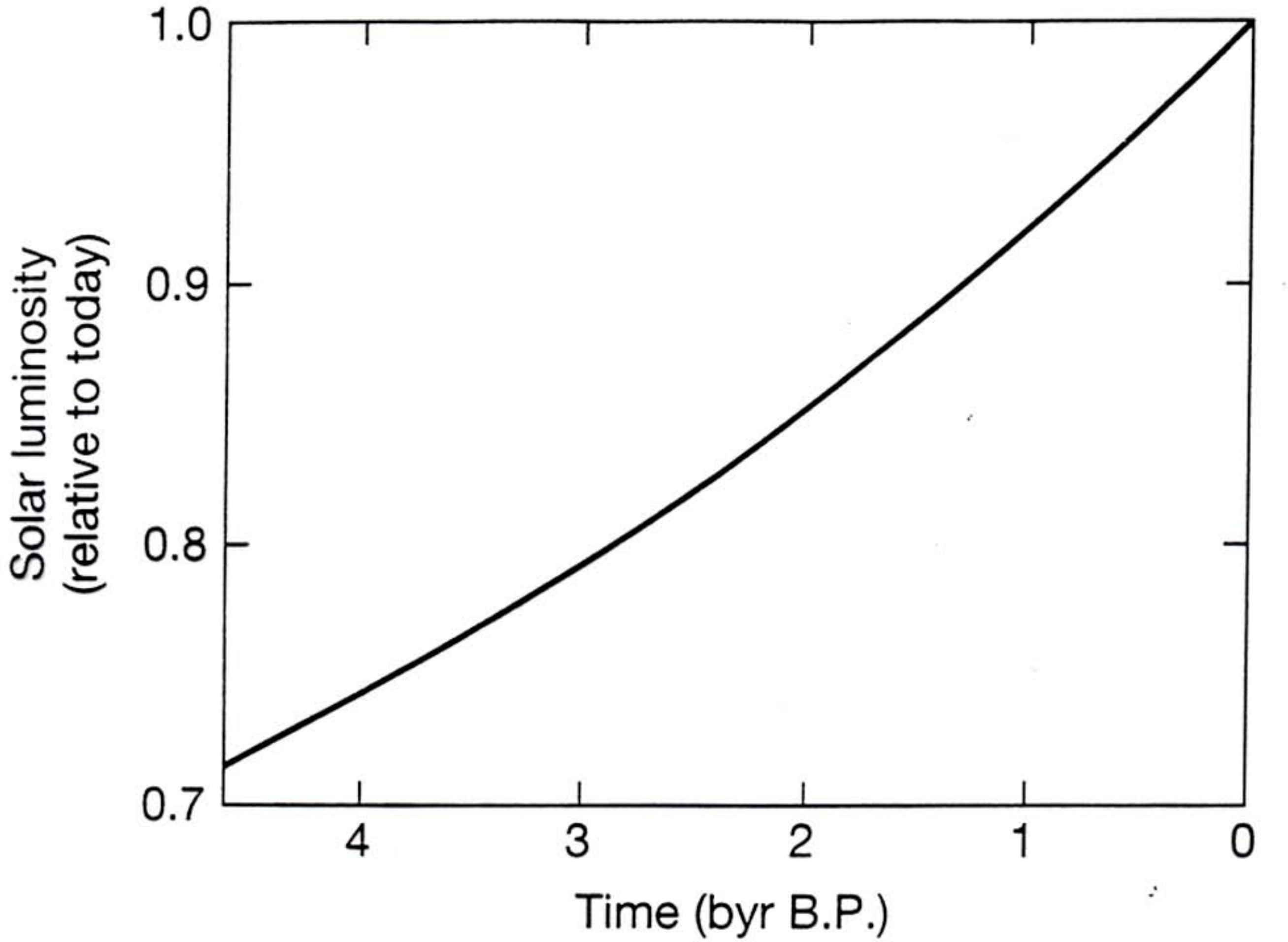
12.842 / 12.301 Past and Present Climate
Fall 2008

The Faint Young Sun Paradox
&
The Geochemical C Cycle
&
Climate on Geologic Time Scales

12.842 Paleo
Lecture #4
Fall 2008

The ‘Faint Young Sun Paradox’



Solar Luminosty ~30% less 4.6 Byr BP

→ Earth should have been frozen until ~2 Byr BP

Faint Young Sun Paradox

4 $^{1}H \rightarrow ^{4}He$
Incr. density= incr. luminosity

Liquid H_2O existed >3.5 Ga (sed. rocks, life, zircon $\delta^{18}O$)

Contemporary Solar Variability

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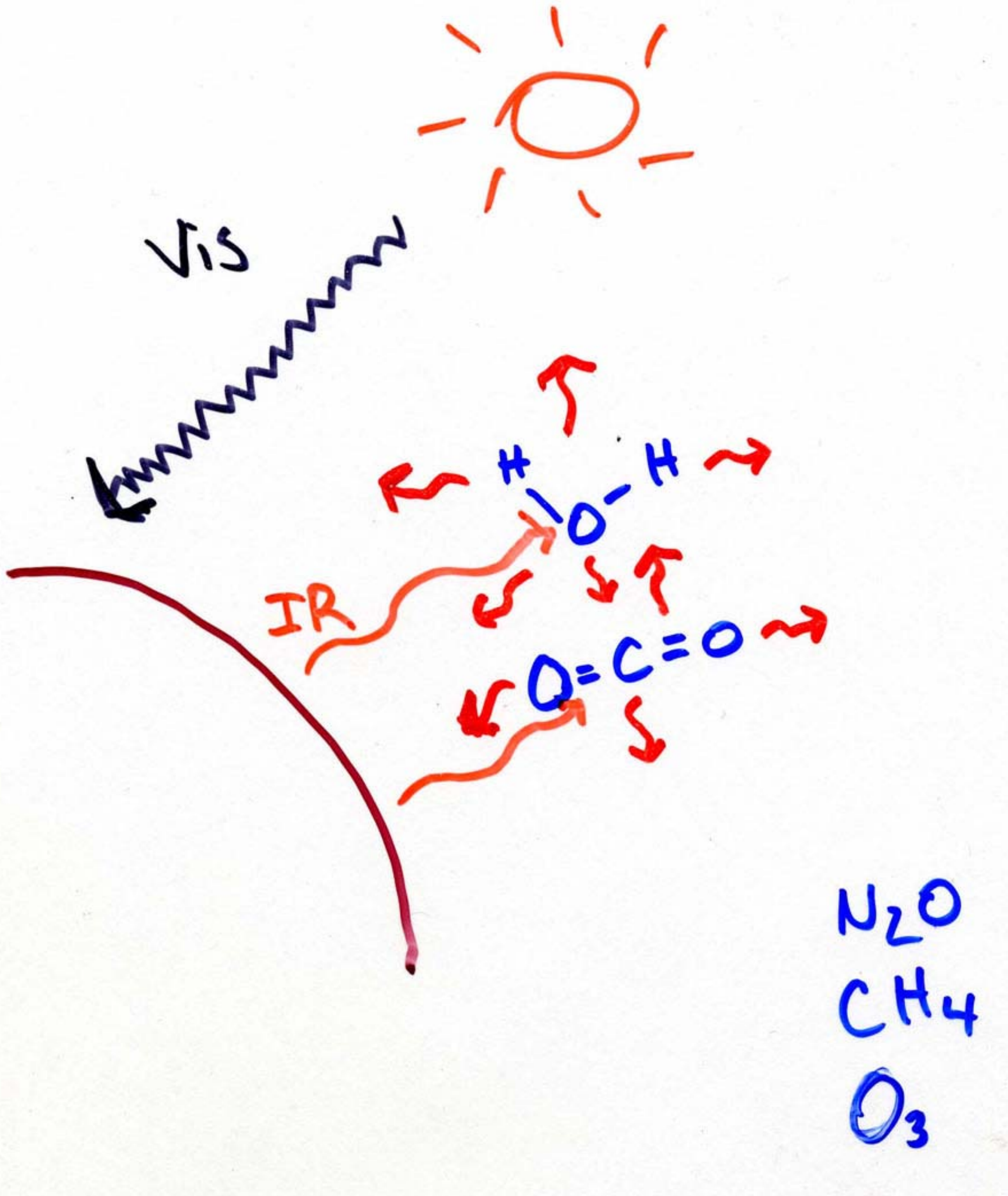
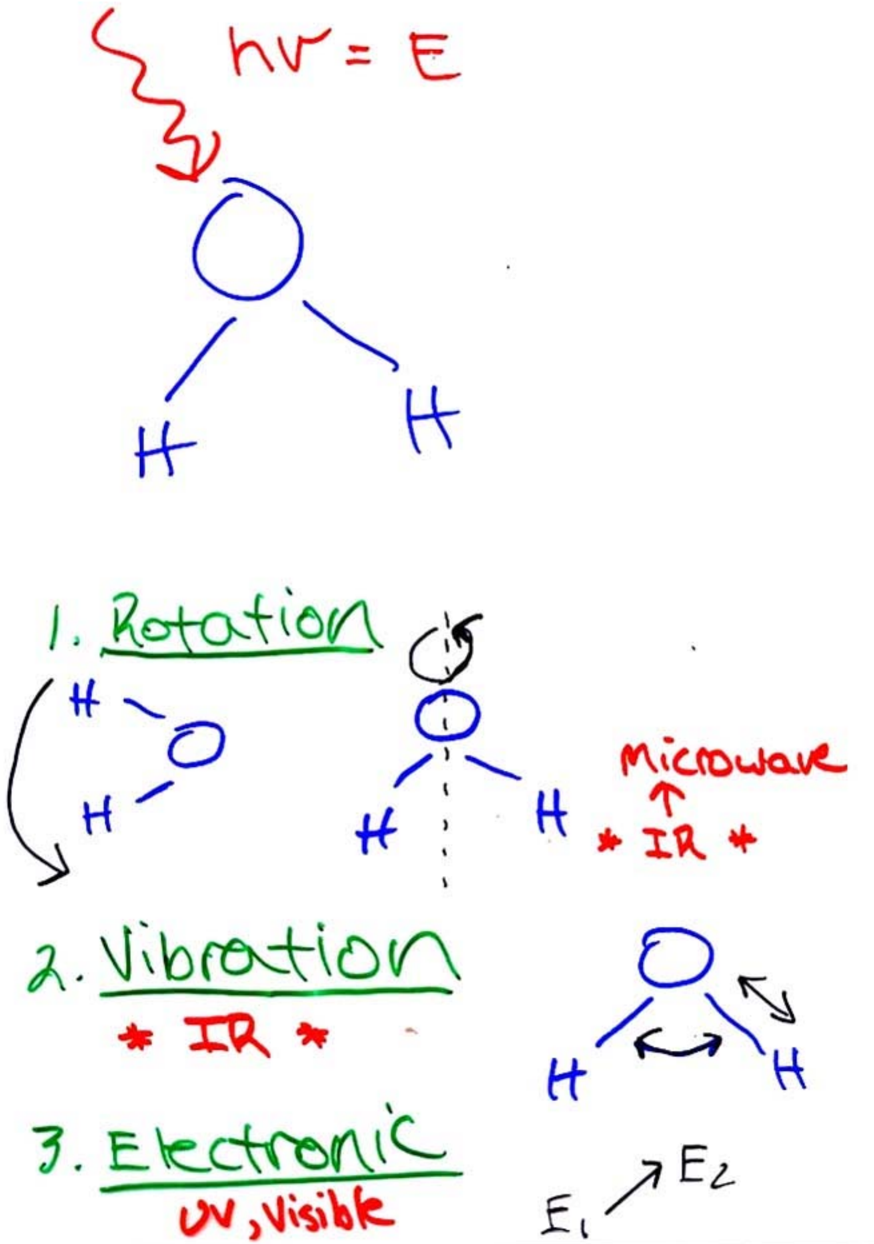
•Contemporary Solar Variability ~0.1%
•Associated with 11-year sunspot cycle



Greenhouse Gases absorb IR radiation efficiently



(1) Molecules acquire energy when they absorb photons.
(2) This energy will be released later as re-emitted photons.
(3) Atmospheric molecules are rotating rapidly (and in aggregate, randomly), so the re-emitted energy is random in direction.
(4) So: half of the re-emitted radiation is directed back towards the earth.

Simple Planetary Energy Balance

$E_{emitted} = E_{absorbed}$

① $E_{emitted}$

- Blackbody w/ effective radiating temperature, T_e

- Stefan-Boltzmann Law

$$E = \sigma T_{eff}^4 \qquad \left(\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4}\right)$$

→ Energy emitted per unit area

$$\sigma = \frac{2\pi k^4}{h^3 c^2}\frac{\pi^4}{15} = 5.67 \bullet 10^{-8} \quad w \quad m^{-2} \quad {}^\circ K^{-4}$$

- For entire surface of Earth

$$E_{emitted} = 4\pi R_{Earth}^2 \times \sigma T_{eff}^4$$

Adapted from
Kump et al. (1999)

② Energy Absorbed

$$E_{absorbed} = E_{intercepted} - E_{reflected}$$

$$= \pi R_E^2 \times S - \pi R_E^2 \times S \times A$$

$$= \pi R_E^2 S (1 - A)$$

$$E_{emitted} = E_{absorbed}$$

$$4\pi R_E^2 \times \sigma T_{eff}^4 = \pi R_E^2 S (1 - A)$$

$$\sigma T_{eff}^4 = \frac{S}{4}(1 - A)$$

$\Rightarrow$ If $\downarrow S$, Then $\downarrow T_{eff}$ or $\downarrow A$

Energy Absorbed

Adapted from
Kump et al. (1999)

$$\sigma \underline{T_{eff}}^4 = \frac{S}{4}(1 - A)$$

× Geothermal Ht. Flux

× Mass Loss of Sun

$$T_{eff} = \sqrt[4]{\frac{S}{4\sigma}(1-A)}$$

Today: $= 255\,K = \underline{-18°C}$

Earth surface Temp $= 15°C$

$$T_s - T_{eff} = \underline{\Delta T_g}$$ Greenhouse Effect

$$15° - (-18°) = 33°C$$

$\downarrow S$ Compensated by $\uparrow \Delta T_g$

Non-greenhouse vs. greenhouse earth surface temperature

Adapted from
Kump et al. (1999)

But: the atmosphere is a leaky greenhouse…

If we assume that the atmospheric gas composition is what it is today, and calculating the full radiative physics assuming that the atmosphere does not convect, then the earth would be ~30°C warmer than it is now. That is, the earth’s greenhouse effect is only ~50% efficient.

The difference is due to convection: when the near-surface air warms up, it rises in the atmosphere and can lose radiation to space more effectively.

Albedo Change

$A \sim 0.3$ Today

$A \sim 0.02$ 30% lower S

→ Way too low for water-covered planet (Clouds)

↑ Geothermal Heat Flux ?

(= Energy from within)

$0.06 \frac{W}{m^2}$ Today

$\sim 0.3 \frac{W}{m^2}$ 4 Ga

→ Way too low to make up heating deficit of $72 \frac{W}{m^2}$ from 30% lower S

Neither albedo nor geothermal heat flux changes can keep the earth from freezing w/ 30% lower S

Adapted from Kump et al. (1999)

Precambrian pCO_2 Estimates

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Kaufman & Xiao (2003), *Nature* Vol. 425: 279-282.

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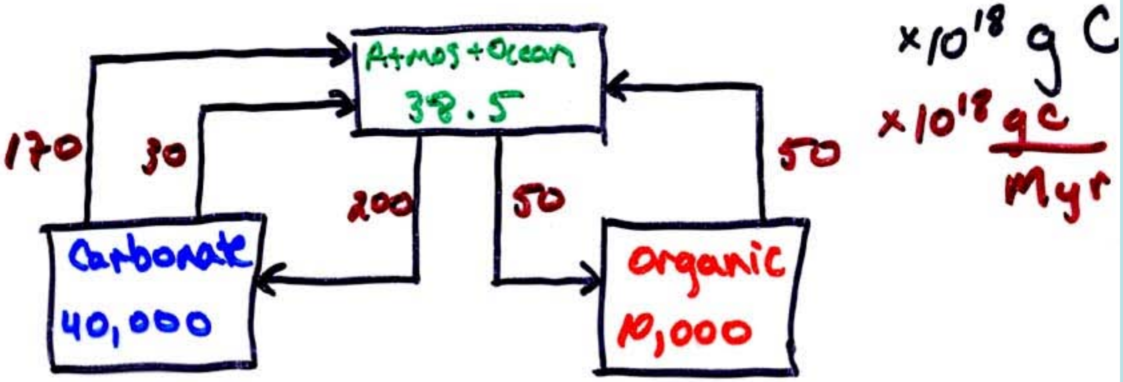
Earth's Climate History:

Mostly sunny with a 10% chance of snow

•What caused these climate perturbations?

1. CO_2 Feedbacks: Geochemical Carbon Cycle

- Transfer of C between rocks and ocean/atmosphere ($>10^6$-yr) can perturb CO_2 greenhouse effect
- Ocean/atmosphere C reservoir small w.r.t. rock reservoir and the transfer rates between them



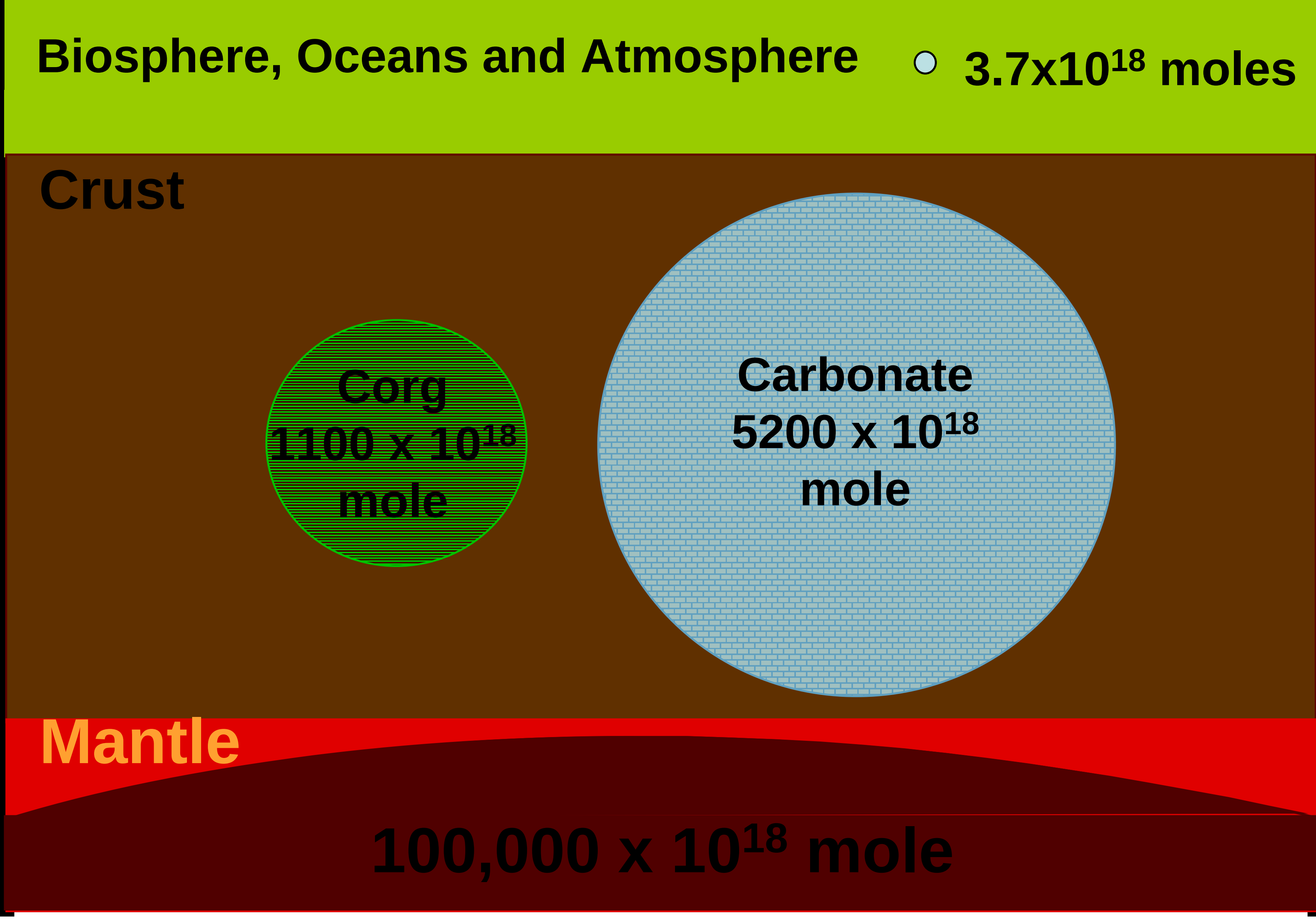
2. Evidence for Long-Term CO_2-Climate Link

3. Case Studies:
   Late Proterozoic Glaciations
   Permo-Carboniferous Glaciations
   Warm Mesozoic Period
   Late Cenozoic Cooling

Carbon Cycle:

Strong driver of climate on geologic timescales

Earth's Carbon Budget



Carbon Reservoirs, Fluxes and Residence Times

Species	Amount (in units of 10^{18} gC)	Residence Time (yr)*	$\delta^{13}C$ ‰ PDB**
Sedimentary carbonate-C	62400	342000000	~ 0
Sedimentary organic-C	15600	342000000	~ -24
Oceanic inorganic-C	42	385	~ +0.46
Necrotic-C	4.0	20-40	~ -27
Atmospheric-CO_2	0.72	4	~ -7.5
Living terrestrial biomass	0.56	16	~ -27
Living marine biomass	0.007	0.1	~ -22

Rapid Turnover

Steady State & Residence Time

Steady State: Inflows = Outflows

Any imbalance in I or O leads to changes in *reservoir* size

Inflow:
60 Gton C/yr

Respiration

Atmospheric CO_2

760 Gton C

Outflow:
60 Gton C/yr

Photosynthesis

1 Gton = 10^9 * 1000 kg = 10^{15} g

The *Residence time* of a molecule is the average amount of time it is expected to remain in a given reservoir.

Example: t_R of atmospheric CO_2 = 760/60 = 13 yr

The Geochemical Carbon Cycle

1. Organic Carbon Burial and Weathering

$$CO_2 + H_2O \underset{\text{Weathering}}{\overset{\text{Burial}}{\rightleftharpoons}} CH_2O + O_2$$

2. Tectonics: Seafloor Spreading Rate

   - Mantle CO_2 from Mid-Ocean Ridges

3. Carbonate-Silicate Geochemical Cycle

   - Chemical Weathering Consumes CO_2
   - Carbonate Metamorphism Produces CO_2

The bio-geochemical carbon cycle

biogeochemical carbon cycle #2

Chemical weathering = chemical attack of rocks by dilute acid

1. Carbonate weathering:

   $CaCO_3 + CO_2 + H_2O \Rightarrow Ca^{2+} + 2\ HCO_3^-$

2. Silicate weathering:

   $CaSiO_3 + 2\ CO_2 + 2\ H_2O \Rightarrow Ca^{2+} + 2\ HCO_3^- + SiO_2 + H_2O$

Carbonates weather faster than silicates

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Carbonate rocks weather faster than silicate rocks…

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Products of weathering precipitated as $CaCO_3$ & SiO_2 in ocean

Kump et al. (1999)

$CaCO_3$ weathering is cyclic (CO_2 is not lost from the system), but calcium silicate weathering results in the loss of CO_2 to solid $CaCO_3$:

$CaCO_3$ weathering cycle

$CaCO_3$ weathering:

$$CaCO_3 + CO_2 + H_2O \Rightarrow Ca^{2+} + 2\ HCO_3^-$$

$CaCO_3$ sedimentation:

$$Ca^{2+} + 2\ HCO_3^- \Rightarrow CaCO_3 + CO_2 + H_2O$$

Silicate weathering cycle (?)

Silicate weathering:

$$CaSiO_3 + \underline{2}\ CO_2 + 2H_2O \Rightarrow Ca^{2+} + Si(OH)_4 + \underline{2}\ HCO_3^-$$

$CaCO_3$ and SiO_2 sedimentation:

$$Ca^{2+} + \underline{2}\ HCO_3^- + Si(OH)_4 \Rightarrow CaCO_3 + SiO_2 \cdot 2H_2O + \underline{1}\ CO_2 + H_2O$$

The weathering of other aluminosilicates results in the loss of CO_2 AND makes the ocean saltier and more alkaline:

Potassium feldspar weathering "cycle"

weathering:

$$2\ KAl_2Si_2O_8 + \underline{2}\ CO_2 + 2H_2O \Rightarrow 2\ K^+ + \underline{2}\ HCO_3^- + 2\ Si(OH)_4 + Al_2O_3$$

(solid)

sedimentation:

$$2\ K^+ + \underline{2}\ HCO_3^- + 2\ Si(OH)_4 + Al_2O_3 \Rightarrow 2\ SiO_2 \bullet 2H_2O + Al_2O_3 + 2\ K^+ + 2\ HCO_3^-$$

Problem:

As CO_2 is buried as $CaCO_3$ in sediments, why doesn't CO_2 eventually vanish from the atmosphere?

(It would take only ~400,000 years of silicate weathering to consume all of the carbon in today's ocean/atmosphere system)

<u>Net Reaction of Rock Weathering</u>

+

<u>Carbonate and Silica Precipitation in Ocean</u>

$$CaSiO_3 + \boxed{CO_2} \rightarrow CaCO_3 + SiO_2$$

- CO_2 consumed
- Would deplete atmospheric CO_2 in 400 kyr
- Plate tectonics returns CO_2 via <u>Metamorphism</u> and <u>Volcanism</u>

<u>Carbonate Metamorphism</u>

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + \boxed{CO_2}$$

- CO_2 produced from subducted marine sediments

Net reaction of geochemical carbon cycle (Urey Reaction)

Carbonate-Silicate Geochemical Cycle

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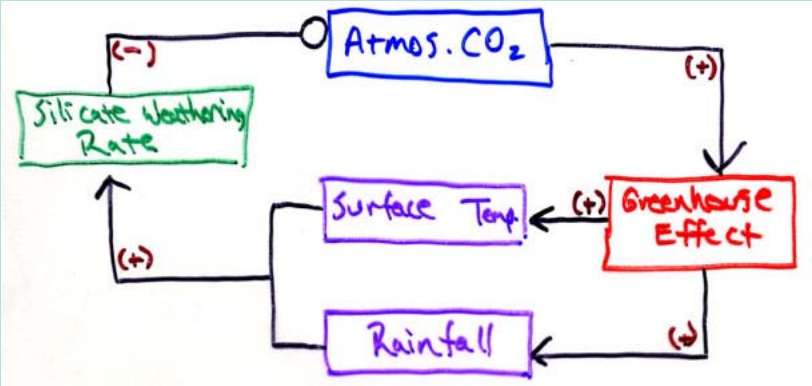
Stanley (1999)

- CO_2 released from volcanism dissolves in H_2O, dissolves rocks
- Weathering products transported to ocean by rivers
- $CaCO_3$ precipitation in shallow & deep water
- Cycle closed when $CaCO_3$ metamorphosed in subduction zone or during orogeny.

- Geologic record indicates climate has rarely reached or maintained extreme Greenhouse or Icehouse conditions....
- Negative feedbacks between climate and Geochemical Carbon Cycle must exist
- Thus far, only identified for Carbonate-Silicate Geochemical Cycle:

Temp., rainfall enhance weathering rates
(Walker et al, 1981)

(i.e., no obvious climate dependence of tectonics or organic carbon geochemical cycle.)



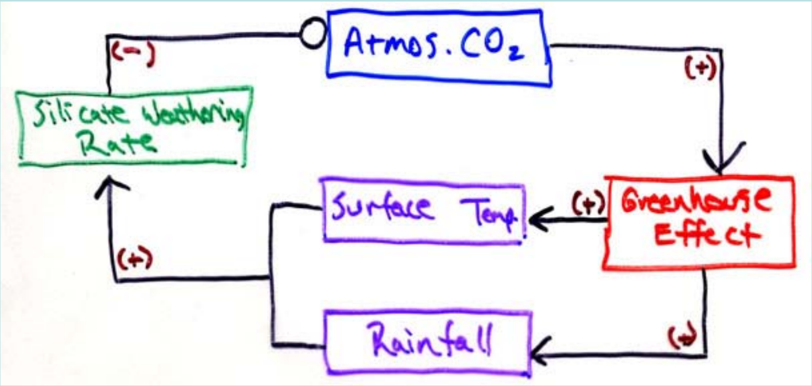
How are CO_2 levels kept in balance?

Feedbacks…

Adapted from Kump et al. (1999)

The Walker (1981) feedback for CO_2 regulation

- (1) CO_2 emitted by volcanoes
- (2) CO_2 consumed by weathering
- (3) If (1) is greater than (2), CO_2 levels in the atmosphere increase.
- (4) As atm. CO_2 rises, the climate gets (a) warmer and (b) wetter (more rainfall).
- (5) Warmer and wetter earth weathers rocks faster. CO_2 is removed from the atmosphere faster.
- (6) CO_2 levels rise until the weathering rate balances volcanic emissions. Steady-state attained (until volcanic CO_2 emissions rise or fall).



The (modified) BLAG [Berner, Lasaga and Garrels) mechanism for long-term CO_2 regulation

- Walker mechanism plus consideration of changes in sea floor spreading rate (induces ~100 myr lag time between CO_2 emissions and ultimate recycling via Urey reaction), volcanism, and other factors influencing carbon cycle (organic deposition and weathering).
- Modified by J. Edmond to include irregularity of $CaCO_3$ deposition (shallow sediments and some basins get "more of their fair share" of $CaCO_3$ deposition, and spreading and subduction are not closely linked spatially (e.g. Atlantic spreads but has little subduction).

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