

The Ice Ages

- The Ice Ages lasted 2.7 Myr BP to about 10,000 yrs ago

- Large Ice sheets covered Northwestern Europe and Northern North America
- Due to orbitally induced changes in northern hemisphere summer insolation
 - Ice volume changes are coordinated with CO₂ changes (shift of carbon between atmosphere and oceans)

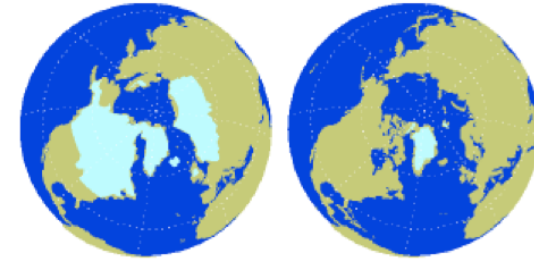
Geologic Evidence For the Ice Ages

- Moraines, erratics, pollen records, etc
- Ocean sediments
 - Oxygen Isotopes in shells of organism in deep sea provide evidence of glacial ice amount
 - Waxing and waning of ice corresponds to changes in insolation (orbit around sun)
- Ice core records
 - Oxygen isotopes record local temperature
 - Air bubbles provide record of CO₂ and other gases
 - Remarkable correlation between local temperature and CO₂
- Cause of glacial cycles
 - Trigger involves changes in summer insolation in northern hemisphere due to orbital changes
 - Ice-albedo and water vapor feedbacks are important
 - CO₂ is coordinated with the changes in ice volume, but it is a minor feedback to the Ice Ages (mainly responsible for SH cooling)

What does an ice age look like?

Last Glacial Maximum Conditions

- Ice sheet extent:
 - Over Canada, this ice sheet was up to 5 km thick
 - Global sea level was **125 meters lower** than today!
 - Greenland 25°C colder, tropics 4°C colder



Last Glacial Maximum

Present

Vocabulary: Isotopes

an atom (or element) is defined by number of protons

H(1), C(6), O(8), Pb(82)

atomic mass: number of protons plus neutrons

H normally 1+0 = 1

C normally 6+6 = 12

O normally 8+8 = 16

isotope: same element, different atomic mass

>> that is, different number of neutrons

¹H (normal), ²H (deuterium), ³H (tritium; radioactive)

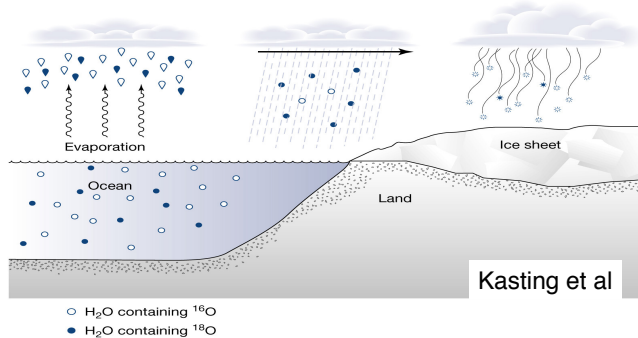
¹²C (normal), ¹³C, ¹⁴C (radioactive)

¹⁶O (normal), ¹⁸O

Isotopic Evidence

^{16}O vs ^{18}O
 "light" (normal) "heavy"

- evaporation selects for "light"
- condensation (precipitation) selects for "heavy"

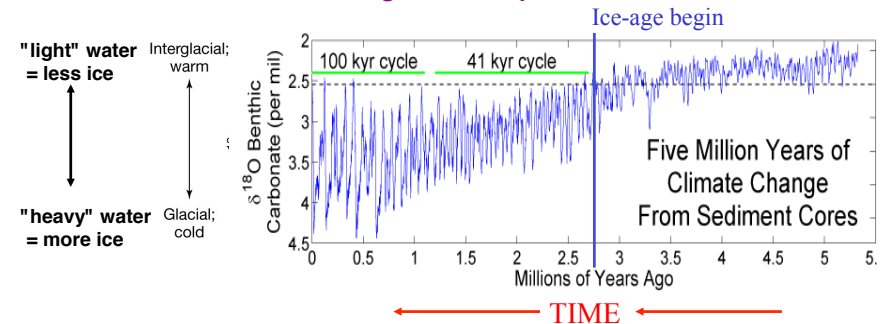


^{18}O in ocean sediments records glacial ice volume: More "light" water in ice-sheets means remaining ocean water is "heavier".

^{18}O in ice-cores indicates local temperature: Colder conditions means more precipitation en route so "lighter" snow.

3 Million Year Record of Global Ice Volume

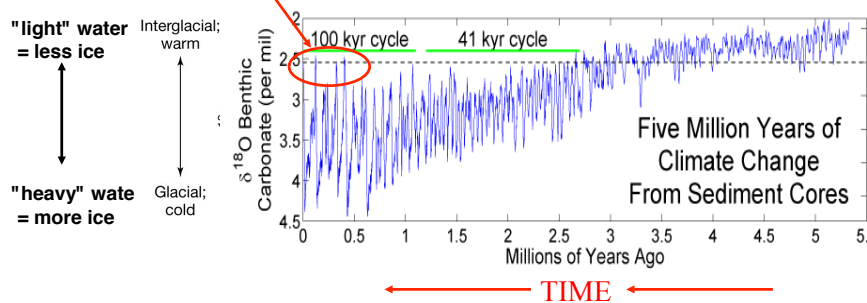
Oxygen Isotope Concentration in Shells of Organisms Growing in the Deep Ocean



- Early on, 40,000 year cycles dominated
 - Obliquity having a direct effect
- More recently, 100,000 year cycles have been most prevalent

3 Million Year Record of Global Ice Volume

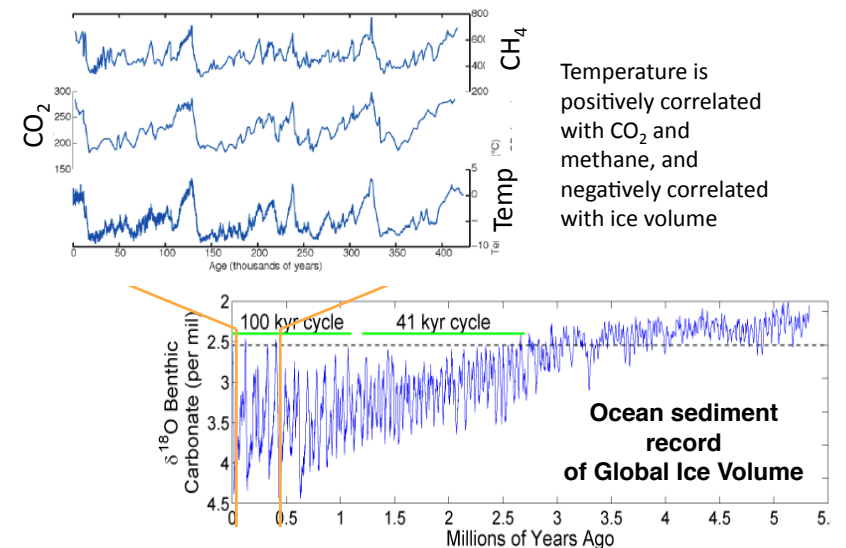
Short (10,000 yr) Warm Episodes



Kasting et al

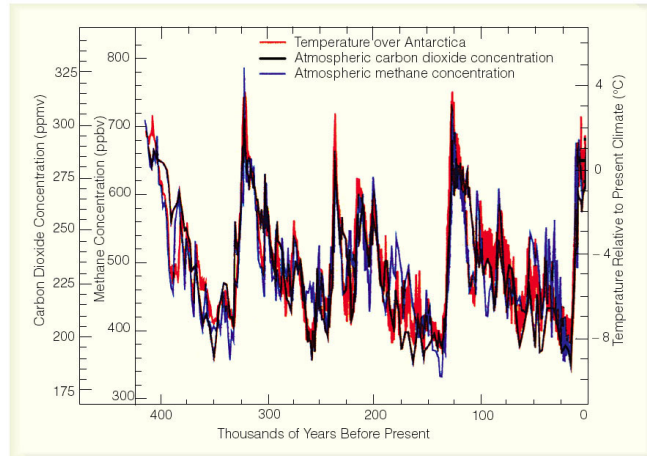
CO_2^* , CH_4^* and Temperature in Vostock Antarctica

* CO_2 and CH_4 are well mixed in the atmosphere, so this is also a global record of CO_2 & CH_4



CO₂*, CH₄* and Temperature in Vostock Antarctica

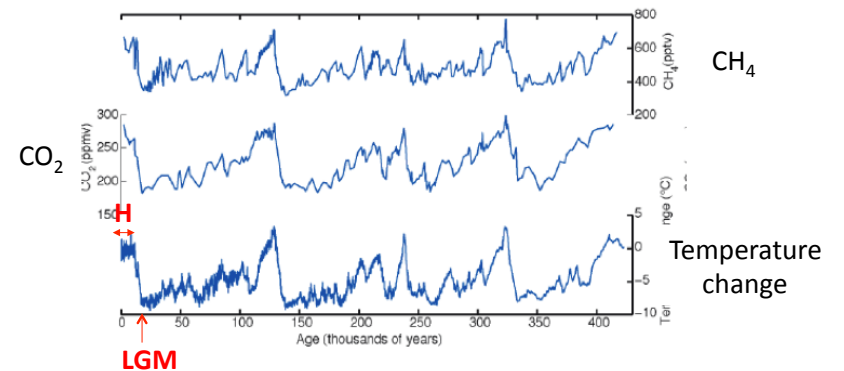
*CO₂ and CH₄ are well mixed in the atmosphere, so this is also a global record of CO₂ & CH₄



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Temperature is positively correlated with CO₂ and methane, and negatively correlated with ice volume

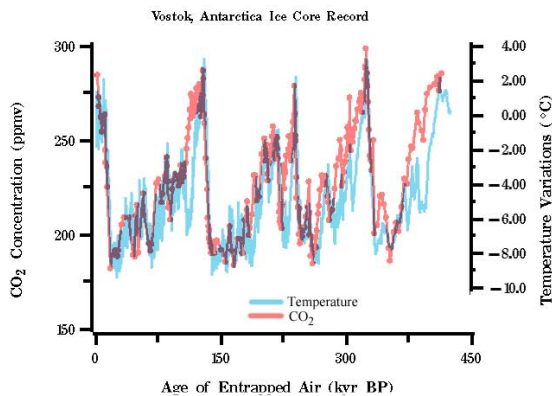
CO₂*, CH₄* and Temperature in Vostock Antarctica



- Starting about 1,000,000 yrs ago, roughly 100,000 year cycles
 - Much more rapid warming, slow & steady cooling
 - Most recent glacial period terminated at the “Last Glacial Maximum” (LGM), 20k yrs ago
 - Holocene (H) started ~ 10k yrs ago

CO₂* and Temperature in Vostock Antarctica

*CO₂ is well mixed in the atmosphere, so this is also a measure of CO₂ everywhere



Source: Jean-Marc Barnola et al. Petit et al.

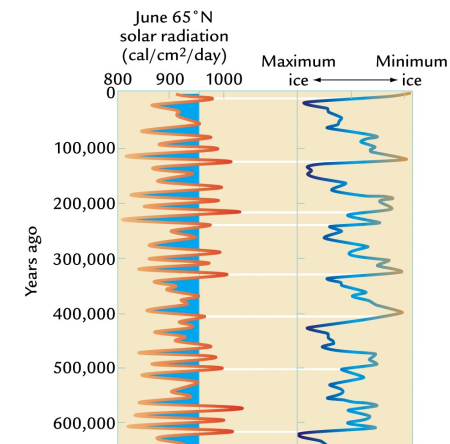
Temperature is highly correlated with CO₂ (and negatively correlated with ice volume)

LGM CO₂ = 180 ppm, preindustrial CO₂ = 280 ppm, current CO₂ = 392 ppm)

Changes in temperature/ice extent lead CO₂ changes slightly

Theory of the Ice Ages:

Orbital induced insolation changes and global ice volume



“Strong summer insolation peaks pace 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 promoted ice accumulation
 - Theory dropped when prediction of timing of glacial conditions didn't match evidence
- Milankovitch (1911)

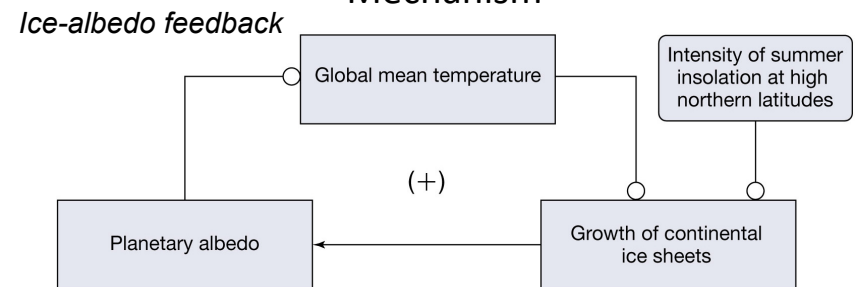
Milankovitch (1911)

- Koppen suggested to M. that summer insolation was the key to the ice ages
 - Winter: too cold to get much accumulation
 - Summer: low-insolation 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 CO₂/methane are positive feedbacks
 - Play important role in setting amplitude of changes

Orbital Theory: Trigger and Feedback Mechanism



Trigger 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. CO₂ and CH₄) seem to be involved.