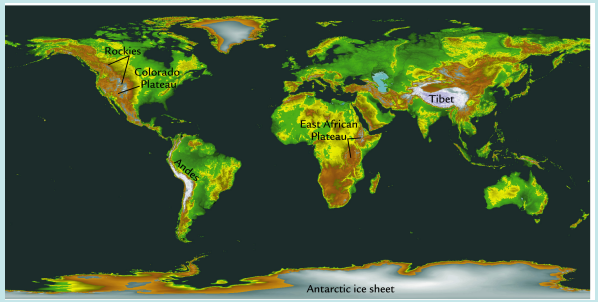
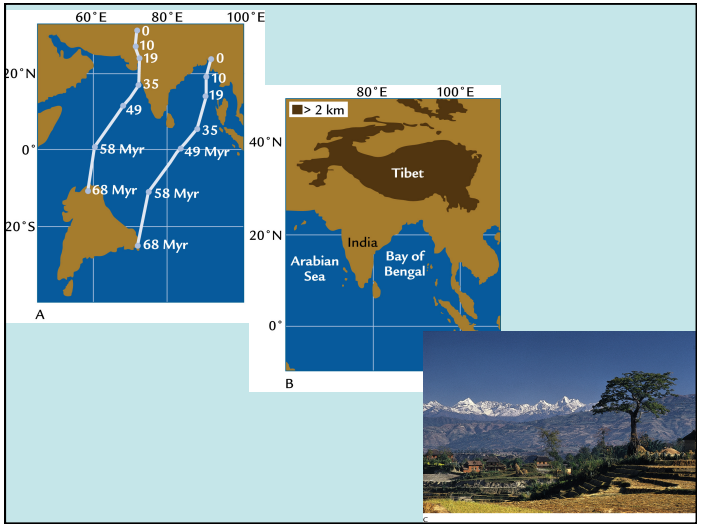
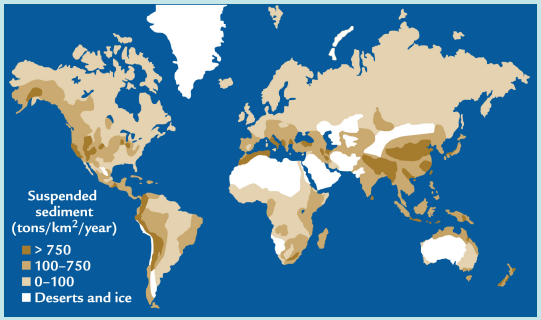
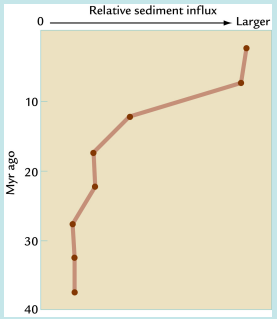
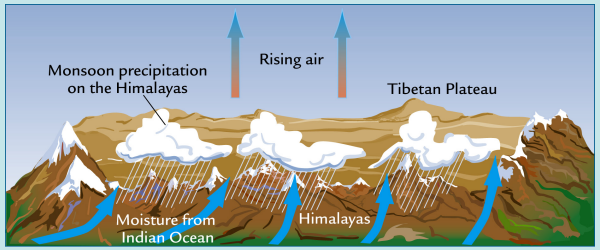
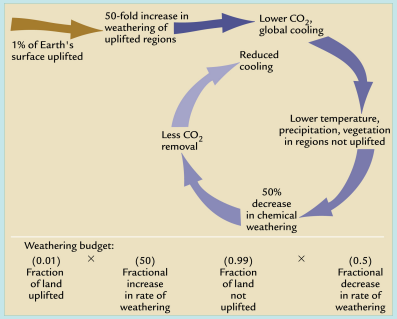

Rockies
Colorado Plateau
Tibet
East African Plateau
Andes
Antarctic ice sheet

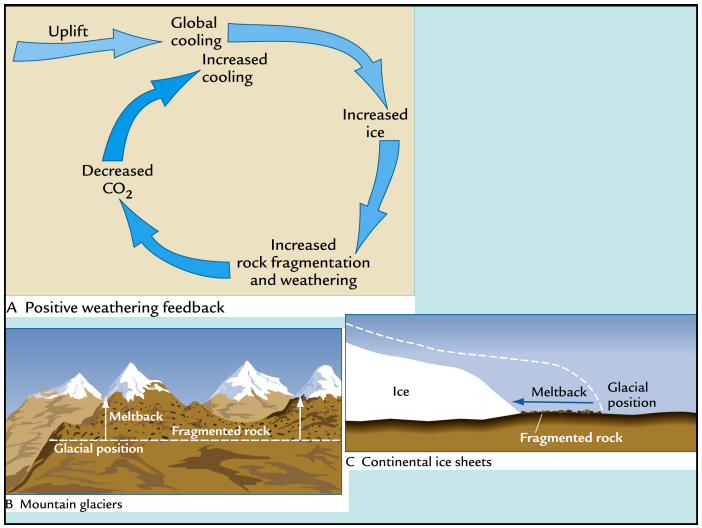

60°E
80°E
100°E
20°N
0°
20°S
0
10
19
35
49
58 Myr
68 Myr
A
80°E
100°E
> 2 km
40°N
20°N
0°
Tibet
India
Arabian Sea
Bay of Bengal
B

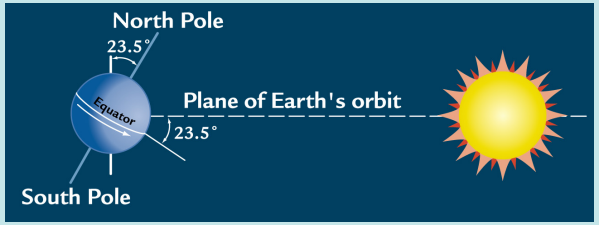

Suspended sediment (tons/km²/year)
> 750
100–750
0–100
Deserts and ice

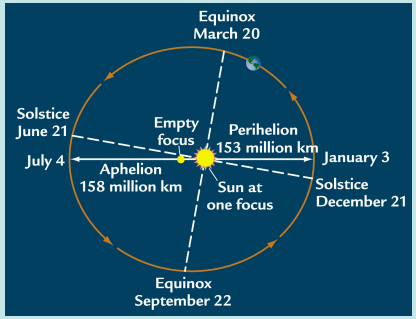

Relative sediment influx
0
Larger
Myr ago
10
20
30
40

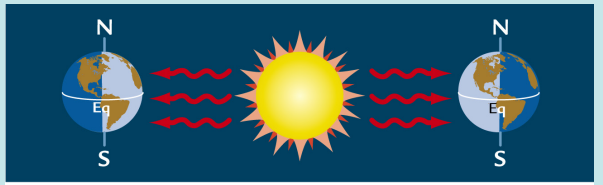

Monsoon precipitation on the Himalayas
Rising air
Tibetan Plateau
Moisture from Indian Ocean
Himalayas


1% of Earth's surface uplifted
50-fold increase in weathering of uplifted regions
Lower CO_2, global cooling
Reduced cooling
Lower temperature, precipitation, vegetation in regions not uplifted
50% decrease in chemical weathering
Less CO_2 removal
Weathering budget:
(0.01) Fraction of land uplifted
×
(50) Fractional increase in rate of weathering
(0.99) Fraction of land not uplifted
×
(0.5) Fractional decrease in rate of weathering

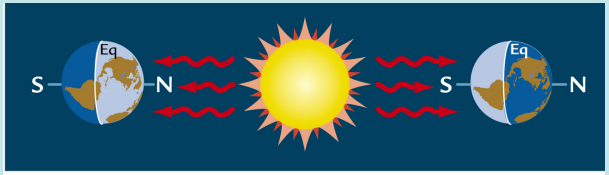

Uplift
Global cooling
Increased cooling
Increased ice
Decreased CO_2
Increased rock fragmentation and weathering
A Positive weathering feedback
Meltback
Fragmented rock
Glacial position
B Mountain glaciers
Ice
Meltback
Glacial position
Fragmented rock
C Continental ice sheets


North Pole
23.5°
Equator
Plane of Earth's orbit
23.5°
South Pole

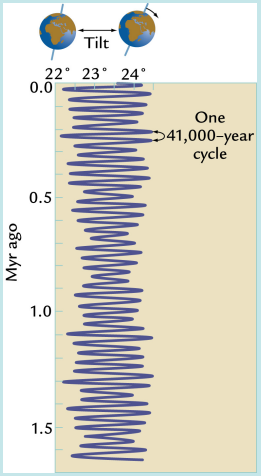


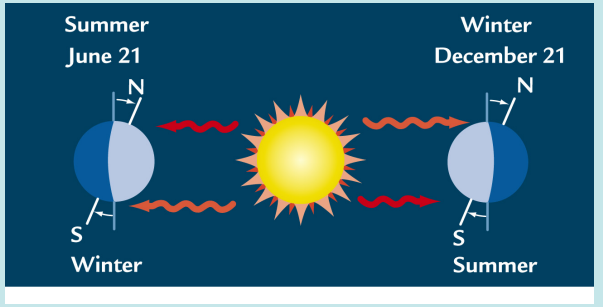


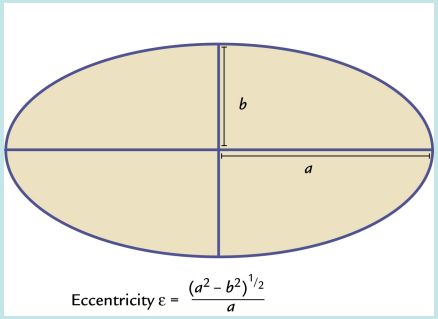
A No tilt

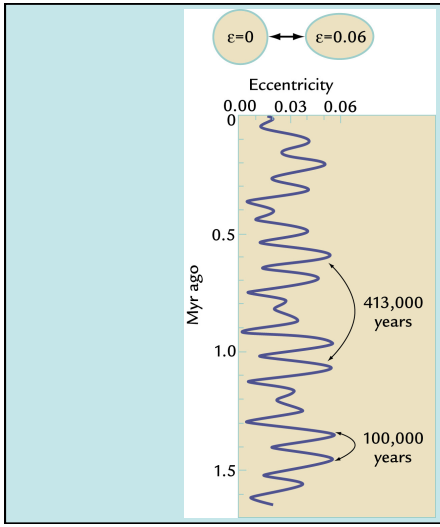


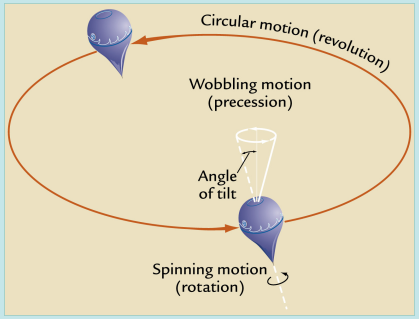
B 90° tilt

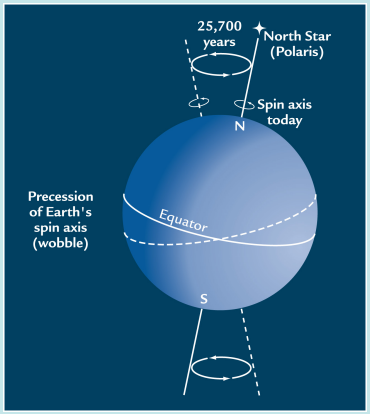


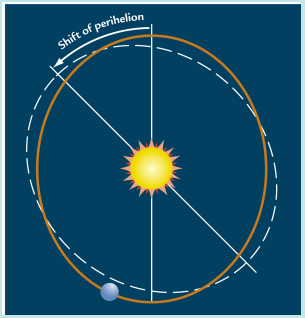


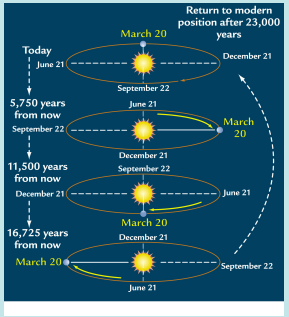

b
a
Eccentricity ε = $\frac{(a^2 - b^2)^{1/2}}{a}$

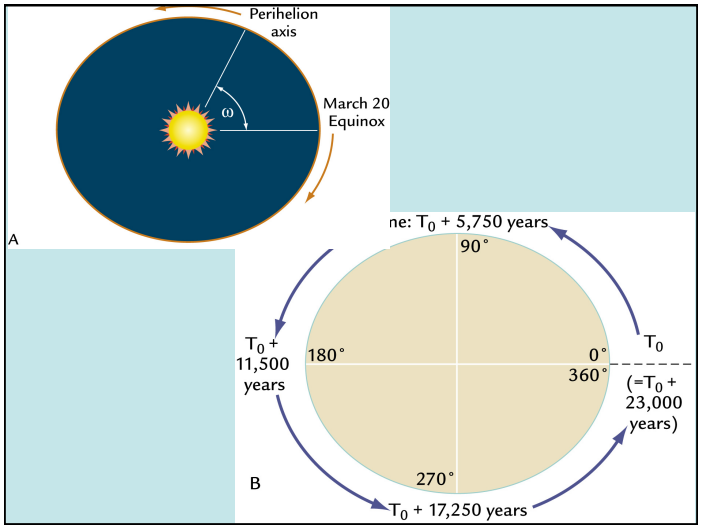

ε=0
ε=0.06
Eccentricity
0.00 0.03 0.06
0
0.5
1.0
1.5
Myr ago
413,000 years
100,000 years

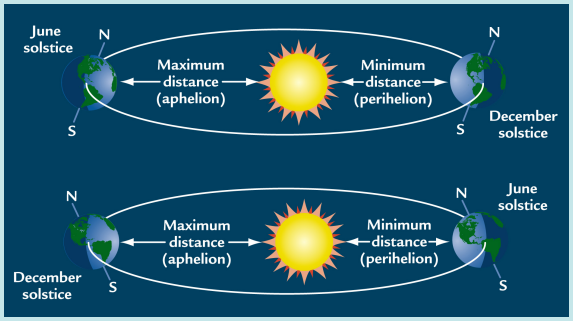

Circular motion (revolution)
Wobbling motion (precession)
Angle of tilt
Spinning motion (rotation)

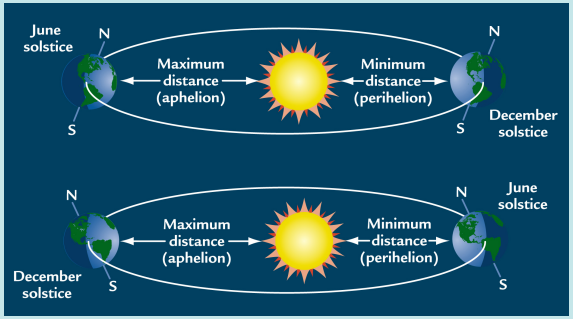

25,700 years
North Star (Polaris)
Spin axis today
N
Precession of Earth's spin axis (wobble)
Equator
S

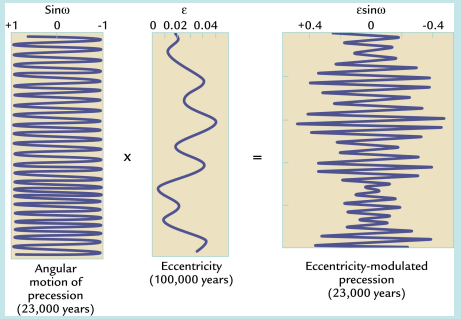

Shift of perihelion

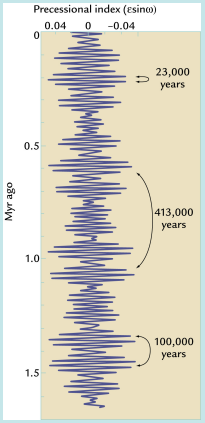

Return to modern position after 23,000 years
Today
March 20
June 21
December 21
September 22
5,750 years from now
11,500 years from now
16,725 years from now

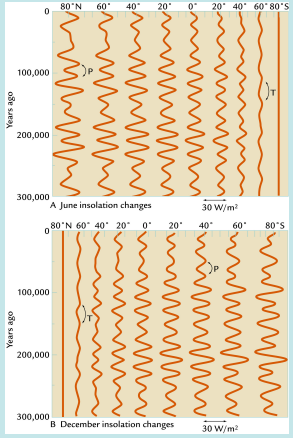

Perihelion axis
ω
March 20 Equinox
A
ne: T0 + 5,750 years
90°
T0 + 11,500 years
180°
0°
360°
T0
(=T0 + 23,000 years)
270°
B
T0 + 17,250 years

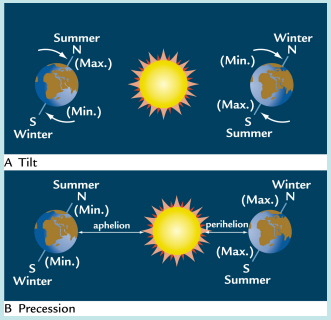

June solstice
N
S
Maximum distance (aphelion)
Minimum distance (perihelion)
December solstice

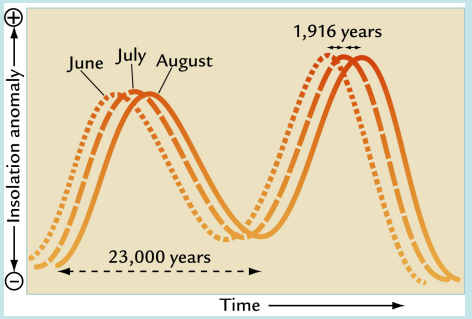

June solstice
N
S
Maximum distance (aphelion)
Minimum distance (perihelion)
N
S
December solstice
N
S
Maximum distance (aphelion)
Minimum distance (perihelion)
N
S
June solstice
December solstice

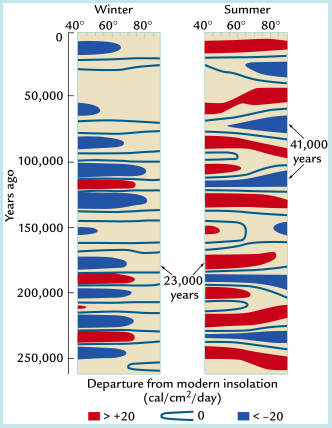

Sinω
+1 0 -1
ε
0 0.02 0.04
εsinω
+0.4 0 -0.4
x
=
Angular motion of precession (23,000 years)
Eccentricity (100,000 years)
Eccentricity-modulated precession (23,000 years)

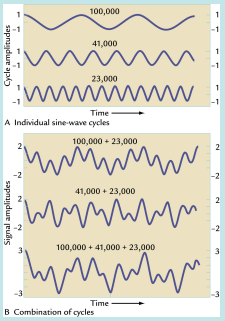

Precessional index (εsinω)
0.04 0 −0.04
0
0.5
1.0
1.5
Myr ago
23,000 years
413,000 years
100,000 years

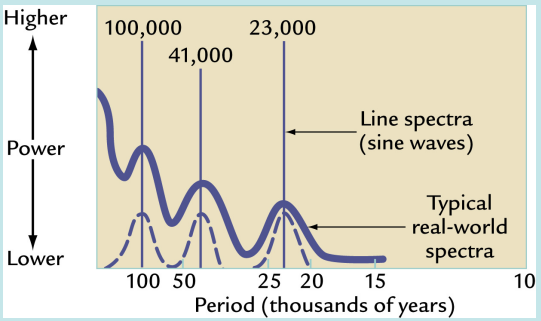

80°N 60° 40° 20° 0° 20° 40° 60° 80°S
0
100,000
200,000
300,000
Years ago
P
T
A June insolation changes
30 W/m²
80°N 60° 40° 20° 0° 20° 40° 60° 80°S
0
100,000
200,000
300,000
Years ago
P
T
B December insolation changes
30 W/m²

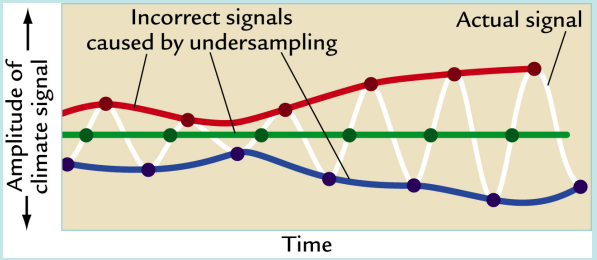

Summer
N
(Max.)
(Min.)
S
Winter
Winter
N
(Min.)
(Max.)
S
Summer
A Tilt
Summer
N
(Min.)
aphelion
S
(Min.)
Winter
perihelion
Winter
N
(Max.)
(Max.)
S
Summer
B Precession

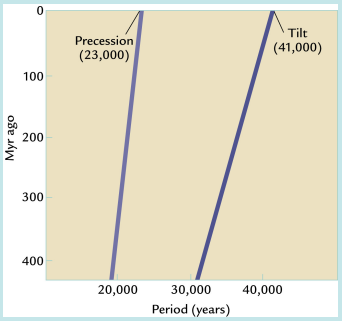

Insolation anomaly
June
July
August
1,916 years
23,000 years
Time

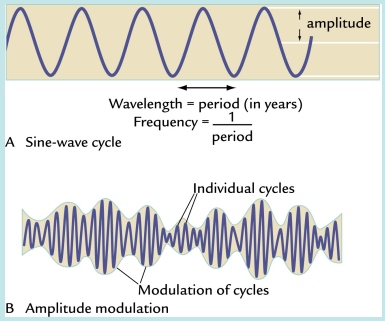

Winter
Summer
40°
60°
80°
0
50,000
100,000
150,000
200,000
250,000
Years ago
41,000
years
23,000
years
Departure from modern insolation
(cal/cm²/day)
> +20
0
< −20

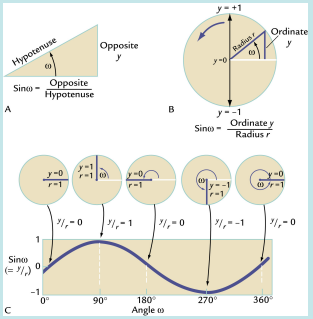
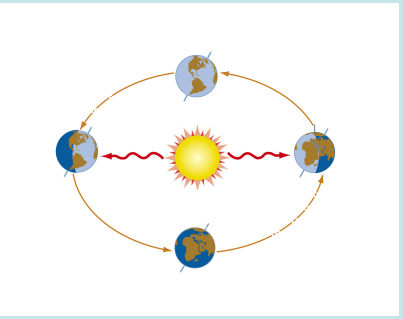

100,000
41,000
23,000
Cycle amplitudes
Time
A Individual sine-wave cycles
100,000 + 23,000
41,000 + 23,000
100,000 + 41,000 + 23,000
Signal amplitudes
Time
B Combination of cycles


Higher
Power
Lower
100,000
41,000
23,000
Line spectra
(sine waves)
Typical
real-world
spectra
100 50 25 20 15 10
Period (thousands of years)


Amplitude of
climate signal
Incorrect signals
caused by undersampling
Actual signal
Time


0
100
200
300
400
Myr ago
Precession
(23,000)
Tilt
(41,000)
20,000
30,000
40,000
Period (years)


amplitude
Wavelength = period (in years)
Frequency = 1/period
A Sine-wave cycle
Individual cycles
Modulation of cycles
B Amplitude modulation


Hypotenuse
Opposite
y
ω
Sinω = Opposite / Hypotenuse
A
y = +1
Radius r
Ordinate
y
y = 0
ω
B
y = −1
Sinω = Ordinate y / Radius r
y/r = 0
y/r = 1
y/r = 0
y/r = −1
y/r = 0
Sinω (= y/r)
1
0
−1
0°
90°
180°
270°
360°
Angle ω
C