**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

**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)
- CO2 + H2O + Sunlight = Release of free O2
- When living things die, organic matter is decomposed (oxidized) back to CO2
- No net change in CO2 or O2 if this happens!
- Slow, steady burial of reduced organic material led to steady increase of O2
- O3 levels increased dramatically around 2.25 billion years ago, allowed ozone layer, land plants, more complex life forms
Snowball Earth

- Early atmosphere was chemically reduced … lots of methane (CH\textsubscript{4}, strong greenhouse gas)
- Release of O\textsubscript{2} consumed methane -> weaker greenhouse effect
- Probably three separate “snowball Earth” episodes

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\textsubscript{2}

- Seafloor spreading -> volcanism releases CO\textsubscript{2}
- Mountain building enhances chemical weathering consumes CO\textsubscript{2}

Uplift Cools Climate

- Rock weathering is a chemical reaction that consumes CO\textsubscript{2}
- Uplift of mountains exposes fresh rock to air, consuming CO\textsubscript{2} and cooling climate over time
**Geologic Thermostat**

**Negative Feedback**
- Warming leads to cooling
- Cooling leads to warming

**CO₂ in Deep Time**

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

**Gondwana Glaciation**

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

**Half a Billion Years**

- Phanerozoic Climate Change
- Negative Feedback
- Warming leads to cooling
- Cooling leads to warming

- CO₂ concentration changes over time
- Estimated CO₂ depends on climate sensitivity

- Gondwana Glaciation
- South Pole position
- Ice sheet movements

- http://commons.wikimedia.org/wiki/File:Phanerozoic_Climate_CHANGE.png

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Scott Denning  CSU  Atmospheric Science
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!)
  - CO$_2$ 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

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

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 10°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

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

Thinking About Glaciers

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!
Tiny Bubbles ... Priceless
Reconstructions from Ice Cores

Ice Age Temperature Changes

Climate Time Scales

• 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

Continental Ice Sheets

Present

20 ka

http://commons.wikimedia.org/wiki/File:Ice_Age_Temperature.png
**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

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**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

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**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

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**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
Orbital Cycles

Orbit Affects Sunshine

NH Summer Sunshine: Ice Modulator

Cold Summers in NH Are Associated with Global Changes

• Combined tilt, precession, and obliquity effects
  change high-latitude
  insolation in summer by as
  much as 30%

• Modulates
  energy available
to melt snow!

- 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”

- 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

“Younger Dryas” Abrupt Cold Event
- Diversion of glacial meltwater from Mississippi to St. Lawrence ~ 11 ka reduced N. Atlantic salinity
- Shut down North Atlantic Deep Water formation, plunged Europe back to full glacial climate conditions

End of the Ice Age

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

Holocene Temperature Variations

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

The Past 2000 Years

Reconstructed Temperature

http://commons.wikimedia.org/wiki/File:2000_Year_Temperature_Comparison.png

The Past 1000 Years

Reconstructed Temperature

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

Modern Alpine Melting
Historical Thermometer Record

Global Temperatures

- Annual Average
- Five Year Average

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