Climate on Geologic Time Scales & The CO$_2$-Climate Connection
Paleoclimate: outline

• Incoming and outgoing radiation balance; greenhouse effect
• Faint Young Sun Paradox
• Global carbon cycle
• Weathering and “reverse weathering”
• Snowball earth climate considerations: can the earth escape from a snowball?

• Climate change examples:
  – Permo-Carboniferous glaciations
    • Continental arrangement
    • Land Plants and carbon cycle
  – Mesozoic warmth:
    • warmer equator, decreased equator-pole temperature gradient, ?higher CO$_2$?
  – Cenozoic cooling
    • ? Lower CO$_2$? (early maybe, but not later). Roles of mountain uplift, weathering, seafloor spreading rates?
  – Pleistocene glaciation cycles
    • Oxygen isotope paleoclimatology
    • Milankovitch insolation cycles
    • Ice cores and greenhouse gas changes
    • Abrupt climate change
Where We’ve Been & Where We Will Go

- Reviewed what processes control CO₂ greenhouse effect over geologic time (i.e., geochem. C cycle).
- And what negative feedbacks (e.g., T-weathering, CO₂-weathering) might keep climate system from reaching &/or remaining in extreme states (e.g., Venus).
- But data (geologic evidence) to support the theory (strong control of climate by CO₂) is lacking*.
- Now turn to geologic evidence for CO₂-climate link during last 500 Myr.

* Prior to ~550 Ma the lack of animals with hard skeletons and vascular plants to date has resulted in little or no fossil evidence of atmospheric CO₂ levels.
Correlation does not require Causation

Figure by MIT OCW.
Low (CO$_2$+S) = Glaciation?

Atmospheric CO$_2$ estimates for the Phanerozoic (540-0 Ma)

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Please see Figure 14.1 from Crowley, T. J. “Carbon Dioxide and Phanerozoic Climate: An Overview.” In Warm Climates in Earth History. Edited by B. T. Huber, K. G. MacLeod, and S. L. Wing. Cambridge, England: Cambridge University Press, 2000.
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Permo-Carboniferrous Glaciations (~300-275 Ma)

Phanerozoic CO$_2$ Evolution

Permo-Carboniferous Glaciations Followed a period of marked CO$_2$ decline

- The CO$_2$ decline likely resulted from the spread of rooted vascular plants in the Devonian, 400-360 Ma.

- Dissolution of bedrock (weathering) from: secreted acids, metabolic CO$_2$ from C$_{org}$ decomposition, & anchoring of clay-rich soil to rock (which retains water).
Phanerozoic CO$_2$ Evolution

Image removed due to copyright restrictions.

Please see Fig. 1 in Berner, Robert A. “The Rise of Plants and Their Effect on Weathering and Atmospheric CO2.” Science 276 (April 1997): 544-547.
C_{org} burial rate estimated from $\delta^{13}C$ in CaCO$_3$

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Please see Fig. 10-9 in Stanley (course text).

Atmospheric O$_2$ estimated from $C_{org}$ burial rate
Low CO$_2$ during Permo-Carboniferous Glaciations Resulted from Massive Burial of C$_{org}$

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High $C_{org}$ Burial Results in High $^{13}C/^{12}C$ in Seawater & CaCO$_3$

On longer time scales, higher burial rates of C, relative to weathering rates, results in elevated $^{13}C/^{12}C$ in atmos./ocean
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- Ferns & alligators in Siberia
- Dinosaur bones in AK (N of Arctic Circle)

Mesozoic Warmth

Jurassic 220-140 Ma

Cretaceous 140-65 Ma

Figures by MIT OCW, adapted from Wikimedia Commons images by ArthurWeasley, Konrad Roeder, and public sources.
20°-60° Warmer at Poles!

2°-6° Warmer at Equator

Decreased Equator-to-Pole Temperature Gradient

Image removed due to copyright restrictions.

Please see Fig. 8-15 in Kump, L. R. et al. The Earth System. Upper Saddle River, NJ: Prentice Hall, 1999.
How to increase polar temperatures? - not so easy

(1) By removing polar ice, the “ice-albedo feedback” is reduced - but this isn’t sufficient.
(2) Increased transport of heat by atmosphere to poles? - this is difficult because heat-transporting eddies are less effective as the equator-pole temperature gradient decreases.
(3) Increased transport of heat by ocean to poles? Also problematical…
(4) Increased polar cloudiness? This could help hold in surface heat, but what keeps the clouds there? Methane? Atmospheric convection?
Photosynthetic fractionation of carbon isotopes depends on $[\text{CO}_2]_{\text{aq}}$

The Rubisco enzymatic photosynthesis pathway can be limited by available free CO$_2$ within a cell. It seems that many photosynthetic algae take up carbon by the diffusion of CO$_2$ across the cell wall. When CO$_2$ is abundant, this process results in a carbon isotope difference of $\sim$30‰; it only uses a part of the available cellular CO$_2$ and shows maximal isotopic fractionation. In the limit of extremely scarce aqueous CO$_2$, the C fixation rate is diffusion limited, and the isotopic composition of the carbon entering the cell is the same as the aqueous dissolved CO$_2$ (i.e., $\sim$-7‰). So as aqueous CO$_2$ becomes more limiting, the isotopic composition of organic matter is shifted to more positive values.
Carbon Isotopic Fractionation Indicates $p\text{CO}_2$

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Please see Fig. 3 in Jasper, J. P. et al. “Photosynthetic Fractionation of $^{13}\text{C}$ and Concentrations of Dissolved CO2 in the Central Equatorial Pacific during the Last 255,000 years.” *Paleoceanography* 9 (1994): 781–798.
Paleo $pCO_2$ Estimates from Carbon Isotopic Fractionation by Algae

![Graph showing the relationship between $\varepsilon_p$ and $[CO_2]_{eq}$](image)

Equations given in text: Eqn. (9), (12)-(17):

$$\varepsilon_p = E_{diff} + (E_p - E_{diff}) \times \frac{C_{int.}}{C_{ext.}}$$

$$\varepsilon_p = 0.7 + 24.3 \times \frac{C_{internal}}{C_{external}}$$

$\varepsilon_{P} = \pm 2.7 \% \text{ Land Plants}$

$\varepsilon_{P} = \pm 25 \% \text{ Phytodetritus}$

$\varepsilon_{diff} = 0.7 \%$
Phanerozoic CO₂ and Climate

Figure by MIT OCW.
Fossil leaf cuticles provide evidence for elevated CO₂ during Mesozoic

SI(%)=SD/(SD+ED)*100%

SD= stomatal density
ED= epidermal cell density

(i.e., the proportion of epidermal cells that are stomata)

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Please see Fig. 4. in Retallack, Gregory J. “A 300-million-year record of atmospheric carbon dioxide from fossil plant cuticles.” *Nature* 411 (17 May 2001): 287 – 290.
Calibrating the Leaf Stomatal “Paleo-barometer”

Extrapolation to high pCO$_2$ not established by calibration data...

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Please see Fig. 1 in Royer, Dana L., et al. “Paleobotanical Evidence for Near Present-Day Levels of Atmospheric CO$_2$ During Part of the Tertiary.” *Science* 22 (June 2001): 2310-2313.
http://droyer.web.wesleyan.edu/Ginkgo.pdf

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Please see Fig. 3 in Retallack, Gregory J. “A 300-million-year record of atmospheric carbon dioxide from fossil plant cuticles.” *Nature* 411 (17 May 2001): 287 – 290.
Response of stomata to [CO$_2$] is species-dependent

Limiting SI-derived paleo-CO$_2$ estimates to times and places when fossilized leaves from extant species exist...
Nevertheless, calibrations of the SI appear accurate for at least the last 9 kyr.
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Cenozoic Cooling
80-0 Ma

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Please see Fig. 2 in Zachos, James, et al. “Trends, Rhythms, and Aberrations in Global Climate: 65 Ma to Present.” Science 292 (2001): 686-693.

Changing continental configuration and ocean basins

80 Million Years Ago

Today

Figure by MIT OCW.
Image removed due to copyright restrictions.

Image removed due to copyright restrictions.

Please see Fig. 3 in Pagani, Mark, et al. “Marked Decline in Atmospheric Carbon Dioxide: Concentrations during the Paleogene.” *Science* 309 (2005): 600-603.
Declining seafloor spreading rates are consistent with decreasing CO$_2$ in early Cenozoic (more continental area to weather as sea-level fall, less subducted CaCO$_3$ recycling)
But sea-level and sea-floor spreading rates in the past are uncertain…

Text removed due to copyright restrictions.

Please see Miller, Kenneth G., et al. “Seafloor Spreading, Sea Level, and Ocean Chemistry Changes.” *Eos* 86 (September 13, 2005): 335.
? Link to Himalayan Orogeny & Uplift of Tibetan Plateau? (Raymo et al.)

Figure by MIT OCW.
Raymo et al. suggest that Increasing Strontium Isotopic Composition of Seawater During Cenozoic Implies Increasing Weathering Rates:

SW $^{87}\text{Sr}/^{86}\text{Sr}$ is balance between:
1. Deep-sea hydrothermal input of non-radiogenic Sr (0.7035)
2. More radiogenic input riverine flux from continental weathering (0.712)

Abyssal carbonate $^{87}\text{Sr}/^{86}\text{Sr}$

$^{87}\text{Rb} \to ^{87}\text{Sr}, t_{1/2} \sim 48 \text{ Gyr}$

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Please see Fig. 1 in Edmond, J. M. “Himalayan Tectonics, Weathering Processes, and the Strontium Isotope Record in Marine Limestones.” *Science* 258 (December 1992): 1594-1597.
Strontium Isotope Systematics

World Average River $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.710$

Ganges-Brahmaputra $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.8$
Co-Variation of $^{87}\text{Sr}/^{86}\text{Sr}$ & CO$_2$ through the Phanerozoic

High CO$_2$?

$\varepsilon_p \sim \varepsilon_{\text{toc}} = \delta^{13}C_{\text{CaCO}_3} - \delta^{13}C_{\text{org}}$

$\varepsilon_p \sim p\text{CO}_2$

High weathering &/or Low magmatism

• Weathering & magmatism may control CO$_2$, but does CO$_2$ control climate?


Boron Isotope paleo-pH method

(a) Distribution of aqueous boron species vs. pH calculated from K values of Hershey et al., (1986).

(b) $\delta^{11}B$ of the two dominant aqueous species of boron vs. pH calculated from the fractionation factor of Kakihana et al. (1977). Also plotted is sea water (diamond) at pH = 8.2.

Figure by MIT OCW.
Cenozoic $p_{\text{CO}_2}$ from B isotopes:

Figure by MIT OCW.
Further Evidence for Low CO$_2$ During Miocene Warm Period

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Please see Fig. 10 in Pagani, Mark, et al. "Miocene Evolution of Atmospheric Carbon Dioxide." *Paleoceanography* 14 (June 1999): 273-292.


Image removed due to copyright restrictions.


http://geology.rutgers.edu/kgmpdf/87-MillerFairbanks.Pocean.PDF
Boron Isotopes in Seawater Also Indicate Large Cenozoic CO$_2$ Decline

- B in seawater: B(OH)$_3$, B(OH)$_4^-$
- Relative abundance controlled by pH
- B incorporated into calcite: B(OH)$_4^-$
- Strong isotopic fractionation between $^{10}$B & $^{11}$B:
  \[ \delta^{11}\text{B} = \left( \frac{\text{B}(^{11}\text{B})_{\text{sample}}}{\text{B}(^{11}\text{B})_{\text{standard}}} - 1 \right) \times 1000\% \]

$^{10}$B = tetrahedral coordination, -19.8‰ relative to $^{11}$B

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Please see Fig. 6 in Zachos, James, et al. “Trends, Rhythms, and Aberrations in Global Climate: 65 Ma to Present.” *Science* 292 (2001): 686-693.

Did a Gas Hydrate Release of Methane (2600 Gt) caused Late Paleocene Thermal Maximum?

• CO$_2$ not the only greenhouse gas we need to consider when evaluating warm episodes.

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Please see Fig. 5 in Zachos, James, et al. “Trends, Rhythms, and Aberrations in Global Climate: 65 Ma to Present.” Science 292 (2001): 686-693.

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Pleistocene
Glacial/Interglacial Cycles
2.65-0 Ma
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Please see Fig. 1 in Imbrie, John, and Imbrie, Katherine Palmer. *Ice Ages: Solving the Mystery*. Cambridge, MA: Harvard University Press, 1979.
Stable isotope paleothermometry

Stable isotope ratios:

\[ \delta^{18}O = \left[ \frac{^{18}O/^{16}O}_{\text{sample}} - \frac{^{18}O/^{16}O}_{\text{standard}} \right] \times 1000 \]

- Urey (1947) calculated that the oxygen isotope fractionation between calcium carbonate and water should be temperature-dependent.
- Epstein (1953) grew molluscs in the laboratory and empirically determined the \(^{18}O\)-T relationship:

\[ \delta^{18}O(\delta_c - \delta_w) \]

Figure by MIT OCW.
• 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 thought 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.
Image removed due to copyright restrictions.

Please see Fig. 4 in Tiedemann, Ralf, et al. “Astronomic timescale for the Pliocene Atlantic d\textsuperscript{18}O and dust flux records of Ocean Drilling Program site 659.” *Paleoceanography* 9 (August 1994): 619-638.
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Please see Fig. 4 in Pisias, Nicklas G., and Shackleton, Nicholas J. “Modelling the global climate response to orbital forcing and atmospheric carbon dioxide changes.” Nature 310 (August 1984): 757-759.
Sea-level estimates from drilling submerged coral terraces

"Fairwards" Sea Level Curve

- □ New Guinea
- ◊ Barbados
- ○ Carribean Islands

Figure by MIT OCW.
Ice Sheet Paleoclimatology
CO₂ During the last 450 kyr from the Vostok (Antarctica) Ice Core

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Please see Fig. 1 in Kump, Lee R. “Reducing uncertainty about carbon dioxide as a climate driver.” Nature 419 (September 2002): 188-190.
Rayleigh distillation of oxygen isotopes

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

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

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

\[
\begin{array}{c|c}
\delta^{18}\text{O} & T=25^\circ C \\
\hline
-9\% & T=25^\circ C \\
1009 & 1000 \\
\text{H}_2^{16}\text{O} & \text{H}_2^{18}\text{O} \\
\end{array}
\]

Cool the vapor to \( 20^\circ C \); allow liquid to condense from vapor:

\[
\begin{array}{c|c}
\delta^{18}\text{O} & T=20^\circ C \\
\hline
-11\% & T=20^\circ C \\
745 & 737 \\
\text{H}_2^{16}\text{O} & \text{H}_2^{16}\text{O} \\
\end{array}
\]

\[
\frac{R}{R_0} = f^{\alpha-1}
\]

\( R_0 \) = initial isotope ratio
\( R \) = isotope ratio after cooling
\( f \) = fraction of water condensed
\( \alpha \) = isotope fractionation factor
Observed $\delta^{18}$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 $\delta^{18}$O of precipitation as a function of the mean annual air temperature at the earth's surface. Note that $\delta^{18}$O values are progressively lighter as the mean annual temperature becomes lower. After Dansgaard (1964).

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

Modern Ocean

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

Last Glacial Maximum (18,000 years Before Present)

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

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

Isotope Mass Balance Equation:

$$M_o\delta_o + M_i\delta_i = M_t\delta_t$$
Transformation of snow into ice

Processes and steps involved in transfer function, which relates concentrations in ice to those in the global atmosphere. Depth and age scales are for Greenland. Snow-to-firn transition is defined by metamorphism and grain growth; firn-to-ice transition is defined by pore closure.

Figure by MIT OCW based on Neftel, et al., 1995.
Gases in Ice Cores

• Bubbles seal off at the bottom of the firn layer, ~80-120 m

• Hence gas is younger than the solid ice that contains it - the “gas age/ice age difference” depends on the accumulation rate

• Most gases are well mixed in atmosphere; so records from Antarctic and Greenland are nearly the same; features of the records can be used to correlate chronologies between hemispheres

• Gases that have been measured:
  – CO₂
  – O₂ (¹⁸O/¹⁶O ratio)
  – CH₄
  – N₂O
Image removed due to copyright restrictions.
Please see Fig. 1 in Blunier, Thomas, and Brook, Edward J. “Climate Change in Antarctica and Greenland during the Last Glacial Period.” *Science* 291 (January 2001): 109-112.
What caused glacial-interglacial CO$_2$ variations?
(still an open question!)

One Possible Scenario for Lower Glacial CO$_2$: The Martin Hypothesis

- Increased:
  - Equator-Pole T gradient, Wind strength, Dust flux to ocean, Iron flux to ocean
- 50% of global 1° production occurs in ocean
- Ocean 1° production is limited by iron (in major regions)
- Higher 1° production draws CO$_2$ out of atmosphere & sequesters it in the deep ocean & sediments
- Colder seawater dissolves more CO$_2$
Two ice cores from Antarctica

Figure 2 Comparison of EPICA Dome C data with other palaeoclimatic records. 

a, Insolation records. Upper blue curve (left axis), mid-July insolation at 65° N; lower black curve (right axis), annual mean insolation at 75°S, the latitude of Dome C. b, δD from EPICA Dome C (3,000-yr averages). Vostok δD (red) is shown for comparison and some MIS stage numbers are indicated; the locations of the control windows (below 800-m depth) used to make the timescale are shown as diamonds on the x axis. c, Marine oxygen isotope record. The solid blue line is the tuned low-latitude stack of site MD900963 and ODP677; to indicate the uncertainties in the marine records we also show (dashed red line) another record, which is a stack of seven sites for the last 400 kyr but consisting only of ODP site 677 for the earlier period. Both records have been normalized to their long-term average. d, Dust from EPICA Dome C.
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) (summer solstice) (northern winter)
The seasons in an elliptical orbit

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

\[ e = \frac{c}{a} = \sqrt{1 - \frac{a^2}{b^2}} \]

Present eccentricity = 0.017
Range: 0 - 0.06
100 & 400 kyr periods
Precession of elliptical orbit
(with respect to fixed stars)
2. Types of Precession

I. Precession of Spin Axis

-13 kyr
-13 kyr

0 kyr
0 kyr

26 kyr Period
26 kyr Period

Top view
Top view

North
North

Vega
North Star

II. Precession of Perihelion

Opposite direction from spin axis precession

:: 23-19 kyr Period

Today: Dec/Jan

June/July

Precession parameter $p$ and eccentricity.

$\rho = e \sin \omega$
Precession influence on climate: why 23,000 years not 25,800?

Initial state:

Northern Summer  Northern Winter

~22,000 years later:

Northern Winter  Northern Summer

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.

$$p = e \sin \omega$$

Equinox, $\pm$ between spring solstice and perihelion
Obliquity (tilt)

Higher obliquity leads to higher summer insolation at high latitudes (and slightly less at low latitudes).
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, effect of obliquity is much stronger
Did increasing Northern Hemisphere summer insolation cause the end of the last ice age?
Absolute chronology and its importance to testing the Milankovitch Hypothesis

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

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

- $^{234}\text{U} \rightarrow ^{230}\text{Th}$ ingrowth in corals: 0-250,000 ka BP

- $^{40}\text{K} \rightarrow ^{40}\text{Ar}$ dating of basalts at magnetic reversals (last one at 780,000 ka BP)
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 ka 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.
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Please see Fig. 4 in Pisias, Nicklas G., and Shackleton, Nicholas J. “Modelling the global climate response to orbital forcing and atmospheric carbon dioxide changes.” *Nature* 310 (August 1984): 757-759.
Oxygen isotopes compared to summer insolation at 65°N

Figure by MIT OCW.
SPECMAP stack. Note terminations (rapid deglaciations)

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1. Why is climate response in 100-kyr band so strong?
   **Observation:** High correlation of δ¹⁸O 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 CO₂, 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.
Abrupt Climate Change

Major climate changes on decadal-century time scales
Two ice cores from central Greenland

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Please see Fig. 1 in Grootes, P. M., et al. “Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores.” *Nature* 366 (December 1993): 552-554.
Abrupt climate swings during the past 100,000 years: the Bolling-Allerod, Younger Dryas, and “stadial/interstadial” “Dansgaard-Oeschger cycles

- Between 10,000-65,000 years ago, there were at least 17 abrupt swings between warmer and colder climate events.

- These events were first observed in the Greenland ice cores, but they have now been seen at diverse sites in the Northern Hemisphere including the tropics.

- These events are not observed in the Antarctic ice cores, save possibly in dampened form.
The Bolling/Allerod warming and Younger Dryas cooling

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Please see Fig. 14 in the Greenland Ice Sheet Project 2 (GISP2) Notebook #3, http://www.gisp2.sr.unh.edu/GISP2/NOTEBOOKS/Notebook_3.html
Image removed due to copyright restrictions.

Please see Fig. 2 in Alley, R. B., et al. “Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas Event.” *Nature* 362 (April 1993): 527-529.
Speleothems: high resolution paleoclimate records from continental sites, with accurate Th/U dates

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Please see Fig. 1 in Wang, Y. J., et al. “A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China.” *Science* 294 (December 2001): 757-759.

And

http://www.niwa.co.nz/pubs/wa/12-2/images/speleo2_large.jpg/view
Ice-Rafted Debris in North Atlantic Sediments

Sand-size (>150 μm) fraction in NW Atlantic Core *Foraminifera*

Sand fraction in HL-2 in NW Atlantic (670-672 cm) *Ice-Rafted Debris*

Jennings *et al.* (1996)

Images removed due to copyright restrictions.
“Heinrich Events”: sudden invasions of the North Atlantic by dirty icebergs

Fig. 3. Core record of Me69-17 from the western peak of the Dreizack. The amount of ice-rafted debris is given as part of the total split (IRD + forams). The amount of one species is given as part of the sum of planktonic forams in a split. The right side of the IRD record shows the stratigraphic markers (Ash I and II, oxygen-isotope stage boundaries).
Paleoclimate: outline

• Incoming and outgoing radiation balance; greenhouse effect
• Faint Young Sun Paradox
• Global carbon cycle
• Weathering and “reverse weathering”
• Snowball earth climate considerations: can the earth escape from a snowball?

• Climate change examples:
  – Permo-Carboniferous glaciations
    • Continental arrangement
    • Land Plants and carbon cycle
  – Mesozoic warmth:
    • warmer equator, decreased equator-pole temperature gradient, higher CO2?
  – Cenozoic cooling
    • ? Lower CO2? (early maybe, but not later). Roles of mountain uplift, weathering, seafloor spreading rates?
  – Pleistocene glaciation cycles
    • Oxygen isotope paleoclimatology
    • Milankovitch insolation cycles
    • Ice cores and greenhouse gas changes
    • Abrupt climate change