The Global Carbon Cycle

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September 2003

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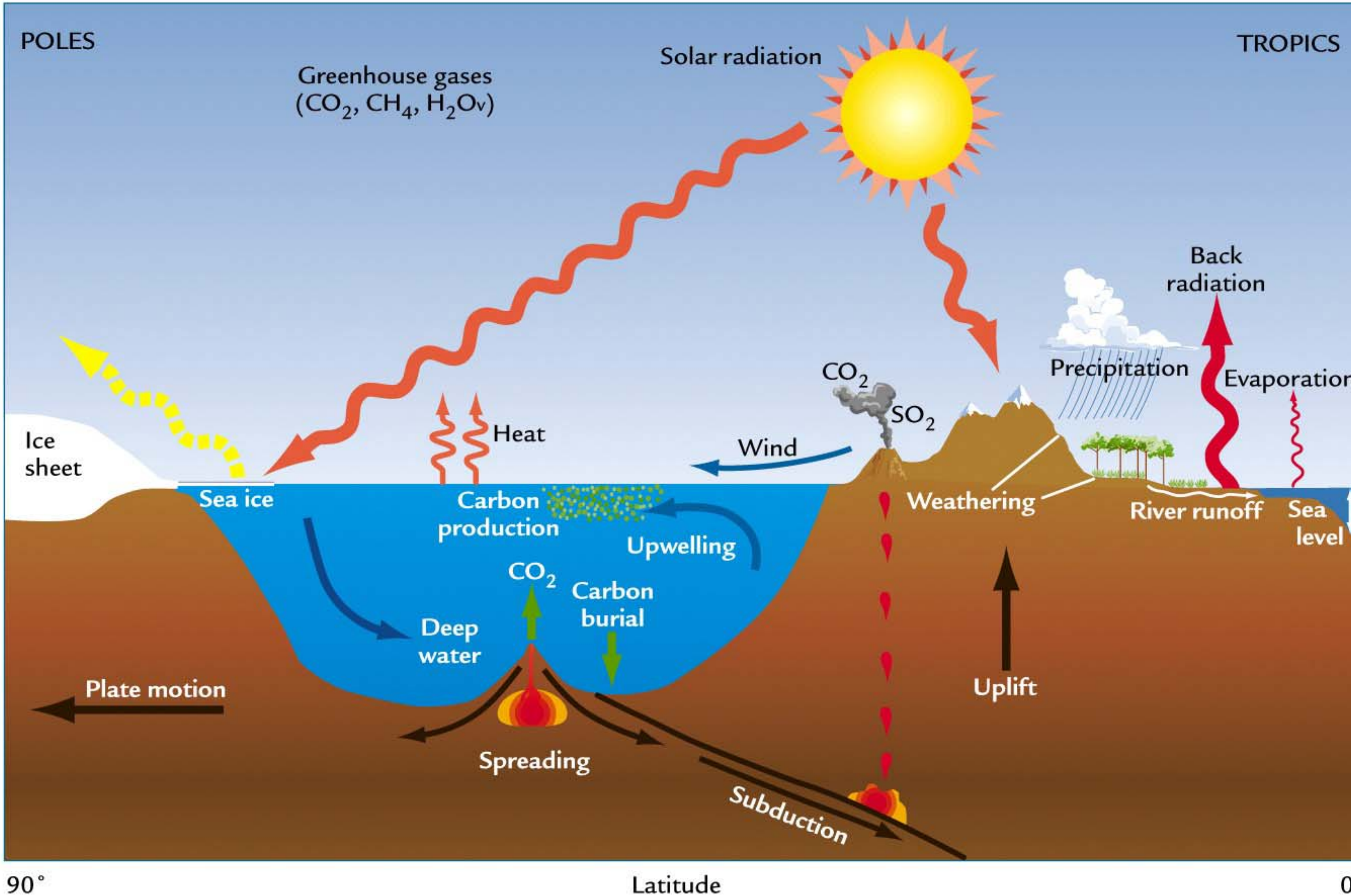
The Carbon Cycle

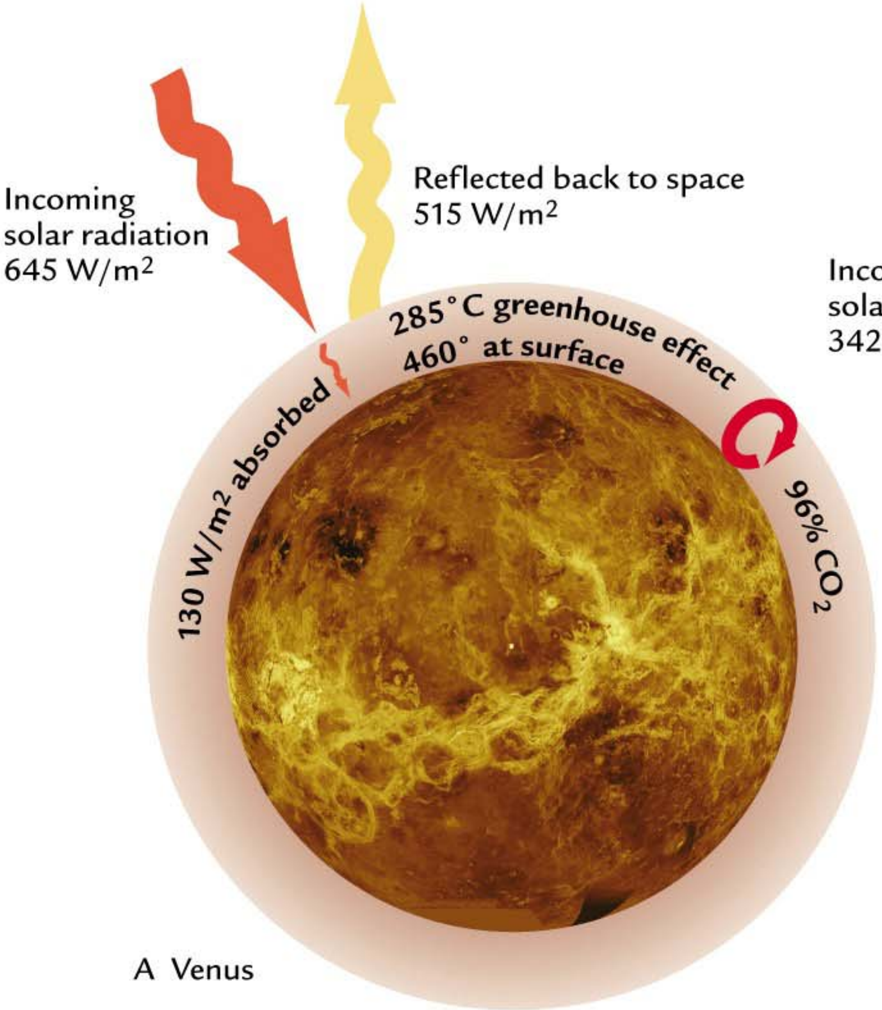


- Look at past climatic change; as controlled by the carbon cycle.

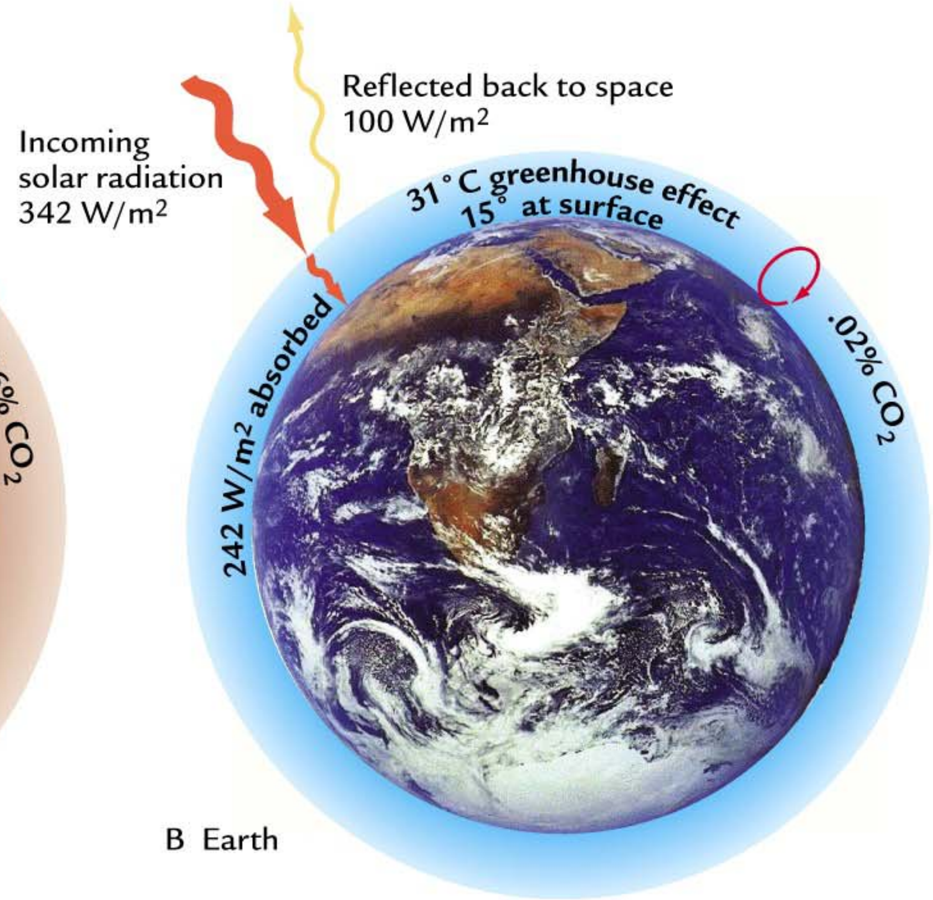
- Interpret the influence of human changes
(Anthropogenic Perturbations)

- Economic and Trade Policies

<u>Venus</u> <u>Earth</u>

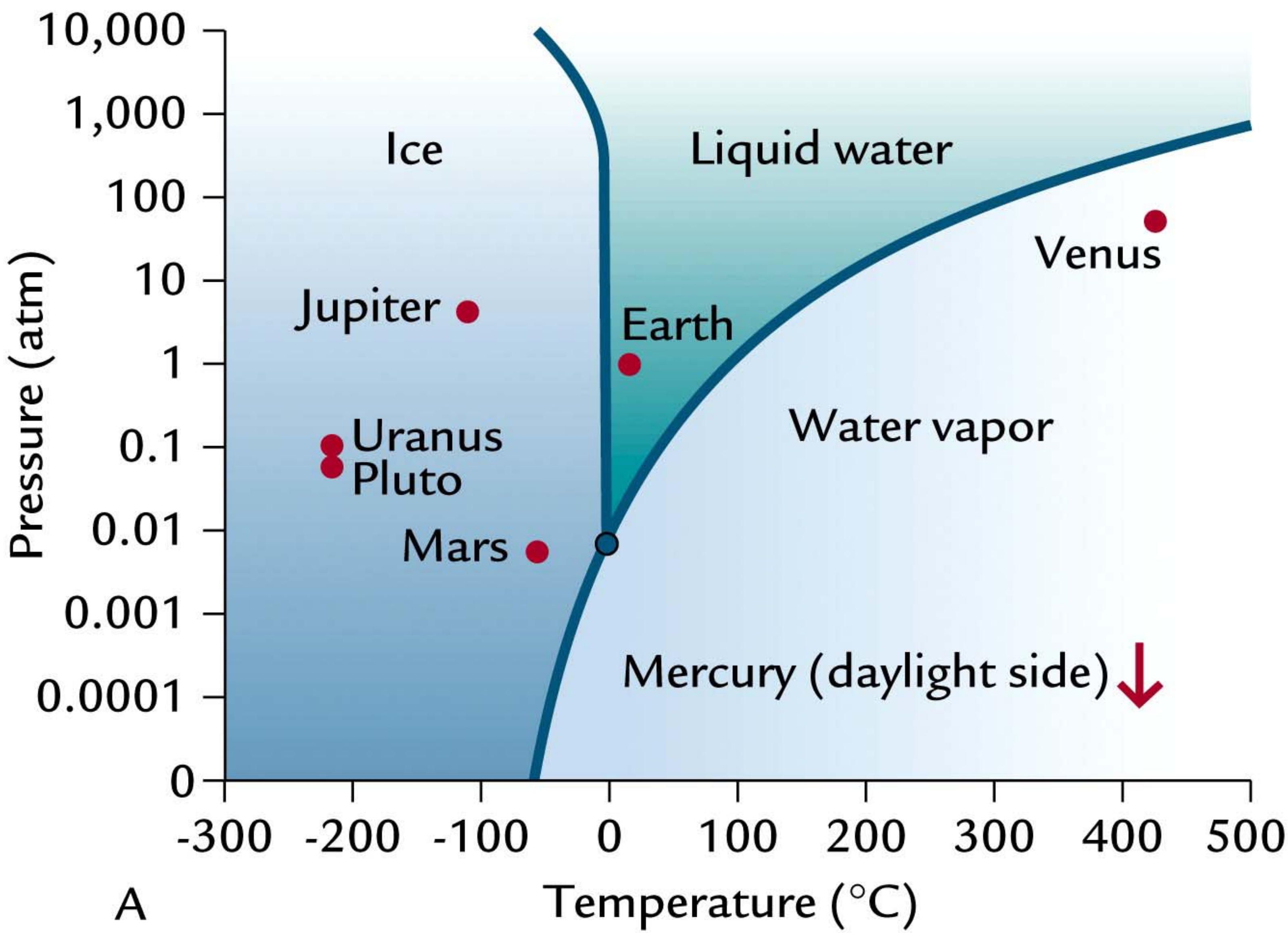


A Venus

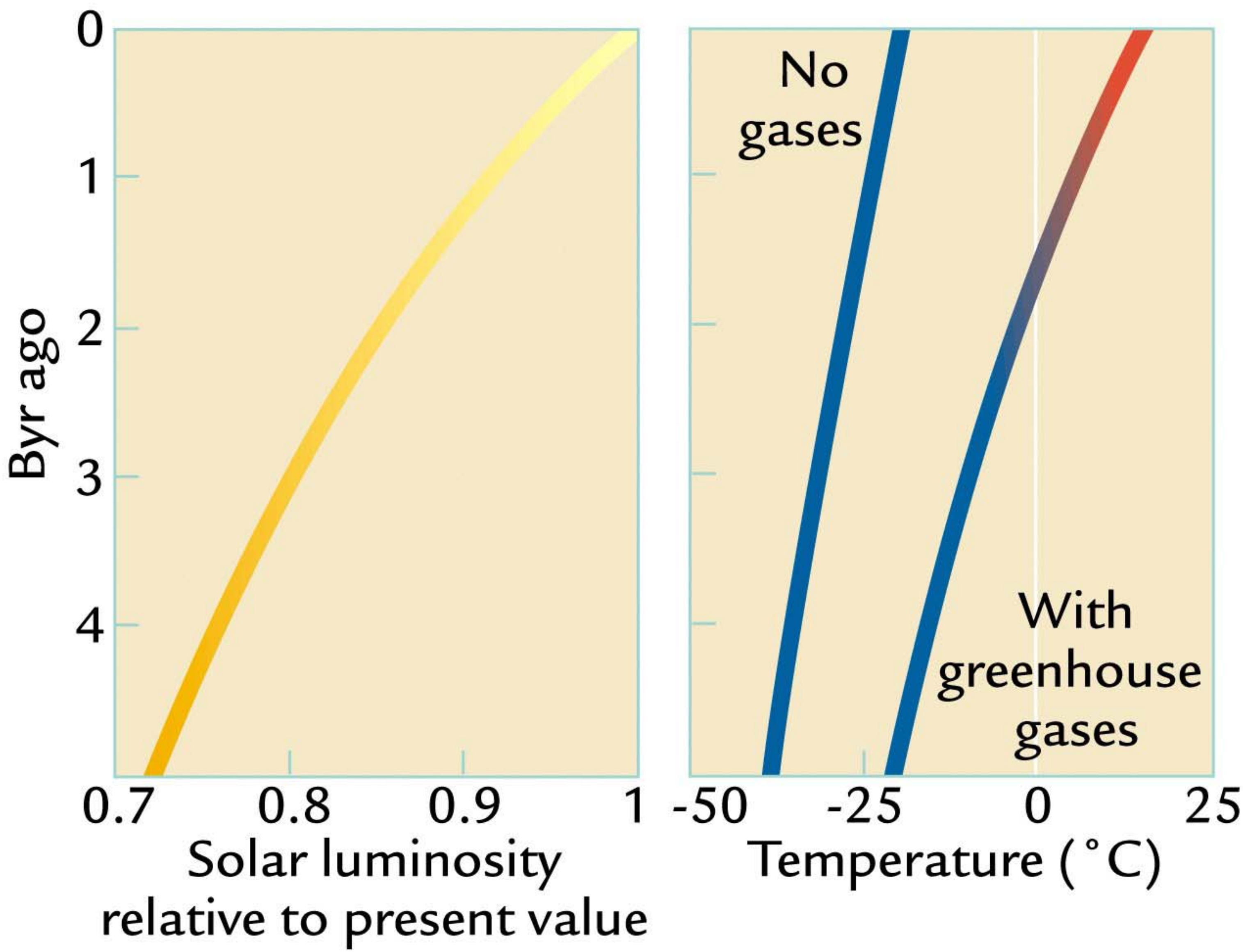


B Earth

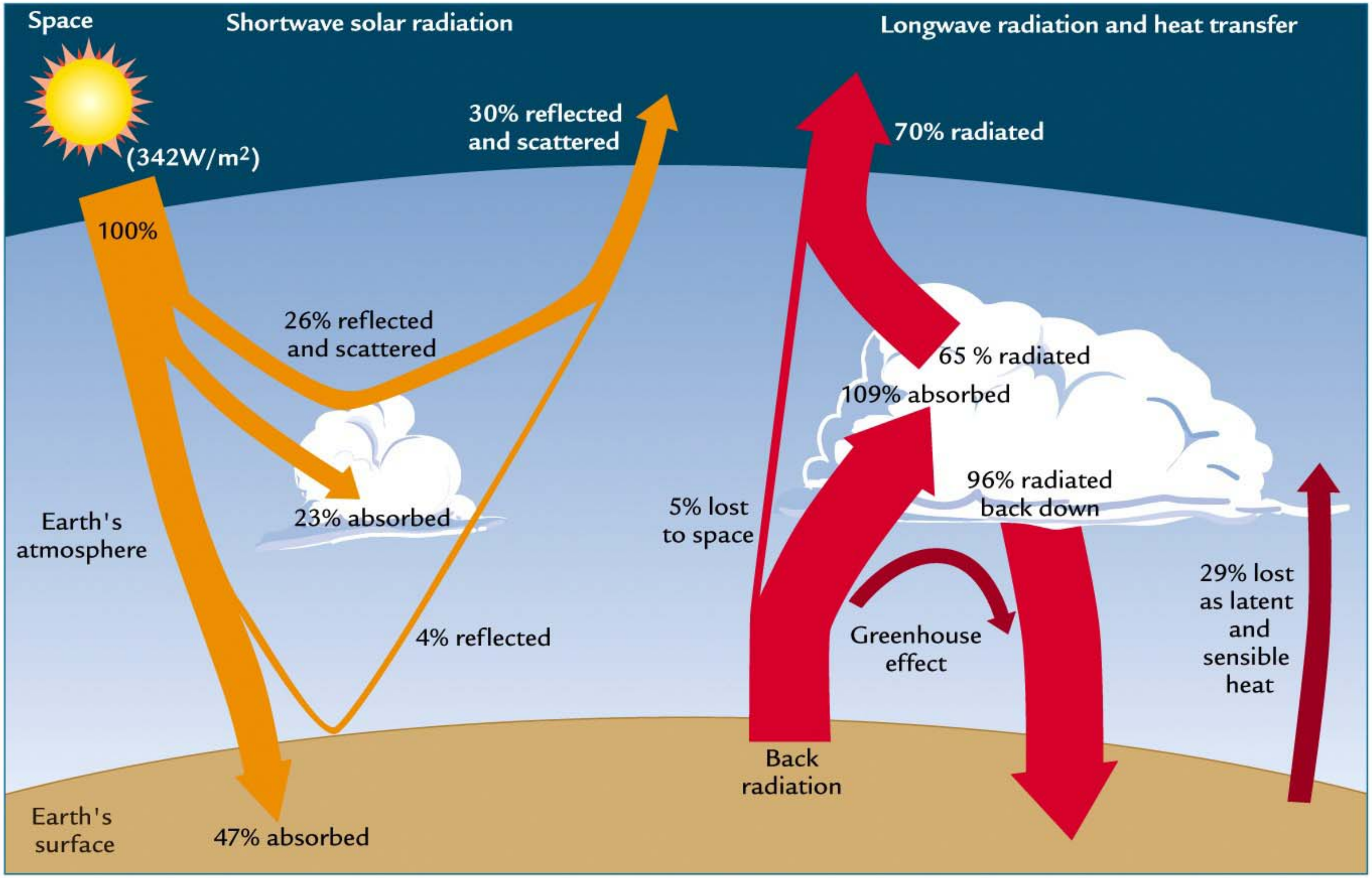
States of water in the solar-system

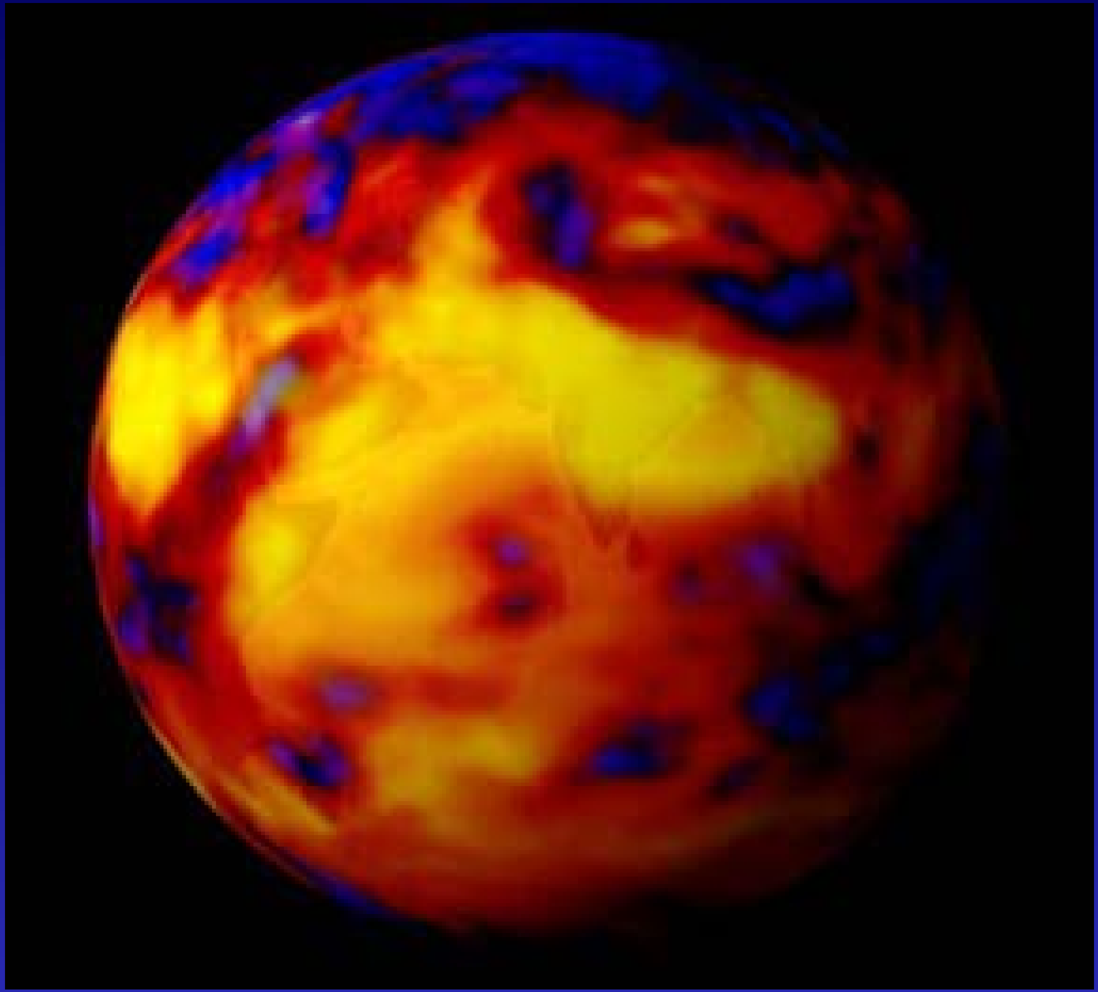


The Faint Young Sun Paradox



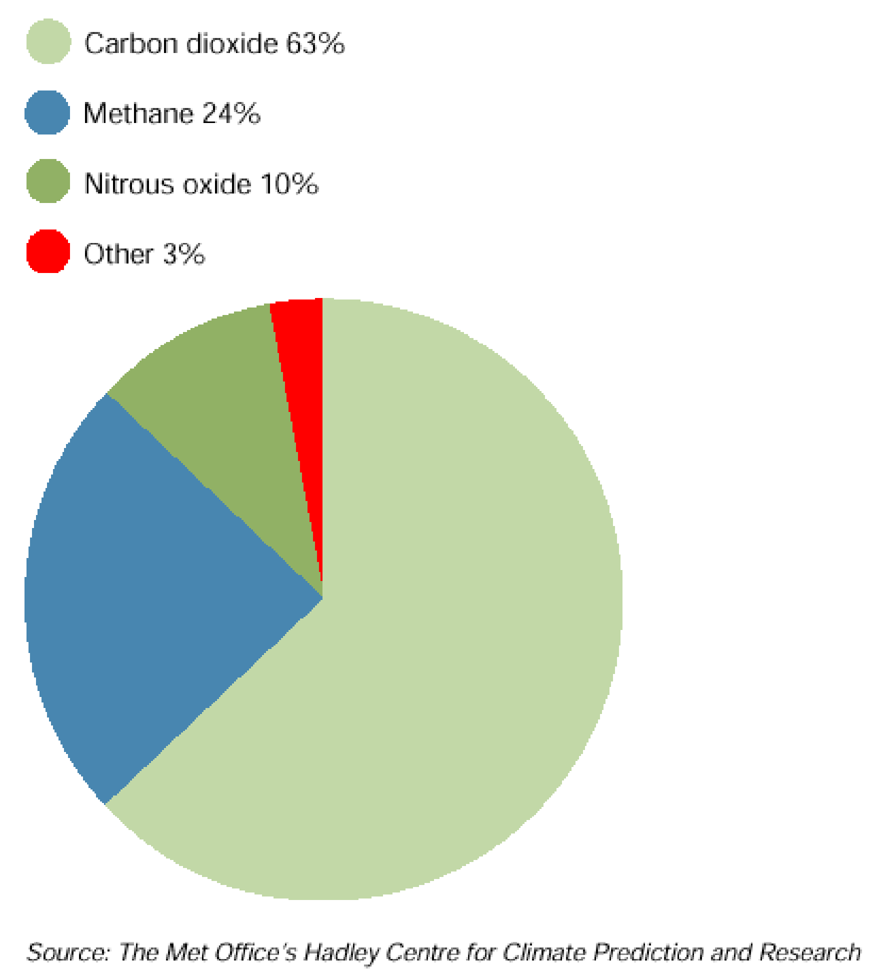
The greenhouse effect



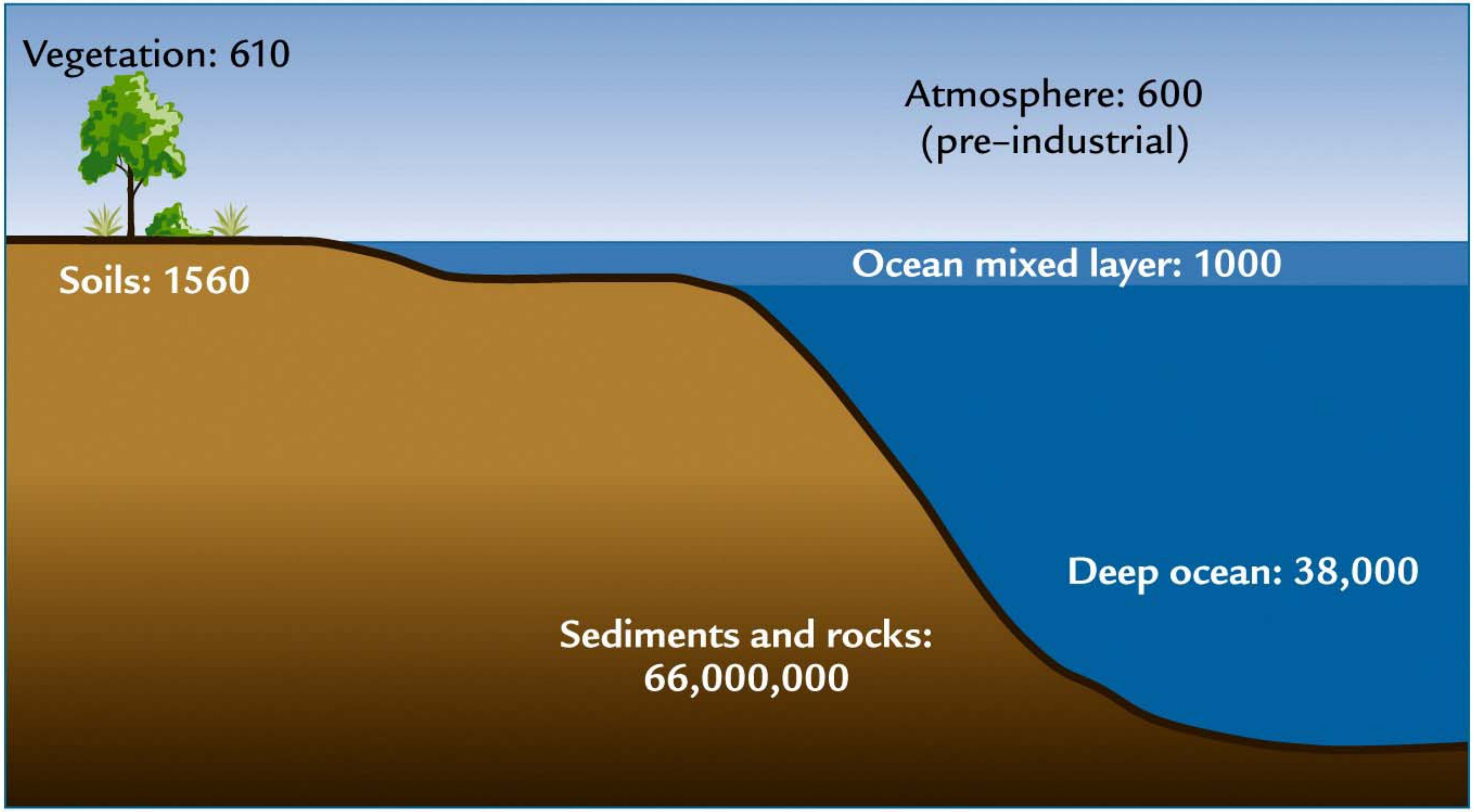


This false-color Terra satellite image of Earth shows infrared heat escaping to space.
Greenhouse gases trap such heat and warm our planet.

Relative percentage composition of greenhouse gases in the Earth's atmosphere



Distribution of carbon reservoirs on Earth

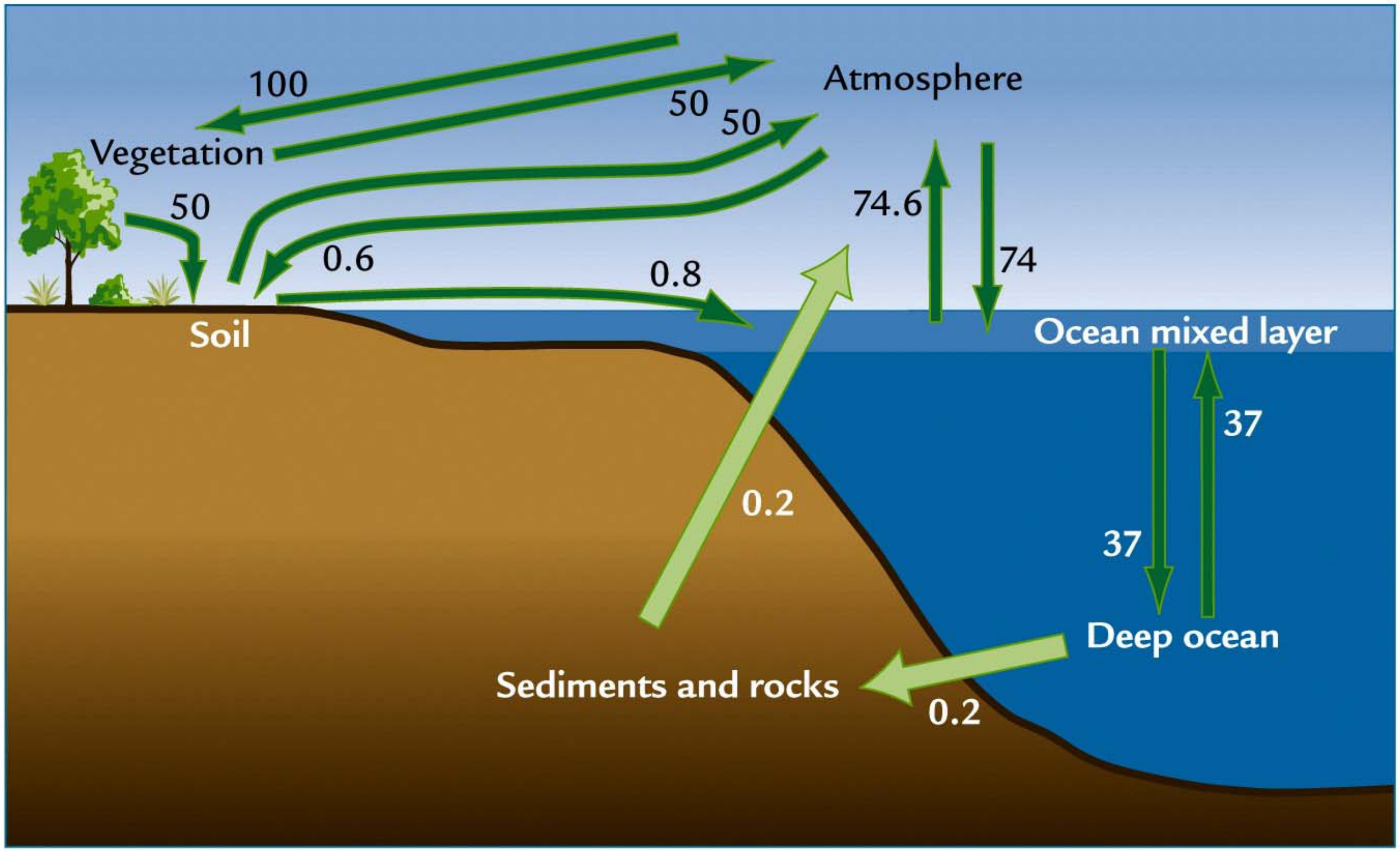


A Major carbon reservoirs (gigatons; 1 gigaton = 10^{15} grams)

Pools	Quantity (gt)
Atmosphere	**720**
Oceans	**38,400**
Total inorganic	37,400
Surface Layer	670
Deep layer	36,730
Total Organic	1,000
Lithosphere	
Sedimentary carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	**2,000**
Living Biomass	600-1,000
Dead Biomass	1,200
Aquatic biosphere	**1-2**
Fossil fuels	**4,130**
Coal	3,510
Oil	230
Gas	140
Other (peat)	250

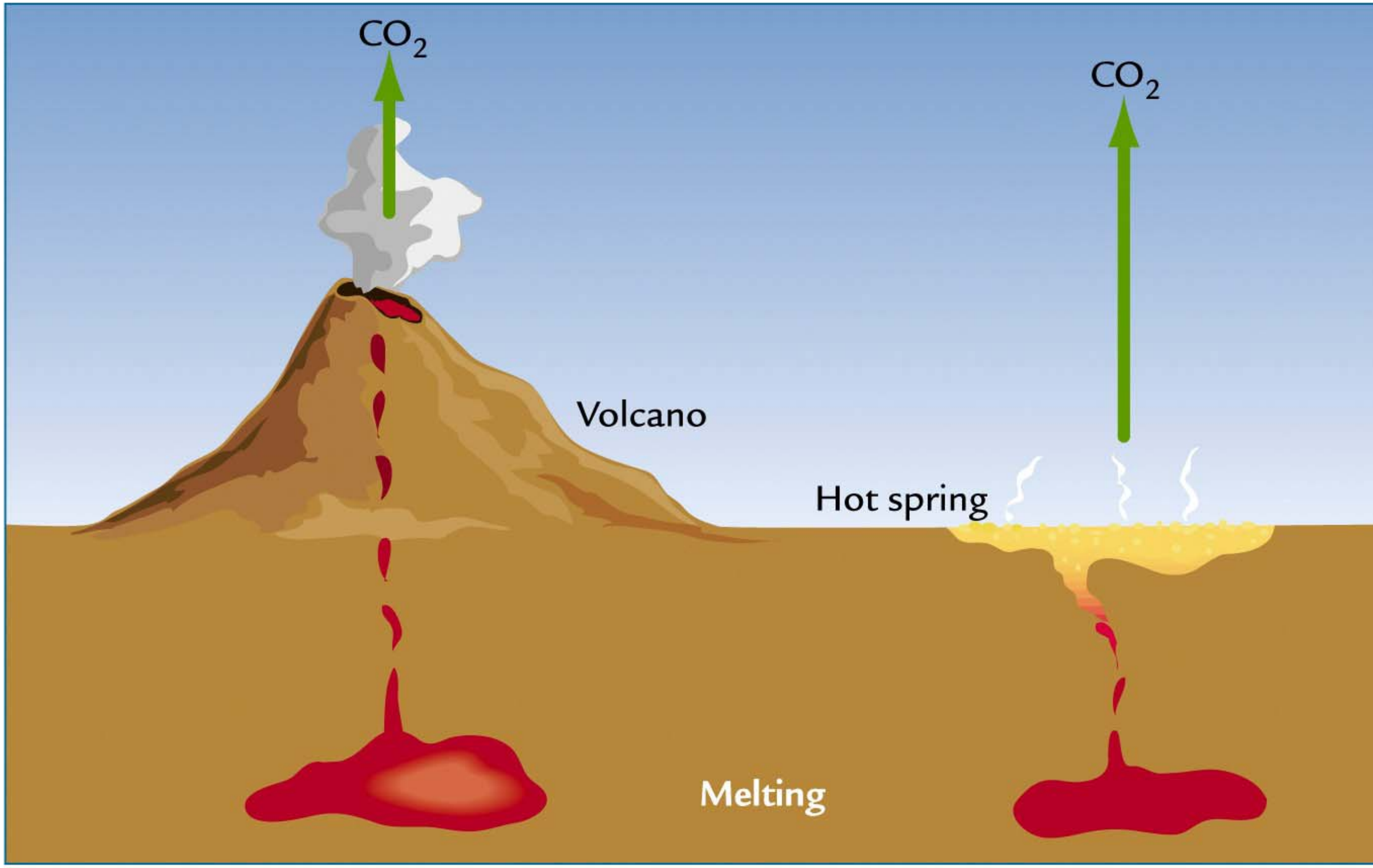
Falkowski et al, 2002 Science, Vol 290, 291-296

Values of carbon exchange between reservoirs



B Carbon exchange rates (gigatons/year)

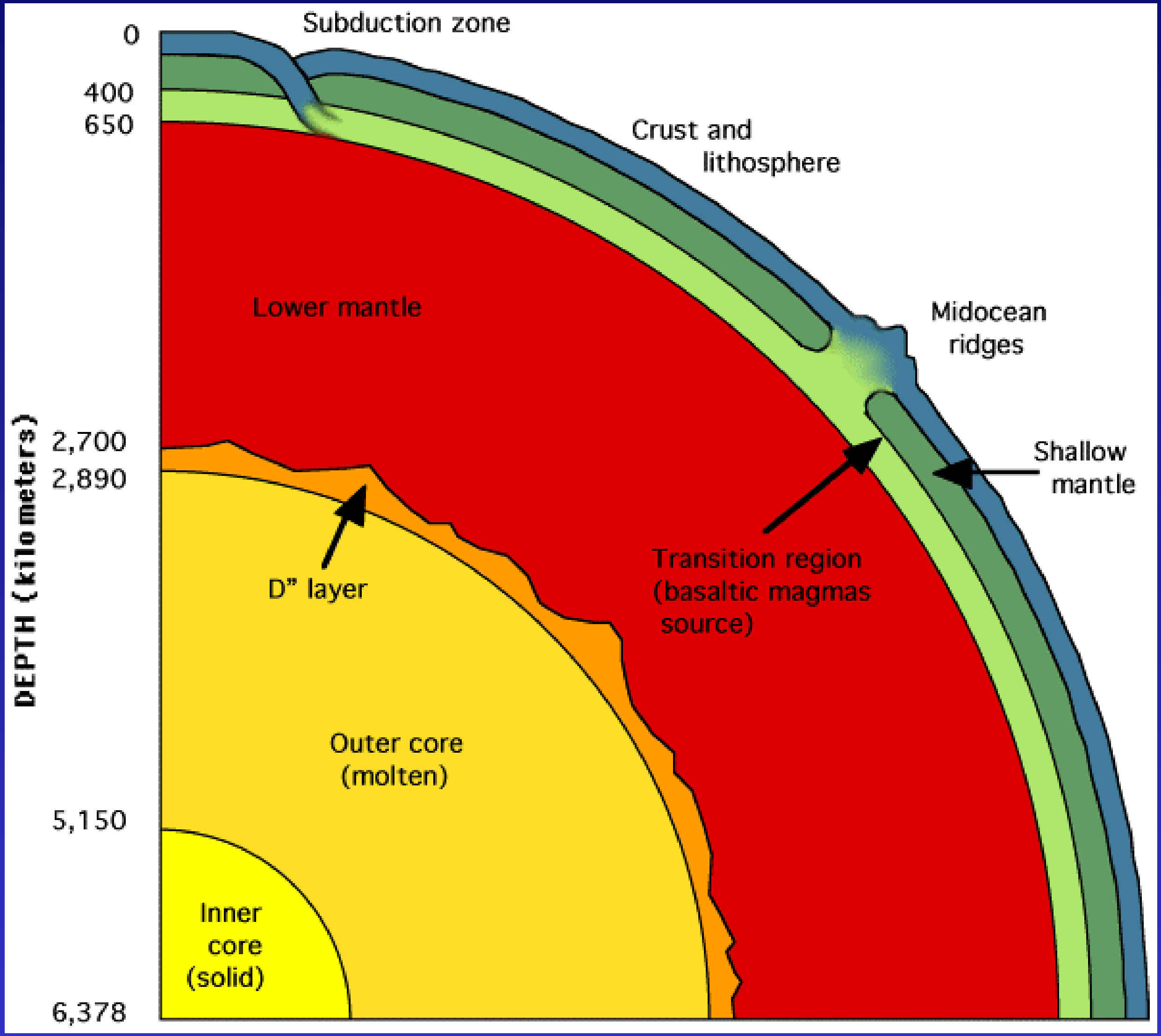
Carbon Degassing



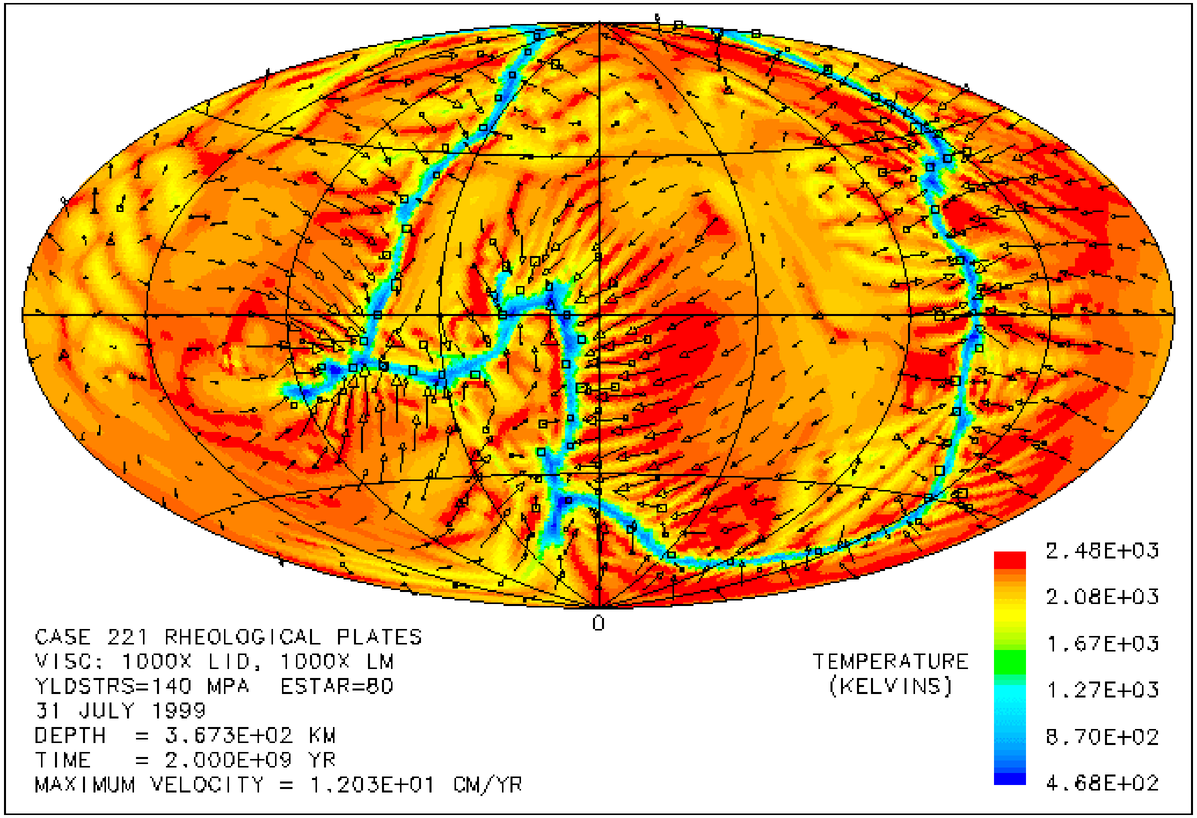
Mörner and Etiope, Global and Planetary Change 33 (2002) 185-203

Methane Hydrates

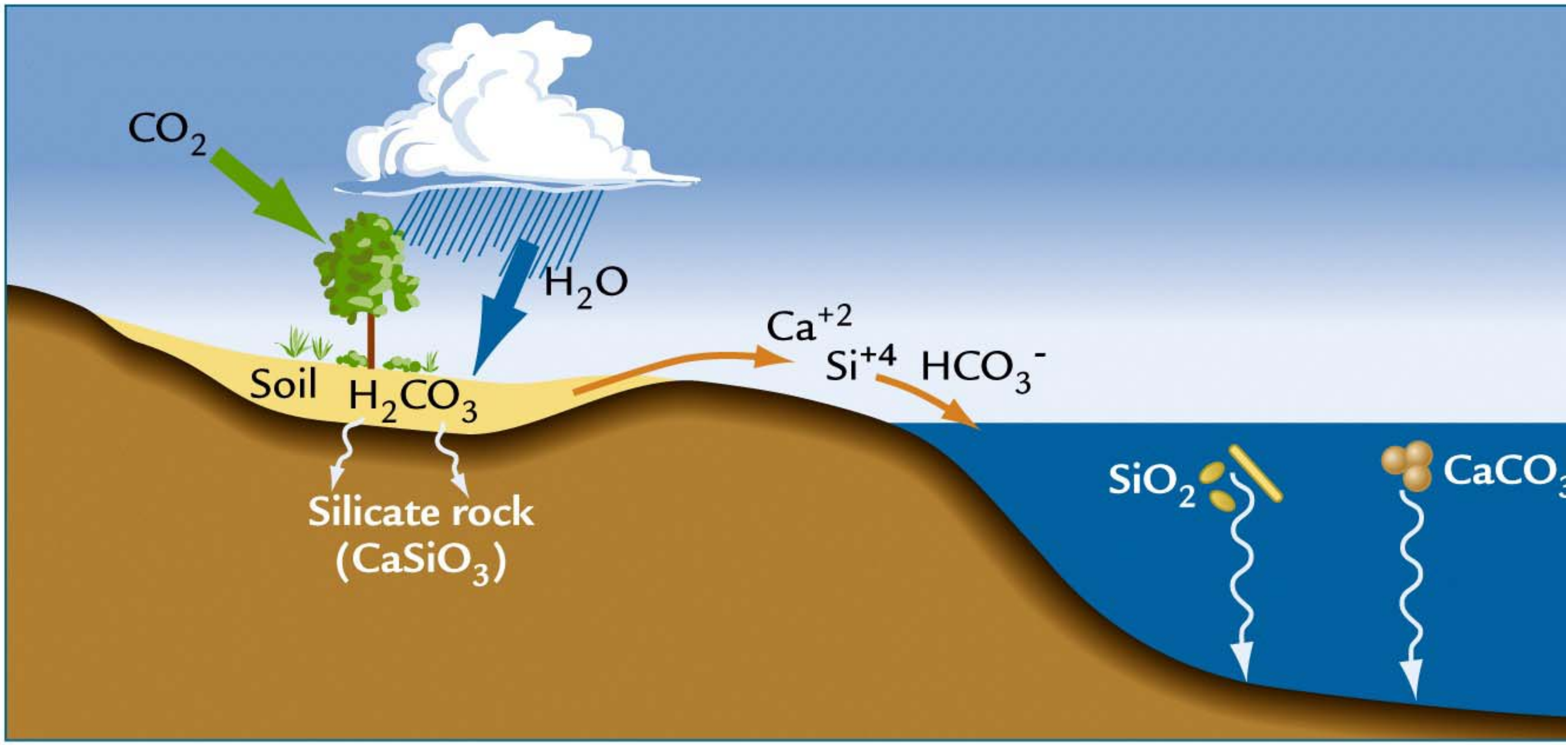
Cross-section through the Earth



The Ring of Fire

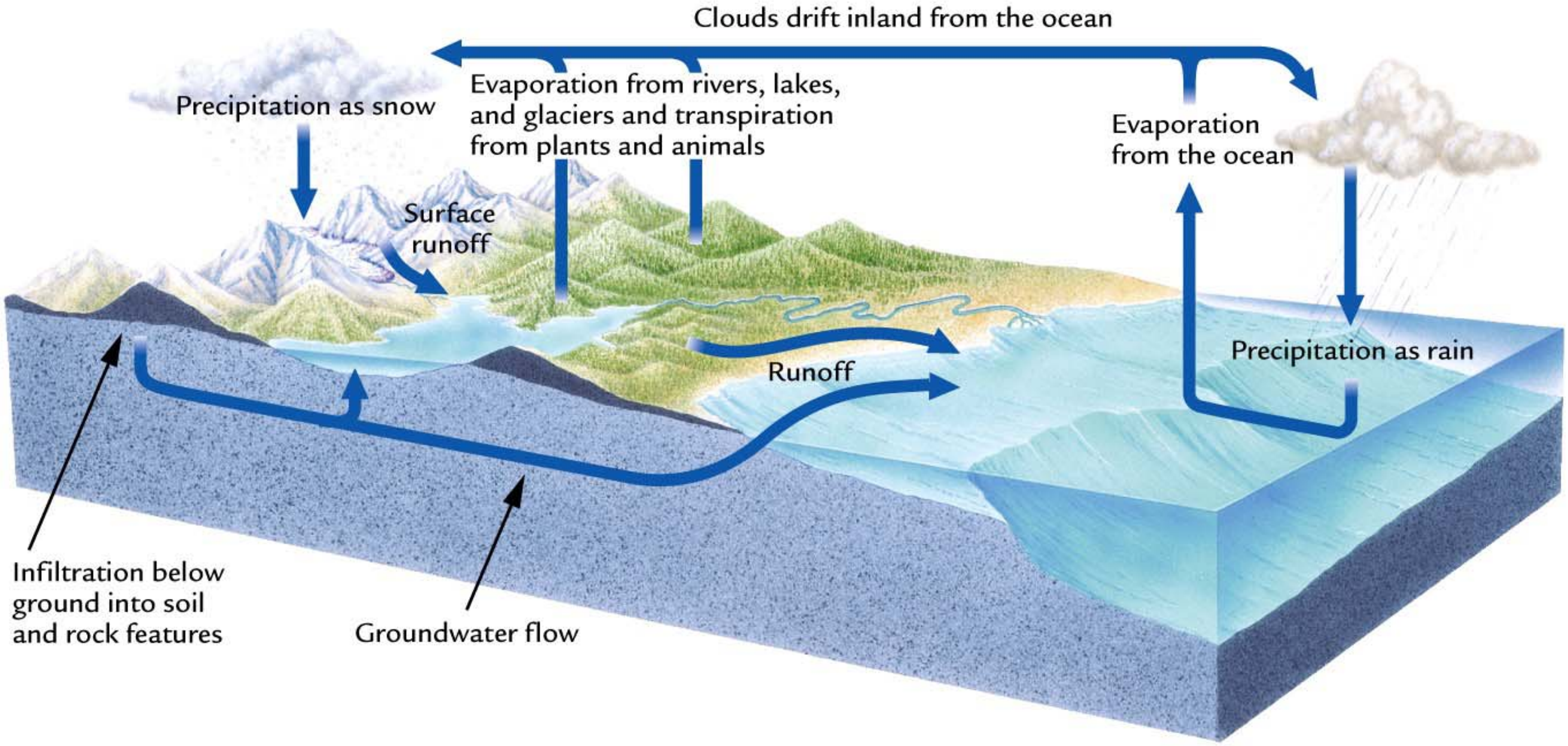


Chemical weathering – Export of CO_2 From the atmosphere

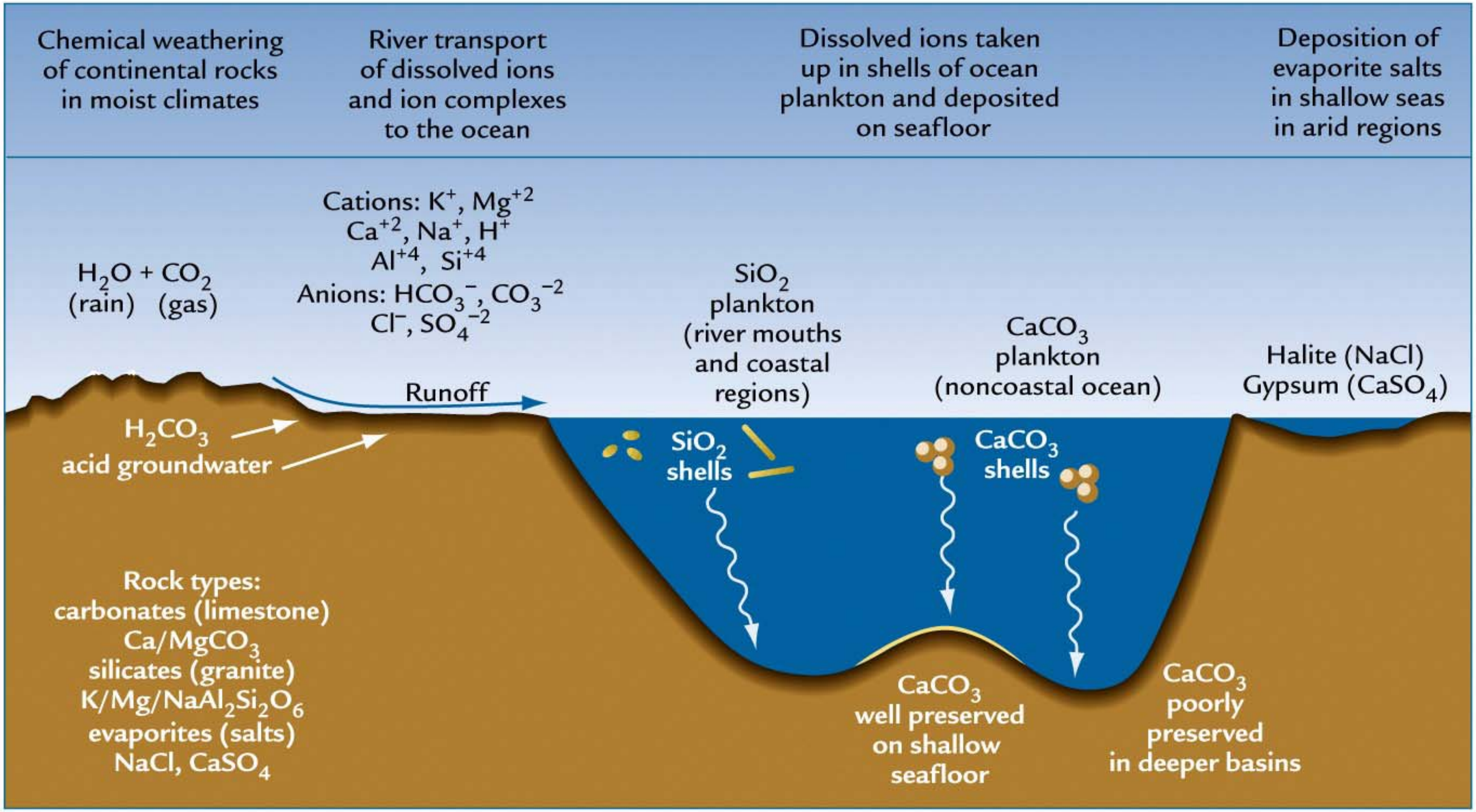


$CaSiO_3$ + H_2CO_3	Ca^{+2} Si^{+4} HCO_3^-	$SiO_2 + CaCO_3$
Silicate bedrock; Carbonic acid in soils	Ions dissolved in river water	Shells of ocean plankton
Weathering on land	Transport in rivers	Deposition in ocean

The hydrological cycle

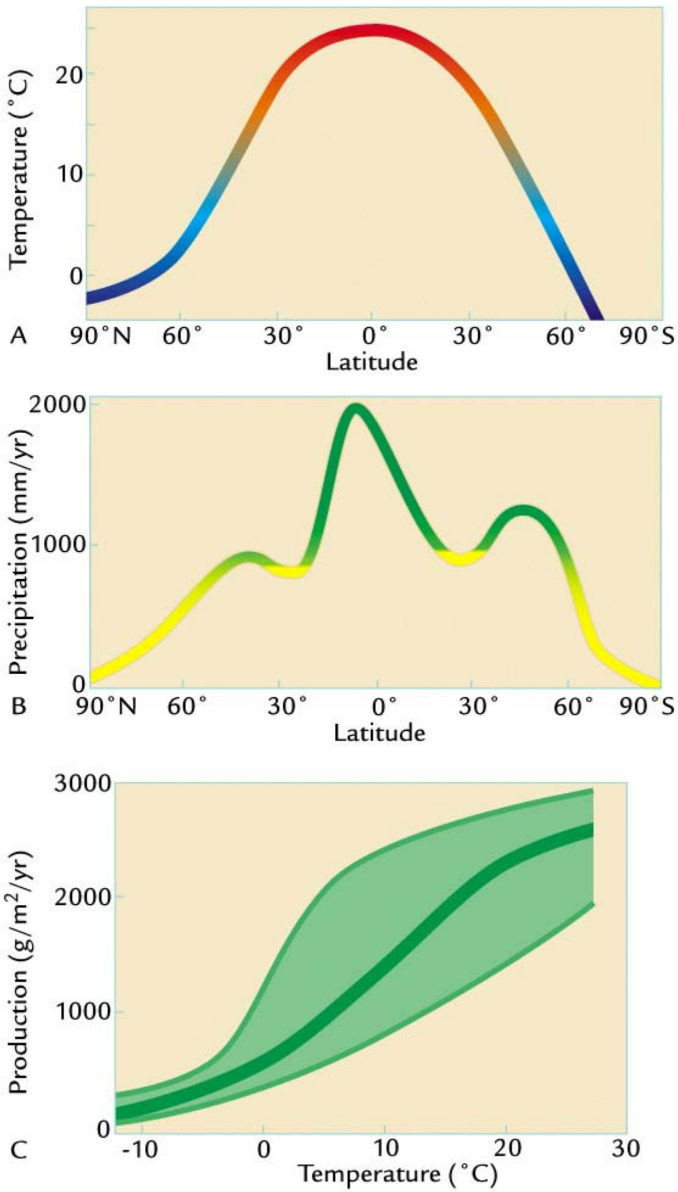


Chemical Weathering



Calcite (Carbonate) compensation depth (CCD) -- The depth in the ocean below which material composed of calcium carbonate is dissolved and does not accumulate on the sea floor

Factors effecting the rate of chemical weathering

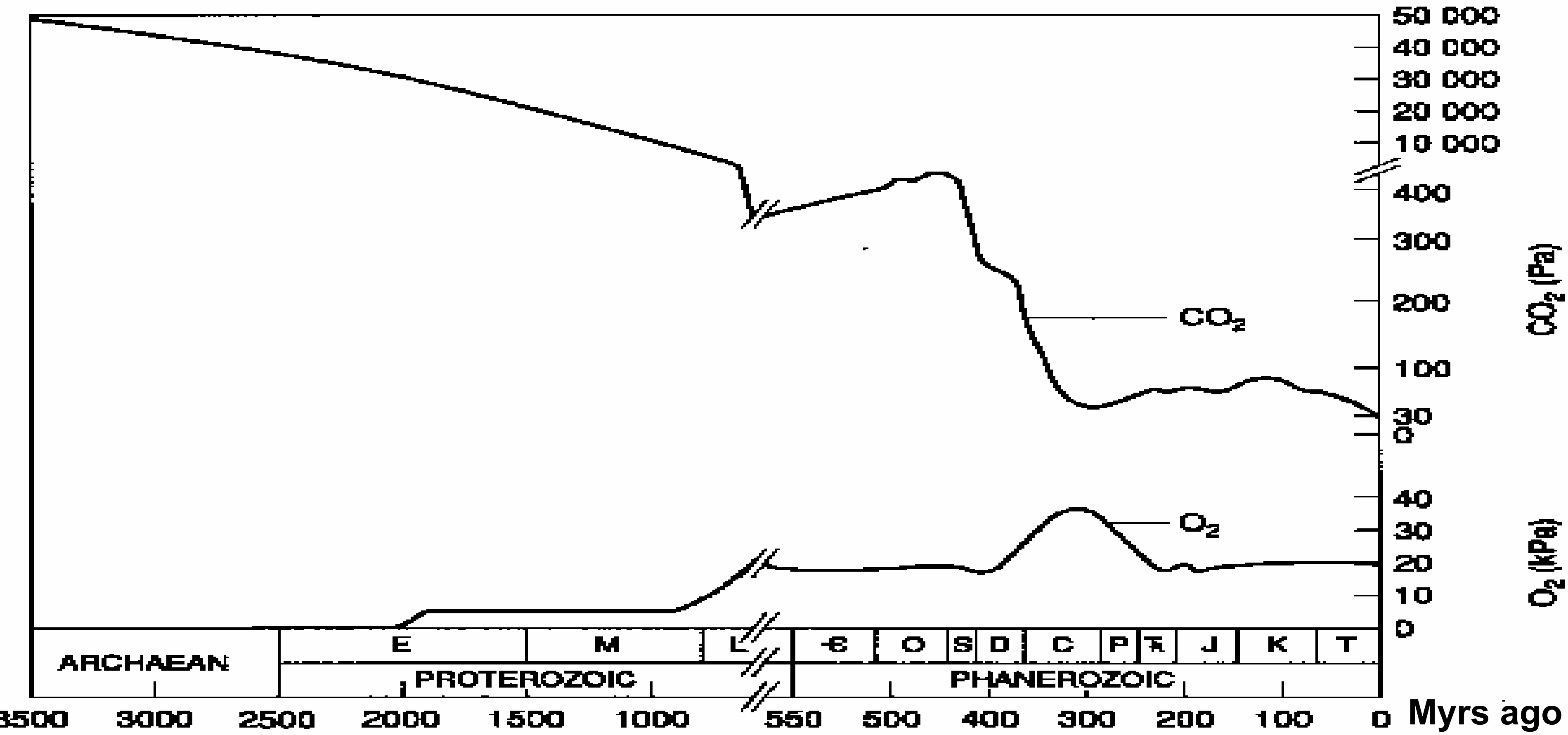


Temperature : Rate of chemical reactions

Precipitation: Amount of H_2O

Vegetation: Efficiency of delivery of CO_2 to the soil

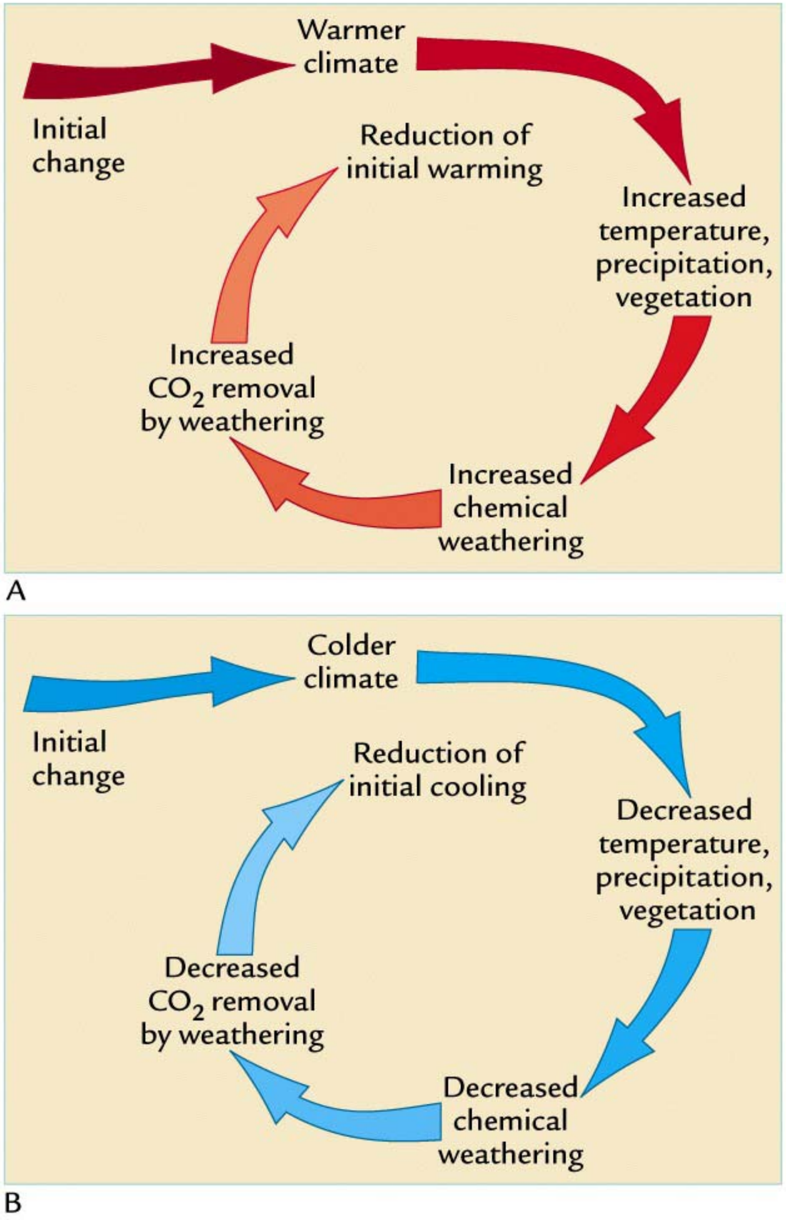
Atmospheric CO_2 Levels



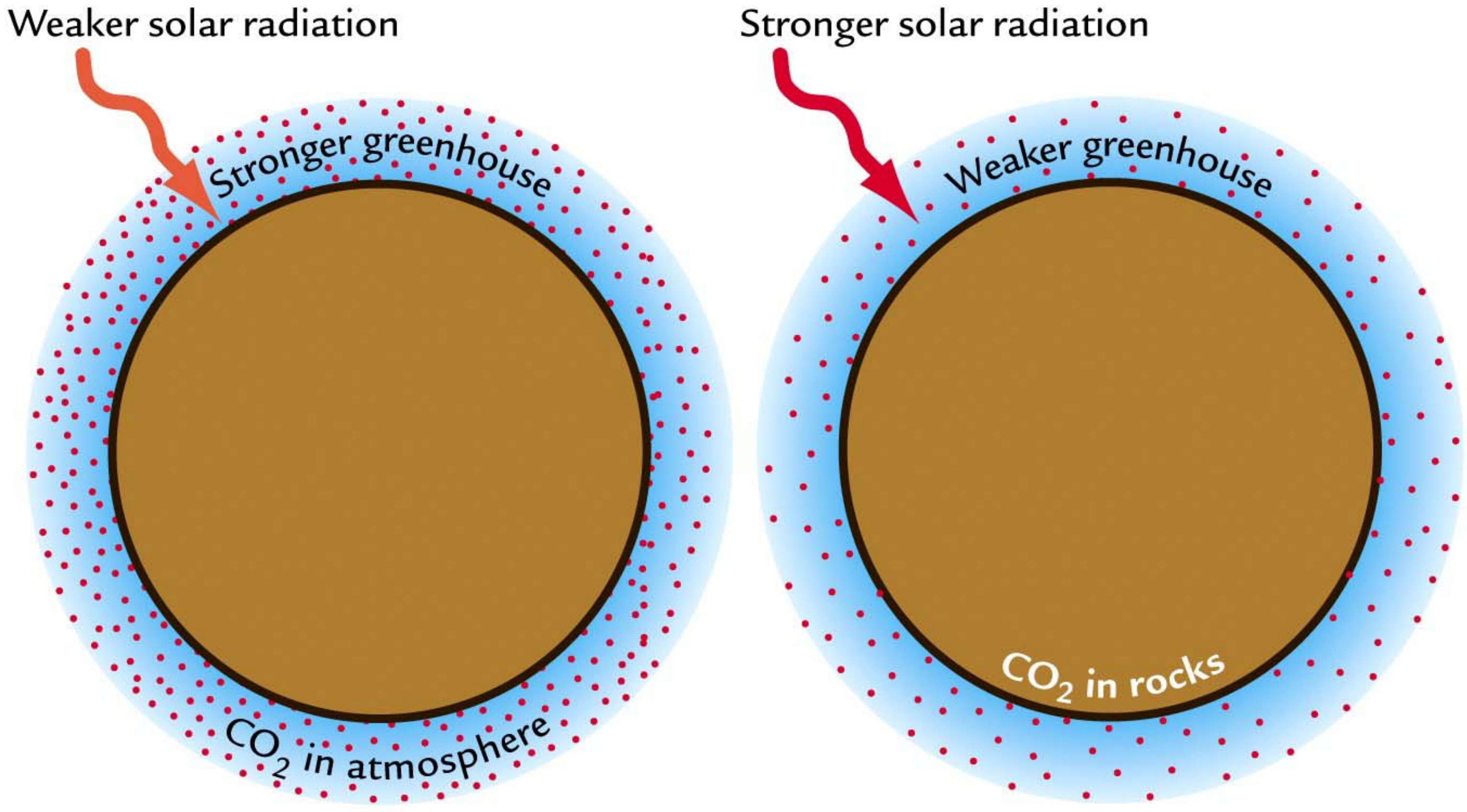
Falkowski and Raven 1997

Faint Young Sun Paradox:

Negative feedback controls.



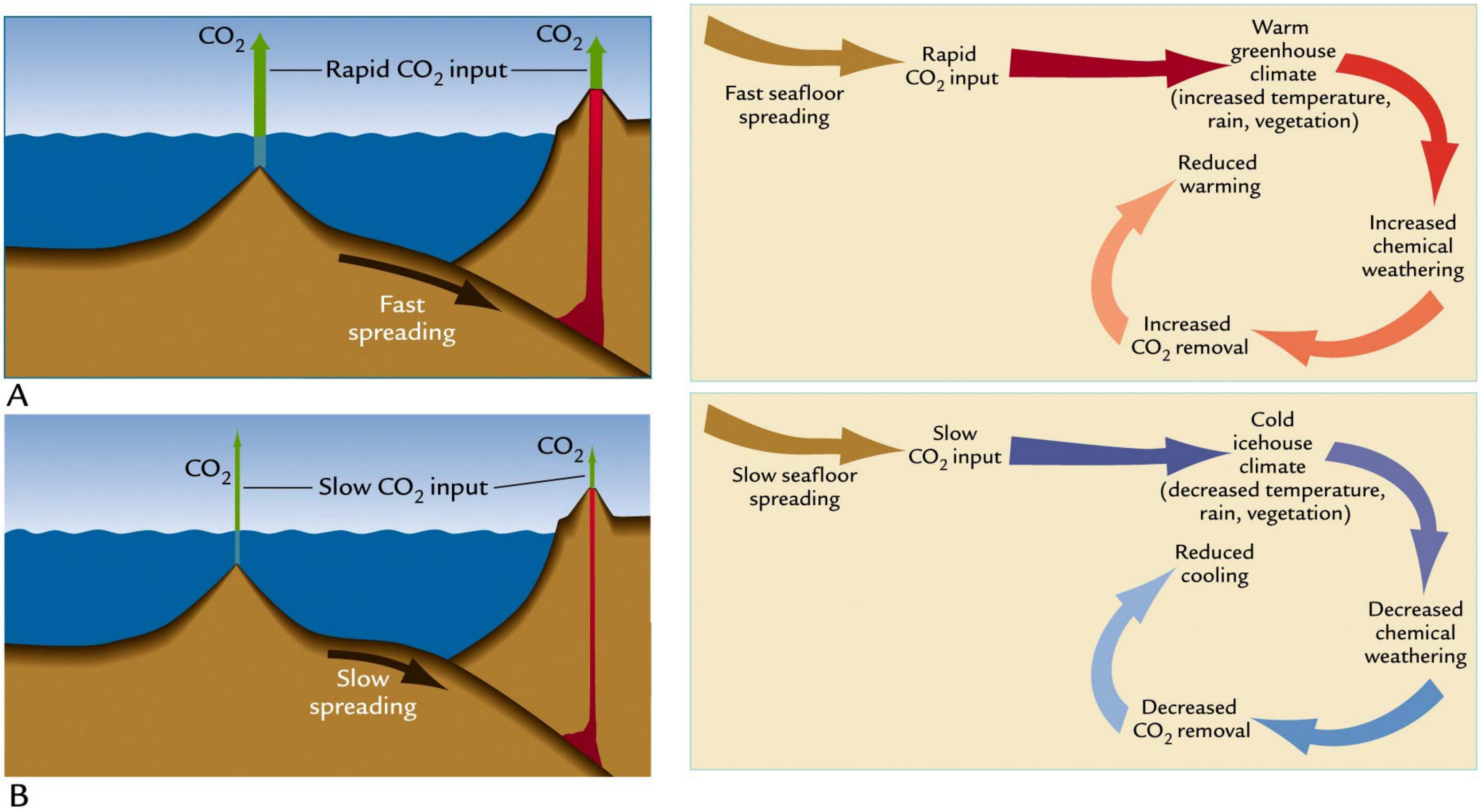
Faint Young Sun paradox: Controlled by the Carbon cycle



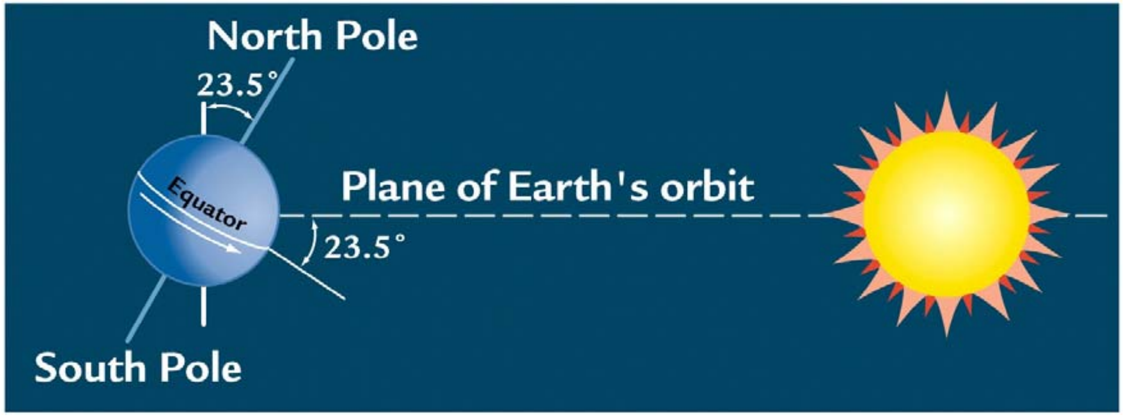
A Early Earth

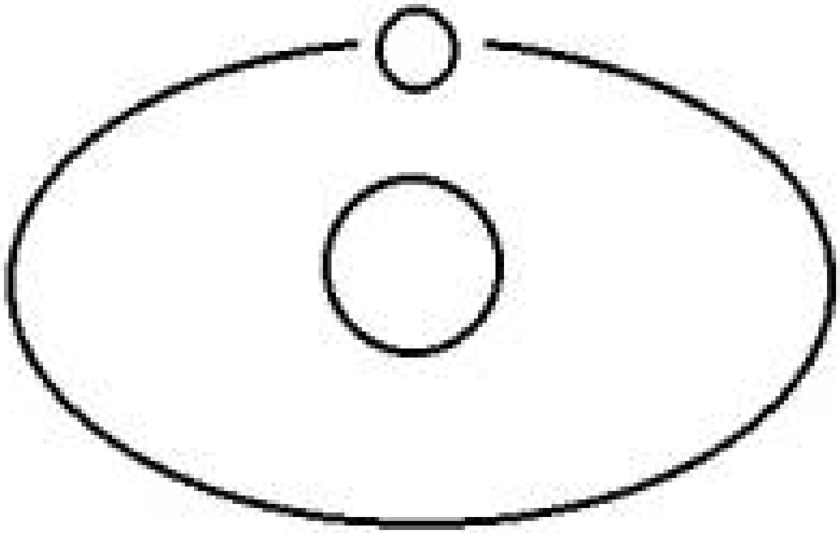
B Modern Earth

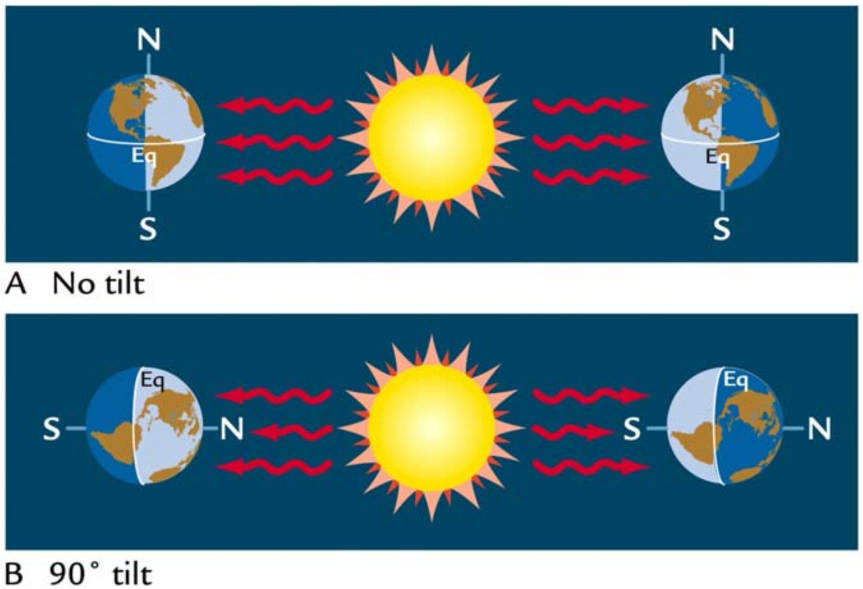
Rate of Tectonic Movement



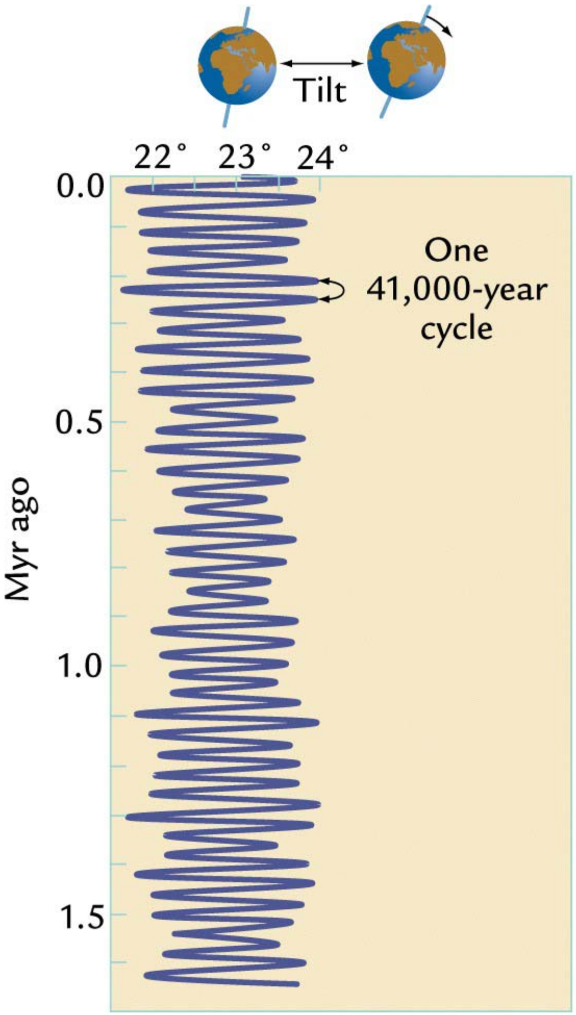
The Earth's Orbit

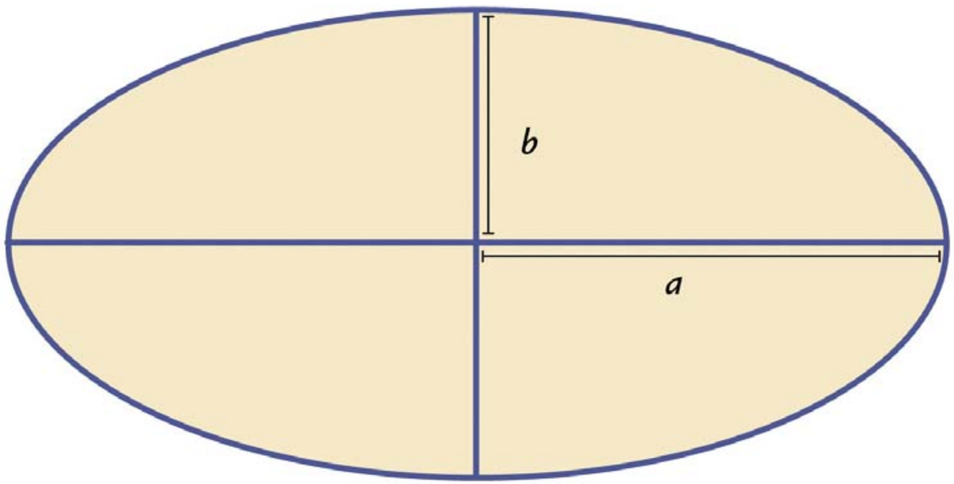




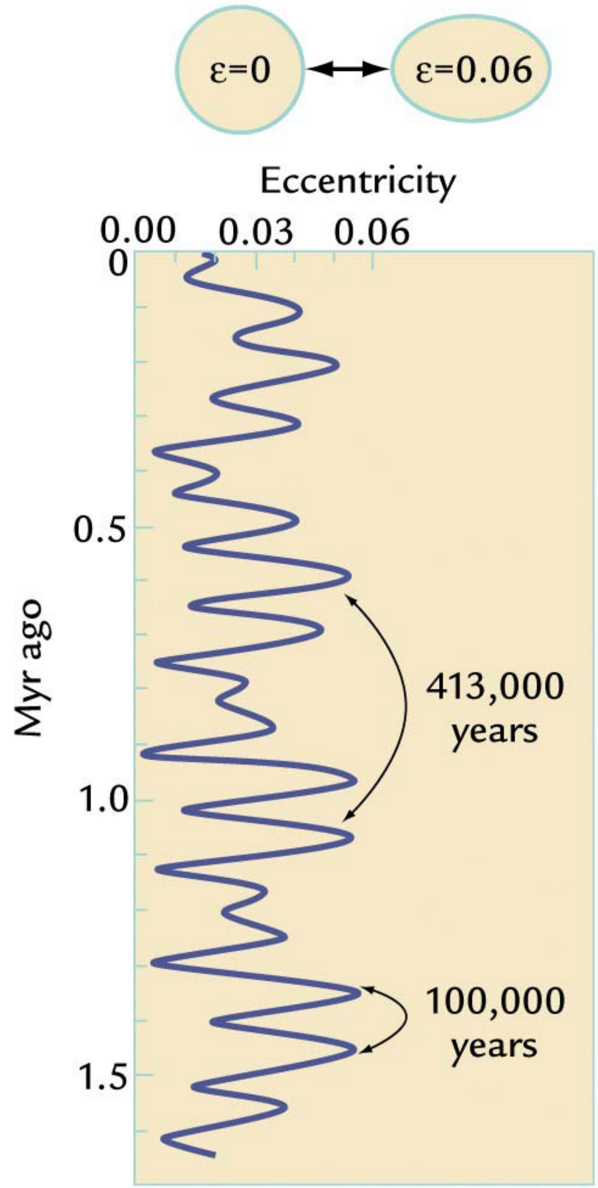


Long-term changes in tilt: Changes in the tilt of the Earth's axis have occurred on a regular 41,000-year-cycle

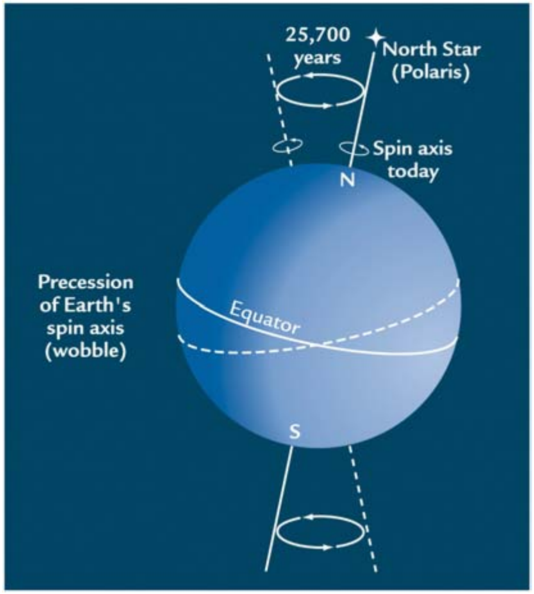




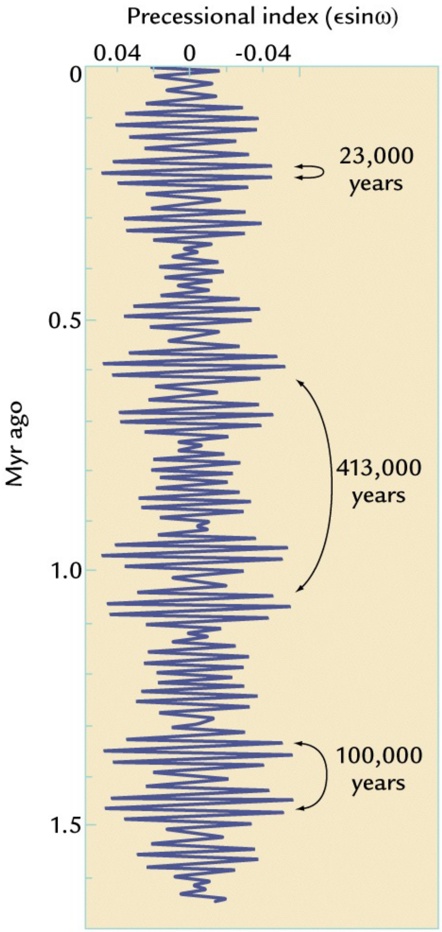
$$\text{Eccentricity } \varepsilon = \frac{(a^2 - b^2)^{1/2}}{a}$$

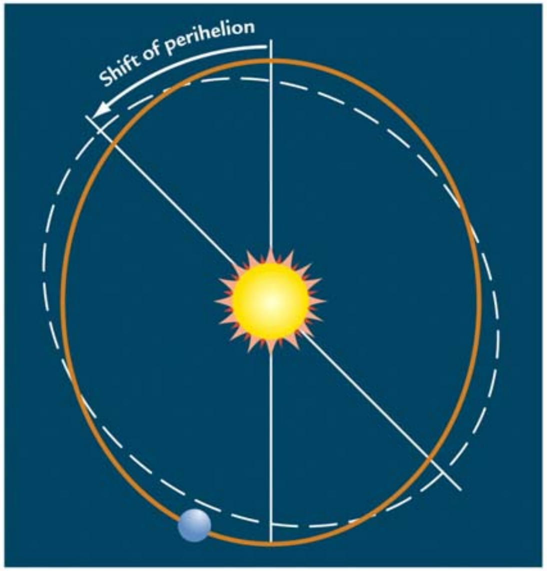


Long-term changes in eccentricity: The eccentricity of the Earth's orbit varies at periods of 100,000 and 413,000 years.

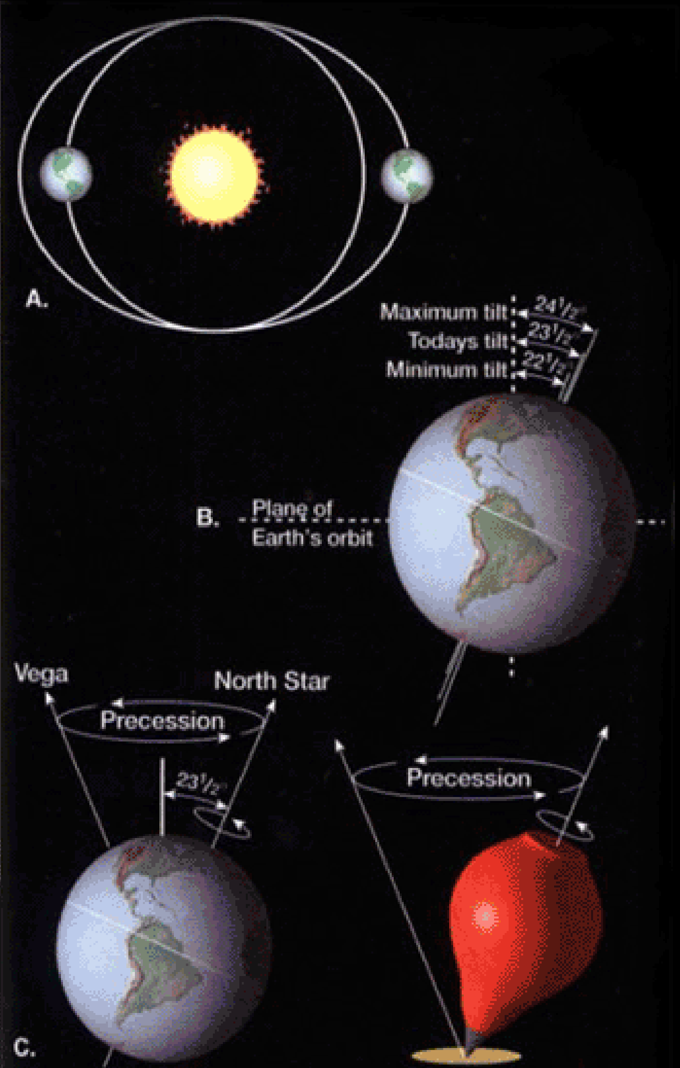


Long-term changes in precession: The precessional index changes mainly at a cycle of 23,000 years



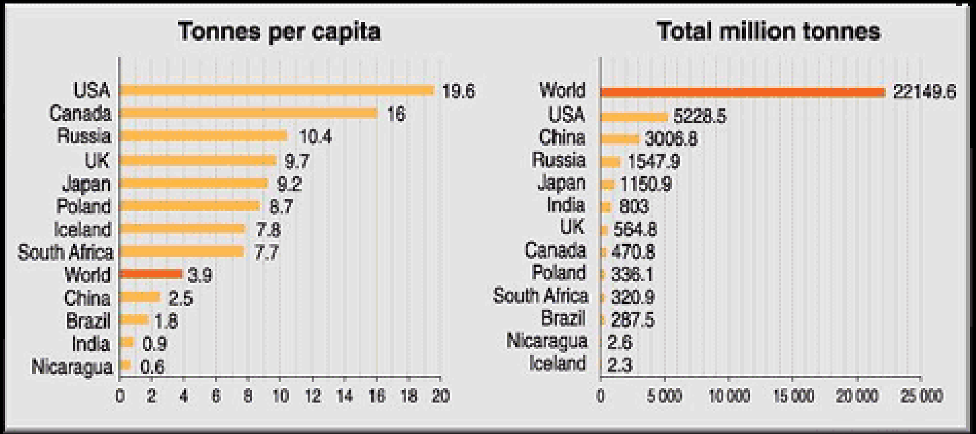


Milankovitch Forcing:
Variation in Incident Solar Radiation Due to Natural Variations in Earth's Orbit



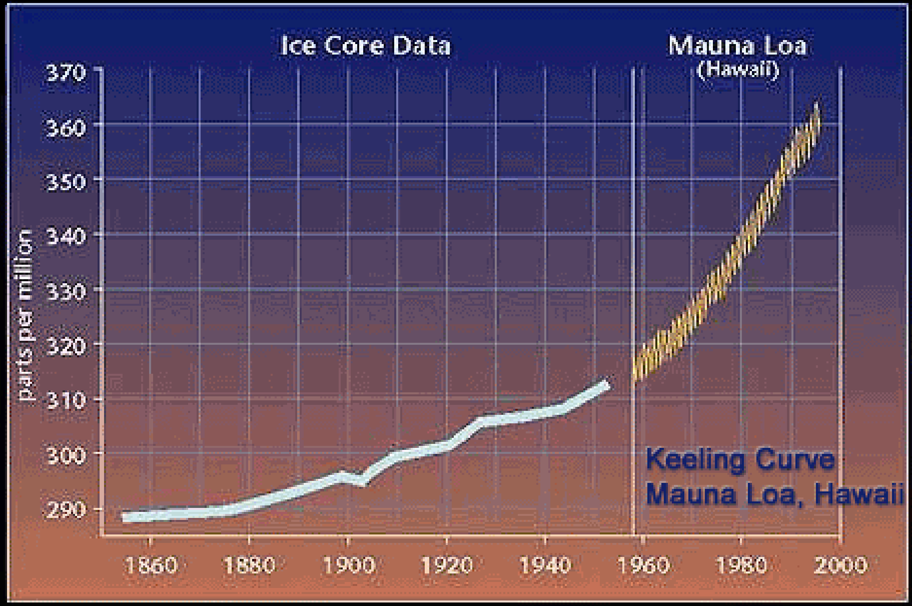
Milankovitch (1941)

Anthropogenic CO_2 Emission

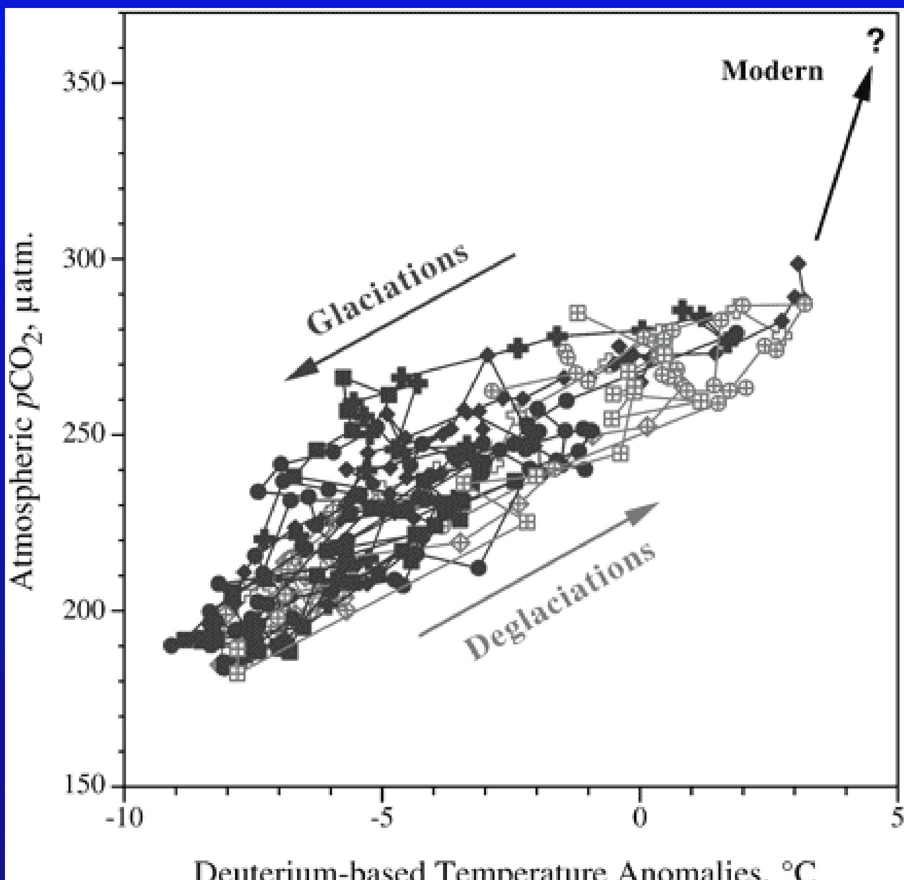


Source:International Energy Agency 1998

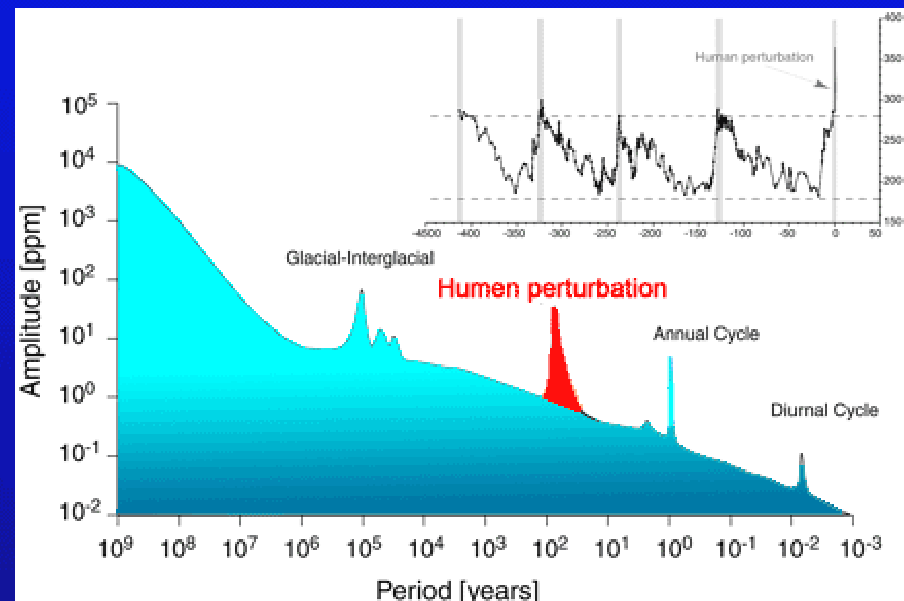
Carbon Dioxide Concentrations



Correlation between pCO_2 and temperature anomalies as recorded in the Vostock ice core. 420,000 year period



Schematic variance spectrum for CO_2 over the course of Earth's history



J. R. Petit et al., Nature 399, 429 (1999).

Falkowski P, Scholes RJ, Boyle E, et al. SCIENCE 290 (5490): 291-296

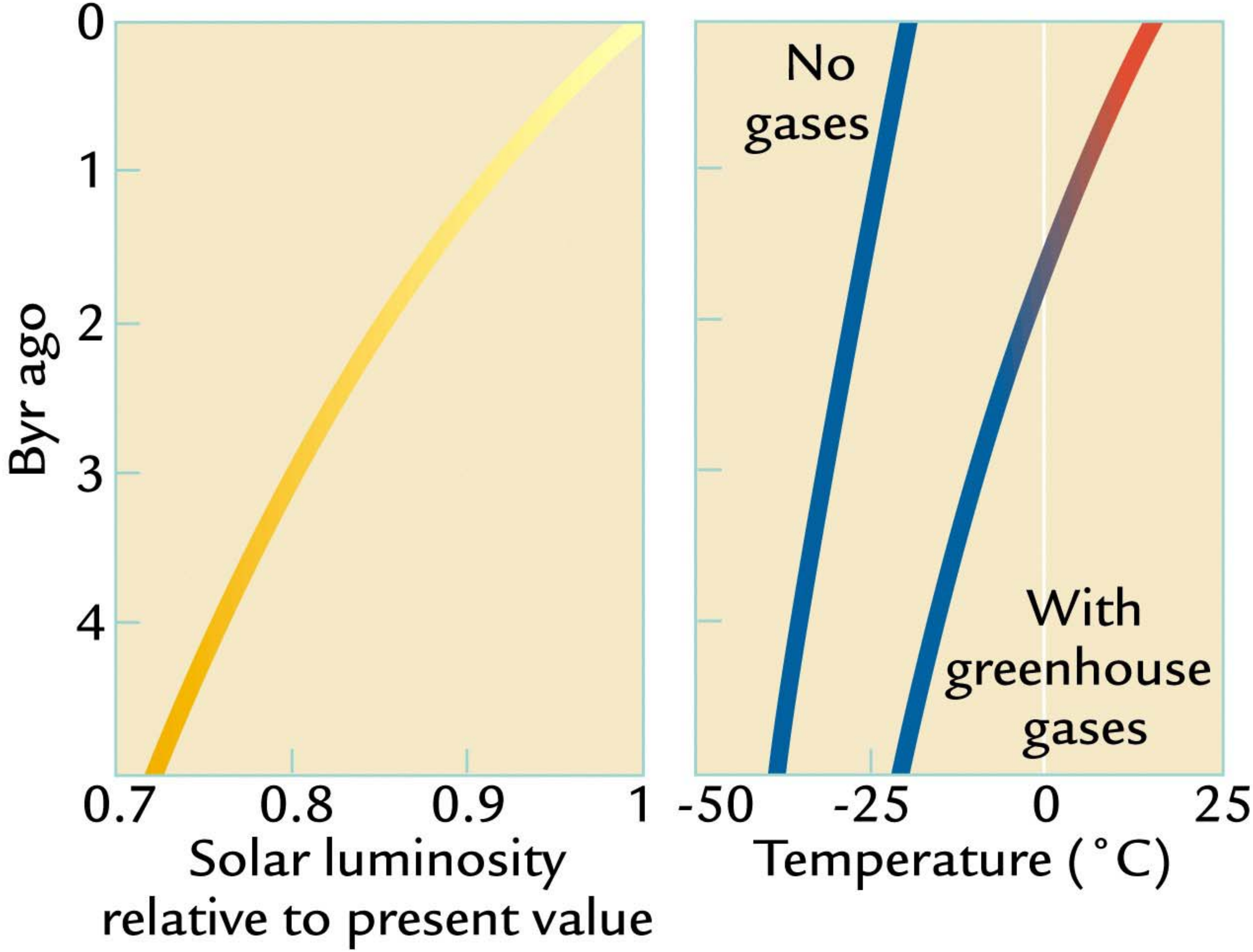
Review of Lecture 1

Aim: Cover the long-term processes of the carbon cycle.

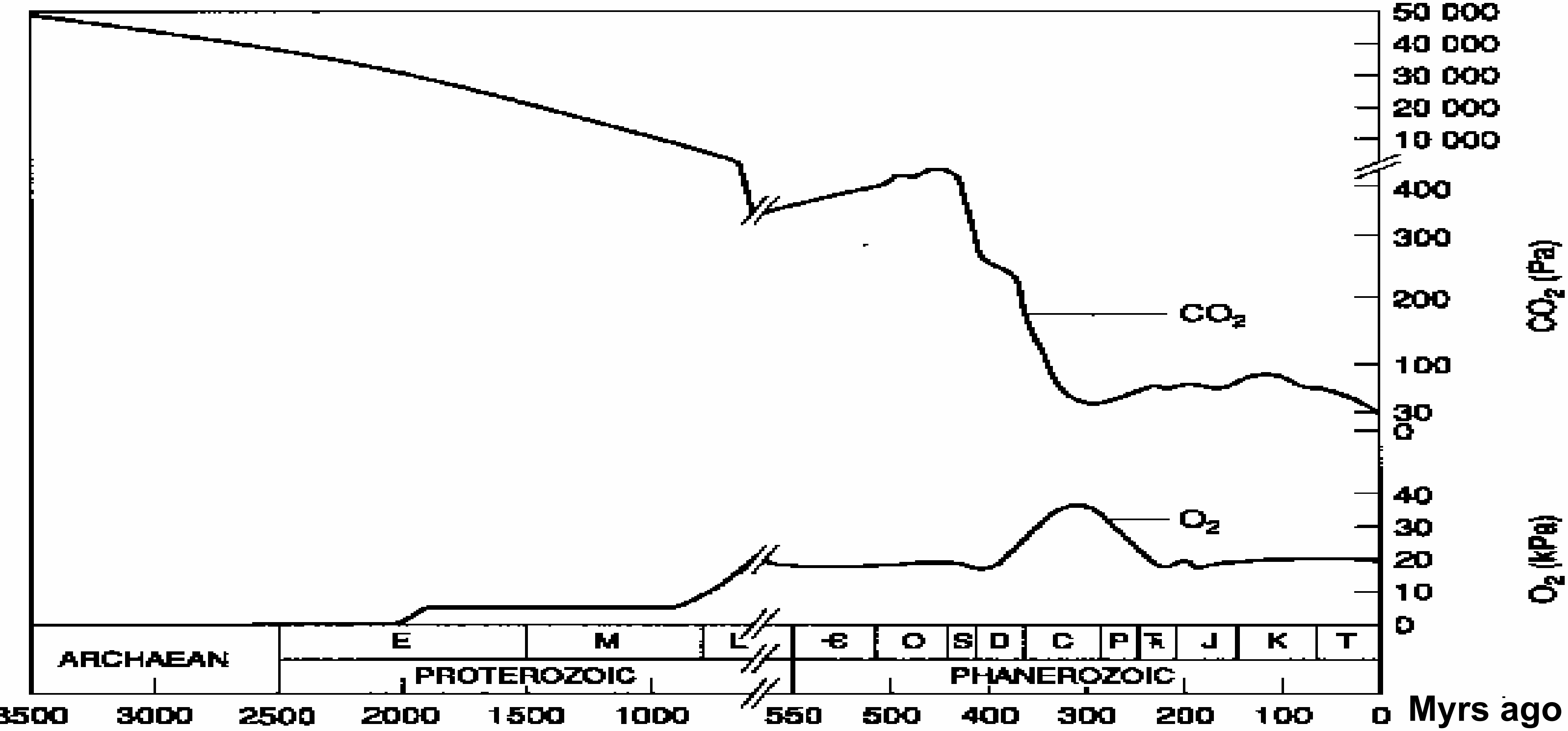
- **CO_2 release into the atmosphere.**
- **Removal of CO_2 from the atmosphere via chemical weathering.**

These processes have existed in a dynamic equilibrium that has kept the Earth's climate relatively constant.

The Faint Young Sun Paradox



Atmospheric CO_2 Levels



Falkowski and Raven 1997

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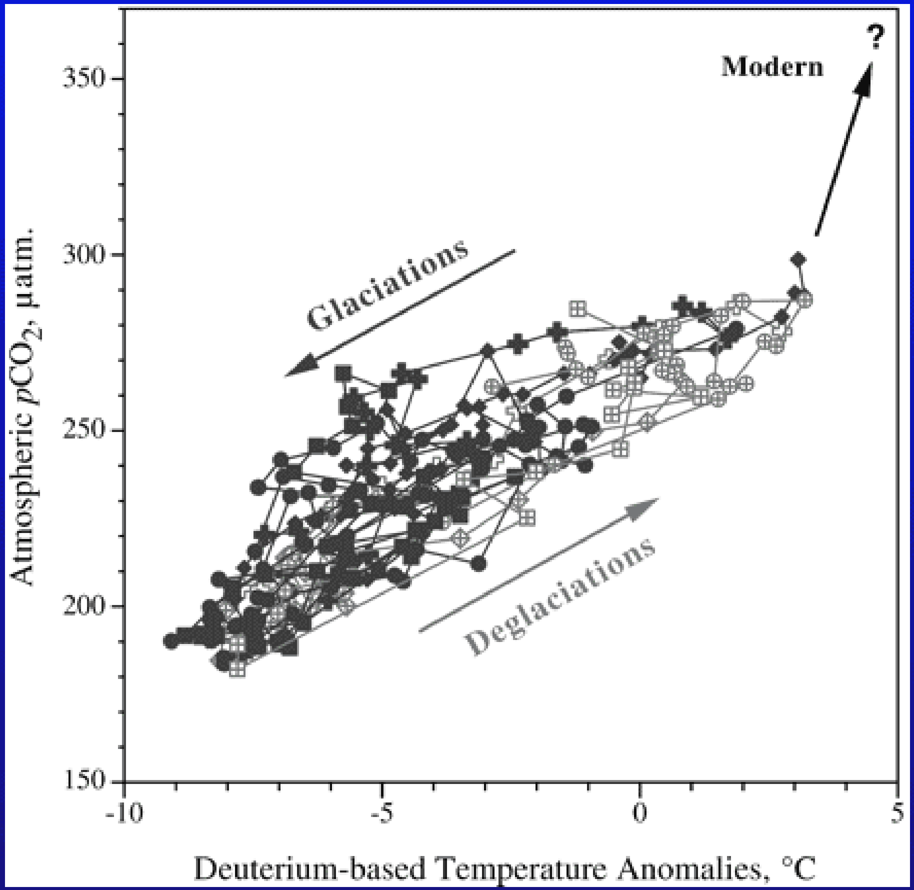

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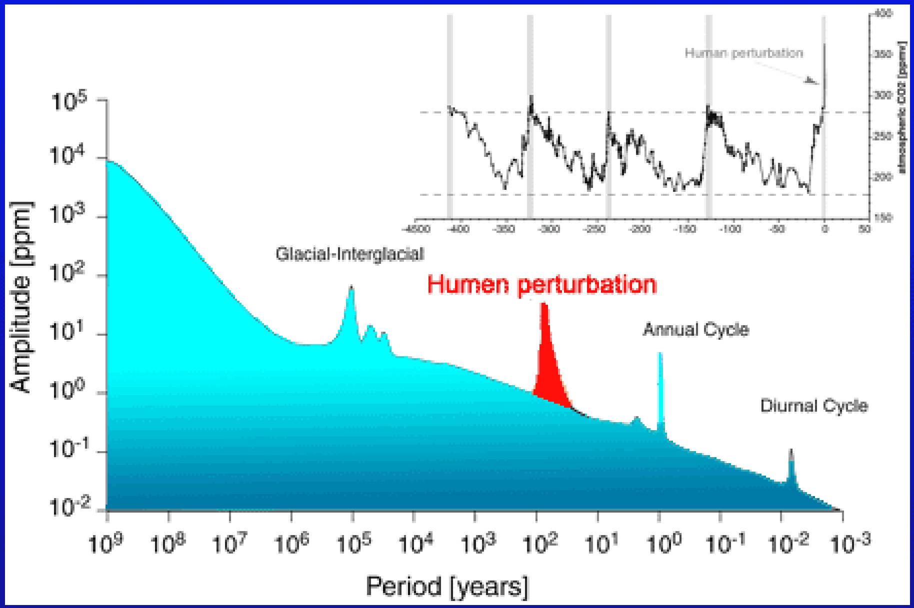

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Falkowski P, Scholes RJ, Boyle E, et al. SCIENCE 290 (5490): 291-296

The Carbon Balance

each year...

- 6.3 Gt from fossil emissions
- 1.6 Gt emitted from land-clearing

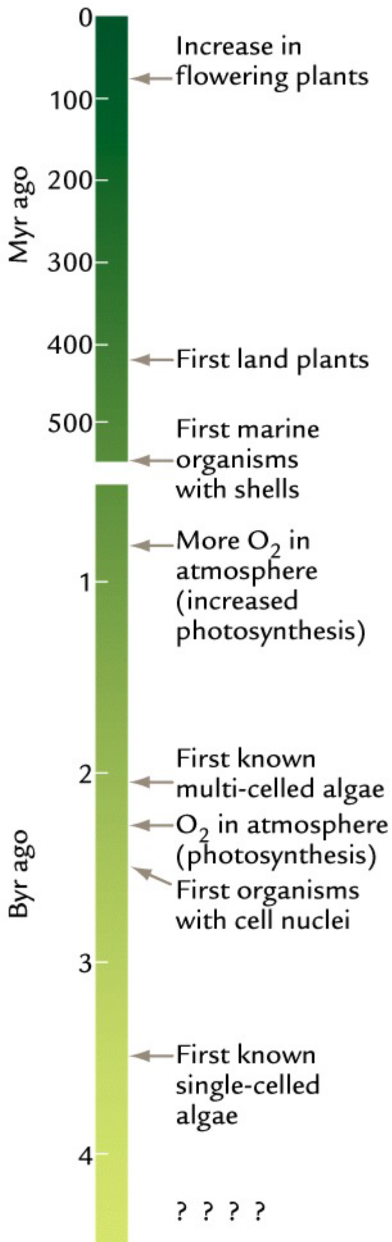
- Leaving a net 7.9 Gt in the atmosphere (estimated)

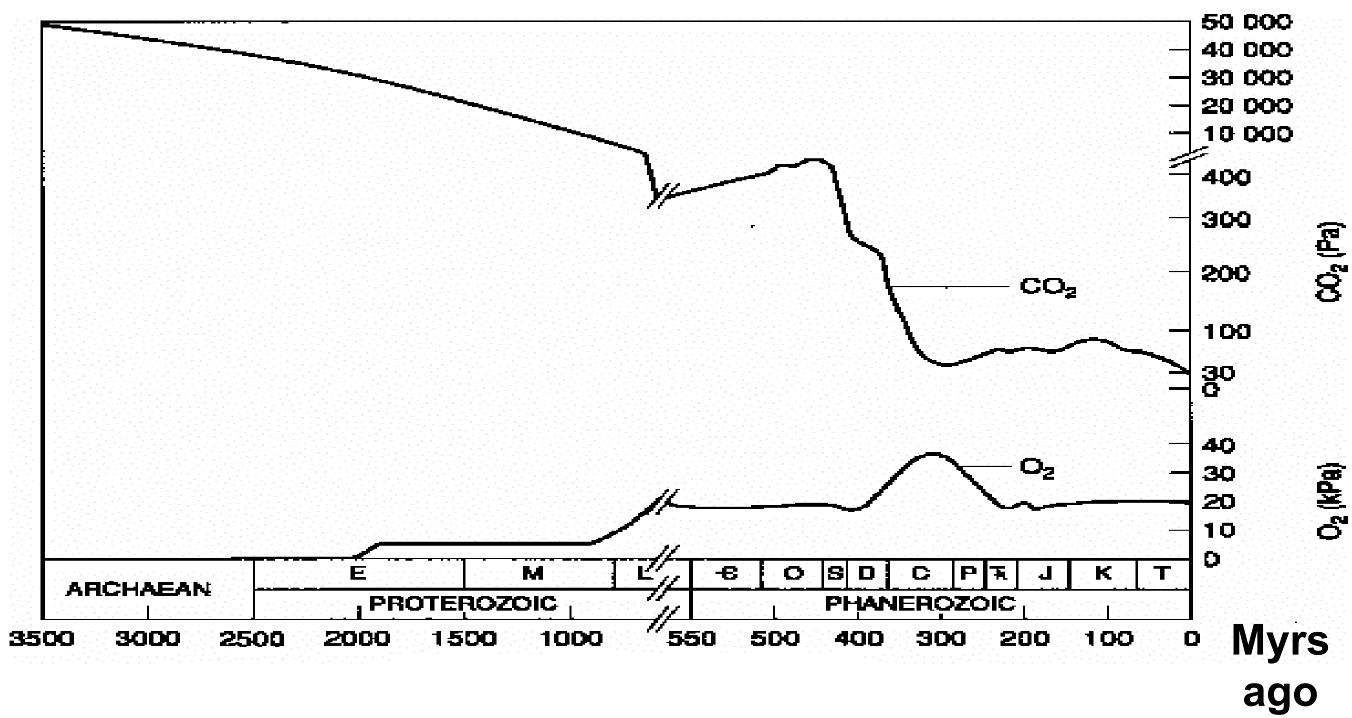
The Balance

each year...

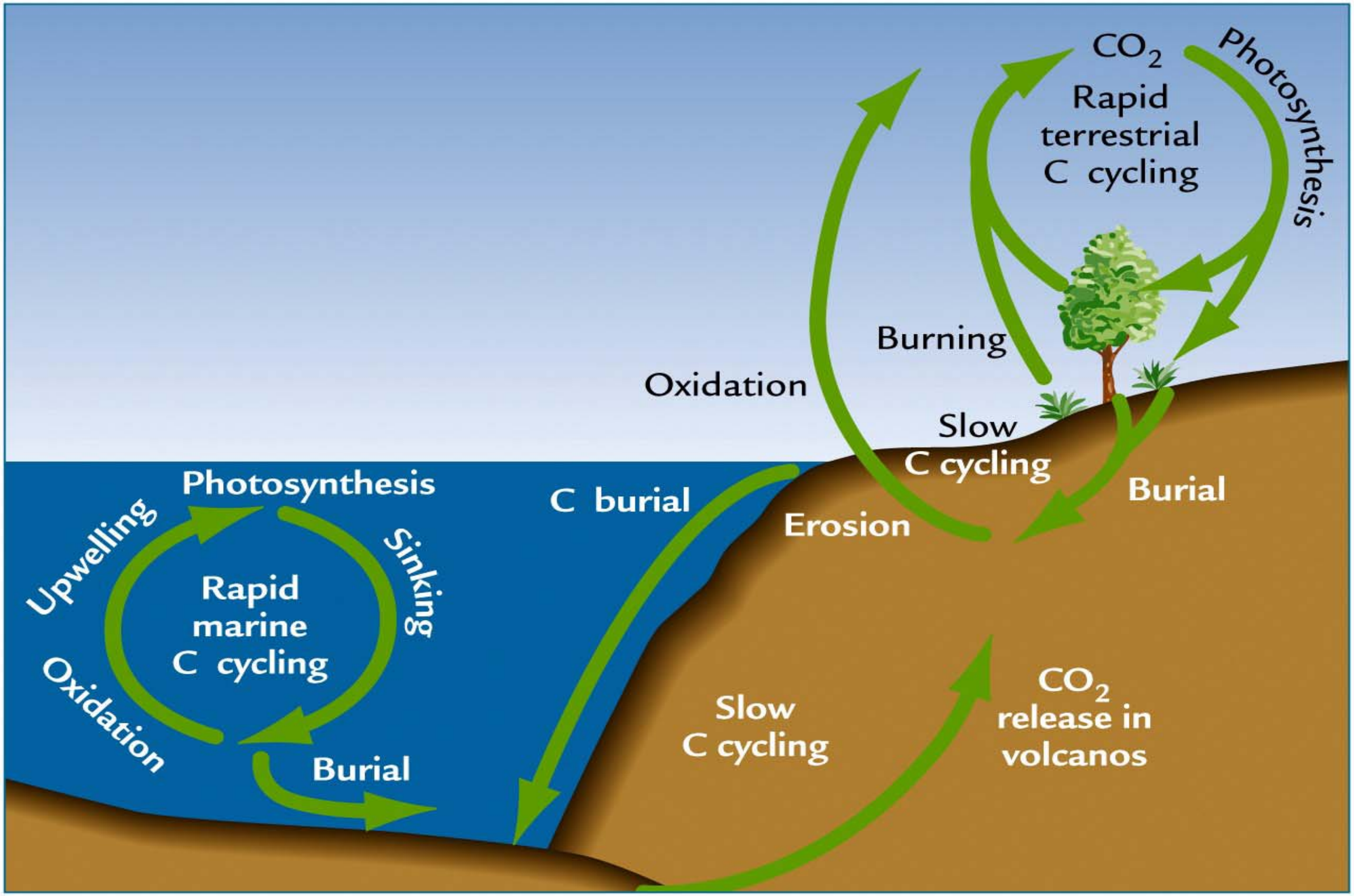
- 6.3 Gt from fossil emissions
- ca. 1.6 Gt emitted from land-clearing
- 1.7 Gt net uptake into ocean systems
- 3.0 Gt into terrestrial systems
- Leaving a net 3.2 Gt in the atmosphere

The evolution and global effect of photosynthetic organisms

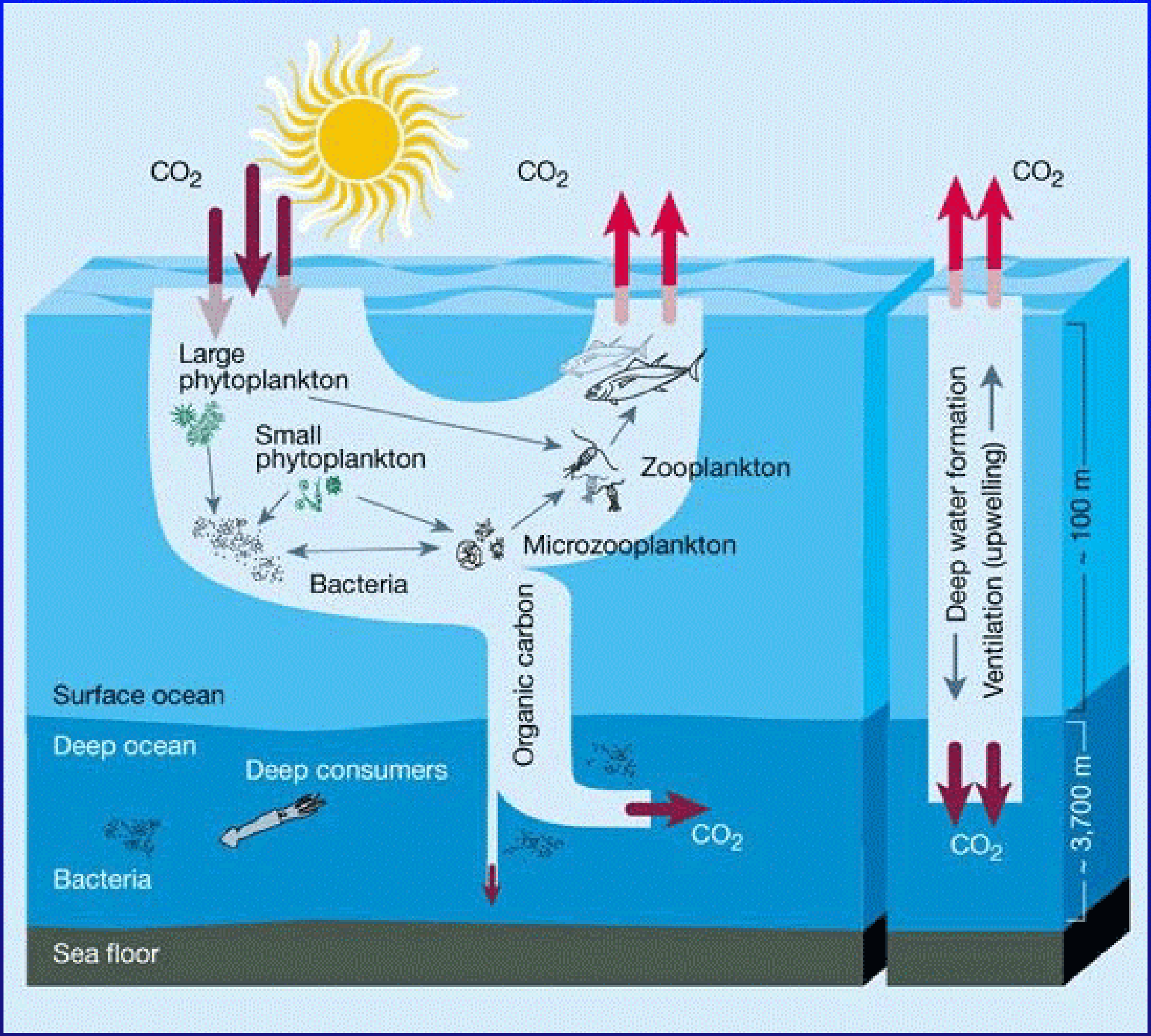




The Organic Carbon Cycle

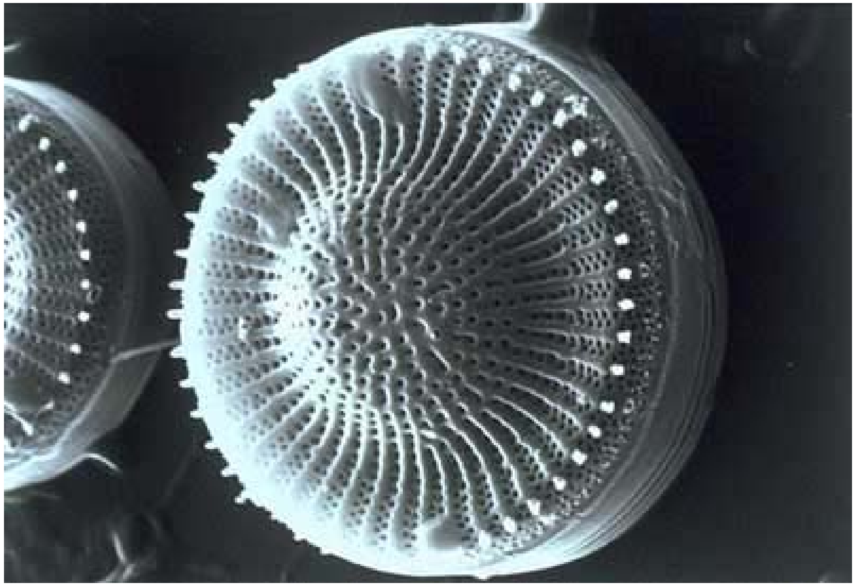


The Biological Pump

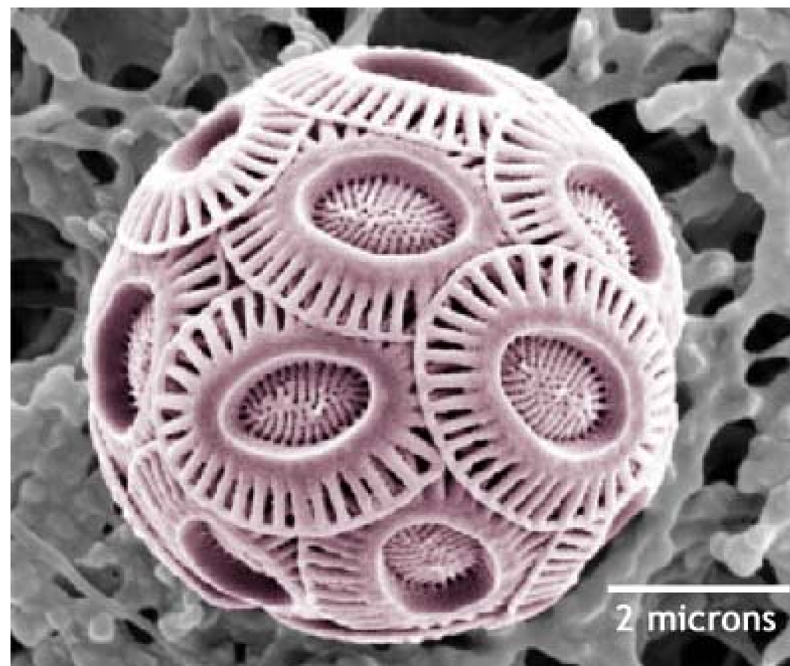


Z.Johanson; S.W., Chisholm Nature, V 40, p685

Diatom



Coccolithophore

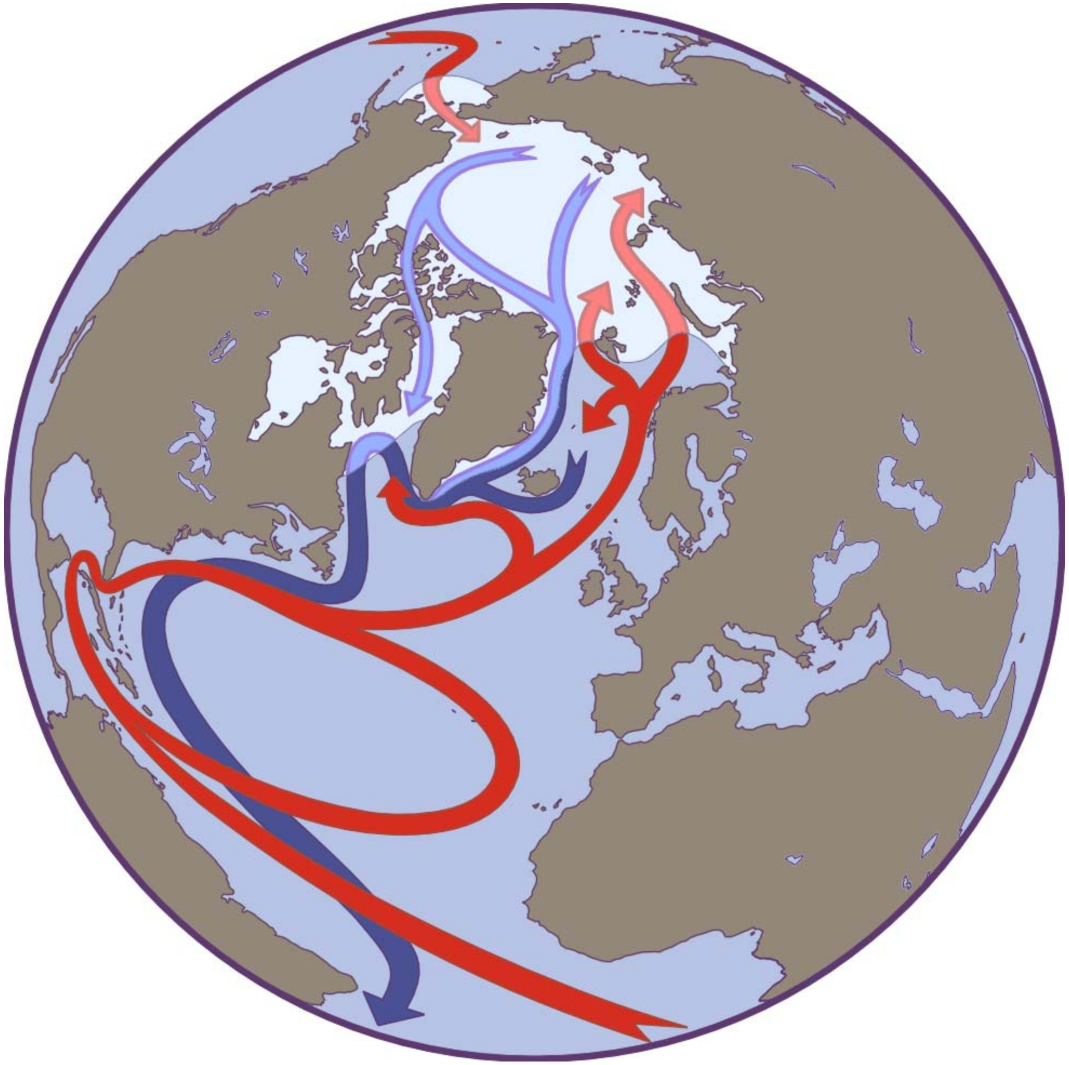


Fertilizing the oceans:

IonEx - Experiments

HNLC: High Nutrient Low Chlorophyll
Iron is the limiting factor.
Hypothesis to fertilize the ocean with iron, increase productivity of the phytoplankton, therefore increase amounts of carbon removed from the atmosphere.

Ocean Circulation

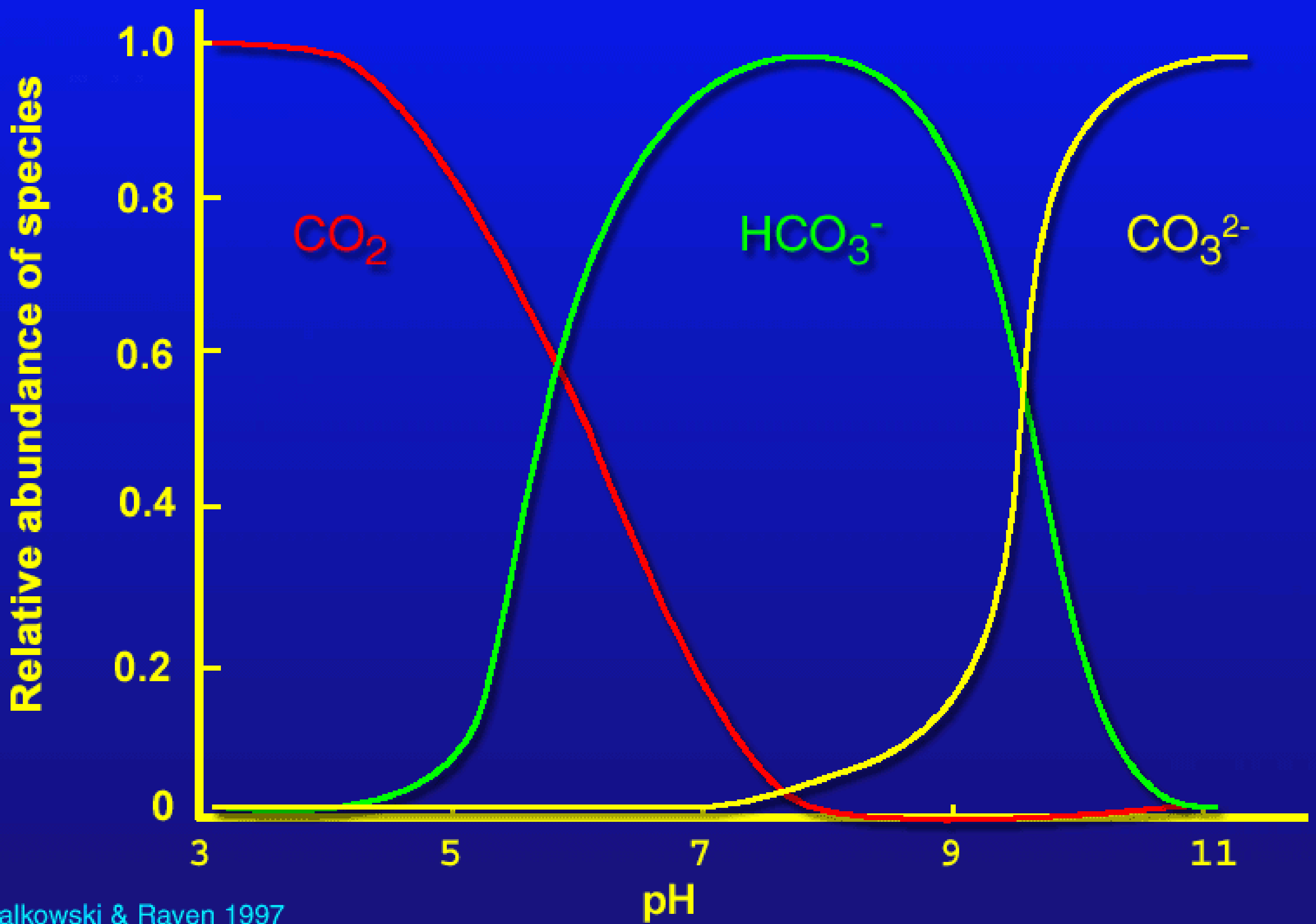


Ocean Sinks

- Solubility pump
  - CO_2 taken up in high latitudes
  - Transported to low latitudes
- Biological pump
  - 45 Gt C /y uptake via a C pool of 1 Gt C of phytoplankton
  - Mostly in low latitudes

The Carbonate System

Speciation of inoganic carbon in aqueous phase as a function of pH



Falkowski & Raven 1997

Inorganic carbon chemistry in aquatic environments

Rapid association - dissociation reactions

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

and

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

Slow hydration (hydroxylation)- dehydration (dehydroxylation)

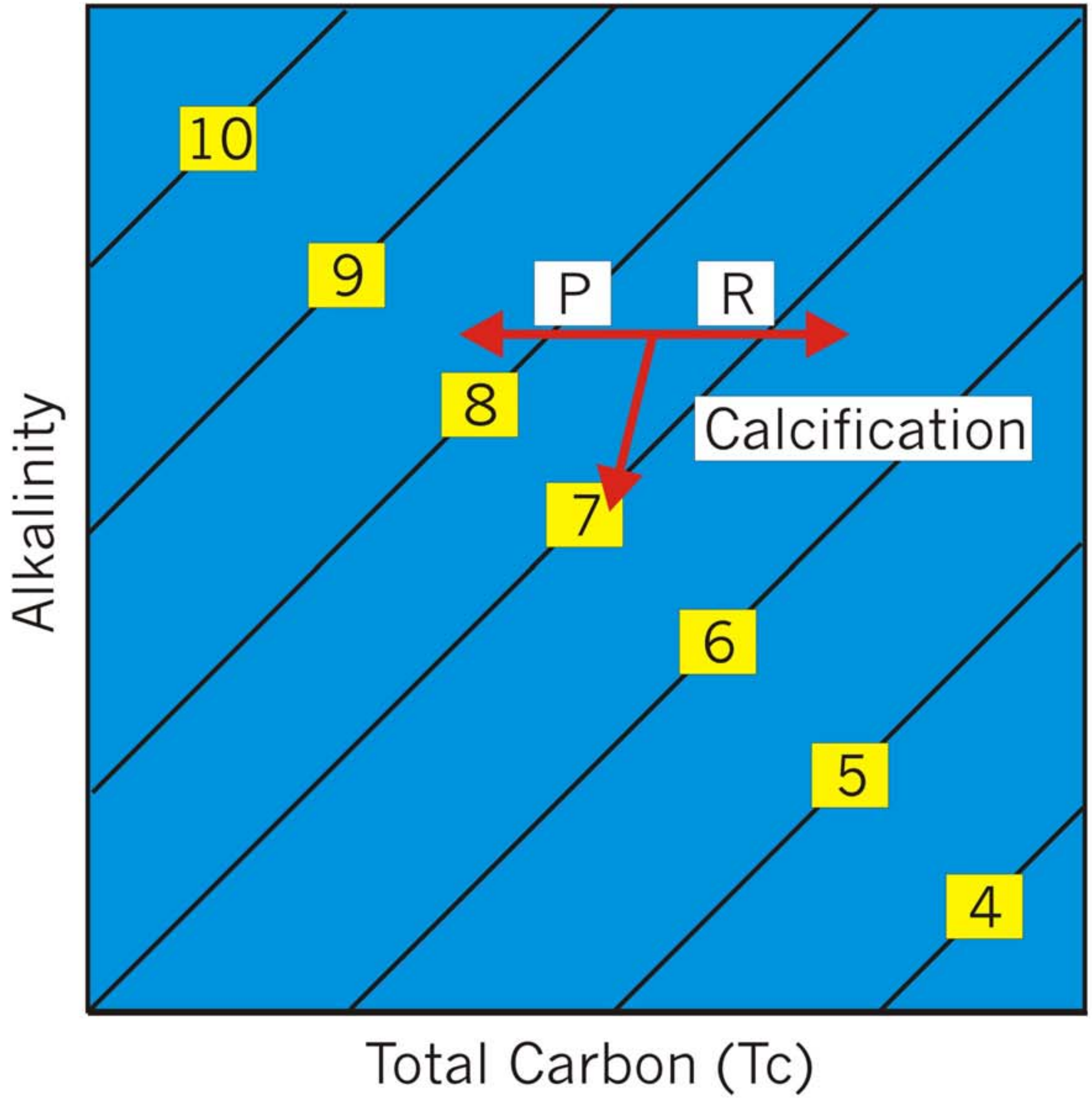
$$H_2O + CO_2 \leftrightarrows H_2CO_3$$

and

$$OH^- + CO_2 \leftrightarrows HCO_3^-$$

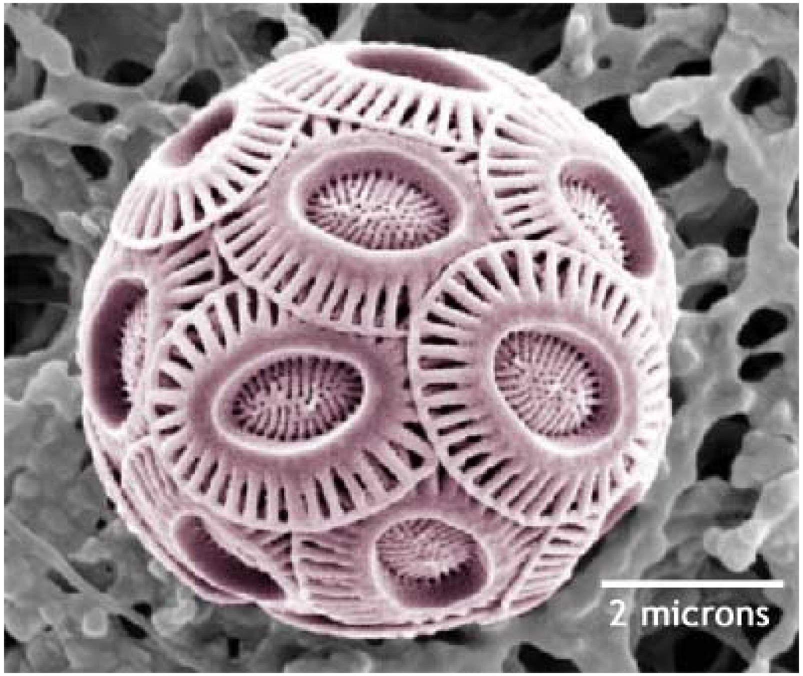
Falkowski & Raven 1997; Johanson 1982

Deffeyes Curve



Foraminifera

Coccolithophore



Oxygen Fractionation

$$\delta^{18}O = \frac{(^{18}O/^{16}O)sample - (^{18}O/^{16}O)standard}{(^{18}O/^{16}O)_{standard}} \times 1000$$

2 stable (nonradioactive) isotopes of Oxygen:
^{16}O – 99.8%; ^{18}O the rest.

Samples with large amounts of ^{18}O have more positive $\delta^{18}O$ values and are ^{18}O-enriched

Samples with small amounts of ^{18}O have more negative $\delta^{18}O$ values and are ^{18}O-depleted

Oxygen fractionation (physical)

- **^{16}O is more easily evaporated than ^{18}O**

- **Leaving water vapor enriched in ^{16}O**

- **If this vapor falls as precipitation and becomes locked up in ice-sheets (a cold climate) then surface waters become relatively ^{18}O enriched**

- **$\delta^{18}O$ values and are ^{18}O-enriched**

Carbon Fractionation

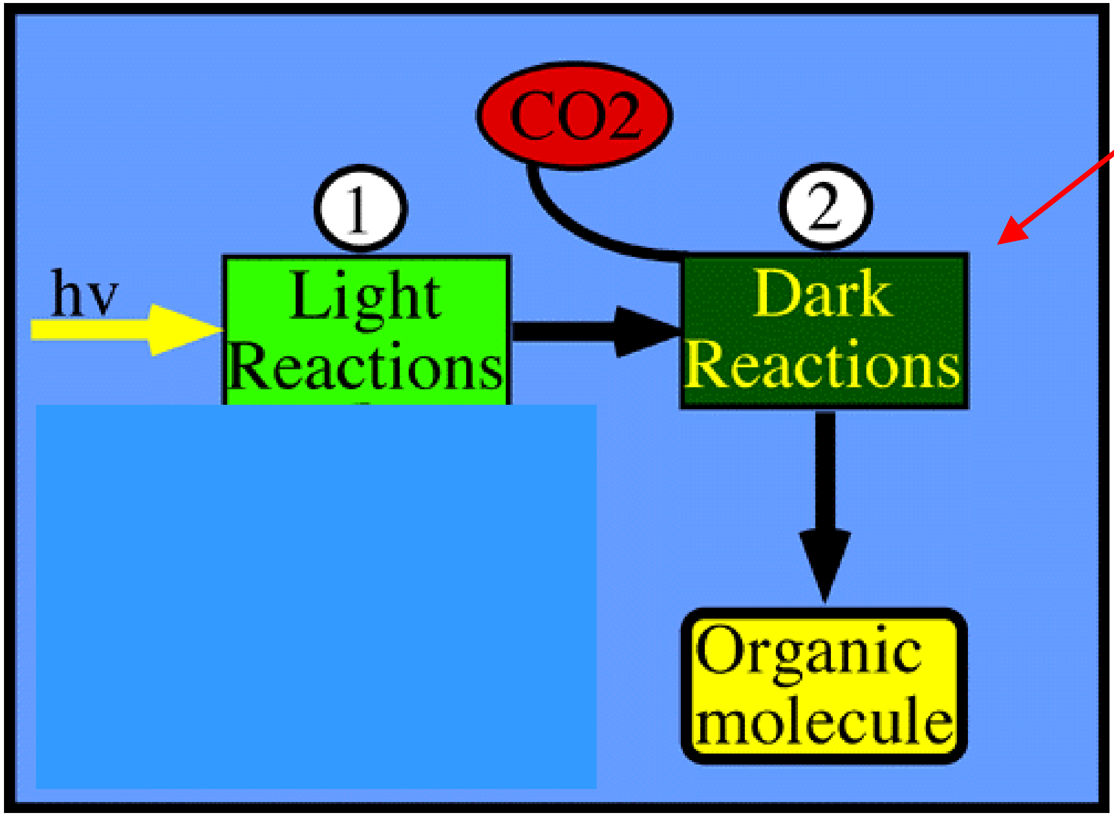
$$\delta^{13}C = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}}{(^{13}C/^{12}C)_{standard}} \times 1000$$

2 stable (nonradioactive) isotopes of Carbon:
^{12}C – 99%; ^{13}C the rest.

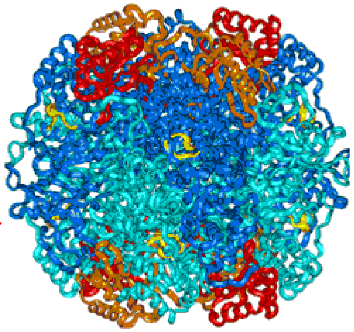
Samples with large amounts of ^{13}C have more positive $\delta^{13}C$ values and are ^{13}C-enriched

Samples with small amounts of ^{13}C have more negative $\delta^{13}C$ values and are ^{13}C-depleted

Carbon Fractionation during Oxygenic Photosynthesis

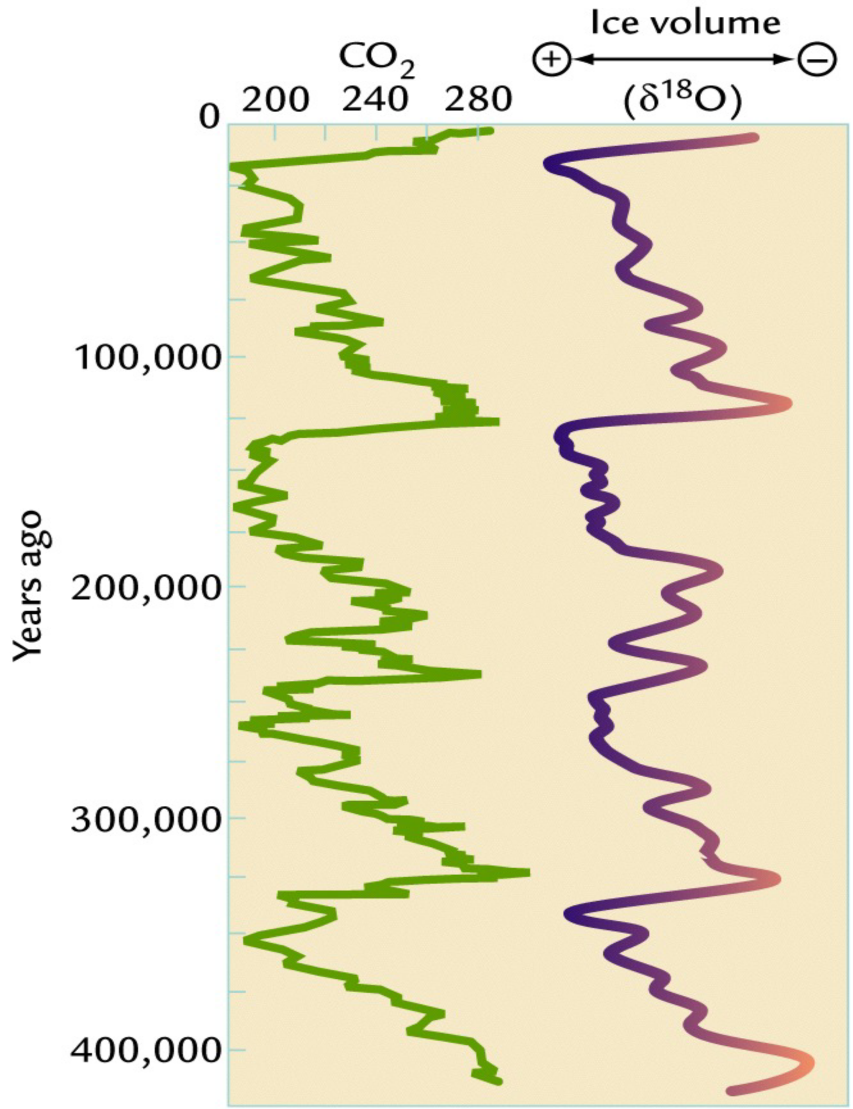


Rubisco: Fixes CO_2



Preferentially fixes ^{12}C

Correlation of atmospheric Carbon and Ice Volume



Falkowski et. al. The Global Carbon Cycle: A Test of our knowledge of Earth as a System. Science; 2000 vol. 290 pp. 291-296

Hoffman et. al. A Neoproterozoic Snowball Earth. Science; 1998 vol.. 281 pp 1342-1346

Berner. Examination of hyphotheses for the Permo-Triassic boundary extinction by carbon modelling. PNAS; 2002 vol. 99 pp. 4172-4177

Norris and Rohl. Carbon cycling and chronology of climate warming during the Palaeocene/Eocene transition. Nature; 1999 vol. 401 pp. 775-778