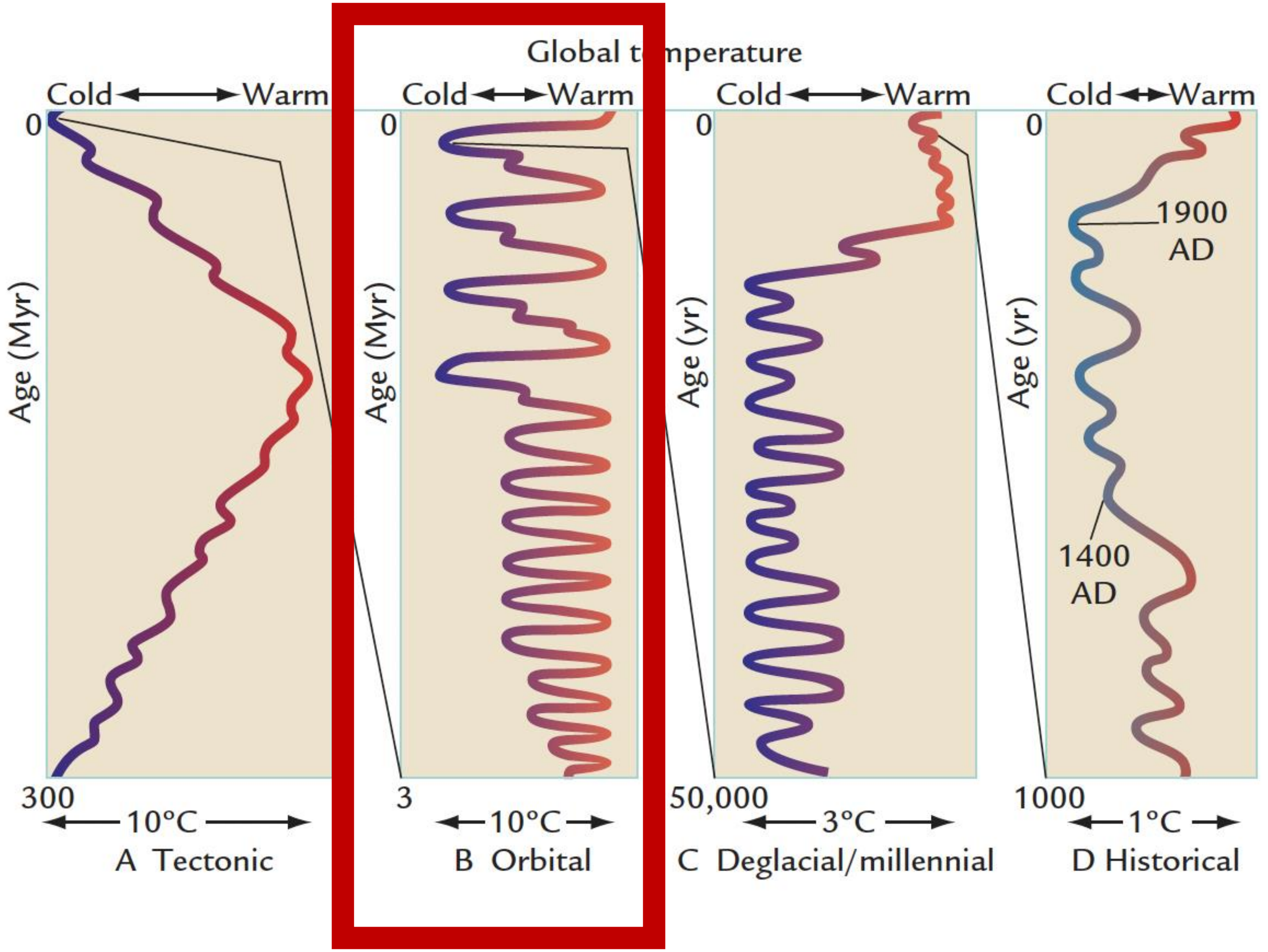
Lecture IV
Orbital-scale climate change

From Ruddiman's EARTH'S CLIMATE – PAST, PRESENT AND FUTURE

Orbital Scale



Earth’s orbit

Two kinds of movements:

1. Rotation
2. Revolution

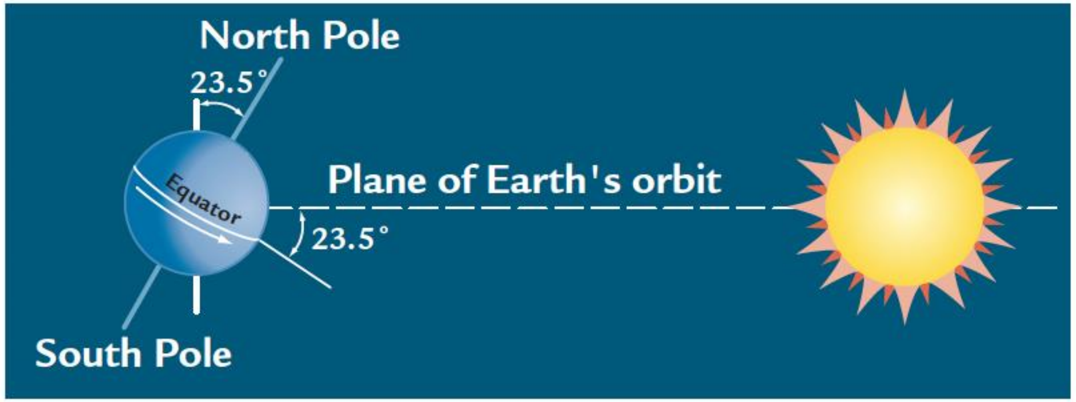
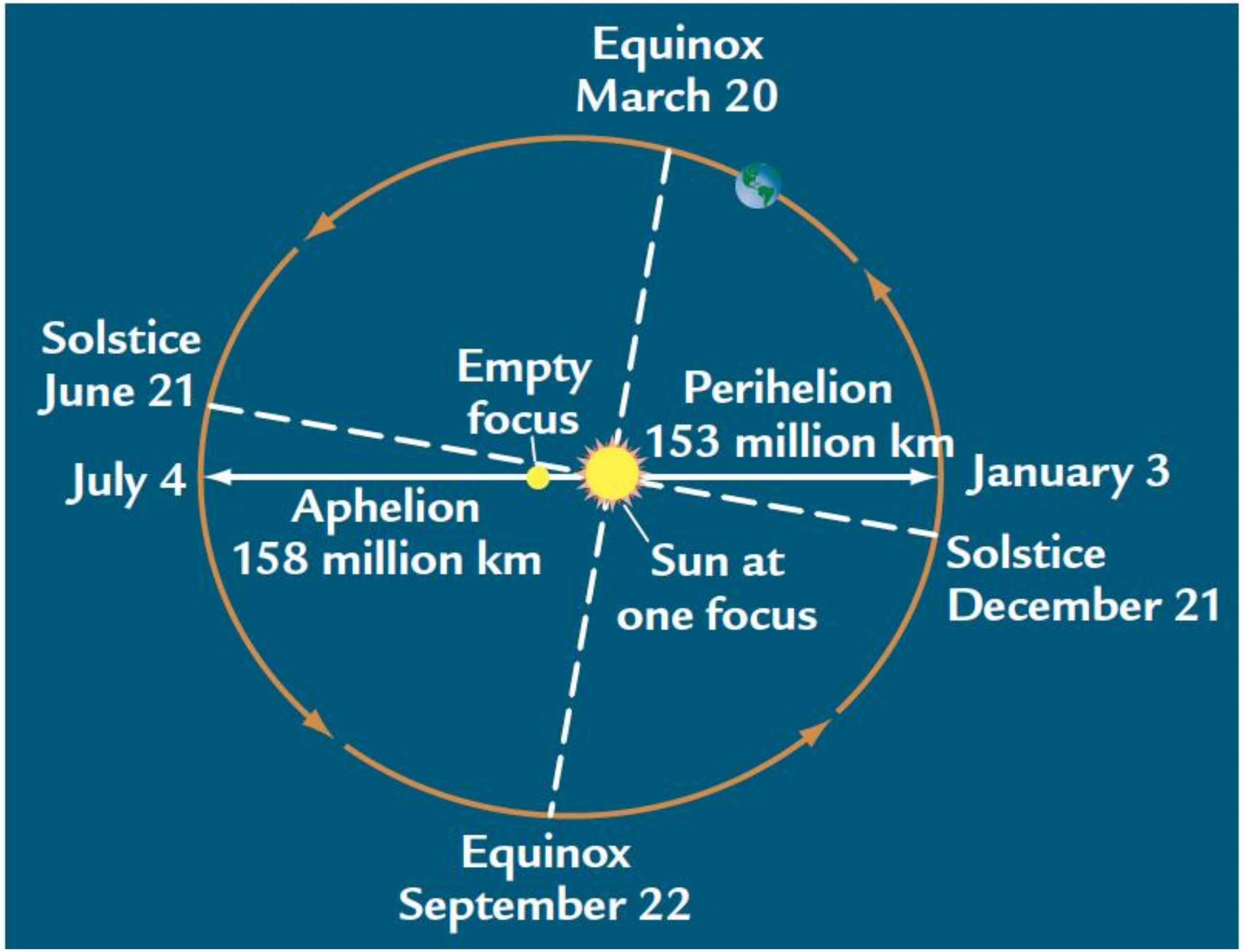


FIGURE 8-1
Earth’s tilt
Earth’s rotational (spin) axis is currently tilted at an angle of 23.5° away from a line perpendicular to the plane of its orbit around the Sun.

Revolution – elliptical orbit

*The position in which Earth is closest to the Sun is called **perihelion** (the "close pass" position, from the Greek meaning "near the Sun"), while the position farthest from the Sun is called **aphelion** (the "distant pass" position,*
from the Greek meaning "away from the Sun").

On average, Earth lies 155.5 million km from the Sun, but the distance ranges between 153 million km at perihelion and 158 million km at aphelion.



Long term changes in Earth’s orbit

I. Changes in Earth’s Axial Tilt Through Time

A No tilt

B 90° tilt

FIGURE 8-3

Extremes of tilt

If Earth’s orbit were circular and its axis had no tilt (A), solar radiation would not change through the year and there would be no seasons. For a 90° tilt (B), the poles would alternate seasonally between conditions of day-long darkness and day-long overhead Sun. (ADAPTED FROM J. IMBRIE AND K. P. IMBRIE, *ICE AGES: SOLVING THE MYSTERY* [SHORT HILLS, NJ: ENSLOW, 1979].)

I. Changes in Earth's Axial Tilt Through Time

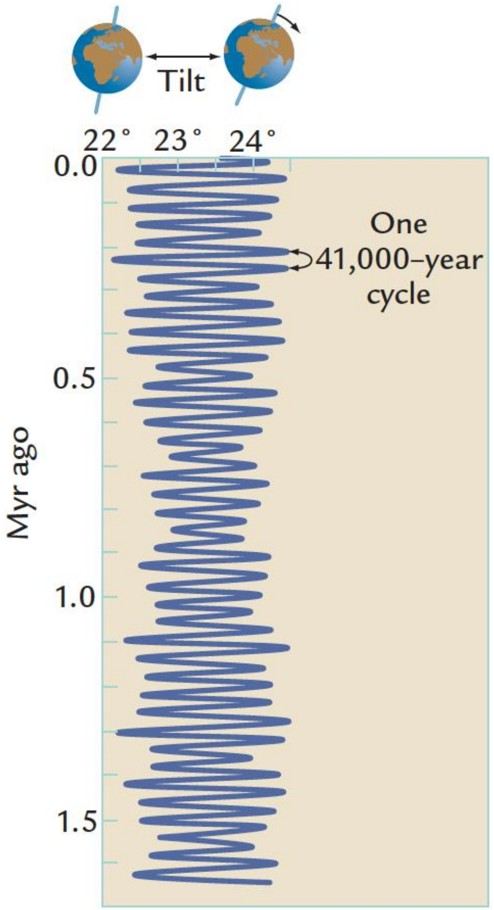


FIGURE 8-4

Long-term changes in tilt

Changes in the tilt of Earth's axis have occurred in a regular 41,000-year cycle.

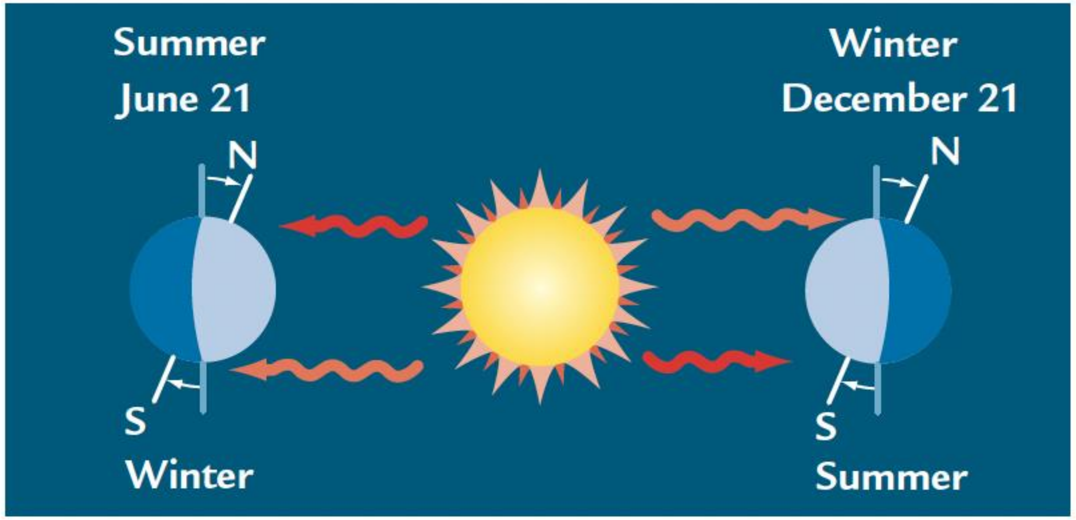


FIGURE 8-5

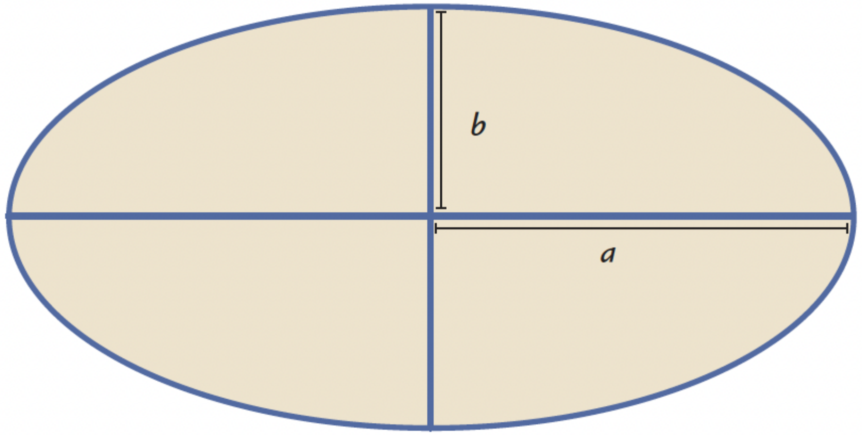
Effects of increased tilt on polar regions

Increased tilt brings more solar radiation to the poles in the summer season and less radiation to the poles in the winter season.

II. Changes in Earth's Eccentric Orbit Through Time

The degree of departure from a perfectly circular orbit can be described by:

where ε is the eccentricity of the ellipse and a and b are half of the lengths of the major and minor axes (the "semimajor" and "seminimor" axes).



$$\text{Eccentricity } \varepsilon = \frac{(a^2 - b^2)^{1/2}}{a}$$

II. Changes in Earth's Eccentric Orbit Through Time

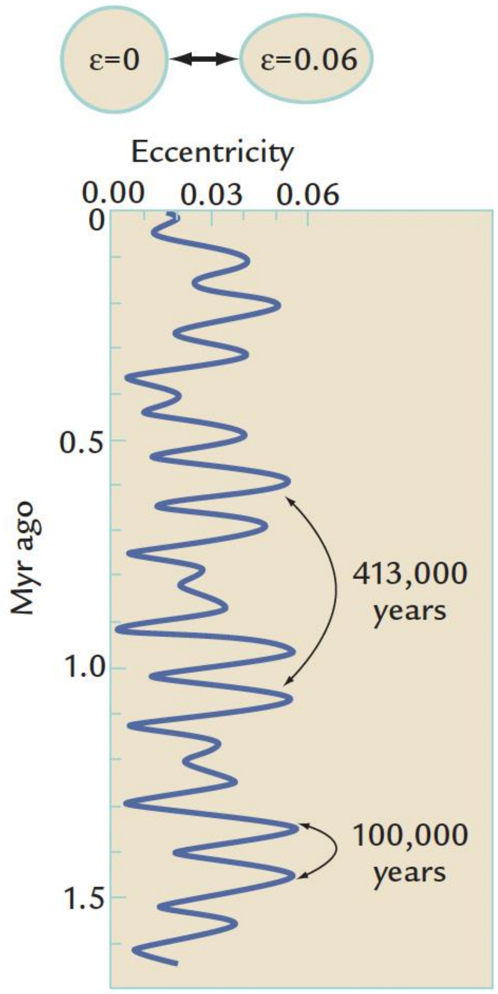


FIGURE 8-7

Long-term changes in eccentricity

The eccentricity (ε) of Earth's orbit varies at periods of 100,000 and 413,000 years.

III. Precession of the Solstices and Equinoxes Around Earth's Orbit

- Earth's wobbling motion, called axial precession, is caused by the gravitational pull of the Sun and Moon on the slight bulge in Earth's diameter at the equator.

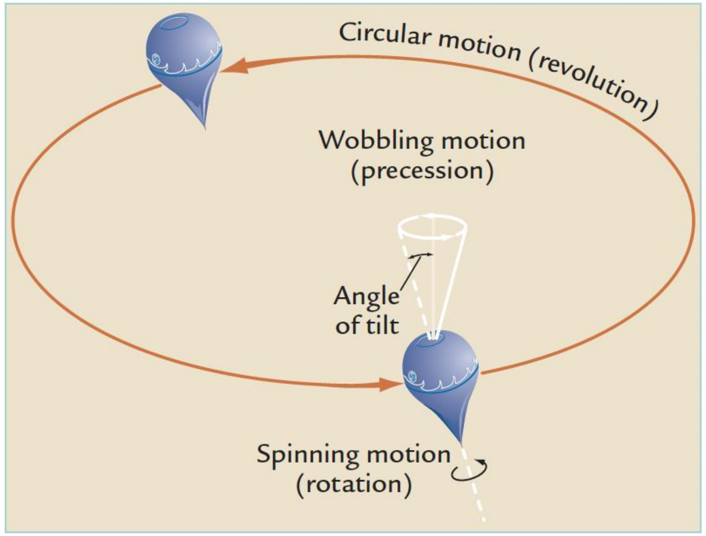


FIGURE 8-8

Earth's wobble

In addition to its rapid (daily) rotational spin and its slower (yearly) revolution around the Sun, Earth wobbles slowly like a top, with one full wobble every 25,700 years.

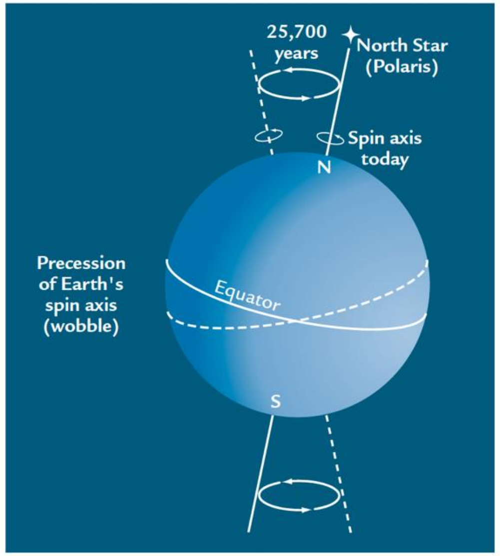


FIGURE 8-9

Precession of Earth's axis

Today, Earth rotates around an axis that points to the North Star (Polaris), but over time the wobbling motion causes the axis of rotation to point to other celestial reference points.

Precession of the ellipse

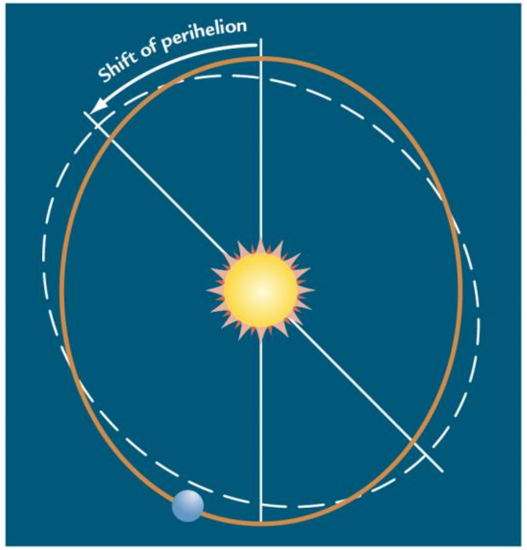
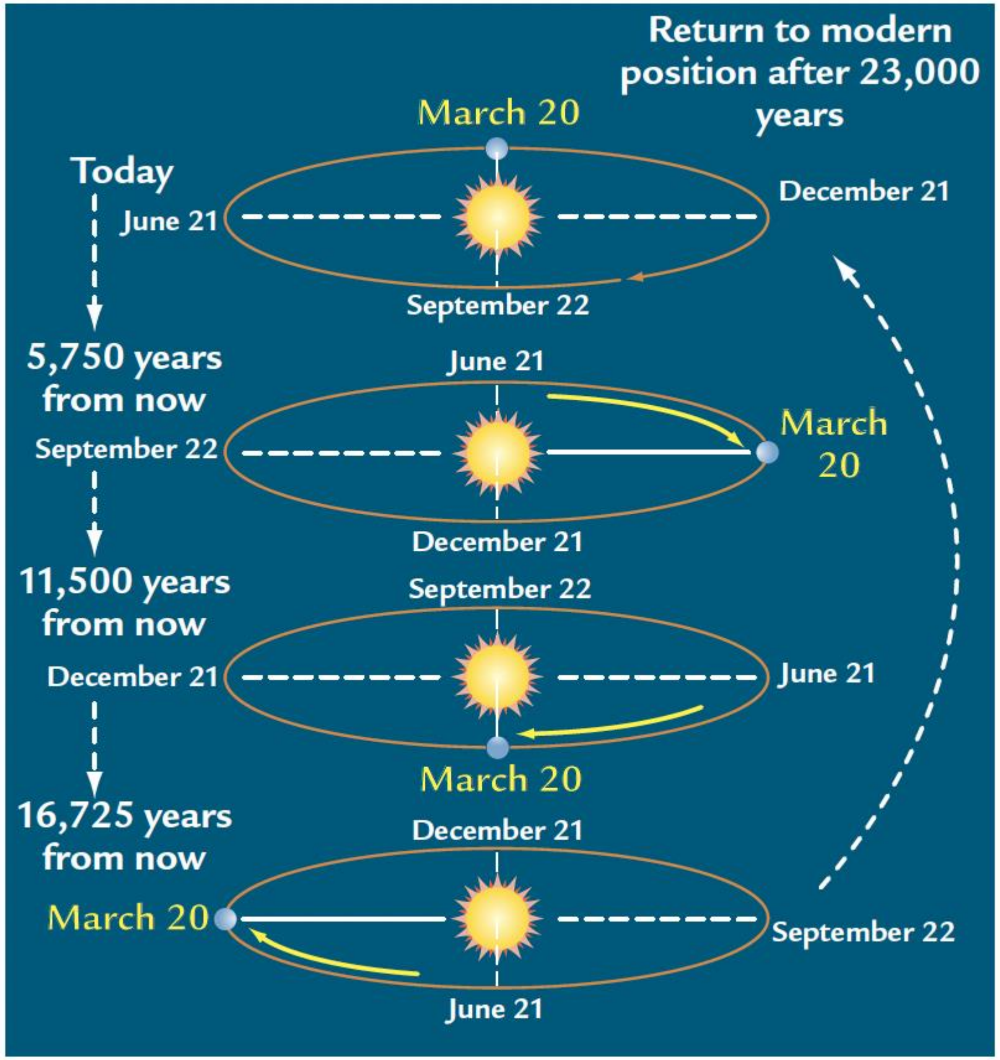


FIGURE 8-10
Precession of the ellipse
The elliptical shape of Earth's orbit slowly precesses in space so that the major and minor axes of the ellipse slowly shift through time. (ADAPTED FROM N. G. PISIAS AND J. IMBRIE, "ORBITAL GEOMETRY, CO_2, AND PLEISTOCENE CLIMATE," *OCEANUS* 29 [1986]: 43–49.)

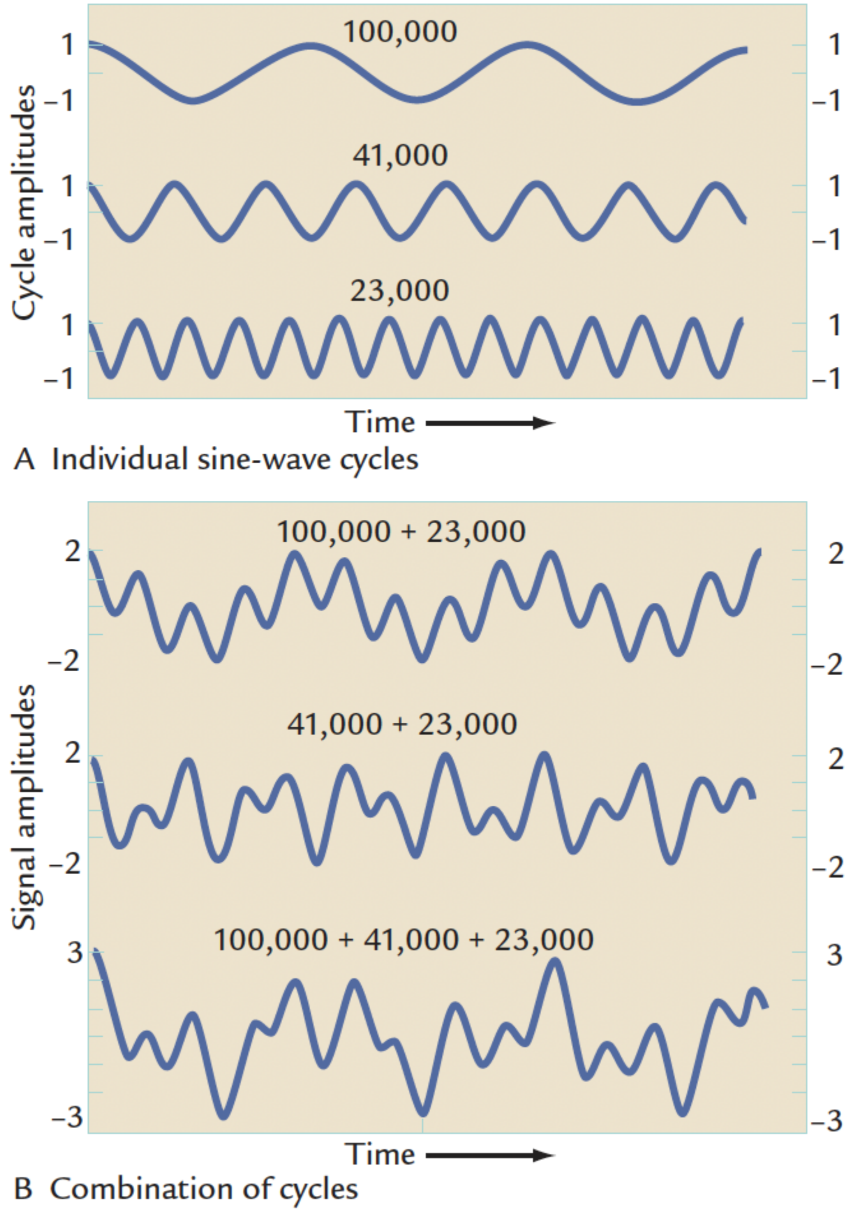
A second kind of precessional motion is known as precession of the ellipse.

In this case, the entire elliptically shaped orbit of the Earth rotates, with the long and short axes of the ellipse turning slowly in space. This motion is even slower than the wobbling motion of axial precession.



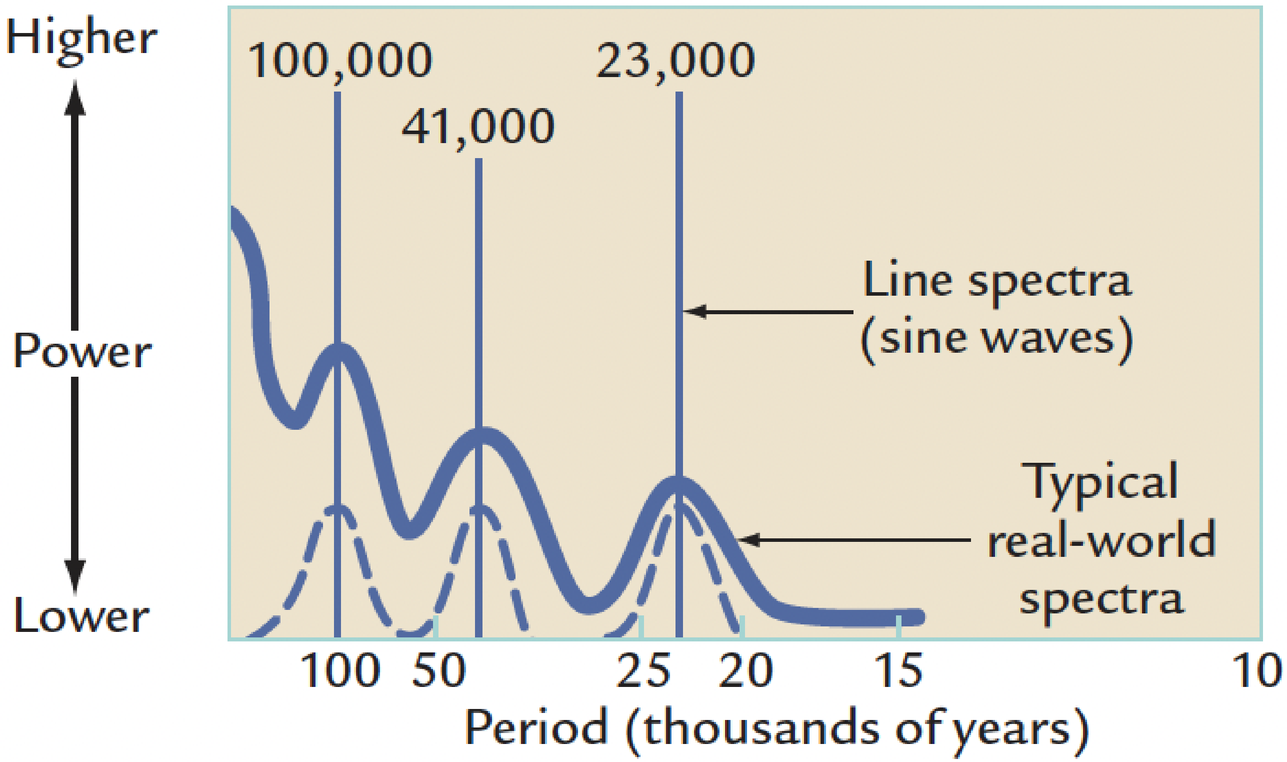
The combined effects of these two precessional motions (wobbling of the axis and turning of the ellipse) cause the solstices and equinoxes to move around Earth's orbit, with one full orbit around the Sun completed approximately every 22,000 years

If perfect sine wave cycles with periods of 100,000 years, 41,000 years, and 23,000 years are added together so that they are superimposed on top of one another, the original cycles are almost impossible to detect by eye in the combined signal.



Spectral analysis

The horizontal axis shows a range of periods plotted on a log scale, with the shorter periods to the right. The vertical axis represents the amplitude of the cycles, also known as their "power." The height of the lines plotted on the power spectrum is related to the square of the amplitude of the cycle at that period.

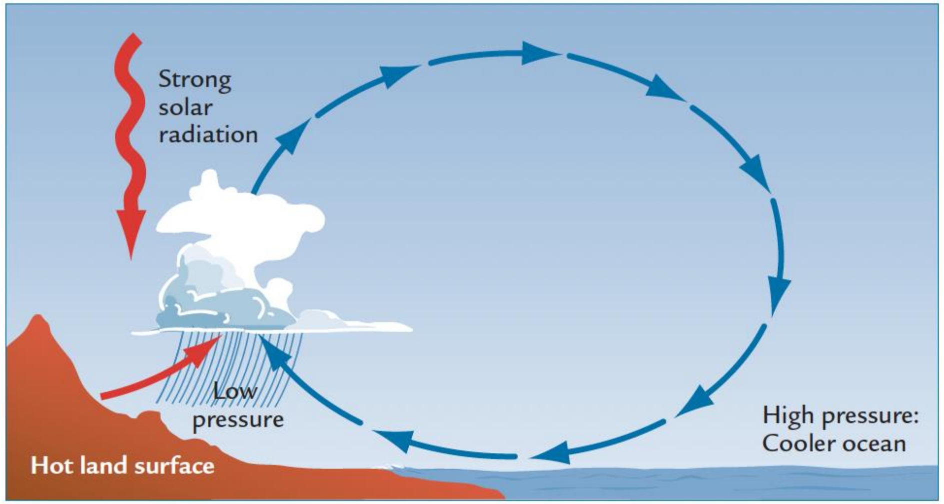


Insolation Control of Monsoons

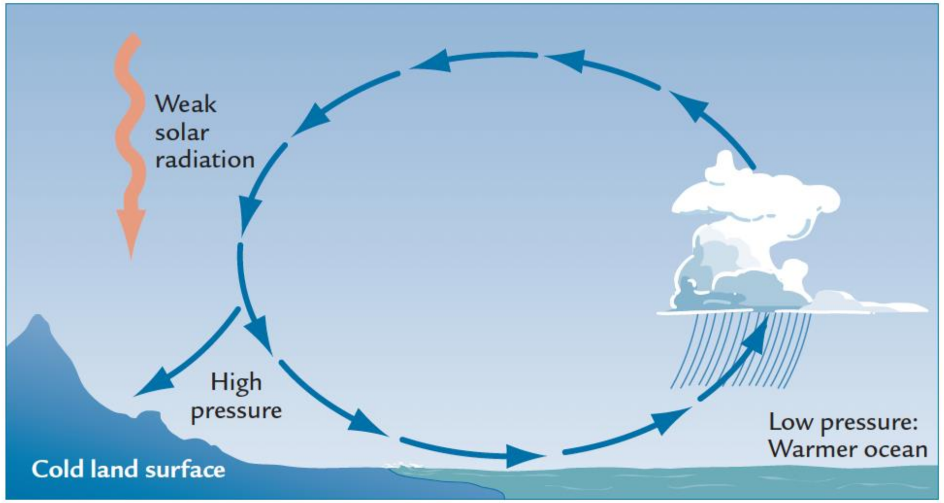
Which hemisphere do strong monsoon circulation occur?

Most strong summer monsoons occur in the Northern Hemisphere because landmasses there are large (Asia and North Africa) and elevations are high (especially in the Tibetan Plateau and Himalayan Mountain region of southern Asia).

Monsoons are weaker in the Southern Hemisphere, where landmasses at tropical and subtropical latitudes are smaller, and high topography is more limited in extent.



A Summer monsoon

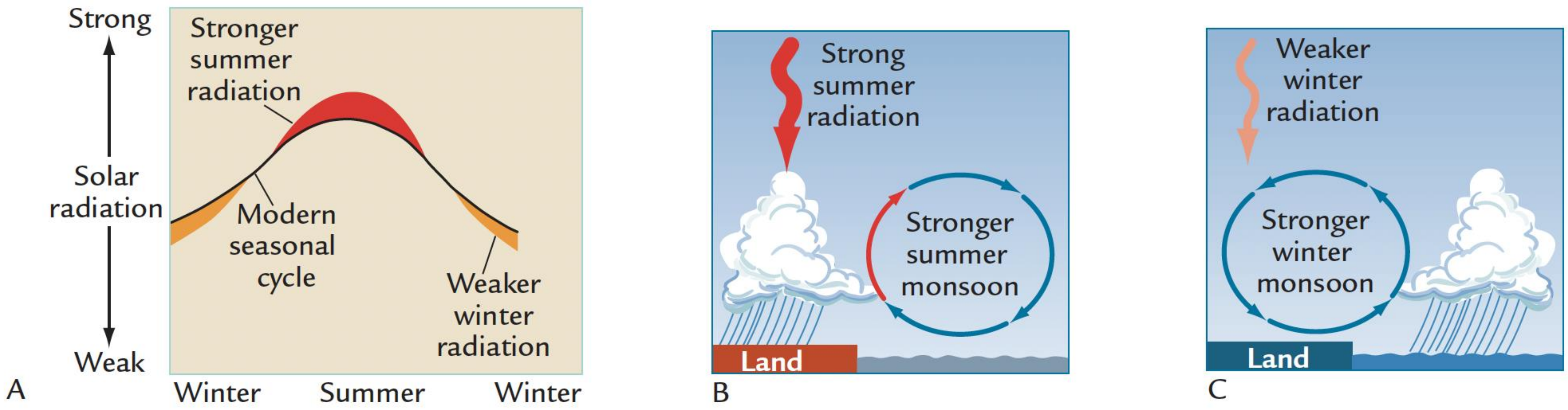


B Winter monsoon

Orbital-Scale Control of Summer Monsoons

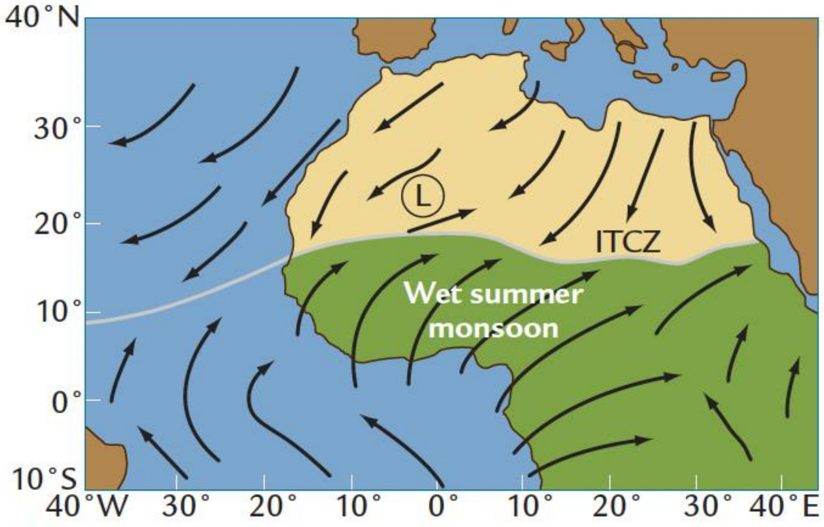
Orbital monsoon hypothesis.

When summer insolation was higher in the past than today, the summer monsoon circulation should have been stronger, with greater heating of the land, stronger rising motion, more inflow of moist ocean air, and more rainfall. Conversely, summer insolation levels lower than those today should have driven a weaker summer monsoon in the past.

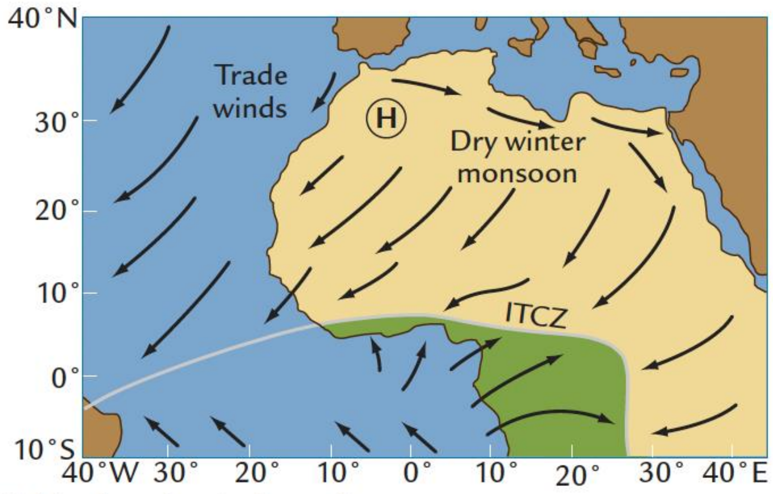


More intense summer insolation maxima and deeper winter insolation minima occur together at any one location. As a result, stronger in-and-up monsoonal flows in summer should occur at the same times in the past as stronger down-and-out monsoonal flows in winter.

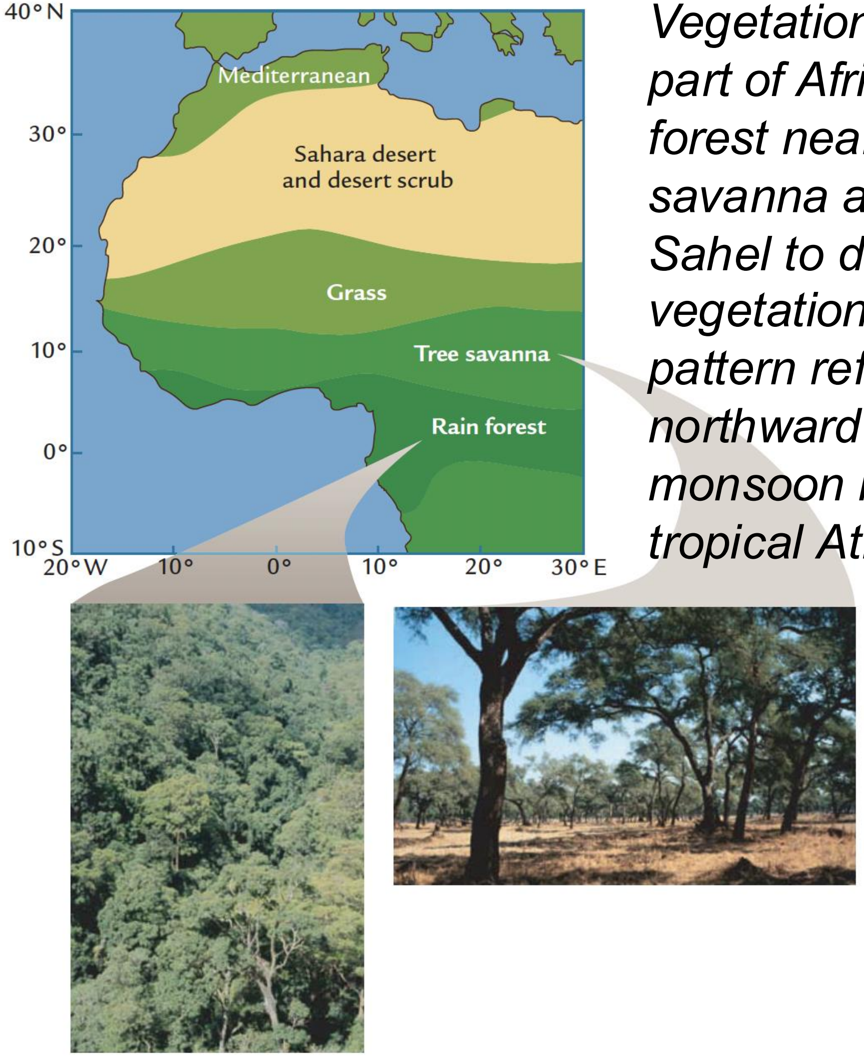
North African monsoon



A Northern hemisphere summer



B Northern hemisphere winter



Vegetation across the northern part of Africa ranges from rain forest near the equator to savanna and grassland in the Sahel to desert scrub vegetation in the Sahara. This pattern reflects the diminishing northward reach of summer monsoon moisture from the tropical Atlantic.

Orbital monsoon hypothesis

Increases in summer insolation heating above a critical threshold value drive a strong monsoon response at the 23,000-year tempo of orbital precession. The amplitude of this strong monsoon response is related to the size of the increase in summer insolation forcing.

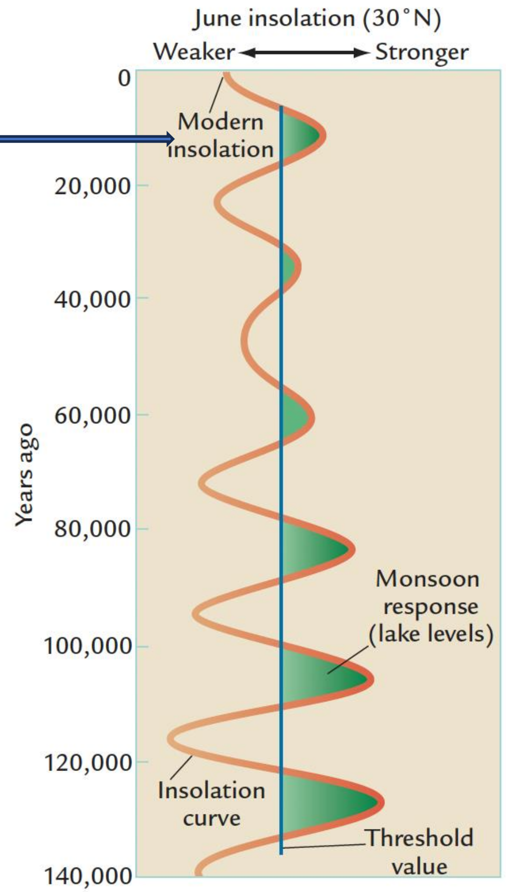
Assumptions:

1. *A threshold level of insolation exists, below which the monsoon response will be too weak to leave any evidence in the geologic record. Example: dry lakes in N Africa and NW India*

2. Stronger insolation should drive stronger monsoons and fill lakes to higher levels.

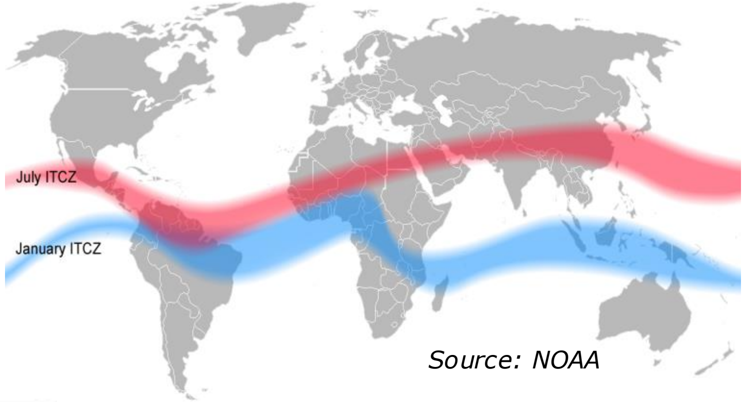
3. Third, we assume that the strength of the monsoon in the past, as recorded in lake level records, is a composite of the average monsoon strength over many individual summers.

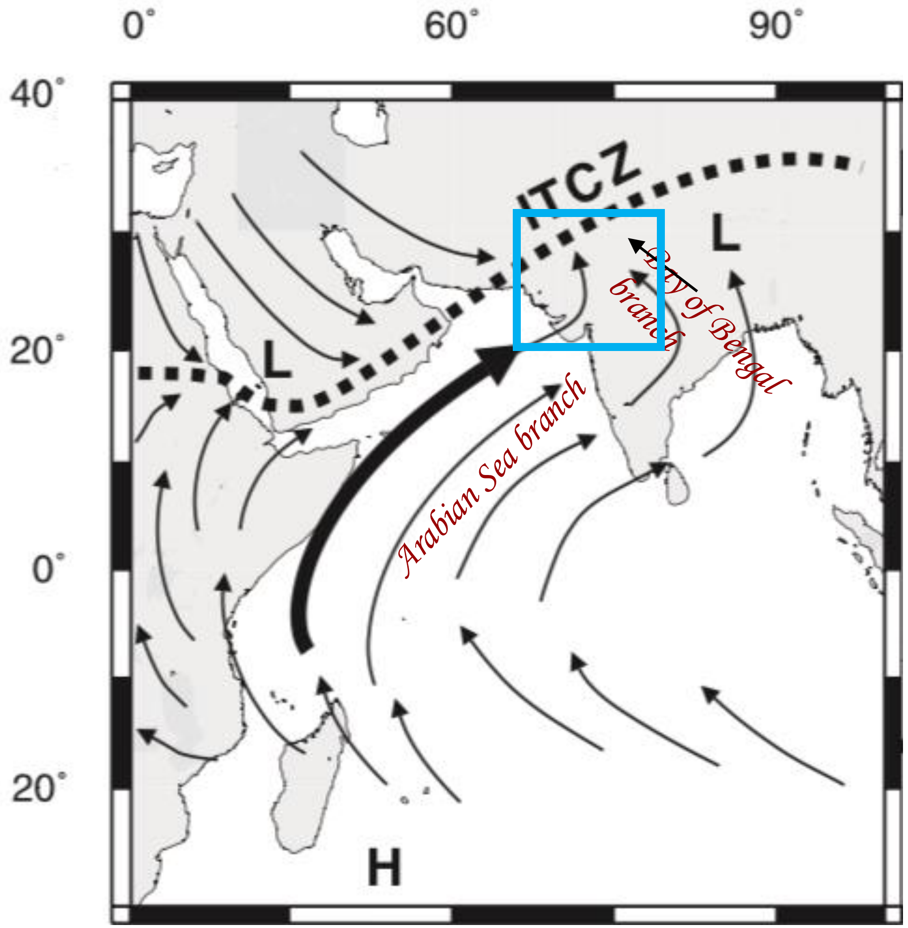
most recent instance when summer insolation values were substantially higher than today occurred near 11,000 years ago.

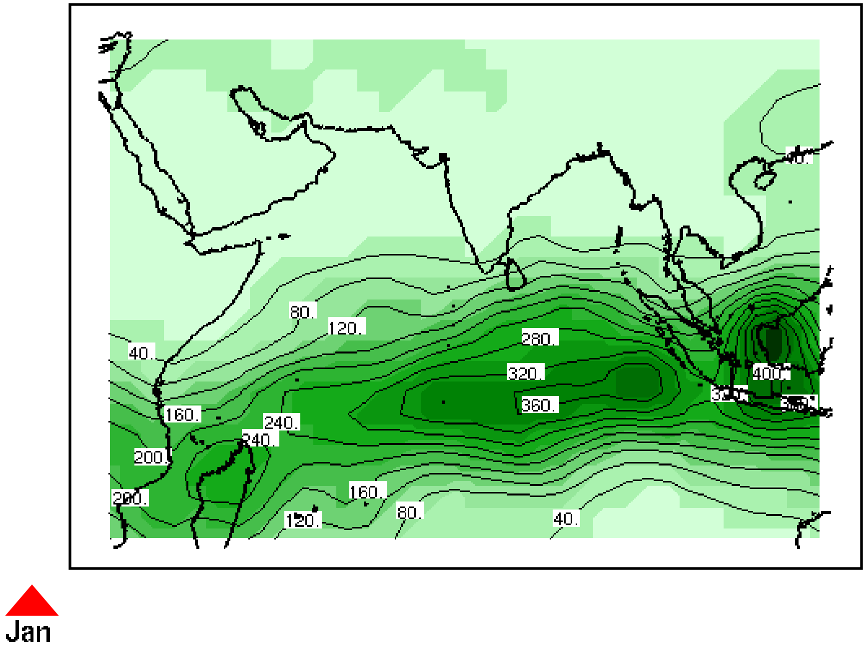


Conceptual model of monsoon response to summer insolation

Indian Summer Monsoon- last 10,000years variability

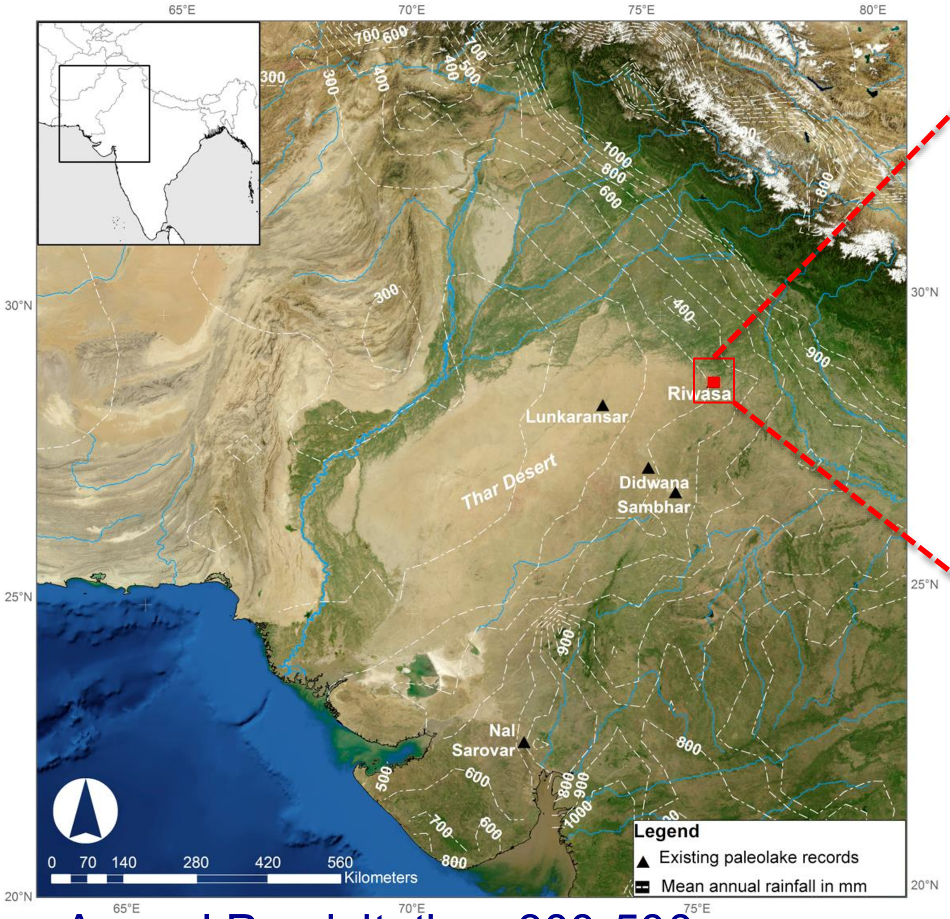


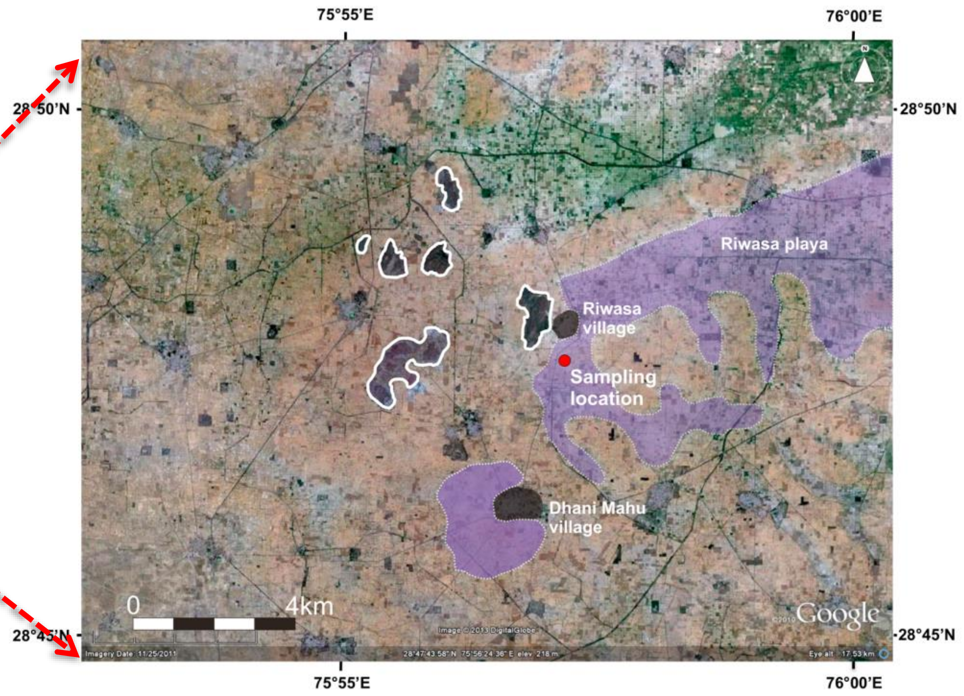




Riwasa

NW India dry Riwasa Lake, Haryana





Annual Precipitation: 300-500mm

Mean annual temperatures: 25.2°C

Max: 42°C (June); Min: 5°C (January)

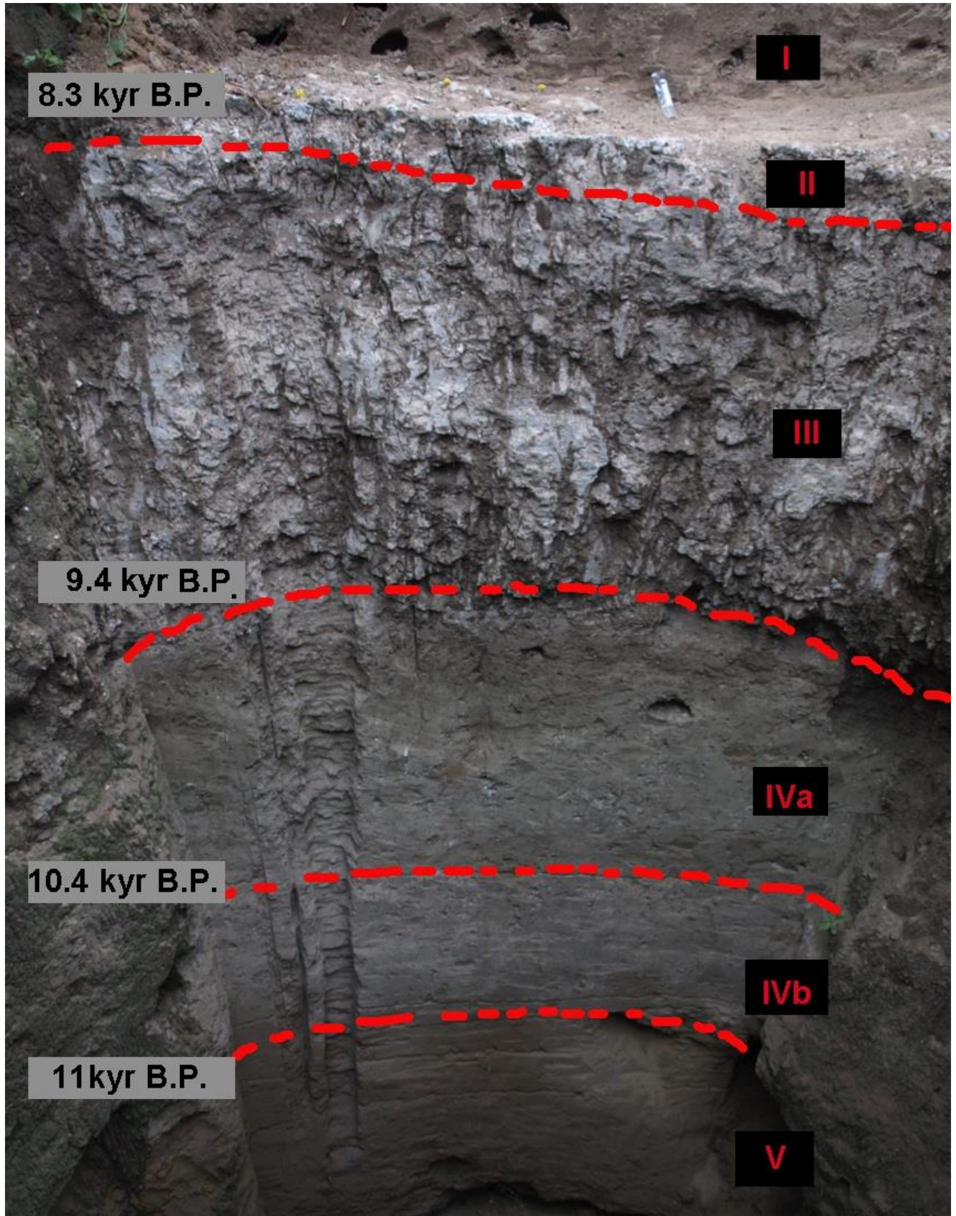
Inselbergs (black with white outlines)

lacustrine deposits (blue areas)

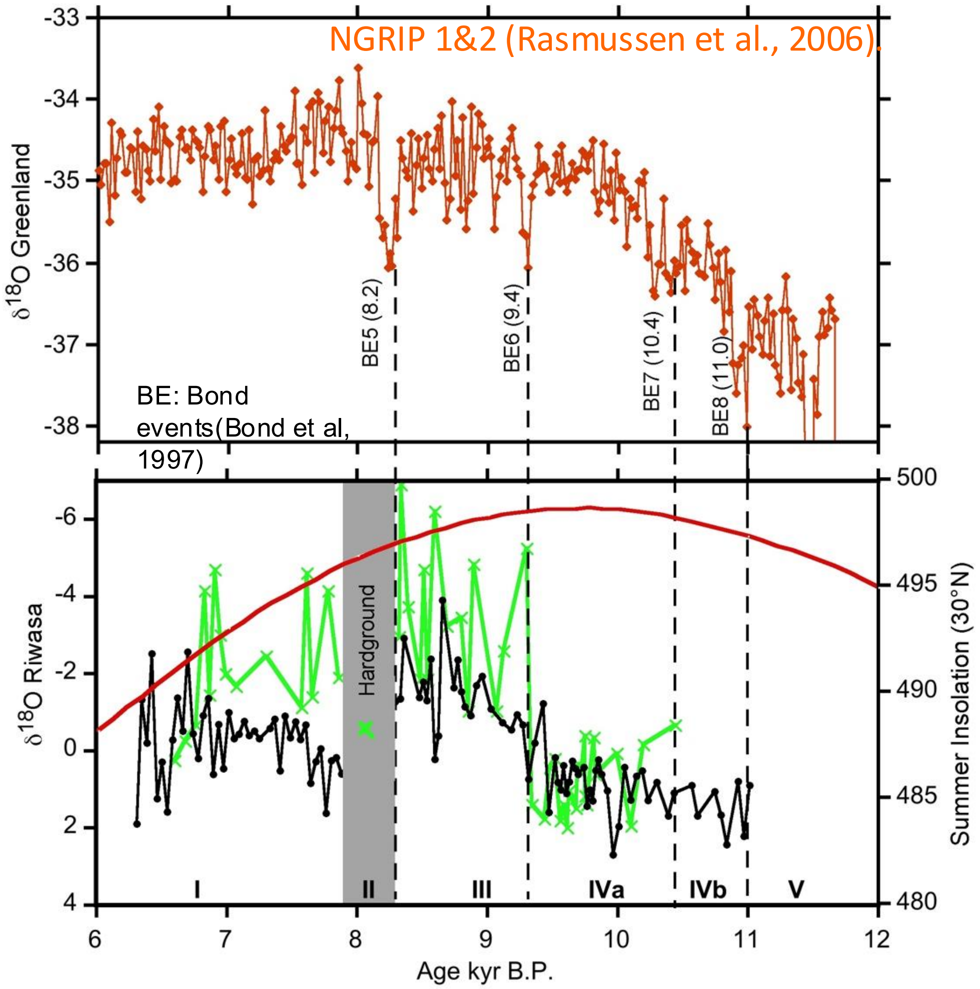
aeolian sand dunes and sheets (unshaded regions)

Sampling location (red dot)

Millennial-scale climate change

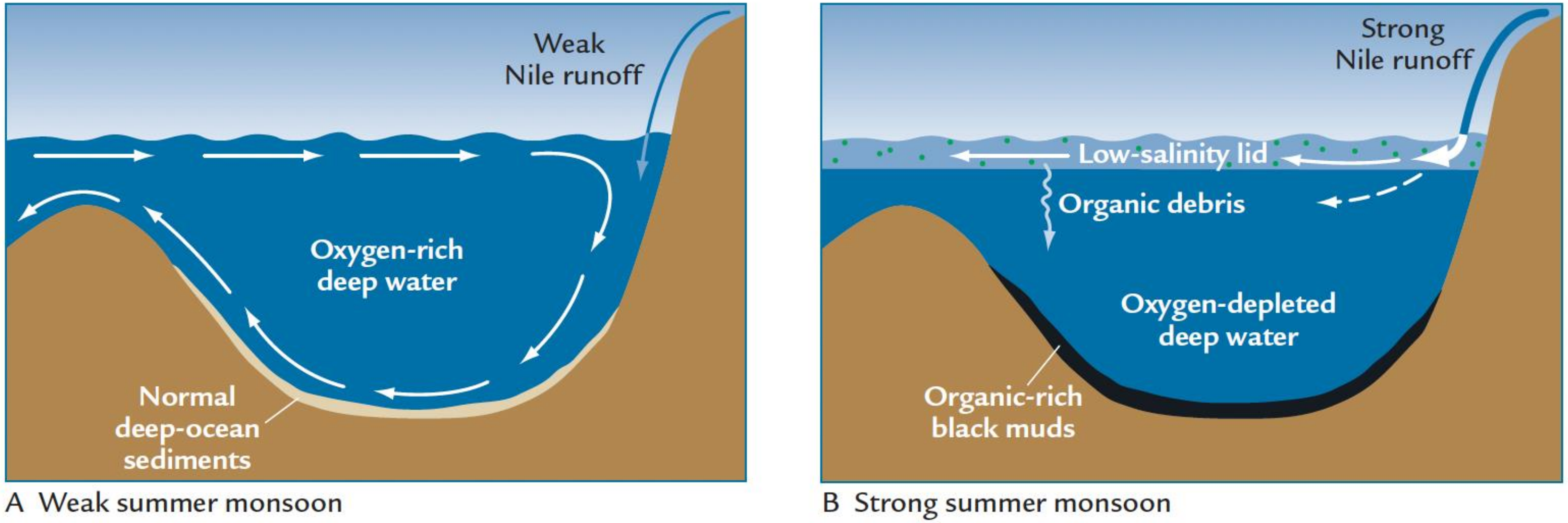


'*Bond Events*' in NGRIP 1&2 and corresponding monsoon variability at Riwasa.



(Y. Dixit, PhD thesis 2013, Univ. of Cambridge)

“Stinky Muds” in the Mediterranean



Mediterranean circulation and monsoons

WHY IS THE WATER SINKING IN THE EASTERN MEDITERRANEAN???

This sinking motion is a result of two factors :

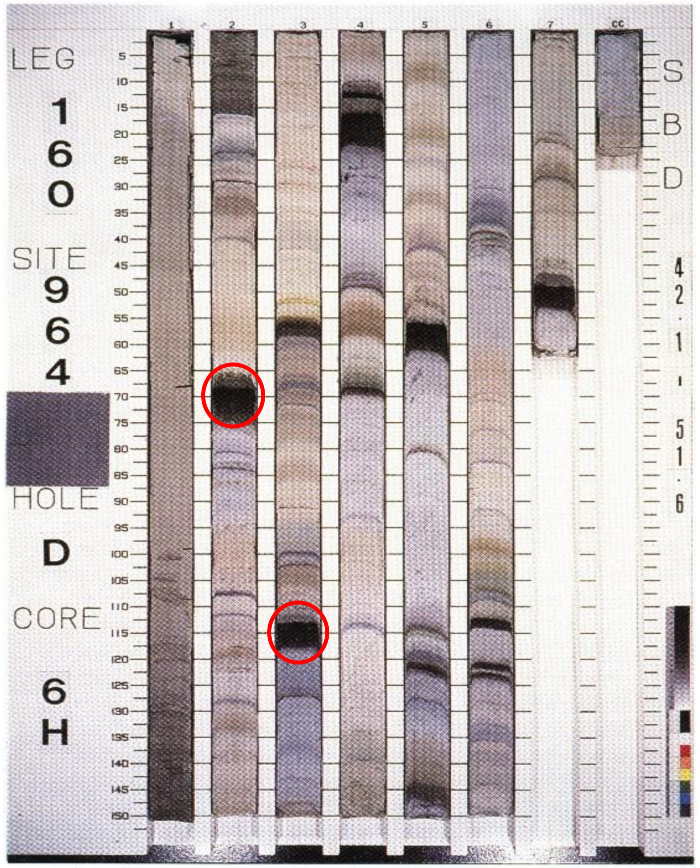
(1) the high salt content of the Mediterranean Sea, caused by the excess of summer evaporation over precipitation, and

(2) winter chilling of salty water along the northern margins of the Mediterranean Sea during incursions of cold air from the north.

Sapropels: Prominent feature of the Mediterranean

- *Mediterranean sediments contain distinct layers of black organic-rich muds, called sapropels.*
- *Their high organic carbon content indicates that they formed at times when the waters at the seafloor were anoxic: they lacked the oxygen needed to convert (oxidize) organic carbon to inorganic form.*
- *The lack of oxygen led to stagnation of the deep waters and deposition of iron sulfides, giving the sediments a "stinky" (rotten egg) odor.*

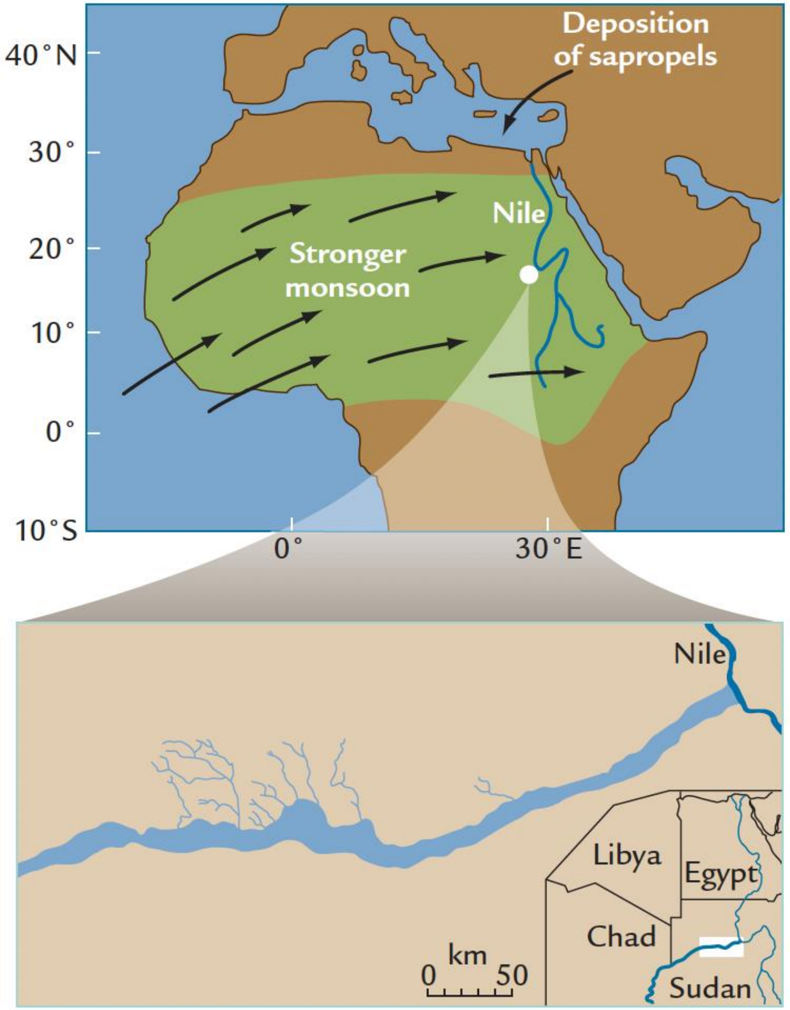
The sapropels were best developed (thickest and most carbon-rich) near the time of the strongest summer insolation maxima, but poorly developed during weaker insolation maxima.



(Richter et al., 1996)

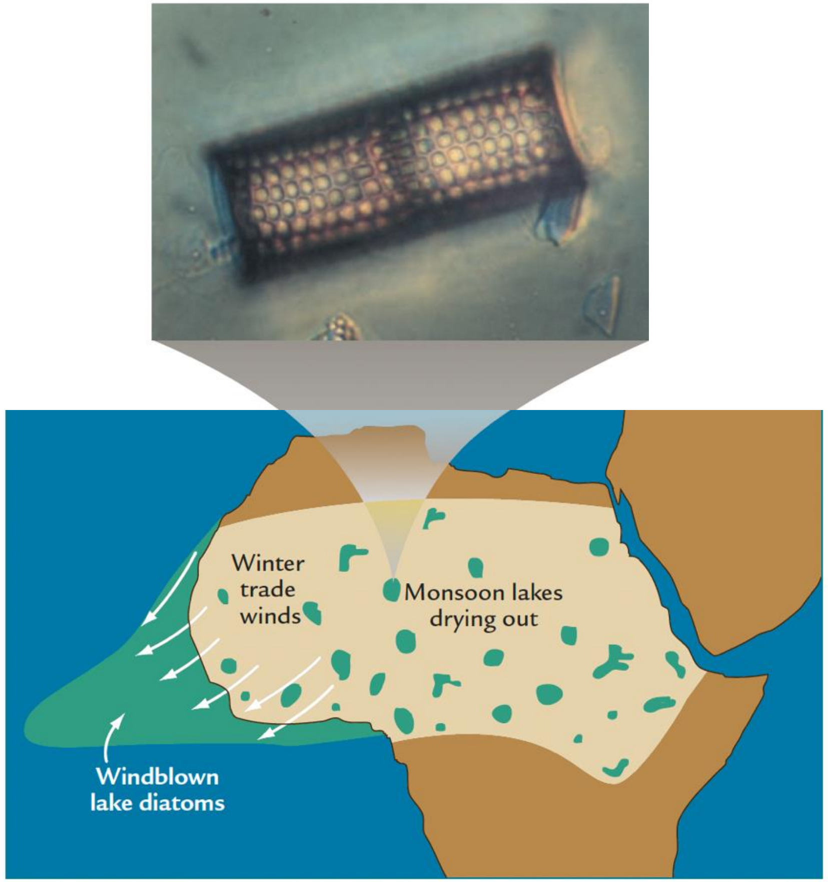
Monsoons and the Nile River

Strong summer monsoons in tropical North Africa periodically produced large discharges of Nile freshwater into the Mediterranean Sea. Satellite sensors have detected riverbed sediments deposited during strong monsoons but now buried beneath sheets of sand in the hyperarid eastern Sahara Desert



This history of sapropel deposition matches very well the conceptual pattern predicted by the orbital monsoon hypothesis

Freshwater Diatoms in the Tropical Atlantic



Drying of monsoonal lakes

North African lakes filled by strong monsoonal rains later dried out and were exposed to erosion by winds. Lake muds containing the freshwater diatom Aulacoseira granulata were carried by winds to the tropical Atlantic.

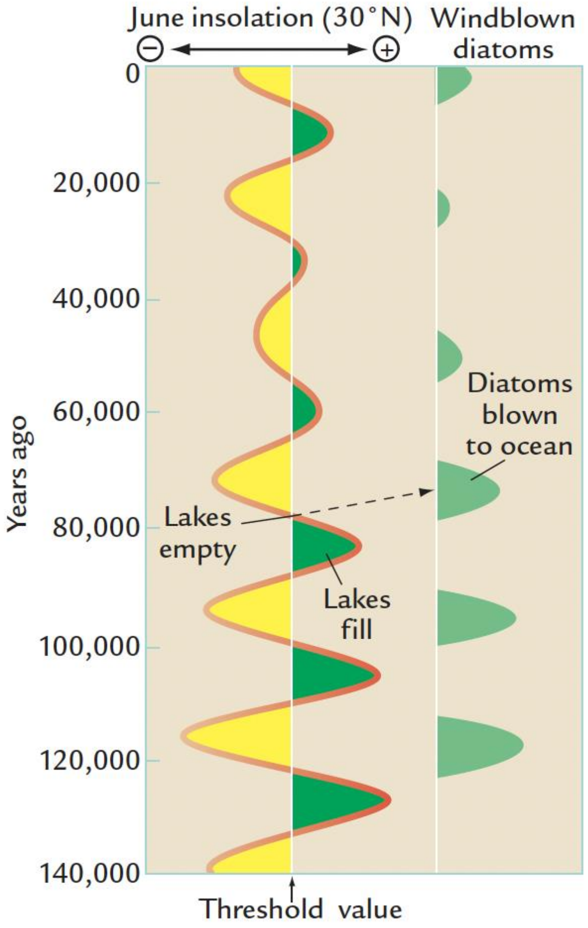


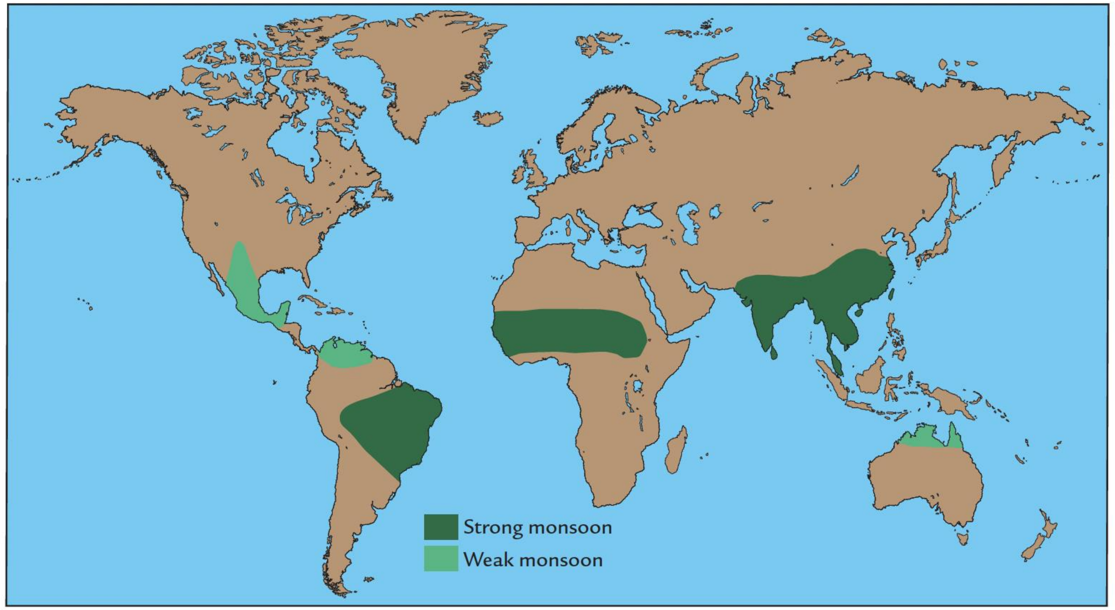
FIGURE 9-9

Delayed diatom deposition in the Atlantic

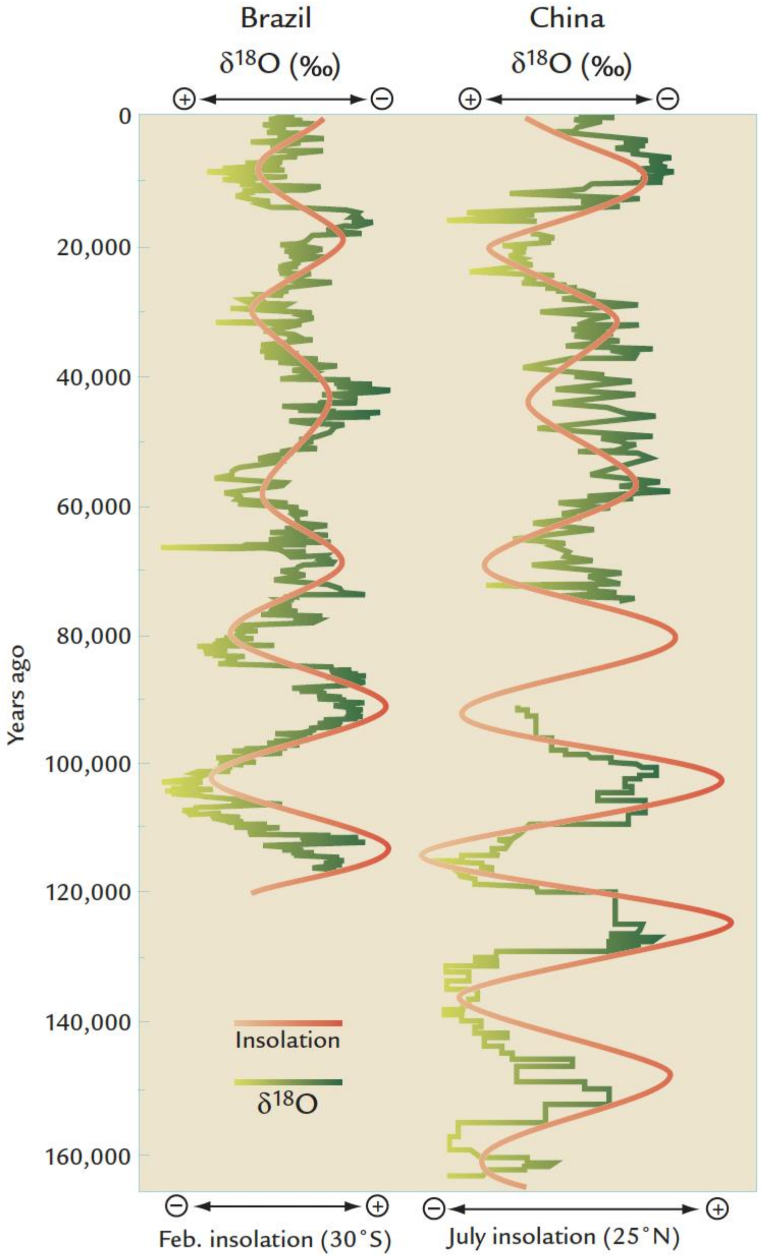
Diatoms from North African lakes were deposited in the tropical Atlantic Ocean several thousand years after the intervals of strongest monsoons, as the lakes dried out.

diatom pulses sent to the ocean lagged well behind the summer monsoon maxima… WHY??

Orbital Monsoon Hypothesis: Regional Assessment



MAJOR MONSOON SYSTEMS



Monsoon signals recorded in sediments

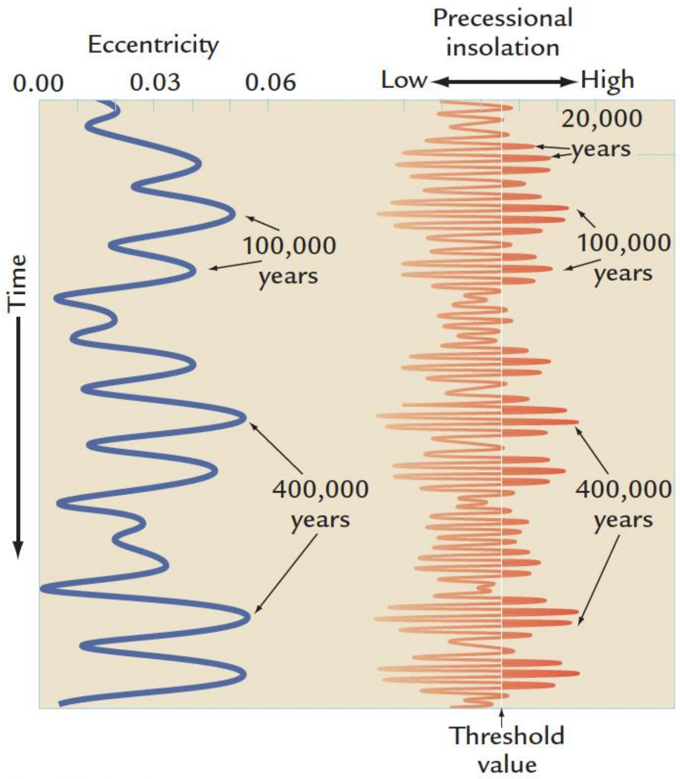
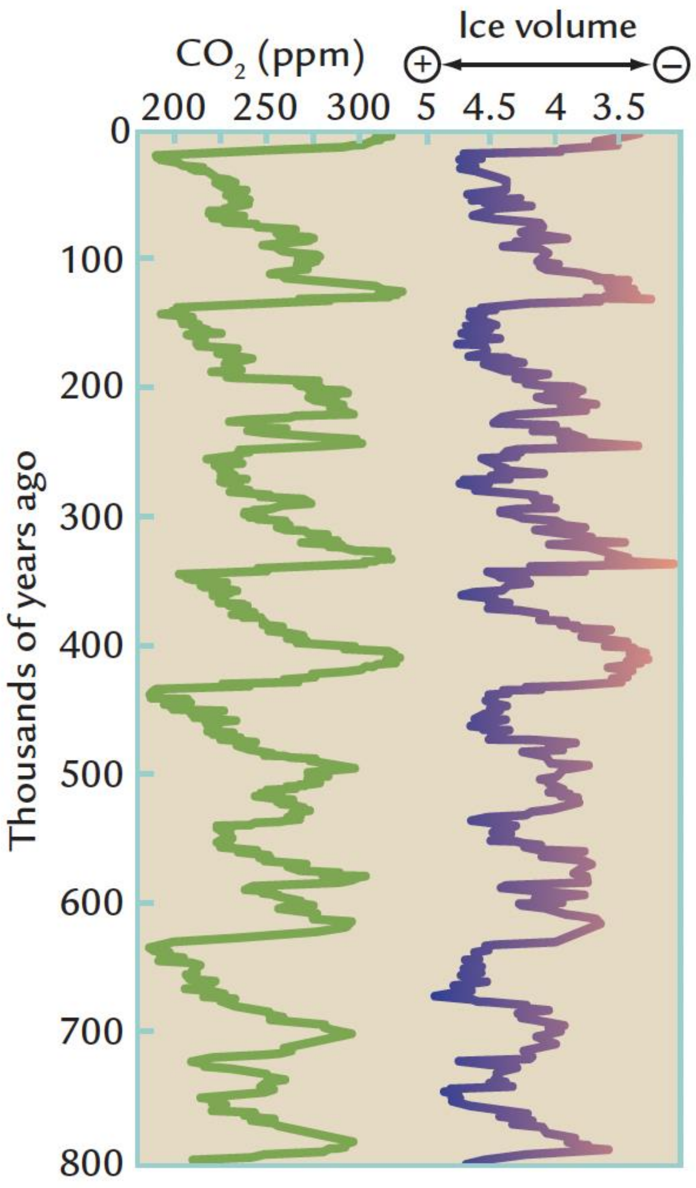


FIGURE 9-14

Monsoon signals recorded in sediments

Monsoonal influences can be detected in older sediment sequences. High orbital eccentricity values (left) should amplify individual 23,000-year precession cycles approximately every 100,000 and 400,000 years (right). The monsoon signal in the sediments could resemble the red-shaded area to the right of the threshold insolation value.

Long-term CO2 changes



Orbital-Scale Carbon Transfers: Carbon Isotopes

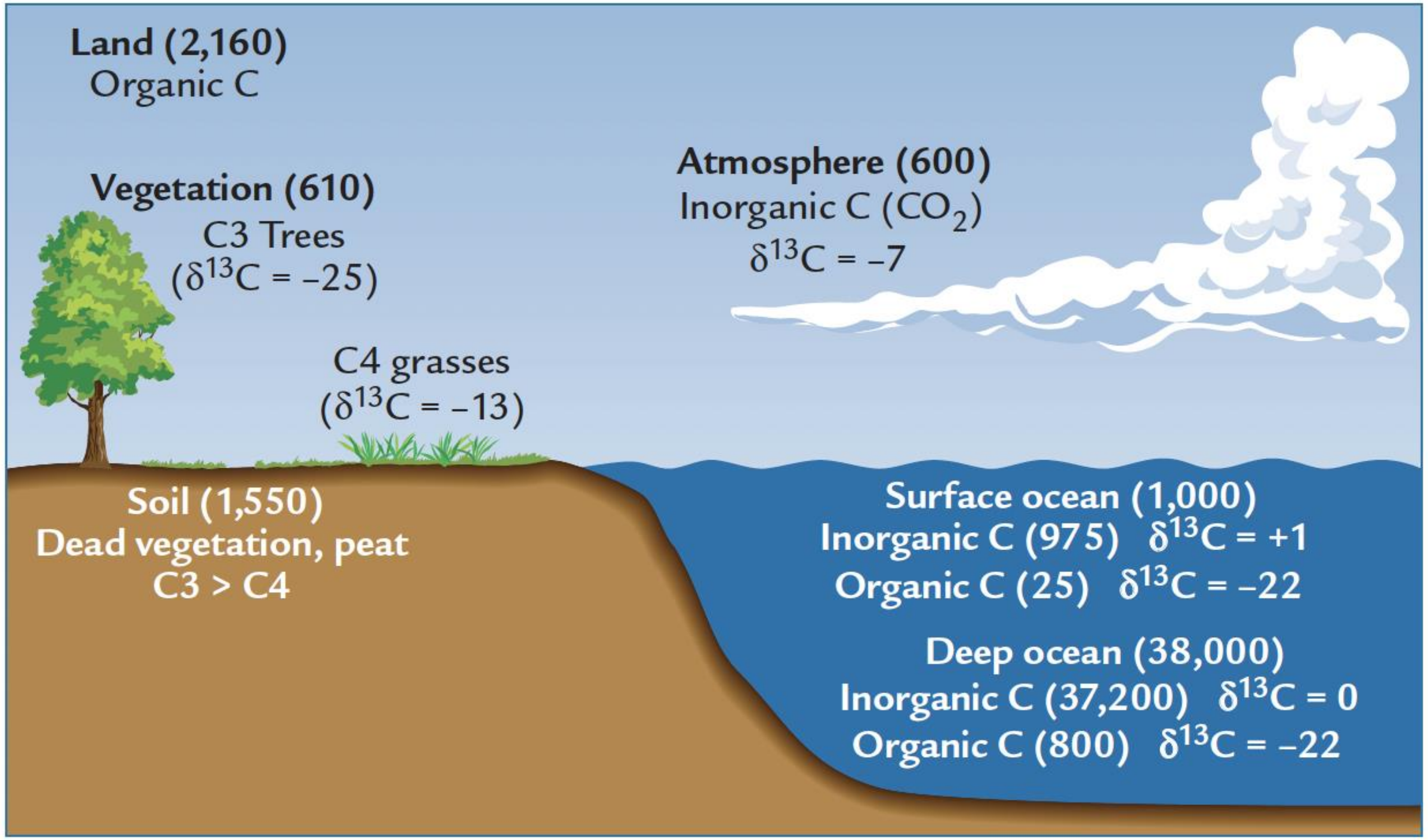
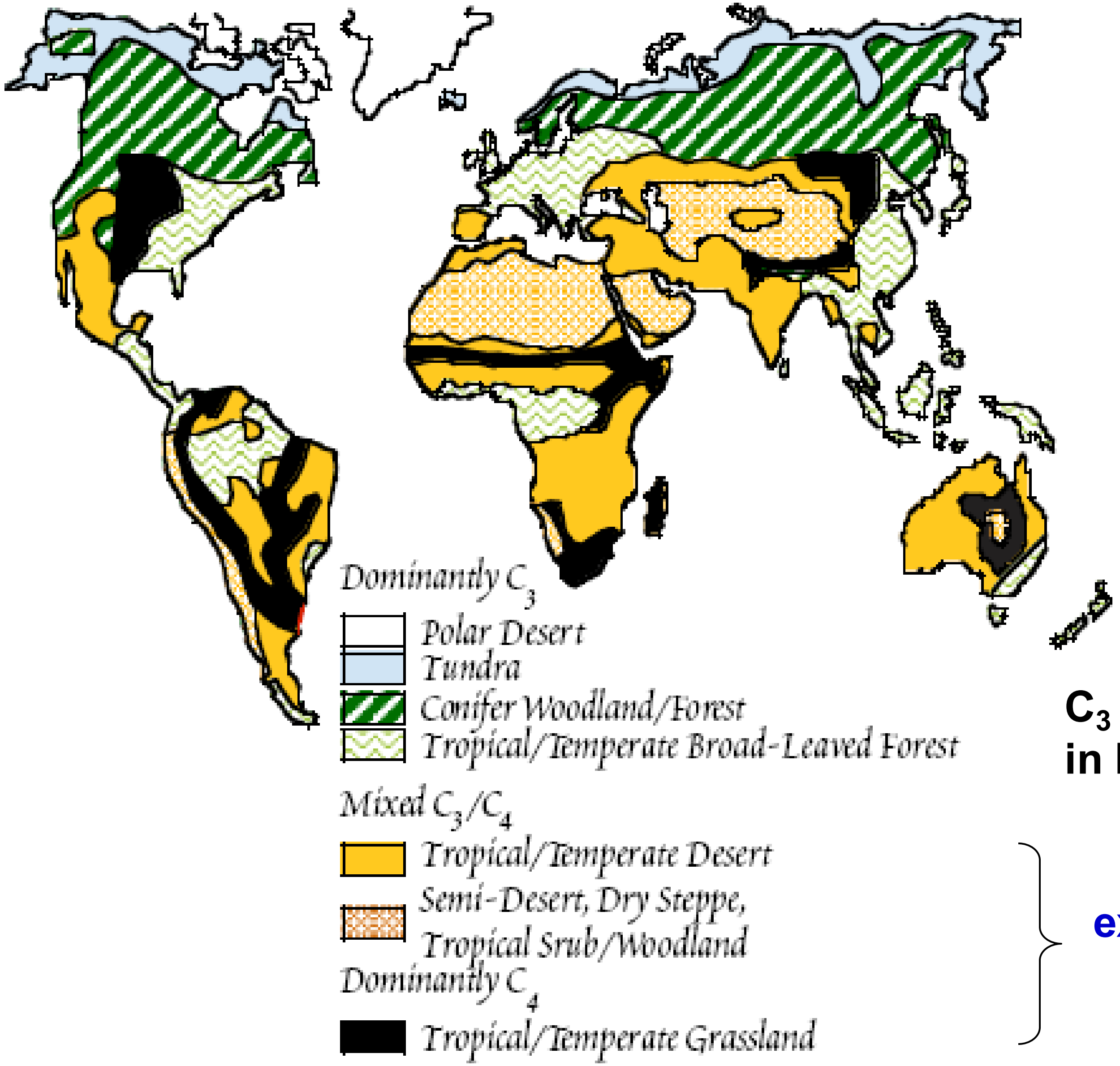


FIGURE 11-5
Carbon reservoir $\delta^{13}C$ values
The major reservoirs of carbon on Earth have varying amounts of organic and inorganic carbon (shown in parentheses as billions of tons of carbon), and each type of carbon has characteristic carbon isotope ($\delta^{13}C$) values.

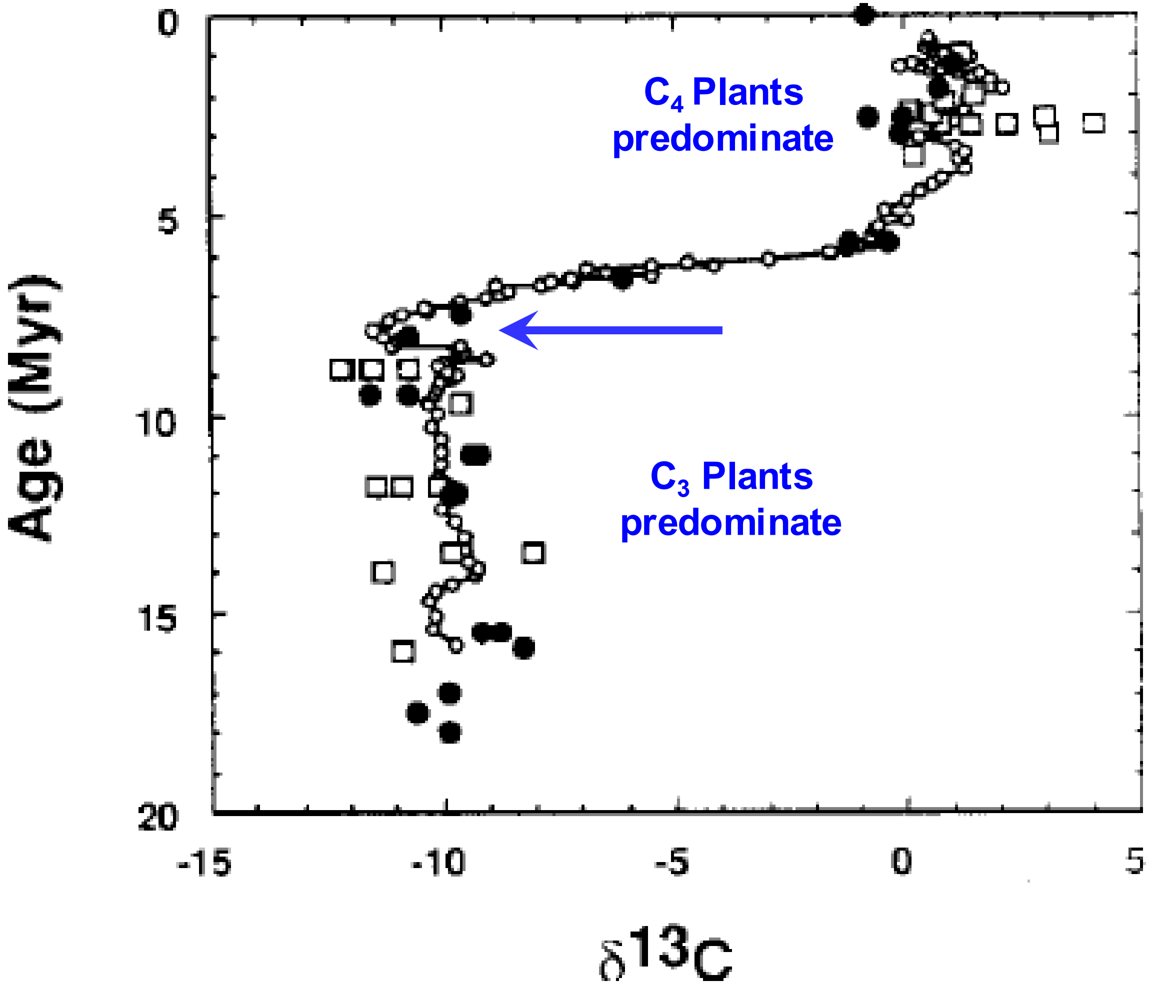
CARBON ISOTOPES AND THE EVOLUTION OF GRASSLANDS



C_3 grasslands occur only in high latitude regions

exclusively C_4 plants.

Carbon isotopic composition in pedogenic carbonates



Small circles are paleosol data from Pakistan, open squares are tooth enamel from Pakistan and filled circles are tooth enamel from N. America. From Cerling *et al., 1993*

Where Did the Missing Carbon Go?

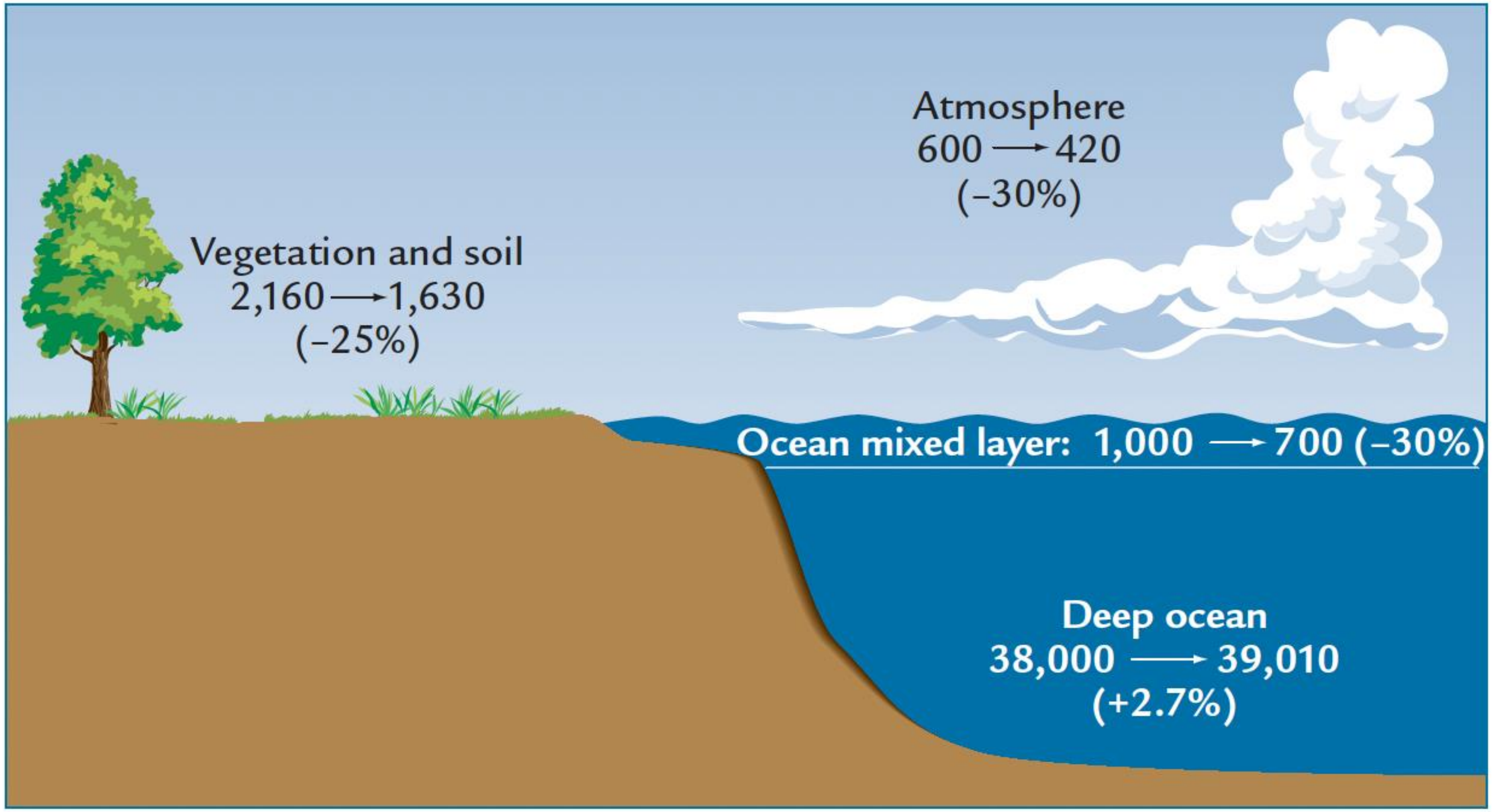
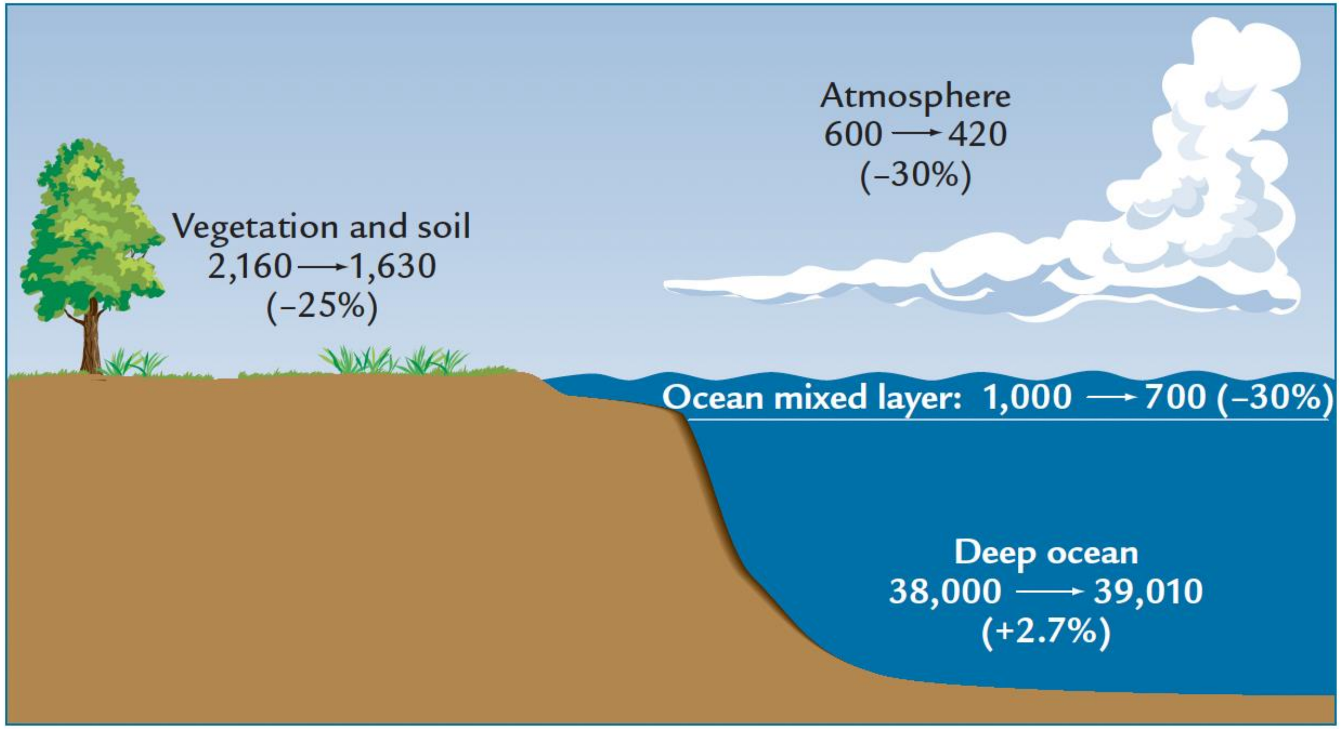


FIGURE 11-7

Interglacial-to-glacial changes in carbon reservoirs

During times like the glacial maximum 20,000 years ago, large reductions in carbon biomass occurred in the atmosphere, in vegetation and soils on land, and in the surface ocean compared to warm interglacial intervals. The total amount of carbon removed from these reservoirs (more than 1,000 billion tons) was added to the much larger reservoir in the deep ocean.

Where Did the Missing Carbon Go?

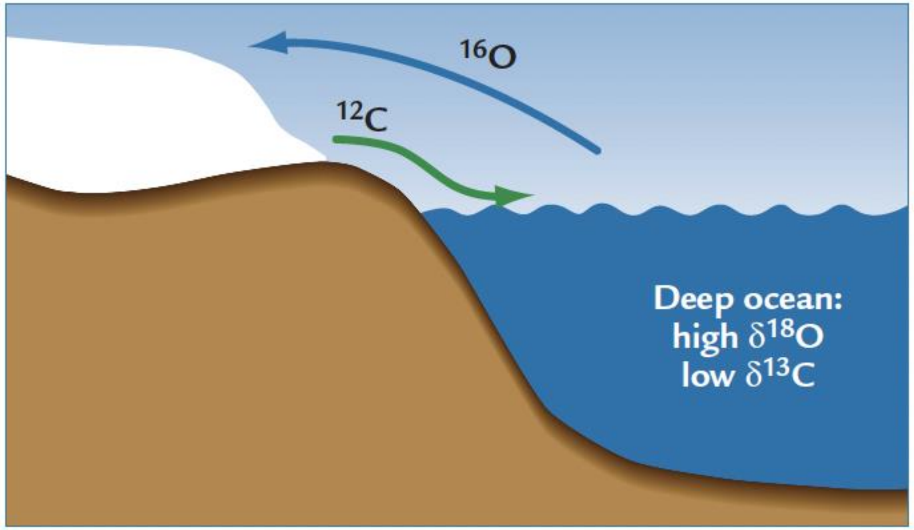


- *The 90-ppm reductions in CO2 values indicate that almost one-third of the carbon in the atmosphere during interglacial times moved elsewhere during glaciations. Converted from ppm concentrations to tons of carbon, this transfer amounted to ~180 billion tons.*
- ***Vegetation-soil reservoir??*** *Continents had less net vegetation cover and held less carbon during glaciations than they did during warm interglacial intervals like today.*
- *the carbon removed from the atmosphere did not go into land vegetation, and now we face the added problem of explaining the carbon missing from not just the atmosphere but also the land.*

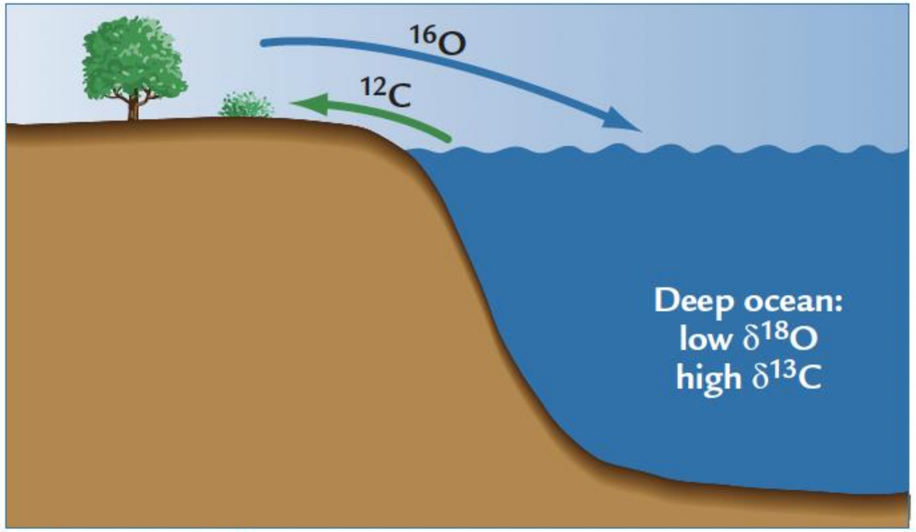
d13C Evidence of Carbon Transfer

- *Organic carbon in terrestrial vegetation is tagged with an average d13C value of -25‰, whereas the large amount of inorganic carbon in the ocean has an average value near 0‰.*

During glaciations, 12C-enriched organic matter is transferred from the land to the ocean at the same time that 16O-enriched water vapor is extracted from the ocean and stored in ice sheets (A). During interglaciations, 12C-rich carbon returns to the land as 16O-rich water flows back into the ocean (B).



A Glacial climate



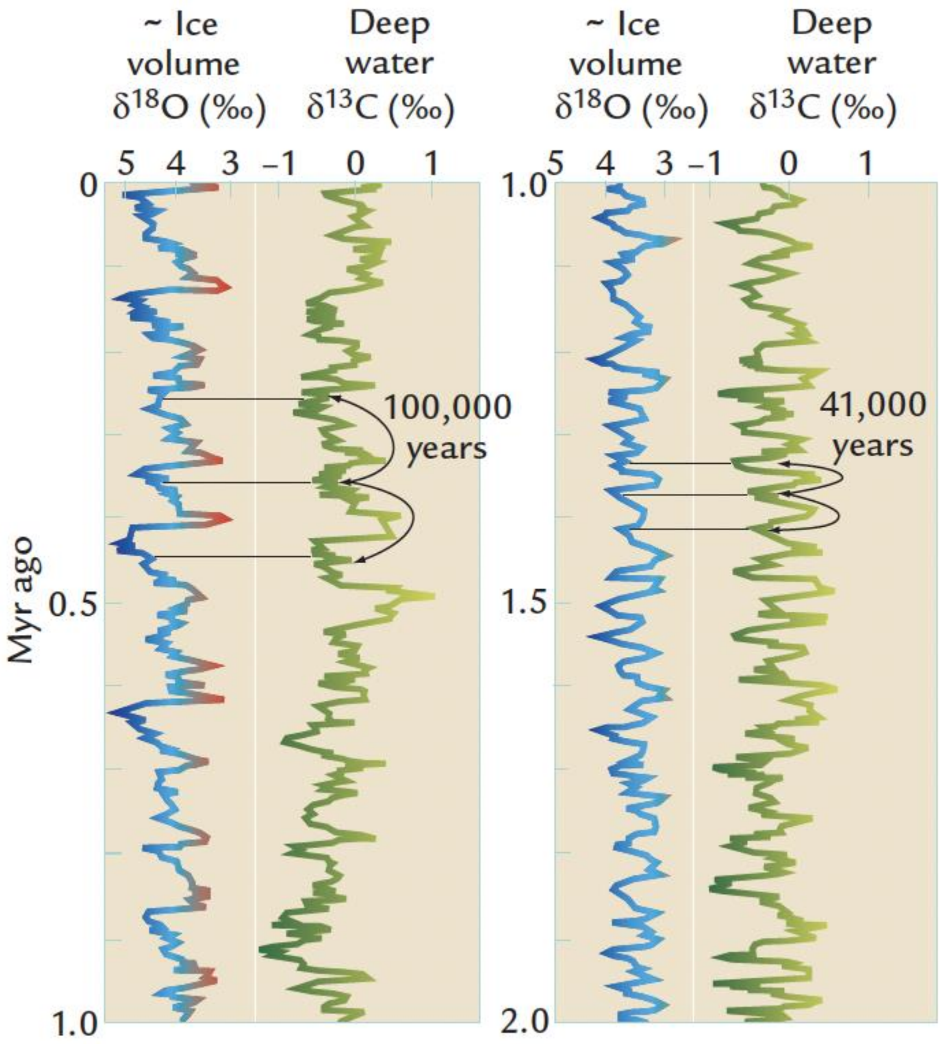
B Interglacial climate

- ***Mass balance calculation to estimate the effect of adding very negative (12C-enriched) carbon to the deep sea during maximum glaciations***

$$\underset{\substack{\text{Inorganic}\\ \text{C in ocean}}}{(38{,}000)}\quad \underset{\substack{\text{Mean}\\ \delta^{13}\text{C}}}{(0‰)} + \underset{\substack{\text{C added}\\ \text{from land}}}{(530)}\quad \underset{\substack{\text{Mean}\\ \delta^{13}\text{C}}}{(-25‰)} = \underset{\substack{\text{Glacial inorganic}\\ \text{carbon total}}}{(38{,}530)}\quad \underset{\substack{\text{Mean}\\ \delta^{13}\text{C}}}{(x)}$$

Solving for x, we find that the mean d13C value of inorganic carbon in the glacial ocean should have shifted from ,0‰ to -0.34‰ because of the addition of 12C-rich carbon transferred from the land.

Long term d13C signals of Carbon transfer



How Did the Carbon Get into the Deep Ocean?

1. Increased CO2 Solubility in Seawater

- *Changes in the average temperature of the ocean during glaciations would have altered the chemical solubility of CO2 in seawater and thereby affected the amount of CO2 left in the atmosphere. Because CO2 dissolves more readily in colder seawater, atmospheric CO2 levels fall by ~10 ppm for each 1 deg C of ocean cooling.*

The 11-ppm CO2 increase caused by higher salinity would have offset just under half of the 20–30 ppm decrease caused by ocean cooling, for a net CO2 drop of ,14 ppm. Most of the observed CO2 decrease of 90 ppm must have occurred by means of other mechanisms.

How Did the Carbon Get into the Deep Ocean?

2. Biological Transfer from Surface Water

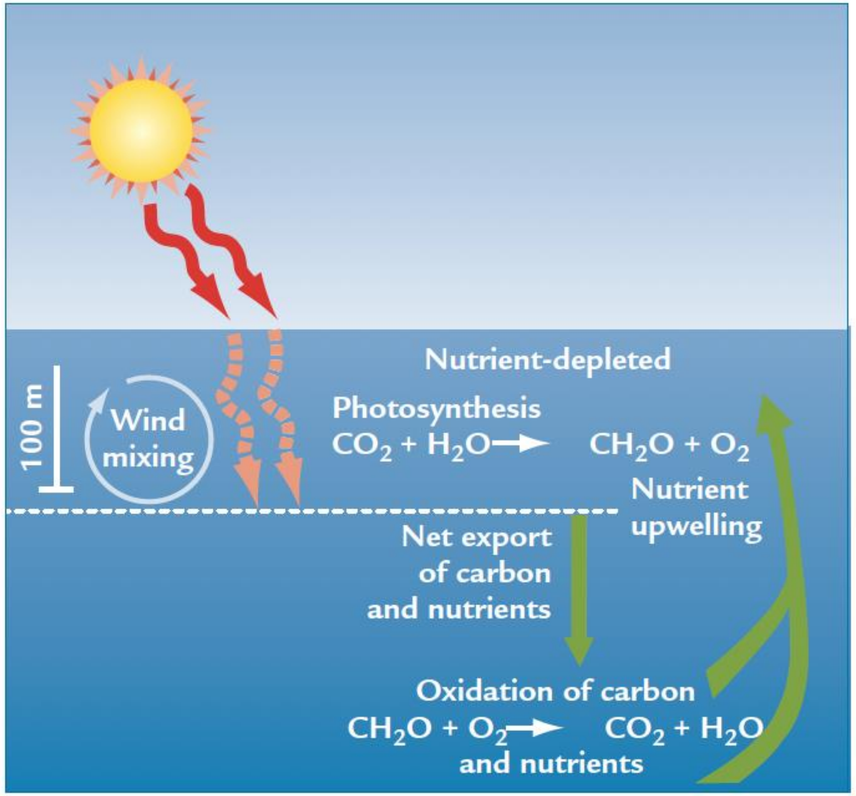


FIGURE 11-10

Photosynthesis in the ocean

Sunlight that penetrates the surface layers of the ocean causes photosynthesis in microscopic marine plankton. After the plankton die, some of their organic tissue sinks to the seafloor and is oxidized to nutrient form. Upwelling returns the nutrients (including organic carbon) to the ocean surface.

Glacial/Deglacial Climate Change

The Last Glacial Maximum