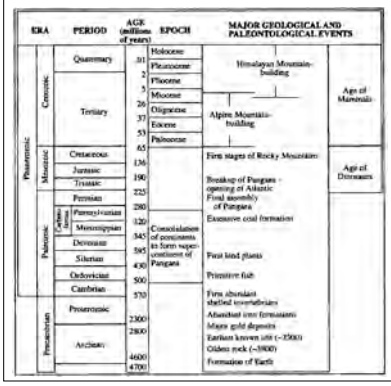
Paleoclimates

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 ("Ga")
- Solar "constant" was ~ 30% less than today
- Impact heating kept surface hot and sterile
- Differentiation of solid materials by gravitational settling following large-scale melting
  - Heavy metallic stuff "sank" to form core and mantle
  - Lighter rocky stuff "floated" to form lithosphere and crust
- Tectonic plates of rigid *lithosphere* carried about on more plastic underlying *asthenosphere*
- Early atmosphere was mostly CO_2 and H_2O
- Condensation of oceans, aqueous chemistry, sedimentation, and life have steadily depleted CO_2

Plate Tectonics and Climate

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

Pangea (310 – 300 Ma)

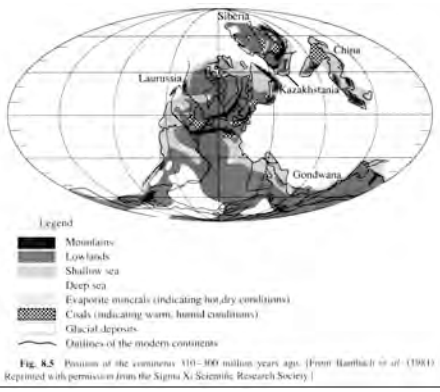


Fig. 8.5 Positions of the continents 310–300 million years ago. [From Hambach et al. (1981)
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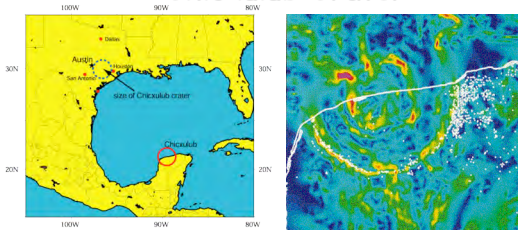
Really Ancient Climates

- 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 Chicxuluib crater was found by mapping gravity anomalies during oil exporation

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 first appeared about 3 Ma

The "Cenozoic Decline"

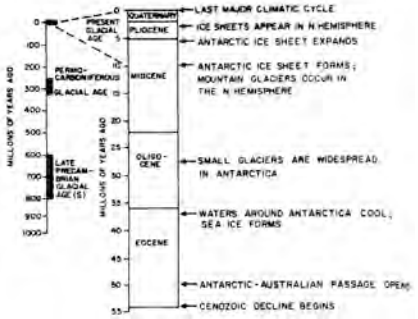
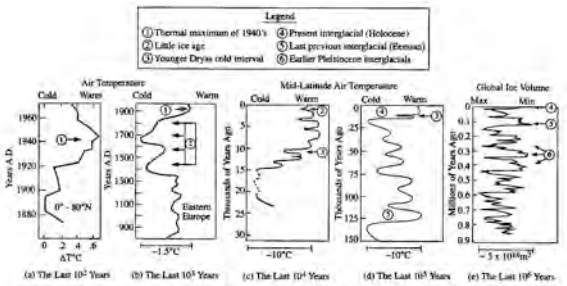
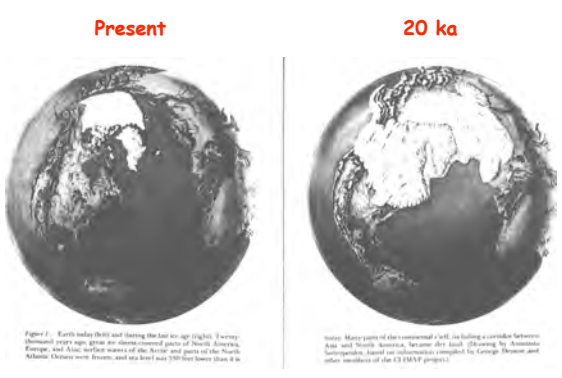


Figure 49. The last billion years of climate. Intervals when ice sheets occurred in polar regions are indicated on the left as glacial ages. An outline of significant events in the Cenozoic climate decline is given on the right.

Paleoclimates at Many Time Scales



Continental Ice Sheets



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

Axial Tilt ("Obliquity")

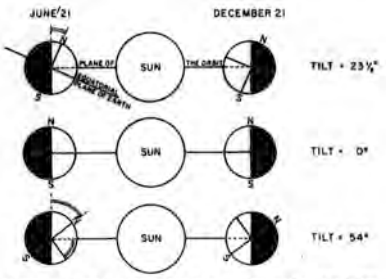


Figure 25. The effect of axial tilt on the distribution of sunlight. When the tilt is decreased from its present value of 23½°, the polar regions receive less sunlight than they do today. When the tilt is increased, polar regions receive more sunlight. The possible limits of these effects (never actually 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

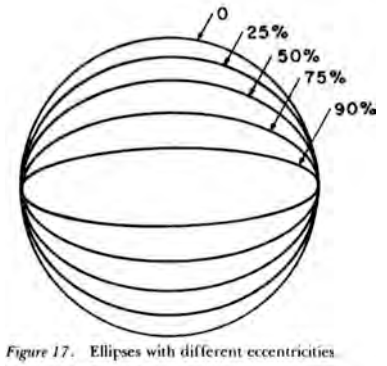
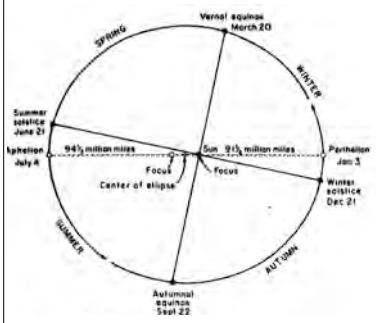


Figure 17. Ellipses with different eccentricities

- 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 Equinoxes



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

Periodicities in Orbital Parameters

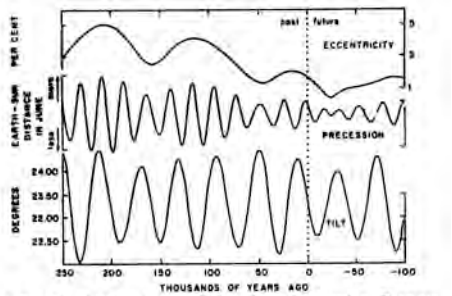
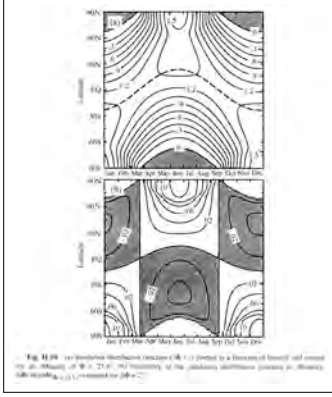


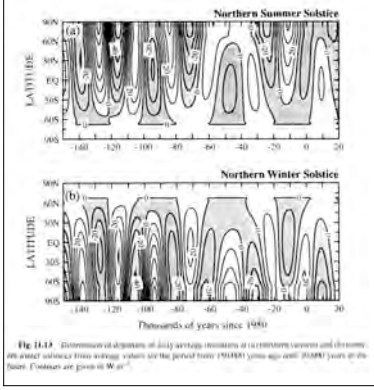
Figure 41. Changes in eccentricity, tilt, and precession. Planetary movements give rise to variations in the gravitational field, which in turn cause changes in the geometry of the earth's orbit. These changes can be calculated for past and future times. (Data from A. Berger.)

Radiative Effects of Obliquity



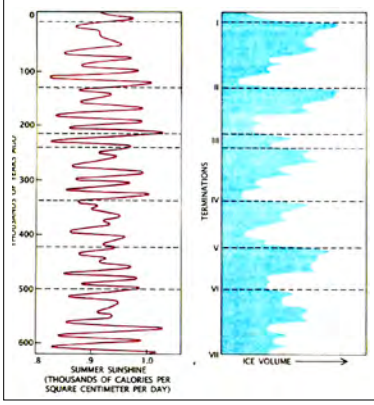
- No change in total SW_{down} at all
- Small changes in annual mean meridional gradient of SW_{down}
- Substantial changes in seasonal distribution of SW_{down} at high latitudes

Overall Radiative Effects



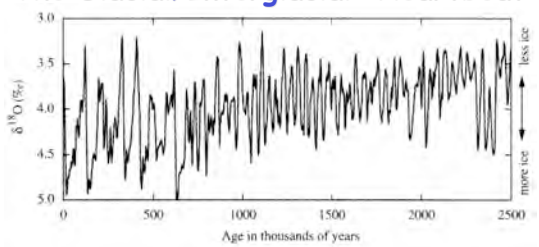
- Combined tilt, precession, and obliquity effects change high-latitude insolation in summer by as much as 30%
- Modulates energy available to melt snow!

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"

The Glacial/Interglacial "Heartbeat"

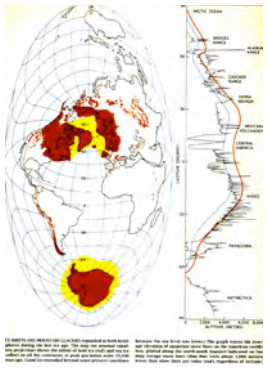


- Isotopic variations in $CaCO_3$ result from withdrawal of huge amounts of (lighter) water from oceans to form ice sheets
- $\delta^{18}O$ of $CaCO_3$ in marine sediments records changes in ice volume over millions of years
- Last 2.5 million years have been punctuated by many cycles of ice ages and interglacial periods

Time Scales and Climate Dynamics

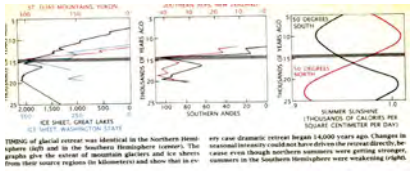
- How long to build an ice sheet?
  - Current winter climate of central Canada features winter precipitation ~ 7.5 cm
  - If all falls as snow and persists through summer, it would take about 40,000 years to build an ice sheet 3 km thick
- Isostatic adjustment: continental crust is deformed by ice mass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

Cold Summers in NH Are Associated with Global Changes



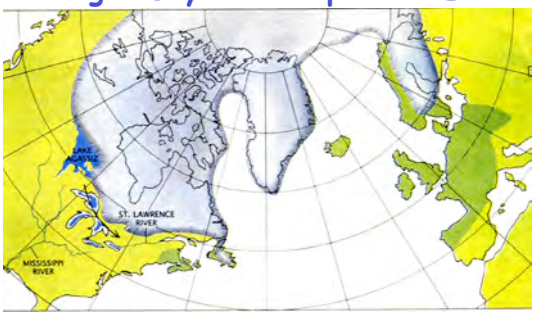
- Orbital changes produced reduced summer insolation at 60° N, but enhanced insolation at 60° S
- Ice age changes in sea ice and in mountain snowlines were recorded at all latitudes
- Why?

Synchronized Glacial Terminations



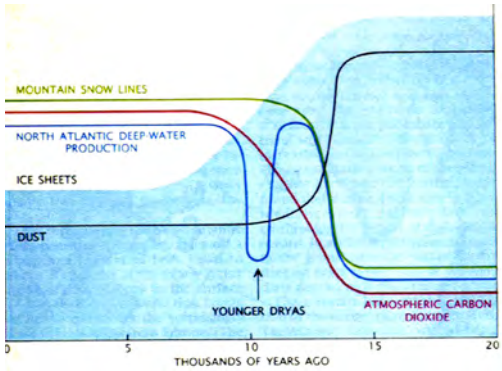
- At about 14 ka, ice sheets and mountain glaciers around the world began to melt
- Could not be caused by local changes in solar radiation, which are assymetric
- Broecker and Denton argue that this was caused by the initiation of NADW formation

"Younger Dryas" Abrupt Cold Event



- 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

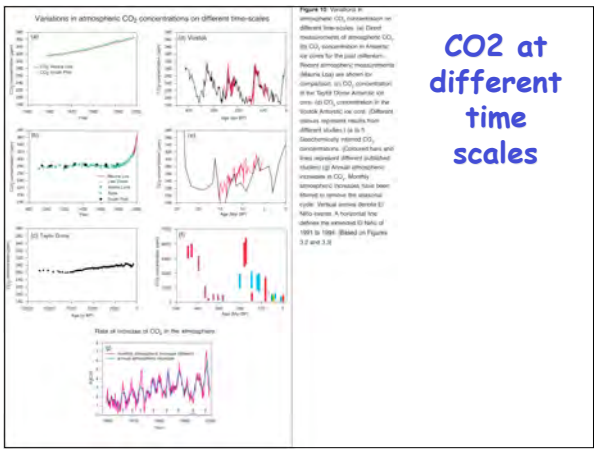
Glacial/Interglacial Transition



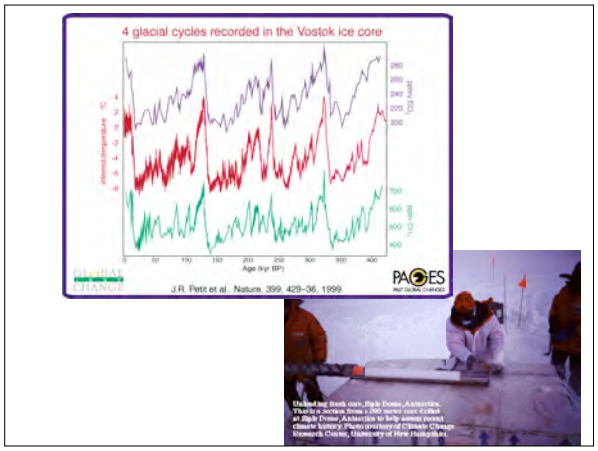
Receding Alpine Glaciers

1850 1970

Figure #6. The Argentiere glacier today and in 1850. Top: In a photograph taken in 1966, the glacier is seen as a small tongue of ice in the upper portion of the valley. Bottom: An etching made about 1850 shows the extent of the glacier during the waning phase of the Little Ice Age in the French Alps. (From L. Lliboutry, 1971.)



CO2 at different time scales

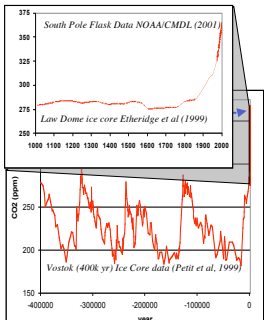


Paleo Carbon Cycling

Over the past 420,000 years atmospheric CO_2 has varied between 180 and 280 parts per million, beating in time with the last four glacial cycles.

Over the last millenium, CO_2 was very steady until the Industrial Revolution, when it began to rise rapidly

The atmospheric mixing ratio of CO_2 is expected to reach 700 to 900 ppm by 2100



Modern Climate Variability

Box TS.2, Figure 1. *A schematic of the changes associated with the positive phase of the NAO and NAM. The changes in pressure and winds are shown, along with precipitation changes. Warm colours indicate areas that are warmer than normal and blue indicates areas that are cooler than normal.*

Changing NAO

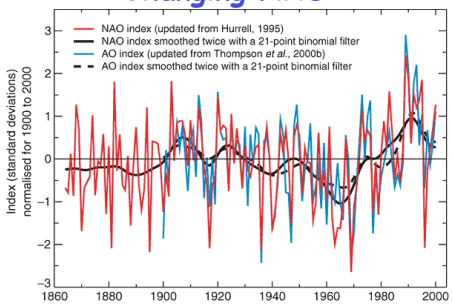
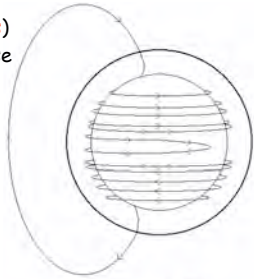


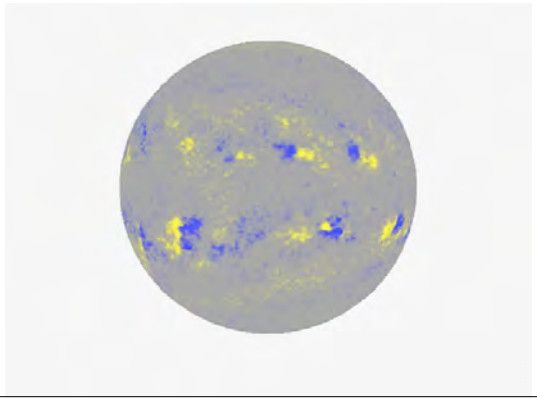
Figure 2.30: *December to March North Atlantic Oscillation (NAO) indices, 1864 to 2000, and Arctic Oscillation (AO) indices, 1900 to 2000, updated from Hurrell (1995) and updated from Thompson and Wallace (2000) and Thompson et al. (2000b), respectively. The indices were normalised using the means and standard deviations from their common period, 1900 to 2000, smoothed twice using a 21-point binomial filter where indicated and then plotted according to the years of their Januarys.*

Solar Variability

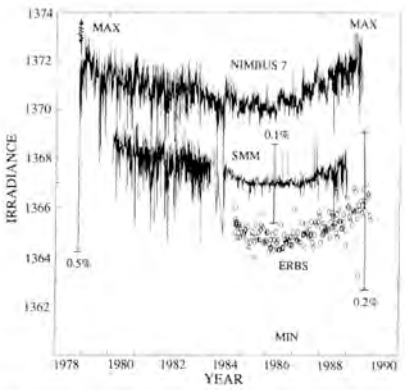
- Sun is an enormous spinning plasma sphere (entirely composed of charged particles)
- Rotating charges induce intense magnetic fields
- Fluid flow follows field (*not buoyancy!*)
- Rapid differential rotation distorts field lines
- They wrap and wrap, tighter and tighter
- About every 11 years, they break down, reorganize, and start again



Solar Cycle



11-year Solar Cycle



- Natural
- Periodic
- Predictable
- Small?
- Not constant over long time scales

Solar Variability Since 1870

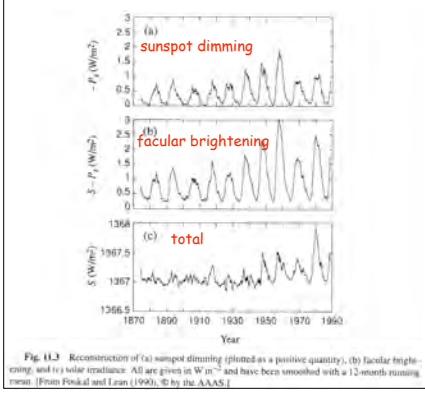


Fig. 11.3 Reconstruction of (a) sunspot dimming (plotted as a positive quantity), (b) facular brightening, and (c) solar irradiance. All are given in W m^{-2} and have been smoothed with a 12-month running mean. [From Foukal and Lean (1990), © by the AAAS.]

Volcanic Aerosol

- Massive releases of particles and (more importantly) SO_2, lofted to tremendous heights in stratosphere
- SO_2 -> H_2SO_4 aerosol in stratosphere
- Can persist for months-years
- Substantial shift from direct to diffuse light

Stratospheric Aerosol Forcing

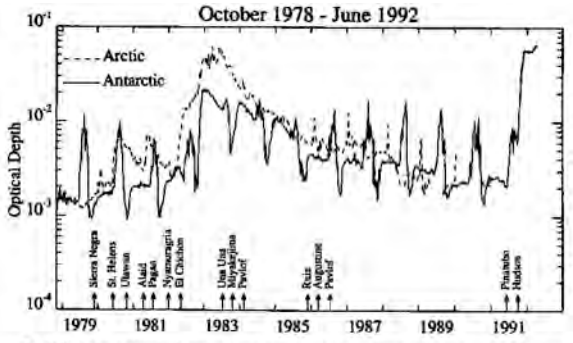


Fig. 11.5 Polar stratospheric optical depth versus time derived from SAM II and SAGE solar extinction measurements. Superimposed on the normal seasonal variations are major injections of aerosols associated with the El Chichón and Mt. Pinatubo eruptions. [From McCormick, *et al.* (1993).]