http://www.people.fas.harvard.edu/~phuybers/Inso/Inso.avi
Lake Level data

For longer view of monsoon, look at cave deposits
Brazil (10°S)  Wang et al., 2004
Orbitally Forced Glacial Cycles
What caused glacial cycles?

- To grow ice need:
  - Warm winters (lots of snow)
  - Cool summers (keep the snow)

- To melt ice need
  - Cool winters (not much snow)
  - Warm summers (melt the snow)
- Ice accumulates at max of 30 cm/yr
- Ice can melt very fast
- Ice sheets will usually have parts that are accumulating and parts that are melting.

**Ice elevation feedback**

- When ice sheet is higher, it can grow at lower latitudes
- Ice sheet sinks as it grows (lessening elevation feedback)
- Ice sheet stays at low altitudes during fast melting (allowing elevation feedback)
Milankovitch Mechanism

- It’s summer insolation that matters most
- Summer insolation at 65°N matters most
  (Where ice sheet of the last ice age disappeared last)
Variations in the Earth's Orbit: Pacemaker of the Ice Ages

For 500,000 years, major climatic changes have followed variations in obliquity and precession.

J. D. Hays, John Imbrie, N. J. Shackleton

1976: Demonstrated that Ice Ages contained orbital signature

Fig. 2. Depth plots of three parameters measured in core RC11-120: $\delta^{18}O$ (solid line), $T_s$ (dashed line), and percentage of *C. dielius* (dash-dot line). Letter designations of peaks on the latter curve are informal designations of various parts of the record.
Fig. 3. Depth plots of four parameters measured in core E49-18: δ¹⁸O (solid line at the top), T₉ (dashed line), percentage of C. davisiama (dash-dot line), and percentage of CaCO₃ (solid line at the bottom). The technique used for CaCO₃ measurement is that of Håkansson (8). A comparison of the lettered intervals of the C. davisiama curve for this core with those for core RC11-120 (Fig. 2) shows that the time represented by the top 1.5 m of RC11-120 is not present in E49-18.
Why doesn’t ice grow and decay with precessional forcing?

- Ice can only grow at 30 cm/yr (3 km high ice sheet takes 10,000 years) at most
- Ice sheets are cumulative record of what has gone on over several cycles
- Thresholds in the system
1980: Demonstrated how a simple, plausible nonlinearity in ice sheet response to insolation leads to the generation of a 100,000 cycle

- Ice grows when 65°N summer insolation is weak
- Ice decays when 65°N summer insolation is strong
- Ice decays 4x faster than it grows
- Ice takes time to grow and shrink

\[ \frac{dy}{dt} = \begin{cases} \frac{1 + b}{T_y} (x - y) & \text{if } x \geq y \\ \frac{1 - b}{T_y} (x - y) & \text{if } x < y \end{cases} \]  

Using values: \( T_y = 17,000 \text{ years}, b = 0.6 \) (corresponding to \( T_x = 42,500 \text{ years}, T_u = 10,600 \text{ years}, \) and \( T_u/T_x = 4 \).
Dating the Quaternary Deep Sea Record

• Paleomagnetic stratigraphy (coarse time resolution)
• $^{14}$C dating of foraminifera shells (only good for last 30-40 kyr)
• Oxygen isotope stratigraphy (orbital tuning)

Creating an Oxygen-Isotope Timescale

• Gather benthic oxygen isotope records
• Normalize the depth scales to best match the records to each other
• “Stack” or average the records
• Apply dates to a few known spots (Magnetic reversals, deglaciation)
• Adjust the rest of the timescale until the stack best matches a model of how ice volume should respond to insolation
Apply timescale to any core with a benthic $\delta^{18}O$ record
Checking the Deep-Sea Orbital timescale using sea level records
Coral terraces correspond to insolation maxima … should they?

… but perhaps there’s a problem with the U/Th dating, not the orbital timescale…

Thompson et al., 2003
Thompson and Goldstein 2006 QSR

Lisecki and Raymo (2005) stack
Size threshold? Latitude threshold?

… are 100 kyr cycles really 80 and 120 kyr cycles? Does obliquity control ice sheets?

Huybers and Wunsch (2005)