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 CO$_2$ changes (shift of carbon between atmosphere and oceans)

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

Geologic Evidence For the Ice Ages

- Moraines, erratic, pollen records, etc
- Ocean sediments
  - Oxygen Isotopes in shells of organisms in deep sea provide evidence of glacial ice amount
  - Waxes and wanes of ice correspond to changes in insolation (orbit around sun)
- Ice core records
  - Oxygen isotopes record local temperature
  - Air bubbles provide record of CO$_2$ and other gases
  - Remarkable correlation between local temperature and CO$_2$
- 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
  - CO$_2$ is coordinated with the changes in ice volume, but it is a minor feedback to the Ice Ages (mainly responsible for SH cooling)

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
  - $^1$H (normal), $^2$H (deuterium), $^3$H (tritium; radioactive)
  - $^{12}$C (normal), $^{13}$C, $^{14}$C (radioactive)
  - $^{16}$O (normal), $^{18}$O
**Isotopic Evidence**

- $^{16}\text{O}$ vs $^{18}\text{O}$
  - "light" (normal)
  - "heavy"
- Evaporation selects for "light"
- Condensation (precipitation) selects for "heavy"

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

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

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**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

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**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$_4$.

Temperature is positively correlated with CO$_2$ and methane, and negatively correlated with ice volume.
**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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**Theory of the Ice Ages:**

Orbital induced insolation changes and global ice volume

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**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

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“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)

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
    \( \rightarrow \) would eventually grow ice sheets
  - Increased summer insolation \( \rightarrow \) more snow melt \( \rightarrow \) easier to shrink ice sheets
  - N. Hem. matters more b/c there’s more land there

- Albedo and CO\textsubscript{2}/methane are positive feedbacks
  - Play important role in setting amplitude of changes

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

Orbital Theory: Trigger and Feedback Mechanism

Ice-albedo feedback

- Global mean temperature
  - Intensity of summer insolation at high northern latitudes

- Planetary albedo
  - Growth of continental ice sheets

   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. CO\textsubscript{2} and CH\textsubscript{4}) seem to be involved.