

Orbital Frequency Climate Variations - The Ice Ages

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Chapter 7 - Astronomical Control of Solar Radiation

Earth's Orbit Today

sections 7-1, 7-2

Long-Term Changes in Earth's Orbit

sections 7-3, 7-4, 7-5

Changes in Insolation Received on Earth

sections 7-6, 7-7

section 7-10

Chapter 9 - Insolation Control of Ice Sheets

Milankovitch Theory: Orbital Control of Ice Sheets

Modeling the Behavior of Ice Sheets

sections 9-1, 9-2, 9-3, 9-4

Northern Hemisphere Ice Sheet History

sections 9-6, 9-7

Is Milankovitch's Theory the Full Answer?

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Note: text italics and indented more than the rest, was not presented in lecture, Fall 2009

Orbital Frequency Climate Variations - The Ice Ages

remember: descent into icehouse

general causes (less outgassing, more uplifts & weathering)

cause of Antarctic glaciation (opening of Drake Passage)

cause of northern hemisphere (closure of isthmus of Panama)

glaciers in northern hemisphere last 2.75 m.y.

oldest ice rafted debris, N. Atlantic, 2.75 m.y.

extensive moraines, including Harbor Hill & Ronkonkoma on LI.

fjords, including the Hudson River

the glaciers advanced & retreated multiple times

classic glacial chronology of North America & Europe recognized at least 4 glacial

and 4 interglacial periods during the Pleistocene Epoch (1.8 m.y. - 10,000 yr)

(don't bother to memorize the names, though you might remember the Wisconsin glaciation as the last one)

the Holocene Epoch in which we live is really just another interglacial period,

unless we change climate enough to cause a termination of the ice ages

Earth's Orbit Today

Earth's tilted axis and the seasons, solstices, and equinoxes

Earth spin axis is tilted 23.5° from perpendicular with the ecliptic plane

it remains pointing in the same direction (to the star Polaris) as it orbits around sun

seasons are the result of the changing attitude between the spin axis and sun

Earth's eccentric orbit, **perihelion** and **aphelion**

Earth closest to sun (perihelion, 153 mil. km) on Jan 3, shortly after Dec solstice

Earth farthest from sun (aphelion, 158 mil. km) on July 4, shortly after June solstice

(don't need to memorize 153 & 158 million km)

Changes in Earth's Orbit

the amount of tilt, direction of tilt, and eccentricity of orbit change slowly

due to gravitational tug of sun, moon, Jupiter, Saturn, etc on Earth

greater tilt = greater seasonality (difference bet. winter cold & summer warmth)

greater eccentricity will cause greater seasonality if perihelion and aphelion occur near the solstices

tilt of the Earth's spin axis varies between 22.2° and 24.5° in 41,000 year cycles

eccentricity of the Earth's orbit varies from

more circular (0.005 - less difference in insolation)

to more eccentric (0.0607 - more difference in insolation)

in ~100,000 year (strong) and 413,000 year (weak) cycles

we are presently closer to the circular extreme (eccentricity = 0.0167)

(don't need to memorize .005, .0167, .0607)

axial precession: the Earth's spin axis "wobbles around once in 25,700 yrs but also,

precession of the the ellipse: the elliptical orbit wobbles around more slowly the result is...

precession of the equinoxes: "wobble" of the axis relative to perihelion & aphelion once in 23,000 years (strong cycle) & 19,000 years (weak)

precession index: the precession of the equinoxes (23,000 yr) signal is modulated (made stronger and weaker) by changing eccentricity

(memorize: precession = 23,000 yr, tilt = 41,000 yr, eccentricity = 100,000 yr)

Changes in Insolation Through Time

variation calculated by month

we can calculate/predict changes in insolation (amount of solar radiation received at the top of the atmosphere) for any month, at any latitude for any time in the past or future, based on the changing tilt, eccentricity, and precession index

insolation calculated for specific month's varies by up to 12% from the average

23,000 yr precession cycles dominate mid-summer insolation variations and low and mid-latitude mid-winter insolation variations

41,000 yr tilt cycles dominate low amplitude mid-winter variations at high latitude

variation calculated by "caloric season"

we can alternatively calculate changes in insolation for half-year caloric seasons

caloric season insolation variations dominated by 23,000 year cycles at low latitude

but 41,000 yr cycles more apparent in high latitude summer season

maximum variation based on caloric season calculation only ~5% from the average

tectonic scale changes

Because of dissipation of energy by tidal forces the Earth's orbit, Earth-moon relationship, etc. have changed over hundreds of millions of years (the Earth spun faster, there were more days in a year, and the moon was closer in the early Paleozoic Era).

Precession and tilt cycles were shorter in the Paleozoic than today. This needs to be considered when looking for orbital scale climate variations in the deep past.

Ice Sheet History

we can study changing climate using oxygen isotope ratios ($\delta^{18}\text{O}$) in marine carbonates

remember: heavier/more positive ratios mean more ice/colder ocean temps.

lighter/more negative ratios mean less ice/warmer ocean temps.

$\delta^{18}\text{O}$ in marine carbonates for the last 2.75 m.y. shows oscillations coincident with orbital variations

41,000 yr tilt cycles dominate the $\delta^{18}\text{O}$ signal from 2.75 m.y. to ~0.9 m.y.

100,000 yr eccentricity cycle dominates the $\delta^{18}\text{O}$ signal from ~0.6 m.y. to present
smaller 23,000 yr precession and 41,000 yr tilt cycles are also present

ice volume vs. ocean temperature

is the $\delta^{18}\text{O}$ signal a faithful record of ice volume changes or does ocean temperature variation interfere with a clear reading of glacial advance and retreat?

dating corals formed at various stages of sea level confirm that $\delta^{18}\text{O}$ is a good record of glacial advance and retreat; $\delta^{18}\text{O}$ maxima and minima correspond to sea level low-stands and high-stands associated with ice-sheet maxima and minima

Insolation Control of Ice Sheets - Milankovitch Theory

controls on ice sheets

snow/ice accumulates at low (winter) temperatures

not too cold or there is little moisture in air

snow/ice melts at high (summer) temperatures

much more snow can melt in warm summers than forms in winter

Milankovitch Theory:

summer temperature variation more important than winter temperature variations

ice sheets would grow when tilt is low and Earth is near aphelion in mid-summer

ice sheets would shrink when tilt is high and Earth is near perihelion in mid-summer

ice sheet behavior

to form permanent ice/glaciers mean annual temperature must be below about $-10\text{ }^{\circ}\text{C}$

this occurs at high latitude and at high elevation

no continent lies at the pole in the northern hemisphere

glaciers can't begin forming over Arctic Ocean, must form over land

equilibrium line: the boundary, based on temp. & snowfall, separating areas where ice mass balance is positive (glaciers grow) from negative (glaciers shrink)
ice sheets would begin to form once summer cooling brought equilibrium line southward off the Arctic Ocean onto land

with continuing ice growth, elevation increases, allowing ice to accumulate and not melt even farther southward (but higher up) - positive feedback

(and don't forget about the positive feedback of the ice-albedo effect)

maximum ice thickness should lag maximum orbital forcing

should lag precession forcing (23,000 yrs) by ~6000 yrs ($\frac{1}{4}$ cycle)

should lag tilt forcing (41,000 yrs) by ~10,000 yrs ($\frac{1}{4}$ cycle)

the weight of the ice causes a small, instantaneous, *elastic* subsidence

and a slow, gradual (thousands of years), but large (~1 km), *viscous* subsidence

with warming and as the equilibrium line moves northward the ice sheets would retreat

since the weight of the ice gradually caused subsidence, gradually lowering elevation

glacial retreat would be hastened

Milankovitch Theory compared to the $\delta^{18}\text{O}$ record

the Milankovitch theory predicts that 23,000 precession cycles should dominate the glacial record because it has the strongest effect on insolation variation (chap 7)

the early period (2.75-0.9 m.y.) of small ice sheets contains 23,000 yr variations in the $\delta^{18}\text{O}$ record, but the 41,000 yr tilt cycle is dominant

the late period (0.6 m.y. - present) also contains 23,000 yr variations in the $\delta^{18}\text{O}$ record,

but the 41,000 yr tilt cycle is stronger, and the 100,000 year eccentricity cycle dominates even though it has, by far, the weakest effect on changing insolation

some other factor must be modifying the effects of orbitally-driven insolation