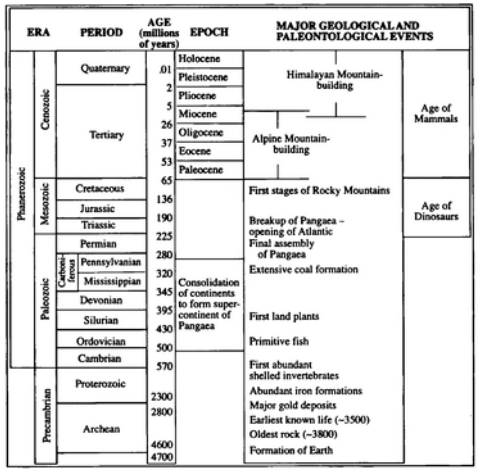
Geologic Time

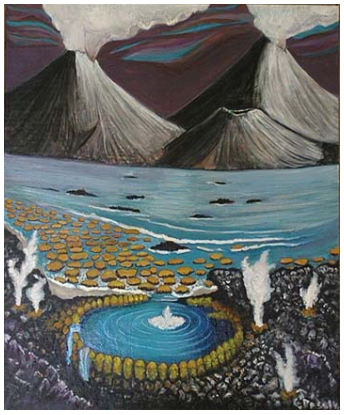


- Precambrian, and then everything else! *(It's always down there)*
- "Primary, Secondary, Tertiary"
- Fossils told this story

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

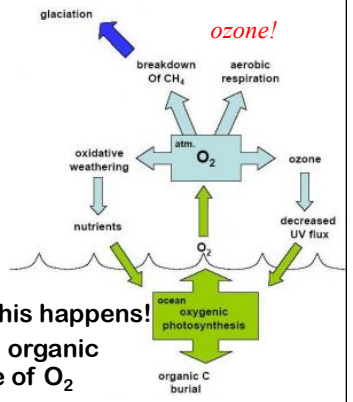
Early Life



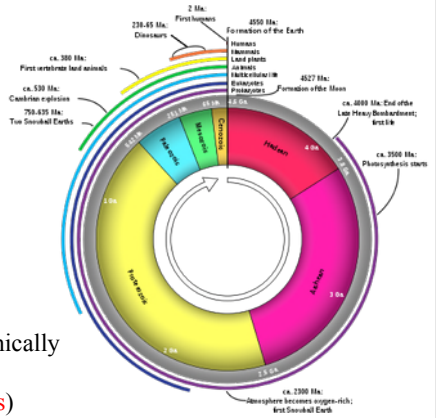
1) Formation of Oceans (H20)
2) Abundance of Carbon Dioxide
3) Sunlight
4) Still no life! But…
   - Lots of Energy (Lightning, UV)
   - Volcanic Bombardment
   - Anoxic
     - Origin of life?
     - Organic Soup

Rise of Oxygen

- Marine photosynthesis evolved at least 2.3 billion years ago (half the age of the Earth)
- $CO_2 + H_20 +$ Sunlight = 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



Snowball Earth



- Early atmosphere was chemically reduced … lots of methane (CH_4 strong greenhouse gas)
- Release of O_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**

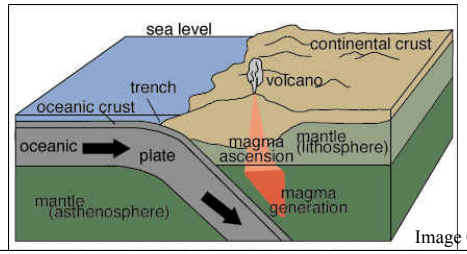
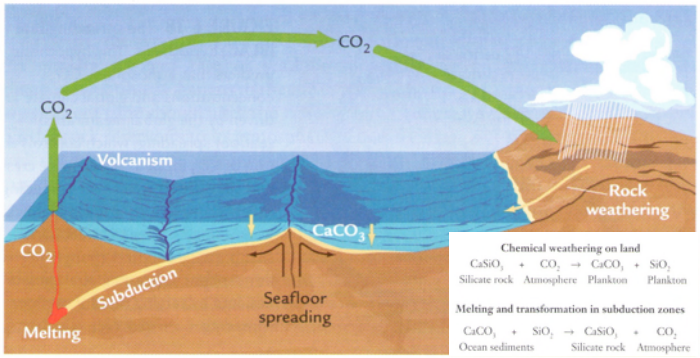


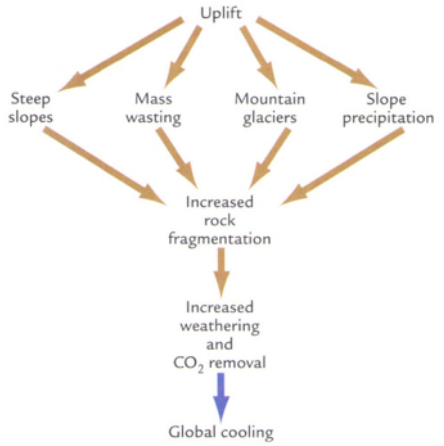
Image Courtesy USGS

Plate Tectonics and CO_2



- **Seafloor spreading -> volcanism releases CO2**
- **Mountain building enhances chemical weathering consumes CO2**

Uplift Cools Climate

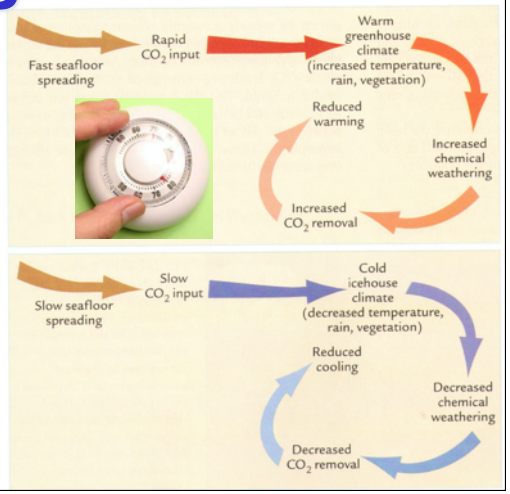


- **Rock weathering is a chemical reaction that consumes CO_2**
- **Uplift of mountains exposes fresh rock to air, consuming Co2 and cooling climate over time**

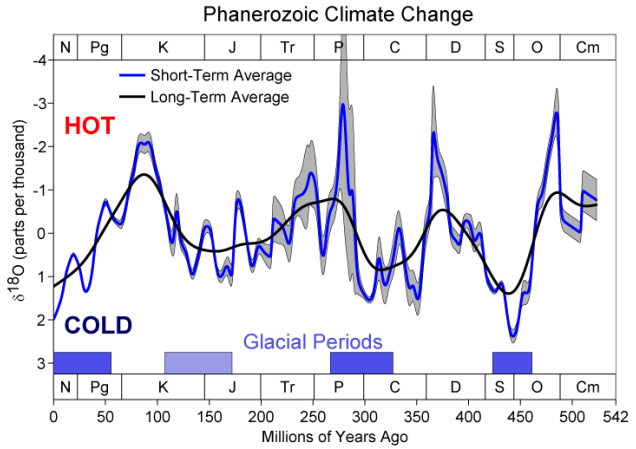
Geologic Thermostat

Negative Feedback

- Warming leads to cooling
- Cooling leads to warming



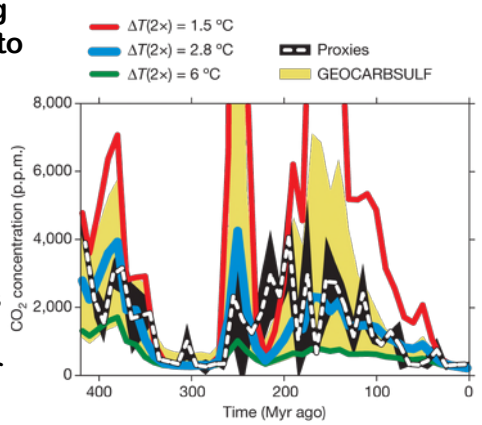
Half a Billion Years



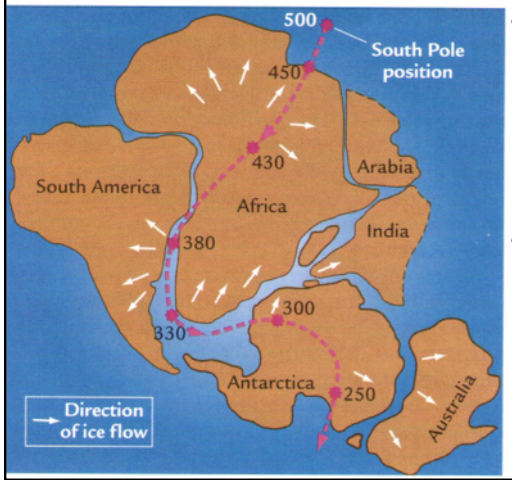
http://commons.wikimedia.org/wiki/File:Phanerozoic_Climate_Change.png

CO_2 in Deep Time

- Use weathering and volcanism to estimate paleo CO_2
- Estimated CO_2 depends on climate sensitivity (less sensitivity requires higher CO_2)



Gondwana Glaciation



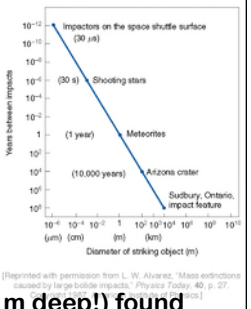
- Continents bunched up at South Pole about 500 million years ago
- Huge ice sheets left deposits and erosion across Southern Hemisphere

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!)
  - CO_2 was 400% to 600% of present concentration

BOOM!

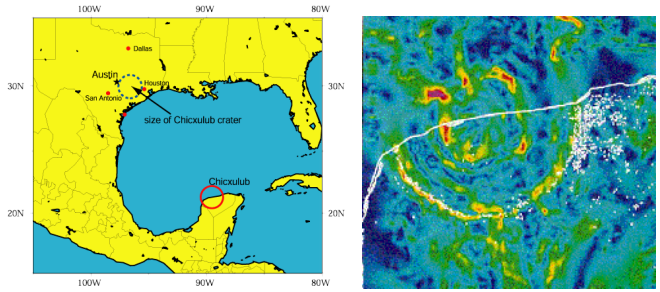
- End of Cretaceous Period (65 Ma) marked by extinction of ~ 75% of living species, including all dinosaurs
- K-T boundary clay layer found all over the world with cosmic levels of Iridium
  - (depleted at Earth's surface during early differentiation settling)



[Reprinted with permission from L. W. Alvarez, "Mass extinctions caused by large bolide impacts," Physics Today, 40, p. 27, July 1987. Copyright 1987, American Institute of Physics.]

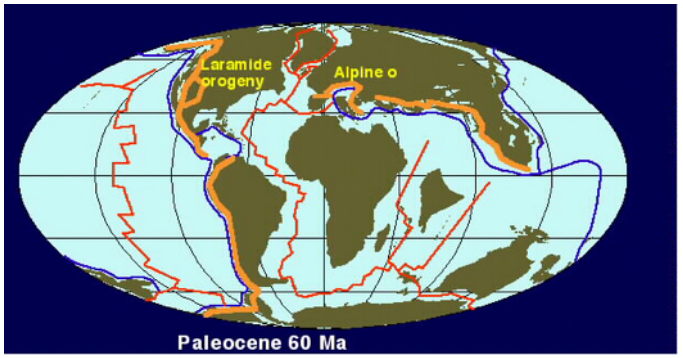
- Huge tsunami deposits (some are 25 m deep!) found throughout Caribbean Basin
- Giant subsurface impact crater (~200 km) in Mexico's Yucatan probably site of asteroid impact
- "Hole in the sky" … years of darkness? *Brrrr!*

Chicxulub Crater



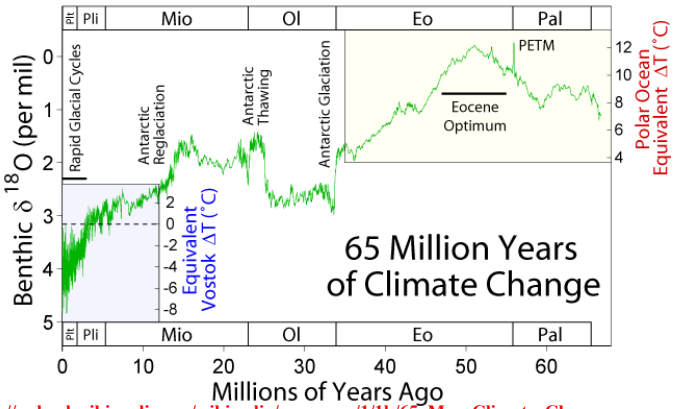
200 km diameter Chicxuluib crater was found by mapping gravity during oil exploration

Paleocene Geography



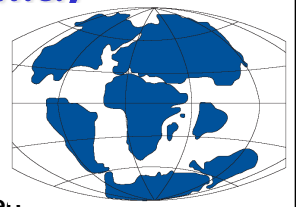
Geography of continents, oceans, and mountain building after the dinosaurs died

Since the Dinosaurs Died



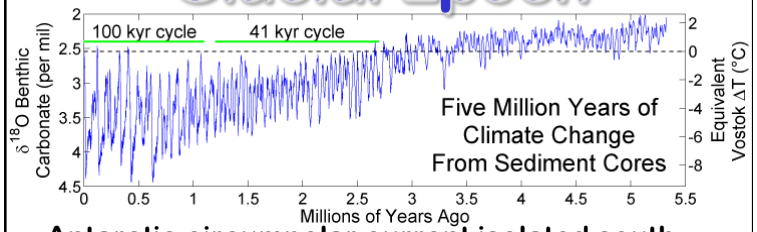
http://upload.wikimedia.org/wikipedia/commons/1/1b/65_Myr_Climate_Change.png

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



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

Thinking About Glaciers

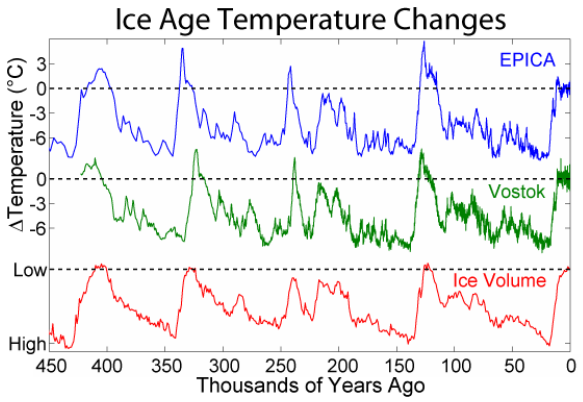
1850 1970

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!


L'AIGUILLE DU MIDI


Tiny Bubbles ... Priceless
Science
25 November 2005
Unloading fresh core, Siple Dome, Antarctica.
This is a section from a 200-meter core drilled
at Siple Dome, Antarctica to help assess recent
climate history. Photo courtesy of Climate Change
Research Center, University of New Hampshire.
125
AAAS

Reconstructions from Ice Cores



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

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

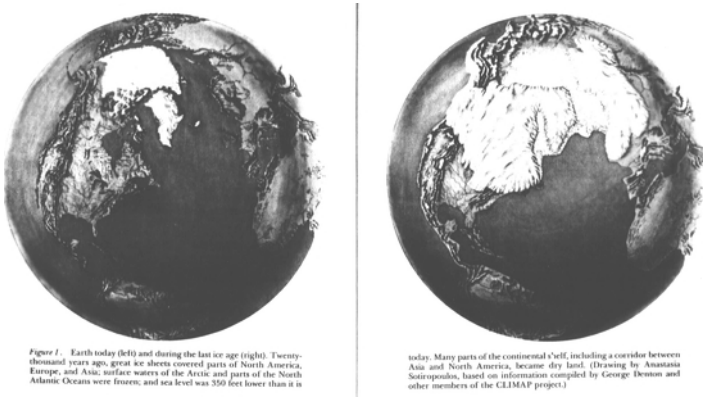
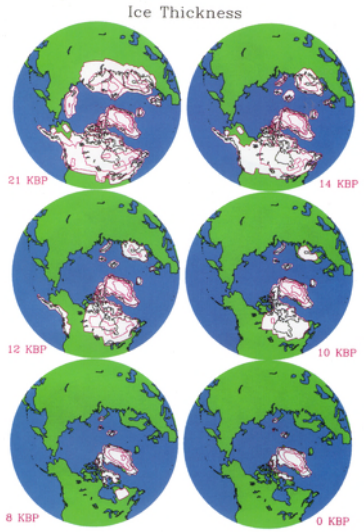


Figure 1. Earth today (left) and during the last ice age (right). Twenty-thousand years ago, great ice sheets covered parts of North America, Europe, and Asia; surface waters of the Arctic and parts of the North Atlantic Oceans were frozen; and sea level was 350 feet lower than it is today. Many parts of the continental s'self, including a corridor between Asia and North America, became dry land. (Drawing by Anastasia Sotiropoulos, based on information compiled by George Denton and other members of the CLIMAP project.)

Melting the ice took a long time!



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")

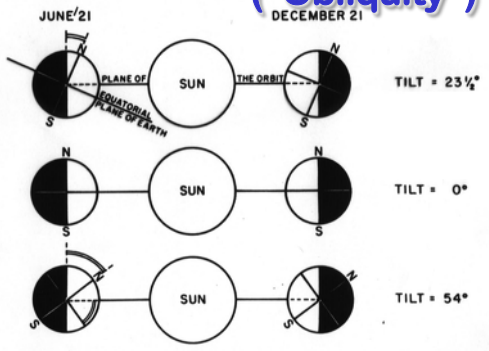


Figure 25. The effect of axial tilt on the distribution of sunlight. When the tilt is decreased from its present value of 23½°, the polar regions receive less sunlight than they do today. When the tilt is increased, polar regions receive more sunlight. The possible limits of these effects (never actually achieved) would be a tilt of 0°, when the poles would receive no sunlight; and 54°, when all points on the earth would receive the same amount of sunlight annually.

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

Eccentricity

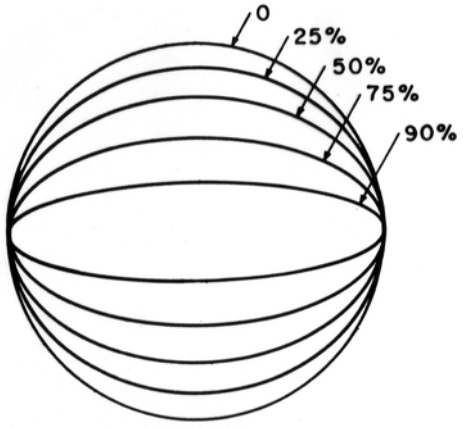
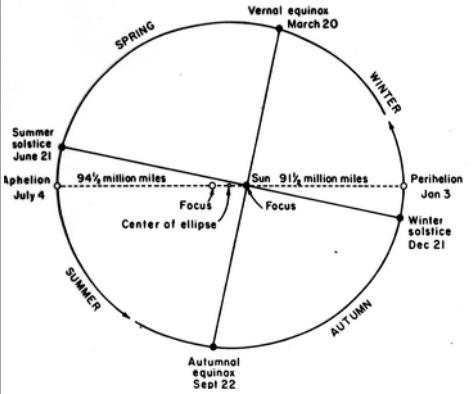


Figure 17. Ellipses with different eccentricities.

- 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

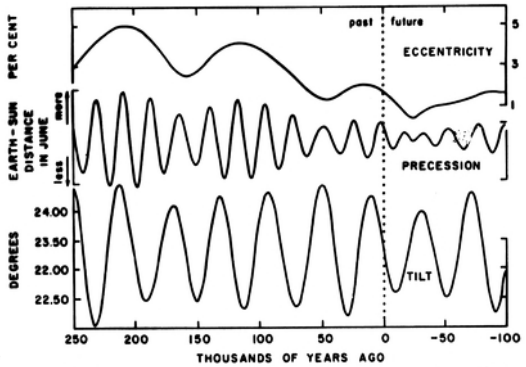


Figure 41. Changes in eccentricity, tilt, and precession. Planetary movements give rise to variations in the gravitational field, which in turn cause changes in the geometry of the earth's orbit. These changes can be calculated for past and future times. (Data from A. Berger.)

Orbit Affects Sunshine

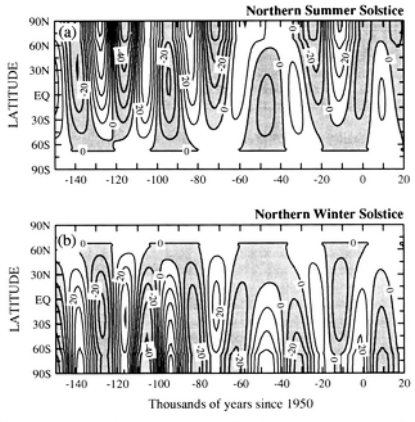
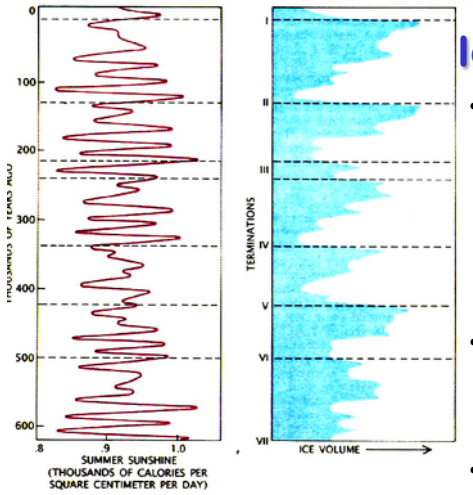


Fig. 11.13 Distribution of departure of daily average insolation at (a) northern summer and (b) northern winter solstices from average values for the period from 150,000 years ago until 20,000 years in the future. Contours are given in W m^{-2}.

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

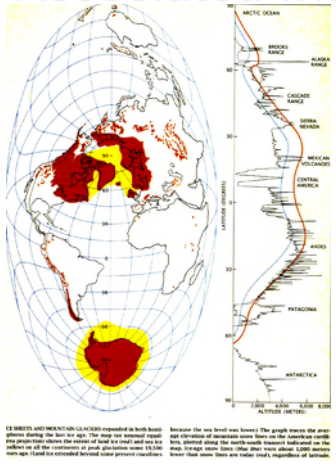
NH Summer Sunshine:



Ice Modulator

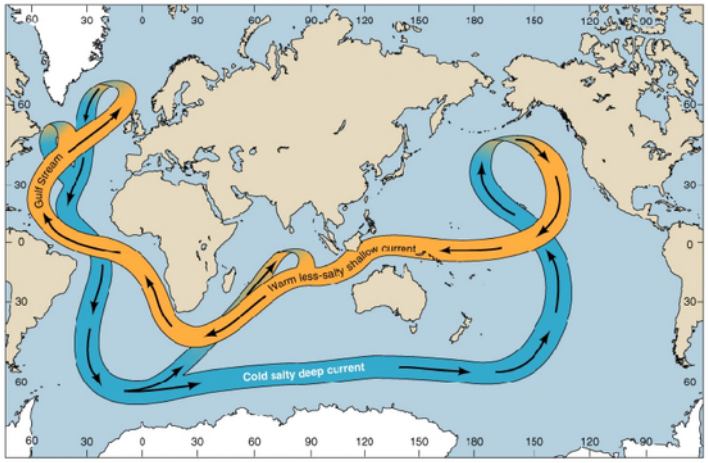
- When summer sun is weak in northern high-latitudes, some snow persists
  - Albedo increases
  - Ice builds up
- When sun comes back, ice melts much more quickly than it came
- "Sawtooth pattern"

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

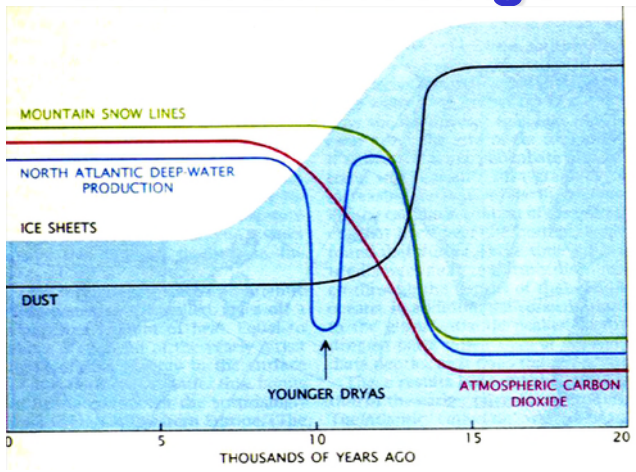
Thermohaline Circulation



"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

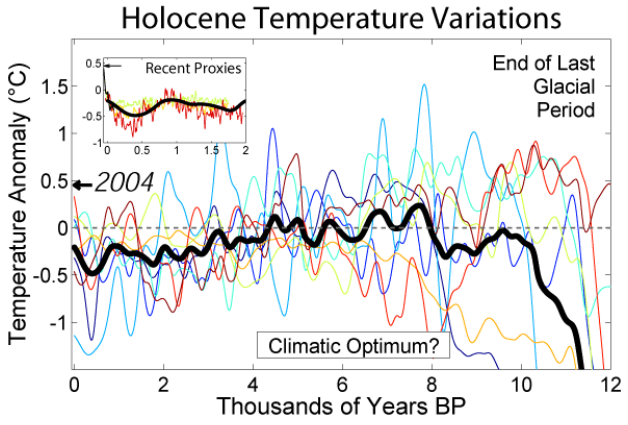
End of the Ice Age



Paleoclimate Proxies

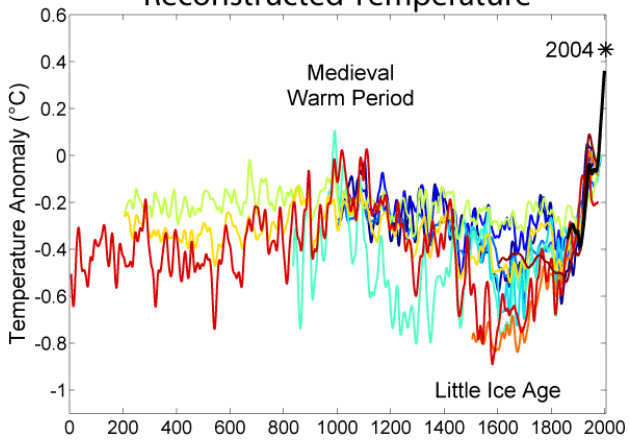
- Isotopic composition of water in ice cores
- Fossil foraminifera
- Pollen in lake sediments
- Fossil materials in rodent nests
- Tree-rings
- Historical records

Since the Ice Melted



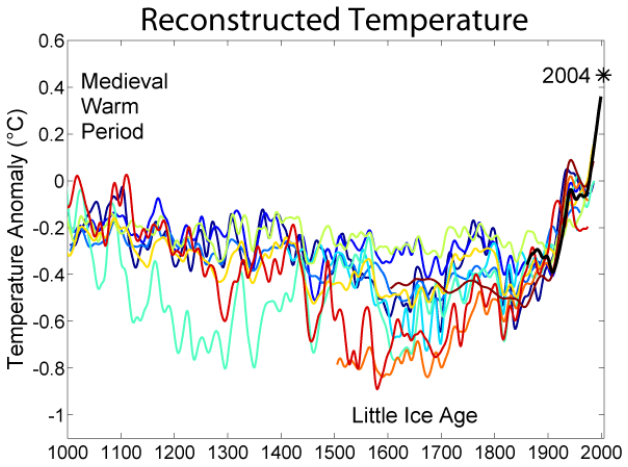
http://commons.wikimedia.org/wiki/File:Holocene_Temperature_Variations.png

The Past 2000 Years



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

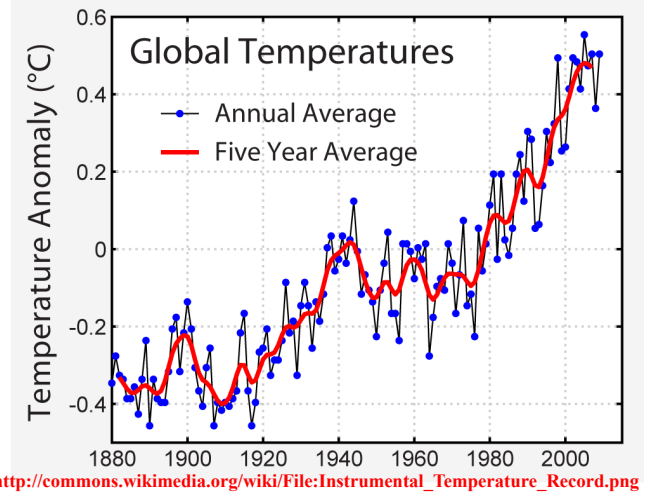
The Past 1000 Years



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

Modern Alpine Melting

Historical Thermometer Record



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