Sources of Climate Records

1. Landforms give ice extent (not continuous, hard to date)
2. Historical records (few hundred years)
3. Tree rings (annual resolution, to about 10 ky)
4. Ice cores (annual to millenial resolution, to about 400 ky)
5. Sediments in the ocean or lakes (usually decades to centuries)
Areas Covered by Ice Sheets 20,000 years ago
Broecker (1992)
Pieter Brueghel: Hunters in the Snow, 1575
Tree Rings

Bristle Cone Pine
Ice Core records
Mt. Kilomanjaro
729 Bubbles in Vostock ice core, Antarctica
Ice Core Record

CO2 from gas bubbles
(cold when low CO2)

Temperature from isotopes

Methane from gas bubbles
(high = wet, when warm)
Ice Core Record

Temperature from isotopes

Aluminum = silicate dust
(arid when cold)

Sodium = sea salt from wind
(windy when cold)

Acid = volcanic eruptions
Note lack of correlation to Temp
Notation for Oxygen Isotopes

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

\[ R_i = \frac{^{18}O}{^{16}O} = 1/500 \]
Light water winds up in ice sheets

Residual ocean water is heavy
Shells of marine plankton

(a) Coccolithophore

(b) Foraminifera (foram)

(c) iatom
Forams grow shells of CaCO$_3$

\[ \text{Ca}^{+2} + \text{CO}_3^{-2} \rightarrow \text{CaCO}_3 \]

ions \quad shell

Forams put on heavy coats because:

1. Ice sheets are light, so oceans are heavy
   \[(\text{H}_2\text{O} \text{ molecules exchange oxygen with } \text{CO}_3^{-2})\]

2. At lower temperatures, forams prefer to take
   \[\text{CO}_3^{-2} \text{ molecules with heavy isotopes}\]
Some Major Changes in Climate

**Known amplitude of changes** (low latitude changes poorly known)

Cenozoic: High latitude drops from 12°C to <0°C particularly thorough Miocene. Eocene was 20°C at 60° lat.

Pleistocene: High latitudes oscillate on 20-100 ky times by 5-10°C

Shorter time scales are also recognized (decades-millenia)
Record of oxygen isotopes in Foram shells.

Note that major ice sheets wax and wane with 100 ky period. Smaller oscillations have 20 ky period.
Milankovitch Curve
(N. Hem. Solar radiation)

Parameters:
precession (22 ky)
tilt (41 ky)
ellipticity (100 ky)

During Pleistocene,
major ice ages
come and go with 100 ky
period, with smaller cycles
matching precession.

Timing fits well, although
amplitude does not
Milankovitch Cycle Pattern

Ice volume, temperature, atmospheric CO2 all have cycles with same periodicity (especially 100 ky and 20 ky)

Seasonality appears to provide timing, but changes in radiation seem too small to explain large climate variations

Perhaps ice cover or CO2 amplify (positive feedback) Milankovitch effects of seasonality

But why does CO2 change so much with climate change? Partly solubility. Rest is hotly debated!!!!