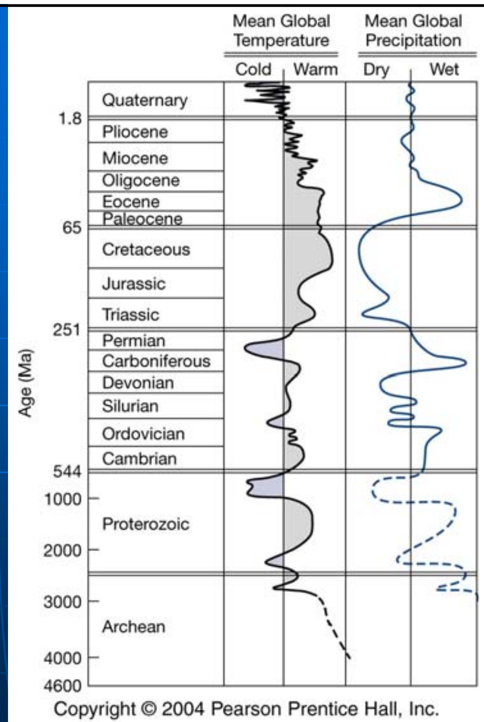
Long-term Climate Change

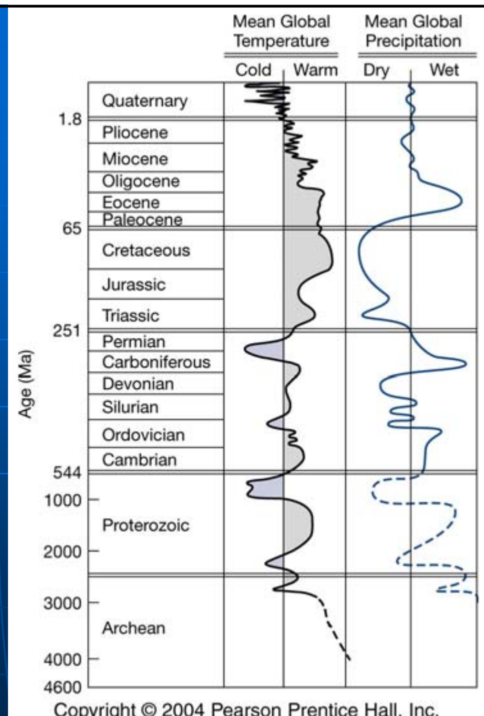
We are in a period of relative warmth right now but on the time scale of the Earth's history, the planet is cold.



Long-term Climate Change

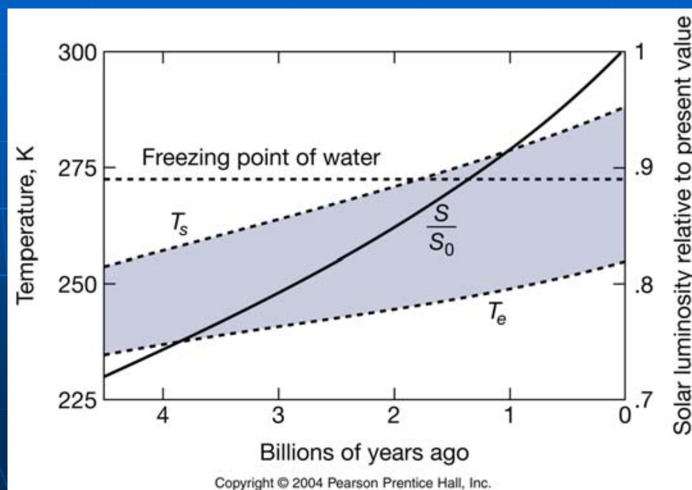
The Archean is thought to have been warmer, or at least as warm, as it is now. But the sun was a lot fainter.

This is the "Faint Early Sun Paradox".



Faint early sun paradox

About 4.6 billion years ago the sun was roughly 30% less luminous than today, but yet the oceans were not frozen. Why not?



Faint early sun paradox

Need another ~70 W/m^2 heat 4 bya to prevent freezing of oceans.

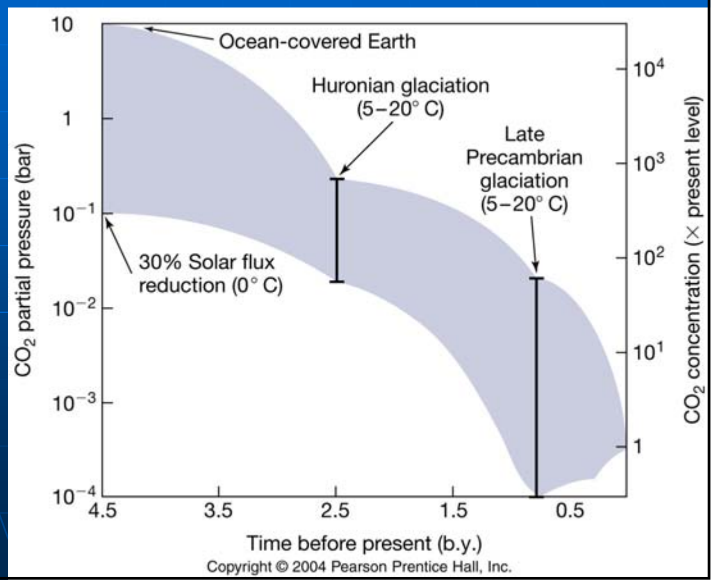
Possible sources:

- additional geothermal flux from interior
  (No - currently 0.06 W/m^2, 4 bya would have been about 0.3 W/m^2)
- albedo/ice cover
  (Unlikely – albedo currently is 0.3, would have needed to be almost 0.)
- much larger G-H effect
  (CO_2 concentration was probably much higher than now.)

Faint early sun paradox

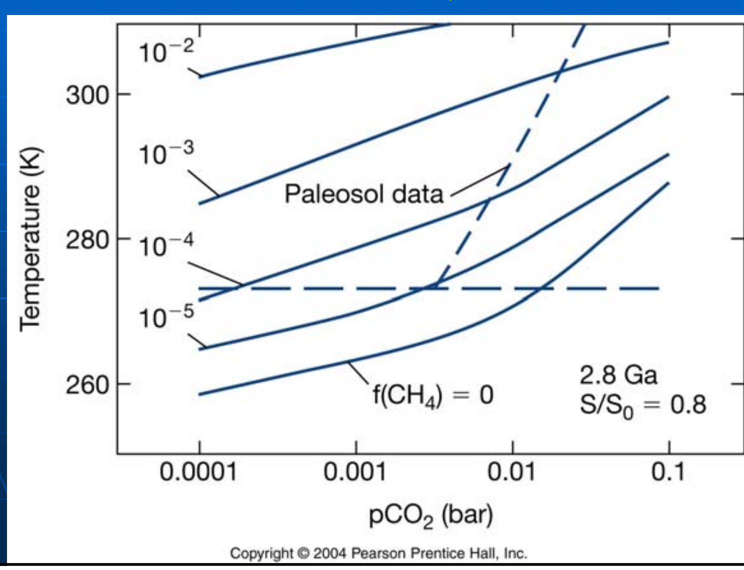
How much CO_2 is necessary to keep the earth from freezing?

About 1000x today, or 0.3 bar



Faint early sun paradox

How much CO_2 is necessary to keep the earth from freezing if CH_4 is also present?



Faint early sun paradox

CH_4 comes from methanogenic bacteria. These convert H_2 from early atmosphere into CH_4 by way of:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

CH_4 is 30x as potent a G-H gas as CO_2.

The early earth is likely to have been kept warmer by a combination of much higher CO_2 and CH_4 concentrations.

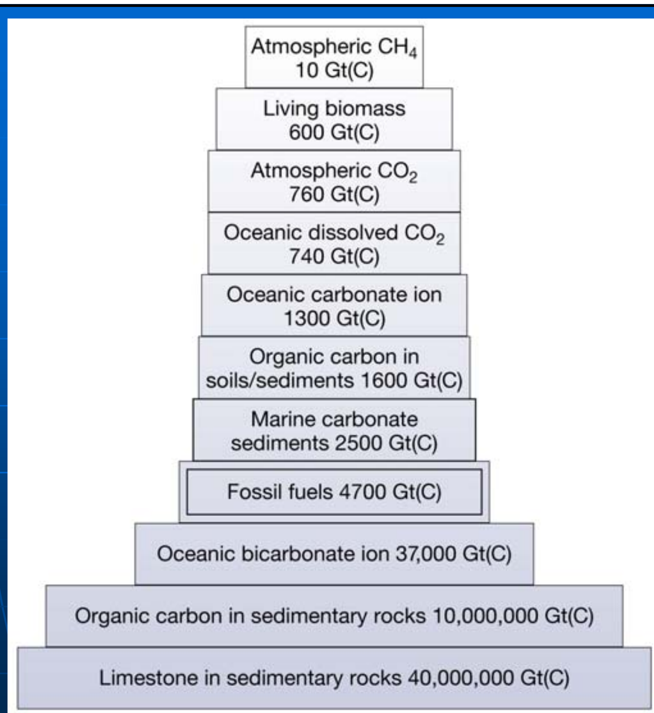
Long-term climate change

How is the climate of the earth controlled over long time scales?

Climate is controlled by a trade-off between solar luminosity and G-H gases – most importantly CO_2.

On a short time scale (less than a century) atm. CO_2 is controlled by respiration, photosynthesis and decomposition.
On a long time scale CO_2 is largely controlled by geological processes.

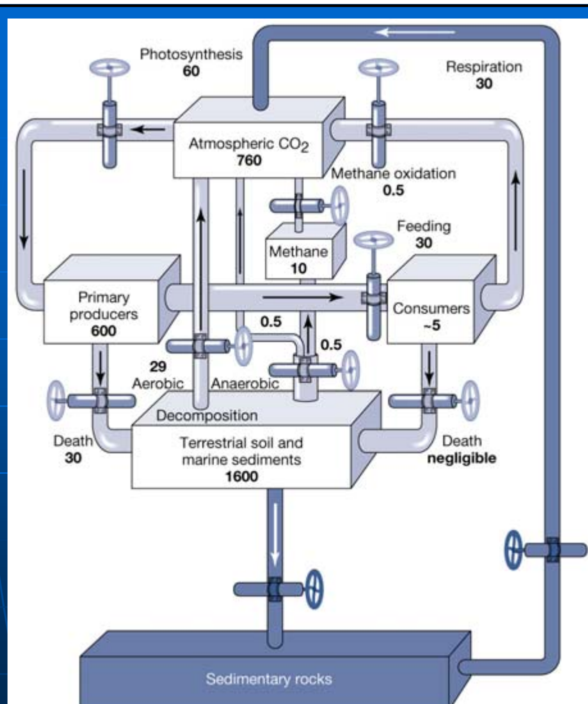
Carbon reservoirs



Short-term Organic Carbon Cycle

inflow to atm: 30 Gt/yr from respiration + 30 Gt/yr from decomposition

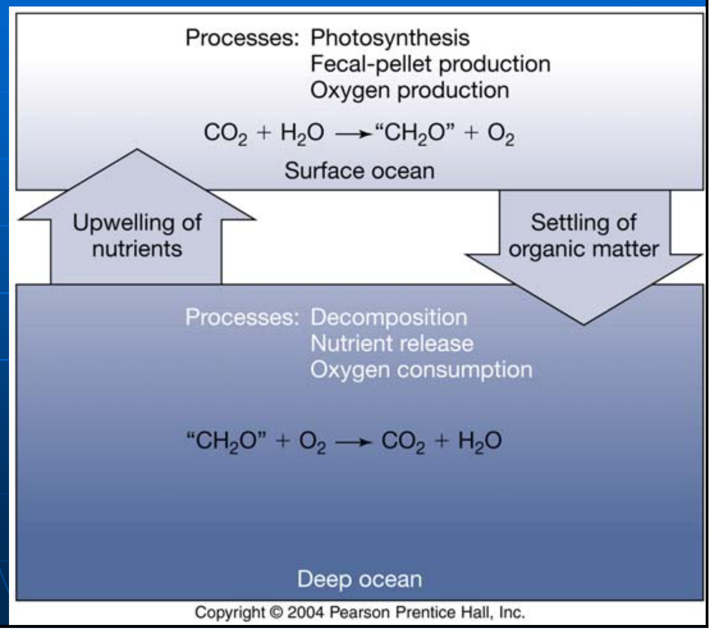
outflow: 60Gt/yr from photosynthesis



Marine Organic Carbon Cycle

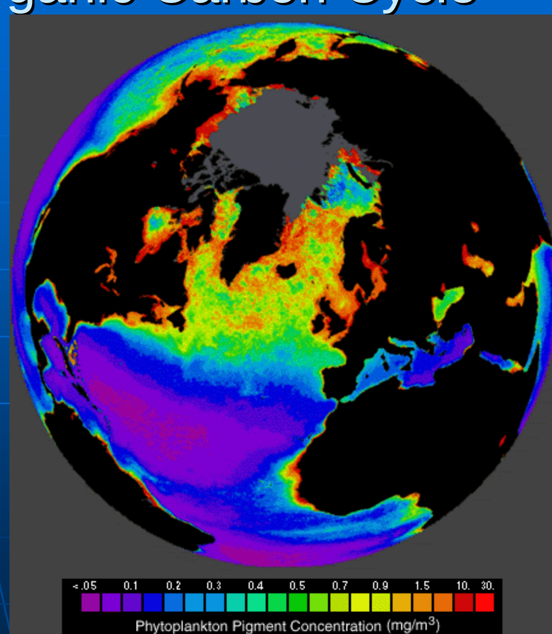
Biological pump

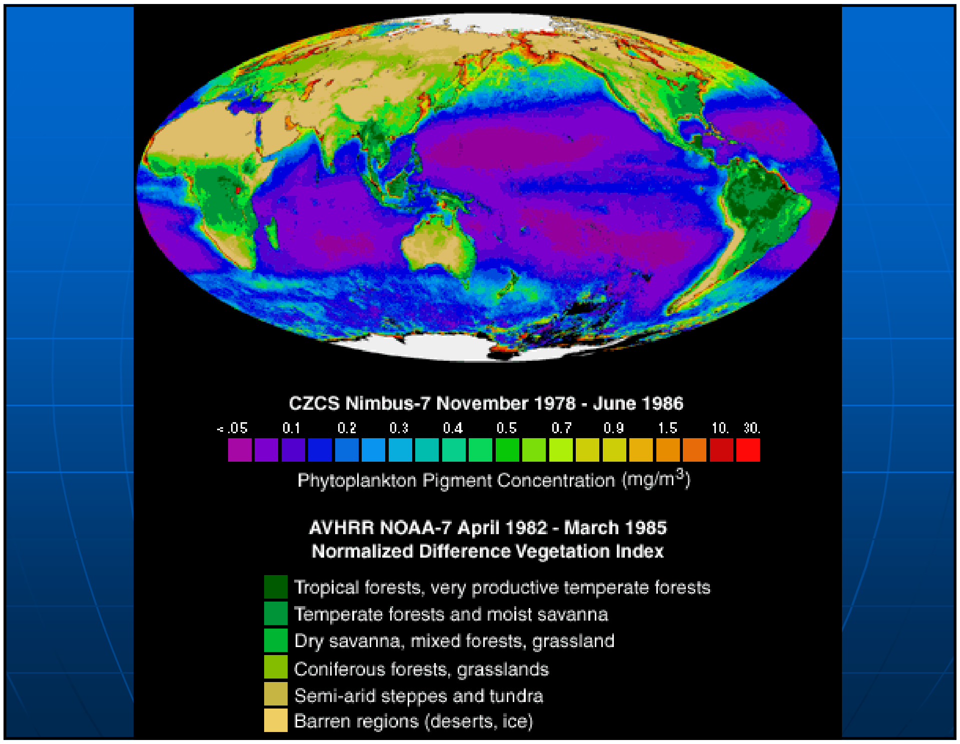
Deep ocean much richer in CO_2 than surface waters.



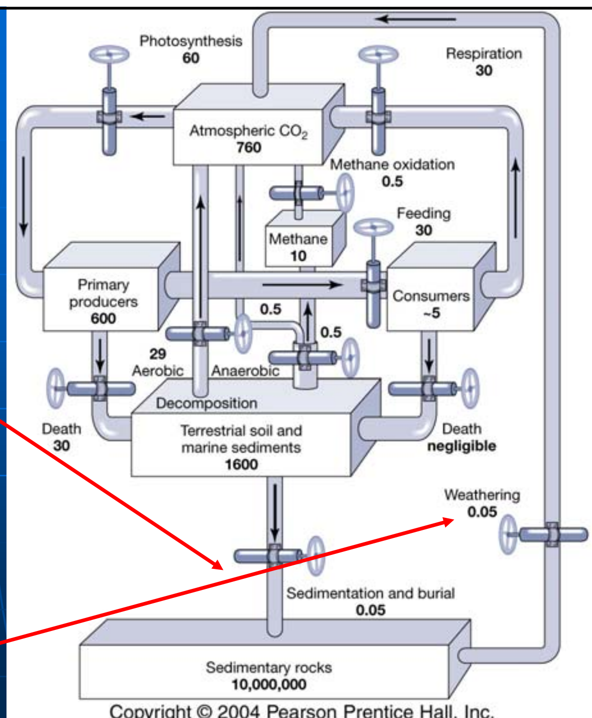
Marine Organic Carbon Cycle

CZCS shows areas of primary productivity in ocean.



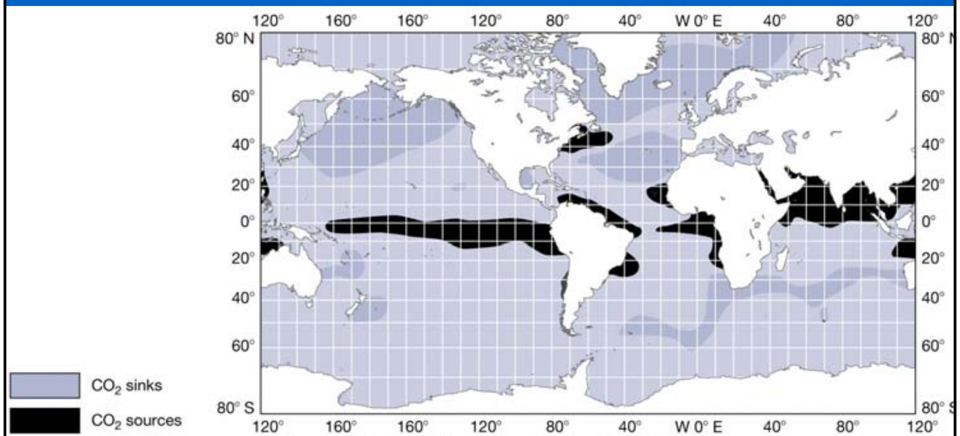


Long-term Organic Carbon Cycle



Human burning of fossil fuels is essentially the weathering process speeded up by a factor of a million or so.

Inorganic Carbon Cycle



Flow of CO_2 is down the concentration gradient.
Ocean is source of atm CO_2 where ocean CO_2 is higher than atm, as in regions of upwelling. Ocean is sink for atm CO_2 where primary productivity is high and CO_2 has been removed from surface water.

Inorganic Carbon Cycle

The ocean's ability to take up excess atm CO_2 is limited.

1. carbon dioxide dissolves in water to produce carbonic acid (H_2CO_3).

$$CO_2 + H_2O \rightarrow H_2CO_3$$

2. carbonic acid molecules dissociate in water to produce bicarbonate ions (HCO_3^-).

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

3. bicarbonate ions dissociate to produce carbonate ions (CO_3^{2-}).

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

4. But this reaction can proceed in either direction. The amounts of bicarbonate and carbonate ions is adjusted according to the pH of the water. If the pH is below neutral (acidic), the reaction proceeds to the left. If it is above neutral, the reaction proceeds to the right.

Inorganic Carbon Cycle

The ocean's ability to take up excess atm CO_2 is limited.

1. CO_2 dissolves -> carbonic acid -> bicarbonate + H^+

$$CO_2 + H_2O \rightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

2. Now pH is lowered, so H^+ reacts with carbonate ion -> bicarbonate ion

$$HCO_3^- \leftarrow H^+ + CO_3^{2-}$$

3. Now the net result is:

$$CO_2 + H_2O + CO_3^{2-} \rightarrow H^+ + HCO_3^- + CO_3^{2-} \rightarrow 2HCO_3^-$$

4. there are 2 more bicarbonate ions and 1 less carbonate ion
5. This can only continue as long as there are carbonate ions in the ocean – But there are a lot more fossil fuels than carbonate ions so ocean's ability to take up excess CO_2 is limited.

Chemical Weathering

1. atm CO_2 dissolves in rainwater to produce carbonic acid (H_2CO_3)
2. Carbonate weathering:
   carbonic acid dissolves calcium carbonate to produce calcium ions + bicarbonate ions.

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

3. Silicate weathering:
   carbonic acid dissolves silicates (eg. wollastonite) to produce calcium ions, bicarbonate ions, silica and water.

$$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O$$

4. RHS gets transported via rivers to ocean

Note: Silicate weathering uses twice as much atm CO_2 as carbonate weathering.

Mineral Deposition

1. marine organisms use calcium ions and bicarbonate ions in seawater to produce their shells (calcite = $CaCO_3$)
2. Carbonate precipitation:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2CO_3$$

3. When these organisms (foraminifera, corals, shellfish) die, their shells sink to the bottom of the ocean. They arrive intact where the ocean depth is less than 4 km (shallow tropical waters and mid-ocean ridges). They dissolve before reaching the bottom of the deep ocean basins.
4. At mid-ocean ridges they are buried by sediments and carried across the ocean by seafloor spreading.
5. When tectonic uplift occurs (after millions of years) the limestones are exposed at the Earth's surface and the cycle continues.

Inorganic Carbon Cycle (Summary)

Carbonate precipitation is just the reverse of carbonate weathering.

In silicate weathering however, there is a net removal of CO_2 from the atmosphere because of the extra carbonic acid molecule used.

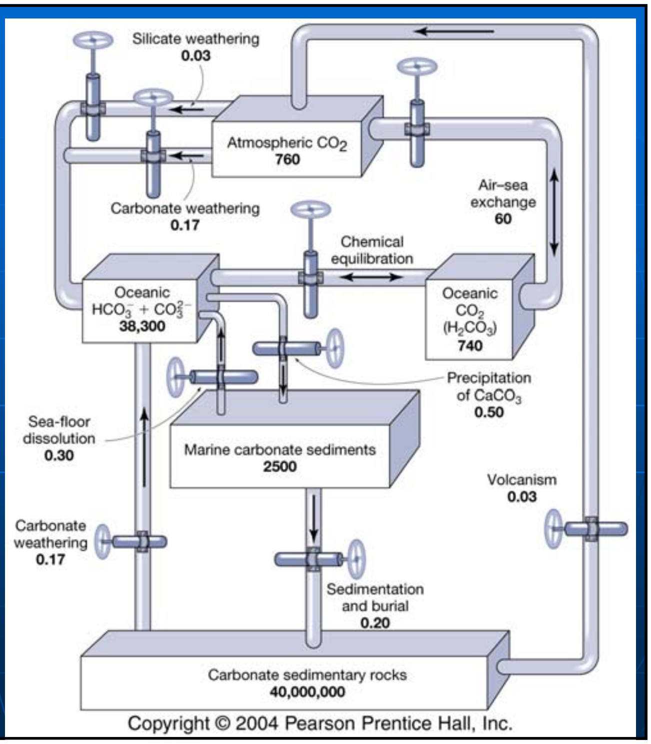
Net result:

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

The rate of conversion of atm CO_2 to limestone by silicate weathering is small (0.03Gton(C)/yr) but must be balanced otherwise the atmospheric supply of CO_2 would be depleted in a million years (using the ocean to supply the atm first).

This is short on geological time scales.

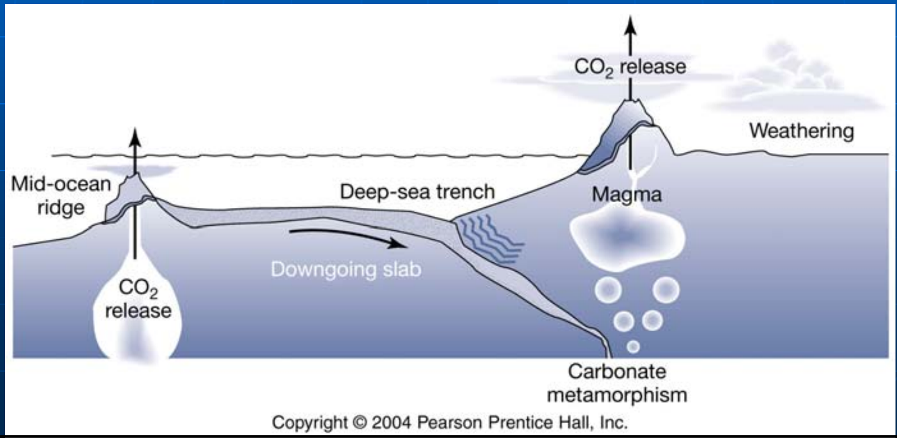
Inorganic Carbon Cycle (Summary)



Carbonate-Silicate Geochemical Cycle

Plate tectonics returns the CO_2 to the atmosphere via metamorphism and volcanoes. Carbonate metamorphism:

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$$

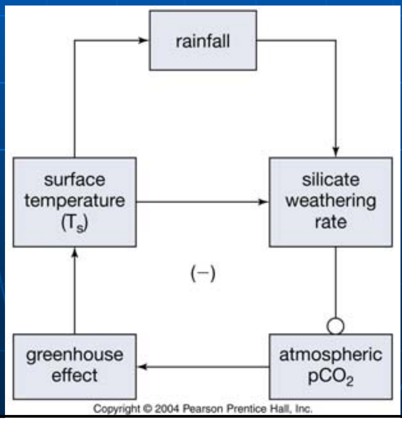


Carbonate-Silicate Geochemical Cycle

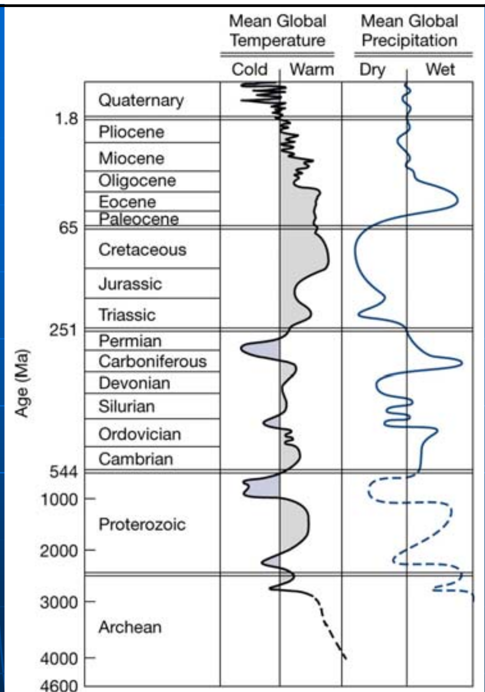
Together silicate weathering, carbonate precipitation and formation of carbonic acid in air are the reverse of carbonate metamorphism.

Over the history of the earth these have balanced out (unlike Mars, which has lost its CO_2-rich atm, and flowing water).

Feedback loops help to keep things in balance:



Long-term Climate Change

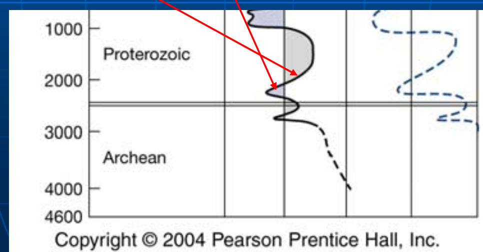


Earth's Historical Climate Change

5 main periods of glaciation. Why?

2.3 bya (Huronian)
Rise in atm. O_2 reacted with CH_4.
CH_4 greatly reduced.
Temp. cooled.

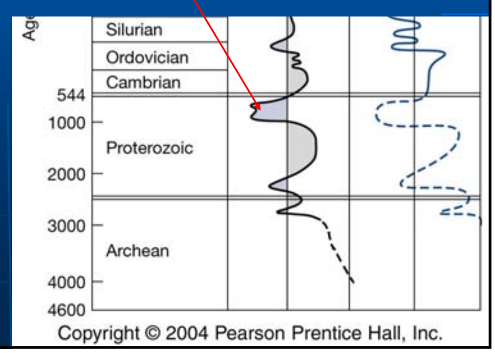
Recovery?
silicate weathering reduced by ice cover or more methanogenesis.



Earth's Historical Climate Change

0.6 – 0.8 bya (late Proterozoic)
"Snowball Earth" – even tropics were glaciated. Why?

All landmasses joined at equator – lots of silicate weathering. Brings down atm. CO_2. Earth cools. Polar ice sheets advance to lower latitudes. At ~ 30^o latitude, positive (albedo) feedback becomes so strong that system is unstable. Oceans freeze. Earth freezes.
Global temp -50^{o}C.
Albedo > 0.6.

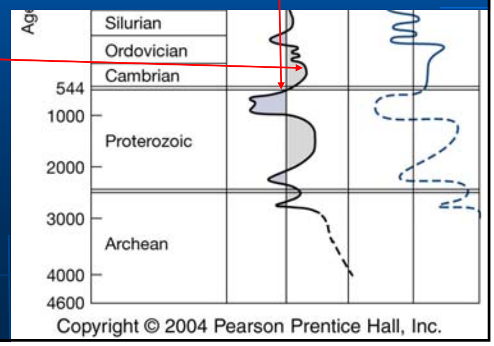


Earth's Historical Climate Change

Recovery from late Proterozoic "Snowball Earth"

Silicate weathering stopped (earth covered in ice).
CO_2 builds up in atm. from volcanic emissions.
(At modern rates of outgassing, CO_2 would reach 0.1 bar (300 x today's) in 10 m.y.)
Temp. increases, ice melts, positive feedback sets in. All ice could melt over a few thousand years.

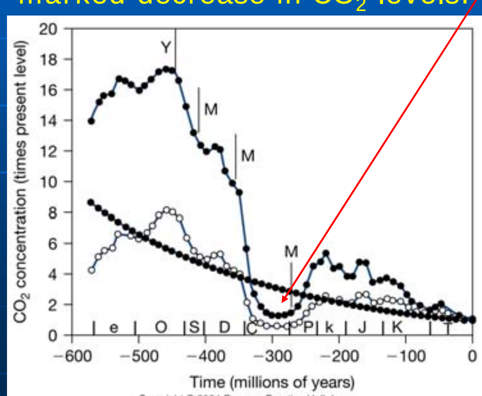
CO_2-rich atm.
low albedo.
surface T: 50 – 60ºC
Lots of silicate weathering.
CO_2 decreases
Climate restored.

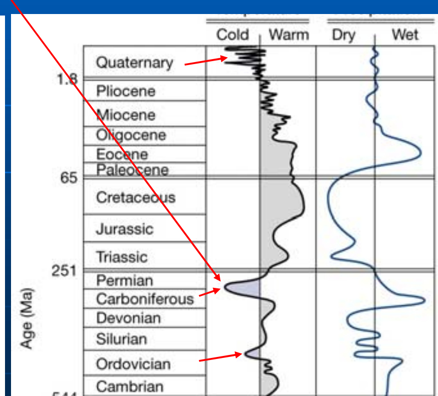


Earth's Historical Climate Change

3 more glaciations in Phanerozoic Eon (544 mya – present).
Ordovician is poorly understood.

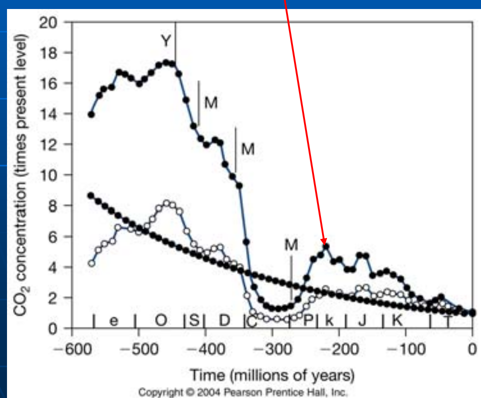
In Carboniferous the organic carbon burial rate doubled as a result of the formation of large coal beds. This led to a marked decrease in CO_2 levels.

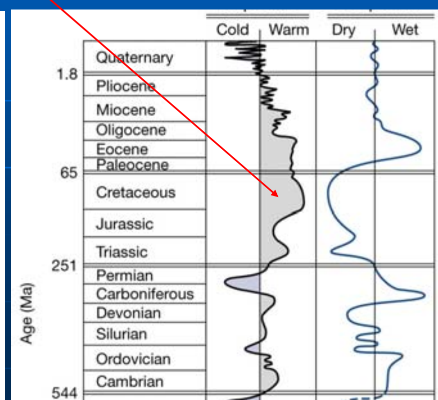




Earth's Historical Climate Change

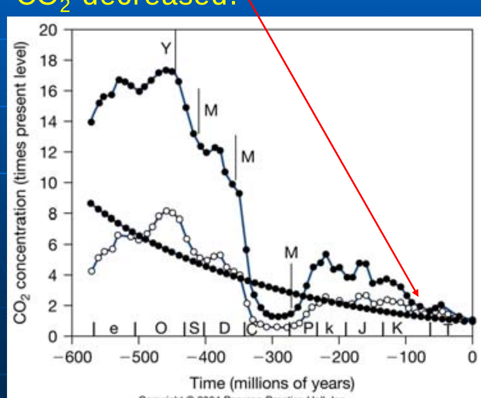
Mesozoic was warm.
2 – 6 ºC warmer at equator.
20 – 60 ºC warmer at poles.
CO_2 levels were 4 x as high. Why? Sea-floor spreading rates were high -> increased carbon metamorphism and volcanism.

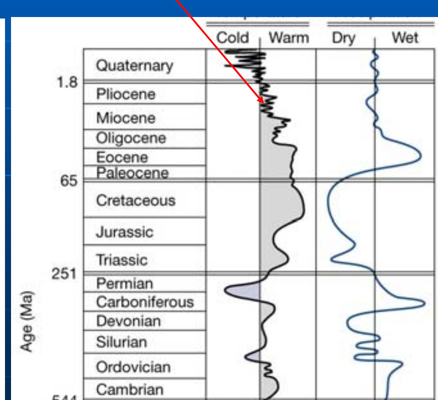




Earth's Historical Climate Change

Cooling occurred during Cenozoic. Why?
Decrease in mid-ocean spreading rates +
India collided with Asia (40 mya). Created massive uplifted terrain (Tibetan Plateau) – more weathering surface and created Asian monsoon rain. Weathering rates increased and CO_2 decreased.





Earth's Historical Climate Change

Thus Earth's climate on a long time scale has largely been controlled by G-H gases – primarily CO_2 and stabilized by silicate weathering.