Quaternary Climate Variations

EAS 303
Lecture 34

Background and History

- Louis Agassiz (1840): recognition of Ice Ages
- Harold Urey (1947): The Thermodynamic Properties of Isotopic Substances
  - calculated temperature dependence of oxygen isotope fractionation between calcium carbonate and water
  - Proposed use of oxygen isotopes to quantify paleotemperatures.
- Samuel Epstein (Urey’s postdoctoral associate) grows mollusks in water of various temperatures. Finds following empirical relationship:
  - $\Delta = \delta^{18}O_{\text{calc}} - \delta^{18}O_{\text{water}} = 15.36 - 2.673 (16.52 + T)0.5$
Swiss-American geologist Louis Agassiz (1807-1873) generally given credit for theory of the Ice Ages. Theory was actually proposed by Swiss engineer Ignaz Venetz. Agassiz set out to disprove it, but ended up convincing himself, and a lot of other people, that Venetz was right.

Venetz and Agassiz recognized that many morphological features of their native Switzerland were carved by glaciers much larger than the present ones.
Ice Ages in North America

- Geologists eventually recognized glacial features in other parts of Europe and in North America, including the Finger Lakes.
- By the beginning of the 20th century, they realized that there had been more than once Ice Age; 4 ice ages eventually recognized (Nebraskan, Kansan, Illinoian, Wisconsinian).

Extent of Northern Hemisphere Glaciation

[Image of map showing ice coverage around 18,000 years before present and modern day]
Milankovitch’s Idea

- While the existence of Ice Ages was well established by the middle of the 19th century, the cause of the glacial cycles remained an open question.
- Starting in about 1915, Serbian astronomer Milutin Milankovitch, building on a 19th century idea of Scotsman James Croll, suggested that Ice Ages were caused by variations in the Earth’s orbit and rotation.
- But how do you test this hypothesis?

Testing the Theory

- In 1947, physicist and Nobel Prize winner Harold Urey predicted that incorporation of the different isotopes of oxygen into calcite shells would depend on temperature.
- He realized that this, along with dating of sediment layers, could be used to test Milankovitch’s hypothesis.
- He assigned the task to his graduate student Cesare Emiliani.
The Record of Climate Change in Deep Sea Sediments

- Ironically, while glaciers are a continental phenomenon, our best record of them is from the oceans.
  - Each period of continental glaciation destroys record of previous one.
  - Deep sea sediments not disturbed by glaciation.
- The question of chronology resolved through isotopic studies of deep sea biogenic sediments.
  - **Principle**: fractionation of oxygen isotopes between carbonate and water is temperature dependent.
  - **Complication**: isotopic composition of a shell also depends on the isotopic composition of water in which the organism grew.

Emiliani and The Quaternary $\delta^{18}O$ Record

- First work on deep-sea sediment cores done by Emiliani (student of Urey) in 1955. Analyzed $\delta^{18}O$ in benthic and planktonic foraminifera from piston cores from world ocean.
- Emiliani’s Conclusions:
  - Last glacial cycled ended about 16,000 years ago.
  - Temperature increased steadily between then and about 6000 years ago.
  - Recognized 14 other global glacial–interglacial cycles over the last 600,000 years.
  - Bottom water in the Atlantic was 2° C cooler; bottom water in the Pacific was only 0.8° C cooler during glacial periods.
  - Fundamental driving force for Quaternary climate cycles was variations in the Earth’s orbit and rotation (Milankovitch Hypothesis).
Revisions since Emiliani

- Refining the time scale
  - paleomagnetic stratigraphy as well as new geochronological tools (\(^{10}\)Be, Th isotopes, etc.)

- Revision of the temperature scale.
  - Average \(\delta^{18}\)O\(_{\text{SMOW}}\) of glacial ice is \(-30\) to \(-35\)‰, not \(-15\)‰ that Emiliani assumed. Thus Emiliani underestimated the effect of changing ice volume on \(\delta^{18}\)O of ocean water, and therefore overestimated the temperature changes.

- Nevertheless, Emiliani’s fundamental conclusions have held up.

Subsequent Approaches: SPECMAP \(\delta^{18}\)O

- Correlating from core to core can sometimes be difficult but is the first step in understanding the global climate change signal.
  - A.”Stacking of five cores” selected by Imbrie et al. (1984).
    - Because the absolute value of \(\delta^{18}\)O varies in from core to core, the variation is shown in standard deviation units.
  - B. Smoothed average of the five cores in A.

- Global curve shows a periodicity of approximately 100,000 yrs.
The Cause of Quaternary Glaciations

- The same 100,000 yrs periodicity was apparent in Emiliani’s initial work and led him to conclude that the glacial-interglacial cycles were due to variations in the Earth’s orbital parameters - the Milankovitch variations.

Milankovitch Parameters

- **Eccentricity, e:** degree the Earth’s orbit departs from circular.
- **Obliquity, ε:** tilt of the Earth’s rotation axis with respect to the plane of the ecliptic; varies between 21.5° and 24.5°.
- **Precession, ω:** variation in the direction of tilt at the Earth’s closest approach to the Sun (perihelion). $w$ is the angle between the Earth’s position on June 21 and perihelion.
**How does this affect climate?**

- Changes in these parameters have negligible effect on the total radiation the Earth receives, but they do affect the *pattern* of incoming radiation (insolation).
- Tilt of the rotational axis determines the latitudinal gradient of insolation and therefore seasonality. It is this gradient that drives atmospheric and oceanic circulation.
- Precession relative to the eccentricity of the Earth’s orbit also affects seasonality. For example, the Earth presently is closest to the Sun in January. As a result, northern hemisphere winters (and southern hemisphere summers) are somewhat milder than they would be otherwise. For a given latitude and season, precession will result in a ±5% difference in insolation.

**Periodicities**

- Variation in tilt approximates a simple sinusoidal function with a period of 41,000 yrs.
- Variations in eccentricity can generally be adequately described with characteristic period of 100,000 years. In detail, however, variation in eccentricity is complex, and is more accurately described with characteristic periods of 123,000 yrs, 85,000 yrs, and 58,000 yrs.
- Variation in precession has characteristic periods of 23,000 and 18,000 yrs.
Quantifying the Milankovitch Hypothesis: Hayes and others (1976)

- First quantitative approach to the problem was that of Hayes et al. (1976). They applied Fourier analysis to the $\delta^{18}$O curve, a mathematical tool that transforms a complex variation to the sum of a series of simple sin functions.
- Then used spectral analysis to show that much of the spectral power of the $\delta^{18}$O curve occurred at frequencies similar to those of the Milankovitch parameters.

Quantifying the Milankovitch Hypothesis: Imbrie (1985)

- Imbrie noted Milankovitch parameters might vary with time, as might the climate system's response to them. Thus, Imbrie treated the first and second 400,000 years of SPECMAP curve separately.
- Also noted that the climate might not respond immediately and might have different sensitivities to different parameters.
- Mathematically stated, if there are two forcing factors ($x$), each might have its own gain ($g$) and phase lag ($\phi$), so the response ($y$) would be
  \[y = g_1(x_1 - \phi_1) + g_2(x_2 - \phi_2)\]
Imbrie constructed a model for response of global climate (as measured by the $\delta^{18}$O curve) in which each of the 6 Milankovitch forcing functions was associated with a different gain and phase. Values of gain and phase for each parameter were found statistically by minimizing the residuals of the power spectrum.

Model compared with the $\delta^{18}$O for the past 400,000 years and the next 25,000 years.

The model has a correlation coefficient, $r$, of 0.88 with the data, meaning that 77% ($r^2$) of the variation in $\delta^{18}$O, (and presumably in ice volume) can be explained by Milankovitch hypothesis.

The correlation for the period 400,000–782,000 yrs is a little weaker, 0.80.
Why does Imbrie’s model work?

- Variations in the Earth’s orbital parameters do not affect average annual insolation the Earth receives, but only the pattern in space and time.
- The key factor seems to be the summer insolation at high northern latitudes. This is, the area where large continental ice sheets develop. Glaciers apparently develop when summers are not warm enough to melt the winter’s accumulation of snow.
- The southern hemisphere, except for Antarctica, which is fully glaciated even in interglacial periods, is largely ocean, and therefore not subject to glaciation.

The Need for “Feedback” Mechanisms

- Variation in insolation not enough to drive climate variations.
- Feedback mechanisms must amplify the Milankovitch forcing function.
  - Albedo
    - Identified by Agassiz.
    - Snow and ice reflect much of the incoming sunlight back into space. Thus as glaciers advance, they will cause further cooling.
    - Additional accumulation of ice in Antarctica does not increase albedo, because the continent is fully ice covered even in glacial times.
    - Hence the dominant role of northern hemisphere insolation in driving climate cycles.
  - Other feedback mechanisms?
    - carbon dioxide
    - ocean circulation
Milankovitch cycles - only a (geologically) recent phenomenon?

- Variations in Earth’s orbit and rotation are not new - they have probably been there for a very long time.
  - They are, however, not time-invariant and are affected and changed by
    - Asteroid impact
    - Tidal friction
    - Gravitational interaction with other planets
    - Distribution of mass on Earth (i.e., plate tectonics)

- There is evidence for Milankovitch cycles of climate change throughout the Phanerozoic (mainly, evidence of ‘rythmic’ rise and fall of sealevel - cyclothems).

- However, the already cold climate of the Earth in the Quarternary essentially amplifies climate changes, because large continental ice sheets can form, allowing albedo to greatly amplify the weak Milankovitch signal.

Short Term Carbon Cycle

- Reservoirs in gigatons:
  - Atmosphere: 750 Gt
  - Terrestrial Biota: 55 Gt
  - Litter, Peat, Soil Carbon: 1400 Gt
  - Deep Ocean: 37600 Gt

- Fluxes in gigatons/yr:
  - Fossil Fuel Burning: 6 Gt
  - Deforestation: 2 Gt
  - Forest Biota: 55 Gt
Quaternary Climate and CO₂

- **Vostok (Antarctica) Ice Core: 400,000 yr record**
  - Temperature change calculated from δD
  - Atmospheric CO₂ from bubbles in ice
  - Similar to marine δ¹⁸O curve (some differences)
  - Consistent with Milankovitch hypothesis
  - CO₂ correlates with temperature change

- CO₂ is probably a major feedback mechanism amplifying the Milankovitch signal.
- These short-term changes must involved redistribution of carbon between atmosphere, ocean, and biosphere.
  - Most likely causes: changes in ocean circulation and bioproductivity.
Turning up the biological pump with wind-blown iron?

- Glacial periods were drier and windier, delivering more Fe to surface ocean, increasing photosynthesis.

Climate and ocean circulation

- Formation of deep water in the North Atlantic plays critical role in climate of the region.
Ice Ages and Atlantic Circulation

- The formation of North Atlantic Deep Water (NADW) and the Gulf Stream play an important role in warming the North Atlantic (particularly Europe). Without them, Europe would have a substantially cooler climate.
- During glacial periods cooler temperatures in the North Atlantic may have reduced the Gulf Stream flow, and shut down associated NADW production, cutting off the flow of thermal energy to the North Atlantic.

Younger Dryas

- Younger Dryas was a period about 11,000 to 12,000 years ago when, after the last ice age, conditions suddenly turned colder again. It affected mainly the North Atlantic.
What caused the Younger Dryas?

- One explanation is that the North Atlantic was flooded with fresh water as glaciers retreated north of the St. Lawrence River. This shut off North Atlantic Deep Water (NADW) production, cooling Europe.
- Other evidence from deep sea cores bears this out: flow of NADW correlates with climate.

Anthropogenic Disturbance of the System and the Global Warming Hypothesis

- Man is disturbing the system by dumping ~ 6 gigatons per year into the atmosphere through burning fossil fuels and ~ 2 Gt/yr through deforestation.
- Svante Ahrenius (1890’s) and later Roger Revelle and Hans Suess (1950’s) predicted this would lead to global warming.
- Charles Keeling began documenting increasing atmospheric CO_2 in 1958.
Short Term Carbon Cycle

- Atmosphere: 750 gigatons
- Terrestrial Biota: 55 gigatons
- Litter, Peat, Soil Carbon: 575 gigatons
- Deep Ocean: 37600 gigatons

Reservoirs in gigatons
Fluxes in gigatons/yr

Increasing Atmospheric CO$_2$

- MACNA LCA OBSERVATORY, HANNA: MONTHLY AVERAGE CARBON DIOXIDE CONCENTRATION

Year: 1958-2004

CO$_2$ Concentration (ppm)
Is Climate Changing?

Annual Global Temperature Anomalies, 1880 - 2004
(From the 1880 - 2003 Mean)

Global Average Temperature and Carbon Dioxide Concentrations, 1860 - 2004

Is Antropogenic CO₂ and CH₄ Driving Change?

Temperature anomalies in Degrees C.

(c) Natural + Anthropogenic Forcing

Model results

Observations