Lecture 2
History of the Earth's Climate
17 January 2018

MET 3103 and 5105: Climate Processes and Impacts

The Sun

- Burns Hydrogen to Helium
  - Called the proton-proton process
  - $4H^{+} \rightarrow He^{++} + 2e^{+}$
  - Eats Protons (Hydrogen nuclei)
  - Converts 2 protons to neutrons emitting 2 positrons (e^{+})
  - Bigger, hotter stars use a process catalyzed by Carbon-Nitrogen and Oxygen
- As Helium dilutes the solar core
  - It becomes denser and smaller, but *HOTTER*
- Sun is 4.5 Byr old, halfway through its life cycle
- About 40% brighter than in was initially
- Will eventually (5 Byr) double in luminosity
- In ~1 Byr, we're poached
- Current surface temperature is ~5800K
- Present *Solar Irradiance* at the Earth is1367 Watts m^{-2} above the atmosphere

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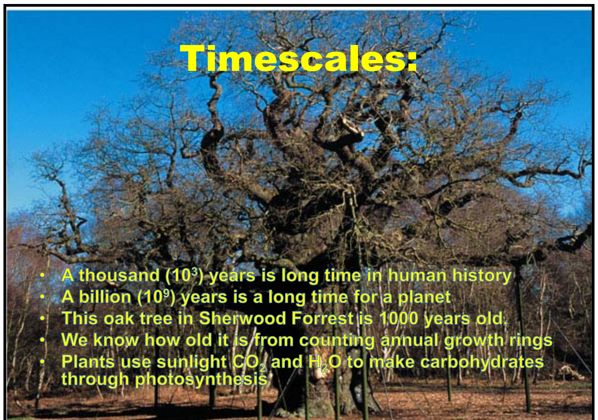
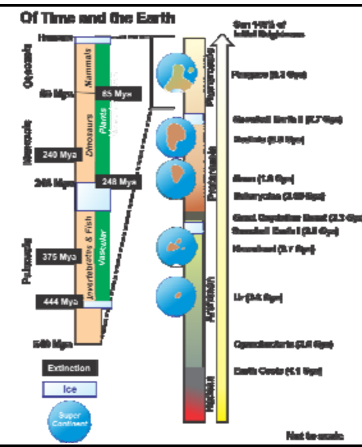
Timescales:

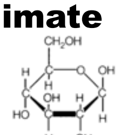


- A thousand (10^3) years is long time in human history
- A billion (10^9) years is a long time for a planet
- This oak tree in Sherwood Forrest is 1000 years old.
- We know how old it is from counting annual growth rings
- Plants use sunlight CO_2 and H_2O to make carbohydrates through photosynthesis

GLOBAL CLIMATE CHANGE, Figure 2.1

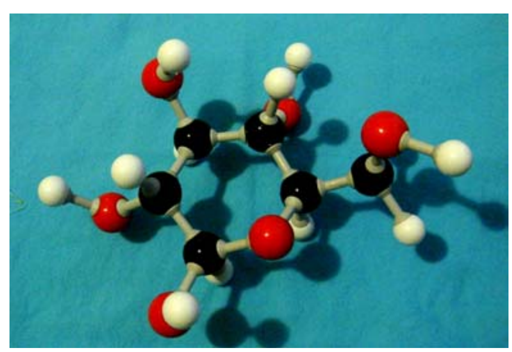


Carbon Reactions & Climate



- Photosynthesis:
  - $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$
- Aerobic Respiration:
  - $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + chemical energy
  - Gets back the original gasses and energy
- Anaerobic (no Oxygen) respiration:
  - $C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$ + chemical (less) energy
  - Gets back energy and CO_2 plus Methane
- Methane Oxidizes in the free atmosphere
  - $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + energy
- Glucose is actually $CH_2OH(HCOH)_4HCO$
  - Has both linear and ring structures, latter predominant

GLUCOSE



CYANOBACTERIA

$2Fe^{++}O + O_2 \rightarrow Fe^{+++}{}_2O_3$

Würstite → Hematite

Insoluble in alkaline conditions

Ozone protects against UV radiation

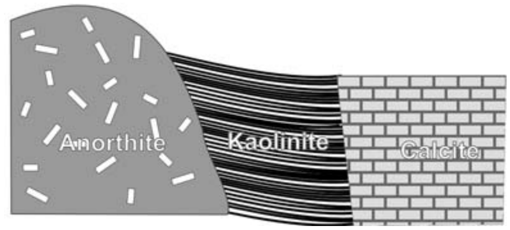
$O_2 + UV \leftrightarrow 2O$

$O_2 + O \leftrightarrow O_3 + UV$

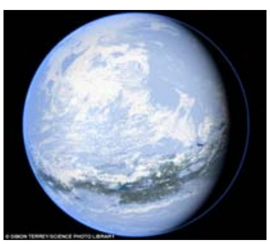
Chemical Weathering of Igneous Rocks Also Consumes CO_2

$H_2O + CO_2 \leftrightarrow H_2CO_3$

$2CaAl_2Si_2O_8 + 2H_2CO_3 + 2H_2O \rightarrow Al_4(Si_4O_{10})(OH)_8 + 2CaCO_3$

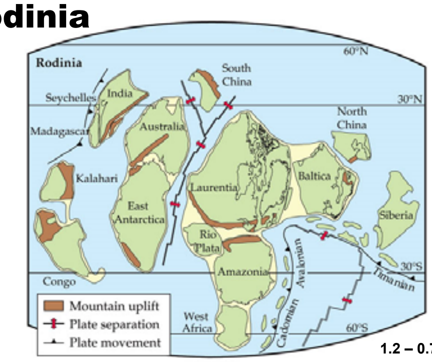


Snowball Earth



- Two episodes:
  - 2.5 BYA, end of Archean
  - 0.8 BYA, Neoproterozoic
- Sun was cooler
- Cyanobacteria decresed atmospheric CO_2
- Newly released O_2 oxidized CH_4
- Ice & snow reflected solar heat
- Planet covered by ice
- Ended as CO_2 from volcanoes and decomposition built up over the ice.
- Gaia Hypothesis: Life cooperates to maintain habitable conditions.

Formation and Breakup of Rodinia



1.2 – 0.75 BYA

GLOBAL CLIMATE CHANGE, Figure 2.5

Chemistry Review

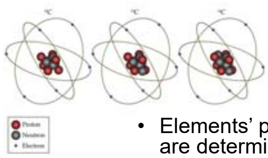
- **Element:** Each atom has the same number of protons in its nucleus and (generally) the same number of electrons orbiting around it
- Properties can be deduced from the **Periodic Table**
- **Molecules** are stable groups of one or more atoms
- Ions are molecules that become charged by gaining or losing an electron. For example carbonic acid dissociates in water to produce a proton and a bicarbonate ion:
  - $H_2CO_3 \rightarrow H^+ + HCO_3^-$

Periodic Table

H																		He
Li	Be												B	C	N	O	F	Ne
Na	Mg												Al	Si	P	S	Cl	Ar
K	Ca		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr		Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	* *	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uuq				

*Lanthanide series	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
* * Actinide series	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Isotopes



- Elements' places in the periodic table are determined by the number of protons, p^+
- They can have varying numbers of neutrons.
- For example ^{12}C, ^{13}C and ^{14}C
- All have 6 protons,
- But they have 6, 7 and 8 neutrons, respectively
- Carbon 14 is **Unstable** with a half life of 5370 years:
  - ½ gone in 5370 yr, ¾ in 10740 yr …

Radioactive Dating

- Decay of ^{14}C:
  - $^{14}C \rightarrow {}^{14}N + e^- + \overline{\nu}_e$
- Cosmic rays make ^{14}C from ^{14}N
- Can determine age from $^{14}C/^{12}C$, i.e., D/P

$$t = \frac{T_{\frac{1}{2}}}{\ln 2}\ln\left(1 + \frac{D}{P}\right)$$

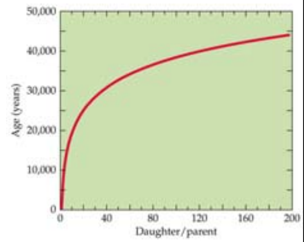


TABLE 2.1 Radioisotopes used in dating ancient rocks, the stable products they turn into, and rates of decay in terms of half-life		

Parent isotope	*Stable daughter product*	*Half-life (billions of years)*
^{235}Uranium	^{207}Lead	0.704
^{40}Potassium	^{40}Argon	1.25
^{238}Uranium	^{206}Lead	4.5
^{232}Thorium	^{208}Lead	14.0
^{87}Rubidium	^{87}Strontium	48.8
^{147}Samarium	^{143}Neodymium	106.0

Source: http://pubs.usgs.gov/gip/geotime/radiometric.html

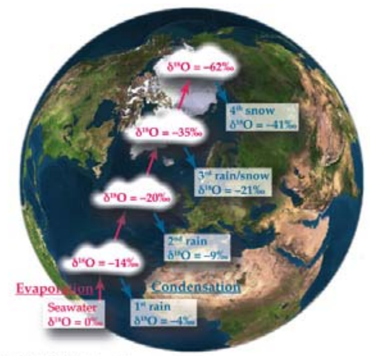
NOTE: Radiocarbon is used to date organic material, not "rocks".

***GLOBAL CLIMATE CHANGE,* Table 2.1**

Isotopes in Phase Changes

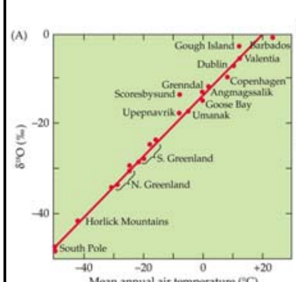
- At a given temperature all particles have the same average kinetic energy = ½ mv^2
- Thus, heavier isotopes are less likely to evaporate and more likely to condense
- For example, two stable isotopes of Oxygen, ^{16}O (99.76%) and ^{18}O (0.20%)
- Their ratio, $\delta^{18}O = [^{18}O]/[^{16}O]$, decreases with latitude because $H_2{}^{18}O$ is less likely to evaporate and more likely to condense
- The same kind of fractionation occurs in forming shells of marine organisms
- But both kinds of fractionation are less pronounced at warmer temperatures

δO¹⁸ as a Function of Latitude

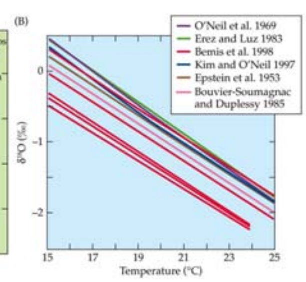


***GLOBAL CLIMATE CHANGE,* Figure 2.9**

Relation of δ¹⁸O to Temperature

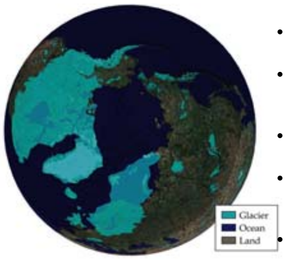


Precipitation



Shells of Marine Organisms

Global Temperature (Actually Ice Volume) Effect



- ^{18}O gets left behind in the sea or falls as rain.
- $\delta^{18}O$ in the icecaps is thus depleted by ~30$^{o}/_{oo}$
- At the greatest advance, there was twice as much ice as now
- Resulting in an increase of oceanic $\delta^{18}O$ of ~1.0 $^{o}/_{oo}$
- This despite the much larger volume of the sea relative to the ice
- Similar fractionation happens with Deuterium (D = ^2H) forming D^1HO or D_2O, only more so.

Carbon Isotope Fractionation in Photosynthesis

- ^{12}C is 98.9% of stable Carbon and ^{13}C is 1.1%
- Plants prefer $^{12}CO_2$ to $^{13}CO_2$
- They can discriminate when CO_2 is abundant.
- When CO_2 is scarce, they take what they can get
- Thus, low values of [^{13}C]/[^{12}C] = $\delta^{13}C$ in organic Carbon indicate abundant CO_2, and conversely
- Depleted values of $\delta^{13}C$ in the inorganic surrounding also indicate abundant CO_2 because most of the ^{12}C ended up in plants.

The Past Billion Years

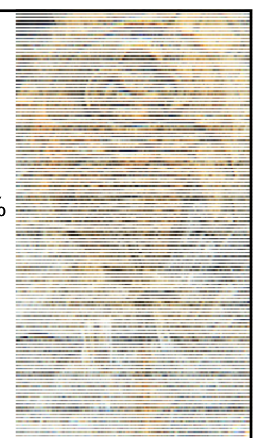
- Only primitive marine plants and animals
- Snowball episode at 730 MYA:
- High $\delta^{18}O$, indicating sequestering of ^{16}O in icecaps.
- Decline in inorganic $\delta^{13}C$, indicating less photosynthesis
- Appearance of F^{++} in sediments, indicating oxygen depletion
- Iridium from meteors accumulated on top of the ice and was concentrated in a shallow layer when it melted
- But not everywhere—Snowball vs. Slushball?
- Glacial till covered by "Cap Carbonates" mark the end of the episode
- Melting was probably fast (2 kyr?)

Contact between glacial marine Ghaub Fm (DF, debris flows; IRD, ice-rafted debris) & Keilberg Mb (CD, post-glacial cap dolostone) on Otavi foreslope, northern Namibia.

Causes

- Bloom emphasizes CO_2 loss through faster weathering of igneous rock (timescale >10^6 yr)
- I don't think so… Other possible causes:
  - Dimmer sun
  - Gaia not fully evolved
  - Solution of CO_2 in the sea (timescale 10^3 yr)
  - Runaway ice-albedo feedback

Cambrian Explosion



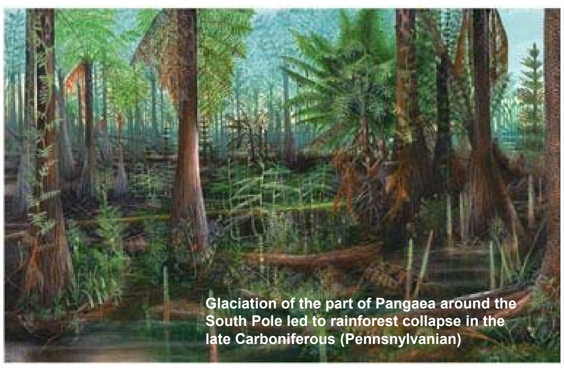
- 540 MYA
- Continents low-lying
- Rising sea covered > 80% of land
- Atmospheric O_2 increased to ~15%
- Ozone layer excluded more UV radiation
- All modern animal phyla emerged

GONDWANALAND

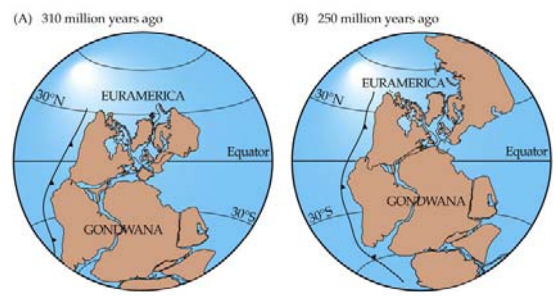
Ordovician-Silurian Extinction

- **440 MYA**
- Perhaps due to glacial onset as Gondwana slid southward
- Sea-level fall eliminated shallow coastal environments
- Subsequently plants began to colonize the land
- Difficult environment
  - Desication
  - Scarce nutrients
  - But more sunlight and faster diffusion of CO2
- Liverworts and then vascular plants emergred

Carboniferous Forest



Emergence of Pangaea



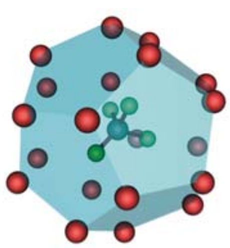
Late Carboniferous

Late Permian

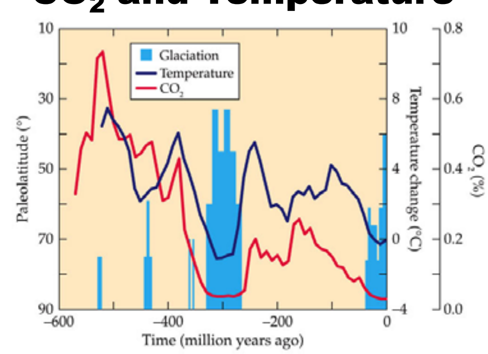
GLOBAL CLIMATE CHANGE, Figure 2.20

The Great Dying

- 251 MYA, Permian→Triassic
- Vascular plants enhanced photosynthesis
  - O_2 rose from 15 to 20%
  - CO_2 declined from 0.5% to < 0.05%
  - Led to falling temperatures and high latitude glaciation
- But Pangaea moved to straddle the equator
  - Lowering Earth's albedo
  - Dry conditions in continental interior led to evolution of gymnosperms (conifers)
- One possible mechanism
  - Warming temperatures led to release of methane from high-latitude marine hydrates
  - 96% of marine and 70% of land species disappeared



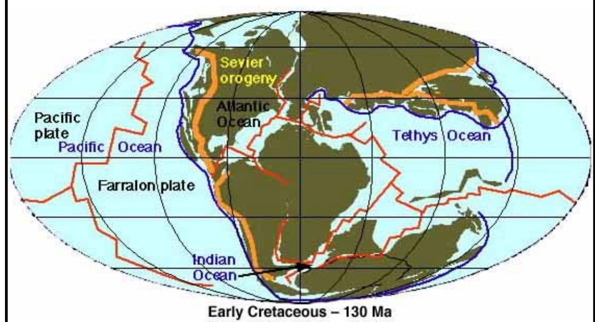
CO_2 and Temperature

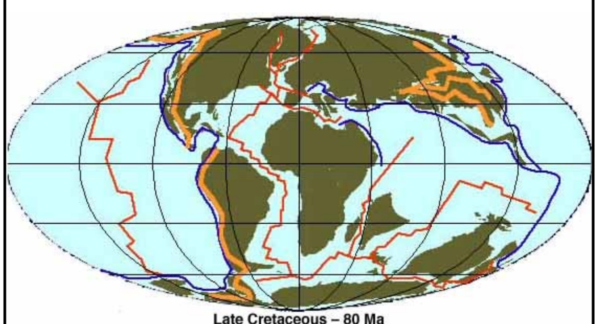


GLOBAL CLIMATE CHANGE, Figure 2.19

The Mesozoic

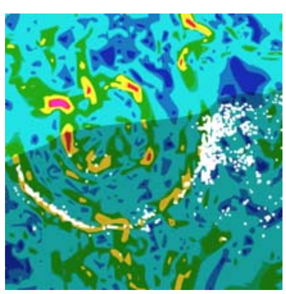
- Dinosaurs!
- 250-65 MYA
- Triassic, Jurassic & Cretaceous
- Warm, dry continents
- Warmer (10ºC) deep ocean than today
- Ice-free poles
- Flowering plants emerged
- Started with the breakup of Pangaea and ended with a bang



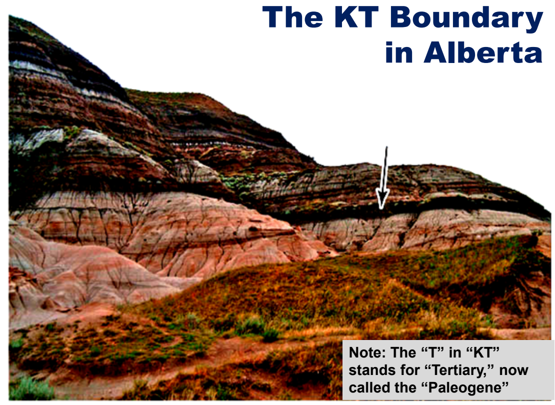


The Impact

- Hit north end of the Yucatan, then underwater
- Immense tidal wave
- Radiant heat started fires
- Scattered soot shocked quartz, tektites, and Iridium worldwide
  - Ir is abundant in meteorites, but most of the Earth's Ir ended up in the core
- Apparently killed all the non-avian dinosaurs
- Impactor was hypothetically one of the Baptistina asteroid family
  - Also lunar crater Tycho
  - But timelines and compositions don't work out



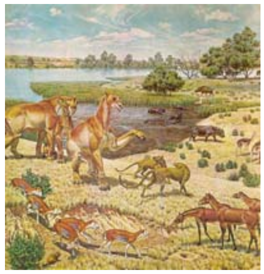
The KT Boundary in Alberta



GLOBAL CLIMATE CHANGE, Figure 2.23

Cenozoic

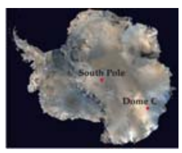
- Started as biota recovered from the KT Impact
- Age of Mammals
- Continents in more or less present configuration
  - Antarctica around S Pole
  - North Pole in landlocked
- Generally a time of cooling and falling atmospheric CO_2 concentration
- Ice caps at both poles by the end



Antarctic Ice Cores

- Laborious drilling through kilometers of ice in 3-m steps
- Ice is in annual layers
  - Snow falls in summer
  - Compacts into ice during winter
  - Contains bubbles of air and isotope signatures
- At Vostok 4000,000 yr of usable core

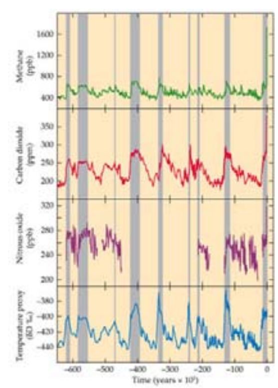
Ice Dome C



- **Operated by European consortium**
- **Ice is thicker (3270 m) than at Vostok with no liquid water lake under it**
- **Analysis to 650 KYA, so far**
- **Data on: δD, CO_2 and CH_4**
- **Eight glacial episodes and 9 interglacials**

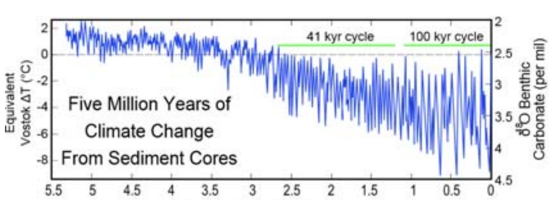
Glacial Cycles from Dome C

- Shows brief warm inter-glacial intervals
- Longer glacial intervals
- 100 KY cycles
- Gradual cooling, quick warming
- Greenhouse gases change in step with temperature
- Timescales mach slow changes in Earth's orbit



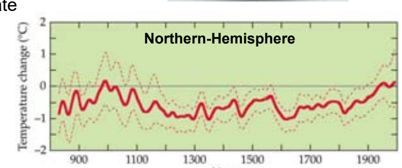
Something Strange With Glacial Cycles

- Marine Isotope Stages
- Reconstructed ocean temperatures from $\delta^{18}O$ in foraminifera and pollen from deep-sea cores
- Matches 100 ky glacial cycle back to ~1 MYA
- Then 41 kyr back to 2.5 MYA
- These periods correlate with changes in Earth's orbital eccentricity and axial tilt, respectively
- Why is there a change in dominant period?

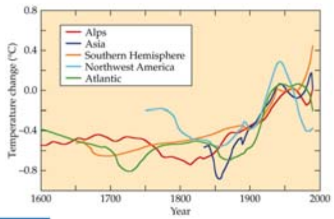


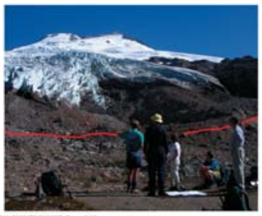
Tree-Ring Reconstructions

- Dendrochronology
- Annual layers added below bark
- Light colored early wood with big cells formed in summer
- Dark colored late wood with small cells formed in winter
- Thickness of rings responds to temperature
- Sequences can be used to determine dates and to reconstruct climate



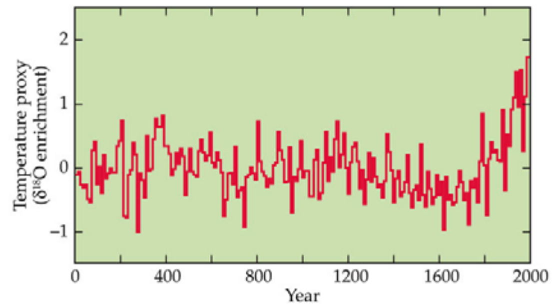
Extents of Mountain Glaciers



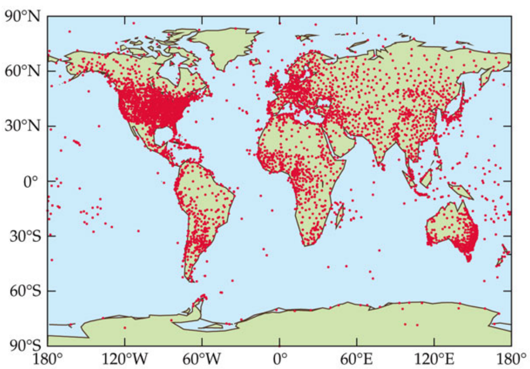


GLOBAL CLIMATE CHANGE, Figure 2.36

Ice Cores from Low-Latitude, High Altitude Glaciers



Direct Instrumental Measurement Sites



GLOBAL CLIMATE CHANGE, Figure 2.40 (Part 1)

SUMMARY

- CO_2 is controlled by photosynthesis and has a significant role in climate
- Earth History:
  - Cyanobacteria make O_2 from CO_2
  - Great Oxidation Event
  - 2 Snowball Earths 2.5 & 0.75 BYA
  - Rodinia & Gondwana
  - Extinctions: 5 including KT
  - Glacial episodes 520, 300 MYA and now
- Isotopes (δ18O, δD, δ13C) as proxies for climate
- Cenozoic 100 Kyr glacial cycles
- Historical temperatures: Medieval Optimum, Little Ice age, & 20th and 21st Century Warming
  - Based upon instrumental record and diverse proxies