Pleistocene Ice Age Cycles 0-2.65 ma

12.842 Lecture 7 Fall 2008

Some images have been removed in this lecture notes due to copyright restrictions.
Pleistocene Glaciations

Image courtesy of NOAA.

• Urey (1947) calculated that the oxygen isotope fractionation between calcium carbonate and water should be temperature-dependent.

\[
\delta^{18}O = 1000 \left[ \frac{R_{\text{sample}}}{R_{\text{std}}} - 1 \right]
\]

• Epstein (1953) grew molluscs in the laboratory and empirically determined the O18-T relationship:

Isotopic temperature scale and original data points of Epstein et al. (1953). Temperature is in degrees Celsius. The \( \delta \) values are the \( \delta \)-corrected values, which are equal to \( \delta_c - \delta_w \). After Epstein et al. (1953).
• Emiliani (1955 and other papers) analyzed foraminifera from piston cores from the deep sea, and made temperature estimates:

• He found multiple cycles of cold and warm periods during the past ~500,000 years.

2. This work created quite a stir, and quickly was criticized on several grounds:
   a. It violated the prevailing 4-ice-age theory from continental geology.
   b. Meteorologists though that the tropical temperature change seemed excessive.
   c. Micropaleontologists thought that their micropaleontological work (G. menardii stratigraphy) contradicted with O-18 record.
   d. Biologists (e.g. Bé) argued that foraminiferal ecological shifts may have altered the depth habitat of organisms (and hence temperatures).
   e. The time scale (based on $^{230}$Th/$^{231}$Pa) was criticized.
   f. Various statistical errors were pointed out.
Rayleigh distillation of oxygen isotopes

Vapor pressure = \( f(T) \)
(Clausius-Clapeyron equation, exponential with increasing \( T \))

At 25°C, the vapor pressure of \( \text{H}_2\text{^{16}O} \) is 0.9% higher than \( \text{H}_2\text{^{18}O} \)

Imagine a 50-50 mixture of liquid \( \text{H}_2\text{^{16}O} \) and \( \text{H}_2\text{^{18}O} \), equilibrated with the vapor phase at 25°C. Separate the vapor from the liquid:

Cool the vapor to 20°C; allow liquid to condense from vapor:

Rayleigh equation: \( \frac{R}{R_0} = f^{\alpha-1} \)

\( R_0 \) = initial isotope ratio
\( R \) = isotope ratio after cooling
\( f \) = fraction of water condensed
\( \alpha \) = isotope fractionation factor

\( \delta^{18}\text{O} = -9\% \)

<table>
<thead>
<tr>
<th>( \text{H}_2\text{^{16}O} )</th>
<th>( \text{H}_2\text{^{18}O} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1009</td>
<td>1000</td>
</tr>
</tbody>
</table>

\( \delta^{18}\text{O} = -11\% \)

<table>
<thead>
<tr>
<th>( \text{H}_2\text{^{16}O} )</th>
<th>( \text{H}_2\text{^{18}O} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>745</td>
<td>737</td>
</tr>
</tbody>
</table>

\( R_0 = \frac{264}{263} \)

\( 745 \times 263 = 737 \times 264 \)
Cumulative Rayleigh Isotope Distillation as a function of temperature

\[ \delta^{18}O \text{ in cloud vapor and condensate plotted as a function of the remaining vapor in the cloud for a Rayleigh process. The temperature of the cloud in degrees Celsius is shown on the lower axis. } \delta^{18}O \text{ values are relative to SMOW. The increase in fractionation with decreasing temperature is taken into account. After Dansgaard (1964).} \]

Figure by MIT OpenCourseWare.
Observed $\delta^{18}\text{O} -$ surface temperature relationship

Note: this line is not the relationship predicted by the Rayleigh distillation curve. It includes many other effects: evaporation-precipitation cycles, cloud-T / surface-T relationships; multiple sources of water vapor at different temperatures, etc.

Mean annual $\delta^{18}\text{O}$ of precipitation as a function of the mean annual air temperature at the earth's surface. Note that $\delta^{18}\text{O}$ values are progressively lighter as the mean annual temperature becomes lower. After Dansgaard (1964).

Figure by MIT OpenCourseWare.
Because they flow, glaciers are filled from their summits:

Vertical cross section of an ice sheet resting on a horizontal subsurface. Ice particles deposited on the snow surface will follow lines that travel closer to the base the farther inland the site deposition. An ice mass formed around the divide (I-I) will be plastically deformed (thinned) with depth as suggested by the lined areas. The dashed curve along the vertical ice core (C-C) shows the calculated horizontal velocity profile $V_x$ (Weertman 1968b). The horizontal arrows along C-C show the adopted approximation to $V_x$ (Dansgaard et al. 1969).

Figure by MIT OpenCourseWare.
Effect of glaciation on the oxygen isotope composition of the ocean

Modern Ocean

Continent

Ocean

$\delta^{18}O = 0\%$

Last Glacial Maximum
(18,000 years Before Present)

Continent

Ocean

Ice

$\delta^{18}O = -30\%$

$\delta^{18}O = +1.1\%$

120 m

Isotope Mass Balance Equation:

$M_o \delta_o + M_i \delta_i = M_t \delta_t$
Sea-level estimates from drilling submerged coral terraces

"Fairwards" Sea Level Curve

- New Guinea
- Barbados
- Caribbean Islands

Age, radiocarbon kyr

Depth below modern Sea Level, m

Age, calendar kyr.
Earth’s Orbital Geometry:
The Milankovitch Hypothesis & the Pacing of Pleistocene Ice Ages
Milankovitch Hypothesis: Historical Perspective

*What:* Astronomical theory of Pleistocene ice ages.

*How:* Varying orbital geometry influences climate by changing seasonal & latitudinal distribution of solar radiation incident at top of atmosphere (insolation).

*Milestones: Hypothesis*

- **Croll (1864, 1875):** Proposed that variations in seasonal influx of energy—the cumulative affect of eccentricity, obliquity & precession—could trigger large climate response.

- **Milankovitch (1920, 1941):** Combined laws of radiation with planetary mechanics to derive insolation curves as function of time (600 kyr) and latitude. Concluded summer insolation at high N. lat. (65°N) critical to growth/decay of ice sheets. "The Milankovitch Hypothesis".
The Seasons

(northern summer) (northern winter)

(edge view)
The seasons in an elliptical orbit

(oblique view, exaggerated eccentricity)
Eccentricity of Present Earth Orbit Around Sun (to Scale)

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

\[ e = \frac{c}{a} = \sqrt{1 - \frac{a^2}{b^2}} \]
Precession of elliptical orbit (with respect to fixed stars)
Obliquity (tilt)

Obliquity varies between ~21.8° and 24.4°; at present the obliquity is 23.44°. Affects the latitude of the tropics and the arctic circle. Period is ~41,000 years, and is relatively regular. Think of this as part of a solar system angular momentum oscillator (angular momentum conserved in solar system, but with transfers between objects).

Higher obliquity leads to higher summer insolation at high latitudes (and slightly less at low latitudes).
Obliquity change re-apportions radiation between polar regions and tropics.
Precession

Precession frequency depends on angular momentum and torque

\[ P = 25,700 \text{ years} \]

Eccentricity amplitude-modulates precession parameter

Fig. 2.10. Precession parameter \( p \) and eccentricity.

\[ p = e \sin \omega \]

\( \omega \) between Spring Equinox + perihelion
Precession influence on climate: why 23,000 years not 25,800?

Initial state:

Northern Summer

Northern Winter

~22,000 years later:

Northern Summer

Northern Winter

Earth’s axis has precessed 22/26 of a cycle, and the eccentricity of the orbit has precessed “backwards” 4/26 of a cycle, bringing us back to a configuration which is equivalent in terms of radiation.
Eccentricity amplitude-modulates precession

Fig. 2.10. Precession parameter $p$ and eccentricity.

$p = e \sin \omega$

$\gamma \angle$ between Spring solstice and perihelion
Periodic changes in orbital geometry modulate solar radiation receipts (insolation)
Insolation at 65°N, June 21

Note: integrated over a full summer-centered half year, the effect of obliquity is much stronger than in this single-day series.
Integrated over a half-year centered on summer, obliquity dominates high latitude insolation and precession dominates lower latitude insolation.
Did increasing Northern Hemisphere summer insolation cause the end of the last ice age?
Milankovitch Hypothesis: Milestones & Support

- **Kullenberg (1947):** Invented deep-sea piston coring.  
  ➔ Recovery of long, continuous climate records possible.

- **Emiliani (1955):** Pioneered use $^{18}$O/$^{16}$O ratio of fossil foraminifera in sediment cores as climate (temp.) proxy.

- **Olausson (1965); Shackleton (1967):** Interpret foram $\delta^{18}$O changes as whole-ocean isotopic shifts caused by ice sheet growth/decay.

- **1960's:** Recognition of magnetic stripes on ocean floor (geomagnetic field reversals) as global stratigraphic markers.

- **Johnson (1982); Shackleton et al (1990):** Use astronomically-driven insolation variations (E, T, P) to derive timescales for deep-sea cores.  
  ➔ Accurately predict age of Brunhes-Matuyama (B/M) magnetic reversal, 780-790 kyr BP. (K/Ar dates for B/M incorrectly placed it at 730 kyr BP.)

- **Baksi et al (1992):** $^{40}$Ar/$^{39}$Ar date for B/M = 783 kyr BP.

- **Raymo (1997):** Multiple $\delta^{18}$O records on 'simple' timescale supports link between N. Hemisphere summer insolation and glacial terminations.

  ➔ Strong support for astronomical influence on climate.  
  (The magnitude of which remains debated…)
Absolute chronology and its importance to testing the Milankovitch Hypothesis

• Carbon-14 dating: 0-25 kyr BP (where reliable “initial C14” calibrations exist)

• Layer counting in sediments and ice cores: 0-40 kyr BP varves, density bands, annual dust cycles (but do you miss some bands or see two where only one should be?)

• $^{234}$U -> $^{230}$Th ingrowth in corals and speleothems: 0-250,000 kyr BP

• $^{40}$K -> $^{40}$Ar dating of basalts at magnetic reversals
How do we estimate a time scale for a marine sediment core or ice core?

- We measure depth and assume it is an increasing function of the age of the deposit (stratigraphy).
- For sediments <25 kyr BP containing appropriate carbonate or organic) fossils, we can measure the $^{14}$C content and determine the age from the atmospheric radicarbon calibration.
- We can determine the $\delta^{18}$O of carbonate fossils and correlate the features to sea level events of known age (from $^{230}$Th-$^{234}$U dating).
- For sediments with appropriate magnetic minerals, we can measure the magnetic alignment and determine the position of known ($^{40}$Ar/$^{39}$Ar dated) magnetic reversals.
- In-between these known dates, we must interpolate using some plausible (but unprovable) scheme.
V19-30 (Shackleton and Pisias, 1984)
Oxygen isotopes compared to summer insolation at 65°N
SPECMAP stack. Note terminations (rapid deglaciations)

Image removed due to copyright restrictions.

Citation: Figure 5. Berger, Andre L. *Milankovitch and Climate*. Kluwer Academic Publishers, June 1984, 544 pages. ISBN: 902771777X.
Milankovitch Hypothesis Challenges:

100-kyr Cycle Problems

1. Why is climate response in 100-kyr band so strong?
   
   **Observation:** High correlation of $\delta^{18}$O cycles with astronomically-driven radiation cycles at E, T & P frequencies suggests causal link in all 3 bands.

   **Problem:** Amplitude of insolation change (~0.2%) is ~10x smaller than in T,P bands.

   **Possible Solution:** E modulates climatic effect of P. High E favors NH glaciation when P causes NH summer to occur at maximum Earth-Sun distance (i.e., Imbrie et al, 1993).

2. Why do glacial cycles switch from 41-kyr to 100-kyr period ~700 kyr BP?
   
   **Possible solution:** L/T cooling trend, perhaps from tectonically-driven decrease in atmospheric CO$_2$, facilitates NH ice sheet growth beyond a critical threshold during insolation minima. These large ice sheets drive climate through feedbacks internal to the climate system (geo-, cryo-, atmo-, hydro-sphere).

3. Why do full glacial Terminations, and ensuing interglacial periods, occur ~430 and ~15 kyr BP when E is very low?
   
   - **Possible solution:** 100-kyr cycle of orbital inclination (Muller and MacDonald, 1995).

   - **Caveat:** no obvious mechanism linking climate to inclination.
Pleistocene Ice Age Cycles

Image removed due to copyright restrictions.
Citation: Raymo, M. E., W. F. Ruddiman, N. J. Shackleton, and D. W. Oppo.

*Evolution of Atlantic-Pacific δ¹³C gradients over the last 2.5 m.y.* EPSL 97 (1990): 353-368.
Earth’s orbit also oscillates in and out of orbital plane every ~100 kyr.

Image removed due to copyright restrictions.
1. Why is climate response in 100-kyr band so strong?
   
   **Observation:** High correlation of $\delta^{18}O$ cycles with
   astronomically-driven radiation cycles at E, T & P
   frequencies suggests causal link in all 3 bands.

   **Problem:** Amplitude of insolation change ($\sim 0.2\%$) is
   $\sim 10x$ smaller than in T,P bands.

   **Possible Solution:** E modulates climatic effect of P.
   High E favors NH glaciation when P causes NH summer to occur at maximum Earth-Sun distance (i.e.,
   Imbrie et al, 1993).

2. Why do glacial cycles switch from 41-kyr to 100-kyr
   period $\sim 700$ kyr BP?

   **Possible solution:** L/T cooling trend, perhaps from
   tectonically-driven decrease in atmospheric CO$_2$,
   facilitates NH ice sheet growth beyond a critical
   threshold during insolation minima. These large ice
   sheets drive climate through feedbacks internal to the
   climate system (geo-, cryo-, atmo-, hydro-sphere).

3. Why do full glacial Terminations, and ensuing
   interglacial periods, occur $\sim 430$ and $\sim 15$ kyr BP when E is
   very low?

   - **Possible solution:** 100-kyr cycle of orbital
     inclination (Muller and MacDonald, 1995).

   - **Caveat:** no obvious mechanism linking climate to
     inclination.