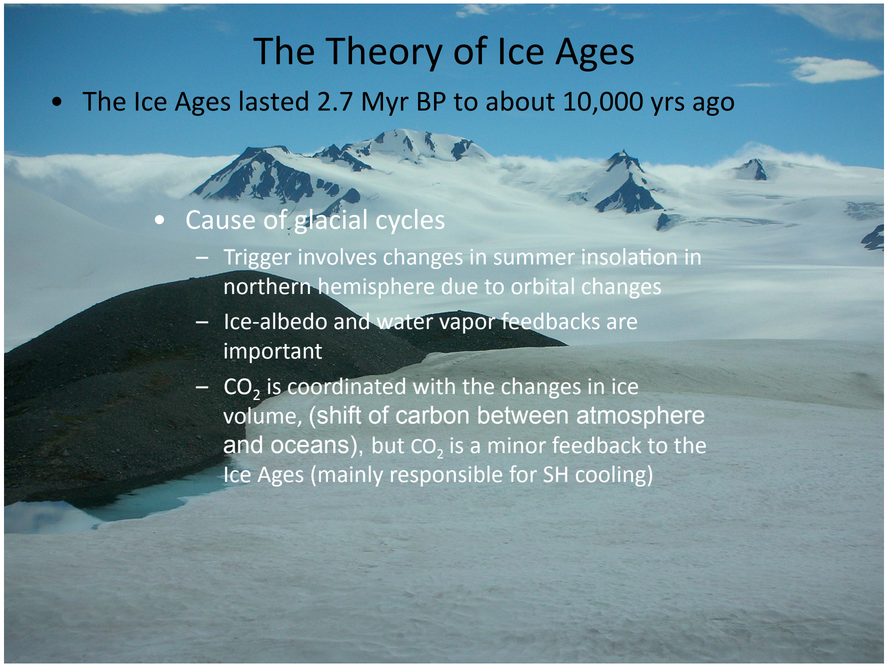
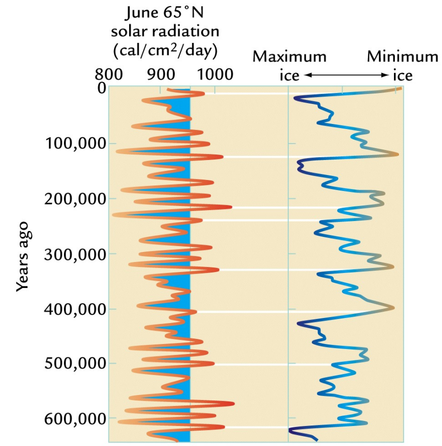


Theory of the Ice Ages:

Orbital induced insolation changes and global ice volume



"Strong insolation in NH summer causes rapid deglaciation"

Brief History of Orbital Theory of the Ice Age Cycles

- Agassiz (1840)
  - Summarized geologic evidence for an ice age
- Adhemar (1842)
  - First to attribute an ice age to orbital changes of Earth around Sun
  - Highlighted precession and # of hours of daylight
- Croll (1864)
  - Postulated *less* winter insolation was key to having an ice age: high eccentricity & winter hemisphere near aphelion (farthese from sun) promoted ice accumulation
  - Theory was dropped when prediction of timing of glacial conditions didn't match evidence
- Milankovitch (1911)

Milankovitch (1911)

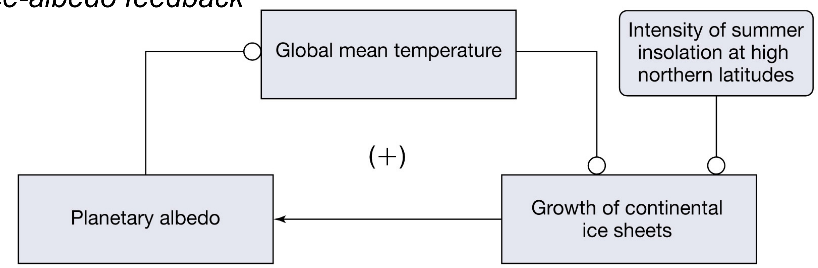
- Koppen suggested to M. that summer insolation was the key to the ice ages
  - Winter: too cold to get much accumulation
  - Summer: low-insulation summers produce less melt in Fall and Spring, allowing winter snow to persist.
- M. calculated summer insolation at 65N vs time
- At the time, proxy data did not support predicted timing of glacial vs interglacial conditions
- New data from ocean sediment cores (and new data methods) clearly showed the ice ages went in cycles, and matched pretty well with summer insolation at 65N

Reasons for Glacial Cycling

- Changes in solar input in the NH summer drive the ice age cycles (Kopen, Milankovitch)
  - Reduced summer insolation would mean less winter snow melt → would eventually grow ice sheets
  - Increased summer insolation → more snow melt → easier to shrink ice sheets
  - N. Hem. matters more b/c there's more land there
- Albedo and CO_2/methane are positive feedbacks
  - Play important role in setting amplitude of changes

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.

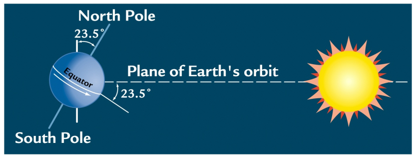
Ice Albedo Feedback

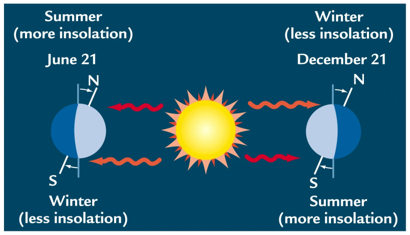
- Probably important for the climate changes in the northern hemisphere during ice age cycles
  - Ice sheets that extend far south into the northern midlatitudes reflect significant sunlight (change the planetary albedo from 0.30 today to 0.32 at the LGM)
- Contrary to popular belief, ice-*albedo* feedback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

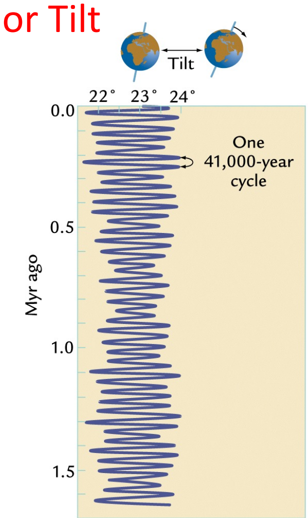




Orbital Variations and Insolation

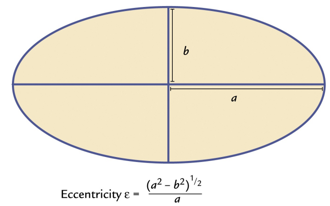
Obliquity or Tilt

- 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
  - Winter & summer insolation anticorrelated (good for Milankovitch's theory)
  - Impacts annual mean insolation at a given latitude
- To fix ideas: in NH high latitudes, less tilt means less summer insolation, more winter insolation and less annual averaged insolation (favors glaciation)
- Variations in tilt angle have no impact on *global* average insolation

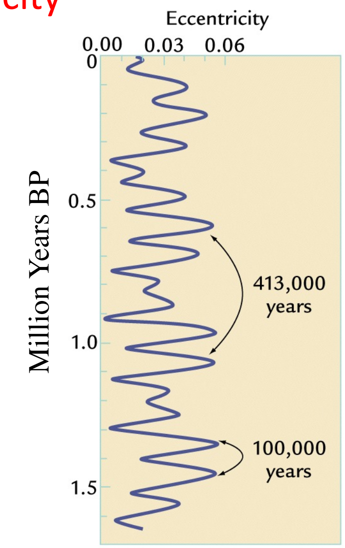


Orbital Variations and Insolation

Eccentricity



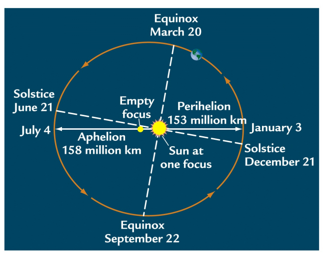
- Eccentricity
  e = $(a^2 + b^2)^{1/2}/a$
- e varies from 0.000 to 0.067 (currently 0.017) with four periods ranging from 95-131 kyr (100kyr) to 413 kyr
- Slight change in global, annual average insolation (0.18%, or 5 Wm^{-2})



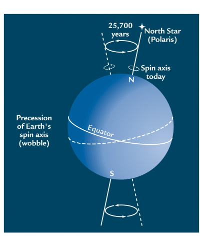
Orbital Variations and Insolation:

Precession

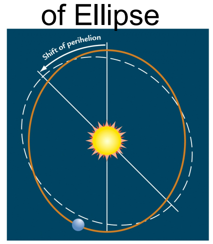
- Precession of Equinoxes is due to:
  - Wobble of Earth's axis of rotation around a line perpendicular to the Earth-Sun plane (21-26kyr)
  - Affects which calendar day the Earth is closest/farthest from the Sun
- *Modulates amplitude of seasonality at all latitudes, especially in the tropics*
- No effect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



Wobble



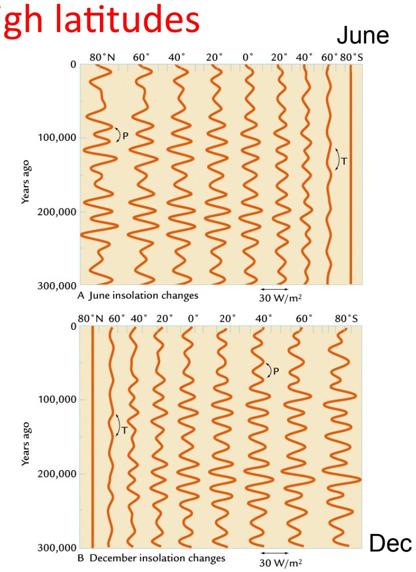
Precession of Ellipse



Orbital Variations and Insolation

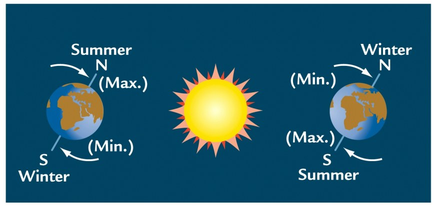
Tropics vs. High latitudes

- 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

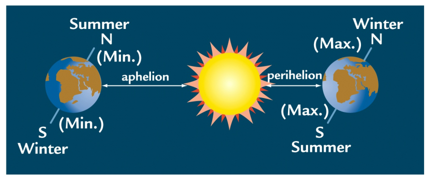


Orbital Variations and Insolation:
Phasing of Hemispheric Insolation

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



A Tilt



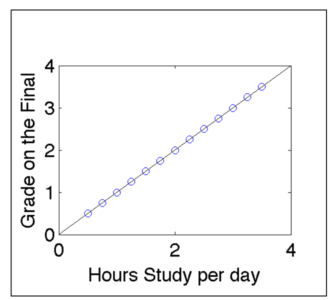
B Precession

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)…

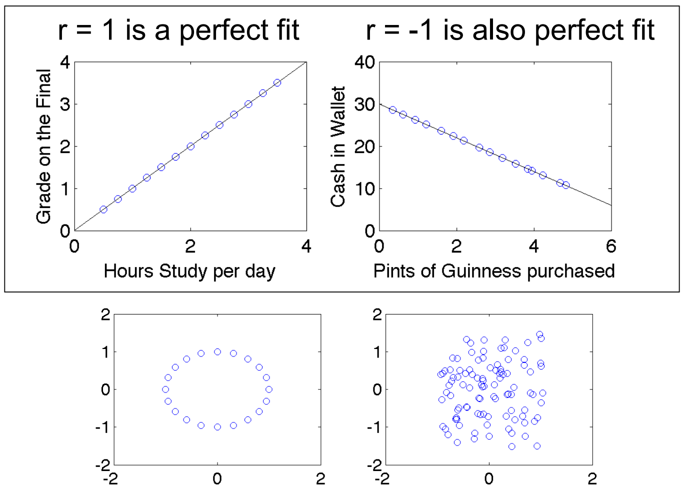
a measure of the goodness of a linear fit between two variables



r = 1 is a perfect fit

Tool: Correlation Coefficient (r)…

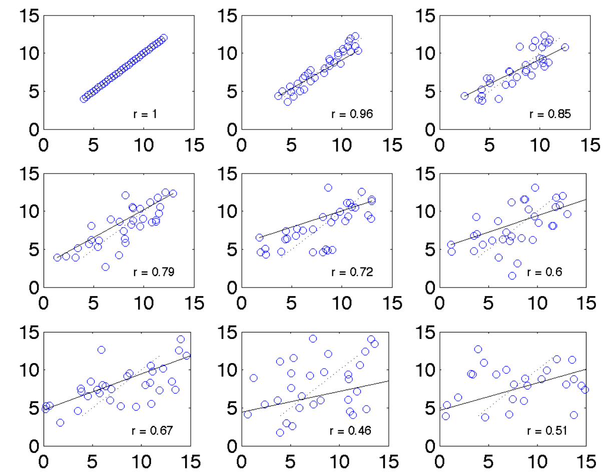
a measure of the goodness of a linear fit between two variables



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

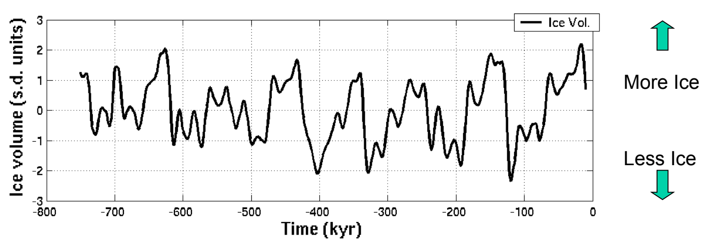
Tool: Correlation Coefficient (r)…

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



| r | = 0.7 is an ok fit

The ice volume time series

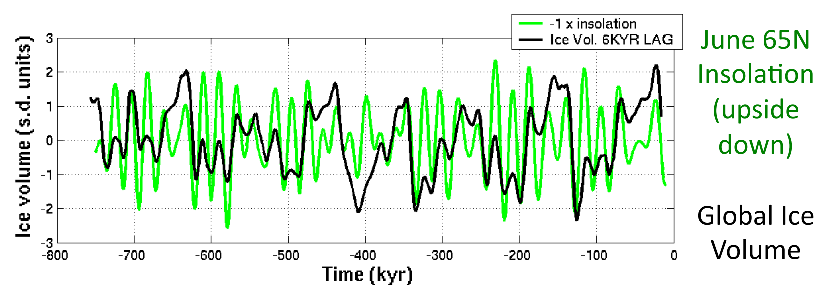


- the fraction of ^{18}O to ^{16}O in the shells of organisms preserved in deep sea sediment cores is proportional to ice volume

- Composite stack from ~ 20 sediment cores

Imbrie et al., 1984

Ice Sheet Growth versus High Latitude Solar



- **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