*** Ended Here - 12/3/08 ***

Substantial evidence exists for a strong link between CO_2 & climate on a variety of timescales…. With some notable exceptions!

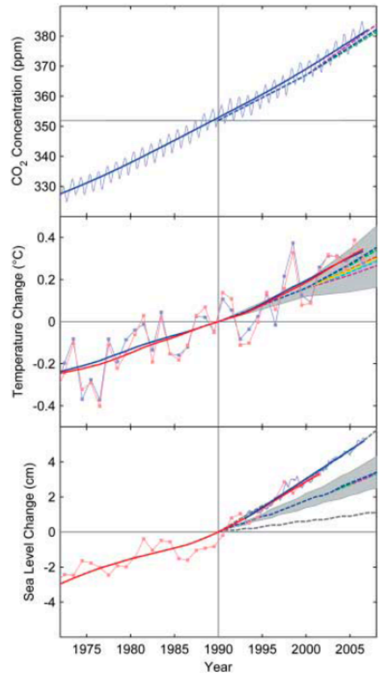
Additional paleoclimate reconstructions & numerical model simulations are necessary. But the biggest (non-controlled) experiment ever attempted is now underway…

CO_2 & Climate: The Planetary Experiment….

• Measured CO_2, Temperature & Sea Level Since 1973 (solid lines)

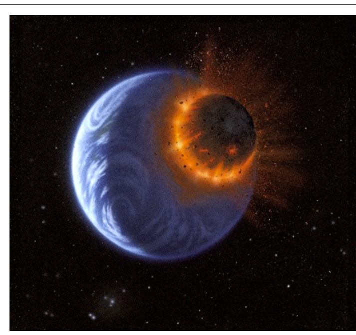
• Compared to Intergovernmental Panel on Climate Change (IPCC) 2001 projections (dashed lines & gray ranges)

• Bottom line: global warming & associated sea level rise from (primarily) CO_2 emissions is greater then even the worst-case scenarios predicted by the most sophisticated climate models



Rahmstorf et al. (2007) *Science* Vol. 316: 709.

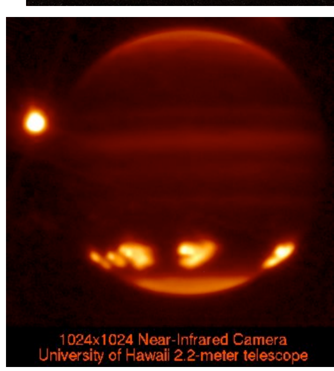
External Influences on Climate



• Impacts from asteroids & comets

• Cosmic rays

• The Sun



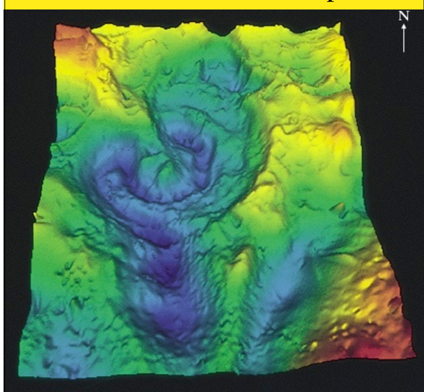
Comet Shoemaker-Levy hitting jupiter, 1994

Comet Hale-Bopp, May 1997, Visalia, CA

Closest approach: 1.315 AU (122 million miles) on 3/22/07

Accretion continues…

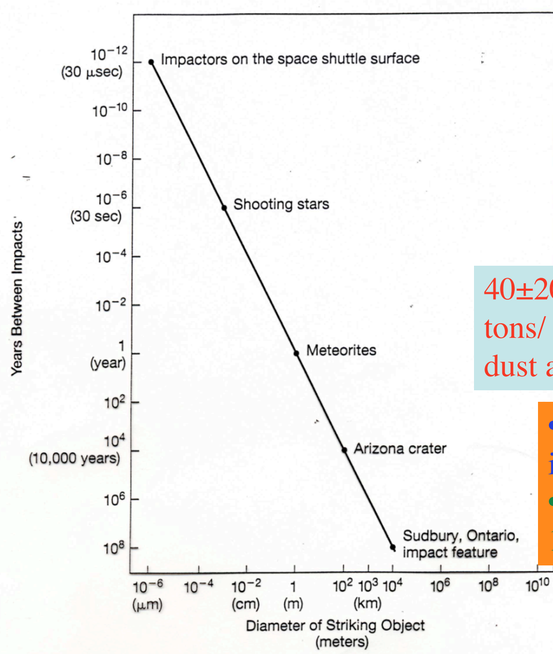
Chicxulub Crater, Gulf of Mexico
- •200 km crater
- •10-km impactor
- •65 Myr BP
- •Extinction of 75% of all species!



Meteor (Barringer) Crater, Arizona
- •1 km diam. Crater
- •40-m diam Fe-meteorite
- •50 kyr BP
- •300,000 Mton
- •15 km/s

http://www.gi.alaska.edu/remsense/features/impactcrater/imagexplain.htm

Size - Frequency Distribution of Impacts



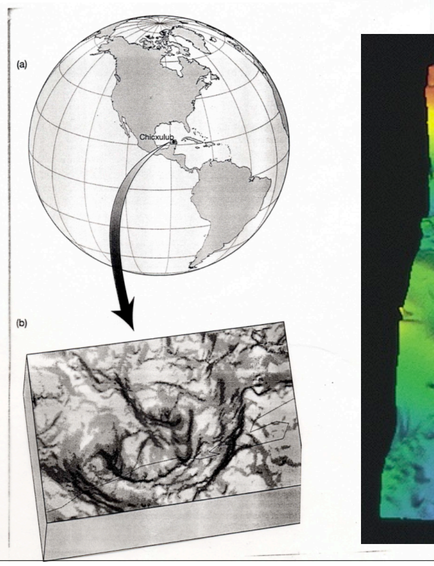
40±20 x 10^4 metric tons/ yr interplanetary dust accretes every yr!

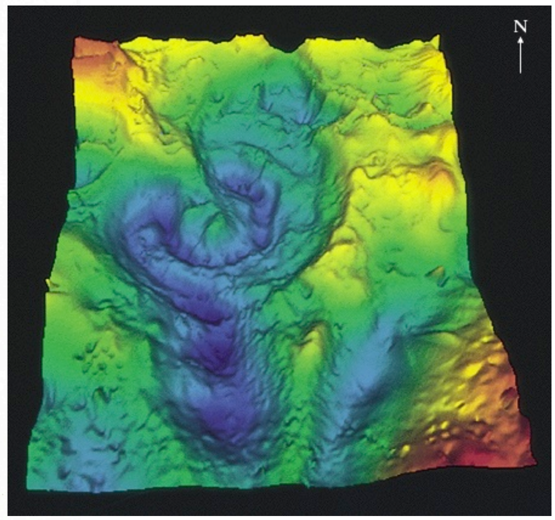
- •100 m object impacts every 10 kyr
- •10 km object every 100 Myr

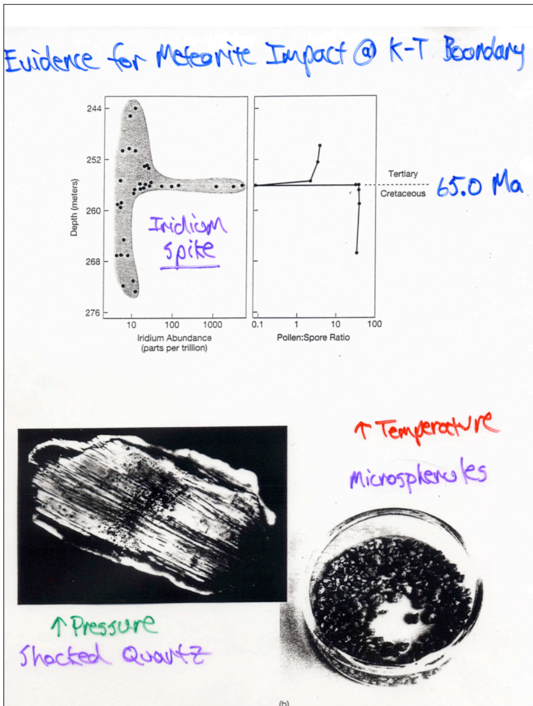
Kump et al. (1999)

Chicxulub Crater
Gulf of Mexico

- •200 km crater
- •10-km impactor
- •65 Myr BP
- •Extinction of 75% of all species!







After a large impact the climate:

1. Initially cools dramatically from particulate material (aerosols) in atmosphere blocking out sun.
2. Then warms dramatically after particles settle out of atmos. & large amounts of CO_2 from vaporized $CaCO_3$ rocks enhance greenhouse effect.

<u>Secondary effects</u>:

- Darkness kills plants, then animals on up food chain
- Ocean acidifies from dissolution of high atmospheric CO_2 & SO_2 in seawater that kills marine life

Phanerozoic History of Extinctions

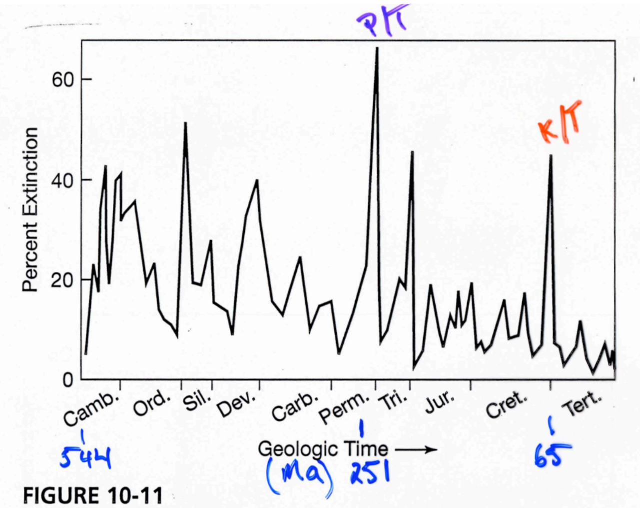


FIGURE 10-11

The fossil record of extinction rate, shown as the percentage of existing genera that went extinct in a particular interval (*stage*) of geologic time. (After Sepkoski, J.J. Jr., *Geotimes,* March, 1994, 15–17.)

Caused by Impacts:

K/T (verified)

P/T (possible)

http://www.cnn.com/TECH/9703/hale.bopp/what.if/index.html

Yes, it will happen

(from CNN, 1997)

Catastrophic comet expected to hit Earth ... someday

(CNN) -- It happens once or twice every million years. A comet or asteroid tears through Earth's atmosphere and smashes into the ground or ocean with enough force to destroy civilization.

The good news:
Scientists will probably spot the object before it hits us.

The bad news:
Even if we get six months warning, there's nowhere to hide.

It sounds like the stuff of Michael Crichton (or for that matter, a rerun on NBC), but in fact, the threat is very real, even if the odds are in our favor. Right now, there are about 2000 large bodies -- also known as NEOs (Near-Earth Objects) -- that cross the orbit of Earth and, in theory, could hit us.

There already have been a handful of close calls in recent years. On March 23, 1989, an asteroid about a half-mile wide crossed the Earth's orbit about 400,000 miles from Earth. The Earth had been in that same spot a mere six hours earlier. On January 17, 1991, an asteroid estimated to be about 30 feet wide passed within 106,000 miles of Earth. It was the closest "near miss" ever recorded.

Smaller objects hit the Earth all the time. Most of them land in oceans or uninhabitated areas, unnoticed. But some make headlines.
car hit my a meteorite

On October 9, 1992, a meteorite smashed through the rear end of a car in Peekskill, New York. No one was hurt, but the Chevy Malibu was totaled. (6.3M/30 sec. QuickTime movie) movie icon

The most vivid example yet of a comet's destructiveness occurred in the summer of 1994, when Comet Shoemaker-Levy 9 collided with Jupiter, creating a spectacular plume that rose above the Jovian cloudtops. (235K/21 sec. AIFF or WAV sound) icon
Shoemaker-Levy 9 strikes Jupiter

NASA scientists take the threat of an impact seriously, but they've had a hard time convincing Washington to fund a proposed early warning system.

26 Myr Period of Extinctions?

Astronomical Hypotheses

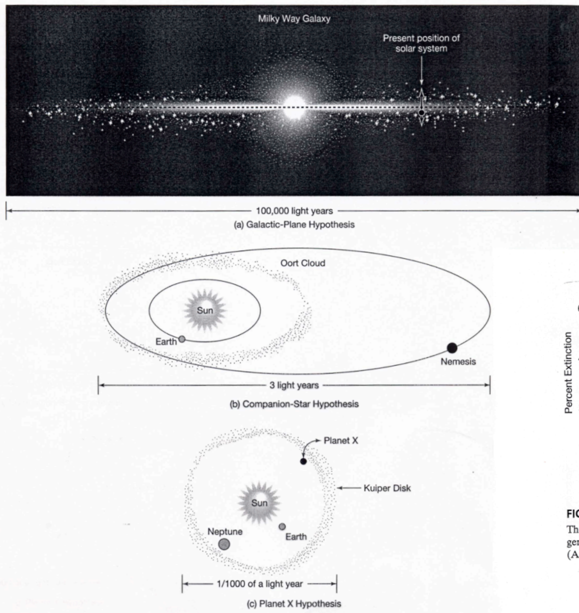


FIGURE 10-12
Three astronomical hypotheses explaining the 26-million-year periodicity in the fossil record of extinction. Figures not drawn to scale. (After Raup, D.M., 1986. See Further Reading.)

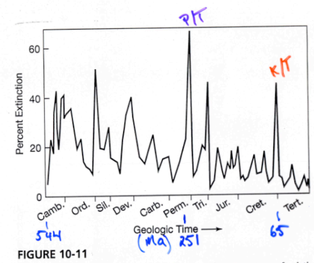
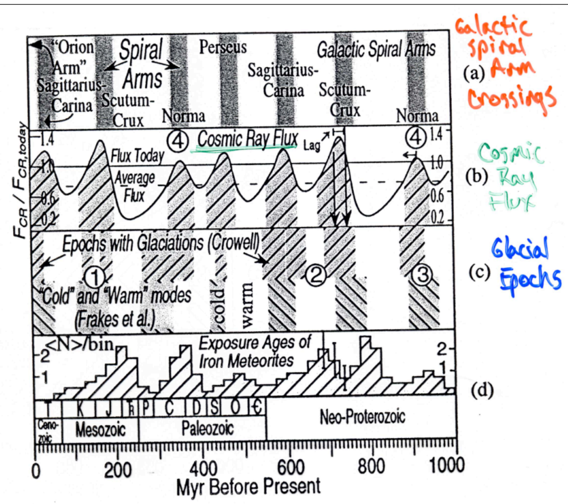


FIGURE 10-11
The fossil record of extinction rate, shown as the percentage of existing genera that went extinct in a particular interval (*stage*) of geologic time. (After Sepkoski, J.J. Jr., *Geotimes*, March, 1994, 15–17.)

Kump et al. (1999)

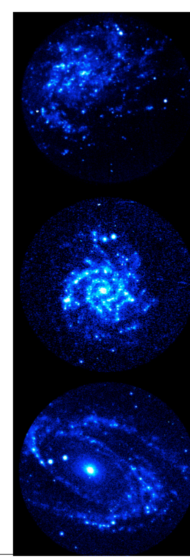
Cosmic Ray Forcing of Climate?



Shaviv (2002), Phys. Rev. Lett., v.89(5): 051102-1-4

$\frac{F_{CR}}{F_{CR,today}}$: 25% – 135%

$\frac{T}{T_{today}}$: +10 –5 K



http://antwrp.gsfc.nasa.gov/apod/ap960409.html

Cosmic Ray Influence on Climate?

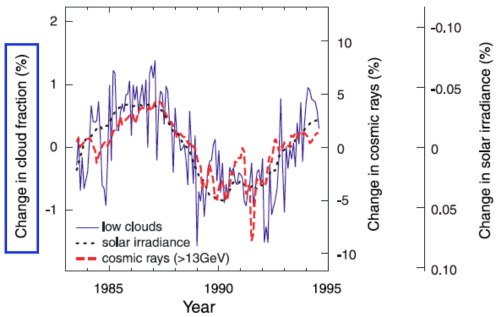


Fig. 1. Variation of low-altitude cloud cover, cosmic rays, and total solar irradiance between 1984 and 1994. The cosmic ray intensity is from Huancayo observatory, Hawaii. [Adapted from (*4*)]

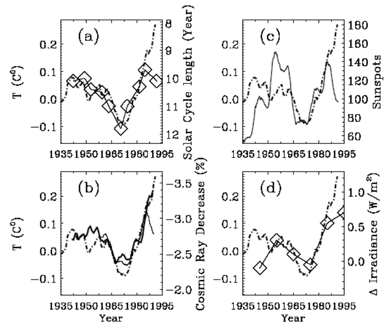
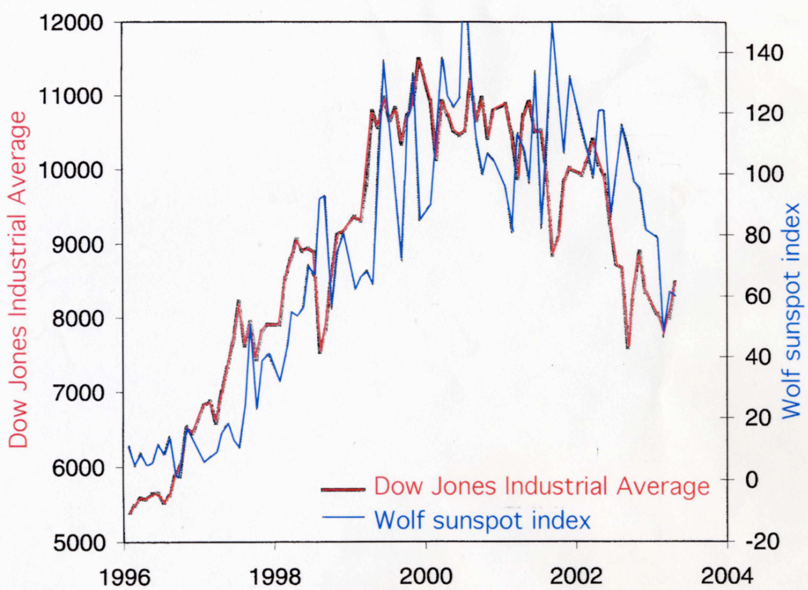


FIG. 3. 11 year average of northern hemispheric marine and land temperatures (dash-dotted line) compared with (a) unfiltered solar cycle length; (b) 11 year average of cosmic ray flux (from ion chambers 1937–1994, normalized to 1965), thick solid line; the thin solid line is cosmic ray flux from Climax, Colorado neutron monitor (arbitrarily scale); (c) 11 year average of relative sunspot number; (d) decade variation in reconstructed solar irradiance (zero level corresponds to 1367 W/m², adapted from Lean *et al.* [6]). Note the 11 year average has removed the solar cycle in (b) and (c).

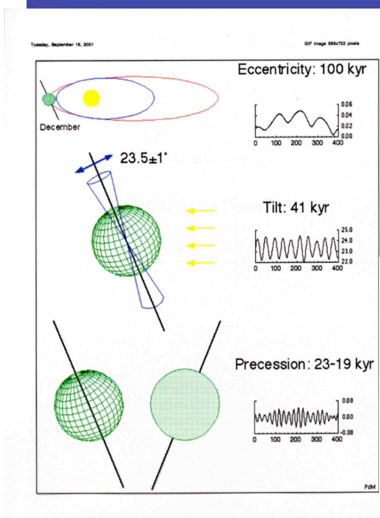
Carslaw et al. (2002) *Science* Vol. 298: 1732-1737.

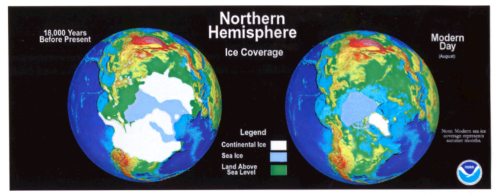
Svensmark (1998) *Phys. Rev. Lett.* Vol. 81(22): 5027-5030.

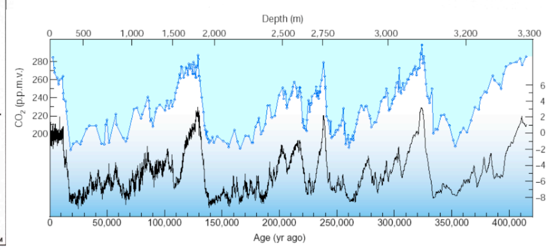
Correlation Is Not Causation

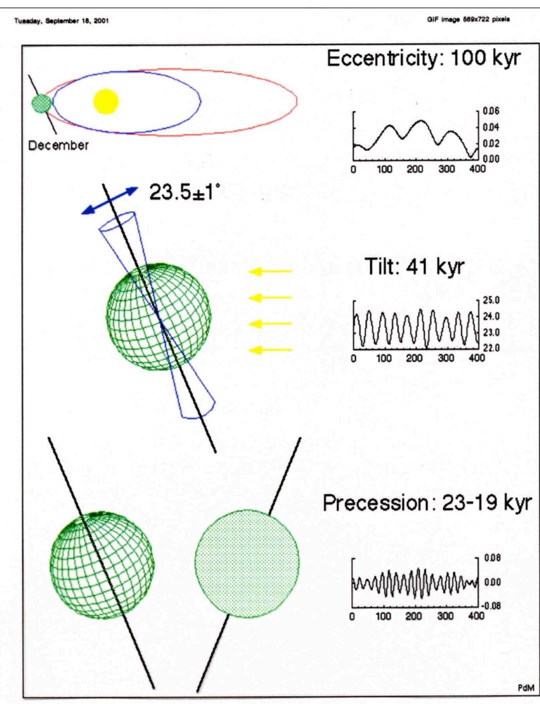


Pleistocene Glaciations









Periodic changes in orbital geometry modulate solar radiation receipts (insolation)

Eccentricity, Obliquity (tilt), Precession

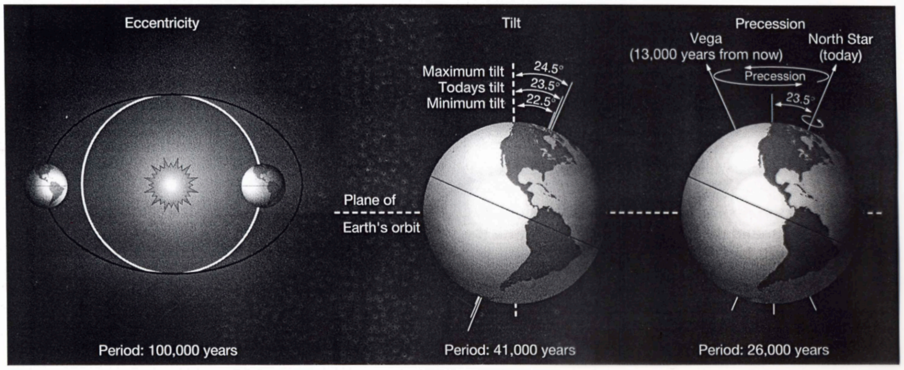
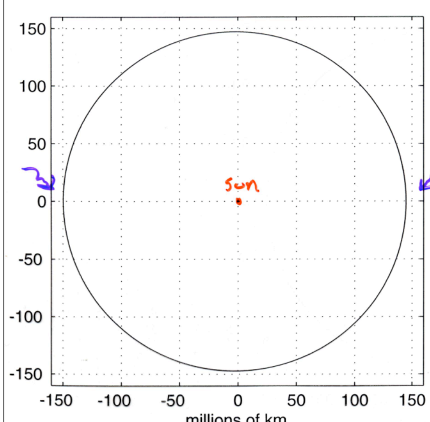


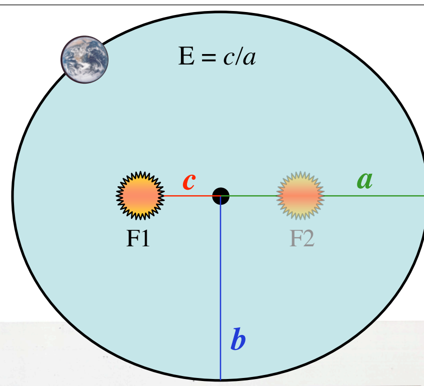
FIGURE 11-5

Aspects of Earth's orbit around the Sun that have implications for climate change. (a) The elliptical nature of the orbit (eccentricity) changes on 100,000-year time scales. (b) The tilt of the spin axis with respect to the plane of Earth's orbit around the Sun (obliquity) changes on a 41,000-year time scale. (c) The orientation of the spin axis in space wobbles (precesses) with periodicities of 19,000 and 23,000 years. (From J.P. Davidson, W.E. Reed, and P.M. Davis: *Exploring Earth: An Introduction to Physical Geology*, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Kump et al. (1999)

Eccentricity of Present Earth Orbit Around Sun (to Scale)





Present eccentricity = 0.017
Range: 0 - 0.06
100 & 400 kyr periods

Muller & MacDonald (2000)

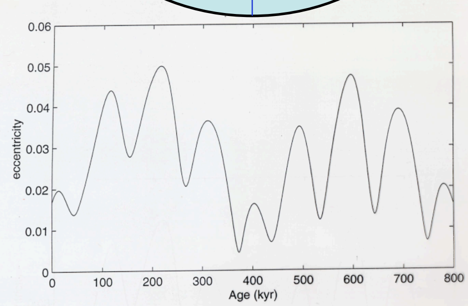


Fig. 2.6. The eccentricity of the Earth's orbit.

Obliquity

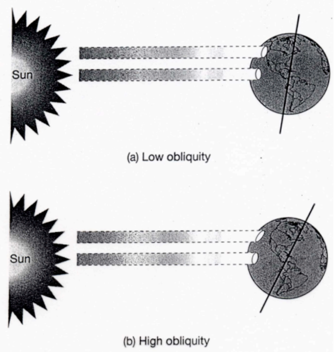


FIGURE 11-7
(a) At low obliquity, Earth has less contrast in insolation between the seasons. (b) At high obliquity, the seasonal contrast is greater.

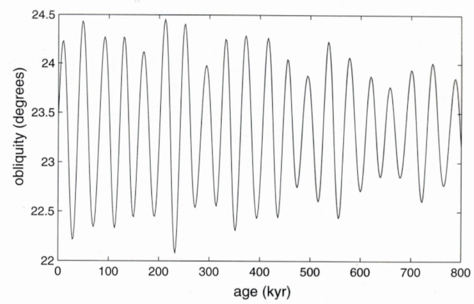
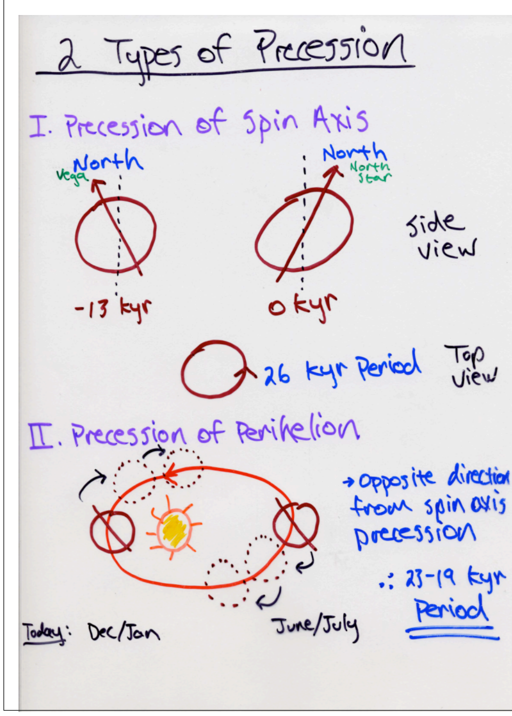


Fig. 2.12. Obliquity.

Muller & MacDonald (2000)

Kump et al. (1999)

Precession



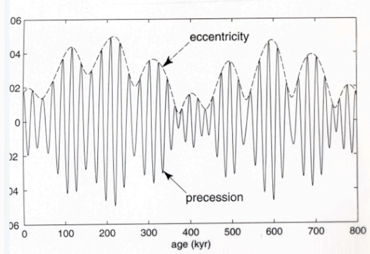


Fig. 2.10. Precession parameter p and eccentricity.

$p = e \sin \omega$

↑ ∠ between Spring ~~Solstice~~ Equinox + perihelion

Muller & MacDonald (2000)

Summer (June 21) Insolation at 65°N

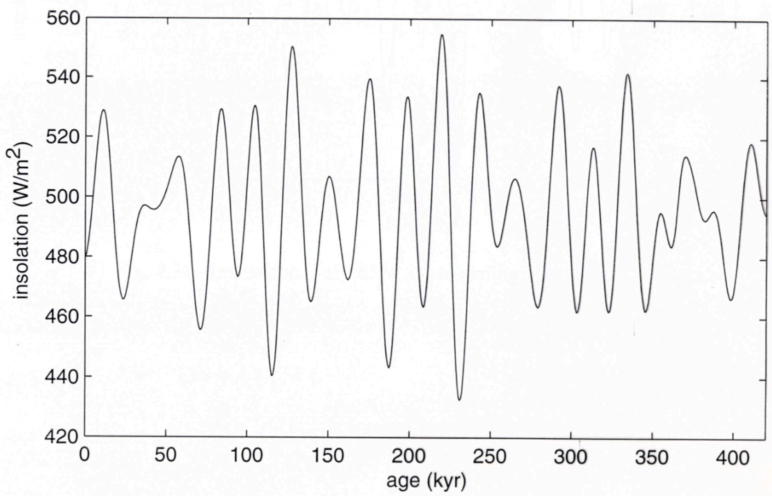
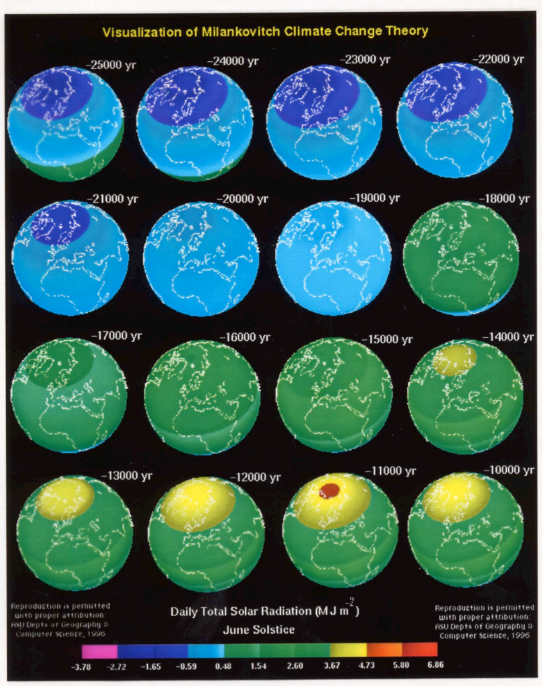


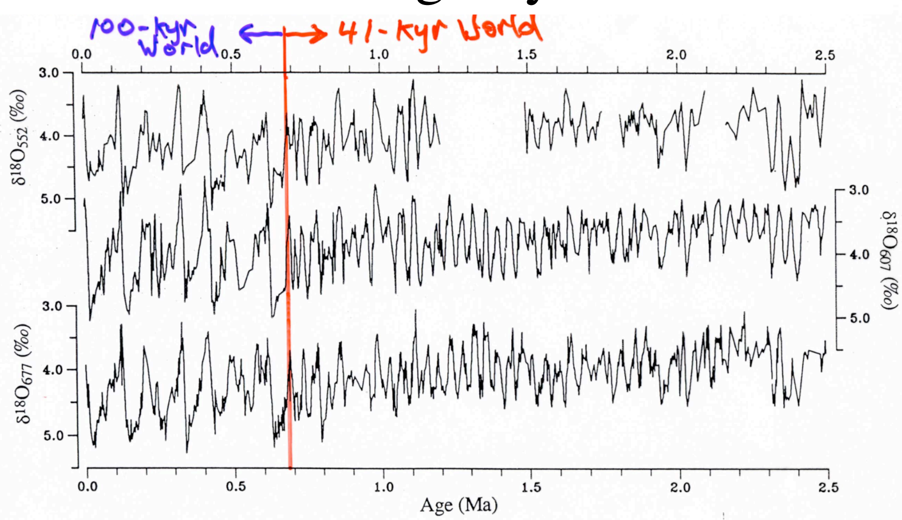
Fig. 4.38. Insolation, July 65N. Note similarity to Fig. 4.37.

Muller & MacDonald (2000)



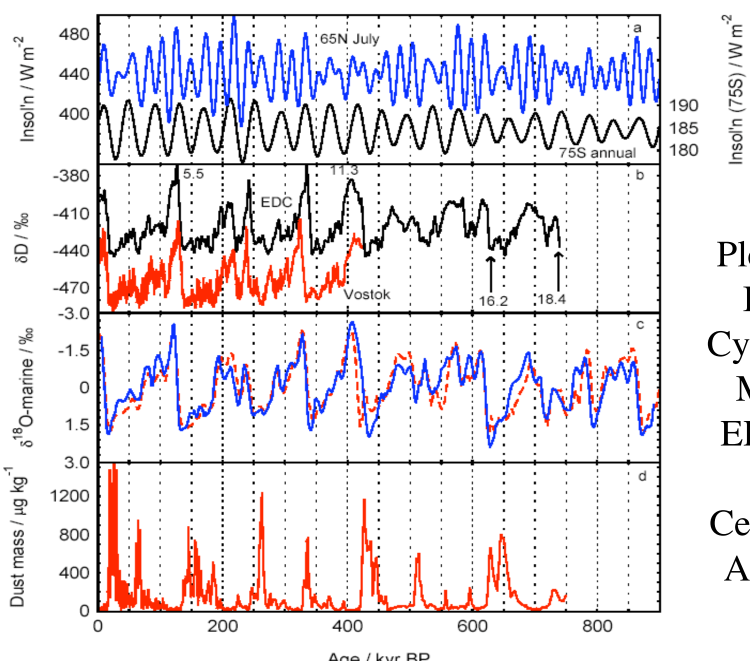
Increasing Northern Hemisphere SUMMER insolation caused the end of the last ice age

Pleistocene Ice Age Cycles 0-2.5 Ma



- $\delta^{18}O$ in benthic foraminifera from marine sediment cores

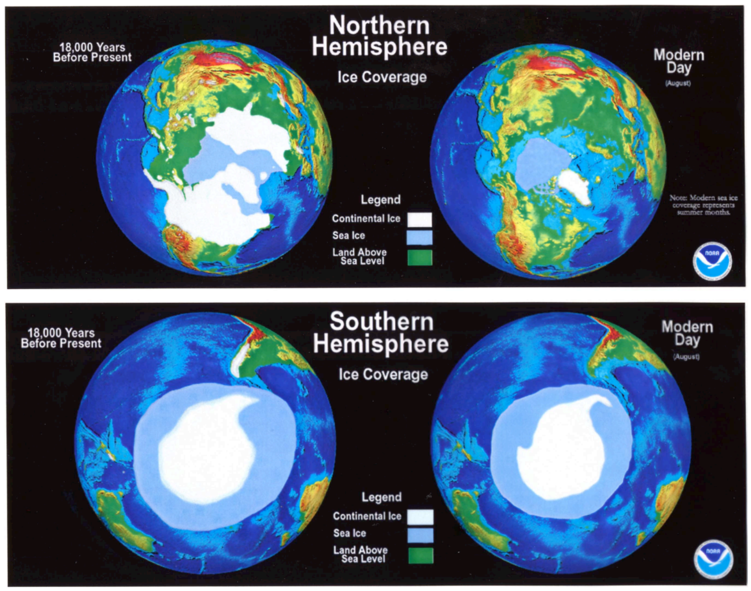
Raymo et al. (1990)



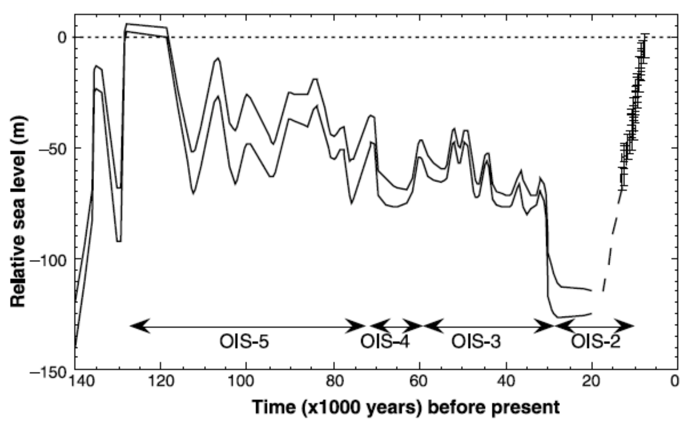
Pleistocene Ice Age Cycles 0-0.8 Ma from EPICA Ice Core, Central East Antarctica

EPICA Community (2004) *Nature* Vol. 429: 623-628

The Last Glacial Maximum, 21 kyr ago



Sea Level Changes During the Last Glacial Cycle



- Inferred from the height-age relationships of raised reefs & depth of submerged fossil corals
- Caused by changes in continental ice volume associated with last glacial cycle

Lambeck & Chappell (2001) *Science*, Vol. 292: 679-686

Present Day Volume of Ice in Glaciers

Estimated Present-Day Area* and Volume* of Glaciers and Maximum Sea Level Rise Potential

From: **Satellite Image Atlas of Glaciers of the World**
Chapter A: Introduction (U.S. Geological Survey Professional Paper 1386-A)
Editors: **Richard S. Williams, Jr., and Jane G. Ferrigno**

Geographic region	Area (km^2)	Percent	Volume (km^3)	Percent volume %	Maximum sea level rise potential (m)**
Ice caps, ice fields, valley glaciers, etc.	680,000[A]	4.24	180,000[A]	0.55	0.45***
Greenland (Inland Ice)	1,736,095[B]	10.82	2,600,000[B]	7.90	6.50
Local ice caps and other glaciers	48,599[B]	0.30	20,000[B]	0.06	0.05
Antarctic	13,586,400[C]	84.64	30,109,800[C]	91.49	73.44****
East Antarctica	10,153,170		26,039,200		64.80
West Antarctica	1,918,170		3,262,000		8.06
Antarctic Peninsula	446,690		227,100		0.46
Ross Ice Shelf	536,070		229,600		0.01
Ronne-Filchner ice sheves	532,200		351,900		0.11
Totals	16,051,094	100.00	32,909,800	100.00	80.44

* Modified from Table 1 in Swithinbank (1985).

http://pubs.usgs.gov/factsheet/fs133-99//gl_vol.html

* Not corrected for Grnld + AA ice below sea level
~10%