Course Outline

Climate 101

- 1/26 Introduction: The Earth System
- 2/2 Energy, Radiation, and Temperature
- 2/9 Winds, Currents, and Water
- 2/16 Climates of the Past
- 2/23 Modern Climate Change

Geologic Time

- Precambrian, and then everything else! (It’s always down there)
- “Primary, Secondary, Tertiary”
- Fossils told this story

Early Earth

- Formed by accretion ~ 4.7 billion years ago
- Solar “constant” was ~ 30% less than today
- Impact heating kept surface hot and sterile
- Very hostile

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Early Life

1) Formation of Oceans (H2O)
2) Abundance of Carbon Dioxide
3) Sunlight
4) Still no life! But...
   - Lots of Energy (Lightning, UV)
   - Volcanic Bombardment
   - Anoxic
     - Origin of life?
     - Organic Soup
**Rise of Oxygen**

- Marine photosynthesis evolved at least 2.3 billion years ago (half the age of the Earth).
- $CO_2 + H_2O + \text{Sunlight} = \text{Release of free O}_2$
- When living things die, organic matter is decomposed (oxidized) back to $CO_2$.
- No net change in $CO_2$ or $O_2$ if this happens.
- Slow, steady burial of reduced organic material led to steady increase of $O_2$.
- $O_2$ levels increased dramatically around 2.25 billion years ago, allowed ozone layer, land plants, more complex life forms.

**Plate Tectonics**

- Continental plates are lighter (buoyant) and rise in collisions, whereas oceanic plates subduct.
- Continents can “bunch up” due to collisions, forming supercontinents (“Pangea,” “Gondwana”).
- Continental drift can radically alter the geometry of ocean basins, with corresponding dramatic changes in ocean circulation and poleward heat transport.

**Plate Tectonics and $CO_2$**

- Seafloor spreading -> volcanism releases $CO_2$.
- Mountain building enhances chemical weathering consumes $CO_2$. 

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**Snowball Earth?**

- Glaciers... and snowball earth?
Uplift Cools Climate

- Uplift
- Mass wasting
- Mountain glaciers
- Slope precipitation
- Increased rock fragmentation
- Increased weathering and CO₂ removal
- Global cooling

Geologic Thermostat

Negative Feedback

- Warming leads to cooling
- Cooling leads to warming

The Long Story of Climate Change

Phanerozoic Climate Change

CO₂ in Deep Time

- Use weathering and volcanism to estimate paleo CO₂
- Estimated CO₂ depends on climate sensitivity (less sensitivity requires higher CO₂)

CO₂ in Deep Time

- ΔT(2x) = 1.5 °C
- ΔT(2x) = 2.8 °C
- ΔT(2x) = 6 °C

- Proxies
- GEOCARBSULF

http://commons.wikimedia.org/wiki/File:Phanerozoic_Climate_Change.png
**Gondwana Glaciation**

- Continents bunched up at South Pole about 500 million years ago
- Huge ice sheets left deposits and erosion across Southern Hemisphere

**Really Ancient Climates**

- **Late Paleozoic (~300 Ma)**
  - Most continents bunched up near South Pole (Gondwanaland)
  - Evidence of ice sheets in Africa, South America, and Australia (contiguous)

- **Middle Cretaceous (~120 Ma to ~90 Ma)**
  - No Atlantic Ocean, Australia attached to Antarctica
  - Ocean bottom temperature ~15° to 20° C
  - No polar ice in either hemisphere
  - Plant and animal fossils ~15° latitude poleward of present ranges (dinosaurs in the Arctic!)
  - CO₂ was 400% to 600% of present concentration

**BOOM!**

- End of Cretaceous Period (65 Ma) marked by extinction of ~75% of living species, including all dinosaurs
- K-T boundary clay layer found all over the world with cosmic levels of Iridium
  - (depleted at Earth’s surface during early differentiation settling)
- Huge tsunami deposits (some are 25 m deep!) found throughout Caribbean Basin
- Giant subsurface impact crater (~200 km) in Mexico’s Yucatan probably site of asteroid impact
- “Hole in the sky” ... years of darkness? Brrrr!

**Chicxulub Crater**

- 200 km diameter Chicxulub crater was found by mapping gravity during oil exploration
Paleocene Geography

- Geography of continents, oceans, and mountain building after the dinosaurs died

Since the Dinosaurs Died

65 Million Years of Climate Change

Cenozoic Climates
(since 65 Ma)

- Gradual global cooling
- Gradual separation of Australia, South America, and Antarctica
  - Antarctica moved into polar position
  - South America and Australia moved north
- Opening of Drake Passage initiated Circumpolar Current in the Southern Ocean
- Ocean surface and bottom temperatures cooled by 10º C
- Cool temperate forest in Antarctica ~20 Ma gave way to ice, reached current volume ~ 5 Ma
- Northern Hemisphere ice sheets appeared about 3 Ma

Slow Descent into a Glacial Epoch

- Antarctic circumpolar current isolated south polar region
- Antarctic ice sheet reduced Earth’s albedo
- Northern ice sheets grow and collapse in a cycle of ice ages

http://upload.wikimedia.org/wikipedia/commons/1/1b/65_Myr_Climate_Change.png

http://www.lorraine-lisiecki.com/stack.html

http://commons.wikimedia.org/wiki/File:Five_Myr_Climate_Change.png

http://commons.wikimedia.org/wiki/wiki/File:Five_Myr_Climate_Change.png
Europeans have been living with glaciers for millennia
They knew what land at glacial margins looked like
It wasn’t much of a stretch to see those same landforms elsewhere!

Reconstructions from Ice Cores

- Ice Age Temperature Changes

- How long to build an ice sheet?
  - Current winter climate of central Canada features winter precipitation ~ 7.5 cm
  - If all falls as snow and persists through summer, it would take about 40,000 years to build an ice sheet 3 km thick

- Isostatic adjustment: continental crust is deformed by ice mass ... sinks under the weight, and then rebounds
  - Ice edges are overrun by ocean water
  - Melting and iceberg calving at edges may explain why ice ages end more abruptly than they begin (“sawtooth pattern”)

- Ice accumulation is limited by precip rates, but melting is not ... contributes to sawtooth pattern

- Changes in deep ocean circulation and thermohaline overturning may act as “trigger” for abrupt shifts

http://commons.wikimedia.org/wiki/File:Ice_Age_Temperature.png
Continental Ice Sheets

Present

20 ka

Melting the ice took 20,000 years!

Orbital Theory of Ice Ages

- Regular changes in shape of Earth’s orbit and Earth-sun geometry as the “timekeeper” of ice ages
- First suggested in mid 19th Century by Adhemar and (later) James Croll
- Quantified by Serbian mathematician Milutin Milankovitch in early 20th Century
- Hard to support with paleoclimate evidence of the day, fell out of favor until mid-1960’s
- Modern paleoclimatic data in 1970’s strongly supported Milankovitch

Tilt of the Earth’s Axis (“Obliquity”)

Changes in the tilt of Earth’s axis of rotation determine the amplitude of the seasonal cycle of solar radiation

Figure 23: The effect of axial tilt on the distribution of sunlight. When the tilt is decreased from its present value of 23½°, the polar regions receive less sunlight than they do today. When the tilt is increased, polar regions receive more sunlight. The possible limits of these effects (never actually achieved) would be a tilt of 6°, when the poles would receive no sunlight, and 54°, when all points on the earth would receive the same amount of sunlight annually.
**Eccentricity**

- Earth’s orbit is an ellipse (not a circle)
- Currently slightly closer to the sun in January than July
- The amplitude of this variation is the eccentricity

**Precession of the Orbit**

- Direction of rotational axis “spins like a top”
- Currently points NH away from sun at closest point
- This minimizes seasonal amplitude of radiation
- Precession reverses this periodically

**Orbital Cycles**

- Combined tilt, precession, and obliquity effects change high-latitude insolation in summer by as much as 30%
- Modulates energy available to melt snow!
NH Summer Sunshine:

Ice Modulator

- When summer sun is weak in northern high-latitudes, some snow persists
  - Albedo increases
  - Ice builds up
- When sun comes back, ice melts much more quickly than it came
- “Sawtooth pattern”

Cold Summers in NH Are Associated with Global Changes

- Orbital changes produced reduced summer insolation at 60° N, but enhanced insolation at 60° S
- Ice age changes in sea ice and in mountain snowlines were recorded at all latitudes

Thermohaline Circulation

- Diversion of glacial meltwater from Mississippi to St. Lawrence ~ 11 ka reduced N. Atlantic salinity
- Shut down NADW formation, plunged Europe back to full glacial climate conditions

"Younger Dryas" Abrupt Cold Event
Glacial/Interglacial Transition

Paleoclimate Proxies
- Isotopic composition of water in ice cores
- Fossil foraminifera
- Pollen in lake sediments
- Fossil materials in rodent nests
- Tree-rings
- Historical records

Since the Ice Melted

The Past 2000 Years

http://commons.wikimedia.org/wiki/File:Holocene_Temperature_Variations.png

http://commons.wikimedia.org/wiki/File:2000_Year_Temperature_Comparison.png
The Past 1000 Years
Reconstructed Temperature

[Graph showing temperature anomaly over 1000 years with key points like Medieval Warm Period and Little Ice Age marked.]

http://upload.wikimedia.org/wikipedia/commons/b/bb/1000_Year_Temperature_Comparison.png

Modern Alpine Melting

[Image of melting glaciers with text overlay.

Historical Thermometer Record

[Graph showing global temperatures with Annual Average and Five Year Average marked.

http://commons.wikimedia.org/wiki/File:Instrumental_Temperature_Record.png

Scott Denning          CSU          Atmospheric Science

Climates of the Past