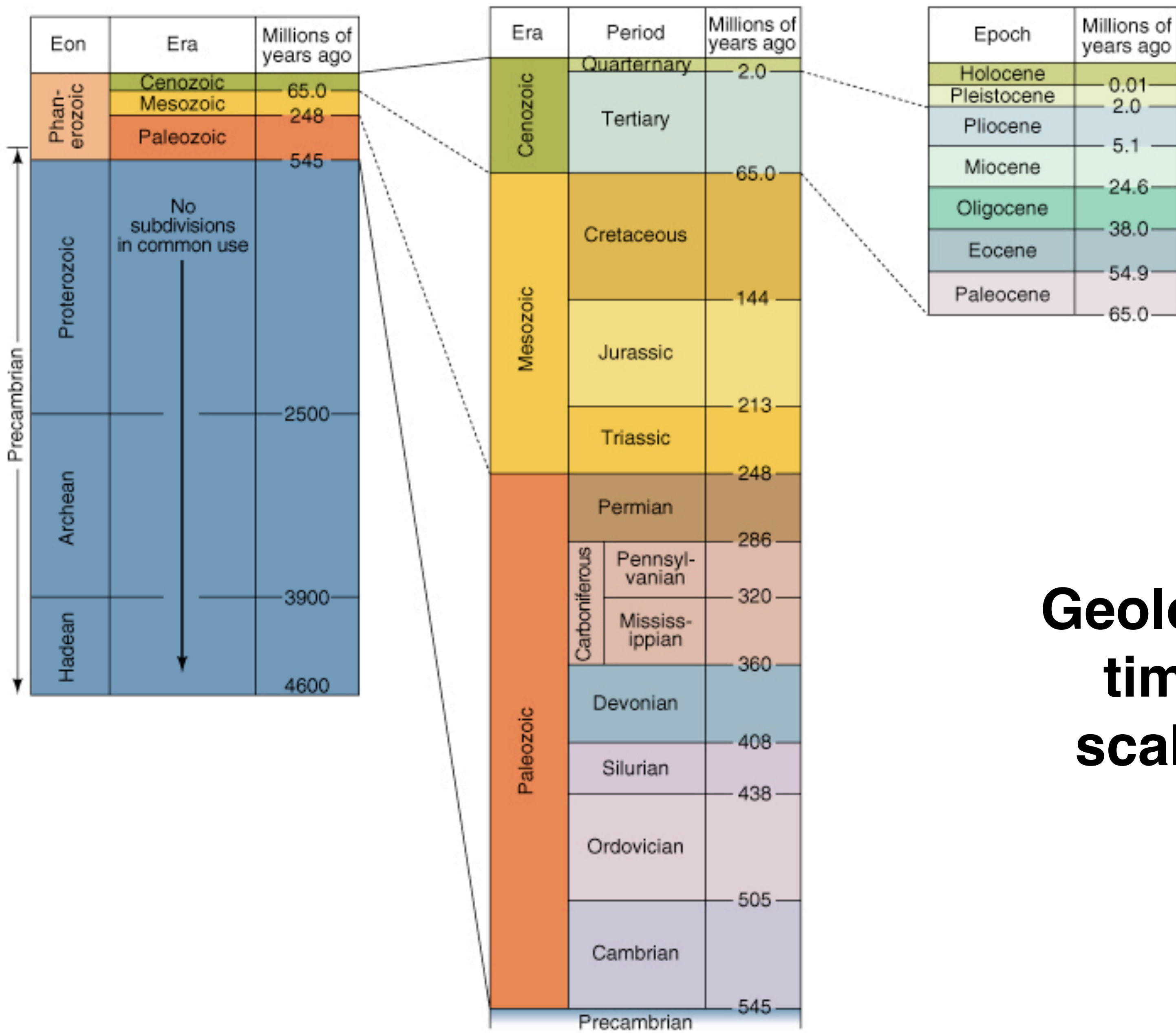
lecture 12

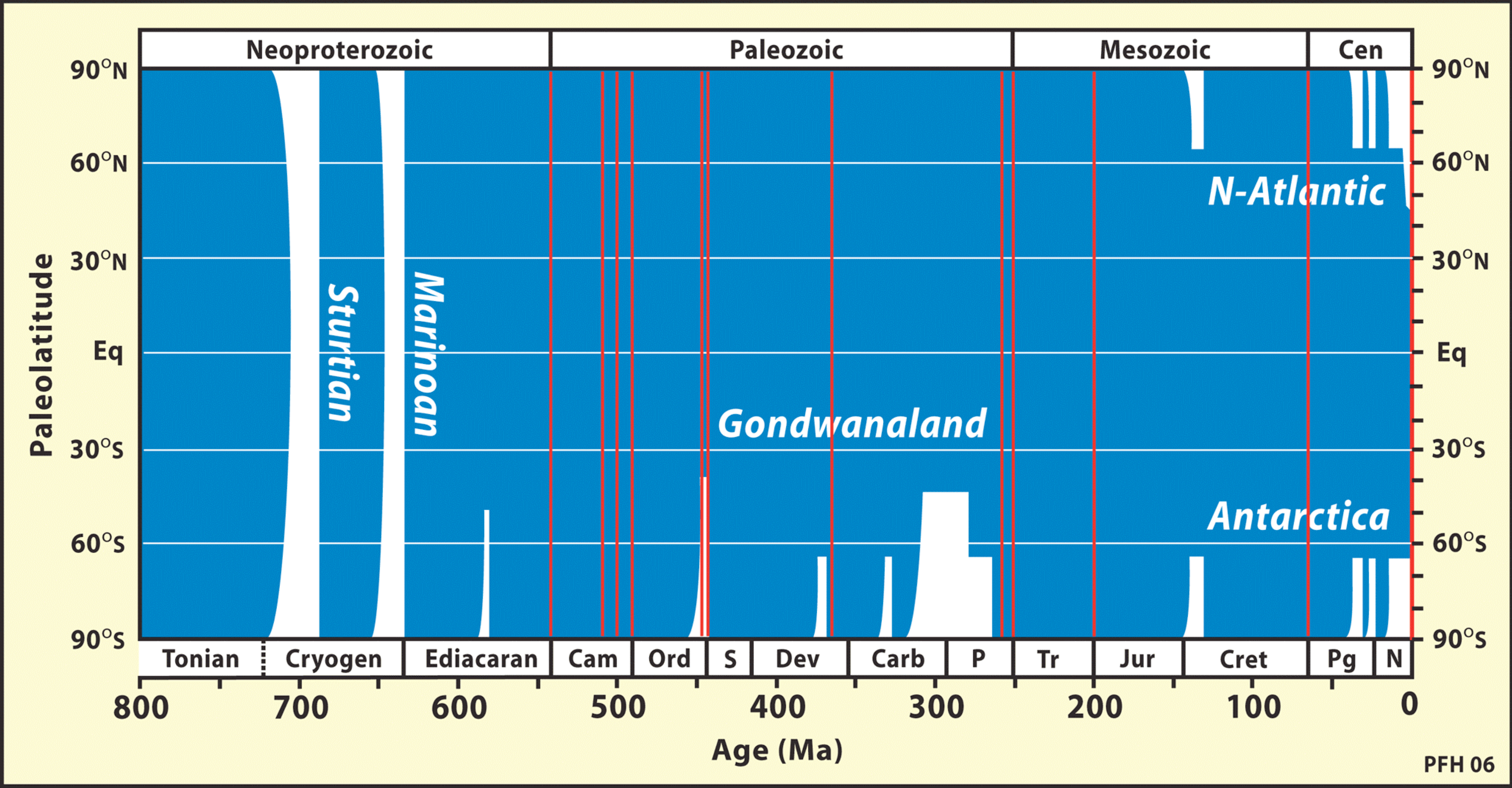
Paleoclimate

OVERVIEW OF EARTH'S CLIMATIC HISTORY



Geologic time scales

Paleogeographic extent of continental ice sheets and permanent sea ice over the last 800 Myr (red lines indicate major mass extinctions)



http://www.snowballearth.org/index.html

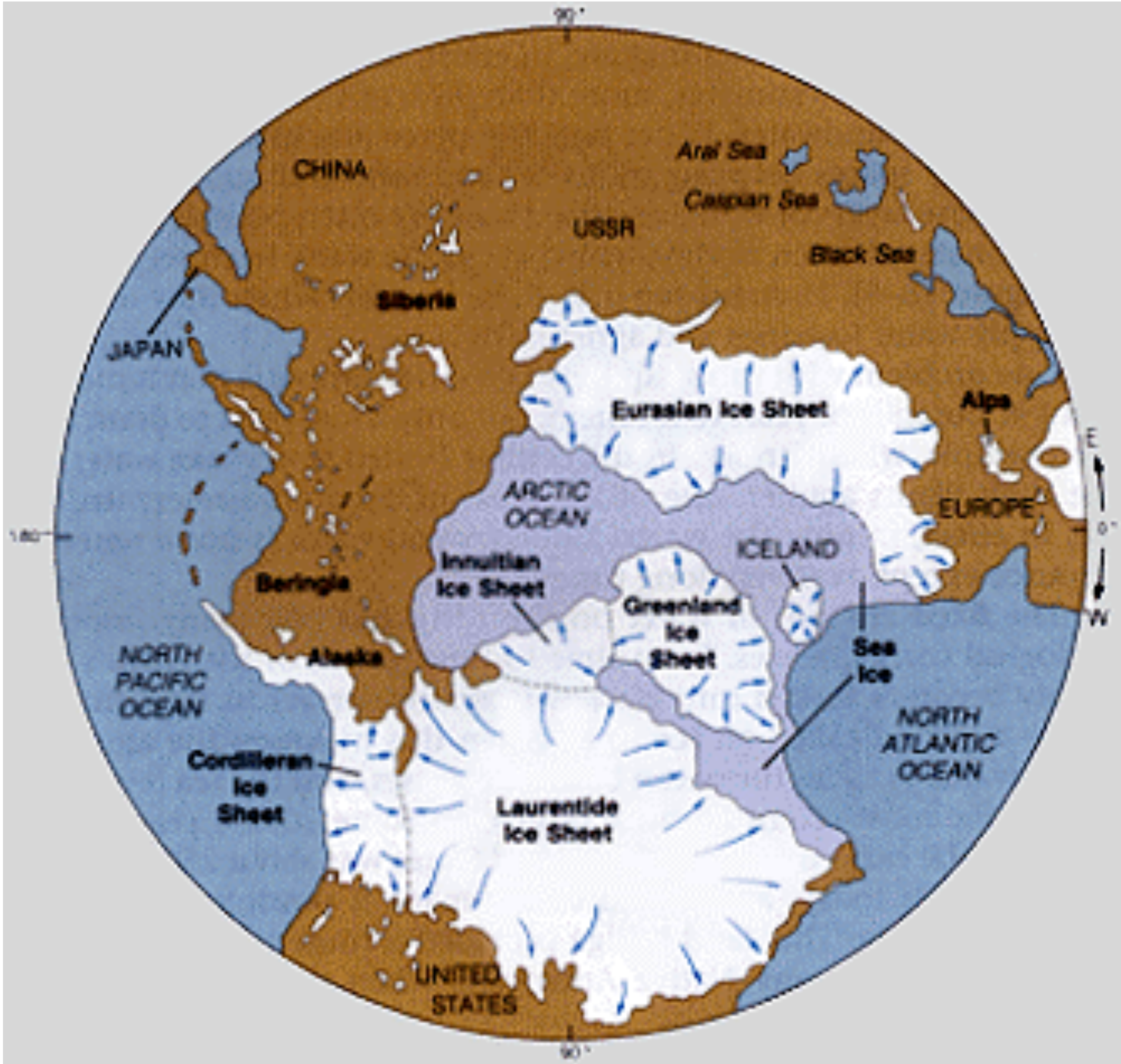
Features of the climate during the Cretaceous period

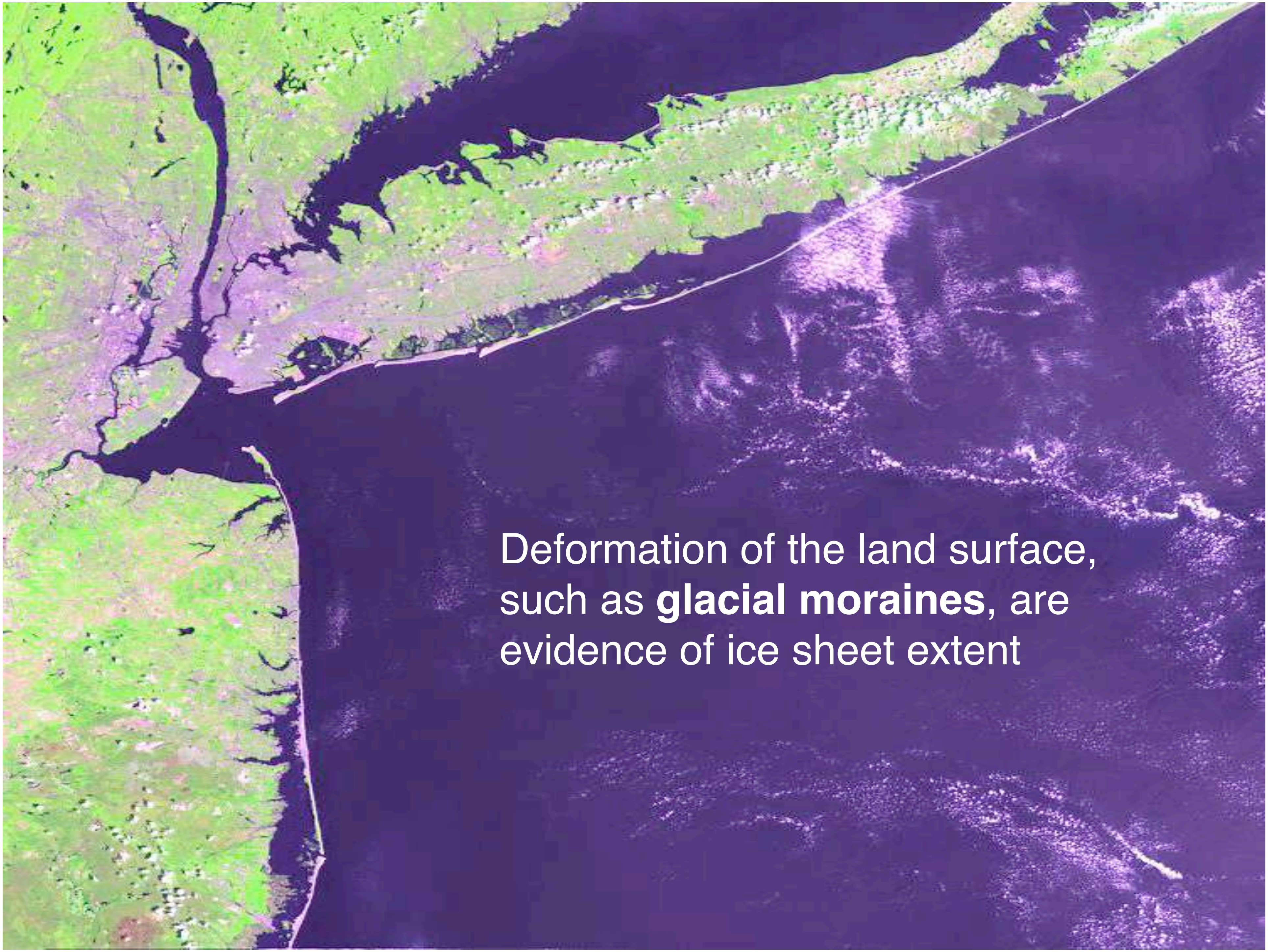
the land-sea distribution during the Cretaceous
image by Ron Blakey, Northern Arizona University

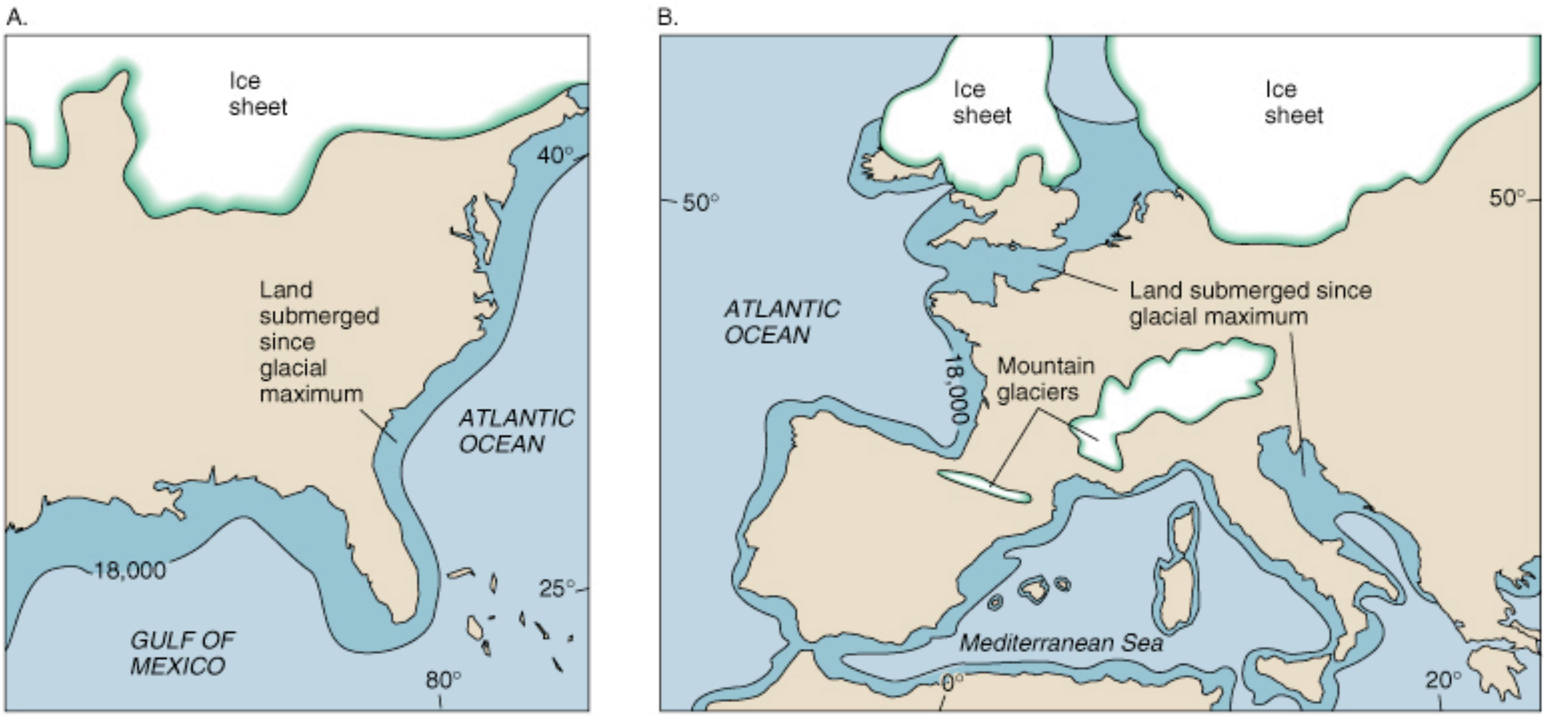
- **Deep ocean temperatures were 15-20 deg C.**
- **No ice at high latitudes.**
- **CO_2 levels were at least 4 times higher than current levels.**
- **Sea level was about 100 m higher than now.**
- **Major biomes were shifted 15 degrees poleward of their present positions.**

THE LAST GLACIAL MAXIMUM

The extent of the northern hemisphere ice sheets at the last glacial maximum. The expansion of these ice sheets resulted in a sea level approximately 130 meters lower than today's.

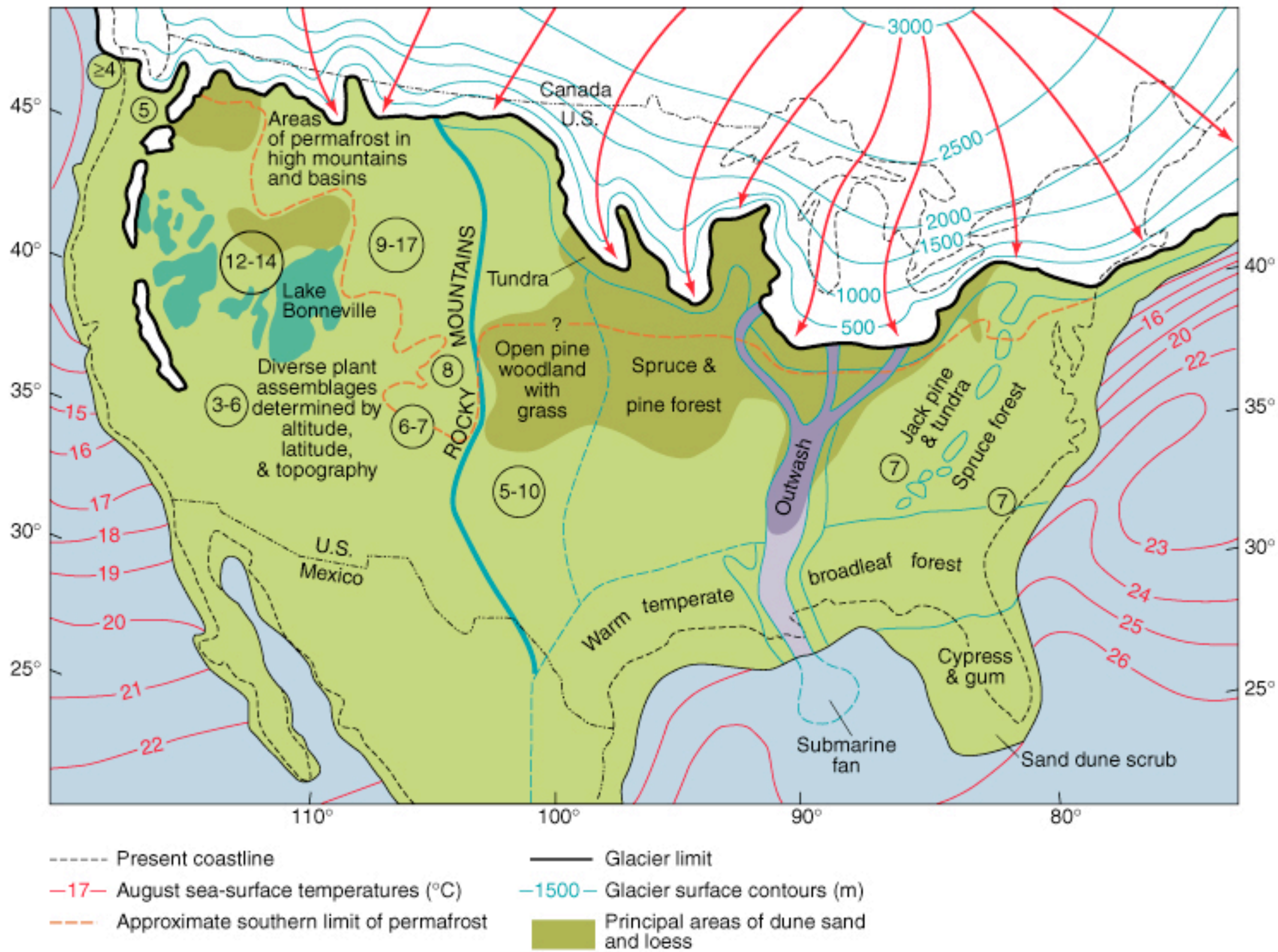



Deformation of the land surface, such as **glacial moraines**, are evidence of ice sheet extent



Because of the lowered sea level, the coastlines during the last ice age differed significantly from today's. North America was connected to Eurasia by a land bridge where the Bering strait is today, and the Mediterranean basin was cut off from the Atlantic.

The **climate** in North America was significantly different...



CLIMAP was a major research program in the 1970s to reconstruct the glacial climate at the LGM by means of fossil evidence from ocean and lake cores. Shown here is the reconstruction of sea surface temperatures. More recent evidence indicates SSTs were even cooler than indicated in the tropics.

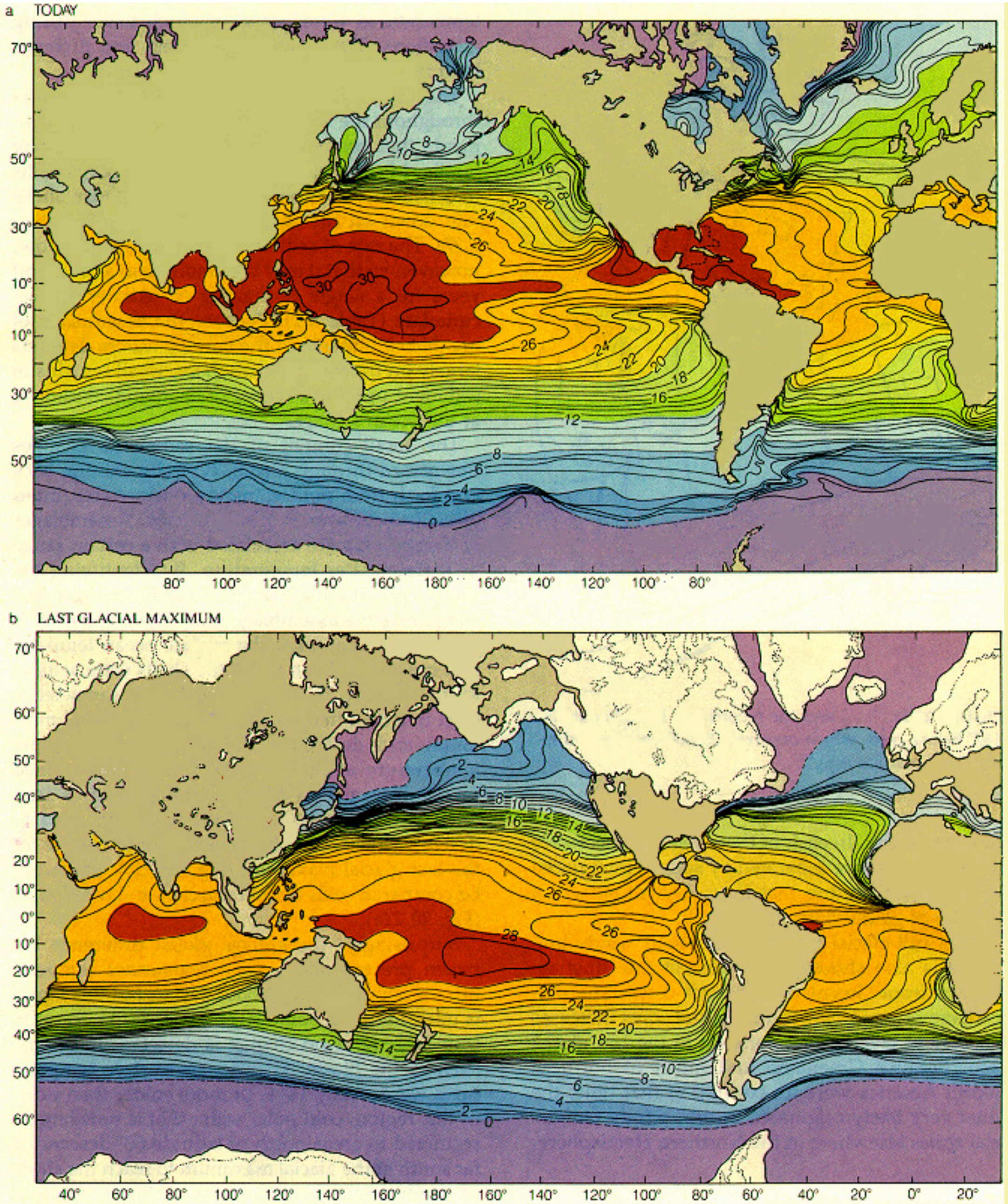


FIGURE 20.22 *(a)* Map showing modern sea-surface temperatures (°C) during August. *(b)* Map showing reconstructed August sea-surface temperatures during the last glacial maximum, about 18,000 years ago. Cold polar water extended far south of its present limit in the North Atlantic, and plumes of cold water flowed westward in the equatorial Pacific and Atlantic. (*Source:* After CLIMAP Project Members, 1976.)

A numerical experiment to elucidate the relative importance of factors affecting the cooling at the LGM relative to the present

Experimental Design

Experiment	E1	E2	E3	E4
Land–sea distribution	P[a]	G[b]	G	G
Continental ice distribution	P	G	G	G
Atmospheric CO_2 concentration (ppm)	300	300	300	200
Snow-free land albedo distribution	P	P	G	G
Length of analysis period (years)	15	8	6	8

[a]P = present conditions.
[b]G = conditions estimated for last glacial maximum.

Table 11.6

Differences in Area-Averaged Annual Mean SST between Pairs of Experiments Conducted by Broccoli and Manabe (1987) in °C

		Global	N. Hem.	S. Hem.
E2–E1	(Ice sheet)	–0.8	–1.6	–0.2
E4–E3	(CO_2)	–1.0	–0.7	–1.1
E3–E2	(Albedo)	–0.2	–0.3	–0.2
E4–E1	(Combined)	–1.9	–2.6	–1.5
CLIMAP		–1.6	–1.9	–1.3

Only those grid points that represent oceans in all experiments are used in computing the differences. Differences between CLIMAP ice age estimates of SST and current values are shown for comparison.

Results

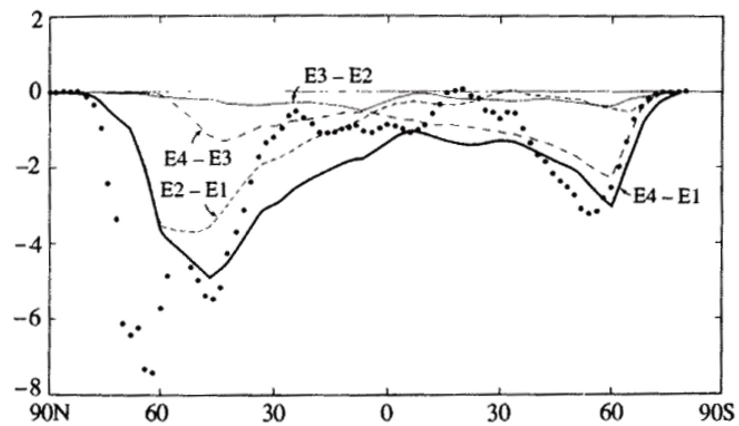
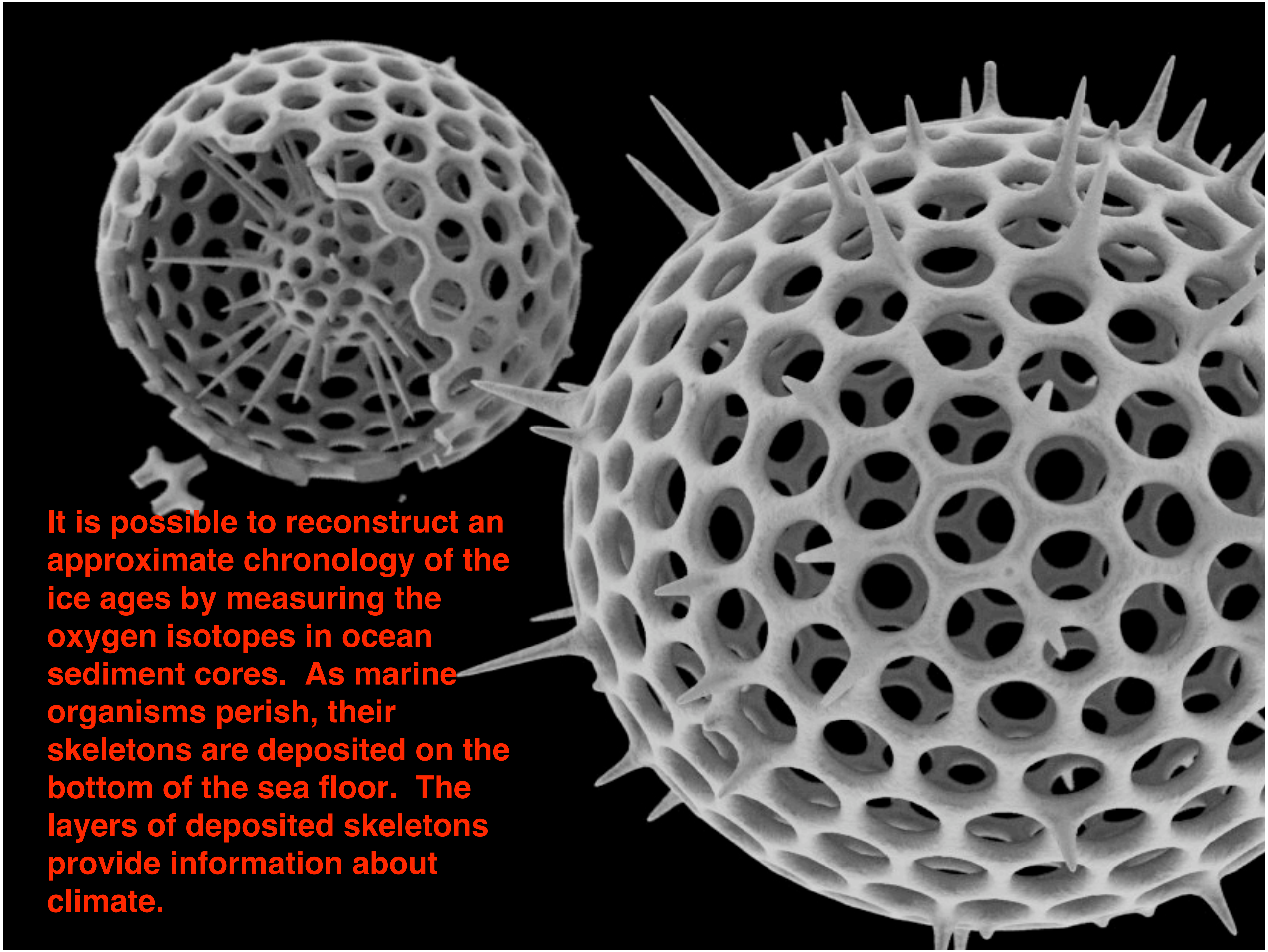
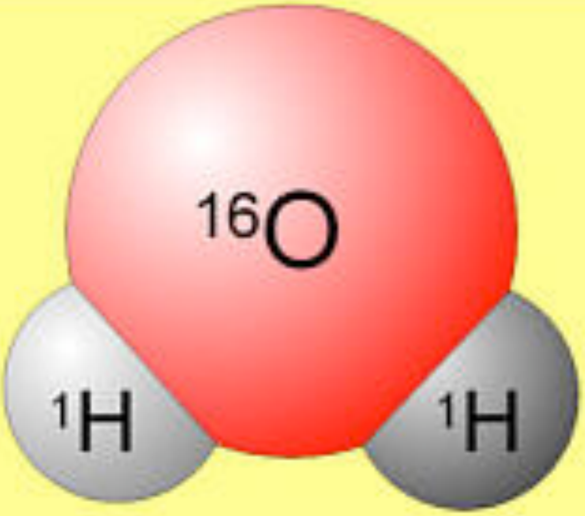


Fig. 11.14 SST changes (°C) induced by various ice age forcing mechanisms in the model of Broc-:oli and Manabe (1987) (various curves) compared with the SST inferred from ocean cores (dots). :2–E1, effect of ice sheets; E3–E2, effect of land albedo; E4–E3, effect of CO_2 concentration; E4–E1, lifference between complete ice age simulation and simulation of current climate.

HISTORY OF GLACIATION DURING THE PLEISTOCENE



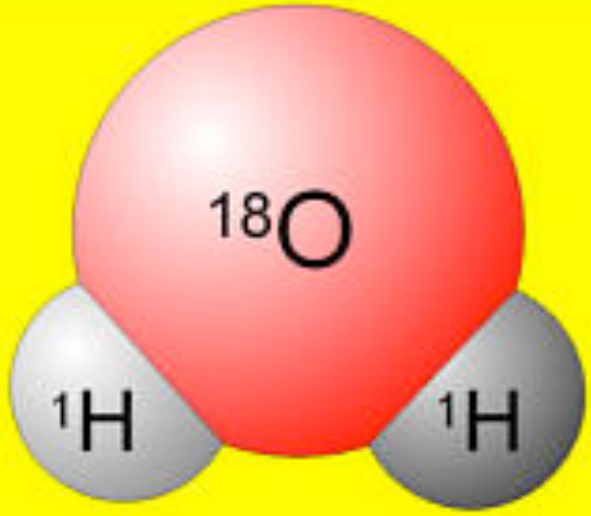
It is possible to reconstruct an approximate chronology of the ice ages by measuring the oxygen isotopes in ocean sediment cores. As marine organisms perish, their skeletons are deposited on the bottom of the sea floor. The layers of deposited skeletons provide information about climate.



$1+1+16 = \underline{\mathbf{18}}$

Molecular weight of ^{16}O water

Makes up 99.8% of water, evaporates more easily, precipitates less easily.



$1+1+18 = \underline{\mathbf{20}}$

Molecular weight of ^{18}O water

0.2% of water, 11% heavier, evaporates less easily, precipitates more easily.

Superscripts show atomic masses of hydrogen and oxygen

ICE VOLUME EFFECT ON OXYGEN ISOTOPES

The ratio of the heavier to the lighter oxygen isotope varies in the ambient seawater because of the variations in total ice volume. The water molecules containing the heavier isotope are less likely evaporate and be incorporated into the ice sheet. So as total ice volume increases, the ocean becomes increasingly enriched in the heavier isotope of oxygen.

TEMPERATURE EFFECT ON OXYGEN ISOTOPES

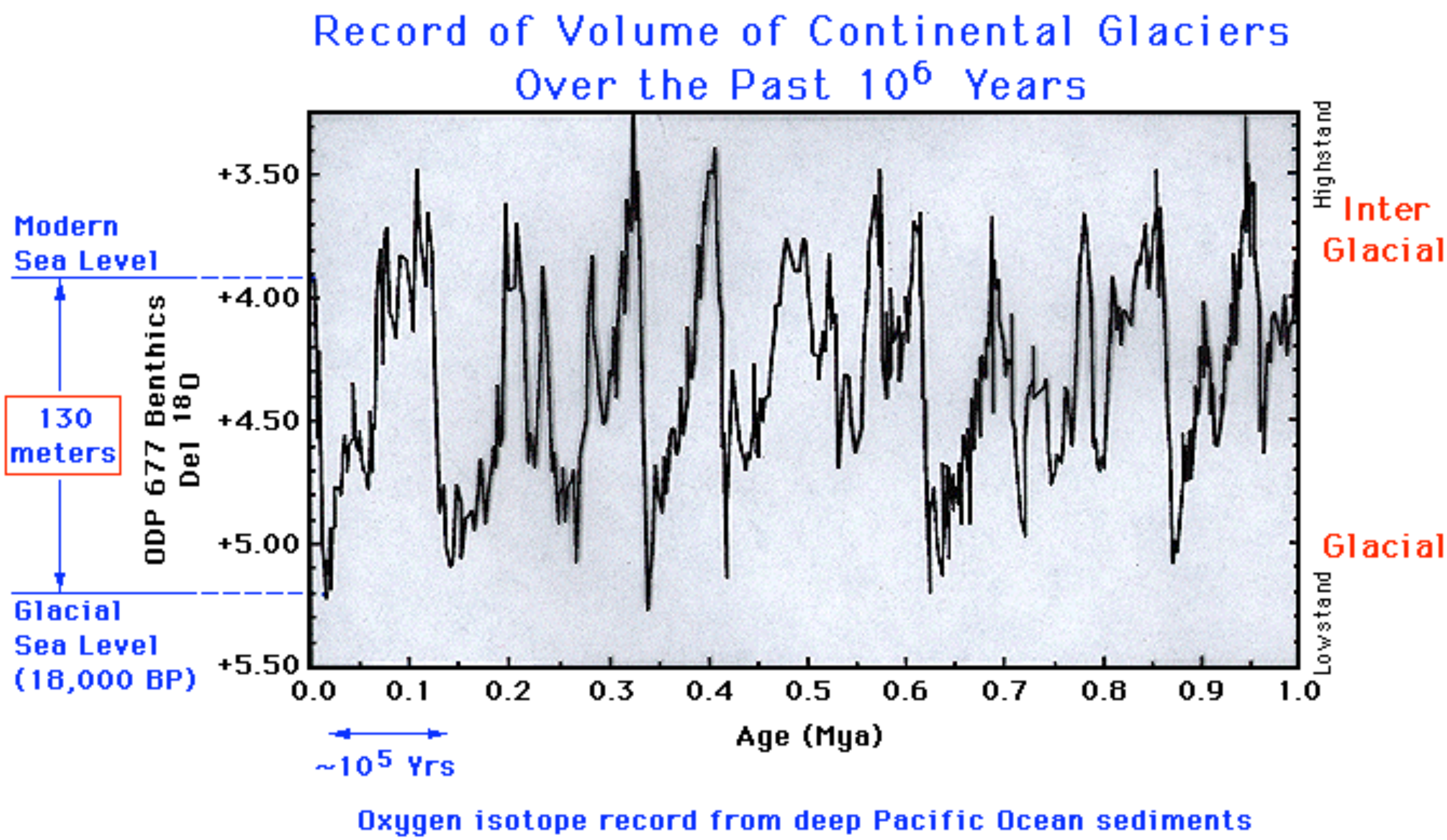
When temperatures are colder, the organisms incorporate more of the heavier isotope of oxygen into their skeletons. Measuring the ratio of the heavier to the lighter oxygen isotope in the skeletons therefore indicates how warm the water was when the organism was alive.

OXYGEN ISOTOPE SIGNATURE IN SEDIMENT CORES

So when ocean temperatures are cold and ice volume is large, the skeletons should be enriched in the heavier isotope. Presumably temperature and ice volume are tightly correlated, so an examination of the oxygen isotope record in ocean sediment cores gives us a clear picture of when the ice ages occurred.

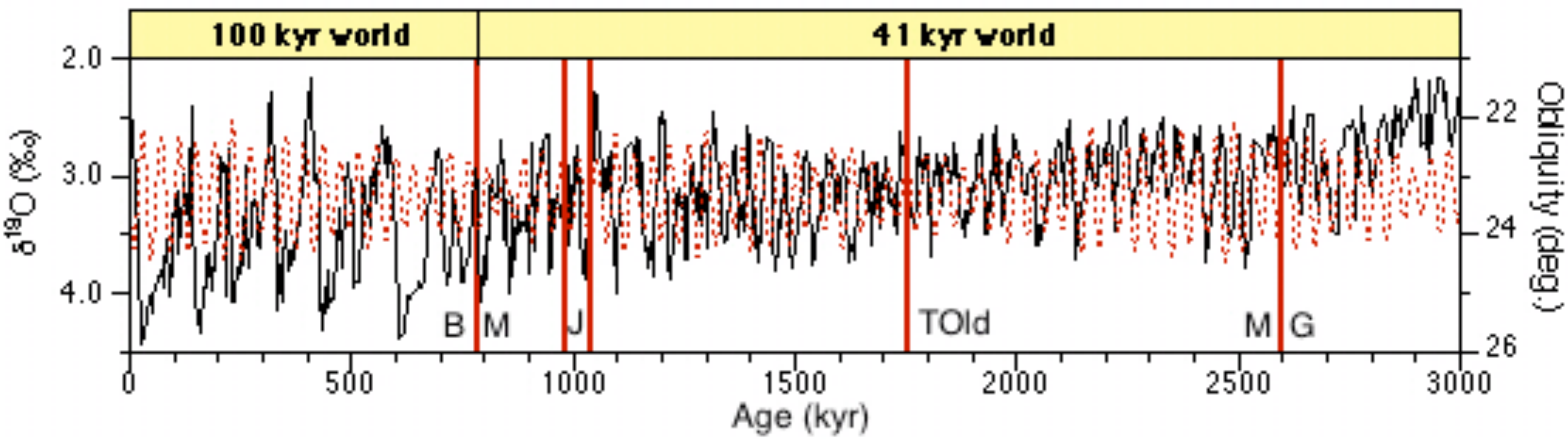
The oxygen isotope ratio is given in terms of a quantity called $\delta^{18}O$, defined by the following expression:

$$\delta^{18}O = \frac{\left({}^{18}O/{}^{16}O\right)_{sample} - \left({}^{18}O/{}^{16}O\right)_{stnd}}{\left({}^{18}O/{}^{16}O\right)_{stnd}}$$



This is the oxygen isotope record from the Pacific Ocean off the coast of South America. It reveals that in the past 1 million years, the ice ages occurred approximately once every 100,000 years.

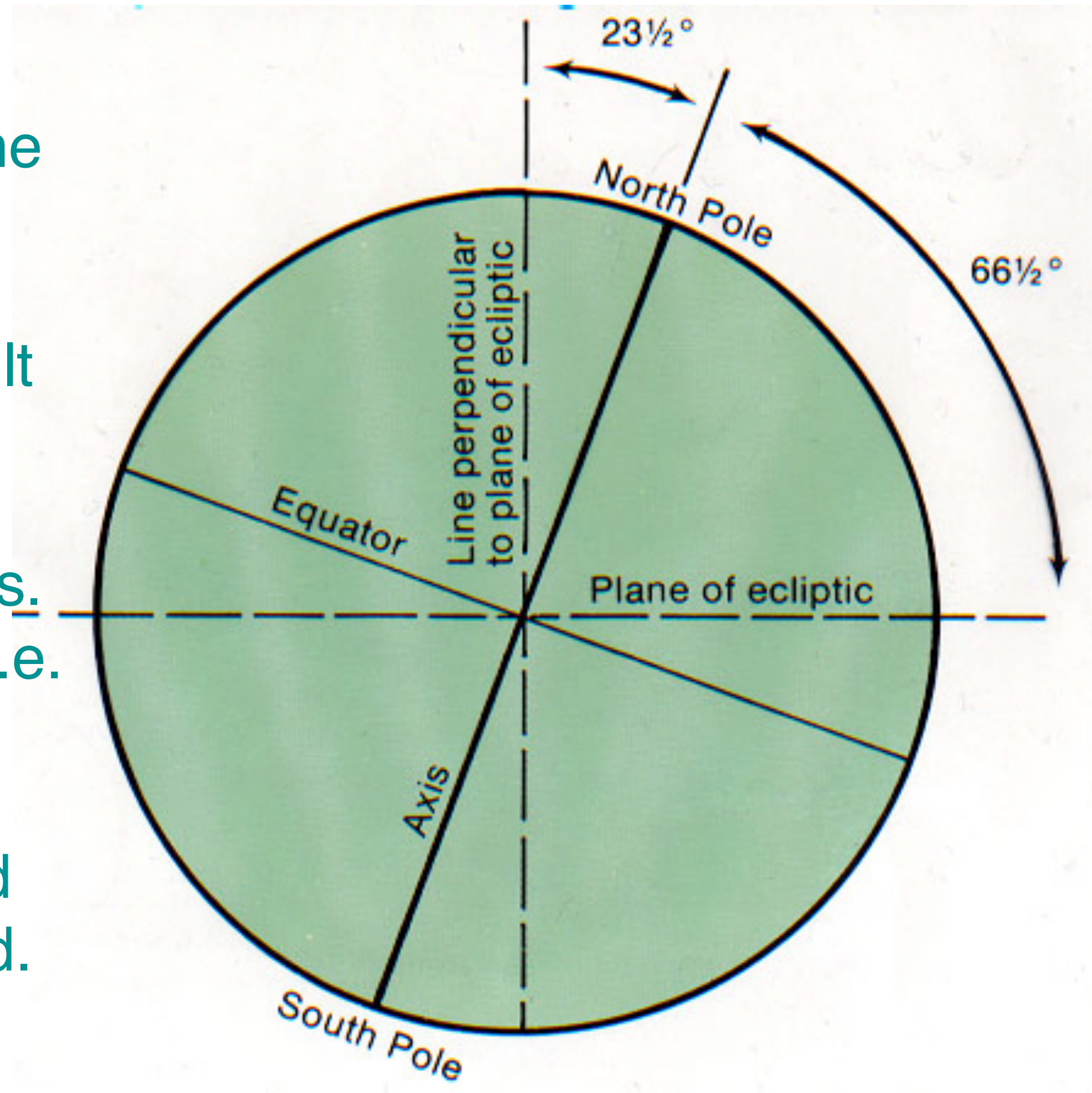
Longer records are found in other ocean basins…



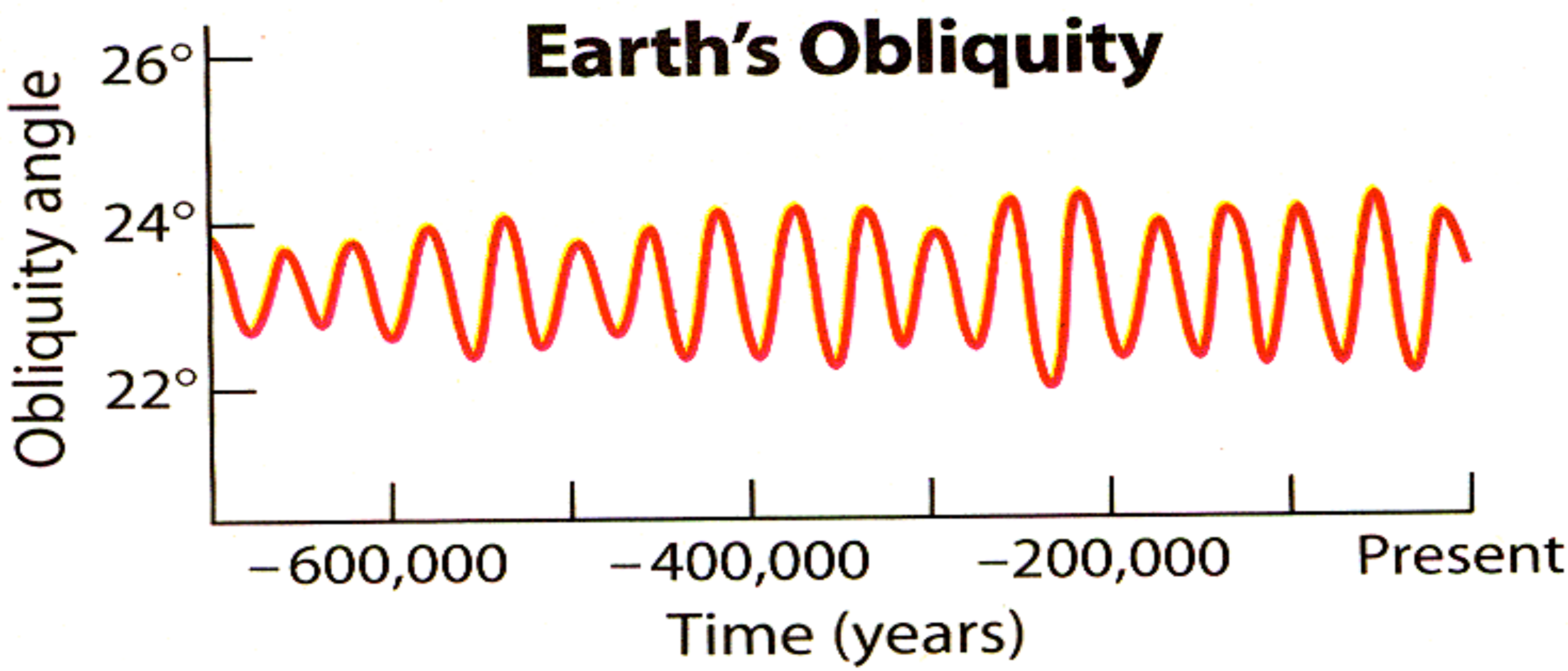
Benthic $\delta^{18}O$ record from DSDP Site 607 in the North Atlantic (solid line). Also shown is orbital obliquity (red dashed line). [Raymo et al. (1990)]

MILANKOVITCH FORCING

The axis about which the earth rotates is tilted relative to the plane of the earth's orbit. This tilt is called **obliquity**. Currently the earth's obliquity is 23.5 degrees. If the obliquity were 0 (i.e. no tilt), the seasonal variation in insolation in each hemisphere would be dramatically reduced.



The tilt of a spinning object can vary; earth is no exception. The obliquity of the earth varies between about 22 and 24 degrees with a period of about 41,000 years.



Sensitivity of the seasonal distribution of sunshine to obliquity variations.

The top panel shows the current normalized distribution function of solar radiation, the bottom panel shows the change in this distribution function if obliquity is increased to 25.5 degrees.

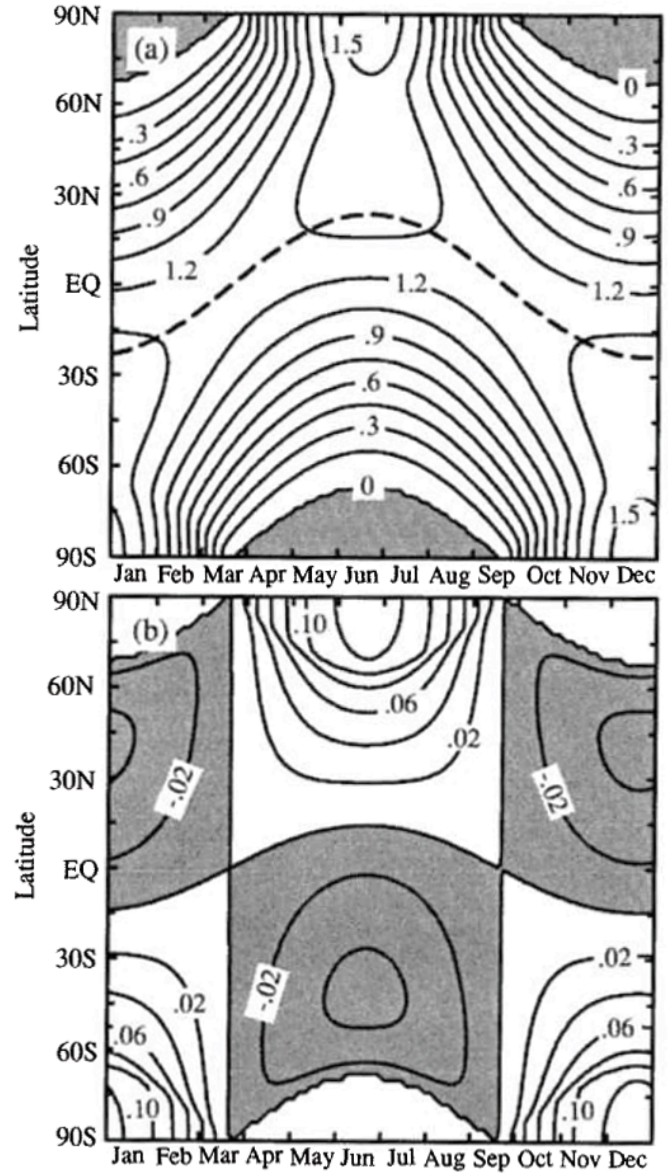
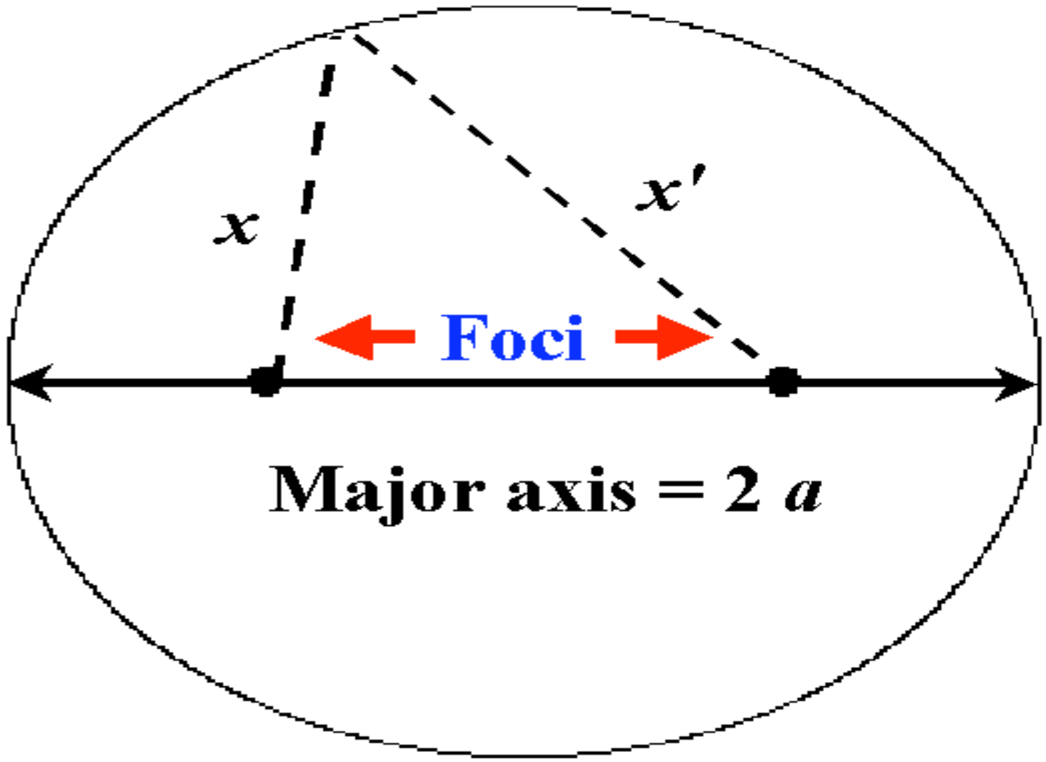
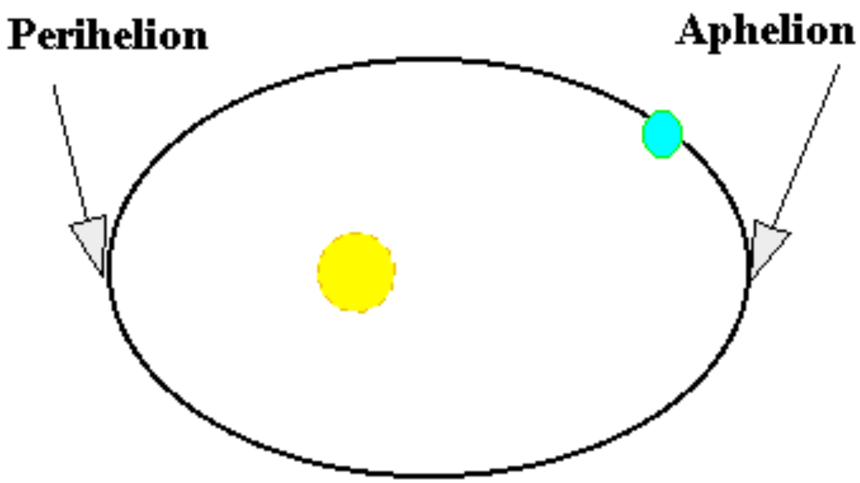


Fig. 11.10 (a) Insolation distribution function $\bar{s}(\Phi,x,t)$ plotted as a function of latitude and season for an obliquity of $\Phi = 23.5°$. (b) Sensitivity of the insolation distribution function to obliquity, $\Delta\Phi(\partial\bar{s}/\partial\Phi)_{\Phi=23.5}$, evaluated for $\Delta\Phi = 2°$.

from Hartmann

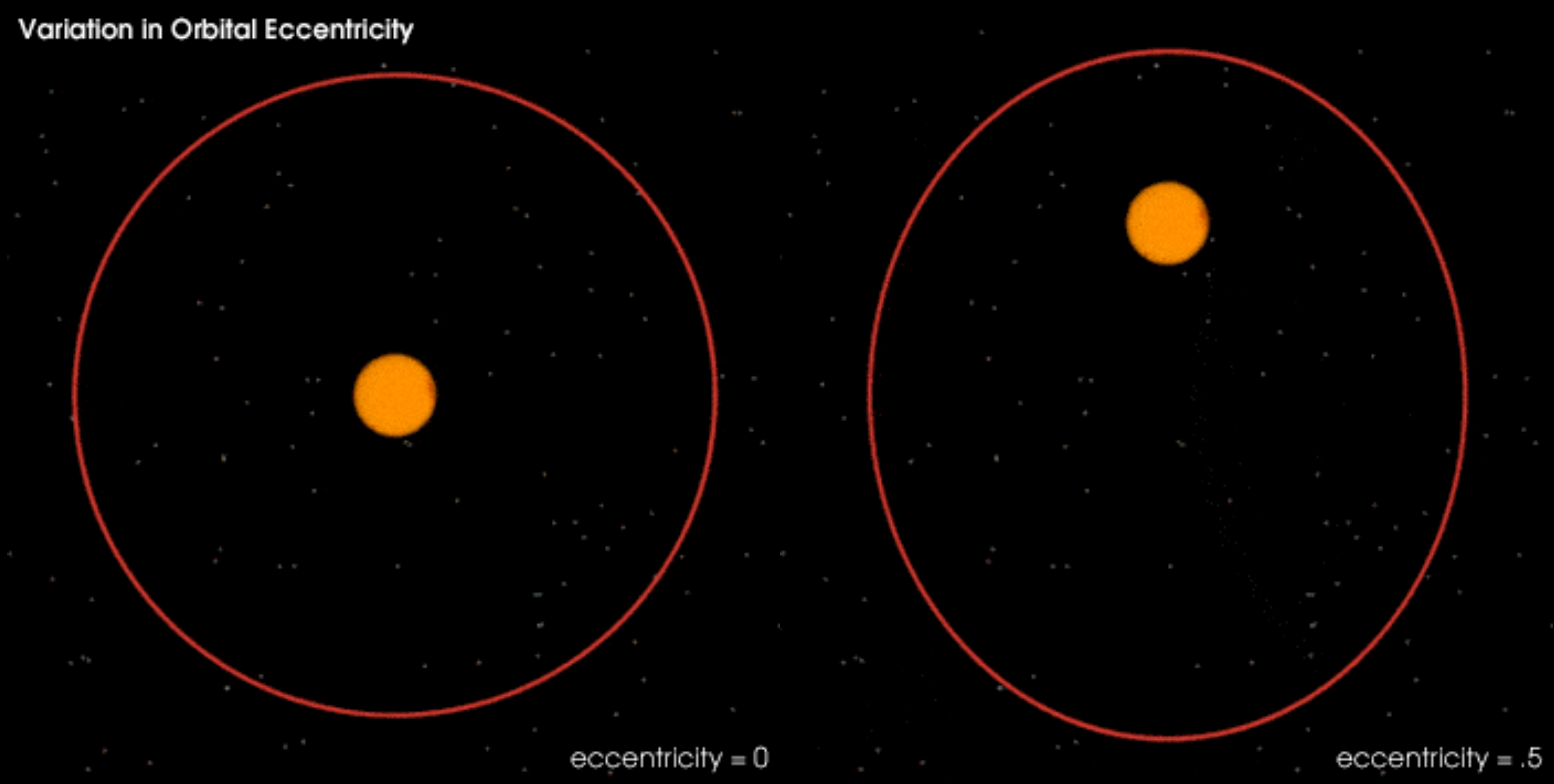


The orbits of the planets are **ellipses** (from Kepler's law). The sun is at one of the two foci of the elliptical orbit.

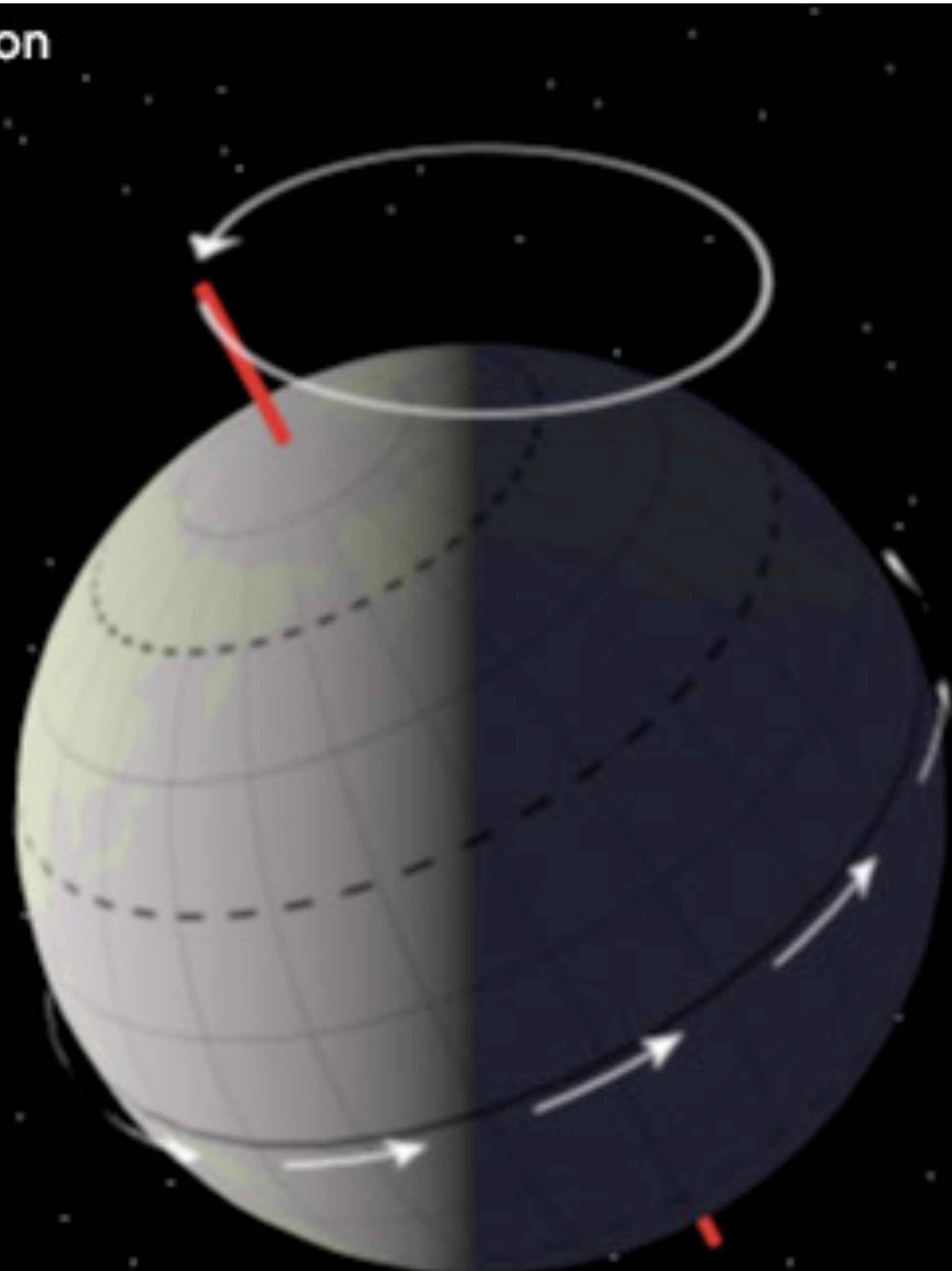


The point in the orbit when the a planet is closest to the sun is called perihelion. The point when the planet is furthest from the sun is called the aphelion.

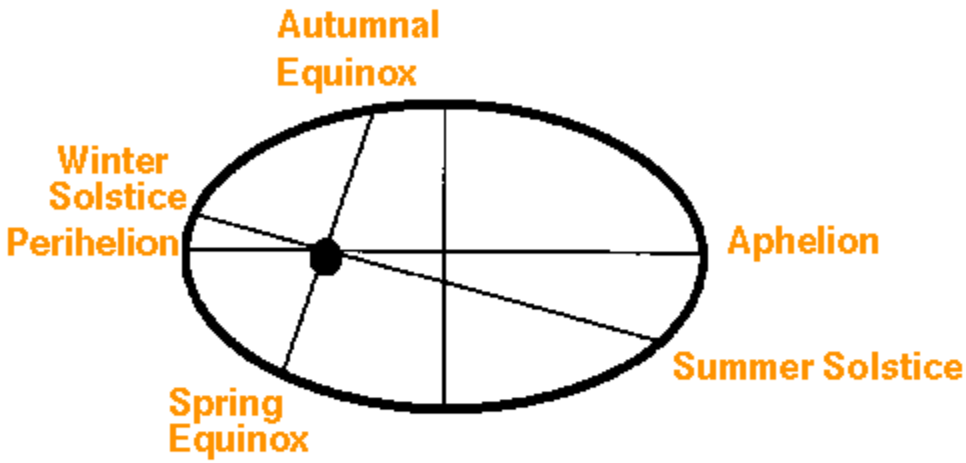
In the case of earth's orbit, perihelion currently occurs in early January, while aphelion occurs in early July. The planet gets more sunshine at perihelion, and less at aphelion, according to the inverse square law.



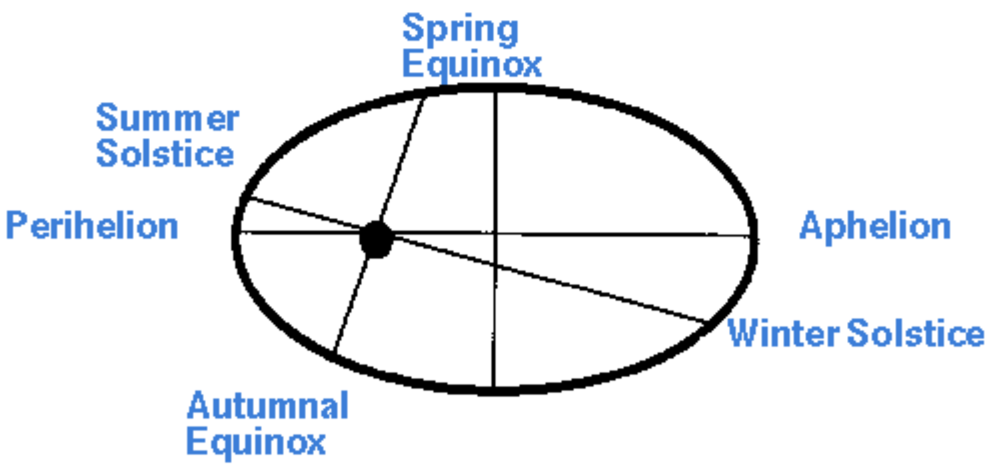
The **eccentricity** of the earth's orbit varies between 0 an 0.06 with a period of about 100,000 years and 400,000 years. This variation is due to the gravitational pull of other planets.



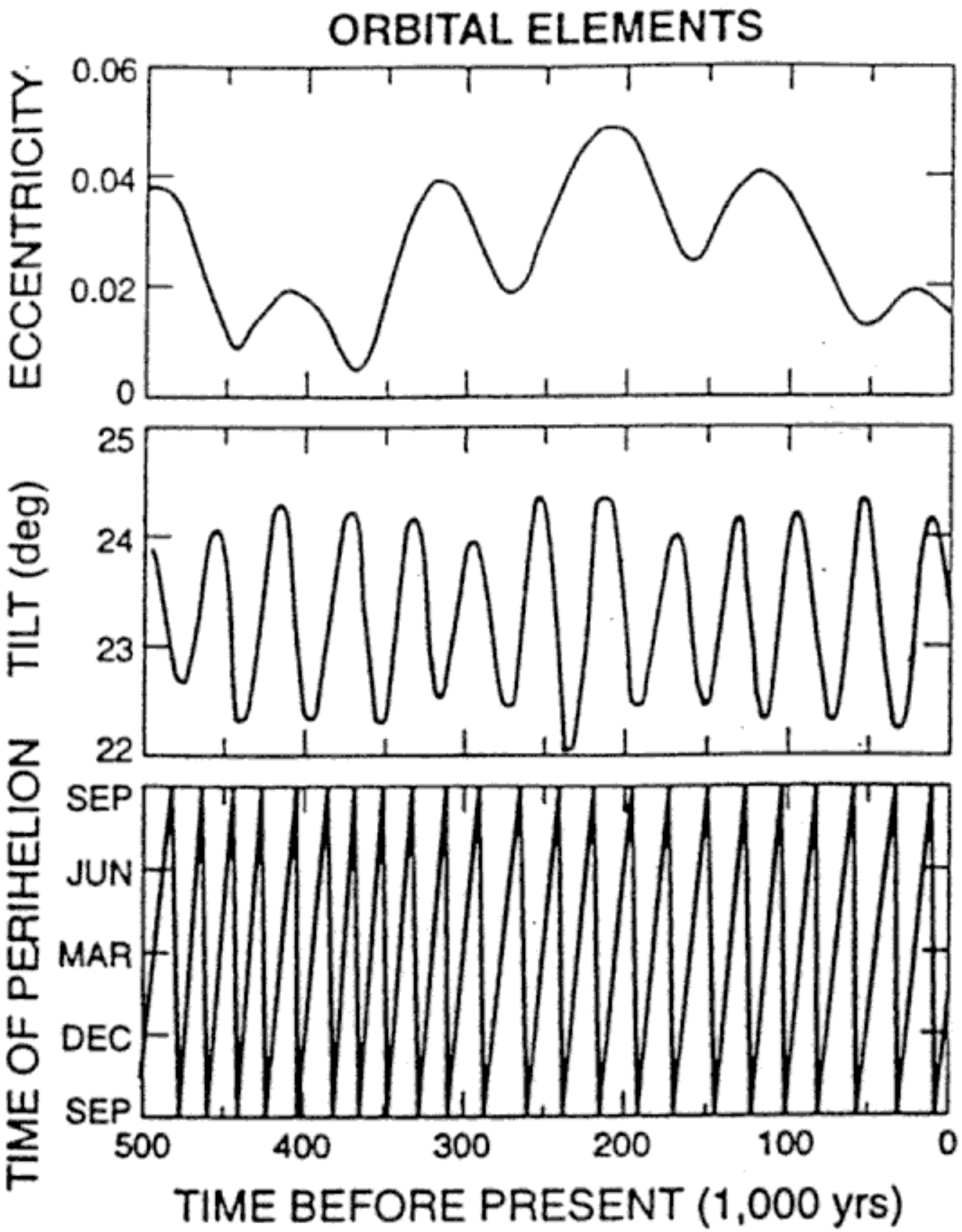
The direction of the earth's spin axis also precesses. This means that the earth's spin axis traces out a circle. Like obliquity, precession occurs on very long time scales. It takes about 20,000 years for the spin axis to trace out a circle once.



The situation now. Aphelion occurs in early July and coincides with northern hemisphere summer.



The situation about 10,000 years ago in the opposite phase of the earth's precessional cycle. Aphelion occurs in early January and coincides with southern hemisphere summer.



Barron (1994), figure 12

Time scales of Milankovitch forcing

Eccentricity varies on a roughly 100,000 year time scale and obliquity on a 40,000 year time scale. One precessional cycle lasts about 20,000 years.

Effect of orbital variations on sunshine

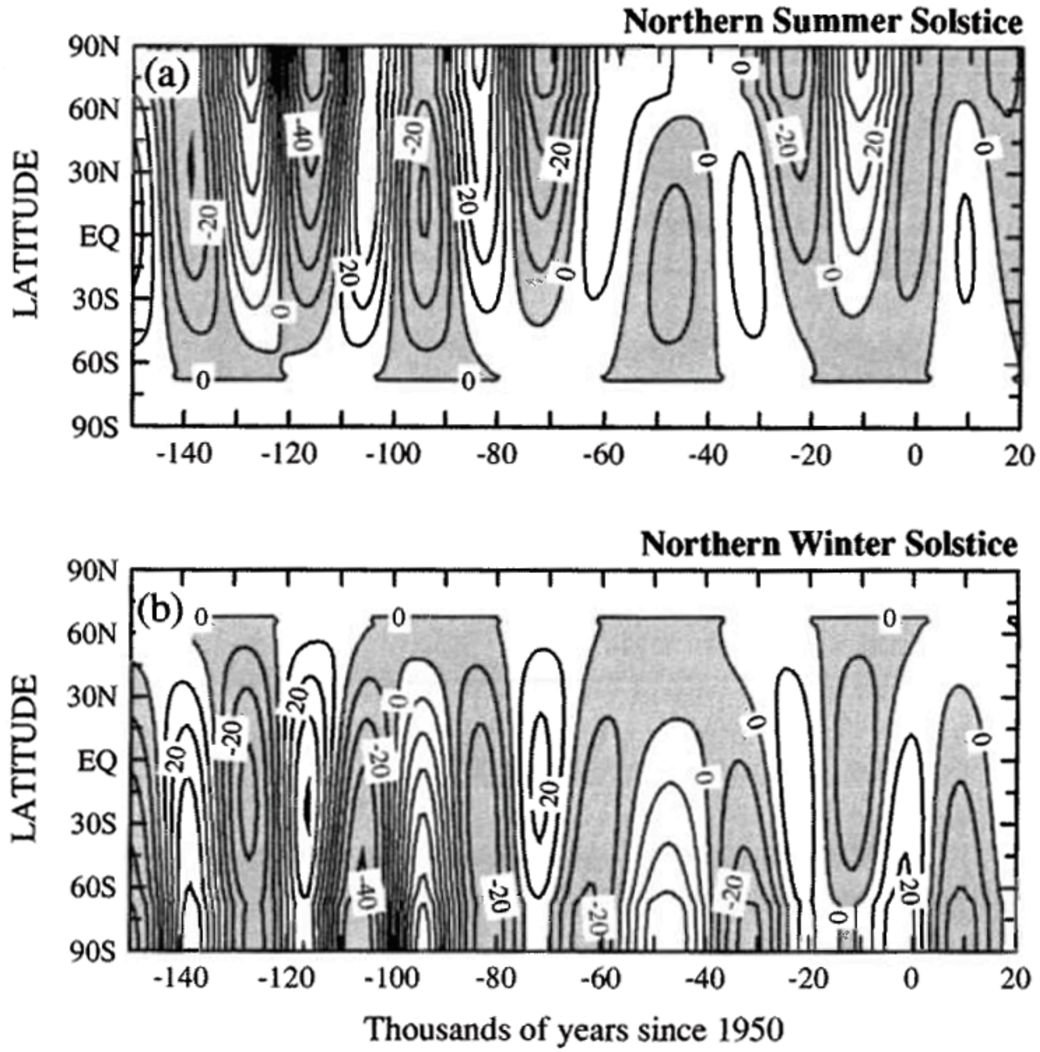


Fig. 11.13 Distribution of departure of daily average insolation at (a) northern summer and (b) northern winter solstices from average values for the period from 150,000 years ago until 20,000 years in the future. Contours are given in W m^{-2}.

from Hartmann

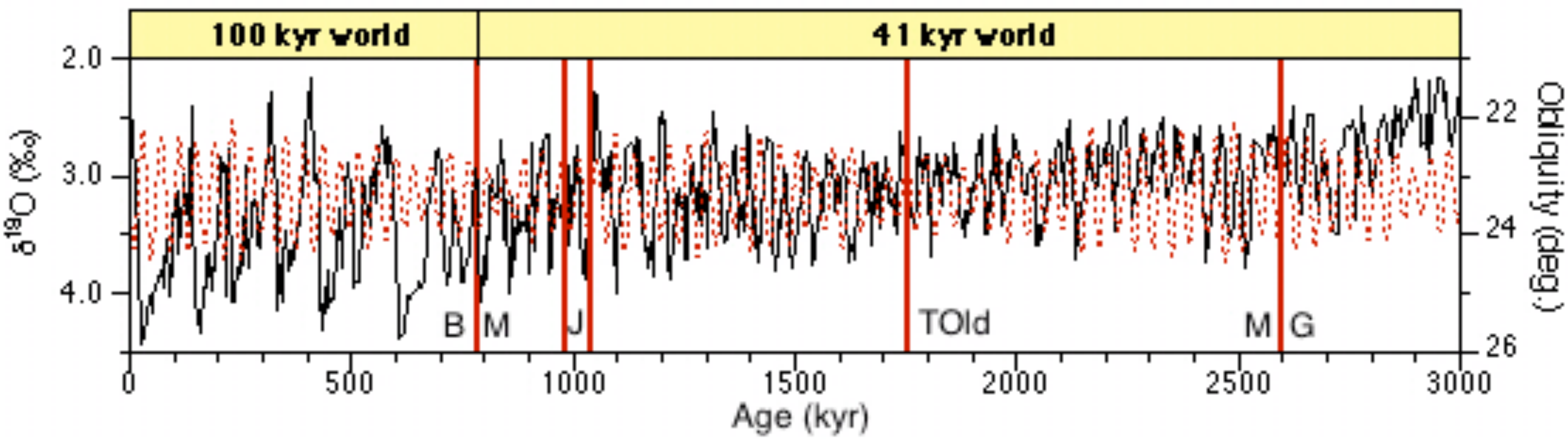
Summary: how orbital variations affect sunshine

<u>Obliquity</u> When obliquity is high, seasonality is enhanced. In mid and high latitudes, more sunshine comes in summer, and less comes in winter. Averaged over the whole year, the high latitudes receive more sunshine, and the low latitudes receive less.

<u>Precession</u> When perihelion occurs at summer solstice, the contrast between summer and winter is enhanced. When perihelion occurs at winter solstice, seasonality is weakened. Precession has little effect on annual mean sunshine.

<u>Eccentricity</u> Changes in the eccentricity of the earth's orbit have very little effect on the annual mean sunshine anywhere. However, they do have a large impact on the amplitude of the precessional cycle. If the earth's orbit is very eccentric, the timing of perihelion in the calendar year becomes more critical.

Returning to the oxygen isotope ratios in the N Atlantic…



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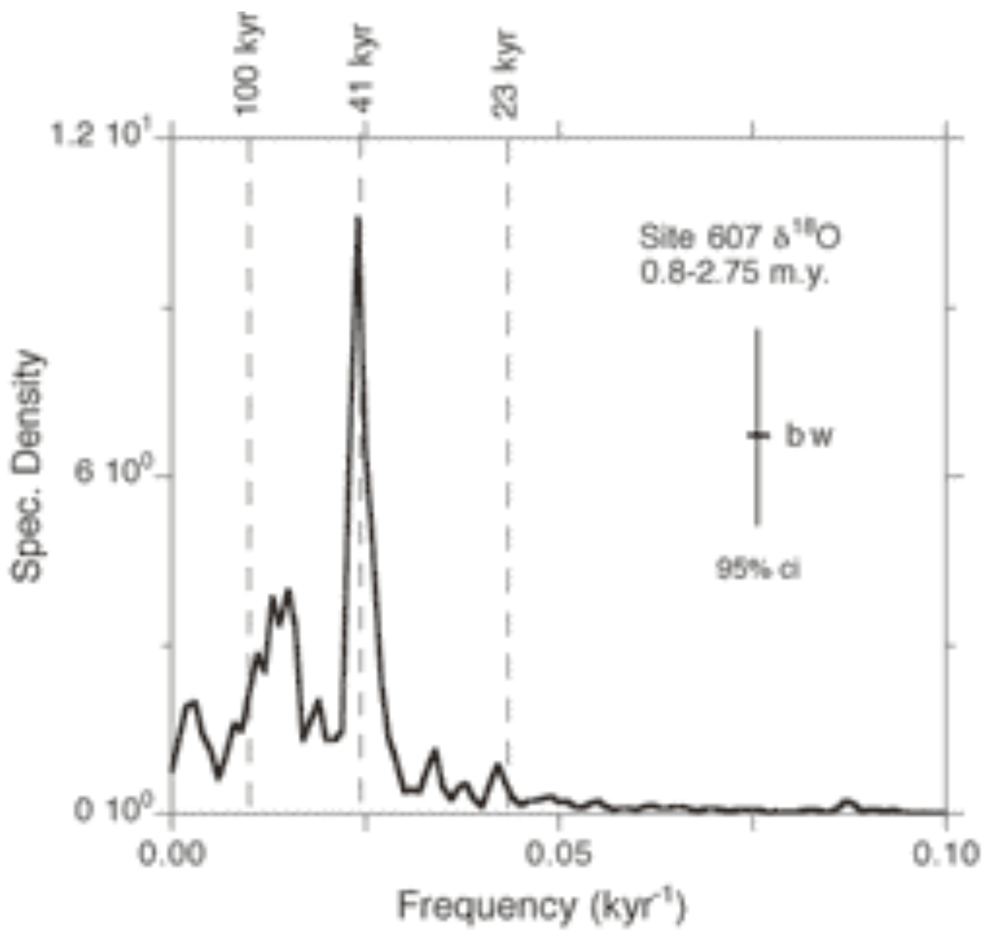
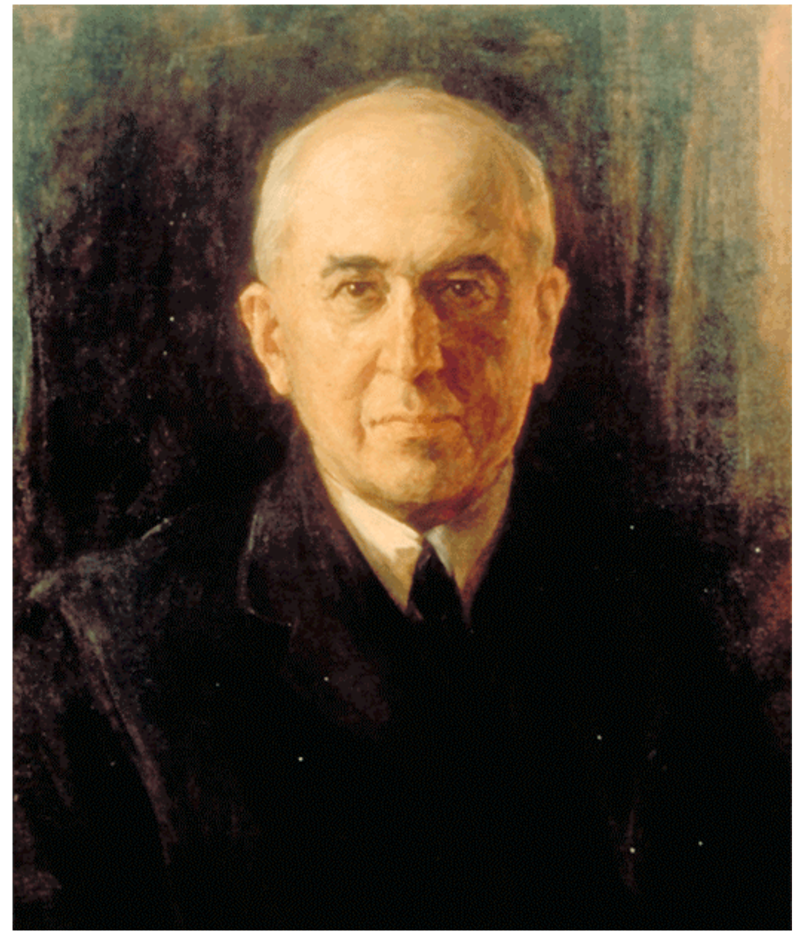
Raymo et al. 1990



Milutin Milankovitch (1879-1958)



Note the clear peaks in the spectrum at the time scales associated with orbital variability. In fact over 95% of the variability occurs at these time scales. The idea that orbital variations might be responsible for climate variability is called the Milankovitch theory of climate.

So how might orbital variations cause ice ages? One idea is that since the ice sheets melt the most in the summertime, the sunshine during this time of year might be important for determining ice volume.

But exactly how orbital variability is translated into the huge observed climate changes remains one of the major unsolved problems of climate. Any satisfactory explanation will probably involve the dynamics of the ice sheets themselves.

Another major unsolved problem: why do the greenhouse gases vary in phase with the ice ages?