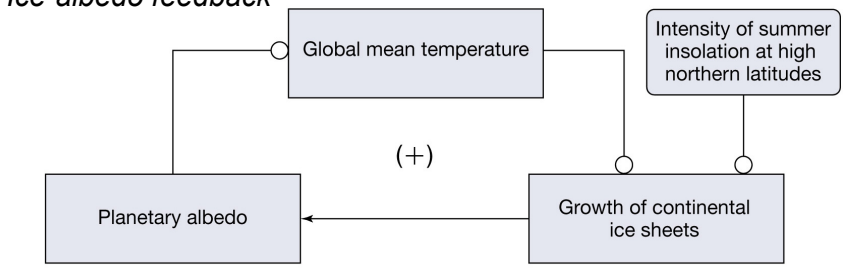
Orbital Theory: Trigger and Feedback Mechanism

Ice-albedo feedback



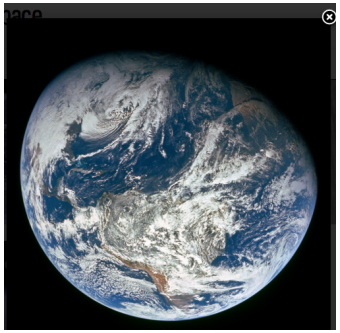
Trigger (change in insolation) with feedback causes ice-sheets...
to grow and keep growing
or
to melt and keep melting

- Other feedbacks are needed to explain the magnitude of the changes.
- Greenhouse gases (e.g. CO_2 and CH_4) seem to be involved.

Ice Albedo Feedback

- Probably important for the climate changes in the northern hemisphere during ice age cycles
  - Ice sheets that extend far south into the northern UW reflect significant sunlight (change the planetary albedo from 0.30 today to 0.32 at the LGM)

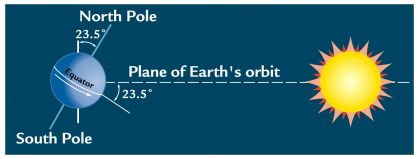
- Contrary to popular belief, ice-*albedo* feedback is not important for for understanding how climate will change over the next millennium due to increasing greenhouse gases

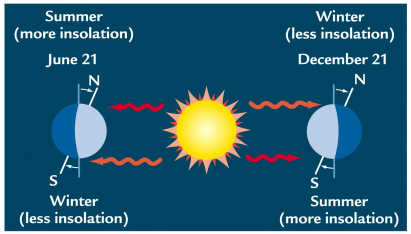


Orbital Variations and Insolation

Obliquity or Tilt

- Tilt angle is presently 23.44°
- Tilt is the main reason why we have large seasonal cycles in mid-latitudes and polar regions
- Variations in tilt angle have no impact on global average insolation

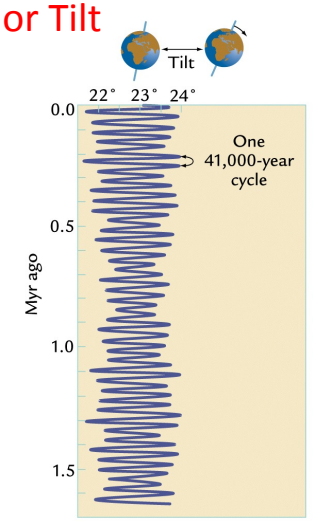




Orbital Variations and Insolation

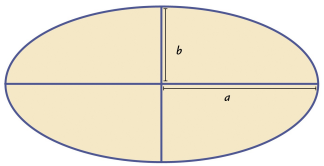
Obliquity or Tilt

- Tilt of axis of rotation varies from 22.5 ° and 24.5 °
  - Dominant period of 41 kyr
- Variations in tilt angle modulate seasonality, especially in high latitudes
  - North-south insolation gradient
  - Winter & summer insolation anticorrelated (good for Milankovitch's theory)
  - Impacts annual mean insolation at a given latitude
- Variations in tilt angle have no impact on *global* average insolation



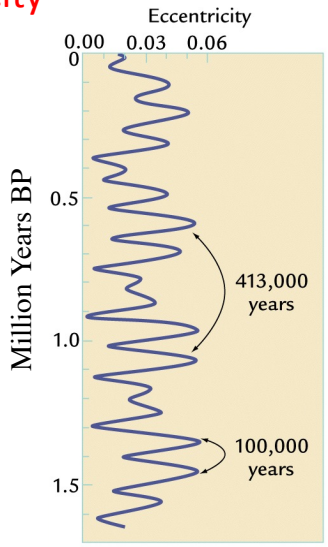
Orbital Variations and Insolation

Eccentricity



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

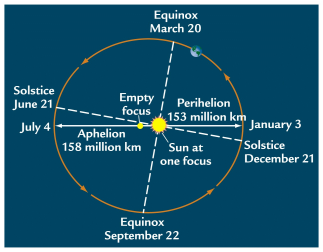
- Eccentricity
  $e = (a^2 + b^2)^{1/2} / a$
- e varies from 0.000 to 0.067 (currently 0.017) with four periods ranging from 95-131 kyr (100kyr) and at 413 kyr
- Slight change in global, annual average insolation (0.18%, or 5 Wm^{-2})



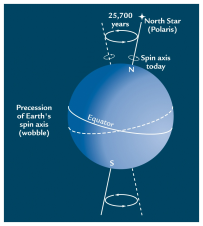
Orbital Variations and Insolation:

Precession

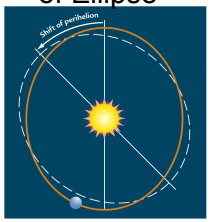
- Precession of Equinoxes is due to:
  - Wobble of Earth's axis of rotation around a line perpendicular to the Earth-Sun plane (21-26kyr)
  - Precession of the ellipse in absolute space
- Affects which calendar day the Earth is closest/farthest from the Sun
- *Modulates amplitude of seasonality at all latitudes, especially in the tropics*
- No effect on the annual mean insulation (anywhere)



Wobble



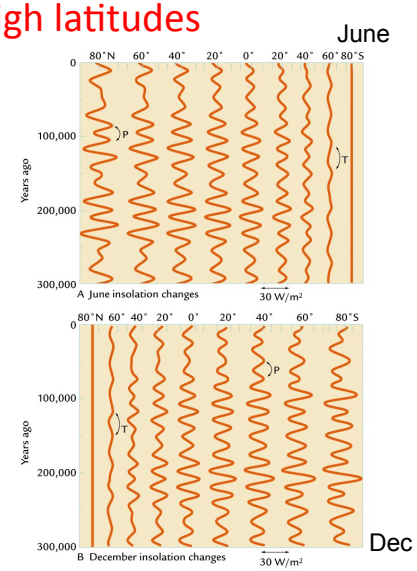
Precession of Ellipse



Orbital Variations and Insolation

Tropics vs. High latitudes

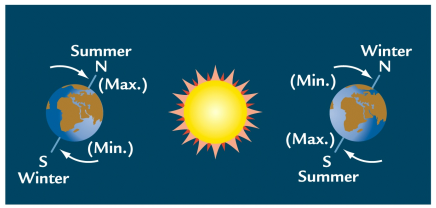
- In the tropics, seasonal insolation changes are predominately due to changes in precession (23kyr)
- In the high latitudes, seasonal changes in insolation are due to both tilt (41kyr) and precessional (23kyr) changes



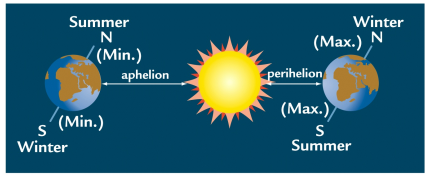
Orbital Variations and Insolation:

Phasing of Hemispheric Insolation

- Tilt changes causes changes in summer insolation that are in phase between the hemispheres. Ditto for winter.
- Precession changes causes changes in summer insolation that are out of phase between hemispheres. Ditto for winter



A Tilt



B Precession

Summary: orbital changes on insolation

- Amplitude of the seasonal cycle of TOA insolation:
  - For reference, today the seasonal cycle is +/- 150Wm^{-2} in the midlatitudes, and +/-15 Wm^{-2} in the tropics
  - The net effect of orbital changes on *seasonal* insolation is ~ +/- 30 Wm^{-2} in the midlatitudes and in the tropics.
  - Precession (23kyr) dominates in the tropics; Precession and tilt (41kyr) affect the high latitudes.

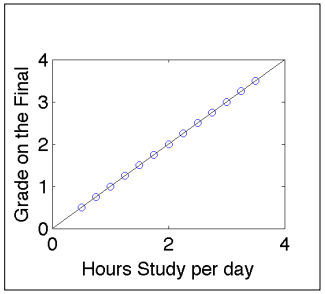
- Within a hemisphere: tilt and precession cause insolation changes in summer that are out of phase with those in winter (double whammy on ice volume).

- Hemispheric Synchroneity:
  - Tilt causes changes in summer insolation that are in phase between hemispheres. Ditto for winter.
  - Precession causes changes in summer insolation that are out of phase between hemispheres. Ditto for winter.

- Only eccentricity can change the global, annual average insolation (by about .18%, or 5 Wm^{-2}) .

Tool: Correlation Coefficient (r)…

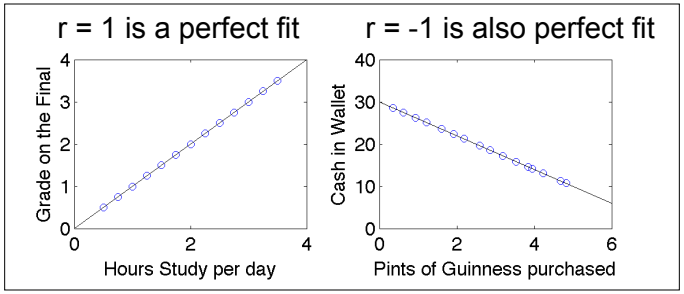
a measure of the goodness of a linear fit between two variables

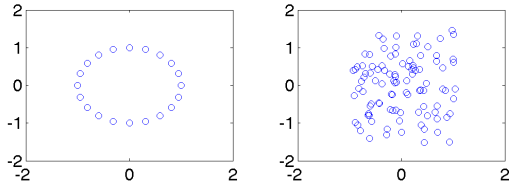


r = 1 is a perfect fit

Tool: Correlation Coefficient (r)…

a measure of the goodness of a linear fit between two variables

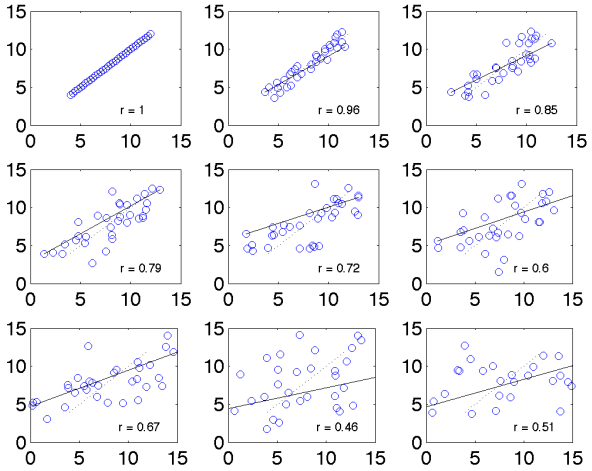




r = 0 means there is no (linear) relationship between the variables

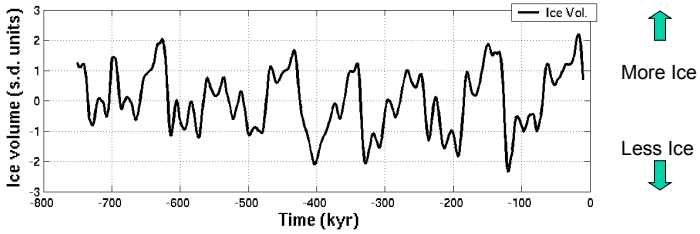
Tool: Correlation Coefficient (r)…

a measure of the goodness of a linear fit between two variables



| r | = 0.7 is an ok fit

The ice volume time series

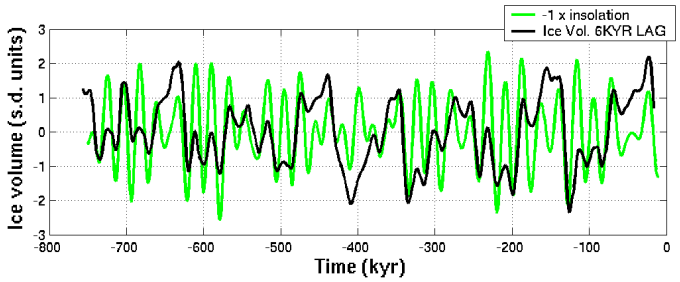


• the fraction of ^{18}O to ^{16}O in the shells of organisms preserved in deep sea sediment cores is proportional to ice volume

•Composite stack from ~ 20 sediment cores

Imbrie et al., 1984

Ice Sheet Growth versus High Latitude Solar



June 65N Insolation (upside down)

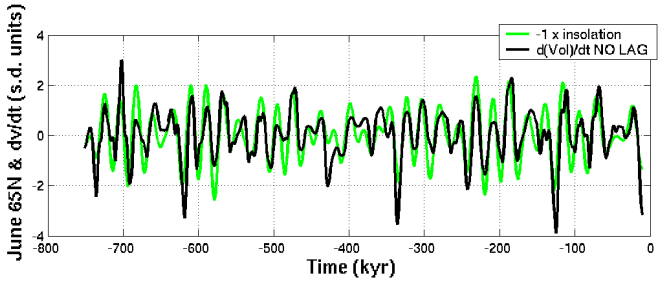
Global Ice Volume

• **maximum correlation of -0.4**
with a 6 kyr lag of ice volume behind insolation
(e.g., low insolation is followed by increased ice)

• more ~100 kyr variability in ice volume than in insolation

Roe 2005

Ice Sheet Growth versus High Latitude Solar



June 65N Insolation (upside down)

Rate of Change of Global Ice Volume

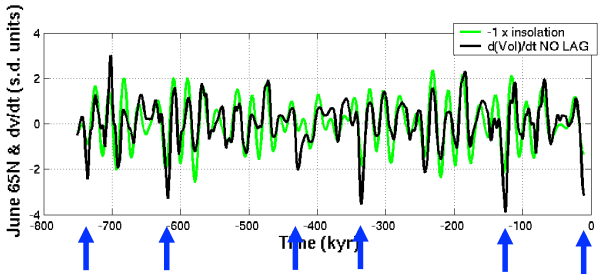
• *Rate of change of ice volume* is more directly related to high latitude NH summer insolation:

Correlation of -0.8 (at zero lag)

Roe 2005

Rate of change of ice volume

• Rate of change of ice volume more directly related to high latitude insolation



• Terminations coincide with insolation maxima - points to insolation trigger

• Major difference is large negative rates of ice change during major deglaciations

What do climate models say?

- Run a climate model (more later) using modern day forcing:
  - 360 ppm CO_2, today's insolation, today's land ice distribution, etc.
- Run a climate model using forcing associated with the Last Glacial Maximum (about 23 kyr ago):
  - 200 ppm CO_2, insolation and land ice distribution for 23kyr BP, etc.
- Take the difference (annual averaged over many years)

Surface Air Temperature: LGM minus Today

One Climate Model

Broccoli 2000

TABLE 2. Annually averaged surface air temperature difference (K)

	Global	Northern Hemisphere	Southern Hemisphere
Land and ocean	−4.0	−5.9	−2.1
Land only	−6.4	−7.9	−3.4
Ocean only	−2.7	−4.1	−1.8

Second Climate Model

Hewitt & Mitchell 1997

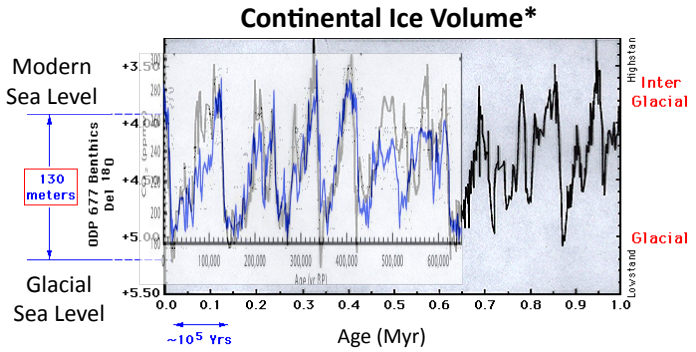
		Globe	N.Hemis	S.Hemis
Total	(simulated)	− 4.4	− 6.5	− 2.3
Topography and surface albedo	(simulated)	− 3.0	− 5.0	− 1.1
CO_2	(estimated)	− 1.4	− 1.6	− 1.2
Insolation	(simulated)	− 0.1	0.1	− 0.2
Total of rows 2, 3, 4		− 4.5	− 6.5	− 2.5

Ice Age Cycles: Some big solved problems

- Current climate is not the only possible one for Earth
  - indeed, glacial conditions seem to be preferred for the past 3Myr
- The ice Age Cycles wax and wane due to changes in the way the Earth Orbits the sun
  - Global climate and CO_2 are intimately intertwined, but CO_2 is acting as a feedback and not the driver of ice age cycles
- A change in global-mean surface temperature of about 4-5C is a massive climate shift
- If the orbital parameter theory is right, small triggers can produce major climate changes under some conditions

The Ice Age Cycles:
Some big unsolved questions

- Why is CO_2 so highly correlated with ice volume?



*Oxygen Isotope composition of benthic organisms preserved in ocean sediment cores

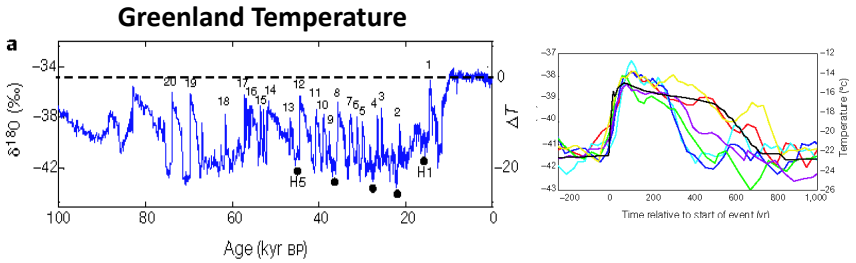
The Ice Age Cycles:
Some big unsolved questions

- Why is CO_2 so highly correlated with ice volume?
  - Simple but incomplete answer: colder water can "hold" more CO_2
- Are changes in CO_2 important for the ice ages?
  - They provide a weak positive feedback in the NH
  - What about the SH? Temperature at Vostok is ~ in sync with NH ice volume. But is ice volume in the southern hemisphere correlated with ice volume in the northern hemisphere throughout the ice ages?
- What causes the major deglaciations?
  - Much more ice is lost in the terminations of an ice age than would be expected by simple increases in summer insolation.

Abrupt Climate Change during the Last Glacial Period

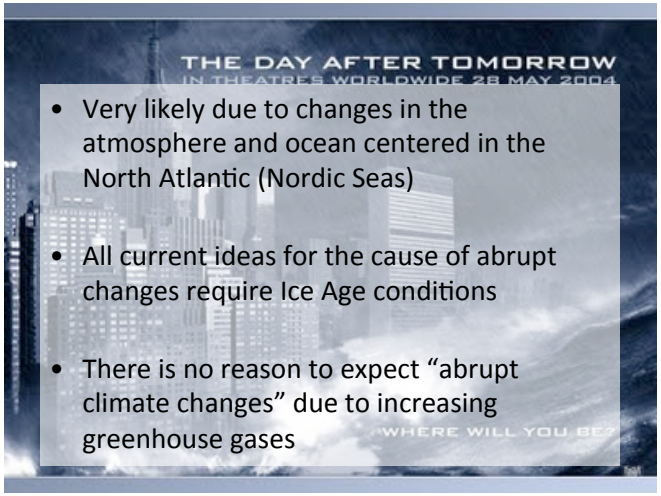
During Glacial stages, the climate system featured large rapid rearrangements.

Dansgaard/Oeschger (D/O) events show:



- Rapid onset of warming at Greenland (10 K in < 30 years!)
- Long-lived (~ 200 - 600 years) warm period, followed by slow decline back to cold conditions

Abrupt Climate Change during the Last Glacial Period



- Very likely due to changes in the atmosphere and ocean centered in the North Atlantic (Nordic Seas)
- All current ideas for the cause of abrupt changes require Ice Age conditions
- There is no reason to expect “abrupt climate changes” due to increasing greenhouse gases